TECHNICAL NOTE

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Three-Dimensional Imaging in Forensic Anthropology: A Test Study Using the Macintosh

REFERENCE: Ackermann RR. Three-dimensional imaging in forensic anthropology: A test study using the Macintosh. J Forensic Sci 1997;42(1):93–99.

ABSTRACT: Forensic anthropologists have unique, albeit usually fleeting, access to modern skeletal remains. By constructing a database of three-dimensional images, such remains can be accessed long after the remains are gone. A method is proposed which uses Macintosh hardware and NIH Image software to preserve remains digitally through red-blue three-dimensional imaging techniques. Additionally, the qualitative and quantitative accuracy of these images is assessed. By creating this type of forensic database, anthropologists can address issues such as populational variance, thereby using modern forensic skeletal remains to explore some of the fundamental issues within anthropology.

KEYWORDS: forensic science, forensic anthropology, imaging, computers, craniometrics

Currently, when a forensic anthropologist receives a case, most of the analysis involves the application of standard rules for sexing, aging, racing, etc. This requisite data collection uses both qualitative observation and quantitative measurement. The collected data is most often of a very specific kind and limited in scope, as the aim is to determine certain factors, with each individual case having a different set of these factors. Later analysis of this information by a researcher hoping to compile a broad and statistically significant set of data may or may not reveal the specific bits of information being sought—the measurement of some particular feature was perhaps not a required factor in the individual case, therefore, the time was not taken to collect what was at the time perceived as extraneous data.

However, using computer imaging to record, measure, and analyze these data would not involve a significantly longer amount of time or a more involved process. In fact, with computer imaging techniques, an impressive data set can be recorded in a fraction of the time it might take to do it manually. Thus, there would exist an enormous amount of data for all kinds of analyses involving both immediate and future research; data which are significantly more complete than the information usually recorded during regular casework. Additionally, this immense information source can be stored permanently in computers, allowing future researchers to explore new paths of inquiry.

Forensic anthropologists strive to gather as much information about the osteological remains being studied as is physically possible. This includes the analysis of basic elements such as length, width, and shape, as well as more specialized components such as pathology, anomaly, and pattern (symphyseal face pattern or rodent gnaw marks, for example). For such analyses, more data is definitely better.

For most osteological analyses, surface information, rather than internal structure, is of primary interest; the majority of important osteological data can be obtained by looking at the surface of bones (except perhaps for studies involving osteon counts and related areas). Such an approach eliminates the need for cross-sectional imaging like the types most frequently used in biological/medical imaging today.[2]

In short, the three-dimensional surface rendering necessary to preserve human remains digitally is truly closer to two-dimensional imaging in its simplicity. In somewhat simplified mathematical terms, when forensic anthropologists analyze an object, they need consider only the surface of that object, the area of which is proportional to the square of its dimensions, rather than the volume, which is proportional to the cube of its dimensions. This external surface analysis (rather than internal) greatly reduces the storage space necessary for data collection (the difference between x-squared and x-cubed) and allows for the use of simpler equipment, thereby reducing both hardware and software costs.

Materials and Methods

It is possible to achieve the goal of imaging bones using relatively simple computer technology which is currently available. Most of the visualization equipment used in biological imaging is significantly more complicated and expensive than is necessary for osteological surface imaging. Computer technology which uses hardware that captures two dimensional images and software that converts these images into three dimensions is the simplest solution to these imaging needs.

Stereographic techniques for reconstructing two-dimensional

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Received 16 Feb. 1996; and in revised form 28 May 1996; accepted 31 May 1996.

[2]CT in particular has been widely used in medicine and recently adopted by anthropologists (1–6). The amount of data produced by this technique, is, however, not always necessary for the needs of the forensic anthropologist. Additionally, the cost of the procedure and the storage hardware can be prohibitive.

image into three dimensions seem most appropriate for three-dimensional surface rendering because of the principle that underlies their development; these techniques strive to imitate human stereoscopic vision (7–10). Obviously, the incredibly complex human optical system creates nearly perfect renditions of three-dimensional objects for the brain to interpret. Likewise, such a stereoscopic method of data accumulation allows for complex and accurate three-dimensional digital representation and easy identification and interpretation of this data by the user.

The necessary hardware consists of a CCD camera and framegrabber, which can interface with any Macintosh computer with at least 4MB of memory and a monitor with the ability to display 256 colors or shades of gray.[3] The software package I chose was NIH *Image,*[4] for three reasons. First, it is useful and easy to use. Second, it is free. Third, the person who developed the software is continually taking suggestions and making improvements on the package. For this test study, because access to the CCD camera and framegrabber hardware was limited, analog black and white 35-mm photographs of the osteological remains were taken and sent them to a photo CD lab for conversion into digital images. For all practical purposes, the product is the same as that obtained through a CCD camera and framegrabber—it simply bypasses hardware costs.[5]

To create three-dimensional images, the premises of stereography were further simplified. The ultimate purpose of stereo imaging is to mimic the stereo vision of the human eye. Rather than taking images from two separate cameras and imposing them, or taking a single image of a landmarked bone, a simpler, more traditional method for creating three-dimensional images was used—red/blue 3-D superimposition. The samples were rotated on a turntable with graduation marks in order to photograph pair images from slightly different angles, much like what is done with the human eyes (Fig. 1). When these digital images are superimposed and one is colored red and the other blue, they can be viewed through 3-D glasses as three-dimensional images; the 3-D glasses are not necessary for the quantitative evaluation, only for the proper qualitative viewing. By photographing these pairs at equal intervals all of the way around the bone, *Image* can be used to stack them into a single image—this rotating three-dimensional image can be measured quantitatively (with the scale calibrated to millimeters) and can be manipulated in a multitude of ways (contrast, zoom, etc.).

For this test study, individual crania (skulls without mandibles) were imaged, some of which have unique qualities that could challenge the capabilities of this technique (Fig. 2). Because problems of scale and resolution seemed negligible, I decided that it would be useful to tackle the complexities of the cranium (overall size, diverse surfaces, etc.). Additionally, the quantitative accuracy and usefulness of the imaging can be assessed by comparing established caliper measurements of the skulls with computer measurements. Also, the cranium is central to the issue of human variation—a subject that I will briefly address later.

Results

Qualitatively, the imaging process used was excellent. It is possible to visualize fine details on the crania, including fissures within the eye orbits Fig. 3. Two trauma cases were specifically included in the sample to see how well the imaging worked when dealing with darkened and damaged crania; although the blackening of cranium 2 did negatively affect the image resolution, this effect was slight and caused only minor contrast problems. The resolution and contrast on cranium 4 remained excellent. An additional bonus with this photographic scanning (Photo CD—as opposed to CCD photography) method is that the images are stored on the CD in five different resolutions—the quality of the image is only truly limited by the amount of memory in the hardware set-up.[6]

Quantitatively, there are some minor problems with absolute measurements which I believe are solvable. Table 1 shows a comparison of cranial measurements taken with both calipers and the computer. The only unlocatable point on the computer image was basion, which could be rectified by rotating the skull in the perpendicular plane, therefore, any measurements which include basion are marked "N/A." Because crania were used, depth and breadth might cause some measurement difficulties. Therefore, when the initial computer measurements did not exactly duplicate the caliper measurements, a crude calibration was done to see if it was possible to reduce the error. Making the assumption that the caliper measurements on cranium 1 are accurate, the pixel/mm value for each linear measurement of cranium 1 were used as dividers to convert the measurements for each of the other four crania to millimeters. These values are as follows: Glab-Opis, 4.505 pixels/mm; Eur-Eur, 4.336 pixels/mm; Zyg-Zyg, 4.770 pixels/mm; Prosth-Na, 4.519 pixels/mm; Ala-Ala, 5.362 pixels/mm; Mastoid length, 5.260 pixels/mm. The final calibrated measurements are reported in Table 1. In order to further reduce these measurement inaccuracies, a Macro program for calibrating the measurements based on a somewhat spherical shape needs to be created.[7] This type of calibration which is generally used to correct data distortion, called geometric transformation, is a generally accepted technique for working with two-dimensional data sets on three-dimensional objects (13). Even without such calibration, the crude calibration technique used here brings most of the measurements below the allowable interobserver error amount of 2 mm.[8]

Depth and breadth are larger considerations when dealing with crania than with any other bones of the body. However, they have caused slight measurement inaccuracies, these do not appear to be insurmountable and should not invalidate the use of imaging processes for storing and analyzing human remains. However, even

[3]An ideal new technology has surfaced—digital cameras such as the Fotoman—where the camera is used just like any 35-mm camera and is plugged into your computer for direct interfacing. In this manner, the framegrabber is eliminated from the necessary system hardware and the necessary field equipment is reduced to something the size of a camera. However, when I used this technology, I discovered that it has glitches that need to be ironed out. First, the image resolution is lower than that of the CCD video cameras. Second, it does not allow the operator to adjust parameters—for each image it automatically adjusts things like contrast and lighting. Due to these problems, the images that I produced were not uniform in contrast and were frequently saturated. However, this is relatively new equipment, and with time and improvement, will be ideal for the kind of imaging that I propose.

[4]NIH *Image* is a public domain image processing and analysis program for the Macintosh written by Wayne Rasband (wayne@helix.nih.gov) at the National Institutes of Health, USA.

[5]However, due to out-of-pocket processing costs, it has also limited the size of my test study.

[6]Although I was only able to use the second to lowest resolution (due to memory constraints) the image was still quite clear.

[7]A Macro program is a program that will automate a complex procedure or complex calculation.

[8]This is, of course, assuming that the caliper measurements are exactly accurate—user error causes ranges of accuracy in even the most finely calibrated calipers. It is important to note that both calipers and computers are incredibly accurate tools—they lose their accuracy in application. If user error for both the caliper and computer is 2 mm, then all of the measurements fall within acceptable error allowances—that is, less than 4 mm between caliper and computer measurements.

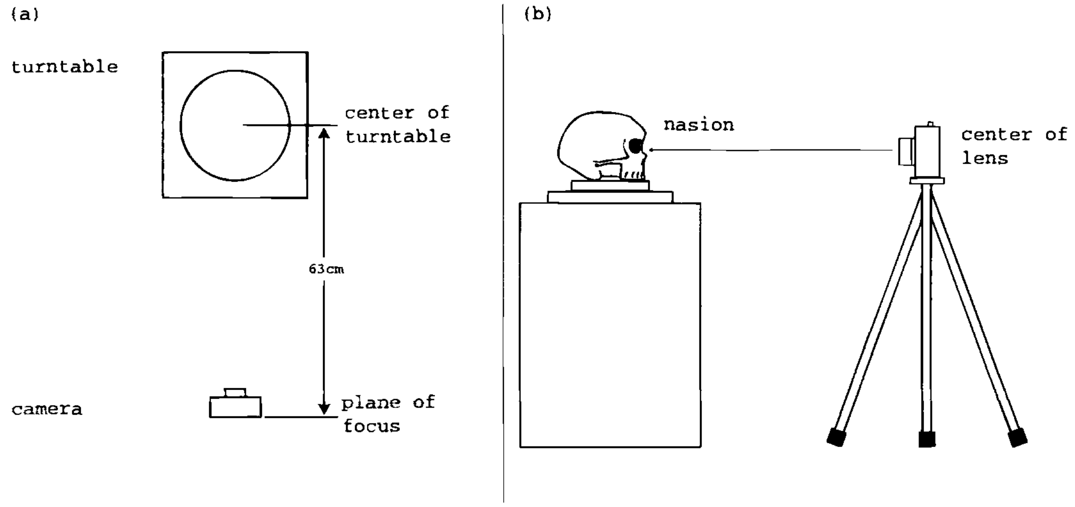

FIG. 1—*The imaging set up.* (a) *plan view;* (b) *lateral view.*

with the slight inaccuracies, the measurements are still useful for comparative quantitative assessment, such as comparing the variation between specimens. Additionally, the ability to view a specimen in three-dimensions on the computer has many benefits when compared to some current methods of archiving skeletal data that simply store huge data pools of measurements.

For example, the University of Tennessee, Knoxville, has assembled an extensive database of osteological measurements. The measurements are largely cranial, with about 75 caliper measurements taken per specimen, although there are also some postcranial data. As of 1989, this database contained over 850 records of forensic cases, 60% of which have documented histories (sex, age, and race); today the number is probably closer to 1500 (14). But what happens if an investigator wants to research measurements that were not recorded? This data bank would then be useless. And what if a researcher wants to correlate measurements with non metric traits, or wants to focus solely on non metric traits? The presented imaging technique will capture shading, texture, detail (such as fissures and minute foramina), pathology, trauma, and other such individually distinctive features with excellent quality. This type of information is not retrievable from a database of measurements. Additionally, the quality of these images far exceeds that of traditional reconstruction techniques that utilize CT data or laser scanning, at a significantly lower price using much less processing time and memory Table 2.

It is also important to note that this technique for imaging skeletal material will build on and could incorporate information collected in databases like the one at the University of Tennessee. Once this process incorporates geometric transformation techniques for data correction and is further calibrated for increased quantitative accuracy, it will equal (or surpass?) the accuracy of such databases for measuring continuous traits. It will, however, also offer accurate analysis of discontinuous traits, providing this and other important qualitative data that a merely numerical database cannot. Further, the quantitative measurements possible are not limited by previously established standard measurements (like the 70+ craniometric measurements in the University of Tennessee database); measuring any points of interest is possible (providing these points have been imaged). Additionally, digital images, such as this technique produces, can be shared via the Internet, particularly now via the World Wide Web and its graphic icon-based interfaces, making national and international collaboration possible and practical.

Intra- and Inter-observer Variability

Intra-observer and Inter-observer variability are important concerns when investigators are performing repeat measurements on skeletal material. By taking repeat measurements of each cranium, it is demonstrated that this imaging technique yields low ranges of intra-observer variability Table 3. Additionally, with automation using pattern recognition techniques, computer measuring offers the opportunity to eliminate inter-observer variability by consistently taking the same measurements, although this development is several years from being practically available. This is particularly significant when a system relies on multiple sources for its data, such as the University of Tennessee database does, and as this data collection system proposes to do.

Applications

Accurate imaging processes have many interesting and useful applications in physical anthropology, and specifically forensic anthropology. Because Native Americans are reclaiming ancestral remains, the skeletal teaching collections around the country are rapidly disappearing. A method for digital preservation of such remains prior to repatriation could be invaluable. Furthermore, once the information is in a digital format, additional analyses can be performed by later individuals without rescanning, thus providing a much-needed new source of highly-accurate raw data for continuing research. The process would also be applicable in forensic anthropology; once the technique is refined, unknown skeletal remains could be input for identification purposes in criminal investigations, and one could imagine the possibility and potential of national and international databases of such images. A modern imaging data base of skeletal material could help to keep such charts current.[9] We live in a constantly changing population

[9]These imaging techniques would also be beneficial in computer engineering, particularly in developing areas such as robotics, to improve digital modeling techniques for further research, and in moving the fields of engineering closer to meaningful applications in biological sciences and biomechanics.

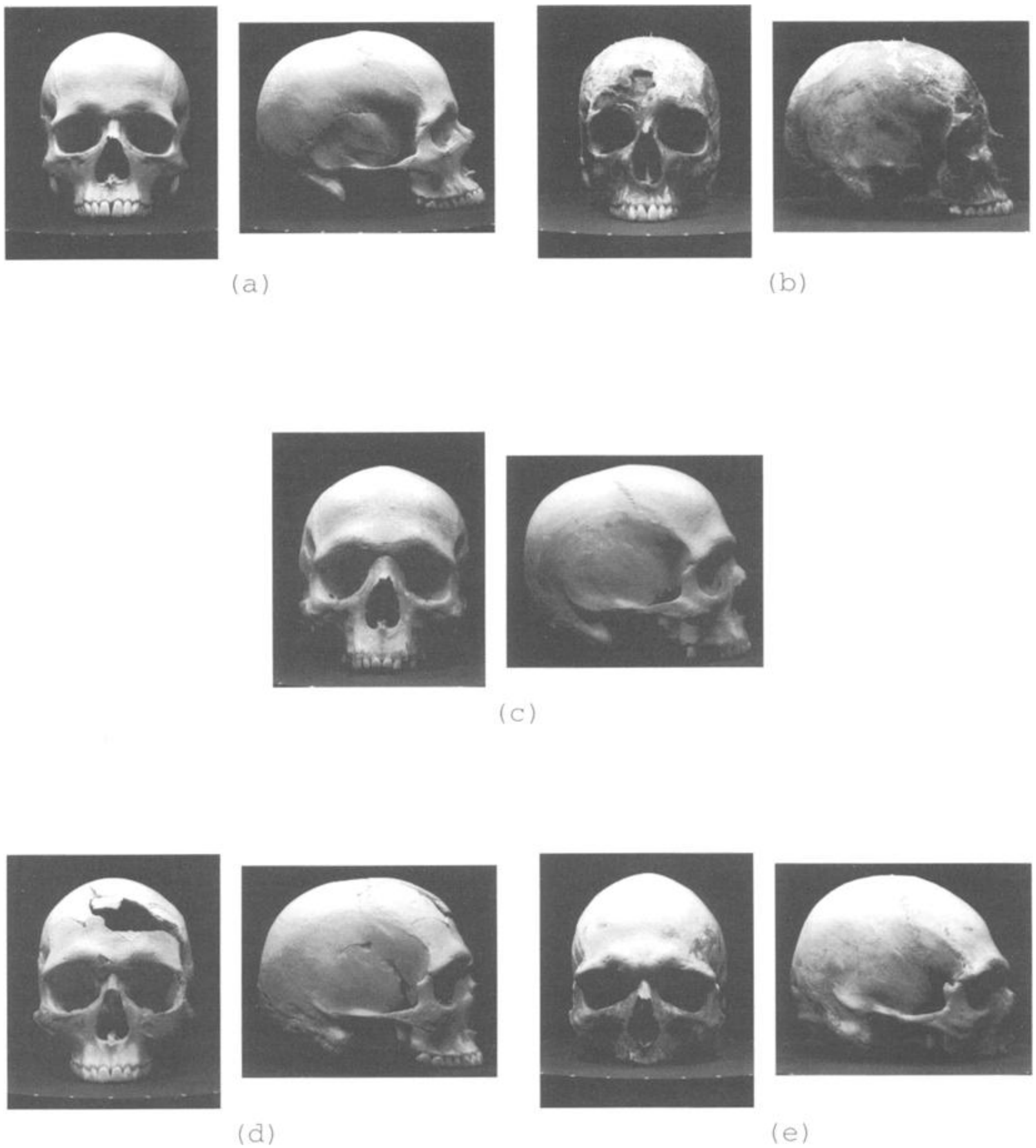

FIG. 2—*The test sample. Note that these images were generated digitally, not photographically.* (a) *Cranium 1—caucasoid, male, sub adult;* (b) *Cranium 2—caucasoid, female, sub adult, burn trauma;* (c) *Cranium 3—mongoloid, male, adult;* (d) *Cranium 4—caucasoid, male, sub adult, blunt force trauma; and* (e) *Cranium 5—mongoloid, male, adult, alveolar resorption.*

amidst a constantly changing world, yet many of the osteological charts forensic anthropologists use for case analysis are decades old (12). These are but some of the practical applications of computer imaging technology.

By compiling a database of digitized casework, forensic anthropologists can access a complete and consistent set of data from each case. Statistically significant amounts of data could be accessed for research on many fronts. As one example, a computerized method of calculating and preserving such statistics would be very helpful in the determination of population characteristics as well as human variability. In fact, it could ultimately provide the means to assess accurately the enormous range of variability on this globe. In such a scenario, anthropologists could build substantial theories about topics such as the disappearance of racial categories through admixture, thereby adding to discussions concerning race (16,17).

Consider the test study discussed in this paper, for example. Although the imaging technique provides decent absolute measurements, it is ideal for relative measurements (such as ratios and other such comparative measurements), just the sort of measurements we should be making with reference to human variability. Comparative measurements could quantify human diversity in terms of ranges and overlap rather than in terms of averages and divisions, as is commonly found in the anthropological literature. Ideally, scientists hope that by collecting data, they can inductively reason to create new theories; establishing a modern three-dimensional data base could afford forensic anthropologists just such an opportunity.

Conclusion

Today, many skeletal collections are rapidly disappearing due to newly instated repatriation laws (18). Forensic anthropologists

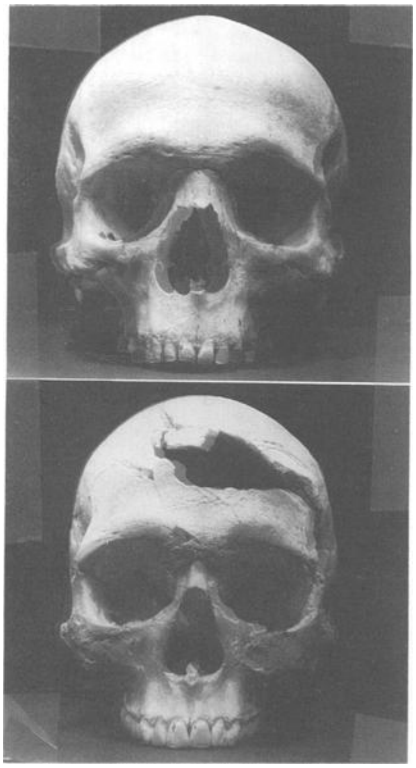

FIG. 3—*Examples of red-blue three-dimensional images. Although these images have been reproduced in black and white, this still provides a sense of the quality and general appearance of the images. In true color on a computer screen, the images appear three-dimensional.*

suffer a similar loss daily as interesting cases are returned to medical examiners' offices and family members. It is essential that anthropologists investigate new methods for capturing this fleeting data by exploring methods for digitally collecting just such information in order to archive both permanently existing (disappearing) collections and to build forensic collections that can be shared digitally around the country. To this end, I have proposed a database of three-dimensional images of osteological remains as the best way to collect and permanently preserve a modern representational skeletal collection.

Having made such a proposal, I addressed some of the practical questions it raises. In particular, this involved locating the type of imaging which might work best to generate the data for this database. Stereographic methods appear to be ideal for collecting surface data, and their premise of mimicking human vision is perfect for those anthropologists who want to see the bones rather than just look at lists of measurements. Having found probable answers to some of the practical questions, a brief experiment was used to test these findings using some of these stereographic techniques to image five crania and determine their qualitative and quantitative accuracy. As shown, it works, it is possible to image osteological remains with low cost (essential to virtually all anthropology departments) and little memory (approximately 1 megabyte per rotating image). The practical questions do have answers.

With the ability to image forensic remains, anthropologists in general will have the opportunity to work with large, diverse, and modern samples of skeletal remains, enabling them to reevaluate analytical approaches currently being used by forensic anthropologists. For instance, collecting large amounts of information digitally could help forensic anthropologists to understand human variation better, a task for which forensic anthropology is uniquely poised. This example is but one possibility among a multitude, which show the potential inherent in a merger between forensic anthropology and computer technology—a merger which could incorporate areas as diverse and numerous as human evolution, population demography, human variability, human adaptability, health and nutrition, medicine, human anatomy, growth and development, and even such fields as biomedical engineering, artificial intelligence, and robotics.

Acknowledgments

I would like to thank Dr. Walter H. Birkby for his support during this research and for providing access to skeletal materials. Also, I am tremendously grateful to Denice Warren and others at Image Processing for Teaching (IPT—an NSF funded project headquartered at the Universiy of Arizona) who not only gave me access to their hardware, but also helped me to become familiar with the software and to think through this imaging method.

TABLE 1—*Calipers versus computers. A comparison of calibrated cranial measurements. The measurements taken are defined by Hooton (11) and used by Giles and Elliot (12), and are expressed in millimeters. The measurements for cranium 1 are absolutely accurate because it was used to determine the calibration dividers.*

	Cranium 1 Caliper/ comp.	Cranium 2 Caliper/ comp.	Cranium 3 Caliper/ comp.	Cranium 4 Caliper/ comp.	Cranium 5 Caliper/ comp.
Ba-Prosth.	102.0/ N/A	96.0/ N/A	102.0/ N/A	98.0/ N/A	104.0/ N/A
Glab-Opis.	177.0/ 177.00	178.0/ 179.58	186.0/ 185.79	193.0/ 189.01	191.0/ 190.04
Eur-Eur.	135.0/ 135.00	126.0/ 126.71	153.0/ 153.94	138.0/ 140.75	140.5/ 139.72
Ba-Breg.	137.0/ N/A	135.0/ N/A	146.0/ N/A	139.0/ N/A	147.5/ N/A
Ba-Nas.	103.0/ N/A	100.0/ N/A	112.0/ N/A	104.0/ N/A	110.0/ N/A
Zyg-Zyg.	120.0/ 120.00	114.0/ 113.55	140.0/ 136.64	134.0/ 132.03	132.0/ 128.64
Prosth-Na.	65.5/ 65.50	68.0/ 67.13	76.5/ 76.57	72.5/ 71.31	66.0/ 64.96
Ala-Ala.	26.0/ 26.00	21.5/ 22.39	25.5/ 25.44	26.0/ 25.06	23.5/ 23.45
Ext. palate br.	62.0/ N/A	N/A	62.5/ N/A	65.0/ N/A	56.0/ N/A
Mastoid length	23.7/ 23.70	23.0/ 22.92	25.0/ 25.18	26.0/ 28.20	28.0/ 27.21

TABLE 2—*System costs. These prices are rounded up from pricings in commercial magazines as of May 1996—Academic pricing is usually slightly lower. For comparative purposes, refer to Bower (15), where the hardware costs are estimated at $700,000.*

	Minimal	Optimal
Hardware	Performa w/ 8MB RAM, 500MB harddrive; $1050	Power Mac w/ 16 MB RAM, 1 GB harddrive; $4600 + extra 32MB RAM; $1200
Monitor	14″ 8-bit color; $350	21″ 24-bit accel. color; $4000
Storage & Communications	CD ROM built in Iomega Zip drive; $250 [$20/100MB cartridge = $0.20/MB]	CD-writer; $2000 [$15/600MB disk = $0.025/MB] 28.8kbaud modem; $250
Information Capture	FotoMan Plus; $650	High-res. black and white digital camera; $2000
	TOTAL = $2300 + cartridges	TOTAL = $14,050 + disks

TABLE 3—*Intra-observer variability. The measurements are expressed in pixels, with approximately 4–5 pixels equaling 1 mm. All of the standard deviations for the measurements are less than 1 mm, with most of them falling below 0.5 mm. The intra-observer (repeat) variability is therefore quite small—certainly within the acceptable range of 2 mm.*

	Cranium 1	Cranium 2	Cranium 3	Cranium 4	Cranium 5
Glab-Opis.	798.55	810.80	836.56	851.34	855.96
	797.43	807.46	837.42	852.76	856.40
	796.23	808.87	837.02	850.37	856.13
	$\bar{X}$ = 797.40	$\bar{X}$ = 809.04	$\bar{X}$ = 837.00	$\bar{X}$ = 851.49	$\bar{X}$ = 856.16
	s = 0.95	s = 1.37	s = 0.35	s = 0.98	s = 0.18
Eur-Eur.	586.04	552.00	668.00	610.36	606.30
	585.03	549.00	666.36	610.55	605.03
	585.01	547.23	668.03	610.02	606.21
	$\bar{X}$ = 585.36	$\bar{X}$ = 549.41	$\bar{X}$ = 667.46	$\bar{X}$ = 610.31	$\bar{X}$ = 605.85
	s = 0.48	s = 1.97	s = 0.78	s = 0.22	s = 0.58
Zyg-Zyg.	573.03	539.18	648.08	632.06	613.24
	572.00	544.21	656.01	631.13	614.21
	572.00	541.33	651.11	626.00	613.18
	$\bar{X}$ = 572.34	$\bar{X}$ = 541.57	$\bar{X}$ = 651.73	$\bar{X}$ = 629.73	$\bar{X}$ = 613.54
	s = 0.49	s = 2.06	s = 3.27	s = 2.66	s = 0.47
Prosth-Na.	295.49	300.57	343.12	323.01	293.25
	296.74	303.73	346.07	322.90	293.75
	295.78	305.84	348.86	320.81	293.75
	$\bar{X}$ = 296.00	$\bar{X}$ = 303.38	$\bar{X}$ = 346.02	$\bar{X}$ = 322.24	$\bar{X}$ = 293.58
	s = 0.53	s = 2.17	s = 2.34	s = 1.01	s = 0.24
Ala-Ala.	139.00	117.04	136.01	136.06	125.00
	140.13	122.15	137.03	133.00	126.19
	139.09	121.00	136.13	134.01	126.06
	$\bar{X}$ = 139.41	$\bar{X}$ = 120.06	$\bar{X}$ = 136.39	$\bar{X}$ = 134.36	$\bar{X}$ = 125.75
	s = 0.51	s = 2.18	s = 0.45	s = 1.27	s = 0.53
Mastoid length	123.02	119.44	132.50	146.56	145.97
	124.48	122.25	135.96	147.05	141.03
	126.49	120.07	128.88	151.40	142.43
	$\bar{X}$ = 124.66	$\bar{X}$ = 120.59	$\bar{X}$ = 132.45	$\bar{X}$ = 148.34	$\bar{X}$ = 143.14
	s = 1.42	s = 1.20	s = 2.89	s = 2.17	s = 2.08

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