Accessibility in Bioarchaeology: Methods of 3D Imaging of Entheses

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Arts

in

Public Issues Anthropology

Waterloo, Ontario, Canada, 2023

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis examines accessibility within the field of bioarchaeology in two methods of generating 3D models of human remains, laser scanning and photogrammetry. These were analyzed for the following attributes: cost, time to perform method, ease of use, accuracy, and the utility of these methods in visual grading of entheses. The accuracy category measured such aspects as colouration and texture of the 3D image in comparison to the remains it was modelled after. The entheses on the 3D models were also visually graded to measure how accurately the 3D models could be evaluated using an ordinal method, such as Villotte's (2006) method of entheseal analysis, in comparison to the same analysis performed with the physical remains. It was found that photogrammetric models were highly accurate at representing the qualitative attributes of the remains (colour, texture, etc.) while being both cost effective and easy to create. The laser scanned models were likewise easy to create, though they were far more expensive, and not qualitatively accurate. However, neither method was sufficiently accurate at entheseal grading. Overall, the aspects of photogrammetry made for a far more accessible method for researchers due to its low costs, ease to implement, and the little time needed for data collection, but it must be done with equipment that can produce higher resolution 3D models.

Acknowledgements

There are many people who I believe deserve to be thanked for helping me get to where I am today.

I would foremost like to thank my supervisor, Dr. Maria Liston, for her support throughout my research and for the many opportunities I have had to learn from her over the past few years.

I would also like to thank Dr. Alexis Dolphin for the care shown to me during my research. As well, for her assistance in shaping the methods of my thesis.

I am sincerely grateful to Dr. Robert Park for allowing me to borrow his laser scanner for my research. Without his contribution, I would not have the thesis that I have today.

Furthermore, I must thank my committee, Dr. Maria Liston, Dr. Alexis Dolphin, and Dr. Robert Park, for helping shape and refine my thesis. Also, I would like to thank Dr. Adrienne Lo and Dr. Jennifer Liu for their contributions to the public issues aspect of my thesis.

I am enormously appreciative of my partner Lauren for her constant support. Thank you as well to my friends and family for whom I could always count on for encouragement.

I would also like to thank the students of my cohort. I could not imagine a better group to have learned and shaped my thesis with. Thank you as well to the many undergraduate students I had the pleasure of learning with and getting to know over the years.

Finally, I am immensely grateful for the individuals in the UWaterloo Anthropology Department's skeletal collection. I am privileged to have been able to learn and hone my skills from them. Without them, I would have no thesis.

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Chapter 1: Issues of Intersectional Accessibility in Bioarchaeology

Much of the knowledge production in Anthropology occurs in well-funded institutions located in the Global North. This centralized production of knowledge is a hinderance to those not privileged enough to have access to these institutions. Efforts have been made to decolonize the production of knowledge within academia, though much work must still be done. Anthropologist Kwesi Kwaa Prah envisions a 'universalism of all voices' where "…all, North and South, learn to look at ourselves, hear others about ourselves and themselves, and above all allow others to speak for themselves" (2008, 96). To do this Harrison (2016) writes that we must move theory-making to decentralized or 'ex-centric' sites. Moving theory-making and research to 'ex-centric' sites would also give voice to feminist and minoritized scholars that work within these Northern institutions but outside of the dominant anthropological traditions (Harrison, 2016).

Issues with intersectional accessibility in bioarchaeology begin with diversity. Even though effort has been made to increase diversity, there still remains a significant lack of diverse voices contributing equally to the field (Overholtzer & Jalbert, 2021; Willermet, 2016). With an onus placed on fieldwork, lingering systemic inequity remains for women and others in the field with families that face barriers for maintaining an active field career (Willermet, 2016). Overholtzer and Jalbert's (2021) analysis of archaeology in Canada found that two-thirds of PhD recipients are women; however, they make up only one-third of archaeology faculty members. This 'chilly climate' has been hypothesized to be a result of several factors, among them being a work environment that is not family-friendly (Wylie, 1993). In an effort to create a better environment for those with care obligations, the creation of methods of performing bioarchaeology that are more timely or flexible with non-normative work schedules are needed.

Moreover, access to the best places to gain practical experience, field schools, is inequitable as they require steep costs to cover flights, lodging, and various other expenses (Heath-Stout & Hannigan, 2020). This further reinforces the systemic issues that perpetuate the lack of diversity in the field as those gaining experience are those that are privileged enough to have the socio-economic means to do so. Therefore, a part of why bioarchaeology as a discipline is still struggling with these issues of accessibility is due to problems raised by affordability. To address these concerns, more affordable means of performing bioarchaeology must be found. This thesis addresses these themes of intersectional accessibility and, as a case study, compares two techniques of imaging human remains, examining both cost and time requirements to use the methods as well as their ease of learning.

As a mainly academic field, funding does exist through grants and scholarships, though many are not directed towards anthropology. Data from the 2021/22 funding year at the University of British Columbia shows the disproportionate rate at which the social sciences receive funding (UBC Research + Innovation, n.d.). Of the over ten thousand awards, the arts only account for just over one thousand (~10%), as opposed to the physical sciences which account for three thousand (~30%) of awards. Therefore, few social sciences researchers get the funding they need, leaving many more without the resources required for their research. During the 2021 competition year the Social Sciences and Humanities Research Council (SSHRC) received 2,388 scholarship and grant applications (Facts and Figures, 2022). Of these, anthropologists received 23 awards out of a total of 40 applicants (Facts and Figures, 2022). This amounts to an overall success rate of about 57.5%. Furthermore, many anthropologists choose not to apply for grants such as these. Estimates place the total number of archaeology PhDs in Canada between 2003 and 2017 at 102 (Overholtzer & Jalbert, 2021). As archaeology falls under anthropology in SSHRC's statistics, it is reasonable to conclude that there is a greater amount of anthropology PhD holders in Canada as of the 2021 funding year. Thus, few anthropologists, in the total pool of eligible anthropologists, apply to and receive an award. Another example comes from funding from the United States-based National Science Foundation (NSF). In 2014, during their semi-annual archaeology funding competition, the NSF provided an average of $178,000 per award, ranging from nearly $50,000 to $350,000 (Archaeology and Archaeometry, n.d). Though this appears to be an excellent source of funding for the field, there are not nearly enough grants to provide opportunities for archaeologists that lack the socio-economic ability to break into the field. Each year the NSF has been providing more grants to archaeologists; however, the latest figure stands at 45 grants awarded in 2022 (Award Search, n.d). A more targeted source of anthropological research funding in the United States comes from the National Endowment for the Humanities (NEH). The NEH's Archaeological and Ethnographic Field Research award of up to $150,000 has a funding success ratio of 11%, having given awards to six of its 55 applicants in 2022 (Archaeological and Ethnographic Field Research, n.d.). Even though there are many sources of large funding, such as the SSHRC, the NSF, and the NEH, many of the awardees of like awards are associated with metropolitan institutions located in the

Global North. Though the funding for anthropology being centered and kept within the Global North is a symptom of many deeper systemic issues tied to its colonial roots, these resources are still mainly benefitting those in the field that have the means and privilege to attend these institutions. Therefore, a way in which data production can be democratized is through the use of research methods that can be applied without the need for immense funding.

Another issue of accessibility within bioarchaeology stems from access to research material and remains. Those who conduct research outside of their country-of-origin face limits to the amount of time they may spend analyzing their materials. This is even more so for those who must first excavate the remains and process them before analysis. Further complicating this are the various laws and regulations that govern the analysis of human remains, that can greatly differ from nation to nation. A recent guide to legislation from numerous countries over each continent has been compiled by Marquez-Grant and Fibiger (2011). Each country has their own methods and legislations for the excavation and examination of archaeological remains (Marquez-Grant & Fibiger, 2011). To take Greece as an example, the Hellenic Ministry of Culture considers human skeletal remains to be cultural goods, as with all other archaeological finds (Prevedorou & Buikstra, 2019). Being governed by Law 3028/2002, a bioarchaeologist must obtain the proper rights and permits to study and publish on bioarchaeological materials through local and regional bureaucracies (Marquez-Grant & Fibiger, 2011; Prevedorou & Buikstra, 2019). All costs associated with the research and conservation of the finds are placed upon the individual or institution sponsoring the research (Prevedorou & Buikstra, 2019). This creates many challenges for the bioarchaeologist, such as "insufficient time, funding, and documentation in the field; conservation needs; and proper storage space—as well as the long time-gap between excavation and analysis" (Prevedorou & Buikstra, 2019, 61). As the visitors to other nations, bioarchaeologists are privileged to conduct research there. However, to create a more accessible field, bioarchaeologists need methods of analysis that keep costs low and can be performed during tight time constraints.

In an effort to address these accessibility concerns, this thesis assesses various approaches of imaging human remains. It will evaluate them on production time, cost, model quality, and ease of learning. By evaluating the methods on production time, guidance can be given to future researchers who are required to strictly budget their time for the reasons previously discussed. For example, this could allow those with care responsibilities to properly account for the time required to perform their research, giving them the tools to continue to provide for those that need them without sacrificing their careers. Moreover, analyzing methods based on cost gives future researchers an edge in preparing for the realities of performing research without significant funding. Finding cost-effective methods of researching could empower those without the economic privilege that comes from metropolitan institutions or the Global North to produce knowledge alongside all other researchers in the field. For this democratized data to be used widely, the data must be of sufficient quality to be used for a variety of purposes. However, some purposes may require differing levels of quality. A contrasting example would be a 3D model created for educational purposes and a model created for research purposes. Here, the research model would need a higher degree of accuracy if the data collected is to be considered valid. Thus, the quality requirements of the model are likely to be dictated by the needs of the model's creator. For this thesis, model quality will be split into three categories: model completeness, model accuracy, and accuracy of entheseal grading. This will allow an understanding of the quality that can be achieved through equivalent commitments to time and cost. The aspect of ease of learning is also important as being able to employ methods that are simple enough to self-teach could have the potential to give more researchers across the world access to those methods. All of these aspects work together to ensure that the methods being used are as widely accessible as possible. This democratization of data and knowledge production is the guiding principle of my thesis.

I intend to publish the second chapter of my thesis in *the International Journal of Osteoarchaeology*. The aims of this journal match strongly with the goals of my research; to advance the methodological study of human remains in a variety of archaeological contexts. In publishing my research to the *International Journal of Osteoarchaeology,* it is my intent to disseminate the information I attain to as wide an audience of other bioarchaeologists as possible to inspire future applications of accessible forms of methodology.

Chapter 2: Accessibility in Bioarchaeology: Methods of 3D Imaging of Entheses

2.1 Introduction

This thesis sets out to evaluate accessible forms of 3D imaging of human remains. The term ‘accessibility’ currently has many meanings and connotations associated with it. For clarity, accessibility will be used in this paper to refer to the intersectional participation in various aspects of academic research. By this definition, something that is accessible should be equally available to any person, regardless of their gender, sex, race, age, etc. Accessibility remains an important issue in bioarchaeology and the discipline of anthropology as a whole. Even as work has been done to democratize academia, the production of bioarchaeological theory and research still comes from a relatively homogenous group of people (Willermet, 2016). To change this lack of diversity, the systemic factors that drive it must be addressed. Two significant factors that contribute to the inaccessibility in bioarchaeology are time and cost (Heath-Stout & Hannigan, 2020; Prevedorou & Buikstra, 2019).

To develop more accessible methods in bioarchaeology, this thesis will evaluate two methods of 3D imaging, laser scanning and photogrammetry, with respect to time and cost. The ease with which the methods can be learned and applied will also be considered. Furthermore, these two methods will be quantitatively and qualitatively analyzed for completeness and accuracy in reference to test photos. The models will also be evaluated on their ability to have Villotte’s (2006) method of entheseal analysis applied to them. Villotte (2006) was chosen as a basis for entheseal analysis for several reasons. First, the method is based upon medical literature, having made a distinction between fibrous and fibrocartilaginous muscle insertions. The method has also been tested for reproducibility and yielded excellent results for fibrocartilaginous insertions, the insertions of interest in this thesis (Havelková & Villotte, 2007).

2.1.1 Entheses

‘Enthesis’ or ‘entheseal surface’ refers to the site of muscle attachment on bone. Although some also use it to refer to attachment sites of ligaments and joint capsules, it will be limited to muscle for the sake of simplicity (Djukic et al., 2018). ‘Entheseal changes’ will be used in reference to variations to the enthesis from physical activity and other related causes of development to align with Havelková et al.’s (2011) definitions. ‘Enthesopathies’ are distinct from ‘entheseal changes’ in that they are used to describe variations to the enthesis due to pathological factors such as disease (Havelková et al., 2011). Previously categorized as musculoskeletal markers, entheseal changes was coined to better represent the complexity of reactions that the enthesis undergoes (Henderson et al., 2013). Many methods of recording and analyzing entheseal changes are currently in use that generally fall under two categories, ordinal scores (visual) and three-dimensional surface area (3D) (Noldner and Edgar, 2013). Studies over the past three decades have worked to use these methods to reconstruct the physical activities of past populations (Djukic et al., 2018). The analysis of entheseal changes is said to allow for the understanding of habitual activities, paving the way for a deeper understanding of the social and gendered division of labour (Djukic et al., 2018; Foster et al.,2014). This interpretation is derived from bone remodelling theory as bone mechanisms adapt to repeated strain, altering the site of attachment to strengthen the connection between bone and muscle (Foster et al., 2014).

However, aside from habitual activity there are many factors that cause repeated strain on the muscles, such as environmental and social conditions, that may not be readily apparent to researchers (Havelková et al., 2011; Villotte et al., 2010). Furthermore, sex, age, and individual variation also contribute to entheseal changes, further confounding the information that can be acquired from entheses (Djukic et al., 2015; Woo and Pak, 2013). It has been found that males have a higher frequency and more advanced expression of entheses than females (Woo and Pak, 2013). In fact, many of the studies proposing methodology have limited their samples to males (Hawkey & Merbs, 1995; Villotte et al., 2010; Karakostis et al., 2017) as hormonal factors, such as oestrogen and androgens, cause differences in bone adaptation and may impact the expression of entheseal changes (Villotte et al., 2010; Foster et al., 2014). However, Agarwal (2012) argues that restricting samples based on sex can be damaging to the conclusions drawn. In doing so, a greater clarity of how entheseal change is expressed may be missed which may continue to keep sex as a confounding factor. In fact, Woo and Pak (2013) only found a significant difference by sex in some entheses.

The differences in entheseal expression between the sexes can also be attributed to differences in activity patterns between males and females in historical and social contexts (Havelková et al. 2011). Thus, the higher correlation of entheseal changes in males may be due to undertaking more physically strenuous activities over their lifetimes. Havelková et al. (2011) note that it is possible for women to have undertaken strenuous work, but it is more likely that their entheseal changes are the result of repetitive tasks. However, body size also strongly correlates to entheseal expression (Karakostis et al,, 2017). A study by Nolte and Wilczak (2013) found that body size impacted entheseal expression on females more than males. This may be due to sexual dimorphism, with males having greater variation in entheses than females (Foster et al., 2014; Nolte & Wilczak, 2013).

2.1.2 3D Modelling in Bioarchaeology

The 1980's ushered in tremendous growth with the launch of IBM's commercial computer that allowed the widespread use of modelling software applied to a vast number of engineering sectors (When Did 3D Modeling Start?, 2021). It was at this point that biological anthropologists became excited by the potential in 3D modelling (Hassett, 2018). The morphological structures of the skeleton began to be quantified using methods and data that mathematically captured their geometric features. A review of the field conducted in 1993 dubbed this approach as 'geometric morphometrics,' touting great advances to be made through this area of study in regard to how data will be collected and analyzed (Adams et al., 2004).

Much of the software used today was made possible by the falling prices of computers during the 1990's that allowed 3D models to be developed and rendered by people for non-commercial uses. 3D printing technologies were developed during this time as well as being integrated into university curriculums. Post-2000, 3D modelling continued the trend of falling prices and wider accessibility for a broad range of disciplines, especially with the advent of internet tutorials (When Did 3D Modeling Start?, 2021). Adams et al. (2004) found that during this decade more researchers than ever before had been incorporating geometric morphometric methods into biological research. However, the technology was still restricted to 2D analyses of 3D objects as 3D digitizers were still far too expensive and limited in their capabilities to be configured to the vast manner of specimens being researched by biological anthropologists. At this time, Adams et al. (2004) were hopeful for the future implementations of 3D modelling in bioarchaeological research and publication, looking to virtual journals to have the ability to properly display 3D models in the way that 2D pictures on printed paper cannot.

Many research institutions have been incorporating 3D surface scanning technologies, such as computerized tomography (CT) scans and magnetic resonance imaging (MRI) into their analyzing processes (Beckett, 2014; Bouton, 2018). As mentioned previously, the technology used to be considerably expensive, but more recent advances have lowered the price and widened its availability. Through the replication of skeletal remains, 3D modeling can serve as an enhanced state of preservation as well as serve for methods of education and outreach without the risks of overhandling the delicate remains (Bouton, 2018; Hassett, 2018). 3D recreations can also be stored easily and widely shared among institutions and researchers, broadening research abilities while eliminating the need to physically be in the presence of the remains (Hassett, 2018). There is also the ability to reuse digital models in perpetuity that the fragility of physical specimens cannot contend with. For example, CT scanning can penetrate tissue, allowing for the production of a 3D replica and analysis of skeletons through non-destructive means (Bouton, 2018). 3D reconstructions also allow for computational statistical analyses that are not possible when working with a physical specimen (Beckett, 2014; Hirst et al., 2018). Though high-quality imagers such as CT scanners are very expensive, some large museums have acquired their own. Other institutions have agreements with local hospitals to book time with their scanning equipment (Bouton, 2018). Scanners such as these also require a specialized technical knowledge to operate and interpret data (Magnani et al., 2020).

Though these 3D imaging technologies remain relatively inaccessible, the ability to create 3D models holds many possibilities. The modelling process allows for the recording of surface area as well as measurements in length, width, and elevation (Nolte & Wilczak, 2013). These measurements either would not be possible manually or would yield higher error rates as opposed to performing them digitally. Modern advances in geometric morphometrics due to digital modelling has allowed researchers to account for size differences, equalizing size before comparison and providing less biased data (Wrobel et al., 2019). Furthermore, computational shape analysis can create landmarks for measurements to help reduce observer error rates (Wrobel et al., 2019). 3D modeling also opens up bioarchaeological analyses to the possibilities of both studying variations that are less overt than typical macroscopic data as well as quantifying data in a matter than relies less on the discrete categories and scores that bioarchaeologists have become accustomed to (Wrobel et al., 2019).

2.1.3 Laser scanning

A more accessible form of 3D imaging than CT or other medical-grade scanning technologies is laser scanning. The scanner bounces many lasers off the object, calculating the distance away from the scanner. The scanner takes this depth data from these many points and recreates the object’s surface. Reconstructions are made from multiple angles and fused together to create the 3D model. Use of these methods in bioarchaeology is relatively new thanks to decreasing prices of these technologies (Noldner & Edgar, 2013).

Initial tests for reliability of 3D methods specifically for entheseal analysis had observer error rates below 15%, similar to those of ordinal scoring methods (Noldner & Edgar, 2013). However, Karakostis and Harvati (2021) have recently developed a system of geometrically fixed points along the 3D model that have reduced the error rates to below 5%. Noldner and Edgar (2013) note that a significant drawback to 3D methods is that they fail when part of the enthesis is obscured due to factors such as taphonomic damage. Furthermore, even though 3D scanners become much more accessible over time, they are still expensive and limited to few institutions (Noldner & Edgar, 2013). 3D scanning is also significantly time consuming, especially in comparison to the relatively quick process of ordinal scoring methods (Noldner & Edgar, 2013). However, 3D scanning methods are more precise than ordinal scoring methods and can capture greater detail in variation (Nolte & Wilczak, 2013).

2.1.4 Photogrammetry

Another tool for 3D imaging is photogrammetry. Photogrammetry involves computationally measuring distances from photographs. This is done by calculating the distance and angle change between multiple photographs of the same object. Though there are a few forms of creating photogrammetric images, the method most relevant to this thesis is Structure-from-Motion (SfM). SfM produces 3D data from many overlapping images (Magnani et al., 2020).

This method of creating 3D models is highly accessible as it only requires a digital camera and a computer to process and render the photographs. In the last ten years, the number of published papers using photogrammetry has increased dramatically (Magnani et al., 2020). This has been due to the ever-decreasing prices along with increasing quality of hardware necessary for analysis. Moreover, digital cameras are no longer the only viable method of capturing high-quality images thanks to the advances in smartphone cameras over the past decade (Magnani et al., 2020; Morgan et al., 2019).

The software for creating photogrammetric models is also becoming more accessible. In the past, few options were available for processing images. High-cost and high-quality software such as AutoDesk ReCap and iWitnessPro were available with tools and interfaces that provided a low knowledge barrier for entry. Free alternatives to these are software such as COLMAP that require extensive tutorials, creating a higher barrier-for-entry. However, new developments have made photogrammetric software much more accessible. In 2021, AliceVision, a non-profit organization of industry and academic partners, created Meshroom (AliceVision Association, n.d). Meshroom is open-source software that provides the capability to create high-quality SfM 3D models with tremendous ease-of-use while also giving the option for far more advanced refinement to suit more advanced users.

Photogrammetry is widely being applied in a variety of bioarchaeological contexts. Digital models of bioarchaeological materials have been analyzed with greater precision than is capable with modern manual implements (Magnani et al., 2020). Photogrammetry also has allowed bioarchaeologists to create digital recreations of field sites, either from the ground or using arial photography, allowing far more precise data collection and analysis. These methods have also been applied to sex estimation (Macaluso, 2011). The study obtained diameter and perimeter area measurements from photogrammetric scans of acetabula to correlate those measurements with sex.

2.2 Materials and Methods

The individuals in this sample were all part of the University of Waterloo, Department of Anthropology Skeletal Collection. This collection consists of 15 individuals. Eight individuals, designated UW1 through UW8 were included in the sample. The age demographic of the sample consisted of four young adults (UW1, UW4, UW6, and UW8), one young/middle adult (UW3), and three middle adults (UW2, UW5, and UW7). The sample consisted of two males (UW1 and UW6), five females (UW2, UW3, UW4, UW5, and UW7), and one individual of ambiguous sex (UW8). The sample was limited to eight individuals due to time restrictions. This will be elaborated upon further in the following section.

Age estimation methods were performed according to the standards set out by Buikstra and Ubelaker (1994). The pubic symphyses were scored based on the categorization of Todd (1921) and Brooks and Suchey (1990). The auricular surface was scored using Lovejoy et al.'s (1985) criteria. Cranial sutures were also graded for closure in accordance with Meindl and Lovejoy (1985). All scores were aggregated to assign each individual into one of the following categories: subadult (0-20 y.o.), young adult (20-35 y.o.), young/middle adult (30-40 y.o.), middle adult (35-50 y.o.), and old adult (50+ y.o.).

Sex estimation methods were similarly in accordance with those outlined by Buikstra and Ubelaker (1994). The ossa coxae were analyzed for the morphological characteristics of the ventral arc, subpubic concavity, ischiopubic ramus ridge, greater sciatic notch, and preauricular sulcus (Buikstra & Ubelaker, 1994; Phenice, 1969). In addition, the skull was assessed for morphological characteristics of the nuchal crest, mastoid process, supraorbital margin, supraorbital ridge, and mental eminence (Buikstra & Ubelaker, 1994).

Each individual was examined for markers of pathology. Pathology identification was informed by Buikstra (2019), Waldron (2009), and Ortner and Putschar (1985). More details on the pathological examination will follow in the next section.

Enthesis identification was guided by medical literature. *Gray's Anatomy* (Gray, 1995) provided detailed descriptions of enthesis areas while both *An Illustrated Atlas of the Skeletal Muscles* (Bowden & Bowden, 2002) and *Illustrated Clinical Anatomy* (Abrahams et al., 2005) offered visual guides for the entheseal boundaries.

2.2.1 Sample Exclusion Parameters

The first set of exclusion parameters comes from literature on entheseal development as it relates to age (Woo & Pak, 2013; Villotte et al., 2010; Havelková et al., 2011). Enthesopathies are common in those of advanced age due to pathological factors associated with aging (Woo & Pak, 2013; Villotte et al., 2010). Havelková et al. (2011) suggest that these are due to degeneration in the skeleton, finding that the prevalence in individuals older than 50 is nearly equal across populations studied. This is supported by other studies finding that differences in entheseal surfaces between different levels of physical activity appear to balance out around 50 years of age (Nolte & Wilczak 2013; Villotte et al., 2009). Nevertheless, prolonged exposure to greater mechanical loads and habitual motion does influence entheses (Foster et al., 2014). For this reason, when applying entheseal analyses, individuals should be restricted to those below the age of 50 to limit the impact of age as a confounding factor. Individuals under the age of 18 are still undergoing development and entheseal changes due to habitual motion may not have had adequate time to form. It is also not well studied how entheses express on subadult populations. Therefore, in accordance with other studies, the age range was restricted to those between the ages of 18-50 years at death (Villotte et al., 2010; Karakostis et al., 2017).

Though some studies analyzing entheses restrict their samples to biologically male individuals (Karakostis et al., 2017; Villotte et al., 2010), due to the nature of this research sex was not a consideration for exclusion. The other referenced studies include analyses based upon inter-individual comparisons of entheses, while this study merely compares entheses with themselves. Methods exist that allow for the comparison of biological males and females that account for body size (Weiss, 2003). However, they were not needed due to the lack of inter-individual analysis.

Pathological changes were observed for the sample. As with Villotte (2006) and Mariotti et al. (2004), pathology was only a basis for exclusion if the pathology interfered or overlapped with the entheses. Pathologies that could cause changes on the entheses are Diffuse Idiopathic Skeletal Hyperostosis (DISH), tuberculosis, and osteoarthritis, to name a few. These present as formation of new bone that can lead to confounding of activity-related changes to the entheseal surface. Villotte et al. (2010) defined a healthy enthesis as a smooth, well-defined imprint on bone, free of vascular foramina, with a regular margin. Any sign of periosteal activity interfering with the enthesis was considered a marker for enthesis exclusion, though not exclusion of the individual. This is due to periosteal activity potentially being due to infection or healed antemortem trauma. Post-mortem damage was similarly not a basis for total exclusion, as long as over half the enthesis could still be analyzed.

Each individual was also evaluated for completeness. If an individual bore non-exclusionary pathology interfering with or was missing over half the total entheses to be analyzed, the individual would be excluded from the sample.

Though not initially a factor for exclusion, time was the factor that forced a significant reduction of the sample size. Once laser scanning commenced, it was apparent that the sample size of individuals and the number of entheses being studied had to be reduced. In the end, the sample size was reduced to eight individuals. Those chosen each met the sample parameters and possessed both the least amount of overall damage and greatest number of assessable entheses.

2.2.2 Entheseal Analysis

Each enthesis was first graded in regard to Villotte's (2006) method. Villotte (2006) created four groups of like entheses that display similar bone remodelling. The first two groups, 1 and 2, are those pertinent to this thesis: (1) fibrocartilaginous insertions that remodel both the centre and tidemark (periphery) of the enthesis where the tidemark is difficult to measure and (2) fibrocartilaginous insertions that remodel the centre and tidemark, where the centre is rarely affected but the tidemark is easily measured. Both groups are then given their own scoring system based on their level of remodelling and are graded from A (least change) to C (greatest change): (1) the tidemark and centre are rated separately, then added together as the entheseal change typically involves both points and (2) the tidemark and centre are rated separately and graded independently as the tidemark tends to only show changes to these entheses (Villotte, 2006).

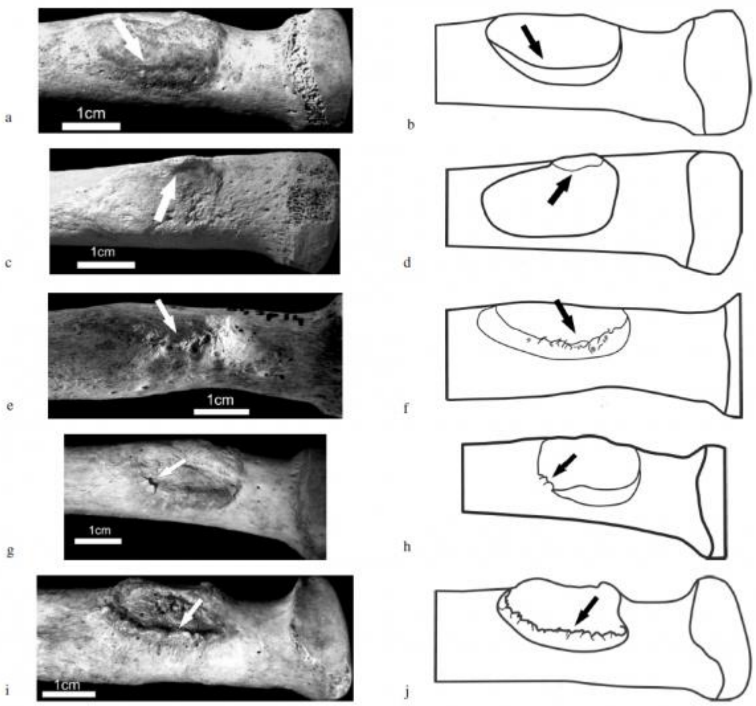

Figure 1: Group 1 entheses: contour modification, example of the radial insertion of m. biceps brachialis

a (picture) and b (diagram)—The contour of this insertion is regular, without modification (arrow). A value of 0 is allotted for contour of a group 1 enthesis with this appearance.

c (picture) and d (diagram)—The contour of this insertion forms a little regular bump (arrow). A value of 1 is allotted for contour of a group 1 enthesis with this appearance.

e (picture) and f (diagram)—The contour of this insertion shows an irregular appearance, without osseous production (arrow). A value of 1 is allotted for contour of a group 1 enthesis with this appearance.

g (picture) and h (diagram)—An enthesophyte is present on the contour of this insertion (arrow). A value of 2 is allotted for contour of a group 1 enthesis with this appearance.

i (picture) and j (diagram)—The contour of this insertion forms a clear irregular crest (arrow). A value of 2 is allotted for contour of a group 1 enthesis with this appearance (Villotte, 2006, 72).

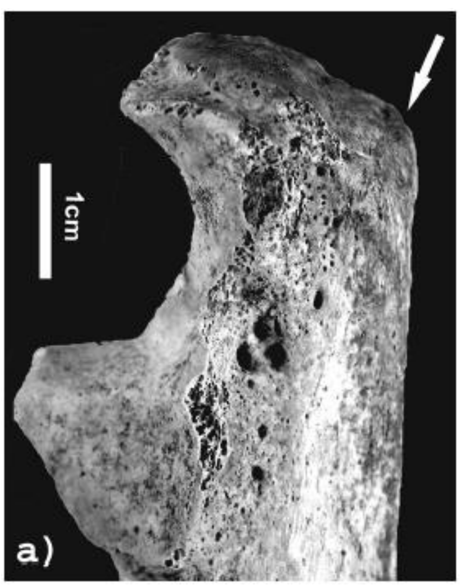

Figure 2: Group 2 enthesis. a—Ulnar insertion of m. triceps brachialis. The contour of this insertion shows no enthesophyte. The surface of the insertion shows no erosion area. A stage A is allotted for a group 2 enthesis with this appearance (Villotte, 2006, 74).

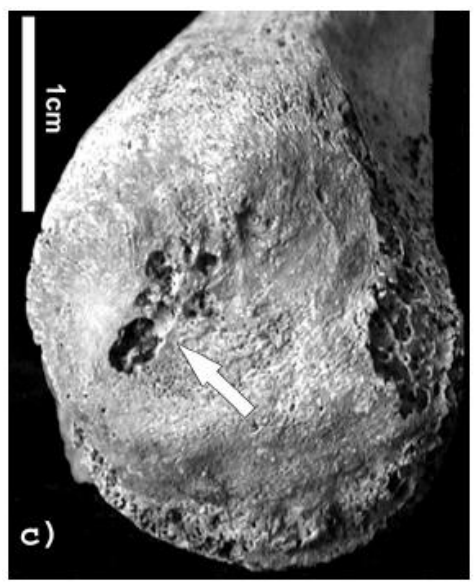

Figure 3: Group 2 enthesis. c—Ulnar insertion of m. triceps brachialis. The surface of this insertion shows a restricted erosion area. A stage B is allotted for a group 2 enthesis with this appearance (Villotte, 2006, 75).

Table 1: Information on entheses analyzed and corresponding groups

Group	**Bone**	**Muscle**
G1	Radius	*m. brachialis*
	Radius	*m. brachioradialis*
	Humerus	*m. subscapularis*
	Humerus	*m. supraspinatus, m. infraspinatus*
	Humerus	*common flexor*
	Humerus	*common extensor*
	Ulna	*m. biceps brachii*
G2	Ulna	*m. triceps brachii*

Entheses chosen for analysis were based on Villotte et al.'s (2010) determination of the 'main' post-cranial fibrocartilaginous entheses. To manage the scope of the research, the entheses of study were limited to those of the upper limbs; more specifically, those of the humeri, radii, and ulnae. On these six bones there are a total of 14 Group 1 entheses and two Group 2 entheses. Each enthesis was scored initially as practice, before being scored a second time to ensure consistency in grading. On each of the eight individuals, 16 entheses were examined. This brought the total number of entheses graded to 128.

2.2.3 Laser Scanning

The entheses were then imaged with a NextEngine 3D Laser Scanner used in conjunction with its ScanStudio software to both image and create the 3D models. The remains were imaged with two bracket scans. Each bracket took three scans from different angles. The difference in angle was manually dictated and changed depending on the shape and size of the enthesis. Therefore, each enthesis model was made up of six individual scans from various angles. Once the scanning was complete the preliminary scans were manually aligned using landmarks on the scans. The aligned scans were then cropped of unnecessary features (background, fasteners, etc.) and spliced together using the software's automated 'fuse' function.

Only partial 3D models were created. The scans were centred on the entheses as it was clear from early in the research process that a full 3D model of the long bones would take far too long to produce for the scope of this research. A 360° scan with the NextEngine scanner finished in

1.5 hours. The upper limb long bones would have each needed three 360° scans, two individual scans for the epiphyses, plus any more individual scans for surface gaps due to contours or holes from post-mortem damage, for example. Therefore, one fully laser scanned bone may have taken upwards of five to six hours to model. Furthermore, the number of scans needed to render a full 3D model was too computationally demanding for the mid-range computer used (see Appendix A for detailed specifications on the hardware used in this research).

2.2.4 Photogrammetry

The methods of photogrammetry used in this study were based on recommendations for photographing crania by Morgan et al. (2019). Each bone was placed on a turntable covered with white cloth to act as a high-contrast backdrop, minimizing shadows. A ring light was set up to create directional lighting. This allowed for greater control over the evenness of the lighting, colour temperature of the lighting, and further reduced shadows. The photos were taken with a 12-megapixel smartphone camera (see Appendix A for full specifications). Approximately 90 photos were taken in total for each enthesis at three different angles relative to the horizontal. These angles were approximately 60 degrees (high), 30 degrees (mid), and zero degrees (low) with the camera about 10 cm away from the centre of the enthesis. Taking 30 photos at each angle allowed for the removal of up to 10 images per angle of lesser than desired quality before model creation. The decision to photograph and model only the enthesis of each bone was for two reasons. The first reason was to attempt to create higher quality models that allowed for the usage of Karakotsis et al.'s (2017) method of capturing 3D surface area. The second reason was to more closely emulate the models being produced by the laser scans.

2.2.5 Meshroom

All photogrammetry models were compiled in Meshroom. Meshroom is open-source software developed by the AliceVision Association. The association is a non-profit made up of industry and academic partners with the goal of democratizing 3D digitalization technologies from photographs (About AliceVision, n.d). More about the AliceVision Association's mission can be found at https://alicevision.org/association/. Meshroom can be downloaded for free from this page: https://alicevision.org/#meshroom.

Being open-source, the Meshroom software is free to download and gives its users a tremendous amount of control. The software is simple to use for beginners in the field and their website contains many tutorials to aid in learning the basics. The software is highly accessible as the main process for creating 3D models requires the user to merely drag the folder of photos into the program and click ‘start.’ So long as the photos are of decent quality and there is enough overlap between the angles, the program should have no difficulty rendering the model. The program automatically runs through the historically tedious processes of aligning the photos. Meshroom also allows for model quality settings to be easily adjusted (low, normal, high, ultra) depending on the desires of the user. As to be expected, the higher the quality settings, the longer the processing time and the greater the computational power required.

One of the downsides to Meshroom is the framework in which it has been developed. It has been developed to use a CUDA (Compute Unified Device Architecture) enabled graphics card, a system found exclusively in Nvidia branded graphics cards. This does present a barrier to accessibility as many computers do not have dedicated graphics cards, and of those that do, not all of them are Nvidia. However, there are workarounds to allowing Meshroom to run without CUDA graphics cards, though it takes more technological knowledge. AliceVision provides step-by-step guides on how to do this: https://github.com/alicevision/meshroom/wiki/Draft-Meshing. The computer used to create the photogrammetry models in this thesis utilized a CUDA enabled graphics card.

For the modelling process, the approximately 90 images taken of each enthesis was whittled down to about 60. This was decided for two reasons: the first being that 60 images reduced the computation time from about 90 minutes to about 50 minutes with no noticeable loss of quality. The second reason was that removing about a third of the sample photos allowed for the picking of the highest quality images. Those images with significant depth blur, motion blur, or poor lighting were removed.

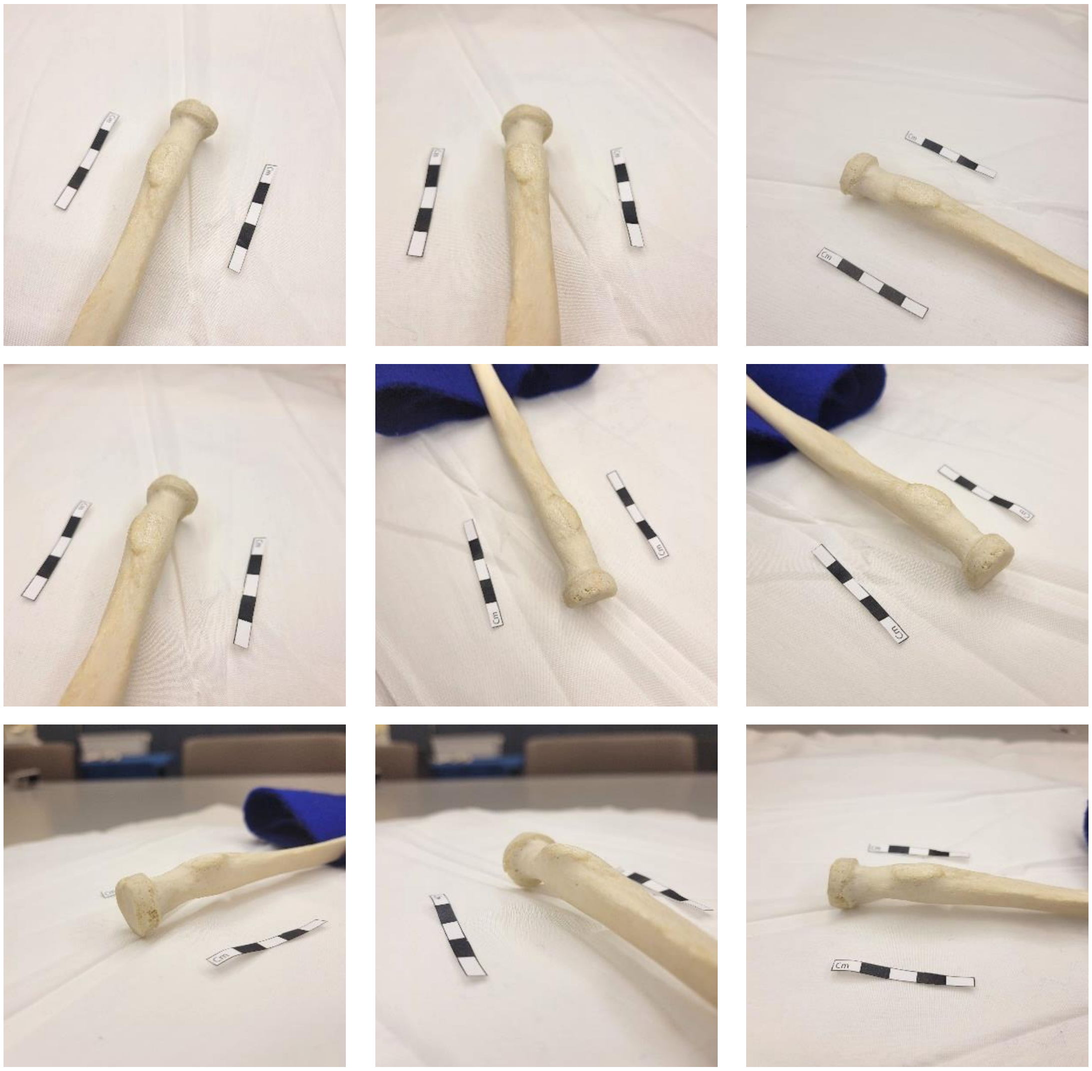

Figure 4: UW5 - Left Radius - Proximal - collection of stills from the photogrammetry data collection process

2.2.6 Surface Area and other Qualitative Data

Karakostis' et al.'s (2017) method of delineating the entheseal boundaries, unfortunately, did not work on the models that were created for this thesis. This may be due to one or both of the two apparent discrepancies between the methods of scanning. The first discrepancy was that Karakostis' method utilized closed surface 3D models, or fully imaged scans. Creating fully enclosed models would make imaging larger bones, such as those in this thesis, a much longer process, and imaging irregularly shaped bones far more difficult. The second discrepancy was that the laser scanner used in this thesis was not of the same precision as that of Karakostis'. The scanner used to produce the 3D models in Karakostis' method has a precision of 9 μm whereas the scanner used in this study has 100 μm precision. This is a crucial point as it indicates that mid- to low-range scanners currently do not have the capability to quantitatively analyze remains in this way, further reducing the accessibility of laser scanning for research or archival purposes.

It is not clear which, if either, are the cause of the issues with this form of analysis. These are merely hypotheses for why Karakostis et al.'s (2017) method was not able to be applied to the models produced for this thesis. However, this may be taken as a potential avenue of further study into this topic.

2.3 Results

2.3.1 Quantitative Analysis

The 3D models created were not able to be assessed for 3D surface area as originally intended due to the lack of model accuracy that will be discussed later. However, the creation of the models is still able to be quantitatively assessed for the duration of time it took to complete the recording and modelling process. This provides insight into the minimum time requirements for each method to be performed to generate 3D models of a similar quality.

Laser Scan

On average, the radii took about 35 minutes to create a full 3D model of each enthesis. This was broken up into two 12.5-minute scans with 5 minutes of manual setup and 5 minutes to manually align and compile the scans. For the ulnae, the models took approximately 40 minutes each. Similarly, the scanning was broken up into two 15-minute scans with 5 minutes of set up and 5 minutes of compiling. Finally, each humeral enthesis also took 40 minutes to model. This was also made up of two 15-minute scans with 5 minutes of setup and 5 minutes of compiling. Overall, to laser scan all 14 entheses for each individual, it took approximately 540 minutes, or about 9 hours total.

Photogrammetry

Each enthesis took about 55 minutes in total to create a 3D model. This timing was made up of 5 minutes of photographing time and 50 minutes of modelling time. Overall, to create the models of all 14 entheses, one individual would take about 770 minutes, or about 13 hours to fully model.

Table 2: Time to produce scan by bone and method

	Photogrammetry			**Laser Scan**			
	Photos	Modelling	**Total**	Setup	Scans (x2)	**Compilation**	**Total**
Radius	5	50	55	5	12.5	5	30
Ulna	5	50	55	5	15	5	35
Humerus	5	50	55	5	15	5	35
All Entheses	70	700	770	70	400	70	540

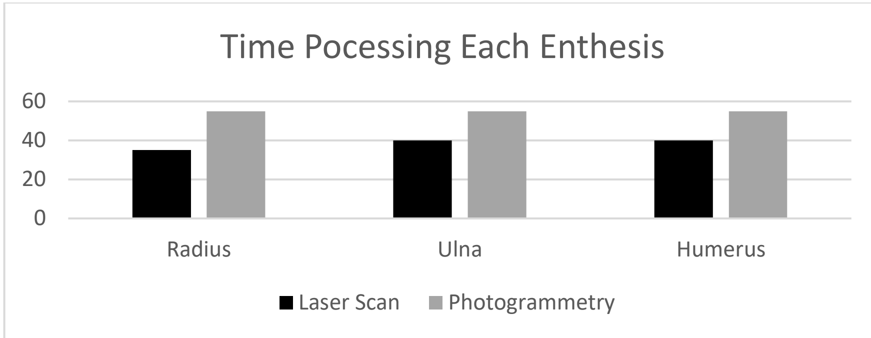

Figure 5: Time to process enthesis by bone

Although creating 3D models for the photogrammetric method took approximately 43% longer than the laser scanning method, breaking up the timing by location of work reveals a much different pattern. The complete workflow of the laser scanning occurred within the lab (38.6 minutes per enthesis on average). For the photogrammetry, only 5 minutes per enthesis were spent in the lab, while the model creation (50 minutes per enthesis on average) occurred on an off-site computer. Thus, the on-site data collection of one individual for photogrammetry was only about 70 minutes, compared to about 540 for laser scanning.

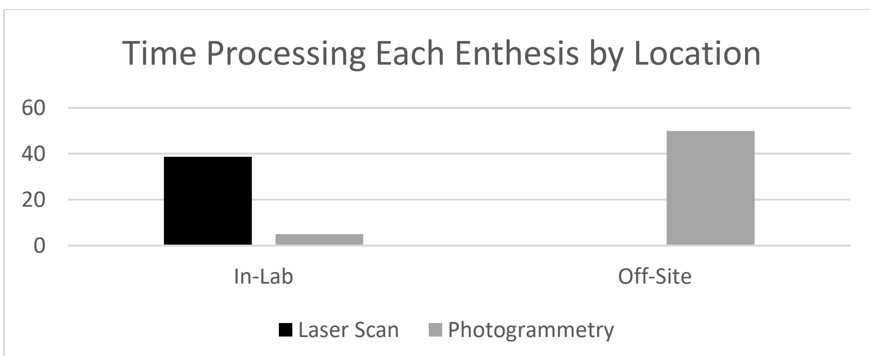

Figure 6: Time to process enthesis by location

2.3.2 Qualitative Analysis

The models produced by each method were judged according to several criteria: Model completeness, model accuracy, and ability to grade entheses visually using the Villotte (2006) method.

Completeness

Model completeness comments on whether surface gaps or other geometric inconsistencies were present on the model. Any discontinuity in the model was considered a surface gap. An example of a surface gap can be seen in Figure 7, indicated by the black arrows. Geometric inconsistencies included jagged edges, distortions, or other geometries that were not representative of the actual remains. Examples of these inconsistencies are indicated by white arrows in Figure 8.

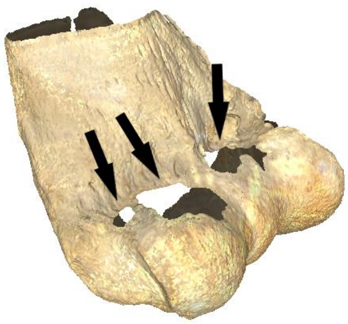

Figure 7: UW5 - Right Humerus - Distal - Laser Scan

Figure 8: UW4 - Right Ulna - Proximal - Photogrammetry

Table 3: Measured rates of 3D model completeness

	Surface Gaps	**Geometric Inconsistencies**
Photogrammetry		
Present	5	17
Present %	4.46%	15.18%
Laser Scan		
Present	49	79
Present %	43.75%	70.54%

In the photogrammetric models, approximately 4% had a surface gap in the model while about 15% had other geometric inconsistencies. This in in comparison to the laser scanned models that had an approximately 44% rate of surface gaps and 71% rate of other inconsistencies. From this data it can be gathered that the photogrammetry models were significantly better at creating a complete model of the bone surface than the laser scanned models.

Figure 9: UW6 - Left Radius - Distal - side by side comparison of photogrammetry (left) and laser scan (right). The photogrammetric model shows no surface gaps, whereas the laser scanned model has various gaps in its surface (circled in black).

Accuracy

Model accuracy comments on how well the model represented colouration, foramina, and texture of the bone as compared to photographs. Figures 10-12 demonstrate these criteria. The black arrows in Figure 10 point to an example of inaccurate colouration on the model. The white ellipses in Figures 10-12 highlight foramina in the different representations. The black rectangles in Figures 10-12 highlight inaccurate texturing of the models. The models were also scored using Villotte's (2006) method of grading the contour and centre as they were at the beginning of the research. A value of 'yes' was given to models that scored within a total of zero to one point of the original visual score. A value of 'no' was given to models that scored a total of two or greater points away from the original visual score.

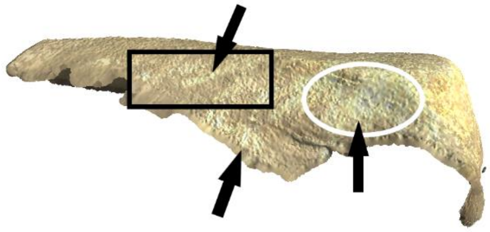

Figure 10: UW2 - Right Ulna - Proximal - Laser Scan. Foramina location circled in white. Discolouration indicated by black arrows. Texture inaccuracy present in black rectangle.

Figure 11: UW2 - Right Ulna - Proximal – Photogrammetry. Foramina location circled in white. Texture inaccuracy present in black rectangle.

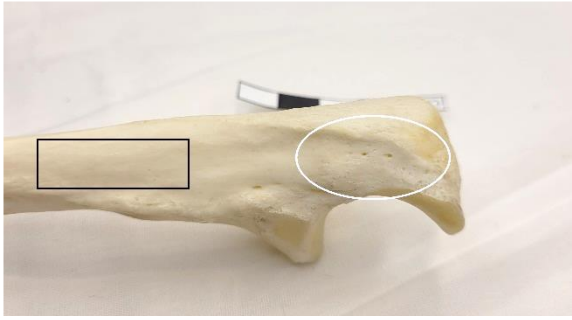

Figure 12: UW2 - Right Ulna - Proximal – Photograph. Foramina location circled in white. Texture in black box is smooth as compared to the inaccuracies of Figures 5 and 6.

Table 4: Measured rates of 3D model accuracy

	Colouration	**Foramina**	**Texture**	**Enthesis Grading**
Photogrammetry				
Accurate	109	107	50	93
Accurate %	97.32%	95.54%	44.64%	83.04%
Laser Scan				
Accurate	31	24	11	74
Accurate %	27.68%	21.43%	9.82%	66.07%

The photogrammetry models produced extremely high rates of accurate colouration (97% accurate) and were representative of most of the foramina (96% accurate). The method of photogrammetry was particularly adept at representing smaller foramina. In terms of the texturing, photogrammetry models tended to appear gritty or rough when the bone surface was generally smooth (45% accuracy). However, even with the high prevalence of inaccurate texturing, the photogrammetry models were accurate enough for the entheses to be graded at a success rate of 83%. The accuracy rates for the laser scanned models were much lower. The colouration accuracy stood at approximately 28%. Most models had unusual streaks of lightness and generally did not reflect the colours of the remains. The most accurate colourations were bones with stains or dried cartilage that were darker. However, many bones had labels with the individual's identifications on them. These affixed numbers were not modelled correctly, showing up as depressions in the bone. This inability to accurately interpret surface changes and colouration is part of what drove the foramina accuracy rate to about 21%. Only larger foramina were accurately modelled, while smaller foramina tended to not be represented at all. The other issue that drove the foramina accuracy rate lower was the inaccurate texturing of the laser scanning. Much like the photogrammetry models the laser scanned models tended to be rough or gritty in appearance. Only 10% of the models showed accurate texturing. With the accuracy issues, the success rate for grading the entheses on the laser scanned models was 66%.

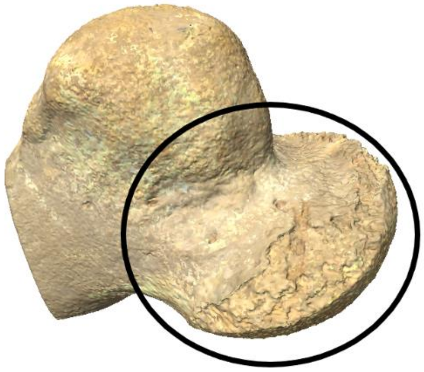

Figure 13: UW6 - Right Humerus - Distal/Medial - Laser Scan. Post-mortem damage circled in black.

Figure 14: UW6 - Right Humerus - Distal/Medial – Photogrammetry. Post-mortem damage circled in black

Figure 15: UW6 - Right Humerus - Distal/Medial - Photograph. Post-mortem damage circled in black.

2.4 Discussion

2.4.1 Laser Scanning

3D laser scanning suffers from various issues that affect the quality of research performed. Firstly, laser scanning is costly. All3DP Pro has put together a 'buyer's guide' to the costs associated with purchasing various scanners of varying qualities (*Best 3D Scanners of 2022, 2022*). Lower-quality scanners cost around $700 whereas higher-quality scanners range above $30,000. Though scanners comparable to the one used in this study (~100um precision) are now cheaper relative to the initial price of this scanner, the quality needed to make this method useful for accurate quantitative analysis quickly climbs into the thousands and tens of thousands of dollars. This makes laser scanning relatively inaccessible to the average researcher. Along with that, those high precision laser scanners are not portable, requiring the research to be conducted in a lab where the equipment is permanently stationed. Bringing remains to an adequate lab is not always logistically possible due to regulations regarding the transportation of archaeological specimen (Prevedorou & Buikstra, 2019).

Moreover, laser scanning takes a considerable amount of time. To create the partial 3D scans in this research, approximately 540 hours of lab time was required. Those desiring to create full 3D models of bone would require significantly more time for processing. Furthermore, researchers may require greater accuracy than what was achieved during this study, pushing scanning time even higher. Time is a significant issue for researchers, especially those working afield (Prevedorou & Buikstra, 2019). The U.S. Bureau of Labour Statistics claims that archaeologists spend approximately four to eight weeks out of the year in the field. Having a method that takes a significant amount of lab time to perform may not be feasible when the archaeologist has other duties to perform simultaneously. Furthermore, women are disproportionately affected by these barriers of time due to obligations of care in their personal lives. In order for laser scanning methods to be more accessible, the technology will need to be able to generate 3D scans at a much faster rate than they do now.

Another aspect of 3D model creation that laser scanning had issue with was the qualitative aspects of the remains. Textures and colourations of the bone surface were highly inaccurate. Laser scanned models were particularly inaccurate when representing trabecular bone that had been exposed to post-mortem damage (See Figure 13 above). Most models had streaks of brightly coloured bone and appeared often rough or lumpy. The issues with texturing likely stemmed from the precision of the scanner itself and would be resolved with a higher precision scanner. Due to both the texturing and colouring issues, small foramina were often not represented on the models. This is a detriment to the quality of the models as fine details such as those being erased can have a great impact on certain analyses such as pathology. Finally, laser scanning also was at a great detriment when scanning ‘irregularly-shaped’ or highly contoured bone. As the laser scanner takes precise scans from a few angles, bones such as the scapulae were highly difficult to capture effectively. It was for this reason that the scapulae were eliminated from the sample of bones captured in this analysis. This systemic issue with laser scanning would significantly increase the time required to model other ‘irregularly-shaped’ bones such as the vertebrae and mandible, perpetuating the already lengthy issues with time.

However, laser scanning does also bring with it a series of benefits. The precise nature of the method allows it to map the topography of surfaces very well. Though this analysis lacked precision, it could be attained through a greater number of scanning angles or through the use of a more precise scanner. Moreover, the NextEngine scanner software had tremendous ease of use. As a researcher who only had a brief tutorial for use of the scanner, it was fairly easy to supplement a lack of intense training with a few video tutorials easily found online. The system of aligning the scans to be fused together did not pose a significant challenge, so long as enough distinguishable marks were present on the bone surface. As a relatively old scanner (released in 2016 and 8 years old as of the writing of this thesis) it is likely that more recent scanners would have similar if not better documentation. This would create a lower barrier for entry to those researchers who do not have the ability to be properly trained on the equipment.

2.4.2 Photogrammetry

The method of photogrammetry similarly had some challenges. As Morgan et al. (2019) posed, the foremost challenge was the act of taking of the photographs themselves. An accurate 3D model made using photogrammetry must be made using high quality photos. These photos need to have no motion blur, no depth blur, and must have even lighting with no shadows. Finding the optimal set up and camera settings takes multiple attempts, however, as a researcher with little photography experience, there are numerous online tutorials that can aid in understanding how to adjust for those issues. Morgan et al. (2019) suggested using a turntable with a white sheet and a ring light to create the best lighting. As for reducing blur, the camera itself will determine how much those can be reduced. The smartphone camera did not have the adequate settings to fully reduce the depth blur, though the motion blur can be accounted for using either a camera stand or a high shutter speed. It should be noted that a camera stand is more optimal as a higher shutter speed can lower the depth of field, increasing the depth blur on the photographs (see Appendix C for more information on the photography aspect of photogrammetry).

Furthermore, the photogrammetric models were not suited for performing certain quantitative measurements. Though the images can be scaled using specific features in analysis software, the model creation does not have the precision necessary to adequately map the minute surface topography. This impedes the accurate analysis of measurements such as 3D surface area, thus making photogrammetry unsuitable for analyses such as that of Karakostis et al. (2019) that relies on this information.

On the other hand, the benefits of photogrammetry are many. The largest differentiator was the speed in which data collection can occur. The photography aspect of photogrammetry was generally quick, especially once the researcher can become comfortable with the process. Having apparatuses such as a turntable and camera mount can greatly enhance the speed at which high-quality photos are taken. Furthermore, the workflow of 3D model creation allows for the lengthy process to be done elsewhere. This greatly enhances accessibility as those who do not have the ability to be present with remains for a significant amount of time will be able to briefly collect their data and then process them in a location that is more convenient for them.

Qualitatively, photogrammetric 3D models also benefit from the way in which they are created. In the stitching together of high-quality photographs, a very precise level of detail is preserved. The models in this study accurately represented small ‘pin-prick’ foramina and colour detail. In contrast with the laser scanner, the photogrammetric models also accurately textured trabecular bone that had been exposed due to post-mortem damage (See Figure 14 above). This is significant as it may be possible to perform a great number of bioarchaeological analyses from the models themselves. For example, morphological analyses of estimating age and sex could be performed as well as pathological identification.

Another axis of accessibility that photogrammetry allows is through its ease of use. Once researchers have a grasp on the photography aspect of the method, the workflow of photogrammetric software such as Meshroom requires very little prior computer knowledge. All the researcher needs to do it to transfer the photographs into a file folder on the analysis computer and drop it into the program. The trickiest aspect of creating the models was finding the correct folder that it was saved to (see Appendix C for tips and tricks to help make the use of photogrammetry easier).

Moreover, photogrammetry has much lower costs relative to laser scanning. With equivalent equipment, the cost of starting from scratch to create a photogrammetric model would be about $800. This in in comparison to $1200 for laser scanning. However, if it is assumed that the researcher already has access to a computer that can run the programs, this cost reduces to approximately $200 and $700 for photogrammetry and laser scanning, respectively. Likewise, if the researcher has a smartphone or other camera that can take photos of sufficient quality, the cost of photogrammetry further decreases to $100. This price is significantly more attainable for many and would thus allow a wider audience to utilize these methods. A full cost breakdown can be found in Appendix B.

2.4.3 Specifications

To get a better comparison of the quality of the scans that the two methods produce, it is pertinent to understand the specifications of the images and software in use. The NextEngine laser scanner uses a camera with 5MP resolution. This is in comparison to the smartphone used for photogrammetry which had a 12MP camera. Therefore, the photogrammetry models had the advantage of having sharper images to process as opposed to those captured by the laser scanner. The higher texture quality of the photogrammetry models over the laser scanner models was likely caused by this attribute.

However, camera resolution is not the only defining aspect of model quality. Mesh accuracy plays a significant part in how well 3D models are created. In this context, mesh accuracy refers to the physical distance between neighbouring points on the 3D model surface. The lower the distance between points, the more accurate the model will be to the physical object. The NextEngine laser scanner has an accuracy of $0.005mm$ or $5\mu m$. For photogrammetry, the process for generating surface points and thus determining the accuracy of the photogrammetric models is more opaque. Meshroom generates the number of points based numerous factors including the number of images and number of matched features in overlapping images. Therefore, it is unclear exactly what mesh resolution the models created in this study were created with. However, the process for determining how many points the program computes is well documented and can be adjusted to suit the user’s needs. Based on the default settings of Meshroom’s Depth Map process, it is highly likely that the mesh resolution was larger in the photogrammetry models than those of the laser scanner models. Thus, the laser scanned models benefitted from more accurate depth measurements.

2.4.4 Applying Entheseal Analysis

The use of Vilotte's (2006) method of evaluating entheseal change was intended to be an estimate of the quantitative 'useability' of these created 3D models. The laser scanned models ended with an accuracy rate of 66% as compared to initial in-person evaluations. In contrast, the photogrammetry models had an accuracy rate of 83%. The high inaccuracy rate of the laser scanned models is a result of the previously established imprecision of texturing due to the quality of the scanner. Though the photogrammetry models had a higher accuracy rate, one in six models produced an inaccurate enthesis evaluation. This is likely due to the lack of minute surface dimension that this photogrammetric method provides. As ordinal entheseal analysis methods are based upon minor geometric details such as surface irregularities and bone growth, accurate representations of surface topography are crucial.

For these reasons, the following is advised against: (1) evaluating entheses on laser scanned 3D models created with scanners of 100μm precision or less, (2) evaluating entheses on photogrammetric 3D models using a similar level of settings in this paper. Taking higher-quality photos, whether with a higher resolution camera or with better optimized settings, and running the photogrammetric software on higher settings could increase the quality of the 3D models to the point where this analysis will be sufficiently accurate. Testing these aspects should be considered a pertinent future avenue of study.

2.5 Limitations

This research suffered from some limitations. The greatest limitation was that of time. The intent was to analyze a greater number of individuals and entheses, but this proved impossible given the length of time to generate the 3D scans. Furthermore, computational power was also a limiting factor as the computer used for the laser scanning consistently was running low on memory, limiting the quality of the scans able to be created. This was also a problem with the photogrammetry computer as the graphics card was under the recommended memory limit, potentially slowing down the processing times for generating 3D models. However, these limitations of time and resources are also what many other researchers face, as discussed in this study. I therefore pose, that these limitations give credence to the necessity of developing methods that are quicker, more cost-effective, and sufficiently accurate.

Another limitation comes from my own personal perspective. I consider myself quite familiar with both the hardware and software components of computers. I also have experience with programming. These experiences compound to create a comfort when faced with new technologies. Thus, I acknowledge that one person's perspective, especially coming from a place of privilege like mine, is not necessarily the best indicator of other people's ability to interact and learn new technologies. I therefore suggest that the findings regarding ease of use be taken for what they are: an opinion from someone who is 'tech-savvy' and has a passion for learning about computers.

2.6 Recommendations for Further Research

Throughout the duration of this study, some avenues of further research that were outside the scope were encountered. The first was that this study focused on the quality of the models produced and the accessibility of producing them. However, due to the scope and manner of testing these methods, sufficiently accurate 3D models were not able to be captured and analyzed. Therefore, it is recommended that future studies focus on the limits of quantitative data that can be captured by each method. Another avenue of potential research is how precisely the camera quality impacts the creation of photogrammetric 3D models. This would allow for a better understanding of the trade-off of researchers using more cost-effective equipment and the impacts it would have on their analyses.

Further research that may yield interesting results is a study of how effectively bioarchaeologists can self-learn methods. Having insight into what makes a method easier to learn has the potential to have lasting reverberations throughout the field.

2.7 Conclusions

This study tested two methods of creating digital 3D models. Laser scanning and photogrammetry were tested for various aspects of their implementation: cost, time, ease of use, and accuracy to physical remains. The 3D models were also tested for how accurate their entheses could be graded relative to an in-person evaluation.

It was found that photogrammetry has low costs, high ease of use, and presented significantly accurate representations of the remains. The process for creating the 3D models was lengthy, however, the vast majority of the time was spent processing the photographs. This aspect can be performed remotely and does not require time in-lab or on-site. The laser scanning process was found to be easy to learn, however, it was also costly and lengthy to generate the models. Unlike the photogrammetry process, the length of time to create laser scanned models is required to be performed in-lab with the remains. Furthermore, the laser scanned models also lacked qualitative accuracy, misrepresenting colouration and minute features due to texturing issues. These aspects could be improved using a higher-quality scanner; however, this would drive the costs to perform this method significantly higher. Compared to photogrammetry, laser scanning was better suited for qualitative measurements as it more accurately captured the surface topography. Overall, photogrammetry makes for a more accessible method than does laser scanning. The ease in which one can learn to use the tools, the low costs, and short timeframe for data collection would allow a wider range of bioarchaeologists to implement these methods in their studies.

As the models produced for this thesis were not of sufficient quality to perform accurate analyses, future researchers can take the specific methods used here as a baseline for their needs. For example, creating educational materials may not require the highest accuracy and thus low time and cost may be the priority. Inversely, 3D models needed for research needs may instead prioritize the quality, increasing the costs and time associated with the modelling process.

Fostering intersectional accessibility is crucial in order to democratize the production of knowledge and increase the diversity of voices in the field of bioarchaeology. To do so, methods need to be cost effective, quick, and easy to learn. By creating methods with these qualities, researchers with time constraints, little to no funding, and those working outside of the metropolitan institutions of the Global North will be better able to add to the ever-growing body of knowledge of our relatively young field.

Bibliography

About AliceVision. (n.d). Retrieved October 31, 2022, from https://alicevision.org/#about

Abrahams, P., Craven, J., & Lumley, J. (2005). *Illustrated Clinical Anatomy*. Hodder Education.

Adams, D. C., Rohlf, F. J., & Slice, D. E. (2004). Geometric morphometrics: Ten years of progress following the 'revolution.' *Italian Journal of Zoology*, *71*(1), 5–16. https://doi.org/10.1080/11250000409356545

Agarwal, S. C. (2012). The Past of Sex, Gender, and Health: Bioarchaeology of the Aging Skeleton. *American Anthropologist*, *114*(2), 322–335. https://doi.org/10.1111/j.1548-1433.2012.01428.x

AliceVision Association. (n.d.). Retrieved October 31, 2022, from http://alicevision.org/association/

Archaeological and Ethnographic Field Research. (n.d.). The National Endowment for the Humanities. Retrieved November 22, 2022, from https://www.neh.gov/program/archaeological-and-ethnographic-field-research

Archaeology and Archaeometry. (n.d). Duke University: Research Funding. Retrieved October 6, 2022 from https://researchfunding.duke.edu/archaeology-and-archaeometry-0

Award Search: Advanced Search Results. (n.d). National Science Foundation. Retrieved October 6, 2022 from https://www.nsf.gov/awardsearch/advancedSearchResult?ProgEleCode=1391%2C1393&BooleanElement=Any&BooleanRef=Any&ActiveAwards=true#results

Beckett, R. G. (2014). Paleoimaging: A review of applications and challenges. *Forensic Science, Medicine, and Pathology*, *10*(3), 423–436. https://doi.org/10.1007/s12024-014-9541-z

Bouton, E. (2018). Replication Ramification: Ethics for 3D Technology in Anthropology Collections. *Theory and Practice*, *1*. https://articles.themuseumscholar.org/2018/06/11/tp_vol1bouton/

Bowden, B. & Bowden, J. (2002). *An Illustrated Atlas of the Skeletal Muscles*. Morton Publishing Company.

Brooks, S.T. & Suchey, J.M. (1990). Skeletal Age Determination Based on the Os Pubis: A Comparison of the Acsadi-Nemeskeria and Suchey-Brooks Methods. Human Evolution, 5, 227-238.

Buikstra J.E. & Ubelaker, D.H. (1994). Standards for data collection from human skeletal remains. Arkansas Archeological Survey.

Buikstra, J. (2019). *Ortner's Identification of Pathological Conditions in Human Skeletal Remains*. Academic Press.

Djukic, K., Miladinovic-Radmilovic, N., Draskovic, M., & Djuric, M. (2018). Morphological appearance of muscle attachment sites on lower limbs: Horse riders versus agricultural population. *International Journal of Osteoarchaeology*, *28*(6), 656–668. https://doi.org/10.1002/oa.2680

Djukic, K., Milovanovic, P., Hahn, M., Busse, B., Amling, M., & Djuric, M. (2015). Bone microarchitecture at muscle attachment sites: The relationship between macroscopic scores of entheses and their cortical and trabecular microstructural design: BONE MICROARCHITECTURE AT MUSCLE ATTACHMENT SITES. *American Journal of Physical Anthropology*, *157*(1), 81–93. https://doi.org/10.1002/ajpa.22691

Facts and Figures. (2022, August 30). Social Sciences and Humanities Research Council. Retrieved October 6, 2022, from https://www.sshrc-crsh.gc.ca/about-au_sujet/facts-faits/index-eng.aspx

Foster, A., Buckley, H., & Tayles, N. (2014). Using Enthesis Robusticity to Infer Activity in the Past: A Review. *Journal of Archaeological Method and Theory*, *21*(3), 511–533. https://doi.org/10.1007/s10816-012-9156-1

Gray, H. (1995). *Gray's Anatomy.* (15th edition). Branes & Nobles Books.

Harrison, F. V. (2016). Theorizing in ex-centric sites. *Anthropological Theory*, *16*(2–3), 160–176. https://doi.org/10.1177/1463499616652516

Hassett, B. R. (2018). Which Bone to Pick: Creation, Curation, and Dissemination of Online 3D Digital Bioarchaeological Data. *Archaeologies*, *14*(2), 231–249. https://doi.org/10.1007/s11759-018-9344-z

Havelková, P., & Villotte, S. (2007). Enthesopathies: Test of reproducibility of the new scoring system based on current medical data. *Antropológia*, *10*.

Havelková, P., Villotte, S., Velemínský, P., Poláček, L., & Dobisíková, M. (2011). Enthesopathies and activity patterns in the Early Medieval Great Moravian population: Evidence of division of labour: Enthesopathies in the Great Moravian Population.

International Journal of Osteoarchaeology, *21*(4), 487–504. https://doi.org/10.1002/oa.1164

Hawkey, D. E., & Merbs, C. F. (1995). Activity-induced musculoskeletal stress markers (MSM) and subsistence strategy changes among ancient Hudson Bay Eskimos. *International Journal of Osteoarchaeology*, *5*(4), 324–338. https://doi.org/10.1002/oa.1390050403

Heath-Stout, L. E., & Hannigan, E. M. (2020). Affording Archaeology: How Field School Costs Promote Exclusivity. *Advances in Archaeological Practice*, *8*(2), 123–133. https://doi.org/10.1017/aap.2020.7

Henderson, C. Y., Mariotti, V., Pany-Kucera, D., Villotte, S., & Wilczak, C. (2013). Recording Specific Entheseal Changes of Fibrocartilaginous Entheses: Initial Tests Using the Coimbra Method: Recording Entheseal Changes. *International Journal of Osteoarchaeology*, *23*(2), 152–162. https://doi.org/10.1002/oa.2287

Hirst, C. S., White, S., & Smith, S. E. (2018). Standardisation in 3D Geometric Morphometrics: Ethics, Ownership, and Methods. Archaeologies, 14(2), 272–298. https://doi.org/10.1007/s11759-018-9349-7

Karakostis, F. A., & Harvati, K. (2021). New horizons in reconstructing past human behavior: Introducing the “Tübingen University Validated Entheses-based Reconstruction of Activity” method. *Evolutionary Anthropology: Issues, News, and Reviews*, *30*(3), 185–198. https://doi.org/10.1002/evan.21892

Karakostis, F. A., Hotz, G., Scherf, H., Wahl, J., & Harvati, K. (2017). Occupational manual activity is reflected on the patterns among hand entheses: KARAKOSTIS ET AL . *American Journal of Physical Anthropology*, *164*(1), 30–40. https://doi.org/10.1002/ajpa.23253

Lovejoy, C. O., Meindl, R. S., Pryzbeck, T. R., & Mensforth, R. P. (1985). Chronological metamorphosis of the auricular surface of the ilium: A new method for the determination of adult skeletal age at death. American Journal of Physical Anthropology, 68(1), 15–28. https://doi.org/10.1002/ajpa.1330680103

Macaluso, P. J. (2011). Sex discrimination from the acetabulum in a twentieth-century skeletal sample from France using digital photogrammetry. *HOMO - Journal of Comparative Human Biology*, *62*(1), 44–55. https://doi.org/10.1016/j.jchb.2010.11.001

Magnani, M., Douglass, M., Schroder, W., Reeves, J., & Braun, D. R. (2020). The Digital Revolution to Come: Photogrammetry in Archaeological Practice. *American Antiquity*, *85*(4), 737–760. https://doi.org/10.1017/aaq.2020.59

Mariotti, V., Facchini, F., & Belcastro, M. G. (2004). Enthesopathies – Proposal of a Standardized Scoring Method and Applications. *Coll. Antropol.*, 16.

Marquez-Grant, N., & Fibiger, L. (2011). *The Routledge Handbook of Archaeological Human Remains and Legislation: An International Guide to Laws and Practice in the Excavation and Treatment of Archaeological Human Remains*. Taylor & Francis.

Morgan, B., Ford, A. L. J., & Smith, M. J. (2019). Standard methods for creating digital skeletal models using structure-from-motion photogrammetry. *American Journal of Physical Anthropology*, *169*(1), 152–160. https://doi.org/10.1002/ajpa.23803

Noldner, L. K., & Edgar, H. J. H. (2013). 3D representation and analysis of enthesis morphology: 3D Quantification Of Enthesis Development. *American Journal of Physical Anthropology*, *152*(3), 417–424. https://doi.org/10.1002/ajpa.22367

Nolte, M., & Wilczak, C. (2013). Three-dimensional Surface Area of the Distal Biceps Enthesis, Relationship to Body Size, Sex, Age and Secular Changes in a 20th Century American Sample: Surface Area of the Biceps Enthesis. *International Journal of Osteoarchaeology*, *23*(2), 163–174. https://doi.org/10.1002/oa.2292

Ortner, D. J. & Putschar, W. G. J. (1985). Identification of Pathological Conditions in Human Skeletal Remains. Smithsonian Institution Press.

Overholtzer, L., & Jalbert, C. L. (2021). A “Leaky” Pipeline and Chilly Climate in Archaeology in Canada. *American Antiquity*, *86*(2), 261–282. https://doi.org/10.1017/aaq.2020.107

Phenice, T. W. (1969). A newly developed visual method of sexing the os pubis. American Journal of Physical Anthropology, 30(2), 297–301. https://doi.org/10.1002/ajpa.1330300214

Prah, K. K. (2008). *Anthropological Prisms: Studies on African Realities*. Centre for Advanced Studies of African Society.

Prevedorou, E.-A., & Buikstra, J. E. (2019). Bioarchaeological Practice and the Curation of Human Skeletal Remains in a Greek Context: The Phaleron Cemetery. *Advances in Archaeological Practice*, *7*(1), 60–67. https://doi.org/10.1017/aap.2018.42

The Best 3D Scanners of 2022 – Buyer's Guide. (2022, September 20). All3DP Pro. Retrieved October 20, 2022, from https://all3dp.com/1/best-3d-scanner-diy-handheld-app-software/

Todd, T.W. (1921). Age Changes in the Pubic Bone. I: The Male White Pubis. American Journal of Physical Anthropology, 3, 285-334.

UBC Research + Innovation. (n.d.). University of British Columbia. Retrieved November 1, 2022, from https://research.ubc.ca/research-excellence/research-funding-statistics/202122

Villotte, S. (2006). Connaissances médicales actuelles, cotation des enthésopathies: Nouvelle méthode. *Bulletins et mémoires de la Société d'Anthropologie de Paris*, *18*(1–2), 65–85. https://doi.org/10.4000/bmsap.1325

Villotte, S., Castex, D., Couallier, V., Dutour, O., Knusel, C. J., & Henry-Gambier, D. (2009). Enthesopathies as occupational stress markers: Evidence from the upper limb. *American Journal of Physical Anthropology*, *142*, 224–234. https://doi.org/10.1002/ajpa.21217

Waldron, T. (2009). Paleopathology. Cambridge University Press.

Weiss, E. (2003). Understanding muscle markers: Aggregation and construct validity. *American Journal of Physical Anthropology*, *121*(3), 230–240. https://doi.org/10.1002/ajpa.10226

When Did 3D Modeling Start? A Brief History. (2021, May 31). SelfCAD. Retrieved October 31, 2022, from https://www.selfcad.com/blog/when-did-3d-modeling-start-a-brief-histor

Willermet, C. (2016). Biological Anthropology in 2015: Open Access, Biocultural Interactions, and Social Change. *American Anthropologist*, *118*(2), 317–329. https://doi.org/10.1111/aman.12529

Woo, E. J., & Pak, S. (2013). Degenerative joint diseases and enthesopathies in a Joseon Dynasty population from Korea. *HOMO*, *64*(2), 104–119. https://doi.org/10.1016/j.jchb.2013.02.001

Wrobel, G. D., Biggs, J. A., & Hair, A. L. (2019). Digital Modeling for Bioarchaeologists. *Advances in Archaeological Practice*, *7*(1), 47–54. https://doi.org/10.1017/aap.2018.47

Wylie, A. (1993). Workplace Issues for Women in Archaeology. In H. Du Cros & L. Smith, *Women in Archaeology: A Feminist Critique* (pp. 245–258). Canberra Department of Prehistory, Research School of Pacific Studies, Australia National University, Canberra.

Appendices

Appendix A: Hardware Specifications

The following is a breakdown of the relevant specifications for the hardware used in this research. The intent of this Appendix is to give the reader further insight into the resources used to produce 3D models of this particular quality.

NextEngine 3D Laser Scanner:

- 5 MP camera
- 0.1 mm resolution

Relevant computer specs for processing laser scans:

- 8 GB RAM
- Intel i5 1.10 GHz CPU

Camera Details:

- Samsung Galaxy S20 FE
- 12 MP camera (SM-G781W)
- Auto HDR
- Photos taken in 1:1 ratio (3024x3024 pixel resolution)
- Automatic capture settings (no flash)

Relevant computer specs for processing photogrammetry scans:

- 24 GB RAM
- Intel i5 3.50GHz CPU
- Nvidia GTX 970 GPU (4GB)

Appendix B: Research Cost Breakdown

The following is a cost breakdown of the various components of this analysis. Estimates were given for items unavailable to purchase currently. Some items were discounted at the time of research. Therefore, it should be noted that these prices are subject to change based on sales, retailers, location, and time from release.

Laser Scanning

- Next Engine Scanner - $2995 USD (http://www.nextengine.com/products)
- 100μm scanners - $700-800 USD (https://all3dp.com/1/best-3d-scanner-diy-handheld-app-software/)
- 50μm scanners - $2200-8500+
- 20-7μm scanners - $30000+
- Comparable laser scanning processing computer - $512+ CAD (Canada Computers)

Lowest Estimated Laser Scanning Cost: $1212 or $2712 or $30512

Photogrammetry

- 12MP Digital Camera - $500+ USD (Best Buy)
- 20.1 MP Budget Camera - $100 USD
- Samsung Galaxy s20 FE 5G $600 (Samsung retail price)
- Comparable 12MP smartphone (Google Pixel 4) - $240 (Amazon sale)
- Comparable photogrammetry processing computer - $590 CAD (Canada Computers)
- Camera Stand $40
- Turntable $25
- White sheets $10
- Ring light $40

Lowest Estimated Photogrammetry Cost: $805

Appendix C: Tips and Tricks for Photogrammetry

The intent of this appendix is to provide future researchers with information that was learned over the course of this research that could aid in learning and utilizing photogrammetry methods.

Information on Exposure Value (EV) and Camera Settings

The quality of the photogrammetry model is tied closely to the quality of the camera. Cheaper cameras or most older smartphone cameras have fewer settings to work with to attain the perfect image. The most important settings and how they should be adjusted are as follows:

- Shutter Speed – should be high to reduce motion blur (1/1000 rather than 1/500)
- Aperture - should be low (high f-number → f/11 rather than f/8) to increase depth of field and decrease depth blur
- ISO – should be lower to reduce the 'noise' in the photo

These three values interplay with each other to alter the EV of the photo. EV can be positive (brighter image) or negative (darker image). Higher ISO, lower shutter speed, and higher aperture all darken the image. Lower ISO, higher shutter speed, and lower aperture all brighten the image. Since cameras are not alike, it is difficult to give precise recommendations on these values. It will be up to the researcher to balance these three settings to take photos that have the suggested characteristics above.

However, if these characteristics are being followed and the exposure value is creating an image that is too dark, the best workaround is to increase shutter speed and use a tripod for the camera. The use of the tripod should limit any movement, reducing motion blur and reducing the need for a high shutter speed.

Tips and Tricks on Using Meshroom

The use of Meshroom is fairly simple due to its design. However, there are a few aspects that may make working with Meshroom easier:

1. **Save location is important –** the final model will be saved deep into the folder that you choose. To make the process simpler, choose an easily accessible location to save your files.
2. **How to change model quality –** in the program, Meshroom has a window at the bottom that displays the workflow of the program. Click on the node called 'FeatureExtraction'

(typically the second node from the left). In the box to the right of the workflow window, you can scroll down and change the ‘Describer Density’ and ‘Describer Quality.’ Ultra will create more faithful 3D models; however, it will greatly increase the processing time and computational power needed. Lowering the quality can increase processing time at the expense of model accuracy.

3. **Viewing your finished 3D model in Meshroom –** to have the model shown in the display window on the top right, you must double-click the node called ‘Texturing’ (typically the rightmost node in the workflow window).
4. **Rename the folder that contains the 3D model –** in the same location that the project was initially saved to, navigate into the ‘MeshroomCache’ folder. From there, enter the ‘Texturing’ folder. Each folder is given a generic string of numbers and letters, making it difficult to distinguish between more than one model. It is my recommendation that you rename that folder to something more recognizable after each scan to save yourself from frustration at a later date.
5. **Viewing your finished 3D model outside of Meshroom –** the file folder that you renamed (see #4) contains a file entitled ‘texturedMesh.’ This is a 3D object that can be viewed in a number of programs. Windows comes with a 3D object viewer installed, so you may double-click that file to view it. Other free programs such as Meshlab and Blender allow you to analyze and edit the model. If you desire to move this file, ensure that you move the entire folder. This folder contains important information that the 3D viewers need to access (colours and textures for example) that will be lost if the ‘texturedMesh’ file is the only one copied.
6. **Guided tutorials are extremely helpful –** there are many advanced aspects of Meshroom that could suit particular needs of researchers. Watching guided video tutorials such as the ones here: https://sketchfab.com/blogs/community/tutorial-meshroom-for-beginners can not only help you when creating your first 3D models, but also aid in achieving a greater use of the program. There is also extensive documentation for the program that can give researchers insight into all aspects of the Meshroom process: https://meshroom-manual.readthedocs.io/en/latest/.