Spring 2020

An Assessment of the use of Photogrammetry in Cranial Metric and Non-Metric Studies

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AN ASSESSMENT OF THE USE OF PHOTOGRAMMETRY IN CRANIAL METRIC AND NON-METRIC STUDIES

by

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A Thesis
Submitted to the Graduate School,
the College of Arts and Sciences
and the School of Social Science and Global Studies
at The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Master of Arts

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May 2020

Published by the Graduate School

THE UNIVERSITY OF SOUTHERN MISSISSIPPI

ABSTRACT

Methods in biological anthropology have made tremendous leaps in recent years and with the increasing rise in technology there is no reason to suspect that this trend will be decreasing. Particularly methods in 3D digitization have not only increased but have also become more accessible in bioarchaeology. One method, photogrammetry, offers bioarcheologists a unique opportunity to easily collect and process cranial metric and non-metric data that can be used to quantify biological relatedness. While these advances are expected to continue, it is ignorant to assume that they represent a fail proof solution. A critical examination is necessary to quantify the accuracy of these techniques in comparison to traditional methodologies. Data on 24 metric and 25 non-metric traits was collected from the physical and digitized crania of 27 individuals to determine the accuracy, precision, and level of identifiability of these traits on photogrammetric models. Percent error, standard deviation, and average level of identifiability was calculated to determine the reliability of photogrammetry in biodistance research. All percent error rates, with the exception of inter orbital breadth, fell beneath an accepted 2% margin, in addition the standard deviation of digital measurements was less than that of physical measurements. However, a number of environmental and technical factors, most notably lighting and processing power, influenced the success of photogrammetric models. Photogrammetry offers bioarchaeologists a new way to collect data while simultaneously increasing collection access and preserving remains for future generations of researchers.

ACKNOWLEDGMENTS

This thesis would not have been possible without the help and guidance of many people. I would first like to thank my committee for their support and guidance throughout my entire graduate career. First, I would like to thank Dr. Danforth, for all her help and guidance throughout my time at USM. Her direction and support have aided considerably in defining my both academic and professional trajectories. I would also Dr. Smith for providing me advice and support in moments of chaos. Finally, I would like to thank Dr. Hayden for the logistical support she provided in not only creating a practical thesis plan, but also sticking to it.

I would next like to thank the people from Michigan State University that provided me with the resources necessary to collect my data. First, Dr. Wrobel for providing me with access to his lab and the software needed to complete this project. I would also like to thank Jack Biggs for opening his home during my data collection session and also providing me with necessary direction throughout my academic career from MSU and beyond. Finally, I would like to thank the MSU Lab for the Education and Advancement in Digital Research for allowing me to utilize the equipment and lab space that without this project would have never happened.

Next, I would like to thank Dr. Elizabeth Graham and the Belize Institute for Archaeology for their permission to conduct this research.

Finally, I would like to thank the people that throughout these past few years have provided me with friendship and necessary guidance to persevere. First, I would like to thank Jeff and Autumn Painter, who have not only kept alive over the last four years but have also played a key role in defining my work as an anthropologist. Next, I would like

to Joanna Klein and JT Lewis for the friendships that have been momentous throughout our time at USM. Finally, I would like to thank the rest of my cohort for the companionship and experiences we have had throughout the last two years.

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CHAPTER I – INTRODUCTION

Introduction

Biological distance analysis utilizes well established methods to determine the degree of genetic relatedness within or between populations to enlighten topics of colonialism, ethnogenesis, regional histories, and migration (Stojanowski and Buikstra 2004, 430-431). Despite criticisms linking the method to racist undertones of previous schools of anthropology, biodistance has championed itself as a noninvasive way to explore phenotypic variability (Stojanowski and Buikstra 2004, 431). These methods have been used to understand migration and population structure in a number of studies. For example, Klaus' dissertation utilized biodistance data to investigate ethnogenesis in the Moche Valley of Peru during the colonial period and determined that population structure became more homogeneous through time, a trend also observed at other mission sites interpreted to be indicative of ethnogenesis (Klaus 2008, 568). Stojanowski also used similar methods to understand population structure and ethnogenesis in colonial La Florida (Stojanowski 2001, vi-vii).

Within biodistance analyses, one of the primary sources of data includes collecting measurements from the various landmarks across the skull (Buikstra and Ubelaker 1994, 61, 74). Biological distance data has traditionally been collected by using the actual physical remains; however, with increasing advances in technology, phenotypic data can also be collected from three-dimensional (3D) renderings (Kuzminsky 2013, 709). For example, Kuzminsky's dissertation research focused on peopling of the Americas using biological distance, employing crania that were digitized with a NextEngine scanner (Kuzminsky 2013, 709). Other studies have also used 3D

scanning as a way to quantify changes in cranial modification practices and group identity (Kuzminsky et al. 2016, 507).

In recent decades the use digital imaging tools has increased drastically within bioarchaeological research. Studies have ranged from analyzing scanned crania to differentiate between subtle cranial fault modification to quantifying networks in cortical bone to general collection maintenance and preservation (Kyle et al. 2013; Jiang, Jáuregui, and White 2008). While many studies have focused on the accuracy of digitization tools such as computer tomography (CT) and three-dimensional scanners, few have addressed the accuracy and precision of photogrammetric data leaving an important gap when assessing the use of this technology (Katz and Friess 2014, 152; Badawi-Fayad and Cabanis 2007, 268).

In another method of digitalization, photogrammetry uses photographs as a way to create 3D renderings of an object. The process involves taking slightly overlapping photographs of an object from various angles (Biggs 2017, 1). These can be obtained in one of two ways: the object is rotated slightly for each photograph, or the photographer rotates slowly around the object taking pictures. In the first method, the object is placed on top of a rotating surface, and rotated slightly for each photograph, roughly between every 18 and 36 degrees, at three different angles: level, mid-level, and superior (Biggs 2017, 2). The second method requires the photographer themselves to rotate around the object collecting photographs at the same increments and levels (Kyle 2013, 3). Photogrammetry can be completed with a range of different cameras and equipment; however, overall startup cost can be decreased, as simple cameras of iPhone quality have shown to create reliable and detailed models.

While numerous studies have utilized photogrammetry in their research, few have focused on quantifying the accuracy of the method in bioarchaeological endeavors (Kuzminsky et al. 2016, 507; Katz and Friess 2014, 152). Much of the current literature has concentrated on comparing photogrammetry with other digitalization methods such as laser scanning, where accuracy of measurements within each of the methods fell within the range of osteometric error (Katz and Friess 2014, 153). However, the issue with properly identifying landmarks on three-dimensional models has proved difficult for some, thus calling into to question the accuracy of measurements obtained from them (Robedizo 2016, 40). In addition specific features of the cranium make it difficult to capture exact morphology; for example the orbits of the eye casts shadows that may make it difficult to render the orbits and associated features including landmarks such as dacryon (landmark located on the inner surface of orbit) or pathology such as cribra orbitalia (Wrobel, Biggs, and Hair 2019, 49; Placiente Robedizo 2016, 43).

While the use of digital methodologies, including photogrammetry, has been increasing rapidly in bioarchaeological research, photogrammetric methods have not been tested for their accuracy or precision (Kuzminsky and Gardiner 2012; Katz and Friess 2014; Wrobel, Biggs, and Hair 2019). This study seeks to quantify these levels to test whether photogrammetry can be reliably used both as a way to preserve physical osteological collections and to collect data. If the method proves successful, then photogrammetry can be a valuable alternative to the handling of physical remains. This means that collections can be better curated, and data can be collected remotely. Until this is proven, this cannot be assured. Bioarchaeology has made great strides in recent decades, particularly in the form of method development and theory engagement;

however, it is only by understanding both the strengths and weakness of our approaches that we can continue to engage with research and push the boundaries of our discipline.

Research Questions

This thesis has three key guiding research questions, all of which focus on illuminating the levels of accuracy and precision of photogrammetric models in bioarchaeological research. They include:

1. What is the accuracy of cranial photogrammetric measurements when compared to dry bone measurements?
2. How precise are cranial photogrammetric measurements when compared to dry bone measurements?
3. How indefinable are non-metric traits on cranial photogrammetric models?

These questions will be used to test the accuracy, precision, and applicability of photogrammetry to bioarchaeological, and specifically biodistance, research pursuits. The following are hypothesized in response to the previous research questions:

1. The accuracy of cranial photogrammetric measurements will be higher when compared to dry bone measurements.
2. Photogrammetric measurements will be more precise than dry bone measurements.
3. Non-metric traits will be less identifiable on photogrammetric models then on physical crania.

CHAPTER II – DIGITIZATION METHODS

Introduction

Recent advances in technology have allowed for digitalization methods to propel both anthropological research and curation beyond what anthropologists originally imagined (Kuzminsky and Gardiner 2012, 2744; Kuzminsky et al. 2016, 507; Asier Gómez-Olivencia et al. 2018, 1; Katz 2017, 29). In bioarcheology these tools have aided researchers in agendas ranging from skeletal reconstructions, cranial modification identification, to geometric morphometric studies focused on investigating the peopling of the New World (Skinner 2017, 68; Kuzminsky et al. 2016, 507; Kuzminsky 2013, 201). In addition, digitization also offers bioarchaeology the opportunity to preserve already fragile skeletal collections for future generations of researchers (Wrobel, Biggs, and Hair 2019, 48). Such methods also allow for the opportunity to form databases that can be accessed remotely, permitting scholars to conduct and collaborate on research projects that may have not been possibilities prior to the such repositories (Wrobel, Biggs, and Hair 2019, 48). Within bioarchaeology, a number of digitization methods have triumphed for various reasons, including laser scanning, computerized tomographic (CT) scanning, and recently photogrammetry (Kuzminsky et al. 2016, 507; Hughes 2011, 57; Wrobel, Biggs, and Hair 2019, 50).

Laser Scanning

Workflow

Laser scanning methods are one of the most popular methods of digitalization for bioarcheologists (Kuzminsky and Gardiner 2012, 2745; Kuzminsky et al. 2016, 507; Wrobel, Biggs, and Hair 2019, 50; Skinner 2017, 71). Laser scanning is capable of

creating a three-dimensional image of external surfaces of an object by taking overlapping scans from varying angles (Kuzminsky and Gardiner 2012, 2745). Within laser scanning, two primary methods are preferred by bioarchaeologists, including individual scanners such as the NextEngine scanner and the Laserarm approach (Kuzminsky and Gardiner 2012, 2745; Skinner 2017, 71; Wilson, Holland, and Sparrow 2017, 129). However, both technologies function in the same fashion. First, the scanner collects surface data of an object, similar to taking a picture of the artifact in question (Kuzminsky and Gardiner 2012, 2745). Next, laser beams slowly move across the surface of the object collecting data points to create the digital geometric form of the artifact (Kuzminsky and Gardiner 2012, 2745). Third, once a scan is done the object is rotated at a predetermined interval in order to collect data for another scan from a different angle (Skinner 2017, 71; Kuzminsky and Gardiner 2012, 2745). This process continues until the number of desired scans are achieved (Kuzminsky and Gardiner 2012, 2745). Figure 1, below, provides an example of how the NextEngine scanner may be set up.

Figure 1. *NextEngine Laser Scanner*

NextEngine laser scanner scanning an artifact (Felicísimo, Polo, and Peris 2013, 14).

After all the scans are completed the individual has the opportunity to trim off unwanted data points and reduce noise in individual scans before combining them into one. Once determined sufficient, individual scans are put together to create the final product, the model which is a collection of the individual edited scans (Kuzminsky and Gardiner 2012, 2745). The only further requirement is that sufficient overlap between individual scans was obtained to ensure sufficient alignment and thus ensuring quality final products (Wilson, Holland, and Sparrow 2017, 129).

Benefits and Drawbacks of Laser Scanning

As laser scanning is a more popular method of digitization within bioarcheology it should come of no surprise that the method is accompanied with a number of benefits. First, final models produced from laser scanning are highly accurate (Kuzminsky and Gardiner 2012, 2745). Objects scanned with high resolution can be as accurate as 0.05 inch with about 150 samples per inch in wide mode or 0.005 inch accuracy with 400 samples per inch in macro mode (Kuzminsky and Gardiner 2012, 2745). In addition, laser scanning has a quicker post-processing time, meaning that scans are collected at the expense of limited human effort post original data collection (Wilson, Holland, and Sparrow 2017, 129). Finally, laser scanning is capable of creating high quality and high resolution models that meet the needs and demands of bioarchaeological and archaeological research and museum conservational goals (Wrobel, Biggs, and Hair 2019, 50).

Despite numerous benefits, laser scanning is accompanied by a number of limitations that must be considered prior to choosing a method of digitization. First, laser scanning can be very expensive, with scanners starting around $5,000 and can easily extend over $50,000 (Kuzminsky and Gardiner 2012, 2745; Wrobel, Biggs, and Hair 2019, 50 ; Mathys, Brecko, and Semal 2013, 203). In addition, software associated with creating models from scans may also be expensive and difficult to obtain without sufficient financial resources (Skinner 2017, 72). Second, the method can be very time consuming if high resolution scans are required, as individual scans can take upwards of an hour a piece, a process that can be very limiting if access to individual collections is already restricted (Wrobel, Biggs, and Hair 2019, 50; Mathys, Brecko, and Semal 2013,

204). Furthermore, laser scanning also poses difficulties if researchers wish to conduct field work, as equipment is bulky and difficult to carry and electricity and laptops are necessary to collect scans (Wrobel, Biggs, and Hair 2019, 50).

Particularly in bioarcheology, laser scanning may pose two distinct challenges. First, the complexity of trabecular bone may make it extremely difficult to scan, and thus such structure may not easily fit into many developed workflows (Wilson, Holland, and Sparrow 2017, 125). Second, shiny surfaces, such as dental enamel and eburnation associated with arthritis, may also be difficult to scan, thus compromising the quality of the final product (Wilson, Holland, and Sparrow 2017, 125).

CT Scanning

Workflow

X-ray Computed Tomography, also known as CT scanning, is a highly accurate method to create three-dimensional renderings of external and internal surfaces of artifacts (Hughes 2011, 58). CT machines first appeared in medical facilities in the 1970s, and it was the first time in which three-dimensional images of the body could be produced (Hughes 2011, 58). However, in the early 2000s rapid changes in technology forever changed medical CT machines and the quality at which physicians could view, diagnosis, and treat the human body (Hughes 2011, 58). Up until this point traditional CT machines consisted of x-ray beams arranged in an arc around a patient, or in this case an artifact (Hughes 2011, 58). This was called the Spiral CT Scanner, and would later be replaced by the Multi-Detector Spiral CT scanner that could collect significantly more scans faster than previously existing models of the machine (Hughes 2011, 59).

CT machines can collect data to create models in one of two ways. The first is through the traditional Multi-detector Spiral CT scanner which utilizes a fixed object and movable radiation source (Shelmerdine et al. 2018, 2; Hughes 2011, 49). The second is micro-CT scanning which utilizes a movable object and fixed radiation source to allow for a range of magnification and image resolutions (Shelmerdine et al. 2018, 2). However, in both methods the premise behind creating three-dimmensional models remians the same. A group of x-rays shines through the object and get absorbed differently depending on the compostion and denisty of material present (Hughes 2011, 58). Figure 2, below, provides a diagram depicting how the process occurs with medical patients. After scans, also referred to as slices, are obtained, they can be stitched togethered on the computer, allowing physicans and researchers alike to explore both the internal and external structures of the human body and material culture (Hughes 2011, 59).

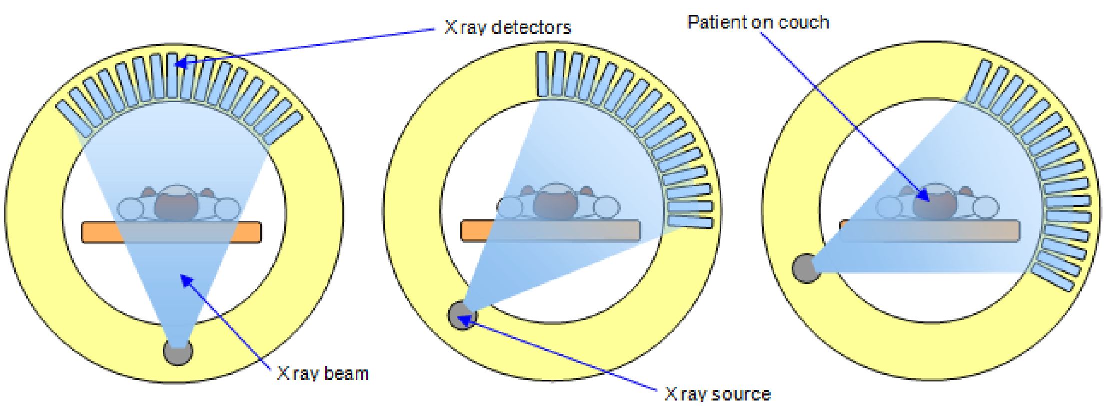

Figure 2. *The position of x-ray beams in a CT machine*

CT machine scanning patient (Gribbs 2016)

Benefits and Drawbacks of CT Scanning

CT scans provide a powerful method in create three-dimensional models and when compared to other methods of digitization offer a number of unique benefits. First

CT models are the only ones to provide a look at the internal structure of an artifact (Gribbs n.d.). In bioarchaeological research, this is of particular interest because it can illuminate the internal structures of elements such as trabecular bone (Hughes 2011, 59). In addition, the method also produces extremely accurate three-dimensional models, with error rates as little as 0.001 mm reported (Wrobel, Biggs, and Hair 2019, 50; Shelmerdine et al. 2018, 6). Third, the method is overall extremely quick; a study that compared methods of digitization reported that CT scanning only required a total 21 minutes to create a model, compared to a total of 270 minutes for photogrammetry and 40 minutes for the FARO ScanArm, a specific type of Laserarm scanner (Mathys, Brecko, and Semal 2013, 204). Finally, CT scans pose little threat to the artifact, as little handling, rotating, or physical maneuvering needs to take place, beyond original placement to create a three-dimensional model (Hughes 2011, 59).

However, while CT scans may seemingly appear as the premier method of digitization, a number of limitations accompany the method and must be considered before moving forward with any project. First, the machinery required is expensive and gaining access to facilities with such equipment may be difficult (Wrobel, Biggs, and Hair 2019, 50). Second, CT machines are not portable, meaning that they cannot be brought into the field or out of particular lab settings (Wrobel, Biggs, and Hair 2019, 50). Third, models produced by CT scans lack surface color and textures, and while for some research agendas this may pose no issue, those requiring topographical surface data or intending to use models for public outreach events may choose to consider another method of digitization (Mathys, Brecko, and Semal 2013, 203). Finally, the file size of final models is extremely large, and as a result cannot be shared online and instead must

be shared through CD or DVDs, thus limiting the accessibility of such data (Wrobel, Biggs, and Hair 2019, 50; Monge et al. 2004, 149).

Photogrammetry

Brief History of Photogrammetry

Photogrammetry is another one of many processes used to create three dimensional digital models. Originally developed in the late 1840s, it was used as an alternative method to obtain measurements and interpret shape from photographs (Skinner 2017; Kuzminsky and Gardiner 2012). From 1849 until the 1980s, photogrammetry was heavily supported by the government, as the method was primarily used by civil and military mappers (Anderson 1982, 200; Jiang, Jáuregui, and White 2008, 824). Without computers, early adopters of photogrammetry used two dimensional photographs to obtain measurements and complete their analysis (Kyle et al. 2013, 2). However, with the development and widespread use of the computer and increases in camera quality, photogrammetry spread.

The process first began appearing in archaeology in the 1980s, and while the benefits were clear for many archaeologists, photogrammetry was too expensive and the associated learning curve was too steep for many (Anderson 1982, 200). Often professionals outside the realm of archaeology were contracted for work on archaeological projects, thus increasing costs and further alienating the tool from popular use (Anderson 1982, 200). But now, close to 40 years later, the cost and ease of utilizing photogrammetry are more attractive than ever before; with various software programs and guides available across the internet, photogrammetry can easily be learned through established workflows, workshops and seminars, or even webinars (König, Shih, and

Katterfeld 2012, 94). More often than not, photogrammetry is now completed by the archaeologists themselves, allowing them to be actively embrace new technology and methodologies. However, throughout this rapid adaptation, there has been little consideration in the development of best practices of photogrammetry in archaeology and bioarchaeology until recently.

Workflow

Terrestrial photogrammetry can be completed in numerous ways; however, the methodologies can be largely grouped into two broad categories. The first method involves a stationary photographer and a rotating object. In this method, depicted in Figure 3 below, a black backdrop is constructed and the objected is placed on top of a rotating surface (Biggs 2017, 1). This method would be used when objects or artifacts are small enough to be easily handled and manipulated, such as lithics, human remains, or ceramic vessels. In the second method, the object remains stationary while the photographer rotates around the artifact (Kyle et al. 2013, 3). This method would be utilized if objects are not easily handled, such as architecture or tombs. In both methods slightly overlapping photographs are collected from various angles surrounding the object (Biggs 2017, 1). Photographs are taken between every 18 and 36 degrees at three different angles: level, mid-level, and superior for both the stationery and motion-based photogrammetry methods (Biggs 2017, 2). After photographs are collected, images are then transferred to a computer where they can be processed for model building.

Figure 3. *Photogrammetry Set-Up*

Photogrammetry set up using turn table method (Wrobel, Biggs, and Hair 2019, 52).

After being saved to a computer, images are then organized and prepared for the final digitization. The first step is to organize images into folders based on individual objects (Biggs 2017, 2). Following data cleaning, images of individual objects are then imported into a chosen processing software program (Biggs 2017, 2). Of available software packages, the most commonly used include Agisoft Metashape and Reality Capture; however, due to its ease of use and affordability, Agisoft is preferred. After images are imported, a mask is created (Biggs 2017, 3). A mask is only necessary if utilizing a stationary method, as it ensures that the software will ignore the background when constructing the rendering. Following the mask, the next step is to align the photographs and create a sparse could (Biggs 2017, 3). Aligning the photographs creates

a sparse cloud, a sort of rough draft of the model as shown in Figure 4, in which the individual has the opportunity to edit and delete inaccurate data points before moving forward (Biggs 2017, 4; Wrobel, Biggs, and Hair 2019, 51).

Figure 4. *Sparse Cloud Stage*

Sparse cloud showing in accurate data points to the right. Model produced by Agisoft Photoscan. Image by Amy Hair.

From the sparse cloud, a dense cloud can be formed (Biggs 2017, 4). The dense cloud contains substantially more data points when compared to the sparse cloud, and thus provides much more detail then the prior. The dense cloud can be seen in Figure 5. Once again, the model is edited and inaccurate data points are removed before moving forward (Biggs 2017, 4).

Figure 5. *Dense Cloud Stage*

Dense cloud produced by Agisoft Photoscan. Image by Amy Hair.

Next, the mesh and texture are created. The mesh and texture provide the bulk of the model's detail and final appearance, changing it from a collection of data points to an actual 3D image with recognizable features (Biggs 2017, 5; Wrobel, Biggs, and Hair 2019, 51). The final model with mesh and texture can be seen in Figure 6 below. The final step is to save the model. The appropriate file format can depend on any number of factors based on project goals. For example, if morphometric analysis is a priority, it may be necessary to save the file as a .ply type, whereas for ease of access and sharing, saving a file as a .pdf may be prioritized. Multiple formats may be selected based on specific research project goals.

Figure 6. *Final Model Stage*

Final model with mesh and texture produced by Agisoft Photoscan. Image by Amy Hair.

Benefits and Limitations of Photogrammetry

As one of many digitalization methods, photogrammetry embodies various benefits for archaeological field work. Early attempts at integrating photogrammetry into the field often cited the method as expensive; however, a decrease in the cost of technology has made photogrammetry an inexpensive alternative to methodologies such as laser scanning (Anderson 1982, 200; Katz and Friess 2014, 152). While the cost of digital SLR cameras can easily reach thousands of dollars, the cost of laser scanners begins in the thousands, and photogrammetry can be used with cameras as simple as an iPhone (Katz and Friess 2014, 152).

Another key benefit to photogrammetry is its portability. Digital cameras can easily be taken into the field on a day to day basis as opposed to typical laser scanners which are too large to take into the field and require external power sources (Wrobel, Biggs, and Hair 2019, 51). Set-up kits, cameras, and lighting sources can all be portable and easily carried into field settings to collect data in more difficult and unforgiving terrain (Wrobel, Biggs, and Hair 2019, 51). This also means that field settings, in addition to individual artifacts, may also be recorded in three dimensions (Anderson 1982, 201).

A final key benefit in photogrammetry is time management. While photogrammetry often entails more work up front in taking photographs, the overall image processing procedure is much shorter than that of laser scanning which takes considerable amounts of time for each scan of an individual object (Wrobel, Biggs, and Hair 2019, 51). In addition, the set up process is also quick when compared to that of other methods such as laser scanning or CT scanning (Wrobel, Biggs, and Hair 2019, 51). As the backdrop only needs to hung up to ensure that light does not reflect off any surfaces, and the camera only needs to be securely mounted on a tripod, the set up process is much quicker when compared other digitation methodologies (Wrobel, Biggs, and Hair 2019, 51).

With so many digitization options available, it is no wonder that photogrammetry does have various disadvantages. First, photogrammetry is not an overtly difficult skill to learn; however, the process is not intuitive. Beyond taking the photographs of object, skills related to specific computer software programs are necessary for creating and analyzing the three-dimensional models (Anderson 1982, 201). While photogrammetry is no longer as difficult as it was when it was first applied to archaeological research in the

1980s, effort is still needed to understand the technological background of the process. In addition, updates to software programs can delay projects; however, such changes should not alter work flows too drastically. Furthermore, such changes advance the field of digitation and push the boundaries of model development and artifact preservation.

Second, as an overall extremely portable method of digitization, various environmental conditions, namely landscape and lighting, may pose severe threats to photogrammetry. Photogrammetry requires a stable or routinely rotating object, this requirement may be difficult to achieve depending on the location and morphology of the unit, site, or artifact in question. For example, specific locations, such as deep units, may make it difficult to fully rotate around and capture detailed images (Unhammer 2016, 28). Lighting is also a key factor in determining the success of the final model; dark images or shadows may threaten the integrity of the final model. In specific environments, such as cave or rock shelter sites, light is a limited commodity and few mitigation attempts seem to offer help. Specifically looking at bioarchaeological research, lighting may make it difficult to identifying various landmarks on skeleton (Robedizo 2016, 40). For example, poor lighting may make the identification of the landmark dacryon, located in the superior portion of the orbital margins, difficult if not impossible to identify. However, these difficulties can be avoided by accurately setting up and testing lightning conditions prior to the final model building process.

Finally, in comparison to other digitization methods photogrammetry, as a result of expediency, is lacking in resolution. Photogrammetry takes considerably less time and energy when compared to other digitization methods, and as a result final model are typically lacking in resolution when compared to other methods' final products (Wrobel,

Biggs, and Hair 2019, 50). However, despite such limitations submillimeter accuracy can still be obtained from photogrammetric models without the hassle of bulky equipment, concerns over external power sources, or laboratory access (Wrobel, Biggs, and Hair 2019, 50).

Previous Tests on Accuracy, Precision, and Identifiability

Photogrammetry is relatively new to archaeological and bioarchaeological research pursuits; however, various studies have tested and compared the methodology to others in several ways. First Evin and colleagues tested the accuracy of photogrammetry when applied to wolf crania and discovered geometric morphometric error rates between 1.95% and 2.04%, rates that that fall within the accepted range of error (Evin et al. 2016, 87). In addition, another faunal based study also found photogrammetry reliable when measurements from the models of Antarctic fur seals were not statistically different than those obtained from the dry bone (Moshobane, Bruyn, and Bester 2016, 267). Specifically within bioarchaeology, scholars have also have found that photogrammetry can be just as accurate as laser scanning given proper set up and calibration (Katz and Friess 2014, 154). Finally, digitalization studies have in general raised the question of the relationship between models and their physical objects, and as a result the level of representation that can be expected out of a three-dimensional rendering (Robedizo 2016, 23). This in turn has raised questions about feature indefinability in bioarchaeological studies, especially in regions of complex morphology such as the cranium (Robedizo 2016, 23). Robedizo in particular questioned the identifiability of pathologies such as cribra orbitalia, and in addition difficult to locate landmarks, such as dacryon, may become even more challenging to identify if models are improperly constructed

(Robedizo 2016, 52). However, research particularly related to the accuracy, precision, and indefinability of metric and non-metric traits in bioarchaeological research is necessary to understand both the benefits and limitations of new methodologies within the discipline.

Conclusion

In comparison, photogrammetry represents a more portable and time and cost efficient method of digitization method when compared to other popular methodologies in bioarcheology such as laser scanning and CT scanning (Anderson 1982, 200; Katz and Friess 2014, 152; Wrobel, Biggs, and Hair 2019, 51-52). Despite various limitations the method represents opportunity for the discipline to advance not only in its technicalities, but also in its abilities to preserve collections for future generations of researchers. Within bioarcheology the accuracy and precision of laser and CT has been well tested and documented; however, those aspects of photogrammetry have begun to have be explored (Evin et al. 2016, 90; Katz and Friess 2014, 155; S. C. Kuzminsky and Gardiner 2012, 2745; Badawi-Fayad and Cabanis 2007, 24). While great technical strides have been made in recent decades, it is only through understanding both the strengths and weaknesses of our methodologies that we can continue to improve and push the discipline pass boundaries that previously could have never been imagined.

CHAPTER III - BIODISTANCE

Introduction

Biological distance is study of genetic relatedness between individuals (Larsen 2015, 357). Microevolutionary processes, as a result of various environmental pressures and genetic backgrounds, are in part responsible for a large part of this biological variation. These variations can be quantified through the use of biological distance methodologies that utilize standardized landmarks and measurements to understand variation between and within populations (Buikstra and Ubelaker 1994, 74). Using measurements from various portions of the skeleton, though most commonly the dentition and cranial morphology, questions related to evolutionary and population history, migration, identity, and more can be addressed (Buikstra and Ubelaker 1994, 69). Despite these advantages, biological distance methodologies are often linked with a time in anthropological history that obsessed with classifying groups and institutionalizing racism; however, the field and method has matured critically since, and biodistance has been applied to a number of studies ranging from adaptation to ethnogenesis to migration (Stojanowski and Buikstra 2004, 430; Armelagos and Gerven 2003, 53).

aDNA

Ancient DNA, also known as aDNA, can be used to investigate interpersonal relatedness in past populations. Mitochondrial DNA, otherwise known as mtDNA, is found in the cytoplasm of every living cell, and thus has the best likelihood of being recovered in archaeological circumstances (Lewis, Buikstra, and Stone 2007, 146). This type of DNA is passed down maternally and can provide a genetic maternal history of the lineage (Lewis, Buikstra, and Stone 2007, 146). Recent advances in aDNA technology

allow us to also extract nuclear DNA. Ancient DNA can illuminate information on general genetics, mating practices, mortuary and spatial patterns, or migration (Lewis, Buikstra, and Stone 2007, 147; Dipierri et al. 1998, 10; Stone 1996,10; Bonatto and Salzano 1997, 1866). However, the invasive and destructive manner of the method combined with the cost of running samples and the risks for contamination have been a limitation for many researchers in the discipline.

Dental Traits

Dental Metric Traits

Dental metrics provide a valuable tool in researching population and evolutionary history in bioarchaeological work. Standardized methodologies suggest three measurements from all teeth in the sample, including mesiodistal diameter, buccolingual diameter, and crown height (Buikstra and Ubelaker 1994, 62). These measurements are typically obtained using sliding calipers and then subjected to statistical analyses such as the standardized mean measure or divergence (Jacobi 1996, 142-144). Tooth size has been shown to be a good proxy for determining genetic relatedness, and when adjusted for sex, the size of individual teeth varies based on the level of relatedness as observed in twin and familial studies (Stojanowski et al. 2017, 517). In addition studies of various populations around the globe have shown that populations sharing genetic backgrounds have more similar tooth size and shapes then those who are not (Hanihara and Ishida 2005, 297). Because tooth size and shape are more heavily influenced by genetics then cranial traits, they may serve as a more reliable form of data in biodistance research (Larsen 2015, 364). While dental metrics provide a valuable and reliable tool in determining metric levels of biological distance in many research studies, a few

disadvantages can be noted, primarily when it comes to heavily worn dentition and rotated teeth (Stojanowski 2004, 318). Examples of dental metrics can be observed in Figure 7 below.

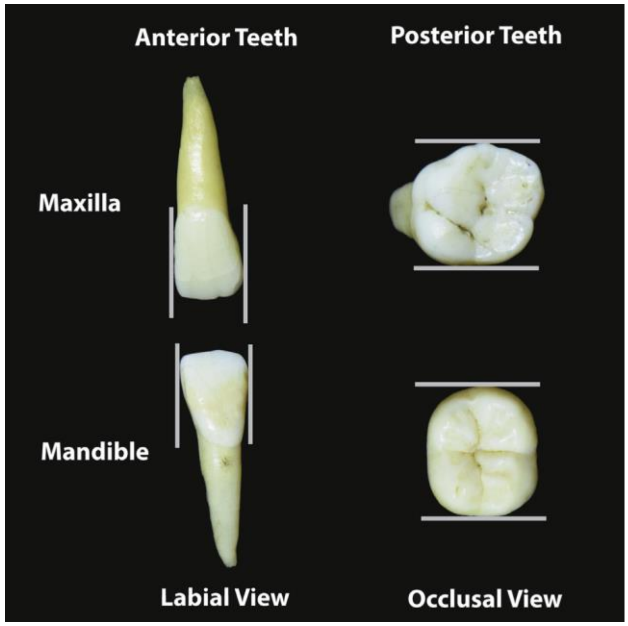

Figure 7. *Dental Metric Traits*

Examples of dental metric traits (Pilloud and Kenyhercz 2016, 138).

Dental Non-Metric Traits

Dental non-metric traits are another tool that can be used to track evolutionary and biological relationships. These morphological traits are scored on their degree of expression from 0 (representing absence of trait) to 5 (indicating extreme expression) based on a series of standardized casts (Buikstra and Ubelaker 1994, 63). Non-metric dental traits include morphological variations such as Tomes' root and shovel-shaped incisors (Figure 8 below) (Scott 1973, 5; Tomes and Tims 1923, 509). Dental non-metric traits have been shown to correlate with mitochondrial DNA from individuals within the same nuclear household (Hubbard, Guatelli-Steinberg, and Irish 2015, 302). Thus, the

increased presence or absences of these traits in a sample would indicate a higher degree of biological relatedness (Larsen 2015, 364). However, difficulties in identifying traits have often led to issues in research studies. For example, worn or fragmented dentition can make the scoring of individuals traits challenging (Robedizo 2016, 40).

Figure 8. *Shovel Shaped Incisors Dental Casts*

Shovel shaped incisors dental casts (Scott et al. 2018, 26).

Cranial Traits

Cranial Metric Traits

Craniometrics provide bioarchaeologists with another source of data in biological distance studies. The human skull is subjected to similar environmental and evolutionary pressures as the dentition and thus provides a valuable resource in determining biological distance (Buikstra and Ubelaker 1994, 69). Cranial metric traits have been shown to reflect underlying genotypes and thus that individuals more related to one another are more likely to share similar cranial morphologies (Herrera, Hanihara, and Godde 2014, 344; Cheverud 1982, 514). Cranial metric data is obtained using standard and sliding calipers to calculate various measurements on the cranium, and mandibular measurements can be acquired through the use of a mandibulometer (Buikstra and

Ubelaker 1994, 70). There are 24 standard measurements that can be obtained from the crania and ten from the mandible; however, with the fragmentary condition of many bioarchaeological assemblages, not all measurements can be obtained in every situation (Buikstra and Ubelaker 1994, 74-78). Cranial metric data can be analyzed using a variety of statistical methods, including those such as calculating the genetic distance or through cluster analysis (C. M. Stojanowski and Schillaci 2006, 64). Some examples of cranial measurements are shown below in figure 9.

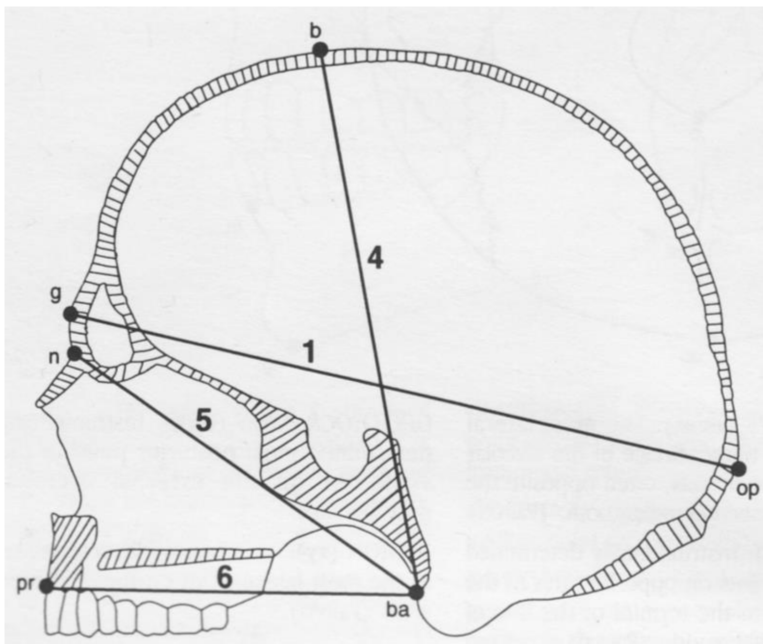

Figure 9. *Cranial Measurements*

Examples of cranial measurements. 1) Maximum Cranial Length, 4) Basion-Bregma Height, 5) Cranial Base Length, and 6) Basion-Prosthion Length. (Buikstra and Ubelaker 1994, 74).

Cranial Non-Metric Traits

A final classification of skeletal biological distance data includes cranial non-metric traits, which are typically analyzed using Mean Measure of Divergence statistics. Similar to dental non-metric traits, these cranial traits are influenced by genetic factors

that can be used to reconstruct biological relatedness (Larsen 2015, 363; Buikstra and Ubelaker 1994, 85). Cranial non-metric traits have been shown to be an expression of the genotype, and that populations more related to one another with show similar frequencies of non-metric traits (Carolineberry and Berry 1967, 270-272). This is because non-metric traits are an expression of the alleles carried by the individuals within a population and inheritance of these traits have been tracked in studies using animals such as rats (Berry 1979, 674). More than 200 cranial non-metric traits have been identified and are typically classified into one of four groups. The first is ossicles, which are small bones within cranial sutures (such as lambdoidal ossicles) (Larsen 2015, 363). These can be observed in Figure 10 below.

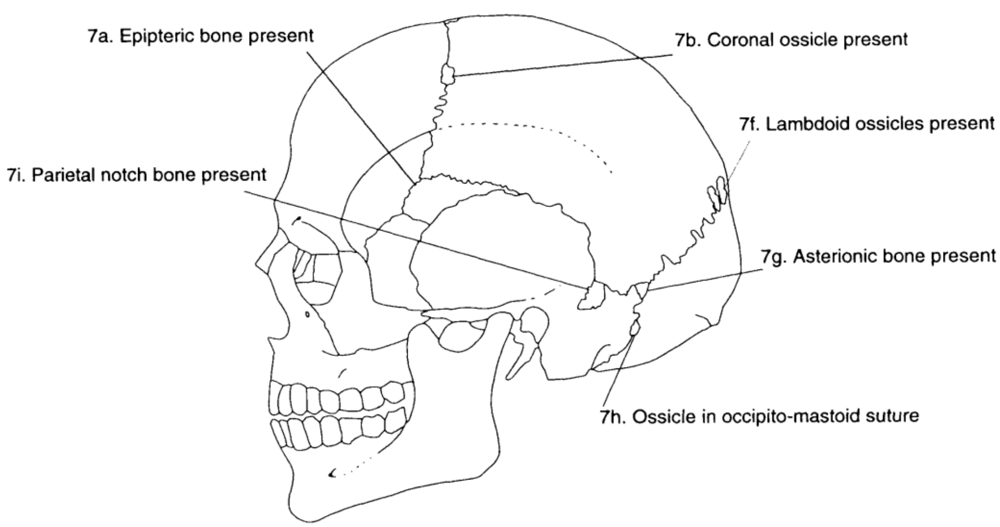

Figure 10. *Cranial Ossicles*

Examples of ossicles on the skull (Buikstra and Ubelaker 1994, 88).

Second, hyperostotic traits include unusual skeletal proliferations, such as atlas bridging (Figure 11), pterygospinous foramen, and caroticoclinoid foramina. These traits can also be examined for population relatedness (Larsen 2015, 363).

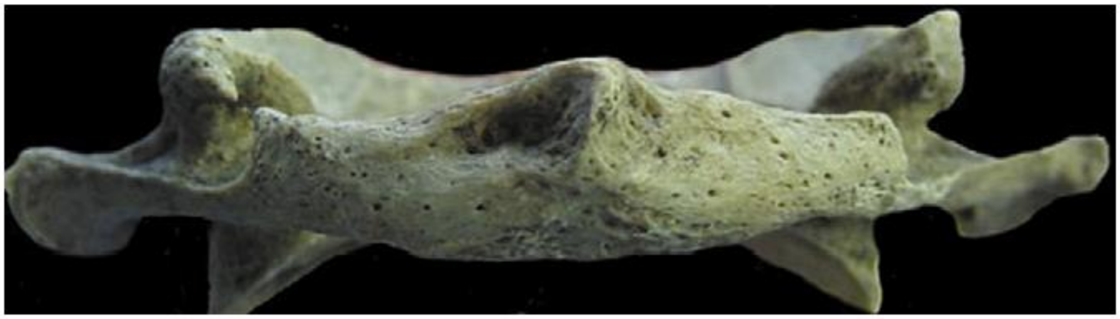

Figure 11. *Atlas Bridging*

Example of hyperostotic traits (Simsek et al. 2008, 687).

The third group is characterized by hypostatic traits, which are those features that include ossification deficiencies, such as the retention of the metopic suture (figure 12) and incompletion of foramen ovale (Larsen 2015, 363).

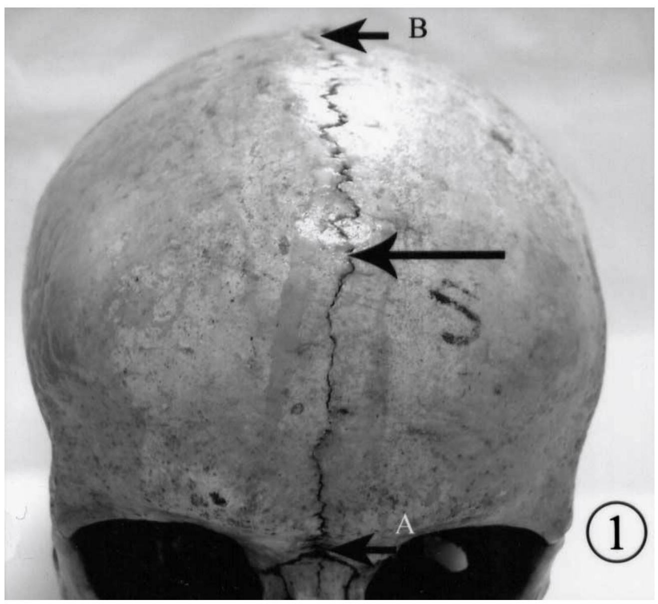

Figure 12. *Retention of the Metopic Suture*

Example of hyperostotic traits (Castilho, Oda, and Santana 2006, 62).

Finally, the fourth category of cranial non-metric traits include foraminal variations, such as double supraorbital foramina seen below in Figure 13 (Larsen 2015, 363). Other foraminal variations include the number of mental foramen and parietal foramina (Buikstra and Ubelaker, 88 1994).

Figure 13. *Foramen Variations*

Double supraorbital foramen variations. Image by Amy Hair.

The argument has been made that cranial non-metric traits should be scored on a dichotomous scale; however, others assert that a graded scale should be used to more accurately represent phenotypic variation (Buikstra and Ubelaker 1994, 85). It is due to this disagreement that a standardized scoring system for cranial non-metric traits has not been put forth; instead it is up to researcher discretion to determine which method of data collection best suits their research goals (Buikstra and Ubelaker 1994, 85). In addition, difficulty identifying and incorrectly identifying non-metric traits can also pose threats to bioarchaeological data sets.

Major Criticisms of Biological Distance

Biological distance studies, while valuable in bioarchaeological research, have faced their share of methodological and ethical debates. Critics state that such

investigations are typically characterized by the metric studies of the late 18th and early 19th centuries that focused on classifying racial variation (Armelagos and Gerven 2003, 54). In the 1880s, Paul Broca developed many of the landmarks, measurements, and cranial indexes that were later used in various studies to rank different races and in restrict immigration into the United States (Armelagos and Gerven 2003, 53). However, with Sherwood Washburn's call for a new physical anthropology in the 1950s, many typological and descriptive approaches were exchanged for methodologies that incorporated a more profound understanding of evolution and adaptation and fit with modern evolutionary theory (Armelagos and Gerven 2003, 55). Despite the widespread use of biological distance methods, critics claim that these methods represent a reversion to a static and typological period of anthropological history (Armelagos and Gerven 2003, 53). These individuals assert research endeavors are overlooking questions of plasticity and function in place of those that focus on regional origins (Armelagos and Gerven 2003, 59).

However, proponents of biological distance methods assert that the methodology is more than a simple classification system. Supporters of biodistance studies state that these criticisms are do not fully comprehend the scope of potential research directions that include more than just migration and racial history, and instead modern biodistance research includes research foci such as human variation, adaptation, and ethnogenesis (Stojanowski and Buikstra 2004, 430).

Another criticism of biodistance is that the nature and degree of hereditability of these traits has been previously debated. Critics assert that cranial shape and size are highly subject to environmental forces, a trend that is mostly a result of Boas' early

research on immigrant cranial forms which suggests that cranial data is more reflective of then environment then the underlying genotype (Sparks and Jantz 2002, 14636). In addition previous research has indicated significant sex and age difference when addressing non-metric traits and has instead suggested that these methods be used in combination with others to speak on genetic relatedness (Corruccini 1974, 440).

Despite these criticisms, proponents of biodistance research assert that phenotypic variability can still be addressed through the use of bedance methodologies (Stojanowski and Buikstra 2004, 430). While the environmental has been shown to impact cranial morphology, numerous studies have shown that cranial form is primarily genetic, with heritability rates ranging from 54.97% to 70.76% (Jelenkovic et al. 2009, 637; Hanihara et al. 2003, 247). Thus indicating that while the environment may induce a plastic response in regards to cranial form, genetics plays a more significant role in determining overall cranial morphology (Jelenkovic et al. 2009, 637). Despite harsh criticisms of biodistance methodologies, these tools can be useful in understanding the microevolutionary process in human history.

Biodistance Studies Using Traditional Methods

Migration Biodistance Studies

Biodistance methods can be used to study genetic relatedness in a number of ways, and often is often utilized in the study of migration. For example, Scherer's analysis of Classic Maya centers utilized dental dimensions as a way to understand population structures (2007, 368). During this period, various sites were growing and declining at different rates (Scherer 2007, 368). Dental metrics were used as a method to understand the degree of relatedness among large centers and specifically as a way to

apply the isolation by distance hypothesis, which states that as individuals are restricted to a specific area, the level of genetic relatedness will increase within the population and decrease with outside populations (Scherer 2007, 369). A total of nine measurements were collected from 321 Classic period individuals from various locations across the Maya region (Scherer 2007, 369-370). Varying levels of genetic distance between sites and regions indicated that the isolation by distance hypothesis can be rejected, as there is no evidence of regional clustering (Scherer 2007, 374). Instead, biological distance data suggests that during the Classic Maya period there was extensive gene flow both among centers and regions, thus suggesting high levels of mobility (Scherer 2007, 377).

Other studies have utilized craniometric data as way to understand migration events in the archaeological record. For example, Jennifer Vollner's dissertation employed cranial metric data as a way to interpret mass migration in ancient Nubia (Vollner 2016, 73). Her research utilized up to 78 cranial and mandibular landmarks for analysis based on both digitized and physical remains (Vollner 2016, 85). Data suggested that despite intense debate over migrants entering Nubia from Egypt during the Medieval period, no mass migration event occurred, and instead biodistance indicates high levels of relatedness among samples (Vollner 2016, 133). This has instead been interpreted as indicating new levels of interaction between the Nubian and Egyptian individuals, as seen by the influence of genetic drift and external gene flow (Vollner 2016, 137).

Kinship Studies

Kinship can also be addressed through the use of biodistance methodologies. For example, Velasco's study employed cranial non-metric traits to understand post-marital residential patterns in the Late Intermediate Period, roughly AD 1000-1476, in the Andes

(Velasco 2018, 906). This study utilized the remains of 152 individuals excavated from open sepulchers at the sites of Yuraq Qaqa and Sahuara located in modern day Peru (Velasco 2018, 910). 43 Non-metric traits were scored according to a four point gradient ranging from absent to complete expression (Velasco 2018, 911). Results of this study indicated that both males and females showed similar levels of phenotypic variability, suggesting that both sexes were equally likely to migrate following marriage (Velasco 2018, 916). This research shed new light on marriage practices and kinship structured migration (Velasco 2018, 917).

Another study utilized both cranial and dental non-metric traits to assess post-marital residence practices in the Pacific Islands (Eubank 2016, 51-52). Traits were scored based on a three-point gradient ranging from absent to full expression and later subjected to a number of statistical tests, such as Generalized Procrustes Analysis, Mantel tests, and Principle Component tests, to explore phenotypic variation between and within the sexes (Eubank 2016, 59). Results showed little variation between male and female migration and suggested that post-marital residential practices in the Pacific Island most likely adhered to a unilineal pattern of marriage customs (Eubank 2016, 116).

Biodistance Studies Using Digital Methods

Evolutionary History Studies

Questions pertaining to evolutionary history and development can also be addressed using digital biological distance methods. For example, Bastir and colleagues' utilized digital biodistance from CT scans to create models of the interiors of crania of various human ancestors including *Australopithecus africanus, Homo erectus, Homo heidelbergensis, Homo neanderthalensis,* and *Homo sapiens* in order to understand the

cranial morphological changes that took place in the middle fossa across the development of the human species (Bastir et al. 2008, 132-133). They identified six landmarks based on the preservation and morphological significance of the region (Bastir et al. 2008, 132). Their results showed little difference in regional size variation; however, shape variation did prove to be statistically significant between the species (Bastir et al. 2008, 134). The use of CT scans in this study allowed the scholars to study the middle crania fossa, a region of the crania impossible to access due to its interior nature, thus providing researchers with more depth than previously possible with traditional methodologies.

Another study was interested in understanding the effect of diet on human cranial facial morphology and masticatory functions. This study digitized a total of 84 morphological landmarks on the cranium using a Microscribe digitizer to investigate the effects of dietary composition in Late Holocene populations in South America (Menéndez et al. 2014, 123). A total of 474 individuals were included in the study and were subjected to tests that analyzed both their individual cranial measurements in addition to cranial shape to assess the correlation between dietary composition and cranial facial morphology (Menéndez et al. 2014, 115). Their results indicated that, contrary to past research, dietary composition did not correlate with bite force and thus did not correlate with cranial facial morphology (Menéndez et al. 2014, 123). This research has shed new light on the complex relationship between masticatory functions, diet, and the surrounding the environment, suggesting that instead the relationship between these factors is more complex than previously assumed (Menéndez et al. 2014, 125).

Ethnogenesis Biodistance Studies

Questions pertaining to ethnogenesis have also been addressed in digital biodistance research. For example, laser scanners have played a significant role in bioarchaeological research, particularly in Kuzminky and colleagues' research that addressed cranial modification variation in South America (Kuzminsky et al. 2016, 510). Their study utilized a NextEngine scanner to digitize the crania of 56 adult individuals from four sites throughout Peru and Chile dating from the Archaic (15,000 B.C.E) to the Late Intermediate period (1476 C.E.) (Kuzminsky et al. 2016, 510-511). The authors took a total of 18 scans and identified 10 cranial landmarks per crania using the software Stratovan Checkpoint (Kuzminsky et al. 2016, 511). Results indicated that not only are 10 landmarks enough to capture the differences in cranial morphology and group identity, but also suggested the possible need for a new type of cranial modification category, or at least increase the recognition of variation and variety within the practice (Kuzminsky et al. 2016, 512).

Another study addressed changes in cranial vault modification during the Post-Classic period, roughly 900-1500 AD, in the Zacapu basin of southern Mexico (Natahi et al. 2019, 418). This study included a total of 55 individuals from the sites of El Palacio and Malpaís Prieto and were scanned using a NextEngine scanner (Natahi et al. 2019, 420-421). Their results indicated that as populations moved in the Zacapu basin during the Post-Classic period cranial vault modfications were drastically different then those of surrounding surrounding populations (Natahi et al. 2019, 418). Three different types of modfication were present and are interpreted to be evidence of preexisting cultural practices, suggesting that migrant populations did not immediately conform to local

customs (Natahi et al. 2019, 429). This research sheds light on not only the cultural changes taking place in the Post-Classic era of the Zacapu basin, but also illuminates previously unacknowledged variabilty in cranial vault modification practices (Natahi et al. 2019, 429).

Conclusion

Biodistance has proven itself a valuable way to study genetic relatedness among individuals and populations, and thus investigate questions related to migration, micro and macro evolutionary processes, and cultural practices such as cranial modification and kinship patterns (Larsen 2015, 357; Vollner 2016, 85; Scherer 2007, 377; Bastir et al. 2008, 132; Kuzminsky et al. 2016, 510; Schillaci and Stojanowski 2003, 11). Traditionally these studies have been accomplished by collecting data from physical remains; however, advances in new digitization technology means that bioarchaeology can both collect their data and preserve their samples for future scholars simultaneously (Wrobel, Biggs, and Hair 2019, 50; Kuzminsky and Gardiner 2012, 2744). However, photogrammetry is still new to bioarchaeology, and while the method has been rigorously tested and proven accurate in many faunal assemblages, methods specific to bioarcheaological research agendas must be tested to assess both the benefits limits of the method within bioarchaeology (Evin et al. 2016, 87; Moshobane, de Bruyn, and Bester 2016, 267).

CHAPTER IV – MATERIALS AND METHODS

Materials

Tipu Site Background

Tipu is located on the Macal River in central western Belize, as seen in Figure 14 (Graham 2011, 52). In pre-Contact times, the site of Tipu did have a Post-Classic component; however, modern use of the land has restricted access and destroyed portions of the site, however, ceramic continuity suggests that Tipu that precontact the site had ties to sites such as those in Petén (Pendergast 1993, 81). What is known in regards to settlement at the site is that by the late Post-Classic, Tipu experienced a resurgence in activity following the Classic Collapse (Andrews 1993, 56). Tipu's vantage point on the Macal River provided key access to control trade and communicate with other settlements in the region, such as those in the Belize River Valley and in the Petén (Graham 2011, 52). Tipu was part of a sphere of association that relied heavily on connections in the western portions of Belize and those communities within modern day Petén (Graham 2011, 58).

Figure 14. *Map of Belize Showing Tipu*

Map of Colonial Belize showing Tipu (Pendergast 1993).

In addition to serving as key Post-Classic site, Tipu also played a significant role during the Contact period. The first church at Tipu was established by 1560, but development could have begun as early at 1543-1544 as Tipu was one of the original *encomiendas* along with other early mission sites such as Lamanai (Graham 2011, 224). The church was intended to serve the entire community and was largely constructed in Spanish style despite small differences that were most likely decided on site in light of friar negotiations with the native Maya identity (Graham 2011, 230; Pendergast 1993, 110). During this time, conversion proved successful as over 600 Maya individuals were buried in association with the church and its cemetery at Tipu (Graham 2011, 191). As a result, the Spanish moved their sights west and began to plan their next assault in the Petén region (Andrews 1993, 56).

In 1618 friars organized a delegation to send to Nojpeten in order to obtain a commitment to Christianity (Graham 1993, 243). This would not be the first encounter the Itzá had with the Spanish, as in 1525 Hernán Cortés meet with the native population while passing through to Honduras (Graham 2011, 243; McKillop 2004, 348). Despite respectfully receiving the Spaniards, Can Ek, the current ruler of Nojpeten, stated that they were not ready to become Christian (Graham 2011, 243). The meeting took a turn for the worse when the friars mistook an effigy of the horse Cortés left behind as idolatry and destroyed it (Graham 2011, 243). Can Ek proceeded to force the delegation out of Itzá territory (Graham 2011, 243). Further efforts to Christianize the Itzá region would occur; however, all attempts would prove futile with Maya resistance (Graham 2011, 244).

As the Spanish continued to push into the Petén, Maya resistance increased throughout the region, and widespread rebellion broke out lasting from 1628-1638 and again from 1639-1641 (Graham 2011, 246). During this period Tipu's significance would increase from that of a mission *visita* outpost to that of a strategic vantage point to gain control of the Itzá to the west (Graham 2011, 251). The riots did send the appropriate message to Spanish authority; as missions in northern Belize were abandoned, large numbers of Maya fled to communities in the surrounding jungles that were seen as safe havens, such as Tipu and Tayasal (Graham 2011, 236). However, by 1695 the Tipu came back under Spanish control after sending representatives to Mérida to ask for a resident priest (Graham, Pendergast, and Jones 1989, 1257). Despite these setbacks, the Spanish continued to push west and increase pressure on the Lake Petén region throughout the 17th century, and on the morning of March 13th, 1697, Nojpetén was attacked and

conquered (Graham 2011, 252; Jones 1998, 295). Following the fall of Nojpetén, Tipu residents were relocated to the Lake Petén Itzá region (Graham 2011, 252).

Study Sample

Individuals included in the study were chosen based on cranial completeness. If at least three cranial measurements could be taken, they were selected to be digitized. A total of 27 individuals comprised the sample, including 12 females and 15 males. Because sex does not weigh into the accuracy or precision statistics of photogrammetric models, the difference in number between the sexes was not seen as significant.

Methods

Digitization

Tipu crania were digitized in December of 2017 using the turntable method. Each cranium was placed on top of a black turntable with a black velvet backdrop. Images were captured using a Nikon D5300 DSLR Camera. In addition, a Chromo Inc. ring light was used to control for lighting conditions. Twenty photographs were taken at three levels: level, mid-rise, and superior. Each cranium was then flipped over and the process was repeated. Thus, a minimum of 120 images were collected per cranium. The 120 photographs ensure that enough overlap is present in each image to aid in the processing procedures. More than 120 photographs may have been collected if it was determined that image was not focused properly or if lighting conditions needed to be modified.

After photographing, images were transferred to a laptop and organized by individual. Models were created using Agisoft Photoscan. All models were built on an ASUS laptop using the high building option. The high power building option allows the computer to devote more processing power to the construction of the model, thus

ensuring the best quality possible was produced. The models were saved in standard project file, a standard poly, and pdf to ensure that these files could be shared and easily accessed. Files were stored locally in addition to an external to hard drive to ensure file longevity.

Physical Metric Data Collection

Physical metric data was collected from the 27 individuals over the course of three sessions. Each of any of the physical or digital data sessions were separated by ten days to ensure measurement validity. A total of 24 different measurements, as noted in Table 1, were collected from each individual if the necessary landmarks were present on the individual (Buikstra and Ubelaker 1994, 74). Measurements were collected with standard lab equipment including both digital spreading and sliding calipers to .01mm of accuracy. When possible, all measurements were taken from the left side. Measurements were then noted in Microsoft Excel.

Table 1 *Cranial Metric Measurements Taken*

Maximum Cranial Length	Biauricular Breadth	Biorbital Breadth
Maximum Cranial Breadth	Upper Facial Height	Interorbital Breadth
Bizygomatic Breadth	Minimum Frontal Breadth	Frontal Chord
Basion-Bregma Height	Upper Facial Breadth	Parietal Chord
Cranial Base Length	Nasal Height	Occipital Chord
Basion-Prosthion Length	Nasal Breadth	Foramen Magnum Length
Maxillo-Alveolar Breadth	Orbital Breadth	Foramen Magnum Breadth
Maxillo-Alveolar Length	Orbital Height	Mastoid Length

Digital Metric Data Collection

Using the original 27 individuals, the same 24 measurements taken in the physical data session were then taken in software program Stratovan Checkpoint. Each of the

digital and physical data sessions were separated by ten days to ensure measurement validity. For each measurement, landmarks were identified and the distance between the two points was calculated by the program. All measurements were taken from the left side if possible and recorded to the 0.01 mm of accuracy. Measurements were then noted in Microsoft Excel. Figure 15 below shows a cranium with the all the available landmarks noted.

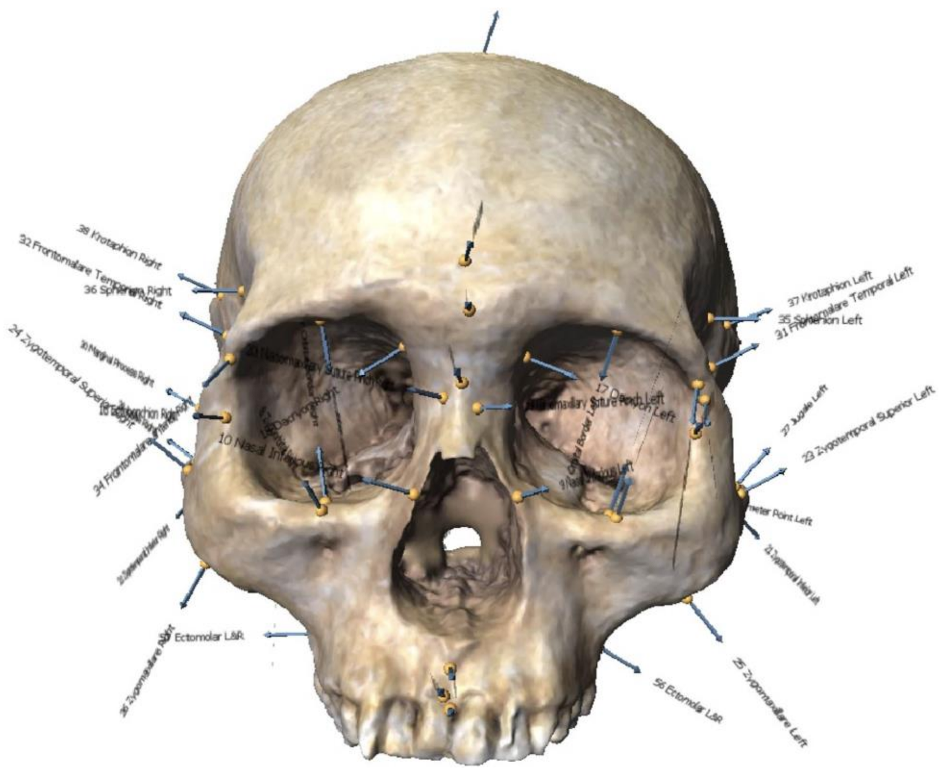

Figure 15. *Cranium with Landmarks Noted*

Cranium with landmarks placed in Stratovan Checkpoint. Image by Amy Hair.

Physical Non-Metric Data Collection

Physical non-metric trait data was collected from the 27 crania. The presence or absence of 24 traits, accepted in bioarchaeological standards, were noted and recorded in

Microsoft Excel (Buikstra and Ubelaker 1994, 87). If traits were missing or obscured by dirt, then then were noted as missing. Remains had been previously preserved in polyvinyl acetate making it difficult clear out crevices without damaging the remains, and thus to ensure the collection's condition for future research, dirt was not removed. Despite development of more detailed recording notation systems, traits were only scored on their presence or absence to ensure that the identifiability of traits was being tested. The 24 traits are listed in table 2.

Table 2 *Non-Metric Traits Evaluated*

Metopic Suture	Asterionic Bone
Supraorbital Notch	Ossicle in Occipito-mastoid Suture
Supraorbital Foramen	Parietal Notch Bone
Infraorbital Suture	Inca Bone
Multiple Infraorbital Foramina	Condylar Canal
Zygomatic-Facial Foramina	Divided Hypoglossal Canal
Parietal Foramen	Flexure of Superior Sagittal Sulcus
Epipteric Bone	Foramen Ovale Incomplete
Coronal Ossicle	Foramen Spinosum Incomplete
Bregmatic Bone	Tympanic Dehiscence
Sagittal Ossicle	Auditory Exostosis
Apical Bone	Mastoid Foramen

Digital Non-Metric Data Collection

Non-metric data was collected from the models of 27 individuals. Models were opened in Agisoft Photoscan for scoring. The presence or absence of traits was noted, and each trait was further scored based of how by how definable each trait was on the individual model. If traits were missing or obscured by dirt, they were recorded as missing. Traits were scored from 0-3 as observed in Robedizo's thesis research and

recorded in Microsoft Excel (Robedizo 2016, 40). The scoring system is as followed:

Scoring System for Non-Metric Traits

0	Absent
1	Low Identifiability
2	Identifiable
3	Highly Identifiable

Statistics

Accuracy

Percent error was calculated to determine how accurate photogrammetric models are when compared to their dry bone equivalencies. Percent error was computed by the following formula: ($\% \ error = \frac{error}{actual\ value}\ X\ 100$). The overall percent error was calculated in addition to percent error rates per individual cranial measurement. Any measurement above the accepted 2% error rate was not to be considered accurate (Williams and Rogers 2006, 730).

Precision

The standard deviation of both digital and dry bone measurements was computed using Microsoft Excel to determine the spread of the measurement values collected throughout the three sessions. The two values were then compared to determine which method was more precise. Finally, if a difference between the two methods was noted, a t-test was performed to determine if the difference were statistically significant.

Non-Metric Traits

The overall average for each individual trait was calculated using Microsoft Excel. The average provided an overall score for exactly how identifiable these traits are on photogrammetric models in addition to illuminating specific traits that suffer with this new methodology.

Conclusion

Cranial metric and non-metric traits are useful tools in determining the level of relatedness between individuals and populations, and when coupled with digitization methods such as photogrammetry the boundaries of the discipline can continue to expand. Despite increasing use of photogrammetry within bioarchaeology, the rates of precision, accuracy, and identifiability need to be assessed, as the reliability of future research relies on understanding both our strengths and weaknesses.

CHAPTER V - RESULTS AND DISCUSSION

Introduction

This chapter will review the results of all three research questions. Using percent error, standard deviation, and mean value, the accuracy, precision, and identifiability of metric and non-metric cranial traits were tested. Following a description of the results a discussion of the findings will take place addressing the variables that may have resulted in such an outcome.

Research Question 1: How accurate are photogrammetric measurements when compared to dry bone measurements?

Results

Overall measurements proved to be accurate, with the average percent error being 0.8% as shown in table 4. Standard deviation of percent error was larger than expect at 1.00; however, as will be discussed in more depth later, interorbital breadth proved to be an outlier with a percent error rate at 4.66%. When this variable was excluded, the average percent error decreased to 0.6% and the standard deviation fell to 0.58.

Table 3 *Accuracy of Photogrammetric Measurements*

	Percent Error	Standard Deviation of Percent Error
Interorbital Breadth Included	0.8%	1.00
Interorbital Breadth Excluded	0.6%	0.58

In addition, percent error was calculated for each of the 24 measurements individually. These values are indicated in table 5 below. All percent error rates, besides inter-orbital breadth, fell well below the 2% threshold deemed to be statistically acceptable for most studies (Williams and Rogers 2006, 730).

Table 4 *Percent Error and Standard Deviation by Measurement*

	Percent Error
Maximum Cranial Length	0.61151074
Maximum Cranial Breadth	0.13644157
Bizygomatic Breadth	1.50755677
Basion-Bregma Height	1.3517183
Cranial Base Length	0.74932036
Basion-Prosthion Length	0.00467508
Maxillo-Alveolar Breadth	0.18847546
Maxillo-Alveolar Length	0.36307933
Biauricular Breadth	0.11916932
Upper Facial Height	1.11023898
Minimum Frontal Breadth	0.06747562
Upper Facial Breadth	1.51909479
Nasal Height	1.86622105
Nasal Breadth	0.16958999
Orbital Breadth	0.27941861
Orbital Height	0.97540059
Biorbital Breadth	0.74088497
Interorbital Breadth	4.65794595
Frontal Chord	0.05775136
Parietal Chord	0.21498755
Occipital Chord	0.88870229
Foramen Magnum Length	0.98039216
Foramen Magnum Breadth	0
Mastoid Length	0.05664107

Discussion

Overall, photogrammetric measurements proved accurate when compared to dry measurements. As a whole, almost all percent error rates fell below the accepted 2% threshold indicating that photogrammetric measurement data can be accepted as accurate when used in place of dry bone measurements. Despite being accurate as a whole, two inter-landmark distances highlighted precautions that must be noted.

First, inter-orbital breadth was noted an outlier with a percent error rate of 4.66% and a standard deviation of 5.32. When excluded from the sample, percent error and standard deviation fell drastically. However, this case highlights the importance of proper landmark identification. The high rate of error observed is attributed to inaccurately identifying the landmark dacryon on the digital model. Dacryon is located in the upper medial portions of the orbits, a region of the cranium that can easily be obscured by shadows. Similar difficulties were experienced on the base skull, as shadows and lighting issues can make it increasingly difficult to appropriately identify points. Properly identifying landmarks is necessary to ensure that not is the right measurement being obtained but also that that measurement is correctly executed. Similar studies using CT scans also showed that landmarks located on less dense bone were more difficult to identify then landmarks on thicker portions of the bone (Williams and Richtsmeier 2003, 499). A possible solution to this limitation is ensuring that sufficient lighting is provided to these regions when they are within the camera scope, this helps to limit shadows and should make identifying landmarks such as dacryon a simpler and more accurate endeavor.

This research demonstrates two important points regarding digitized humans remains. First, cranial morphology plays a significant role in determining the indefinability of each trait, as surrounding features may play a key role is accurately identifying each feature (Williams and Richtsmeier 2003, 499). Second, it illuminates that each digitization method is prone to issue with feature identifiability as a result of environmental and morphological characteristics (Williams and Richtsmeier 2003, 498).

Thus, individual scholars need to assess the individual pros and cons of each method available and determine which best suits their research needs.

Second, the measurements with the lowest percent error rates were those that utilized easily identifiable points on the cranium. For example, to obtain the measurement associated with the frontal chord the researcher simply measures from bregma to lambda, landmarks that are both located at the intersections of two sutures. As a result of being easily identified, the frontal chord only had an error rate of 0.2%. Such measurements on average proved to be more accurate when compared to measurements that relied on minimum and maximum points such as bizygomatic breadth whose error was 1.5%. Measurements that included easy to identify landmarks were more accurate then more subjective points across the cranium. The sample was composed of young individuals, of which had limited cranial suture closure, making easier to identify landmarks such as bregma and lambda. Other landmarks also followed a similar pattern; for example identifying upper facial breath can also prove difficult as both landmarks require obtaining a minimum and maximum point. Previous research focusing on the interobserver rates between metric traits confirms that measurements relying on minimum and maximum point are most likely to experience increased error rates, a trend that photogrammetric models seemingly do not break (von Cramon-Taubadel, Frazier, and Lahr 2007, 31).

Research Question 2: How Precise are Photogrammetric Measurements when Compared to Dry Bone Measurements?

Results

When compared the standard deviation of digital measurements obtained from photogrammetric models was smaller than the standard deviation of measurements obtained from dry bone, as shown in table 5 below. A test was then conducted to determine if the variation observed between dry done and digital measurements was significant. The p-value of the standard deviation was less then alpha, set at .05, and thus the observed difference is statistically significant.

Table 5 *Standard Deviation of Dry Bone and Digital Methodologies*

Dry Bone Measurements	0.05
Digital Measurements	0.07

Discussion

As the standard deviation for digital measurements is smaller than that of dry bone measurements, digital measurements can be considered more precise then that of traditional methodologies. This can be attributed to a number of circumstances; however, most notable is the use of the template feature in Stratovan Checkpoint. This feature makes it possible for researchers to create a template of landmarks on a single specimen that can then be auto applied and adjusted for the remainder of the sample. As a result, there is less manual placement and adjustment of landmarks, thus leaving less room for observer error between specimens. All individual landmarks must be adjusted before moving forward, but this template feature not only saves time, but also helps with ensuring that all available landmarks are properly placed. This feature allows researchers

to gain to much more nuanced understanding of cranial morphology through the use of features such as sliding slices. These slices allow the user to specifically look for areas of interest based on the surrounding geography of the object. For example, slices make it easier to locate points of minimum and maximum regions by allowing the user to see various cuts of the object from varying angles, thus making it simple to identify such points with limited observer error.

Research Question 3: How Identifiable are Non-Metric Traits on Photogrammetric Models?

Results

The average score for identifiability was computed at 2.82 on a scale of 0-3. An average above a score of 2 was considered to be identifiable, whereas an average score below 2 was considered to be difficult to identify. In addition, the average identifiability was calculated for each individual non-metric trait, of which only five were below a score of 2. Those observed in Tipu are listed below in table 7; those that were absent from the sample were excluded.

Table 6 *Average Identifiability of Cranial Non-Metric Traits*

Supraorbital Notch	2.88235294
Supraorbital Foramen	2.8125
Infraorbital Suture	2.81818182
Multiple Infraorbital Foramina	3
Zygomatic-Facial Foramina	3
Parietal Foramen	2.75
Epipteric Bone	3
Coronal Ossicle	3
Apical Bone	3
Lambdoid Ossicle	3
Asterionic Bone	3
Inca Bone	3
Condylar Canal	1

Table 7 (continued).

Divided Hypoglossal Canal	1
Flexure of Superior Sagittal Sulcus	2.42857142
Foramen Ovale Incomplete	1.5
Foramen Spinosum Incomplete	1.66666667
Tympanic Dehiscence	1
Auditory Exostosis	2
Mastoid Foramen	2.77777778

Discussion

On average non-metric traits were easy to identify, despite issues suggested in previous studies (Robedizo 2016, 40). Robedizdo's study primarily focused on issues of identifying pathologies across different portions of the human skeleton, including the crania (Robedizo 2016, 39). Her results indicated that digitization methods such as laser scanning may obscure the surface morphology (Robedizo 2016, 40). In addition, identifying non-metric traits on physical remains has proven to be difficult in some studies. For example, a prior study has shown that the definition of individual non-metric plays a key role in how accurately they are identified, indicating that traits that are more clearly defined are more easily identifiable, whereas those with more ambiguous descriptions are more difficult to identify (Gualdi-Russo, Tasca, Brasili 1999, 549). In addition to ambiguous definitions, another study has showed that inconsistencies in scoring methodologies has contributed to both disagreements and inaccuracies in cross study comparisons (Freire and Dunford 2012, 187). This study instead suggested that cranial non-metric traits are overall easy to identify; however, a few traits, those with scores less than 2, were notably difficult to identify on models. These includes the condylar canal, divided hypoglossal canal, foramen ovale completion, foramen spinosum

completion, and the presence of a tympanic dehiscence. This is possibly due to the location and nature of such traits on the cranium, most of which are small and located on the inferior portion of the cranium near the foramen magnum, an area of the cranium that is often obstructed on 3D models as a result of shadows. This limitation can possibly be resolved by adjusting for lighting conditions, by ensuring that sufficient light is provided to these regions during photographing. The individual can thus control for shadows, making it easier to identify these traits on the final model.

All other traits located on the cranial surface were fairly easy to identify which can be attributed to a number of technical factors. First, the camera used to photograph the crania, a Nikon D5300 DSLR Camera, is a high-quality professional camera. Thus, the images obtained from the camera are expected to be of professional quality. A drastically different level of quality could be observed if lower standard equipment were to be employed. In addition, all components of each model were built on high quality, a processing level that not only requires significant time, but also significant computer processing power. This may not be available on all research projects, thus limiting final product quality. Finally, the surrounding environment was favorable to data collection, as external power sources were available, and lightning did not fluctuate throughout the day. If external power was not available and the primary source of light was natural, the final models could have easily been compromised. As a result, this study suggests that photogrammetry may represent a better alternative to collecting non-metric data than laser scanning.

In order to ensure proper identification of non-metric traits it is crucial that scholars invest in the time necessary to guarantee proper environmental condition and

data collection methods. This can range from ensuring that a minimum of 20 photographs are taken per rotation to that of doubling checking the lighting in both the immediate environment and in the photographs. Ensuring quality data collection further guarantees that non-metric traits will be properly identified in the final model.

CHAPTER VI - CONCLUSION

Findings

This thesis explored whether photogrammetry can serve as an alternative to traditional dry bone methodologies in biodistance studies. In the first set of comparisons, tests on the accuracy of photogrammetric measurements found that almost all measurements fell within the range of accepted error. However, it is important that researchers ensure that landmarks are properly identified to guarantee as much accuracy as possible, a task that while seemingly simple may be complicated on photogrammetric models as a result of environmental issues such as shadowing.

Second, the test comparing the precision of photogrammetric measurements to that of dry bone measurements found that photogrammetry is more precise then traditional methodologies. This can be attributed to the various tools available in software programs that allow users to autogenerate landmarks and make further adjustments improving accuracy. These tools make it easier for scholars to repeatedly identify the same point as a specific landmark, thus increasing precision.

Finally, overall, non-metric traits are highly identifiable on photogrammetric models. These results are contradictory to Robdezido’s thesis research that suggests the identifiability of traits and pathologies is more difficult to identify on digital representations (Robdezido 2016, 43). This is most likely the result of high-quality equipment including cameras and light in addition to the use of high processing power when creating the models. However, a handful of landmarks, such as presence of a condylar canal or divided hypoglossal canal, the completion of foramen ovale or spinosum, and the presence of a tympanic dehiscence were difficult to identify as a result

of their small and subtle nature coupled with their locations on the inferior portion of the cranium which led to issues with shadows on the inferior portion of the cranium. Overall, photogrammetry models represent a reasonable alternative to collecting cranial metric and non-metric data when compared with traditional methodologies.

Significance

As photogrammetry was found to be both accurate and precise, the field of bioarchaeology stands to gain a great deal, particularly in relation to collection preservation. Skeletal collections are extremely fragile artifacts, and the constant handling that results from physical data collection threatens their survival for future generations of researchers. The use of photogrammetry and other digital imaging techniques reduces this tendency and ensure that collections can be both study and preserved now and for generations to come.

In addition, the use of photogrammetry in bioarchaeology also increases the opportunity for data access throughout the discipline. As photogrammetric models are easily stored and shared data can be more easily shared through the discipline, individuals may no longer have to devote resources to travel. Instead models can be shared easily though the use of email or cloud service sites such Google Drive or Dropbox, thus promoting both open access principles and collaboration in the discipline. Embodying such an open nature also alludes that the development of bioarchaeological photogrammetric databases. These resources can aid research in numerous ways ranging from increasing sample sizes and representing a new way in which to train future researchers.

Future Research

This study was limited by two key factors: first, it only tested the differences of photogrammetry when compared to dry bone methodologies. Further research can test the accuracy and precision of metric traits in addition to the identifiability of non-metric traits across digital imaging technologies. Previous studies have compared photogrammetry with laser scanning however, a united study comparing the accuracy, precision, and identifiably of traditional methodologies with that of photogrammetry, laser scanning, and CT scanning has yet to be conducted. Such a study would address the most popular of available traditional and digital biodistance studies and provide a resource for scholars to determine which workflow can best be incorporated into their specific research agendas.

Second, this study was limited by only including cranial metric and non-metric traits. Dental traits provide a key resource is evaluating the genetic relationship between samples. As the overall size and morphology of teeth is notable smaller than that of the cranium, future research can focus on addressing the accuracy, precision, and identifiability of metric and non-metric traits on dental remains. Such a study would allow for more possibilities to not only test the limits of the methodology, but also provide researchers with a new line of data to include in their research.

Conclusion

This study showed the photogrammetry represents an accurate and precise method to collect cranial metric and non-metric data. By testing the method with that of traditional data collection procedures, photogrammetry can be incorporated into research agendas without concern surrounding the reliability of the method. Photogrammetry

represents an opportunity for bioarchaeologists to change and propel the discipline in novel ways. Notably, the method preserves skeletal collections for future generations of researchers. In addition, the method also encourages the acceptance of principles associated with the open access movement, a set of principles that have the opportunity to drastically change the way in which both scholars and the public interact with the discipline. This study showed the photogrammetry represents an accurate and precise method to collect cranial metric and non-metric data, thus further encouraging best practices in preservation and open access throughout the discipline.

References

Anderson, Richard C. 1982. “Photogrammetry: The Pros and Cons for Archaeology.” *World Archaeology* 14 (2): 200–205.

Andrews, Anthony. 1993. “Late Postclassic Lowland Maya Archaeology.” *Journal of World Prehistory* 7 (1): 35–69.

Armelagos, George J., and Dennis P. Van Gerven. 2003. “A Century of Skeletal Biology and Paleopathology: Contrasts, Contradictions, and Conflicts.” *American Anthropologist* 105 (1): 53–64. https://doi.org/10.1525/aa.2003.105.1.53.

Asier Gómez-Olivencia, Alon Barash, Daniel García-Martínez, Mikel Arlegi, Patricia Kramer, Markus Bastir, and Ella Been. 2018. “3D Virtual Reconstruction of the Kebara 2 Neandertal Thorax.” *Nature Communications* 9 (1): 1–8. https://doi.org/10.1038/s41467-018-06803-z.

Badawi-Fayad, Jackie, and Emmanuel-Alain Cabanis. 2007. “Three-dimensional Procrustes Analysis of Modern Human Craniofacial Form.” *The Anatomical Record: Advances in Integrative Anatomy and Evolutionary Biology:* 290 (3): 268–76.

Bastir, Markus, Antonio Rosas, Daniel E Lieberman, and Paul O’Higgins. 2008. “Middle Cranial Fossa Anatomy and the Origin of Modern Humans.” *The Anatomical Record: Advances in Integrative Anatomy and Evolutionary Biology* 291 (2): 130–40.

Berry, R.J. 1979. “Section I. Genes and Skeletons, Ancient and Modern.” *Journal of Human Evolution* 8 (7): 669–77.

Biggs, Jack. 2017. “Updated Photogrammetry Workflow.” Manuscript on file, Department of Anthropology, Michigan State University, East Lansing.”

Bonatto, Sandro L., and Francisco M. Salzano. 1997. “A Single and Early Migration for the Peopling of the Americas Supported by Mitochondrial DNA Sequence Data.” *Proceedings of the National Academy of Sciences* 94 (5): 1866–71.

Buikstra, J.E., and D.H. Ubelaker. 1994. *Standards for Data Collection from Human Skeletal Remains: Proceedings of a Seminar at the Field Museum of Natural History, Organized by Jonathan Haas*. Vol. 44. Arkansas Archeological Survey Research Series. Fayetteville, Arkansas: Arkansas Archeological Survey.

Carolineberry, A., and R.J. Berry. 1967. “Epigenetic Variation in the Human Cranium.” *Journal of Anatomy* 101 (Pt 2): 361.

Castilho, S.M.A., Y.J Oda, and G.D.M. Santana. 2006. “Metopism in Adult Skulls from Southern Brazil.” *International Journal of Morphology* 24 (1): 61–66.

Cheverud, James M. 1982. “Phenotypic, Genetic, and Environmental Morphological Integration in the Cranium.” *Evolution* 36 (3): 499–516.

Cooper, David M.L., Andrei L. Turinsky, Christoph Wilhelm Sensen, and Benedikt Hallgrímsson. 2003. “Quantitative 3D Analysis of the Canal Network in Cortical Bone by Micro-computed Tomography.” *The Anatomical Record Part B: The New Anatomist* 274 (1): 169–79.

Corruccini, Robert S. 1974. "An examination of the meaning of cranial discrete traits for human skeletal biological studies." *American Journal of Physical Anthropology* 40(3): 425-445.

Cramon-Taubadel, Noreen von, Brenda C. Frazier, and Marta Mirazon Lahr. 2007. “The Problem of Assessing Landmark Error in Geometric Morphometrics: Theory, Methods, and Modifications.” *American Journal of Physical Anthropology* 134 (1): 24–35.

Dipierri, José E., Emma Alfaro, Veronica L. Martínez-Marignac, Graciela Bailliet, Claudio M. Bravi, Silvina Cejas, and Néstor O. Bianchi. 1998. “Paternal Directional Mating in Two Amerindian Subpopulations Located at Different Altitudes in Northwestern Argentina.” *Human Biology* 70 (6): 1001–10.

Eubank, Brittney A. 2016. “A Comparison of the Utility of Craniometric and Dental Morphological Data for Assessing Biodistance and Sex-Differential Migration in the Pacific Islands.” Thesis, Missoula, MT: The University of Montana.

Evin, Allowen, Thibaud Souter, Ardern Hulme-Beaman, Carly Ameen, Richard Allen, Pietro Viacava, Greger Larson, Thomas Cucchi, and Keith Dobney. 2016. “The Use of Close-Range Photogrammetry in Zooarchaeology: Creating Accurate 3D Models of Wolf Crania to Study Dog Domestication.” *Journal of Archaeological Science: Reports* 9: 87–93.

Felicísimo, Ángel M., María-Eugenia Polo, and Juan A. Peris. 2013. “Three-Dimensional Models of Archaeological Objects: From Laser Scanners to Interactive Pdf Documents.” *Technical Briefs in Historical Archaeology* 7: 13–18.

Freire, Shannon, and Ashley Dunford. 2012. "Reliability Study of Methods for Scoring a Non-Metric Human Osteological Trait." *Field Notes* 4(1): 173-191.

Graham, Elizabeth A. 2011. *Maya Christians and Their Churches in Sixteenth-Century Belize*. Gainesville, FL: University Press of Florida.

Graham, Elizabeth A., David M. Pendergast, and Grant D. Jones. 1989. “On the Fringes of Conquest: Maya-Spanish Contact in Colonial Belize.” *Science* 246 (4935): 1254–59.

Gribbs, Keith. 2016. “Computerised Axial Tomography (CAT or CT).” School Physics. 2016. http://www.schoolphysics.co.uk/age16-19/Atomic%20physics/X%20rays/text/CAT_scanning/index.html.

Gualdi-Russo, E., M. A. Tasca, and P. Brasili. 1999. "Scoring of Nonmetric Cranial Traits: a Methodological Approach." *The Journal of Anatomy*: 195: 543-550.

Hanihara, Tsunehiko, and Hajime Ishida. 2005. “Metric Dental Variation of Major Human Populations.” *American Journal of Physical Anthropology:* 128 (2): 287–98.

Hanihara, Tsunehiko, Hajime Ishida, and Yukio Dodo. 2003. "Characterization of biological diversity through analysis of discrete cranial traits." *American Journal of Physical Anthropology:* 121 (3): 241-251.

Herrera, Brianne, Tsunehiko Hanihara, and Kanya Godde. 2014. “Comparability of Multiple Data Types from the Bering Strait Region: Cranial and Dental Metrics and Nonmetrics, MtDNA, and Y-chromosome DNA.” *American Journal of Physical Anthropology* 154 (3): 334–48.

Hubbard, Amelia R., Debbie Guatelli-Steinberg, and Joel D. Irish. 2015. “Do Nuclear DNA and Dental Nonmetric Data Produce Similar Reconstructions of Regional Population History? An Example from Modern Coastal Kenya.” *American Journal of Physical Anthropology* 157 (2): 295–304.

Hughes, Stephen. 2011. “CT Scanning in Archaeology.” *Computed Tomography-Specialist Applications* 2011: 57–70.

Jelenkovic, Aline, Alaitz Poveda, Charles Susanne, and Esther Rebato. 2009. “Contribution of Genetics and Environment to Craniofacial Anthropometric Phenotypes in Belgian Nuclear Families.” *Human Biology* 80 (6): 637–54.

Jiang, Ruinian, David V. Jáuregui, and Kenneth R. White. 2008. “Close-Range Photogrammetry Applications in Bridge Measurement: Literature Review.” *Measurement* 41 (8): 823–34.

Jones, Grant D. 1998. *The Conquest of the Last Maya Kingdom*. Stanford, California: Stanford University Press.

Katz, David, and Martin Friess. 2014. “Technical Note: 3D From Standard Digital Photography of Human Crania—A Preliminary Assessment.” *American Journal of Physical Anthropology* 154 (1): 152–58. https://doi.org/10.1002/ajpa.22468.

Katz, Jared. 2017. “Digitized Maya Music: The Creation of a 3D Database of Maya Musical Artifacts.” *The Past Now Showing in 3D: Case Studies in 3D Archaeology* 6: 29–37. https://doi.org/10.1016/j.daach.2017.08.004.

Klaus, Haagen D. 2008. “Out of Light Came Darkness: Bioarchaeology of Mortuary Ritual, Health, and Ethnogenesis in the Lambayeque Valley Complex North Coast of Peru (AD 900-1750).” Dissertation, Columbus, Ohio: The Ohio State University.

König, G., P. T. Y. Shih, and C. Katterfeld. 2012. “E-Learning - Best Practice in Photogrammetry, Remote Sensing and GIS - Status and Challenges.” *The International Archives of the Photogrammetry* XXXIX-B6 (1): 91–96. https://doi.org/10.5194/isprsarchives-XXXIX-B6-91-2012.

Kuzminsky, Susan C.. 2013. “Human Craniofacial Variation among Pacific Rim Populations through the Holocene: A Test of the Coastal Migration Hypothesis Using 3D Morphometric Methods.” Dissertation, Santa Barbara, California: University of California, Santa Barbara.

Kuzminsky, Susan C., and Megan S. Gardiner. 2012. “Three-Dimensional Laser Scanning: Potential Uses for Museum Conservation and Scientific Research.” *Journal of Archaeological Science* 39 (8): 2744–51. https://doi.org/10.1016/j.jas.2012.04.020.

Kuzminsky, Susan C., Tiffiny A. Tung, Mark Hubbe, and Antonio Villaseñor-Marchal. 2016. “The Application of 3D Geometric Morphometrics and Laser Surface Scanning to Investigate the Standardization of Cranial Vault Modification in the Andes.” *Journal of Archaeological Science: Reports* 10: 507–13. https://doi.org/10.1016/j.jasrep.2016.11.007.

Kyle, Stephen, T. Luhmann, Stuart Robson, and Jan Boehm. 2013. *Close-Range Photogrammetry and 3D Imaging*. Berlin, Germany: De Gruyter.

Larsen, Clark Spencer. 2015. *Bioarchaeology: Interpreting Behavior from the Human Skeleton*. 2nd ed. Cambridge, UK: Cambridge University Press.

Lewis, Cecil M., Jane E. Buikstra, and Anne C Stone. 2007. “Ancient DNA and Genetic Continuity in the South-Central Andes.” *Latin American Antiquity* 18 (2): 145–60.

Mathys, Aurore, Jonathan Brecko, and Patrick Semal. "Comparing 3D digitizing technologies: what are the differences?" In *2013 Digital Heritage International Congress (DigitalHeritage)*, vol. 1, pp. 201-204. IEEE, 2013.

Menéndez, Lumila, Valeria Bernal, Paula Novellino, and S. Ivan Perez. 2014. “Effect of Bite Force and Diet Composition on Craniofacial Diversification of Southern South American Human Populations.” *American Journal of Physical Anthropology* 155 (1): 114–27. https://doi.org/10.1002/ajpa.22560.

Monge J., Schoenemann P.T., Lewis J.E., Glotzer D. 2004. “The CT database at the University of Pennsylvania Museum.” *American Journal of Physical Anthropology*. 123 (Suppl 38):149

Moshobane, M. C., P. J. N. de Bruyn, Marthán N. Bester, J. Shelton, O. Weyl, J. van der Walt, S. Marr et al. 2016 ."Assessing 3D photogrammetry Techniques in Craniometrics." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 6: 267-273.

Natahi, Sélim, Michael Coquerelle, Grégory Pereira, and Priscilla Bayle. 2019. “Neurocranial Shape Variation among Tarascan Populations: Evidence for Varying Degrees in Artificially Modified Crania in Pre-Hispanic West Mexico (1200–1400 AD).” *American Journal of Physical Anthropology* 170 (3): 418–32.

Pendergast, David M. 1993. “Worlds in Collision: The Maya/Spanish Encounter in Sixteenth and Seventeenth Century Belize.” In *Proceedings of the British Academy*. 81: 105-143. UK: Oxford University Press Oxford.

Pilloud, Marin A., and Michael W. Kenyhercz. 2016. “Dental Metrics in Biodistance Analysis.” In *Biological Distance Analysis*, edited by Joseph T. Hefner and Marin A. Pilloud, 135–55. London, UK: Elsevier.

Robedizo, Bebelyn Placiente. 2016. “The Identifiability of Osteological Traits on 3D Models of Human Skeletal Remains.” Thesis, Lunds, Sweden: Lunds Universitet.

Scherer, Andrew K. 2007. “Population Structure of the Classic Period Maya.” *American Journal of Physical Anthropology* 132 (3): 367–80. https://doi.org/10.1002/ajpa.20535.

Schillaci, Michael A., and Christopher M. Stojanowski. 2003. “Postmarital Residence and Biological Variation at Pueblo Bonito.” *American Journal of Physical Anthropology* 120 (1): 1-15. https://doi.org/10.1002/ajpa.10147.

Scott, G. Richard, Marin A. Pilloud, David Navega, J. d’Oliveira, Eugénia Cunha, and Joel D. Irish. 2018. “RASUDAS: A New Web-Based Application for Estimating Ancestry from Tooth Morphology.” *Forensic Anthropology* 1 (1): 18–31.

Scott, George Richard. 1973. “Dental Morphology: A Genetic Study of American White Families and Variation in Living Southwest Indians.” Dissertation, Tempe, Arizona: Arizona State University.

Shelmerdine, Susan C., Ian C. Simcock, John Ciaran Hutchinson, Rosalind Aughwane, Andrew Melbourne, Daniil I. Nikitichev, Ju-ling Ong, Alessandro Borghi, Garrard Cole, and Emilia Kingham. 2018. “3D Printing from Microfocus Computed Tomography (Micro-CT) in Human Specimens: Education and Future Implications.” *The British Journal of Radiology* 91 (1088): 1–8.

Simsek, Serkan, Kazim Yigitkanli, Ayhan Comert, Halil I. Acar, Hakan Seckin, Uygur Er, Deniz Belen, Ibrahim Tekdemir, and Alaittin Elhan. 2008. "Posterior Osseous Bridging of C1." *Journal of Clinical Neuroscience* 15 (6): 686–88.

Skinner, Jessica L. 2017. "County Poor Farm Cemetery: A Replicable Method for Restoring Individuality." *A Journal of Collegiate Anthropology* 9 (1): 68–77.

Stojanowski, Christopher. 2001. "Cemetery Structure, Population Aggregation, and Biological Variabilty in the Mission Centers of La Florida." Dissertation, Albuquerque, New Mexico: The University of New Mexico.

Sparks, Corey S, and Richard L Jantz. 2002. "A Reassessment of Human Cranial Plasticity: Boas Revisited." *Proceedings of the National Academy of Sciences* 99 (23): 14636–39.

Stojanowski, Christopher M. 2004. "Population History of Native Groups in Pre-and Postcontact Spanish Florida: Aggregation, Gene Flow, and Genetic Drift on the Southeastern US Atlantic Coast." *American Journal of Physical Anthropology:* 123 (4): 316–32.

Stojanowski, Christopher M., and Jane E. Buikstra. 2004. "Biodistance Analysis, a Biocultural Enterprise: A Rejoinder to Armelagos and Van Gerven (2003)." *American Anthropologist* 106 (2): 430–31. https://doi.org/10.1525/aa.2004.106.2.430.

Stojanowski, Christopher M., Kathleen S. Paul, Andrew C. Seidel, William N. Duncan, and Debbie Guatelli-Steinberg. 2017. "Heritability and Genetic Integration of Tooth Size in the South Carolina Gullah." *American Journal of Physical Anthropology* 164 (3): 505–21.

Stone, Anne Carol. 1996. "Genetic and Mortuary Analyses of a Prehistoric Native American Community." Dissertation, State College, PA: Pennsylvania State University.

Tomes, Charles Sissmore, and Henry William Marett Tims. 1923. *A Manual of Dental Anatomy: Human and Comparative*. London, UK: Macmillan.

Unhammer, Ole Fredrik. 2016. "Methodological Evaluation of Digital Photogrammetry in a Middle Stone Age Cave Context. A Case Study from Blombos Cave, South Africa." Thesis, Bergen, Norway: The University of Bergen.

Velasco, Matthew C. 2018. "Ethnogenesis and Social Difference in the Andean Late Intermediate Period (AD 1100–1450): A Bioarchaeological Study of Cranial Modification in the Colca Valley, Peru." *Current Anthropology* 59 (1): 98–106. https://doi.org/10.1086/695986.

Vollner, Jennifer Maria. 2016. "Examining the Population History of Three Medieval Nubian Sites Through Craniometric Analyses." Dissertation, East Lansing, MI: Michigan State University.

Williams, Brenda, and Tracy Rogers. 2006. "Evaluating the Accuracy and Precision of Cranial Morphological Traits for Sex Determination." *Journal of Forensic Sciences* 51 (4): 729–35. https://doi.org/10.1111/j.1556-4029.2006.00177.x.

Williams, Frank L'Engle, and Joan T. Richtsmeier. 2003. "Comparison of Mandibular Landmarks from Computed Tomography and 3D Digitizer Data." *Clinical Anatomy:* 16 (6): 494–500.

Wilson, Andrew S., Andrew D. Holland, Tom Sparrow, David Errickson, and Tim Thompson. 2017. “Laser Scanning of Skeletal Pathological Conditions.” In *Human Remains: Another Dimension*, 123–34. London, UK: Academic Press.

Wrobel, Gabriel D., Jack Biggs, and Amy Hair. 2019. “Digital Modeling for Bioarchaeologists.” *Advances in Archaeological Practice* 7 (1): 47–54.