Effects of Edentulism on the Structure of the Human Mandible

ANDREW DOBERSTEIN
FALL 2017

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Biology
with honors in Biology

Reviewed and approved* by the following:

Timothy Ryan
Associate Professor of Anthropology
Thesis Supervisor

Stephen W. Schaeffer
Professor of Biology, Assistant Department Head for Graduate Education
Honors Adviser

* Signatures are on file in the Schreyer Honors College.
ABSTRACT

The bones in the human body are constantly remodeled as osteoclasts and osteoblasts remove and add bone in order to adjust to changing mechanical conditions. Much research has been done with respect to how our diet, the way in which we exercise, and our genetics influence skeletal morphology and its responsiveness to external environmental conditions.

This study seeks to determine the effects of tooth loss on the shape of the mandible. Specifically, I seek to understand how the structure of the human mandible is altered as a result of the progressive loss of teeth during life in order to better understand the role of changing mechanical forces on mandibular shape. I predicted that tooth loss would be reflected in the shape of the mandible. I expected that tooth loss would explain structural variation particular to the alveolar crest and the mandibular corpus. I tested the null hypothesis that edentulation, or tooth loss, along with age and sex do not have any effect on the structure of the human mandible. A sample of 30 human mandibles were digitized and landmarked with the intent to use geometric morphometrics to identify structural variation among each mandible in the observed population. The morphometric data were used to assess shape variation in relation to the degree of edentulism, age, and sex.

The data collected through this study suggest that edentulation does contribute to changes in mandibular shape. Specifically, the loss of teeth leads to a widening of the mandibular corpus to form more of a “U-shape” as opposed to a more “V-like-shape” present in individuals with teeth. Additionally, tooth loss results in considerable alveolar ridge resorption and an increase in the gonial angle. Age and sex also correlate significantly with changes in mandibular structure, as older female individuals tended to be prone to the same mandibular restructuring observed in
edentulous mandibles. The reason for this is not certain. This study identifies the structural changes that occur upon tooth loss in the hopes that future research will be done to preserve the integrity of the mandible for edentulous patients, while improving the lives of millions.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................iv

LIST OF TABLES ..........................................................................................................v

ACKNOWLEDGEMENTS ...............................................................................................vi

1. Introduction .............................................................................................................. 1
   1.1 Overview of Edentulation .................................................................................... 1

Chapter 2 Materials & Methods .....................................................................................4
   2.1 Characteristics of Sample Population ................................................................. 4
   2.2 Sample Identification ......................................................................................... 5
   2.3 Scanning and Processing of Mandibles .............................................................. 7
   2.4 Anatomical Landmarking .................................................................................... 8
   2.5 Geometric Morphometrics, Procrustes Analysis, and PCA ..............................12

Chapter 3 Results ........................................................................................................13
   3.1 Principal Components and Edentulation ........................................................... 13
   3.2 Structural Variation Described by Other Factors ..............................................19

Chapter 4 Discussion ..................................................................................................25
   4.1 Edentulation and Mandibular Structure ............................................................25
   4.2 Age and Mandibular Structure ........................................................................27
   4.3 Sex and Mandibular Structure .........................................................................29
   4.4 Relation to Previous Work ...............................................................................30
   4.5 Implications of these Data ...............................................................................32
   4.6 Supplemental Thoughts ...................................................................................33

Chapter 5 Conclusion ..................................................................................................35

Appendix A  Code Used in R Studio .........................................................................36

BIBLIOGRAPHY .........................................................................................................44
LIST OF FIGURES

Figure 1 Map of North America showing geographic location of this sample of Oneota people in what is modern day Illinois. .................................................................4

Figure 2 Depiction of landmark placement on each mandible. Orange points are landmarks. Green points are semilandmarks. (1) Condyle. (2) Coronoid Process. (3) Gnathion. (4) Alveolar Border of Corpus. (5) Inferior Border of Corpus. (6) Gonion. ......................11

Figure 3 Barplot showing the percent variance described by each principal component. The first three principal components explain 48.4% of the data. The remaining 51.6% of the data is described by the next 27 principal components, and were thus not considered. ..........13

Figure 4 Effect that tooth loss has on shape change along PC1 and PC2. The blue region represents individuals who have not experienced any tooth loss. The purple region represents those who have experienced tooth loss limited to their molars. The green region represents individuals who have experienced molar tooth loss as well as incisor, canine, and/or premolar tooth loss. The red region represents individuals who have experienced tooth loss limited to their incisors, canines, and premolars. .................................................................14

Figure 5 Superimposed representation of mandibular structure as described along PC1 from the superior, lateral, and anterior perspectives. The blue mandible represents the minimum extreme shape along PC1. The orange mandible represents the maximum extreme shape along PC1. .........................................................................................16

Figure 6 Visual representation of the changes to mandibular shape observed from the superior, lateral, and anterior perspectives along PC1. PC1 minimum represents the extreme structure of mandibles described by negative principal component 1 values. PC mean represents the mean mandibular shape described by each of the individuals analyzed in the sample. PC1 maximum represents the extreme structure of mandibles described by positive principal component 1 values ..........................................................................................16

Figure 7 Visual representation of the changes to mandibular shape observed from the superior, lateral, and anterior perspectives along PC2. PC2 minimum represents the extreme structure of mandibles described by negative principal component 2 values. PC mean represents the mean mandibular shape described by each of the individuals analyzed in the sample. PC2 maximum represents the extreme structure of mandibles described by positive principal component 2 values ..........................................................................................17

Figure 8 Superimposed representation of mandibular structure as described along PC2 from the superior, lateral, and anterior perspectives. The blue mandible represents the minimum extreme shape along PC2. The orange mandible represents the maximum extreme shape along PC2. .................................................................................................17

Figure 9 Effect that tooth loss has on shape change along PC1 and PC3. The blue region represents individuals who have not experienced any tooth loss. The purple region represents those who have experienced tooth loss limited to their molars. The green region represents individuals who have experienced molar tooth loss as well as incisor, canine, and/or
premolar tooth loss. The red region represents individuals who have experienced tooth loss limited to their incisors, canines, and premolars.

Figure 10 Scatterplot describing the effect that age has on structural variation as measured by PC1 and PC2. Black points labeled with the number “1” represent individuals estimated to have been between the ages of 17 and 25 at their time of death. Red points labeled with the number “2” signify individuals estimated to have been between 25 and 50 years old at their time of death. Green points labeled with the number “3” represent individuals estimated to have been 50+ years old at their time of death.

Figure 11 Shows the variation among age groups of individuals as they relate to changes in mandibular structure along PC1 and PC2. The pink region represents individuals in the youngest age group from 17-25 years of age at the time of their death. The green region represents individuals in an intermediate age range between the ages of 25 and 50 at the time of their death. The blue region represents the oldest individuals in the sample who were 50 years old or older at the time of their death.

Figure 12 Scatterplot describing the effect that age has on structural variation as measured by PC2 and PC3. Black points labeled with the number “1” represent individuals estimated to have been between the ages of 17 and 25 at their time of death. Red points labeled with the number “2” signify individuals estimated to have been between 25 and 50 years old at their time of death. Green points labeled with the number “3” represent individuals estimated to have been 50+ years old at their time.

Figure 13 Scatterplot describing the effect that sex has on structural variation as measured by PC1 and PC2. Black dots represent females and red dots represent males.

Figure 14 Scatterplot describing the effect that sex has on structural variation as measured by PC2 and PC3. Black dots represent females and red dots represent males.

Figure 15 Scatterplot comparing centroid size as it relates to sex prior to GPA alignment. Black dots represent females and red dots represent males.
LIST OF TABLES

Table 1 Table displaying identifying information about each individual in the sample population analyzed. Information included in this table includes population identification number, sex, age, and degree of tooth loss. .................................................................6

Table 2 Description of Analyzed Mandibular Landmarks. This table provides the landmark name, a description of each landmark, and the type of landmark as defined by Type I, Type II, or Type III. .................................................................9
ACKNOWLEDGEMENTS

I would like to thank Dr. Simone Sukhdeo and Lily Doershuk for their unwavering encouragement and willingness to introduce me to the technology and software utilized in the Primate Functional Morphology Lab over the past two and a half years. Additionally, thank you Dr. Stephen Schaeffer for your recognition of my hard work and your support of my pursuit of honors in Biology during my time at Penn State. To Dr. Tim Ryan, thank you for your guidance throughout the entirety of my undergraduate education. I will forever be grateful for your willingness to introduce me to the Primate Functional Morphology Lab, which has immensely enhanced my undergraduate education. Finally, thank you to my family for your continuous support of my research and all of the endeavors which I have embarked on throughout my life.
1. Introduction

1.1 Overview of Edentulation

Edentulation, otherwise known as tooth loss, is a common process associated with aging, high impact stresses, insufficient diet, medical disorders, and improper dental hygiene (Nowjack-Raymer & Sheiham, 2003; Lee, 2004). While the prevalence of tooth loss is increasing in developing countries, rates of edentulism are decreasing in developed countries (Polzer, et. al, 2010). Still, some estimates suggest that edentulism affects about 26% of the 60+ year old population in the United States (Polzer, et. al, 2010). Throughout history, edentulous individuals have suffered from decreased ability to communicate and masticate, ultimately leading to decreased ability to acquire nutrients necessary for survival through diet (Hutton, Feine, & Morais, 2002).

Research has shown that upon tooth loss, alveolar ridge resorption often occurs. The alveolar ridge is the osseous part of the jaw that contains the tooth sockets. Pietrokovski and Massler (1967) suggested that tooth extraction leads to ridge resorption on the lingual, or tongue, side of the mandible. Another study found that much of this ridge resorption is due to osteoclast activity breaking down mandibular trabecular bone (Bertl, et al., 2015). This observed resorption of the alveolar ridge is of concern because it might lead to injury and difficulty performing daily tasks that require the mouth.

Modern advances in technology have decreased, and occasionally eliminated, the negative effects associated with edentulation. Such technological advancements include the
advent of dentures and dental implants. Although each of these prosthetic innovations reduce the observed mechanical deficiencies that might result from edentulism, they fail to preserve the integrity of the mandible. Specifically, removable dentures are associated with alveolar ridge resorption while dental implants placed in an already resorbed region are associated with increased loading stress, and thus, greater risk of injury (Knezović-Zlatarić, Čelebić, & Lazić, 2002; Meijer, et al., 1992). However, for much of the world, and for the majority of human history, prosthetic dentistry did not exist, and it is not affordable for everyone in the areas in which such technology does exist.

Previous studies have sought to determine how tooth loss affects mandibular structure. Hutchinson, Farella, and Kramer (2015) used geometric morphometrics to analyze the effects that edentulism has on a modern human population. Their findings suggest that tooth loss results in shorter alveolar height, a shorter mandibular body, a larger gonial angle, a taller ramus, a larger bicondylar width, and a more obtuse mental angle (Hutchinson, Farella, & Kramer, 2015). Other research looking at the effects that tooth loss has on the changes to overall facial structure indicates that when each component of facial structure is analyzed on an individual basis, alveolar resorption was the only significant change observed (Small, Brits, Hemmingway, 2014). Research seeking to examine the different morphometric variations of human mandibles, based upon data collected via manual measurements, found that edentulous mandibles increase in intercondylar distance, and gonial angle, as Hutchinson, Farella, and Kramer determined, but decrease in virtually every other measurement of mandibular size (Chrcanovic, Abreu, & Custódio, 2011). As is evident from these three studies alone, multiple approaches have been used to analyze the effect that tooth loss has on mandibular structure, and each approach has resulted in different conclusions.
This study uses a 3D geometric morphometric approach to analyze the structural effects of edentulism on individuals who do not have access to prosthetic dental appliances. Specifically, I analyzed the mandibles from a pre-contact Native American archaeological collection dated to approximately 1300 AD. I made the assumption that by collecting data from a large enough sample size in a cross-sectional manner, I could argue that changes to mandibular structure can be accurately attributed to certain characterizing features. While examining a single mandible does not provide reliable data about the mandibles of the entire population, analyzing the mandibles of 30 individuals provides evidence for a notable trend. I predict that tooth loss will result in significant shape changes to the human mandible, such as alveolar ridge resorption, as has been previously described. I also predict that the mandibular corpus will undergo structural transformation as a result of changes to masticatory loading that might be expected with tooth loss. The null hypothesis for this study is that edentulation, age, and sex have no effect on mandibular shape.
Chapter 2
Materials & Methods

2.1 Characteristics of Sample Population

The population analyzed in this study contained Native American individuals classified by the archeological community as members of the Oneota culture. Specifically, the Oneota people lived in what are modern day Iowa, Illinois, Minnesota, and Wisconsin beginning as early as 900 AD up until about 1600 or 1700 AD (Gibbon, 1972). Over the culture’s period of most prominent existence, they underwent a significant transition in sustenance methods. Initially, the Oneota people were primarily hunters, gatherers, fishers, and fowlers (Gibbon, 1972). Over time, Oneota culture gradually shifted to a more secure method of sustenance through developments using horticultural-based food production (Gibbon, 1972). Maize became the crop used most by the Oneota people, and with increased yields of maize came a softer diet, and developments in
crop collection and storage (Gibbon, 1972). It is believed that the transition to a softer diet increased the number of individuals affected by edentulism (Cornejo, et al., 2012). In the following thesis I will consider the lifestyle of the Oneota, when necessary, in my biological analysis of their mandibular structure.

2.2 Sample Identification

Mandibles were selected from a skeletal collection currently housed at The Pennsylvania State University, loaned from the Illinois State Museum. The individuals in this collection were recovered from a burial site in Illinois located at the Norris Farms Archaeological Site. To ensure that observed variation in mandibular structure was not a result of skeletal development during the transition into adulthood, mandibles were only selected from individuals estimated to be 17 years old or older. Age at death estimates were taken from the museum collection records and were based on standard osteological methods. Individuals were grouped, based upon age, into three categories. These categories included young adults ranging in age from 17 and 25, middle-aged adults between the ages of 25 and 50, and older adults, estimated to be 50 years old and older. Ten individuals within each age group were randomly selected to ensure a diverse sample covering a broad range of ages. Thirty total individuals were analyzed for this experiment. Seven individuals are estimated to be males, while 23 individuals are estimated to be females. Each mandible studied in this experiment was a part of a complete, or nearly complete skeleton. Information regarding sex was largely determined by evaluation of skeletal characteristics, including pelvic shape. It is important to note the sex disparity, which might influence our analysis of the effects of sex on shape changes in the mandible.
Table 1 Table displaying identifying information about each individual in the sample population analyzed. Information included in this table includes population identification number, sex, age, and degree of tooth loss.

<table>
<thead>
<tr>
<th>ID</th>
<th>Sex</th>
<th>Age</th>
<th>Tooth Loss</th>
<th>ID</th>
<th>Sex</th>
<th>Age</th>
<th>Tooth Loss</th>
</tr>
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<td>38.5</td>
<td>Posterior</td>
<td>820658</td>
<td>F</td>
<td>18.5</td>
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<td>819921</td>
<td>F</td>
<td>60.5</td>
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<td>M</td>
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<td>820726</td>
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<td>None</td>
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<tr>
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<td>Both</td>
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<tr>
<td>819951</td>
<td>F</td>
<td>50</td>
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<td>820740</td>
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<td>34</td>
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</tr>
<tr>
<td>819953</td>
<td>F</td>
<td>62.5</td>
<td>Both</td>
<td>820744</td>
<td>M</td>
<td>46.5</td>
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</tr>
<tr>
<td>819955</td>
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<td>48</td>
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<td>821110</td>
<td>F</td>
<td>19.5</td>
<td>None</td>
</tr>
<tr>
<td>819961</td>
<td>F</td>
<td>54</td>
<td>Both</td>
<td>821129</td>
<td>F</td>
<td>19</td>
<td>None</td>
</tr>
<tr>
<td>819975</td>
<td>M</td>
<td>17.5</td>
<td>None</td>
<td>821134</td>
<td>F</td>
<td>77</td>
<td>Anterior</td>
</tr>
<tr>
<td>819991</td>
<td>F</td>
<td>54</td>
<td>Anterior</td>
<td>821211</td>
<td>F</td>
<td>27.5</td>
<td>Posterior</td>
</tr>
<tr>
<td>819997</td>
<td>F</td>
<td>55</td>
<td>None</td>
<td>821320</td>
<td>F</td>
<td>44</td>
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</tr>
<tr>
<td>820652</td>
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<td>18.5</td>
<td>None</td>
<td>821349</td>
<td>F</td>
<td>24</td>
<td>None</td>
</tr>
</tbody>
</table>

Tooth loss was present to varying degrees throughout the skeletal sample, allowing for analysis specific to edentulation. Tooth loss was classified according to region of observed edentulism within the mandible. Only tooth loss that occurred during the individual’s life was recorded, determined through examination of alveolar morphology. Each mandible was scored as none, anterior, posterior, or both, anterior and posterior. “None” indicated no significant tooth loss.
loss. “Anterior” indicated incisor, canine or premolar tooth loss in the front of the mouth. “Posterior” indicated molar tooth loss in the back of the mouth. “Both” indicated significant tooth loss in both regions. Further analysis regarding the possible effects that alternate factors such as age and sex have on mandibular shape was also conducted.

2.3 Scanning and Processing of Mandibles

Each mandible was removed from its storage location on an individual basis to reduce the possibility of mixing up individual identification. Once obtained, each mandible was placed on a rotating stand with the condyles facing up. The Artec Space Spider 3D Scanner (Artec 3D, Luxembourg) was used to scan the mandibles. The Space Spider is a structured light scanner that relies on blue light technology to produce accurate, high quality images (Artec 3D, 2017). Using the Artec Space Spider 3D scanner, each mandible was rotated and scanned at a rate of 8 frames per second. A sufficient scan consisted of anywhere between 500 and 1,100 total photo frames. Once sufficiently scanned from an angle in which the condyles were in the air the mandibles were flipped to a position in which the condyles were resting on the rotational platform, with the inferior alveolar border in the air. These two scans were then digitized and processed, using the Artec Studio 11 software. The first processing step involved removal of the platform upon which the mandibles were mounted. Next, each individual’s multiple scans were precisely aligned, providing a complete view of the mandible, containing combined images from each scanned angle. Following alignment, local and global registration were performed and outlier points were removed using an automatic algorithm in the software. Finally, the scans were fused to be closed or watertight, reducing the multiple scans to one solid object. Texture was then applied to the
sharp fusion model, producing a digitized 3D dataset of each mandible. Each processed mandible was saved as a mesh file.

2.4 Anatomical Landmarking

Landmarks were chosen to capture the shape of the entire mandible. A total of 27 landmarks were placed on each respective mandible, many of which represent standard anatomical landmarks used in craniofacial analyses (Williams & Richtsmeier, 2003). Three categories of mandibular landmarks were developed; Type I, Type II, and Type III landmarks (Bookstein, 1997). Type I landmarks are the most consistent and most accurate, as they are based on the location of a point defined by obvious homologous structures (Bookstein, 1997). Type II landmarks are based on the location of a point defined by geometry (Bookstein, 1997), such as the most medial part of the mandibular condyle or the most central point on the mandibular alveolus. Type III landmarks are defined with reference to another point (Bookstein, 1997). An additional two Type II landmarks were placed on the point of greatest curvature along the mylohyoid projection viewed from a superior angle. These points acted as anchors to measure the curve associated with the alveolar crest. Each landmark and its definition is listed in Table 2.
Table 2 Description of Analyzed Mandibular Landmarks. This table provides the landmark name, a description of each landmark, and the type of landmark as defined by Type I, Type II, or Type III.

<table>
<thead>
<tr>
<th>Landmark Identification</th>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Condyle (L,R)</td>
<td>Most lateral point on the mandibular condyle</td>
<td>Type II</td>
</tr>
<tr>
<td>Superior Condyle (L,R)</td>
<td>Most superior point on the mandibular condyle</td>
<td>Type II</td>
</tr>
<tr>
<td>Medial Condyle (L,R)</td>
<td>Most medial point on the mandibular condyle</td>
<td>Type II</td>
</tr>
<tr>
<td>Posterior Condylar Projection (L,R)</td>
<td>Most posterosuperior point on the mandibular condyle</td>
<td>Type II</td>
</tr>
<tr>
<td>Coronoid Process (L,R)</td>
<td>Most superoanterior aspect of the coronoid process</td>
<td>Type II</td>
</tr>
<tr>
<td>Superior Anterior Coronoid Process (L,R)</td>
<td>Most anterior projection on the superoanterior border of the ascending ramus</td>
<td>Type II</td>
</tr>
<tr>
<td>Mylohyoid Projection (L,R)</td>
<td>Most medial projection of mylohyoid line</td>
<td>Type II</td>
</tr>
<tr>
<td>Alveolar Border of Corpus (L,R)</td>
<td>Directly above the mental foramen</td>
<td>Type III</td>
</tr>
<tr>
<td>Inferior Border of Corpus (L,R)</td>
<td>Directly below the mental foramen</td>
<td>Type III</td>
</tr>
<tr>
<td>Infradentale</td>
<td>Most central point on mandibular alveolus</td>
<td>Type III</td>
</tr>
<tr>
<td>Gnathion</td>
<td>Most anteroinferior point on the mental symphysis</td>
<td>Type II</td>
</tr>
<tr>
<td>Mental Spine</td>
<td>Most superior aspect of mental spine</td>
<td>Type II</td>
</tr>
<tr>
<td>Mandibular Foramen (L,R)</td>
<td>Most inferior point of mandibular foramen</td>
<td>Type II</td>
</tr>
<tr>
<td>Inferior Posterior Ascending Ramus (L,R)</td>
<td>Junction of gonial angle and posterior border of the ascending ramus</td>
<td>Type I</td>
</tr>
<tr>
<td>Gonion (L,R)</td>
<td>Junction of ascending ramus and mandibular corpus on inferior border</td>
<td>Type I</td>
</tr>
</tbody>
</table>

Mandibles were landmarked using the Viewbox software (dHAL Software, Kifissia, Greece). A mesh file of a single mandible with a majority of teeth present was uploaded to the program to design a landmark template which could be applied to each mandible in the sample. The landmarks were digitized onto their respective locations (Table 2). Once the landmarks were selected, semilandmarks were projected on to the superior alveolar crest and the inferior border.
of the mandibular corpus to measure the curvature of each. The template consisted of 59 total points, the 27 landmarks described previously (Table 2) and 32 semilandmarks to analyze each curve. The template was then applied and precisely adjusted to fit each individual in the sample, and the landmarked mandibles were saved.
Figure 2 Depiction of landmark placement on each mandible. Orange points are landmarks. Green points are semilandmarks. (1) Condyle. (2) Coronoid Process. (3) Gnathion. (4) Alveolar Border of Corpus. (5) Inferior Border of Corpus. (6) Gonion.
2.5 Geometric Morphometrics, Procrustes Analysis, and Principal Components Analysis

Analysis of the landmarked data was completed using the geomorph package in R and R Studio (R Development Core Team, 2008; Adams, et al., 2017). The code that was used to run the analyses necessary for proper analysis can be found in Appendix A. Using the code, a General Procrustes Analysis (GPA) was run to isolate the shape of each mandible as determined by the selected landmark configurations. GPA consists of three steps. In the first step, otherwise known as translation, the landmark configurations were calculated and the resulting centroids were aligned. In the second step, commonly known as scaling, the distance from the centroid to all of the configured landmarks was calculated and scaled so that each mandibular centroid was the same size, eliminating size as a factor influencing any observed variation in mandibular shape. The third step of the GPA is rotation, in which all of the translated and scaled configurations are rotated until there is minimal distance between matched landmarks. Completing the GPA removes variables such as size and orientation from the analysis.

Next, using the same statistical software, a Principal Components Analysis (PCA) was performed. This analysis serves to develop a linear combination of the variable data, in this case, mandibular shape. This step sought to determine the shape change that defines the most variation in the data. A principal component is essentially an orthogonal axis which best describes variation in the cloud of data points associated with each mandible.
Chapter 3

Results

3.1 Principal Components and Edentulation

The PCA analysis using the GPA-aligned coordinates resulted in a 30 principal components describing the total variance of the data (Figure 3). The first three principal components explain about 48.4% of the mandibular variation while the remainder of the variation is described by the remaining 27 principal components (R Development Core Team, 2008; Adams, et al., 2017). For this study, only the first three principal components, or directional variations, were taken into consideration.

Figure 3 Barplot showing the percent variance described by each principal component. The first three principal components explain 48.4% of the data. The remaining 51.6% of the data is described by the next 27 principal components, and were thus not considered.

PC1 and PC2 account for a combined 36.2% of the observed variation. Analysis of PC1 and PC2 indicates that mandibles of individuals who have suffered severe degrees of tooth loss
are easily distinguishable from the mandibles of individuals who are fully dentate. Individuals with both anterior and posterior tooth loss at their time of death have positive PC1 values while individuals without any tooth loss at their time of death have negative PC1 values. Individuals who have tooth loss limited to either anterior teeth or molar teeth fall in between those who have not lost any teeth and those who have lost all of their teeth. Edentulism had no apparent pattern of variation along PC2. These trends are supported by statistical analysis, which suggests that the effects of tooth loss on the shape change associated with PC1 is statistically significant, with a p-value of 0.0001. By contrast, shape change along PC2 was not significant (p = 0.4736).

![PCA for Full Set: PC1 vs. PC2](image)

Figure 4 Effect that tooth loss has on shape change along PC1 and PC2. The blue region represents individuals who have not experienced any tooth loss. The purple region represents those who have experienced tooth loss limited to their molars. The green region represents individuals who have experienced molar tooth loss as well as incisor, canine, and/or premolar tooth loss. The red region represents individuals who have experienced tooth loss limited to their incisors, canines, and premolars.

Variants of PC1, which explains an estimated 21.4% of mandibular variation (Figure 3), were observed to differ primarily in size of the gonial angle, degree of alveolar ridge resorption, and bicondylar width and shape as measured from an overhead view. Mandibles falling towards
the negative PC1 values were narrower from condyle to condyle, more “V-shaped”, with less alveolar ridge resorption, and a smaller gonial angle as measured from ramus to corpus. Their positive PC1 value counterparts were wider, more “U-shaped”, with more alveolar ridge resorption, and larger gonial angles as measured from ramus to corpus (Figures 5 and 6).

PC2 explains about 14.8% of the observed mandibular variation (Figure 3). While there was still variability regarding alveolar crest resorption and bicondylar width, PC2 also highlighted more significant variation with respect to the gonion. Individuals who tended to fall on the negative side of the scale measuring variation in PC2 had skinner, “V-shaped” mandibles as observed from an occlusal perspective, decreased alveolar crest resorption, and flatter gonion. As expected, individuals falling on positive PC2 had wider, “U-shaped” mandibles as observed from an occlusal perspective, with increased alveolar crest resorption, and gonion that protruded to a more prominent degree (Figures 7 and 8).
Figure 6 Visual representation of the changes to mandibular shape observed from the superior, lateral, and anterior perspectives along PC1. PC1 minimum represents the extreme structure of mandibles described by negative principal component 1 values. PC mean represents the mean mandibular shape described by each of the individuals analyzed in the sample. PC1 maximum represents the extreme structure of mandibles described by positive principal component 1 values.

Figure 5 Superimposed representation of mandibular structure as described along PC1 from the superior, lateral, and anterior perspectives. The blue mandible represents the minimum extreme shape along PC1. The orange mandible represents the maximum extreme shape along PC1.
Figure 7 Visual representation of the changes to mandibular shape observed from the superior, lateral, and anterior perspectives along PC2. PC2 minimum represents the extreme structure of mandibles described by negative principal component 2 values. PC mean represents the mean mandibular shape described by each of the individuals analyzed in the sample. PC2 maximum represents the extreme structure of mandibles described by positive principal component 2 values.

Figure 8 Superimposed representation of mandibular structure as described along PC2 from the superior, lateral, and anterior perspectives. The blue mandible represents the minimum extreme shape along PC2. The orange mandible represents the maximum extreme shape along PC2.
When PC1 was plotted against PC3, explaining a combined 33.6% of the variation in the data, there appears to be a minor degree of separation between fully edentate and fully dentate individuals along PC3, suggesting that edentulism has a slight effect on shape change along PC3. With caution, one might suggest that individuals who have lost both anterior and posterior teeth have more negative PC3 values while individuals without any tooth loss might have more positive PC3 values. Individuals with partial tooth loss appear to have intermediate PC3 values. However, after further statistical analysis this trend has a p-value of 0.5284, which suggests that no significant relation between edentulism and shape change along PC3 exists.

![Figure 9](image-url) Effect that tooth loss has on shape change along PC1 and PC3. The blue region represents individuals who have not experienced any tooth loss. The purple region represents those who have experienced tooth loss limited to their molars. The green region represents individuals who have experienced molar tooth loss as well as incisor, canine, and/or premolar tooth loss. The red region represents individuals who have experienced tooth loss limited to their incisors, canines, and premolars.

PC3 explained about 12.2% of mandibular variation in this sample (Figure 3). Shapes falling along negative PC3 possessed skinnier, “V-shaped” mandibles as viewed from an overhead perspective, more alveolar crest resorption, and a shorter mandibular symphysis.
Individuals falling on the positive side of the scale had wider, “U-shaped” mandibles as viewed from an overhead perspective, less alveolar crest resorption, and a taller mandibular symphysis.

3.2 Structural Variation Described by Other Factors

It is important to consider factors other than edentulism as possible sources of shape variation. While tooth loss appears to play a prominent role in changing mandibular shape, age and sex also appear to influence the observed shape variation.

![PCA for PC 1 and PC 2](image)

Figure 10 Scatterplot describing the effect that age has on structural variation as measured by PC1 and PC2. Black points labeled with the number “1” represent individuals estimated to have been between the ages of 17 and 25 at their time of death. Red points labeled with the number “2” signify individuals estimated to have been between 25 and 50 years old at their time of death. Green points labeled with the number “3” represent individuals estimated to have been 50+ years old at their time of death.

Based on these data, older individuals generally have more positive values along PC1, while younger individuals tend to have PC1 values that are negative. As was expected,
individuals of intermediate ages display significant variation, with some individuals having positive PC1 values while others have negative values. Based upon these data, there is nothing to suggest that age has any significant effect on PC2. This conclusion is supported by statistical analysis, which suggests that age’s correspondence with structural variation along PC1 has a significant p-value of 0.002. Unlike PC1, however, age was not found to have a significant influence on observed variation along PC2, as the associated p-value was 0.24. Figure 11 shows the same data while making apparent the variation within each age range’s PC1 and PC2 values. Figure 11 shows that variation among young adults is noticeably less than that of middle aged and older individuals.

![PCA for Mandible: PC1 vs. PC2](image)

Figure 11 Shows the variation among age groups of individuals as they relate to changes in mandibular structure along PC1 and PC2. The pink region represents individuals in the youngest age group from 17-25 years of age at the time of their death. The green region represents individuals in an intermediate age range between the ages of 25 and 50 at the time of their death. The blue region represents the oldest individuals in the sample who were 50 years old or older at the time of their death.

In order to analyze the extent to which age explains mandibular variation along PC3 a scatterplot describing the effect that age has on PC2 and PC3 was developed.
Figure 12 Scatterplot describing the effect that age has on structural variation as measured by PC2 and PC3. Black points labeled with the number “1” represent individuals estimated to have been between the ages of 17 and 25 at their time of death. Red points labeled with the number “2” signify individuals estimated to have been between 25 and 50 years old at their time of death. Green points labeled with the number “3” represent individuals estimated to have been 50+ years old at their time of death.

No obvious trend was observed (Figure 12), suggesting that age had no significant effect on either PC2 or PC3. Statistical analysis provided a p-value of 0.239 when age’s effect on PC3 was calculated, suggesting that there is in fact no significant correlation between age and mandibular variation along PC3.
In addition to age, sex was found to describe some of the observed mandibular variation in the experimental population. When individuals were plotted and characterized by sex a clear differential existed along PC1. Males trended towards more negative PC1 values, while females were determined to lean towards having positive PC1 values. Individual 820740, who is estimated to be a 34 year old male, was an outlier who was found to have a positive PC1 value. A variety of possible explanations for this exist including genetic factors, malnutrition, and possible improper identification as a male. Using statistical coding via RStudio the p-value describing the relationship between sex and variation along PC1 was significant at a value of 0.005. No relationship between sex and PC2 was noticed, and this was supported by the calculated p-value of 0.148 (Figure 13).

![PCA for PC1 and PC2](image)

Figure 13 Scatterplot describing the effect that sex has on structural variation as measured by PC1 and PC2. Black dots represent females and red dots represent males.
Similar analysis was conducted regarding sex and its effect on PC3. As with PC2, no significant correlation was found between structural changes along PC3 and sex. In fact, the observed relationship between sex and PC3 was even less present than observed with PC2. This is supported by the calculated p-value regarding sex and its relationship to changes along PC3. This respective p-value was found to be 0.435 (Figure 14).

![PCA for PC2 and PC3](image)

Figure 14 Scatterplot describing the effect that sex has on structural variation as measured by PC2 and PC3. Black dots represent females and red dots represent males.

It is important to note that while sex was proven to be significantly influential only in structural variation along the PC1 axis after GPA alignment, sex remains important regarding mandibular structure prior to removing the influence of variables such as size. When considering centroid size as determined via mandibular landmarking, males typically have larger mandibular centroids than their female counterparts (Figure 15). Of course, while analyzing the effects that sex has on mandibular structure, centroid size was standardized, removing its influence on the collected data.
Figure 15 Scatterplot comparing centroid size as it relates to sex prior to GPA alignment. Black dots represent females and red dots represent males.
Chapter 4
Discussion

The data collected in this study indicate that throughout one’s life, they are likely to undergo significant mandibular restructuring. Specifically, with increasing age and tooth loss, mandibles appear to experience an increase in alveolar ridge resorption, bicondylar width, and gonial angle size. As expected, each individual experiences changes to their mandibular structure to different extents. Several possible causes of these changes exist. Edentulism, age, and sex were each found to significantly correlate with changes to mandibular structure, suggesting that mandibular structure is not determined by a single variable, but by a combination of factors which each influence mandibular shape.

4.1 Edentulation and Mandibular Structure

As hypothesized, edentulous individuals were found to exhibit significantly different mandibular shapes compared to individuals with teeth. This pattern suggests that progressive loss of dentition and associated functional changes in the masticatory system have major impacts on mandibular shape. Tooth loss appears to correspond with wider, more “U-shaped” mandibles, with more alveolar ridge resorption, and larger gonial angles as measured from ramus to corpus. The observed increase in gonial angle is directly related to the noted changes in alveolar dimensions. This is because the alveolar ridge does not experience resorption in a uniform manner, with the peak resorption occurring around teeth 19 and 30, or the first molars. As the angle of the alveolar ridge increased, so did the angle between the mandibular body and condyle. Likewise, mandibles that retain larger numbers of teeth tend to be narrower from condyle to
condyle, more “V-shaped”, with less alveolar ridge resorption, and a smaller gonial angle as measured from ramus to corpus.

The changes in mandibular shape observed with edentulism are significant. Any alteration in biological structure can potentially influence biomechanical processes, but it has been shown that the structural changes associated with edentulism decrease masticatory efficiency. Sheiham and Steele (2000) suggest that the ability to eat certain foods is dependent upon the presence and distribution of natural teeth. Such foods include carrots, apples, well-done steak, and nuts (Sheiham & Steele, 2000). The observed alveolar ridge resorption, increase in bicondylar width, and increased gonial angle associated with tooth loss can therefore decrease the ability for individuals to obtain the nutrients necessary for a healthy life. Analysis of the increased gonial angle observed in edentulous mandibles is particularly interesting because the masseter, a muscle critical for mastication in mammals, inserts in the region. The change in the gonial angle size observed with edentulation represents a significant shift in anatomical structure of the mandible, and potentially decreases the efficiency of masseter function and action.

Edentulism has been found to influence more than just diet. Edentate individuals struggle to communicate, as many languages utilize sounds that depend on the positioning of the lips, teeth, and tongue (Molly, Nackaerts, Vandewiele, Manders, Van Steenberghe, & Jacobs, 2007). With respect to oral health, edentulism has been found to be associated with sensory deficiencies in the salivary glands, and oral musculature (Emami, de Souza, Kabawat, & Feine, 2013). On a more holistic note, edentate individuals were found to experience a 13% increased risk of total death than their dentate counterparts (Abnet, Qiao, Dawsey, Dong, Taylor, & Mark, 2005). This increased risk of total death is partly due to the observed 35% increased risk of upper GI cancer death, 28% increased risk of heart disease death, and 12% increased risk of stroke death.
observed in edentate individuals (Abnet, Qiao, Dawsey, Dong, Taylor, & Mark, 2005). These health effects are related to the structural changes associated with edentulism. An individual’s inability to properly speak, for example, is directly related to the presence of teeth, while overall health is likely a secondary effect associated with changes in diet caused by alveolar ridge resorption, increased bicondylar width, and increased gonial angle size after tooth loss.

4.2 Age and Mandibular Structure

Data collected in this study indicate that older individuals, in this case, people who were 50 years old or older, tend to have higher PC1 values than younger individuals. Middle-aged individuals between the ages of 25 and 50 were found to have a wide spread of PC1 values. Young individuals below the age of 25 had negative PC1 values. This suggests that as an individual ages they are likely to experience mandibular widening into more of a “U” shape. Additionally older individuals typically experience higher levels of alveolar ridge resorption and increased gonial angles as a result. The degree to which individuals experience such changes is highly variable. These conclusions are based upon the assumption that older individuals once had mandibles shaped in a similar way as the younger population has in this study. It is unlikely that such drastic changes in mandibular morphology occurred over the course of a generation, and that the older population identified in this study was born with wider mandibles. Further support of this assumption is the notable trend that intermediately aged individuals have mandibular shape characteristics in between, yet more variable than, those of young individuals and older individuals.
Young individuals have a consistent mandibular shape, representing, in a sense, how the human mandible is biologically designed. Analysis of structural data of those individuals who are older in age clearly shows an increased variability of mandibular shape. Several possible reasons for this exist. One possible explanation is that there is less variation regarding the shape of younger mandibles because populations of young individuals are less exposed to external factors which can influence mandibular shape such as diet, environment, and disease than their older counterparts. These factors can influence the rate at which tooth loss occurs. It is safe to assume that members of the Oneota groups were each influenced by different environmental factors. Therefore, when comparing two individuals of the same age, one might have exquisite dental health while another might be completely edentulous. A different, and more likely, explanation for the increased structural variability observed with age is that mandibles change to varying degrees as biomechanical processes change. For example, muscles used for mastication might weaken as one ages, leading to an altered biting mechanism, and a subsequent change in mandibular structure.

When considering the effect that age has on mandibular structure, it is important to consider the osteological paradox. The osteological paradox is essentially the notion that deducing information about an individual based off of skeletal remains is difficult and often counterintuitive because skeletal structure is not always indicative of age, but rather of overall health (Siek, 2013; Wood, et al., 1992). Relating to mandibular condition, the people with the highest longevity likely had dentition which was able to handle a nutritious diet, enable proper communication, and support a healthy lifestyle for a long period of time. This could be attributed to a variety of things including genetics, nutrition, and environment, and thus, many individuals who survived to older ages might have more complete dentition. Alternatively, it is plausible that
those with unhealthy oral habits, poor genetics, and a hostile environment lost their teeth at earlier ages. For this reason predicting the ages of the individuals in our sample is difficult because, counter to popular belief, it is possible that many of our edentulous samples were younger than predicted, while many individuals with full dentition might have been older than predicted. The osteological paradox is not limited to the mandible. All skeletal remains are vulnerable to the same paradox as it relates to bone degeneration and disease (Siek, 2013; Wood, et al., 1992). It is ultimately difficult to distinguish the effects that age has on mandibular structure from the effects that edentulism has on mandibular structure. As an individual ages, they are often exposed to increased risk of edentulation, and these two variables are highly related. Previous research has found that age, alone, does not have any influence on masticatory performance and bite force (Hatch, Shinkai, Sakai, Rugh & Paunovich, 2001).

4.3 Sex and Mandibular Structure

Another factor determined to have a significant influence on the observed variation in mandibular structure is sex. Prior to GPA alignment and Procrustes analysis, in which each mandible was standardized to remove size and orientation as influencing factors of variation, males had overwhelmingly larger mandibular centroids than females (Figure 13). There was one outlier, however, a male, who appeared to have the smallest mandibular centroid size. This individual was a 38-year-old male with partial tooth loss of teeth identified as 17, 20, 22, 23, and 29 using the standard teeth identification numbers (Justi Educational Department, 2003). The surprising nature of his small mandibular centroid could be due to a variety of factors including
genetics, improper nutrition, or even human error. It is possible that his centroid landmarks were mischaracterized or that this individual’s sex was misidentified. After GPA alignment and Procrustes analysis, when the differentiating characteristic of each mandible in our sample was shape, it was observed that sex explains much of the variation along PC1. This was backed up by statistical analysis which showed a p-value of 0.005. This rejects the null hypothesis that sex does not influence mandibular shape. Specifically, females were found to have higher PC1 values indicating that they are more likely to have wider, “U-shaped” mandibles, with large gonial angles and increased alveolar ridge resorption. This is not surprising as women are known to have a higher prevalence of osteoporosis and experience a greater risk of bone fracture than men (Cawthon, 2011).

4.4 Relation to Previous Work

Previous work seeking to identify the changes to mandibular structure that are related to edentulation, age, and sex have produced conflicting results. Some evidence suggests that edentulation significantly alters multiple components of mandibular shape. Hutchinson, Farella, and Kramer (2015) suggest that tooth loss results in shorter alveolar height, a shorter mandibular body, a larger gonial angle, a taller ramus, a larger bicondylar width, and a more obtuse mental angle. Small, Brits, and Hemingway (2014), however, suggest that changes in mandibular structure associated with edentulism are limited to the alveolar ridge. Minor, but not significant, facial changes including changes to the upper facial height and palate shape were also observed (Small, Brits, and Hemingway, 2014). In Small, Brits, and Hemingway’s study the limited changes to facial structure observed when compared to the significant reduction in alveolar ridge
height indicate that the alveolar ridge is more susceptible to changes with tooth loss than the face. A possible explanation for this could be that the facial skeleton is integrated with the rest of the skull, which may limit how much it can change, while the alveolar ridge is directly integrated with the dentition. This, in turn, has implications for mastication, as there could be a shift in patterns of occlusion, further affecting the mechanics of the masticatory process. It would be interesting to determine how much facial change is observed using methods that detect significant mandibular change with edentulation. It is possible that upon tooth loss the face experiences just as much variation as the mandible, but because Small, Brits, and Hemingway only observed structural changes limited to the alveolar ridge, there was not as much facial variation observed.

The data collected in the present study identify a trend suggesting that mandibular shape changes to an extent in between that of these two previous studies. Based upon cross-sectional analysis, alveolar ridge resorption was commonly found to occur to a significant degree in edentulous individuals. The observed data also showed an increase in bicondylar width, and an increase in gonial angle size in edentulous individuals compared to their dentate counterparts. The results did not show any clear indication that edentulation increases the height of the mandibular ramus or decreases the length of the mandibular body. Because the data were consistently observed among individuals classified into four groups, those without any tooth loss, those with anterior tooth loss, those with posterior tooth loss, and those who were completely edentulous, there is reasonable support to the notion that we can identify tooth loss as a mandibular structure-altering characteristic. In order to prove this indefinitely it might be a good idea to perform a longitudinal study in which researchers digitize and analyze the mandibles of living individuals throughout their life, paying close attention to how the mandible changes as
one loses teeth. Such a study would require decades, if not centuries, to complete, and it would be incredibly costly.

Like the present study, these previous studies analyzed adult morphology using geometric morphometric techniques. While these studies used morphometric data to analyze mandibular and craniofacial structure, the data gathered in the current study were collected using more advanced three dimensional techniques, with an increased number of mandibular landmarks, providing more precise data. Specifically, Hutchinson, Farella, and Kramer (2015) only used 28 mandibular landmarks. Small, Brits, and Hemingway (2014) used 45 fixed landmarks, in addition to some sliding landmarks, across the entirety of the facial skeleton. This study used 27 fixed landmarks and 32 sliding landmarks entirely on the mandible. Additionally, previous studies primarily looked at modern populations from the 19th and 20th centuries. This analysis analyzed mandibles from anywhere between the 10th and 16th century, before dental appliances, which could potentially influence mandibular structure, were widely available.

4.5 Implications of these Data

The influence of edentulism on mandibular shape is substantial. Dentures are a common prosthetic solution to tooth loss, but while dentures can help patients with mastication and aesthetics, they fail to prevent the structural changes associated with tooth loss from occurring (Tallgren, 2003). Thus, the estimated 37.9 million people who will need dentures in the United States in 2020 will be prone to experiencing the mandibular changes associated with edentulism (Douglass, Shih, & Ostry, 2002). Patients treated with partial dental bridges, or artificial teeth cemented to natural dentition, are vulnerable to these mandibular changes as well. If no effort is
made to prevent the mandibular shape changes that come with edentulism identified through this study, patients will experience increased difficulty finding prosthetic solutions that will fit their morphing mandible (Kelsey, 1960). It is for these reasons that further developments must take place to ensure that all people have access to affordable treatments that act to prevent mandibular shape change. One such solution is dental implant surgery prior to structural alteration and alveolar crest resorption or after a bone graft is performed. Research supports the notion that proper dental implantation reduces alveolar bone resorption (Jacobs, et al., 1993). In one study seeking to determine what effects different treatments had on antagonistic jaw resorption, complete denture wearers were found to have the most resorption, while individuals with implant-supported overdentures had limited resorption (Jacobs, et al., 1993). Similarly, dental implants have been shown to be more effective with regards to bite strength than complete dentures (Gibbs, et al., 1986). Previous studies have shown that individuals with normal dentition were found to have an average bite strength of 162 lbs (Gibbs, et al., 1981). Individuals with complete dentures were found to have a reduced bite strength of just 35 lbs (Colaizzi, et al., 1984). Individuals with implant supported overdentures were recorded to have an average bite strength of 51 lbs (Spossetti, et al., 1986). While treatments involving implants help reduce resorption, and increase bite strength, they are not perfect, and further innovation is required to maintain mandibular structure upon experiencing edentulation.

4.6 Supplemental Thoughts

It was surprising that edentulism, age, and sex had little effect on PC2 or PC3. This is not to say that these factors had no effect on PC2 and PC3, but their effect is not large enough to be
attributed to the observed variation along PC2 and PC3. Overall, older females who have lost a majority of their teeth are most likely to experience the mandibular shape changes described by a high PC1 value, as these groups of individuals were all found to have positive PC1 values. While much of the information collected through this experiment is applicable to modern populations, the data should be applied with caution. The samples used in this experiment lived in an environment more prone to the forces of mother nature with fewer technological advancements than are present today. Although the Oneota people were early consumers of maize, they did consume a harder diet than most modern people do, which suggests that they likely had stronger oral muscles. Future research is needed to develop a more clear distinction between the effects that age and edentulism have on mandibular structure. A majority of the young individuals analyzed in this study were fully dentate, and in order to collect more conclusive data specific to which characteristic, age or edentulism, influences mandibular shape more, one must seek out a young population with a greater distribution of dental health. Future studies regarding mandibular variation are required to better understand the vulnerabilities associated with a modern edentulous mandible, and to develop affordable and functional treatments to provide the best quality of life to those who are edentulous.
Chapter 5

Conclusion

Like other areas of the body, the bone associated with the human mandible is subject to a variety of changes throughout one’s lifetime. Unlike other areas of the human body, however, the mandible is subjected to a multitude of structural changes because of the always-changing nature of the dentition. This study sought to bring to light the structural changes that the mandible experiences with one such change to the dentition. Specifically, this study determined that the process of edentulation, or tooth loss, results in a wider, “U-shaped” mandible with increased alveolar ridge resorption, and a related increase in gonial angle. These structural changes often make everyday tasks that require the oral cavity difficult for edentulous individuals. Most susceptible to said structural changes are ageing women who have experienced tooth loss. The people least likely to experience these mandibular shape changes are young males with complete dentition. This study was conducted on individuals of the Oneota tribe who were unfamiliar with much of the knowledge that we are aware of today regarding oral hygiene. It is important to promote a healthy diet and a healthy oral cleansing routine among modern populations to reduce cases of edentulism. At the same time, it is important that access to quality treatment is made available to those who are experiencing tooth loss in order to maintain the integrity of their mandibles.
Appendix A

Code Used in R Studio

To install required RStudio Packages:

```
```r
#install.packages("rgl") # don't forget to use the quotation marks!
#install.packages("ape") # this installs the ape package
#install.packages("geomorph") # this installs the geomorph package
#install.packages("Morpho") # this installs the Morpho package
#install.packages("calibrate") # this installs the calibrate package
```
```{r}
library(rgl) #opens package required for 'rgl'
library(ape) #opens package required for 'ape'
library(geomorph) #opens 'geomorph' package
library(Morpho) # opens "Morpho" package
library(calibrate) #opens 'calibrate' package
library(plyr)
library(ggplot2)
```

To Create the Data Array:

```
```r
setwd("C:/Users/Andrew/Desktop/RStudio_Andrew")
filelist <- list.files(pattern = ".txt") # 2
names <- gsub(".txt","",filelist) # 3
coords = NULL # 4
for (i in 1:length(filelist)) {
  tmp <- as.matrix(read.table(filelist[i]))
  coords <- rbind(coords,tmp)) # 5
coords <- arrayspecs(coords,59,3) # 6
dimnames(coords)[[3]] <- names # 7
dim(coords) # 8 (This should read: 59 3 30)
coords[1,,] # 9 (This should show the first x,y,z coordinate for each individual)
```
```
To Define Semilandmarked Curves:

```r
setwd("C:/Users/Andrew/Desktop/RStudio_Andrew")
curves <- read.csv("curveslide.csv",header=TRUE)
```

Procrustes Analysis and Principal Components Analysis:

```r
GPA <- gpagen(coords, curves = curves, ProcD = FALSE,
              print.progress = TRUE)
```

```r
PCA <- plotTangentSpace(GPA$coords, legend = TRUE) # runs your PCA!
summary(PCA) # tells you how much of your data's variance is explained by each principal component (a.k.a. how much of the data cloud's dimensions are explained by a single principal component axis)
```

```r
pvar <- (PCA$sdev^2)/(sum(PCA$sdev^2)) # don't worry about it, it's about how much variance is explained
names(pvar) <- seq(1:length(pvar)) # setting up the bar plot
barplot(pvar, xlab= "Principal Components", ylab = "% Variance") # plotting it so you should see the bar plot before!
```

To Visualize Principal Components Analysis:

```r
setwd("C:/Users/Andrew/Desktop/RStudio_Andrew") # 1
grouping <- read.csv("Grouping1.csv", header = TRUE)# 2
ID <- grouping$ID # 3
sex <- grouping$Sex # 4
sex2 <- grouping$Sex2 # 5
age <- grouping$age # 6
agecat <- grouping$AgeCat # 6
agecat2 <- grouping$AgeCat2
ToothLoss <- grouping$ToothLoss
loss <- grouping$ToothLoss # 7 (anterior vs. posterior vs. both)
loss2 <- grouping$ToothLoss2 # 8 (numeric, so 0 = anterior, 1 = posterior, both = 2)
```
To Make PCA plots:

```{r}
plot(PCA$pc.scores[,1],PCA$pc.scores[,2], col = agecat, bg = agecat, pch = 16, xlab = "PC 1", ylab = "PC 2", main = "PCA for PC 1 and PC 2")
textxy(PCA$pc.scores[,1],PCA$pc.scores[,2],agecat)
```

```{r}
plot(PCA$pc.scores[,2],PCA$pc.scores[,3],col = agecat, bg = agecat, pch = 16, xlab = "PC2 (14.864%)", ylab = "PC3 (12.172%)", main = "PCA for PC2 and PC3")
textxy(PCA$pc.scores[,2],PCA$pc.scores[,3],agecat)
```

```{r}
plot(PCA$pc.scores[,1],PCA$pc.scores[,2],col = sex, bg = sex, pch = 16, xlab = "PC1 (21.397%)", ylab = "PC2 (14.864%)", main = "PCA for PC1 and PC2")
textxy(PCA$pc.scores[,1],PCA$pc.scores[,2],sex)
```

```{r}
plot(GPA$Csize,PCA$pc.scores[,1],col = sex, bg = sex, pch = 16, xlab = "Centroid Size", ylab = "PC1 (21.397%)", main = "PCA for Centroid Size vs. PC 1")
textxy(GPA$Csize,PCA$pc.scores[,1],sex)
```
To View Clusters in Scatterplots:

```r
pc1pc2 <- as.data.frame(PCA$pc.scores[,1:2]) # 1
pc1pc2 <- cbind(pc1pc2,agecat2) # 2
find_hull <- function(pc1pc2) pc1pc2[chull(pc1pc2$PC1, pc1pc2$PC2), ] # 3
hulls <- ddply(pc1pc2, "agecat2", find_hull) # 4
plot1 <- ggplot(pc1pc2, aes(x=PC1, y=PC2,color=agecat2,fill=agecat2)) +
  geom_point(shape=16) +
  geom_polygon(data = hulls, alpha = 0.5) +
  labs(x = "PC1 (21.397%)", y = "PC2 (14.864%)") +
  ggtitle("PCA for Mandible: PC1 vs. PC2") +
  theme_classic() # 5
plot1 # 6
```

```r
pc1pc2.t <- as.data.frame(PCA$pc.scores[,1:2])
pc1pc2.t <- cbind(pc1pc2.t,loss)
find_hull.t <- function(pc1pc2.t) pc1pc2.t[chull(pc1pc2.t$PC1, pc1pc2.t$PC2), ]
hulls.t <- ddply(pc1pc2.t, "loss", find_hull.t)
plot2 <- ggplot(pc1pc2.t, aes(x=PC1, y=PC2,color=loss,fill=loss)) +
  geom_point(shape=16) +
  geom_polygon(data = hulls.t, alpha = 0.5) +
  labs(x = "PC1 (21.397%)", y = "PC2 (14.864%)") +
  ggtitle("PCA for Full Set: PC1 vs. PC2") +
  theme_classic()
plot2
```

```r
pc1pc3.t <- as.data.frame(PCA$pc.scores[,1:3])
pc1pc3.t <- cbind(pc1pc3.t,loss)
find_hull.t <- function(pc1pc3.t) pc1pc3.t[chull(pc1pc3.t$PC1, pc1pc3.t$PC3), ]
hulls.t <- ddply(pc1pc3.t, "loss", find_hull.t)
plot2 <- ggplot(pc1pc3.t, aes(x=PC1, y=PC3,color=loss,fill=loss)) +
  geom_point(shape=16) +
  geom_polygon(data = hulls.t, alpha = 0.5) +
  labs(x = "PC1 (21.397%)", y = "PC3 (12.172%)") +
  ggtitle("PCA for Full Set: PC1 vs. PC3") +
  theme_classic()
plot2
```

```r
pc3pc1.t <- as.data.frame(PCA$pc.scores[,3:1])
```
To Visualize Shape Changes Along the PC Axis:

```r
plotTangentSpace(GPA$coords, axis1 = 1, axis2 = 2, warpgrids = T) # PC 1
```

```r
plotTangentSpace(GPA$coords, axis1 = 2, axis2 = 3, warpgrids = T) # PC 2
```

```r
plotTangentSpace(GPA$coords, axis1 = 3, axis2 = 1, warpgrids = T) # PC 3
```

Multivariate Regression:

```r
procD.lm(PCA$pc.scores[,1] ~ GPA$Csize, iter = 999, RRPP = TRUE,
       print.progress = TRUE)
```
```
```{r}
procD.lm(PCA$pc.scores[,2] ~ GPA$Csize, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
procD.lm(PCA$pc.scores[,3] ~ GPA$Csize, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
sex3 <- as.factor(sex)
procD.lm(PCA$pc.scores[,1] ~ sex3, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
sex3 <- as.factor(sex)
procD.lm(PCA$pc.scores[,2] ~ sex3, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
sex3 <- as.factor(sex)
procD.lm(PCA$pc.scores[,3] ~ sex3, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
procD.lm(PCA$pc.scores[,1] ~ age, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
procD.lm(PCA$pc.scores[,2] ~ age, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
procD.lm(PCA$pc.scores[,3] ~ age, iter = 999, RRPP = TRUE, print.progress = TRUE)
```
```
```{r}
agecat2 <- as.factor(agecat)
procD.lm(PCA$pc.scores[,1] ~ agecat2, iter = 999, RRPP = TRUE,
print.progress = TRUE)
````
```r
agecat2 <- as.factor(agecat)
procD.lm(PCA$pc.scores[,2] ~ agecat2, iter = 999, RRPP = TRUE,
        print.progress = TRUE)
````
```r
agecat2 <- as.factor(agecat)
procD.lm(PCA$pc.scores[,3] ~ agecat2, iter = 999, RRPP = TRUE,
        print.progress = TRUE)
````
```r
procD.lm(PCA$pc.scores[,1] ~ agecat2, iter = 999, RRPP = TRUE,
        print.progress = TRUE)
````
```r
ToothLoss2 <- as.factor(ToothLoss)
procD.lm(PCA$pc.scores[,1] ~ ToothLoss2, iter = 999, RRPP = TRUE,
        print.progress = TRUE)
````
```r
ToothLoss2 <- as.factor(ToothLoss)
procD.lm(PCA$pc.scores[,2] ~ ToothLoss2, iter = 999, RRPP = TRUE,
        print.progress = TRUE)
````
```r
ToothLoss2 <- as.factor(ToothLoss)
procD.lm(PCA$pc.scores[,3] ~ ToothLoss2, iter = 999, RRPP = TRUE,
        print.progress = TRUE)
````
```r
ToothLoss2 <- as.factor(ToothLoss)
summary(lm(PCA$pc.scores[,1]~ToothLoss2))
````
```r
ToothLoss2 <- as.factor(ToothLoss)
summary(lm(PCA$pc.scores[,2]~ToothLoss2))
````
ToothLoss2 <- as.factor(ToothLoss)
summary(lm(PCA$pc.scores[,3]~ToothLoss2))
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ACADEMIC VITA

Andrew M. Doberstein
doberstein.andrew@gmail.com

Education
The Pennsylvania State University, Schreyer Honors College
Eberly College of Science
University Park, PA
Class of 2017
Bachelor of Science, Biology

Related Academic Experiences
Primate Functional Morphology Lab
Undergraduate Research Assistant
University Park, PA
September 2015-December 2017
- Developed and implemented honors thesis project; Identified effects that edentulation has on mandibular structure
- Collaborated with team members to develop lab studies and support dissertation project research
- Collected and analyzed quantitative bone data from different primate populations

Learning Assistant, Physics 251
University Park, PA
August 2016-August 2017
- Attended lectures and facilitated an active learning environment
- Answered student questions in a constructive fashion

Campus and Community Sustainability Expo
Undergraduate Poster Presentation
University Park, PA
August 2016-December 2016
- Developed and applied soil quality tests for Penn State’s student farm
- Authored and designed a poster which was presented at the Campus and Community Sustainability Expo

Honors & Awards
Eberly College of Science Marshal for Fall 2017 Commencement
R. Metz, Jr., Betty and Dennis Lynn Headings Scholarship
FEEA Award of Academic Excellence
Edward C. Hammond Jr. Memorial Scholarship in Biology
The Evan Pugh Scholar Junior Award
President’s Freshman Award

Work Experience
Target Corporation
Montgomeryville, PA
June 2014-December 2017
Hardlines Team Member
- Ensured guest satisfaction by answering questions and assisting with purchasing decisions
- Maintained shelf supply to keep store visually appealing to guests
- Operated cash register in efficient manner and with high level of accuracy

Other Professional Involvement
Current Events Club
University Park, PA
February 2017-December 2017
Founder and President
- Facilitated student led discussions regarding events happening around the world in order to foster a global perspective among students at Penn State.
• Managed the club’s administrative needs including membership, finances, and public relations.

**Penn State Pre-Dental Society**

*Secretary*

- Actively supported other pre-dental students in the pursuit of a career in dentistry
- Maintained membership records and communicated important club events to general members
- Communicated with members of the local dental community
- Participated in service events benefitting the local community

**Volunteer at the Paterno Catholic Student Faith Center**

- Welcomed guests and answered questions about the faith center.
- Assisted visitors in finding their way around the building.
- Answered phones and directed calls to proper individuals.

**Penn State Dance Marathon**

- Fundraised benefitting the Four Diamonds Foundation
- Supported families affected by pediatric cancer

**Penn State Club Cross-Country**

- Trained for and competed in intercollegiate club cross-country races

**Hatboro-Horsham High School College Ambassador**

- Spoke with high school students about successful practices in college

**Volunteer at the Bennett Family Center**

- Helped students foster their imagination through art projects

**Relay For Life**

- Fundraised money for the American Cancer Society
- Participated in a 24 hour walkathon to raise awareness for those affected by cancer