How has the morphology of the human mandible varied in response to the dietary changes that have occurred in Britain between the Neolithic and Post-Medieval periods?

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University College London

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Declaration

I, Cara Stella Hirst, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.
Abstract

Unlike cranial morphology, human mandibular morphology has been found to be influenced primarily by environmental as opposed to genetic factors. Previous research has demonstrated that significant morphological changes have occurred in the mandible during the Agricultural and Industrial Revolutions when widespread dietary changes occurred, and diet became softer. During this time the size of the mandible decreased, and mandible morphology became more gracile. This research however has typically focussed on comparisons between two time periods associated with a large dietary transition. For this reason, it is not known if the reported changes in mandible morphology represent a consistent reduction in mandibular robusticity or rather fluctuation between periods associated with dietary variability. Furthermore, it is unclear how susceptible the mandible is to smaller dietary changes.

The aim of this thesis is to investigate how responsive mandible morphology is to the dietary changes that have occurred in Britain from the Neolithic through to the Post-Medieval periods. It is hypothesised that mandible morphology is responsive enough to mechanical stimuli that more minor dietary changes will also result in morphological variation. Results indicated that in general mandible morphology became increasingly gracile over time, while more pronounced morphological changes are associated with major dietary transitions such as the intensification of agriculture and the Industrial Revolution. Moreover, significant increases in gracilisation occurred between the Anglo-Saxon and Medieval period, potentially indicating that the dietary changes that occurred during the Industrial Revolution were more gradual than previous research has indicated. In addition to the more prominent morphological changes, smaller morphological fluctuations occurred such as during the Roman occupation. It is concluded that the mandible is more responsive to smaller dietary changes than demonstrated by previous research and the morphological variation associated with these major dietary transitions may not have been as simple or rapid as previously assumed.
Impact Statement

This research has provided further support for a relationship between mandible morphology and diet, supporting previous research which reported that significant changes in mandible morphology were associated with the Agricultural and Industrial Revolutions. This research has gone beyond previous research which has focussed on large scale dietary transitions to demonstrate the susceptibility of the mandible to reflect smaller dietary changes.

Additionally, this research may provide some support for the theory that arable agriculture was not readily adopted in Britain and that domesticated crops may not have formed a key part of dietary intake until the Bronze Age. Previously these theories were principally based on a lack of evidence in the archaeological record. However, this study provides support for a significant reduction in masticatory activity between the Neolithic and Bronze and Iron Age individuals. While not providing conclusive evidence, these results are consistent with a shift to a more cereal based diet and decrease in the relative consumption of animal protein and tougher wild plants.

Furthermore, by comparing 3D GMM with traditional linear measurements this research has demonstrated the relative superiority of 3D analysis for analysing shape changes in the mandible. Arguably this study indicates the need to re-evaluate existing research that has focussed exclusively on linear measurements.

With regards to promoting future research and preserving skeletal material, where possible the 3D scans produced during this project will be made available for future research. The nature of this accessibility will however vary depending on the requirements of the curating institutions. Copies of the 3D scans will be sent to all curating institutions which may be utilised for internal research or accessed by external researchers. Additionally, for the sites that consent to this, the availability and access requirements for these scans will be detailed online and in any future published research with this material.
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The earliest evidence of anatomically modern humans (AMH) in Britain can be dated to the around 43,000-42,000 BP, at the start of the Upper Palaeolithic (Higham et al. 2011, Pollard 2008, White et al. 2006). Despite the early occupation of Britain, it was not until the Neolithic around 6000-5300 BP when an increase in population growth is evident in the archaeological record (Woodbridge et al. 2014). Since the Neolithic there has been an extensive and detailed archaeological and historical record in Britain, which documents a number of significant socio-cultural, technological and environmental transitions (Colquhoun 2008, Drummond and Wilbraham 1957, Pitts 2008, Pollard 2008, Tattersall 1968). Previous, archaeological and historical research has also revealed several significant dietary changes occurring in Britain since the Neolithic. These dietary transitions are associated with a number of factors such as: the introduction of new technologies, flora and fauna; the movement of people including migrations and invasions; and behavioural changes such as religious, political and socio-cultural. For instance, the Roman invasion and occupation of Britain brought with it technological and cultural changes that significantly altered diet, as well as introducing new animals and plants (Chenery 2010, Cheung et al. 2012, Redfern 2010, van der Veen et al. 2013). Additionally, religious changes in Medieval Britain resulted in new dietary restrictions, reducing the consumption of meat, and increasing the reliance on fish (Müldner and Richards 2005). Moreover trade routes established during the 18th century allowed sugar to be imported in vast quantities and sold at a low price, leading to a boom in the consumption of sugar in Britain (Richardson 1987).

Reconstructing diet in bioarchaeology can take many different forms including the analysis of dental pathology (Esclassan et al. 2009, Mant and Roberts 2015, Wasterlain et al. 2009), nutritional deficiencies (Van der Merwe and Steyn 2010), as well as isotopic analysis from bones and teeth (Chenery 2010, Makarewicz and Sealy 2015, Müldner and Richards 2005, Le Huray and Schutkowski 2005, Redfern 2010). These methods typically focus on the nutritional components of food, for instance a high prevalence of carious lesions among an assemblage may indicate increased carbohydrate consumption (Hillson 1979, 2001, 2002), while
scurvy indicates a lack of dietary vitamin C (Waldron 2008). Another important element of diet is texture, which is influenced by both the raw components of food, as well as food processing techniques such as cooking and grinding. Food texture, including hardness, stickiness and moisture release influence human masticatory activity (Foster et al. 2006, Koe et al. 2013). Skeletal tissue is known to be sensitive to local mechanical strain, this mechanical strain contributes to the morphological variation recorded between and within species (Carter and Beaupre 2001). As such changes in masticatory activity are suggested to influence the morphology of the masticatory apparatus.

The morphology of the masticatory apparatus varies between species based on the relative functional demands of their diet. Craniofacial morphological variations however, are in no means limited to interspecies comparisons. Since the emergence of anatomically modern humans (AMH) significant changes to the shape and size of the human crania and mandible have occurred, with a trend towards a smaller more gracile form among modern populations (Balter 2005, Lahr 2010, Lahr et al. 1996, Stringer et al. 1984). In the Palaeolithic (2.6mya-10,000 BP), AMH crania were large and robust, with prominent supraorbital features and occipital tori, the mandible was deep and robust with large teeth, especially molars (Anderson 1968, Duarte et al. 1999, Schwartz and Tattersall 2002). By the Palaeolithic-Mesolithic transition both the crania and mandible were beginning to become more gracile, it was not until the post-Pleistocene period when major changes to the craniofacial morphology occurred (Borgognini and Repetto 1986, Bae et al. 2014, Lahr 1996, 2010a, Lahr et al. 1996, Sefcakova et al. 2011, Trinkaus 2005). These changes included a reduction in the size of the craniofacial complex, as well as increased gracilisation and cranial shortening (Bae et al. 2014, Lahr 1996, Trinkaus 2005, Ungar and Teaford 2002). Additionally tooth size, as well as the size and robusticity of the mandible decreased, with reductions most noticeable in the mandibular condyles and temporomandibular joint (Brace et al. 1987, Carlson and Van Gerven 1977, Lahr 1996, Larsen 2006). It is during this time that important population and cultural changes occurred. Human populations were moving and intermixing at a level not previously seen, and a global shift from a hunter-gatherer towards agriculturalist subsistence pattern occurred (Brace et al. 1987, Carlson and Van Gerven 1977, Larsen 2006, Lieberman et al. 2000). While several theories have
been proposed to explain these morphological changes, it is generally considered that changes in mandible morphology are at least partially the result of these dietary transitions (Brace 1964, Brace et al. 1987, Calcagno and Gibson 1988, Carlson and Van Gerven 1977, Lieberman 2008, Varrella 1990, y'Edynak 1989, y'Edynak and Fleisch 1983).

While genetic coding will produce the basic structure of bones, unless they are mechanically functional, and undergoing physical strain they will not fully develop (Fell 1956, Gillespie 1945, Howell 1917, Lanyon 1980, Lanyon et al. 1982, O'Connor and Lanyon 1982, Moore 1965, Washburn 1947). As muscles exert force on bone this results in bone remodelling, which acts to attain a shape which better withstands the mechanical forces exerted on them (Dorfl 1980a, 1980b, Tsai et al. 2009). Studies investigating this relationship have principally focussed on the long bones of the upper and lower limbs as they experience comparatively high levels of mechanical strains and strain cycles during everyday activities (Meakin et al. 2014). Conversely the crania and other bones whose principal function is protection of internal organs experience minimal mechanical strains, as such their morphology is less influenced by mechanical strain (Carter 1984, Stolk et al. 2001). Craniofacial skeletal morphology is therefore generally considered to be more influenced by genetic influences (Tircoveluri et al. 2013, Ueda et al. 1998). Genetic influences in craniofacial morphology have been extensively analysed however, these studies have argued that the mandible more greatly reflects mechanical strain as opposed to genetic influences (Cleaver 1937, Hrdlička 1940a, 1940b, Maki et al. 2000, Smith 2008, von Cramon-Taubadel 2011). The susceptibility of the mandible to muscular strain is in part the result of varying groups of muscles which attach to the mandible, originate at different points, have different functions and nerve supply (Dewey 1920, Scott 1957). The masticatory muscles are the strongest muscles in the skull, and are the primary muscles which impart mechanical strain upon the mandible (Rando et al. 2014). Dietary changes have been reported to result in alterations to masticatory activity and the strain these muscles place on the mandible, which have been demonstrated to induce bone remodelling and result in morphological changes to the mandible (Proffit and Fields 2000, Tsai et al. 2009).
As discussed within Britain there have been a number of dietary transitions, starting with the introduction of agriculture in the Neolithic which is associated with increases in dental pathology, reductions in skeletal growth and a general decline in nutrition, as well as the increased prevalence of several diseases (Blaser 2006, Eshed et al. 2005, Larsen 1995, 2006). Agricultural populations have also been associated with a softer diet, as many of the early domesticated plants were prepared by boiling to a soft sticky consistency (Larsen 1995, Powell 1985). Similarly, the Industrial Revolution in Britain is thought to have brought about widespread dietary changes resulting in a softer more processed diet, which is evident in mandible morphology (Rando et al. 2014). This trend towards a softer diet is continuing today. Studies have found that morphological changes in the mandible are present between Medieval and contemporary populations (Hanihara et al. 1981, Mohlin et al. 1978, Shiono et al. 1982, Yamada and Kimmel 1991). Furthermore, Martin and Danforth (2009) reported statistically significant morphological changes in the mandible over the last century, among populations from the USA. It has been suggested that such differences are the result of increased food processing techniques, resulting in a softer diet (Yamada and Kimmel 1991, Waugh 1937, Wood 1971, Inoue 1980, Shiono et al. 1982, Corruncini and Lee 1984).

The majority of these previous studies however, have focussed on comparisons between two periods or groups which are associated with significant dietary transitions. As such the potential for fluctuating changes in mandible morphology occurring over long periods of time have not been fully investigated. Moore et al. (1968) and Lavelle (1972) did investigate changes in mandible size and shape among several periods in Britain. The results from this study determined a reduction in mandibular size occur over time with more statistically significant changes occurring among later periods (Moore et al. 1968). However, these studies relied on linear measurements which have been argued to be insufficient in analysing mandible morphlogy (Humphrey et al. 1999). Since these studies technological and statistical advances allowing the capture and analysis of 3D data have greatly advanced the field of geometric morphometrics (GMM). A longitudinal 3D GMM analysis will arguably provide a greater understanding of how human mandible morphology has changed in Britain over time which was not possible in these previous studies.
This thesis aims to investigate how dietary changes in Britain between the Neolithic and Post-Medieval period have influenced mandible morphology. While previous studies have demonstrated that morphological changes have occurred in response to large dietary transitions, this study differs from these by both the implementation of 3D geometric morphometric analysis, and in the analysis of multiple time periods. This thesis is organised as follows: Chapter 2 discusses the methods employed in bioarchaeology for the reconstruction of diet based on skeletal and dental analysis of human remains, followed by a discussion of the dietary and cultural changes that have occurred in Britain since the Neolithic, incorporating archaeological and historical evidence. Chapter 3 will discuss anatomically modern human craniofacial evolution and the key theories that have been proposed to account for the gracilisation and reduction of the modern human crania, mandible and dentition. This will then lead into a review of the bone remodelling process and the relationship between bone remodelling and physical stimuli, as well as other factors which may influence bone remodelling. Chapter 4 will detail human mandibular morphology including the muscles of mastication. This chapter will also cover the animal, clinical and archaeological evidence for a relationship between diet, mastication and mandible morphology, as well as other extraneous factors which have been found to influence mandible morphology. Chapter 5 details the material and methods which were utilised to address these questions. The results are provided in Chapter 6 and discussed in relation to the literature review in Chapter 7. Finally, this thesis will conclude with a summary of the overall results and discussion in Chapter 8.

1.1 Research questions
Within archaeology major dietary changes in Britain over time are associated with corresponding changes in mandible morphology. The impact of dietary changes on mandible morphology over time in Britain, however, has not been fully investigated; at least not since significant methodological improvements have occurred. Instead the majority of previous studies have focused on specific large-scale dietary transitions. It is not known therefore how susceptible the mandible is to smaller dietary changes. Archaeological assemblages in Britain shall be used for this research due to the vast amount of historical literature and
previous archaeological studies which detail life and dietary changes in Britain over time. Furthermore, the early invasions by Romans and Anglo-Saxons provides examples of documented dietary changes beyond the frequently analysed Agricultural and Industrial Revolution. The primary aim of this research is to investigate how changes in diet is reflected in dental and skeletal tissue beyond the major dietary transitions, additionally there are further research questions outlined below outlined below.

1.1.1 How has mandible morphology changed over time in Britain?
Variation in mandible morphology will be analysed among time periods in Britain and compared to historical reports and archaeological evidence of diet and food processing behaviours, as well as dental pathology among the present sample and previously published studies. Previous studies have found significant morphological changes in the mandible occurring after large dietary transitions, such as the agricultural and industrial revolution. It is hypothesised therefore that the most significant changes in mandible morphology will occur during the Industrial Revolution, when there is a well documented change to a softer more processed diet, resulting in a decreased in masticatory forces. Smaller changes to mandible morphology are also expected to occur in other periods which are expected to correspond with lesser dietary and cultural changes, such as those that occurred during and after the Roman invasion.

1.1.2. Has sexual variation in the mandible changed over time in Britain?
The mandible is known to be sexually dimorphic and is utilised in several sex estimation methods. However, the degree of sexual dimorphism has been shown to vary between assemblages and over time. Research has shown that the rights and role of women in Britain has changed over time and as such diet has varied between males and females. It is therefore hypothesised that the degree of sexual dimorphism will vary between periods.

1.1.3. Does mandible morphology vary in relation to social status?
Socioeconomic status is known to differ among the Priory and Cemetery assemblage at the Medieval site of St Gregory’s in Canterbury (Hicks and Hicks 2001, Miszkiewicz 2015, Miszkiewicz and Mahoney 2016). Historical data indicates that low status individuals in Medieval Britain would have typically
consumed soft diets, low in animal protein and primarily consisting of carbohydrates in the form of pottage and bread. The diet of high social status individuals appears to have been more susceptible to changes over time, but would have typically included higher levels of animal protein and foods sweetened with honey and in later periods sugar. It is hypothesised therefore that mandible morphology among low social status individuals will reflect a soft diet with low levels of masticatory stress and exhibit less morphological variation over time, compared to higher social status assemblages.

1.1.4. What is the relationship between dental wear and mandible morphology in British assemblages? And are these changes consistent with previously published studies?
Dental attrition is more frequently associated with diets which contain large amounts of grit, typically introduced during food processing methods. It is not however known the extent at which dental attrition relates to mandible morphology.

1.1.5. How does the level of variation in mandible morphology over time in Britain compare with global geographic variation in mandible morphology?
Previous studies have reported that mandible morphology is more greatly influenced by environmental factors rather than genetics, however other research has suggested some genetic influence on mandible morphology. As a number of migrations and invasions have occurred in Britain during the time frame of this study it is necessary to investigate how population history may influence mandible morphology. It is hypothesised that variation in Britain over time will exceed geographic variation in mandible morphology.
2.1 Diet and Culture

Aspects of food, cooking and eating have long been studied in the field of archaeology, and the importance of these studies stretch far beyond understanding the value of food as a nutritional requirement for survival. It has been stated that: “next to breathing, eating is perhaps the most essential of all human activities, and one with which much of social life is entwined (Mintz and Du Bois 2002, 102). In both archaeological and anthropological studies, diet has been found to relate to external factors, beyond simply the relative availability of food items or nutritional requirements (Dietler and Hayden 2010, Scott 2008). Anthropological studies have consistently demonstrated the value of food in larger socio-cultural processes, foods can convey a range of cultural meanings and are dependent on their socio-cultural context (Mintz and Du Bois 2002, Murcott 1982). For example, “a mouthful of wine will convey very different meanings to the professional wine taster, the bon viveur, the Christian celebrating Holy Communion and the alcoholic down-and-out” (Atkinson 1980, 79).

Throughout time and across cultures, food has played a part in people’s identity whether in the types of food they eat, the meaning behind food, or how meals are made prepared or served (Fischler 1988, Mintz and Du Bois 2002, Narayan 1995). As a social and cultural activity, food and cooking is argued to serve both to “solidify group membership and to set groups apart” (Mintz and Du Bois 2002, 109). Food choice, processing and consumption patterns therefore vary between populations, within populations and over time, forming an important component of social behaviour and the creation and maintenance of social relationships (Kuhnlein and Receveur 1996, Mintz and Du Bois 2002). Within groups, age, sex, and social status have all been shown to influence the presence and quantity of certain food items in diet (Le Huray and Schutkowski 2005) and the identification of dietary differences within groups in archaeology has allowed for a greater understanding of social, cultural and economic differences (Crabtree 1990, Pilcher 2017, Smith 2010, White 2005). For instance, analysis of
the zooarchaeological record in Kahikinui, Maui, Hawaii revealed differential access to fatty greasy ‘luxury’ foods among elite households while consumption of the Polynesian rat (Rattus exulandii) is evident among commoner households (Kirch and O’Day 2003). Furthermore isotopic analysis of males and females from a late/sub Roman site in Britain at Queensford farm, Oxfordshire, revealed nitrogen isotope levels differed between males and females indicating that females had less animal/fish protein in their diet (Fuller et al. 2006).

Dietary differences can be shaped by history, culture, religion, or environment, therefore the analysis of dietary differences between groups can be used to trace movement of cultures (Buhay et al. 2013, Hakenbeck et al. 2010, Knudson et al. 2012, Meiggs and Freiwald 2014, Warde 1997), as well as the many factors associated with changes in food related behaviours including political or religious changes, trade, migration, and technological advancements (Kosiba et al. 2007, Reitsema et al. 2010, Valentin et al. 2014, Van Gerven et al. 1995, Warde 1997). For instance the introduction of Christianity to Britain led to many dietary restrictions on the consumption of animal protein, which resulted in fish protein being increasingly relied upon (Adamson 2004). Dietary changes can also stimulate cultural changes. Increased food production associated with the advent of agriculture led to sedentarism, technological developments and increasingly stratified societies (Ahmed 2014, de Saulieu and Testart 2015, Diamond 2002). Storable food surpluses brought about by agriculture could be used to feed full-time craftspeople, inventors, kings, bureaucrats, nobles and soldiers. These food surpluses therefore led to social stratification, political centralisation and standing armies (Diamond 2002). Because food and eating have strong cultural connections, what is considered edible varies individually or depending on preparation as well as how, when and where the food was consumed. Therefore, understanding diet at an individual and group level among past populations can reveal important clues regarding the influence of culture (Eriksson and Lidén 2013). Dietary behaviour reflecting larger social, political and cultural factors, can be more easily understood in more recent British history, however within the archaeological record this relationship is still being deciphered.

As dietary behaviour extends far beyond the breakdown of food items consumed within an individual’s lifetime it is necessary to extend the scope of study in order to more fully understand these dietary changes and the factors
which may have influenced them. When reconstructing dietary changes, within the archaeological record there has been a tendency for research to focus on the large transitions such as the Agricultural and Industrial Revolutions. While this research has proved very valuable, and significant differences have been found regarding dental pathology, dental wear and mandible morphology associated with these large dietary transitions (Bosman 2016, Eshed et al. 2005, Larsen 1995, Mant and Roberts 2015, Rando et al. 2014, Tayles et al. 2000), smaller dietary or cultural changes which may well have significantly impacted dietary behaviour have so far have been largely overlooked.
2.2 Reconstructing Diet in Archaeology

Reconstructing subsistence patterns has long been a part of archaeological research with elements of subsistence behaviours reconstructed from material finds such as food processing equipment, botanical remains or zooarchaeological evidence (Crabtree 1990, Spataro and Villing 2015). Evidence for subsistence however does not directly provide evidence for diet among past populations. While material, archaeobotanical and zooarchaeological evidence associated with human archaeological sites may indicate dietary behaviours such remains may instead provide evidence for other subsistence behaviours. For instance archaeobotanical remains may represent human consumption or animal fodder, similarly zooarchaeological evidence may indicate consumption but also the use of other animal by-products such as wool, or use for labour, while the function of material remains may be also misinterpreted. Therefore, the interpretation of this evidence is limited, particularly when investigating within group and individual differences. As such, evidence from the analysis of dental and skeletal remains is frequently used to infer diet among past populations. As the dentition is the only tissue which is preserved in the archaeological record that comes in to direct contact with the dietary environment the analysis of dental wear\(^1\) and pathology – principally dental caries which is discussed in section 2.2.1 - can be used to infer subsistence behaviours, and other features of human lifestyle (Alt et al. 1998, Hillson 1979, Powell 1985).

This section will briefly describe some of the most frequently employed methods for inferring diet from skeletal and dental tissue discussing the information that may be gained from these analyses as well as the limitations of these methods. These approaches will then be incorporated into the subsequent sections of Chapter 2, to complement the material record and historical reports in detailing the large cultural and dietary changes in Britain since the Neolithic.

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\(^{1}\) Dental wear is created via tooth on tooth contact during normal masticatory movement, as well as para-masticatory behaviours high degree of dental wear is associated with diets high in grit or other abrasive materials (Alt et al. 1998).
2.2.1 Dental Caries

A dental caries is identified as a “destruction of enamel, dentine and cement resulting from acid production by bacteria in dental plaque” (Hillson 2002, 255). The prevalence of carious lesions has long been associated with diets high in carbohydrates and sugars (Burt et al. 2006, Ortner and Putschar 1981, Touger-Decker and van Loveren 2003). Carbohydrates and sugars decrease the pH of the oral environment when metabolised by bacteria within the oral cavity, and this pH decrease results in demineralisation of the enamel, forming a carious lesion (Burne and Marquis 2000, Gagnon et al. 2013, Hillson 2002, Lingstrom et al. 2000, van Houte 1994). In addition to the consumption of carbohydrates, the prevalence of carious lesions is influenced by oral hygiene, food texture and frequency of eating, or intervals between eating (Green and Hartles 1966, Gustafsson et al. 2009, Johansson et al. 2010, Quensel et al. 2009, Touger-Decker and van Loveren 2003). Among pre-agricultural assemblages, the prevalence of carious lesions has been very low, although not unknown (Karsten et al. 2015). However, with the introduction of agriculture and cultivated cereal crops, the proportion of carbohydrates in the diet increased and so did the prevalence of carious lesions, a trend which has been recorded globally (Larsen 1995, Lukacs 1992, Tayles et al. 2000, Temple and Larsen 2007).

2.2.2 Stable Isotope Analysis

Carbon and nitrogen isotopes isolated from dentine or bone collagen have been used to infer diet across the archaeological record (Katzenberg and Waters-Rist 2018). Carbon stable isotopes are used to distinguish between the consumption of C3 and C4 plants (Makarewicz and Sealy 2015, Richards et al. 2003, van der Merwe 1982). C3 plants are adapted to cold and wet environments and comprise approximately 85% of all plant species, while C4 plants tend to thrive in hot and dry conditions and the few edible species include maize and sugar cane. In North America this has been used to track agriculture, specifically maize consumption (Makarewicz and Sealy 2015, Vogel and Van Der Merwe 1977). However in Europe there are very few C4 plants, so this isotope is used to distinguish terrestrial foods from marine foods such as fish and shellfish (Ehleringer 2017).
Nitrogen isotopes are used to distinguish protein sources, as nitrogen isotopes increase through the trophic system. This is particularly useful for investigating weaning practices and the consumption of terrestrial or marine proteins (Ambrose 1991, Hedges and Reynard 2007, Richards et al. 2002). The majority of terrestrial animals consumed by human are herbivores and therefore have a low $^{15}$N ratio. Conversely marine animals are typically higher in the trophic system and therefore have a higher $^{15}$N ratio (Holder et al. 2017, McMahon et al. 2015). Moreover, breast fed children have a higher $^{15}$N than weaned children because they are acquiring their protein from humans this is illustrated in figure 2.2.1 (Schurr 2018, Tsutaya and Yoneda 2014). While the potential value of isotopic analysis makes this a useful method in reconstructing diet in archaeology there are also a number of limitations, such as the potential to overestimate the contribution of animal protein when plotting Nitrogen and Carbon isotopes and the inability for isotope analysis to distinguish between meat and dairy consumption (Makarewicz and Sealy 2015, O’Connell 2018). Isotope analysis is also limited to reconstructing the relative proportion of these components in diet, and does not reveal food processing behaviours (Makarewicz and Sealy 2015).
Figure 2.2.1 Trophic level diagram. Diagram detailing the Nitrogen 15 ($^{15}\text{N}$) levels among different species and humans, arrows indicate an increase in Nitrogen-15 with the highest levels at the top. The chain on the left shows a marine diet which results in a higher $^{15}\text{N}$ ratio compared to the terrestrial diet on the right. Breast feeding infants who have a higher $^{15}\text{N}$ ratio compared to adult humans are shown at the top level for both chains for both sides.
2.2.3 Skeletal pathology

Pathological conditions that have been used to infer aspects of diet can be divided into dietary deficiency diseases, and diseases which may result from an excess of certain dietary components. Disease caused by a deficiency in dietary components which are evidenced on skeletal remains include scurvy, rickets and osteomalacia. Scurvy is caused by a deficiency in vitamin C which is present in fruits and vegetables. High prevalence of scurvy among archaeological assemblages indicates a lack of fresh fruits and vegetables that may occur during times of famine or long sea voyages (Mays 2014, Van der Merwe and Steyn 2010). However the skeletal manifestations of scurvy are difficult to identify and scurvy is considered to be underrepresented in the skeletal collection (Armelagos et al. 2014, Waldron 2008). Rickets and osteomalacia are the pathological responses to vitamin D deficiency in children and adults respectively. Vitamin D can be acquired from the diet but is also influenced by exposure to sunlight (Hardy 1992, Mays and Brickley 2018, Waldron 2008). Diseases associated with diets of excess that may be evident in the skeleton include gout and DISH (Diffuse Idiopathic Skeletal Hyperostosis) with both of these diseases being associated with ‘rich’ diets high in red meat and alcohol (Fuller et al. 2006, Holgate and Steyn 2016, Kuo et al. 2015, Quintelier et al. 2013, Tritsaroli 2018, Waldron 2008). A high prevalence of DISH has been recorded among monastic assemblages and high-status individuals (Giuffra et al. 2010, Reale et al. 1999, Rogers and Waldron 2001, Jankauskas 2003, Mader et al. 2013, Pillai and Littlejohn 2014, Verlaan et al. 2007). However, both conditions differentially affect men and are influenced by numerous other factors, limiting their ability to reconstruct diet amongst past populations (Fornaciari et al. 2018, Holgate and Steyn 2016, Kuo et al. 2015).
2.3 Britain Since the Neolithic

In order to investigate how mandible morphology may have been influenced by diet in Britain it is necessary to first discuss the known dietary changes that have occurred between the Neolithic and Post-Medieval periods. This is particularly necessary as previous studies have focussed primarily on the major dietary transitions, whereas this study focusses on understanding the potential morphological responses to minor dietary changes. Therefore, a more detailed understanding of British dietary history is required. Moreover, as discussed in section 2.1 diet is influenced by a number of socio-cultural factors beyond the environment. Therefore, in addition to the historical and archaeological evidence for diet this section will also discuss the evidence for socio-cultural and technological changes that may have influenced people’s relationship with food.

2.3.1 Before the Neolithic: Coasts and Islands

There is evidence for anatomically modern humans (AMH) inhabiting Britain since 36.4-34.7 kya, based on skeletal remains excavated from Kents Cavern, Touguay (Higham et al. 2011). While these remains are only fragmentary other archaeological sites have yielded more complete skeletal remains of AMH dated to the Upper Palaeolithic (38,000 - 10,000 BP) (Soressi and Dibble 2003, Tolan-Smith 2008). Of the earliest human skeletal remains in Britain, two of the most researched sites are Paviland Cave, South Wales (dating to c. 30,000 BP) and Gough’s Cave, Somerset (Aldhouse-Green and Pettitt 1998, Harrold, 1980). Excavations of Gough’s Cave, dated to the late Upper Palaeolithic, having yielded more artefacts than any other British Palaeolithic cave site, including the discovery of the skeletal remains of a young adult male nicknamed ‘Cheddar man’ in 1903 CE (Jacobi and Higham 2009). However, with the exception of these few notable sites there is relatively little archaeological evidence of humans in Britain prior to the Neolithic after which the number of archaeological sites (especially those with human remains) increases substantially.

Before considering Neolithic Britain, it is first necessary to briefly discuss evidence of humans from the Mesolithic. The Mesolithic period in Britain, generally spans from 9,500 - 3,800 BCE and during this time people in Britain are thought to have lived in small hunter-gatherer populations (Bailey and
Due to differential preservation, material culture during the Mesolithic is generally comprised of worked stone including flint, chert and quartz (Cooper et al. 2017). Based on comparisons with stone tools from mainland Europe it is suggested that there was little contact between these areas (Cummings 2017). In addition to stone tools, there have been a number of worked antler and bone finds thought to have been used for working on leather and hides (Cummings 2017, Little et al. 2017). There is also evidence of the exploitation of marine and coastal environments including consumption of the larger marine mammals, numerous fish, crustacean and mollusc species. For instance, at the Mesolithic site of Meiklewood near Stirling, Scotland, the remains of a Rorqual whale were excavated (Clark 1947, Smith et al. 2010), while a Mesolithic site in Argyll revealed the remains of a grey and spotted seal (Clark 1946, Smith et al. 2010). Furthermore, at Mesolithic middens in Oronsay and Fife there is evidence of fishing from boats with the remains of cod, crabs, lobsters, sea bream, conger eel, haddock, salmon, skate and shark (Milner et al. 2004, Renfrew 1985). Therefore at coastal sites during the Mesolithic it is generally considered that diet was dominated by marine foods, based on both the zooarchaeological record as well as stable isotope analysis of human remains (Cummings 2017, Richards et al. 2003, Schulting and Richards 2002). Inland, however, there is evidence of hunting for large game that roamed wild during this period (Renfrew 1985) with the Mesolithic site at Star Carr, Yorkshire, revealing skeletal remains of large game including red deer, roe deer, elk, wild oxen and wild pig (Clark 1954, Renfrew 1985).

The available archaeological evidence indicates that Mesolithic populations in Britain were generally drawn towards coastal environments and small islands, whether this is due to the resources available or as a defensive strategy is still debated (Cummings 2017, Milner et al. 2004, Momber 2000). Rises in sea level since the Mesolithic combined with a relatively high proportion of coastal sites further limits the availability of archaeological evidence (Cummings 2017, Momber 2000). Due to poor preservation there is very limited information available concerning the behaviour and activities of Mesolithic people in Britain, beyond large game hunting and exploitation of coastal environments. However, this all changed after the introduction of domesticated plants and animals into
Britain during the Neolithic, as populations expanded and the landscape was changed through deforestation (Brown 2002, Woodbridge et al. 2014).

2.3.2 Neolithic Britain: Domestication, Deforestation and Pottery

The term ‘Neolithic’ was first coined in the 19th century and referred to a particular way of making stone tools, however this term was later extended to refer to the domestication of plants and animals (Çilingiroğlu 2005). The Neolithic period in Britain (4000 – 2500 BCE) now encompasses prehistory from the beginning of farming until the introduction of metal working. Typically, the Neolithic period in Britain is associated with a ‘package’ of innovations which includes domesticated plants and animals, monuments, new stone tools and pottery (Çilingiroğlu 2005, Cummings 2017, Thomas 1988). It is thought that the introduction of the ‘Neolithic package’ was staggered in Britain. First established in South East England around 4000 BCE after being introduced from mainland Europe, it is thought to have taken a further one hundred years before this spread beyond South West England and by 3800 BCE this ‘package’ is thought to have spread around Britain (Cummings 2017, Whittle 2002).

Table 2.3.1: Neolithic Britain. The time range for the Early and Late Neolithic period in Britain (Pollard 2008)

<table>
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<tr>
<th>Neolithic Britain</th>
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<tr>
<td>Early Neolithic (4000 BCE- 2900 BCE)</td>
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<td>Late Neolithic (3000 BC- 2500 BCE)</td>
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The introduction of domesticated animals from mainland Europe alongside domesticated wheat, flax and barley led to significant dietary changes. These new domesticated animals and plants brought many advantages not provided by their wild counterparts, such as the nutrients and calories provided by the regular milk and meat obtained from domesticated animals, while domesticated crops provided a source of carbohydrates which allowed the production of bread, porridge and beer (Copley et al. 2003, Dineley and Dineley 2000, Fairbairn 2000b, Richards 2000). The increased availability and control of food is generally considered to have freed up people’s time, allowing for the development of an increasingly complex material culture, tools and settlements so that by the end
of the Neolithic considerable cultural, economic and technological regional diversity had evolved in Britain (Brown 2002, Thomas 1988). Additionally technological advancements including pottery are present in the material culture and are thought to have also led to dietary and behavioural changes (Scheinfeldt and Tishkoff 2013), as well as rapid population growth (Stevens and Fuller 2012). This section will discuss the dietary and cultural environment of Neolithic Britain, which will be divided into flora, fauna, material cultural and settlements.

2.3.2.1 Flora
The advent and development of agricultural practices during the Neolithic resulted in a number of alterations to the environment which is reflected in changes in flora and fauna recorded in the archaeological record (Brown 2002, McClatchie et al. 2014, Tresset 2015). The earliest cultivation of cereals in Britain is dated to around 4000 BCE (Bishop 2015, Brown 2007, Stevens and Fuller 2012). The three main crops introduced during this period were wheat, barley and flax, with wheat and barley appearing to be the main cultigens (Dennell 1976, Welmoed 2008). While the presence of cereal impressions in pottery, querns and ards from Neolithic sites provide evidence of cereal cultivation (Bishop 2015, Brown 2007, Cummings 2017, Fairbairn 2000a, Richards 2000, Stevens and Fuller 2012), cereal remains are largely underrepresented, with crop waste in general including chaff, weed seeds and grains scarce in the archaeological record (Stevens and Fuller 2012). It has been argued that the underrepresentation of cereal crops may be related to the transient nature of Neolithic settlements or the storing of fully processed cereals (Bishop 2015, Stevens and Fuller 2012). Unfortunately, because cereal grains are poorly preserved there is little evidence to determine what proportion of diet was comprised of domesticated crops (Stevens and Fuller 2012). However, as carbonised cereal deposits are low compared to wild botanical remains, it has been suggested that while cultivated crops arrived in Britain during the Neolithic this agriculture was not readily adopted and wild plants still formed an important part of diet (Richards 2002, Whittle 2000). This is further supported by the low prevalence of carious lesions – which is associated with the introduction of agriculture and high carbohydrate diets (Da-Gloria et al. 2017, Karsten et al. 2015, Munoz 2017) - among individuals from the British Neolithic (Lunt 1974, Tattersall 1968).
2.3.2.2 Fauna

In contrast to cereal cultivation the introduction of domesticated animals around 3,500 BCE soon led to the establishment of herds of domestic sheep, goats, cattle and pigs. (Renfrew 1985). Zooarchaeological records suggests these domesticates were widely adopted as they dominate the faunal assemblage comprising between 90-95% of zooarchaeological remains (Cummings 2017, Cummings and Harris 2011, Thomas 1988, Thomas and McFaydyen 2010). This is supported by isotope analysis of human bone collagen which recorded low values of $\delta^{15}$N, interpreted as a diet rich in terrestrial animal proteins (Richards and Hedges 1999, Schulting and Richards 2002). Isotope analysis from human bone collagen also indicates that marine resources were rapidly abandoned in Europe, including in Britain, during the Mesolithic-Neolithic transition (Milner et al. 2004). For example, isotope analysis of human bone collagen from 164 Early Neolithic and 19 Mesolithic individuals from a range of contexts revealed that Neolithic individuals showed a strongly terrestrial isotope signature while Mesolithic individuals had only a moderate-strong marine isotope signal (Bogaard et al. 2007, Milner et al. 2004, Richards et al. 2003, Schulting and Richards 2002).

During the Early Neolithic, cattle were the most abundant/important domestic species in Britain (Brown 2002, Copley et al. 2003, Viner et al. 2010). A large number of young cattle have been excavated from sites in southern Britain; these show evidence of cut marks, with some bones split open for marrow (Renfrew 1985, Serjeantson 2006). While domesticated animals were evidently used for their meat, sheep, goats and cattle also produced milk which was widely used, with 50-60% of ceramic vessels containing traces of dairy lipids (Copley et al. 2003, 2005a, 2005b, Cummings 2017). In addition to meat and milk, there is evidence that domesticated cattle were also used to plough fields, pull carts and move large objects (Cummings 2017).

It is generally considered that wild animals only played a minor role in the diets of the people of Neolithic Britain, as they only comprise 5% of faunal assemblages (Cummings 2017, Cummings and Harris 2011, Schulting and Richards 2002). Despite this, there is archaeological evidence that hunting still played a role in food acquisition. Roe, fallow and red deer were hunted all over Britain, and are found at a high proportion at some Neolithic sites (Baker et al. 2000).
2017, Brownes 2018, Cummings and Harris 2011, 2014, Parmenter et al. 2015. Additionally, the remains of wild horses, boar, brown bear and beaver have all been identified among Neolithic sites (Renfrew 1985). Red deer were seemingly the most frequently and widely hunted fauna in Britain with evidence of skeletal remains excavated from human sites from Dorset to Orkney (Milner et al. 2004, Thomas 2004, Ward 2005). In addition to providing large amounts of protein, deer antlers were used to create a wide range of tools (Cummings 2017, Ray and Thomas 2018, Renfrew 1985). Several species of large game disappeared from Britain during the Neolithic and Early Bronze Age including elk and wild oxen (Clutton-Brock 1989, Cotton 2006, Evans 2015, O'Regan 2018, Renfrew 1985, Serjeantson 2011). These extinctions may be related to human behaviour either through hunting or the deforestation that occurred across Britain during this time (Cummings and Harris 2014).

While isotopic evidence indicates that there was a general decline in the relative proportion of marine protein consumed during the Neolithic, coastal sites reveal large shell middens similar to those from the Mesolithic. At these sites the most common species were oysters limpets, winkles and mussels (Milner et al. 2004, Renfrew 1985). There have been a few examples of Neolithic sites with substantial oyster mounds such as River Forth estuary (5000-3000 BCE) and along the west and north coast of Ireland (Milner et al. 2004). There is also evidence of consumption of sea urchins at Northton Harris (Renfrew 1985) during the later Neolithic/Early Bronze Age. In addition to marine protein, sea birds are also thought to have been an important food source (Serjeantson 2011, Serjeantson and Field 2006). At Morton, Fife, the remains of guillemots and other sea birds are thought to be evidence of human consumption of sea birds (Renfrew 1985). While at Skara Brae and Rousay in Orkney there is evidence of gannets, eider ducks, pink-footed geese and swans thought to have been used as both a food source and for their feathers (Dockrill and Bond 2009, Renfrew 1985).
2.3.2.3 Material Culture

As with the Mesolithic, lithic tools still dominate the material culture excavated from Neolithic sites although variation in form suggest use of these tools is considerably different (Cummings 2017, Miles 2016, Pitts and Jacobi 1979). These stone tools included sickles, scrapers, borers and arrow heads. Another stone tool which characterises early Neolithic Britain is the stone axe and while some stone axes were thought to have been used for wood cutting or other practical purposes, others were smooth and highly polished until they shined and bear no evidence of a functional use (Cummings 2017, Harding 2010, Walker 2015). These highly polished axes may have been used for ritual or ornamental use (Norton 2016, Walker 2015). Some of the variation in stone axes excavated from Neolithic sites are illustrated in figure 2.3.1. In addition to stone tools there is also a greater number of organic material culture items compared to earlier periods although this is still comparatively sparse due to the preservation of organic material. Excavated material includes a wooden bowl, a wooden stirrer, bows, a wooden club, a mat and boxes made of birch bark, and woven reed baskets (Cummings 2017, Gibson et al. 2017, Hart et al. 2015, Ray and Thomas 2018).

![Figure 2.3.1: Neolithic stone tools in Britain. This illustrates some of the variation in form of stone tools (scale 1 cm) that have been excavated from Neolithic sites in Britain courtesy of the Portable Antiquities Scheme, images taken from: https://finds.org.uk.](https://finds.org.uk)
While there is limited evidence of cooking and food preparation from Neolithic Britain, some inferences can be made regarding food preparation based on the material available. Grain-rubbers and querns – in the form of saddle querns, used for the grinding of wheat, were common during the Neolithic (Curwen 1937). Saddle querns (illustrated in figure 2.3.2) remain the predominant type of quern until the Iron Age when they were replaced with the more efficient rotary querns (Renfrew 1985). The presence of grinding stones somewhat contrasts with the archaeobotanical evidence which does not strongly support a reliance on cereals.

In addition to stone tools, pottery first appears during this period and was also used for the preparation and consumption of food. This early pottery first appeared as round bottomed undecorated bowls, but by the late Neolithic grooved wear pottery was predominant (Mukherjee et al. 2007, Peacock 1969, Renfrew 1985). Evidence of charring and spalling on Neolithic pottery indicates its use in cooking placed on or above the fire. The analysis of charred residues on the inside of Neolithic pottery further indicates it was used for the cooking of animal products as well as heating milk (Copley et al. 2005b, Copley et al. 2003, Copley et al. 2005a, Cummings 2017). In addition to cooking, pottery was used for food storage as well as in salting, drying and smoking (Cummings 2017, Renfrew 1985). The Neolithic sites of Rinyo and Links of Notland in Orkney also revealed small ovens near the hearths in houses (Childe 1949, Rathbone 2013). However, the general lack of evidence for ovens at other sites suggests that ovens were not frequently used until the Late Iron Age (LIA) (Renfrew 1985).

Figure 2.3.2: Saddle Quern. An example of a Neolithic saddle quern (scale 1cm), this quern is from Norway and is on display at the Archaeological Museum, University of Stavanger. The base is 660 mm in length and 320mm in breadth. Image taken from: https://per-storemyr.net/2015/12/13/beautiful-neolithic-and-iron-age-querns-from-norway-on-the-history-of-grinding-grain/
2.3.2.4 Settlements and Monuments

The introduction of agriculture allowed for the development of larger communities, which in turn brought about new settlements forms (Fairweather and Ralston 1993, Thomas 1988) and an increased variation in types of settlement, including large timber halls (Brophy 2007, Cummings 2017, Fairweather and Ralston 1993, Thomas 1988). These settlements predominantly consisted of a small number of short-lived, often seasonal buildings. In the later Neolithic (specifically in the Orkney islands) there is also evidence for a number of stone-built villages, although these were not a common occurrence. The most famous of which is Skara Brae as illustrated in figure 2.3.3 (Castleden 2002, Cummings 2017, Simpson et al. 2006). During the early Neolithic the majority of settlements were located in areas where light soil would have reduced the workload required for development of farmland. However, in the later Neolithic, agricultural settlements expanded and there was little distinction between regions. This may indicate developments in agricultural practices and community size as the expansion into regions would have required more intensive management of the land (Cummings 2017, Cummings and Harris 2014, Gearey et al. 2000).

Figure 2.3.3: Skara Brae, Orkney. Photograph of Skara Brae located on mainland Orkney (Hirst 2019).
The final part of the 'Neolithic package' are lithic monuments which have been found all over Britain. As with settlements monuments varied considerably in form and material and included: stone circles, timber circles, pit circles, henges and multi-monument complexes (Cummings 2017, Richards 1996). Many of these monuments still stand today and dominate the landscape such as the Ness of Brodgar, in Orkney, illustrated in figure 2.3.4 (Richards 1993). There has been considerable discussion, with little consensus, regarding the significance of these monuments. It has generally been considered that these were sites where people came together, and although the specific purpose for the sites is debated, it is likely that an exchange of goods, culture and technology took place therein (Cummings 2017).

Figure 2.3.4: Ness of Brogda, Orkney. Photograph showing the standing stones at Ness of Brodgar, Orkney (Hirst 2019).

Timber trackways are another new feature of the Neolithic landscape the most well-known being ‘Sweet Track’ dated to between 3807-3806 BCE with evidence that it was repaired twice, in 3804 and 3800 BCE (Berstan et al. 2008, Cummings 2017, Hillam et al. 1990). These trackways were used for travelling across
marshland and a number of different construction techniques were utilised. Timber trackways may indicate increased communication and trade between Neolithic settlements (Coles et al. 1973, Cummins 2017, Hillam et al. 1990) a theory that is supported by the large number and varied material finds recovered along trackways (Coles et al. 1973, Cummins 2017, Whittle 2002, Whittle et al. 2011). Analysis of lithic tools from Neolithic sites further supports the existence of trade networks and some tools such as the Langdale Axe, which were manufactured from rock in the Lake District, have been found all over Britain and Ireland (Cummins 2017, Walker 2015).

2.3.2.5 Changes that occurred in the Late Neolithic
Among the majority of Neolithic sites, cattle bones dominate the faunal assemblage although among later Neolithic sites, associated with groove wear pottery, there is a higher proportion of porcine remains (Albarella and Serjeantson 2002, Craig et al. 2015, Cummins 2017, Serjeantson 2006). For instance, at the site of Durrington Walls, Wiltshire, dated to 2800-2400 BCE, 8500 faunal specimens were excavated, the majority of which were identified as domestic cattle and pigs (Albarella and Payne 2005). An analysis of lipids from 222 grooved-ware sherds by Mukherjee et al. (2008) revealed animals fats, as well as some plants and beeswax. The majority of these animals fats were of ruminant or porcine origins. It is thought the late Neolithic woodland regeneration led to pigs replacing cattle as the preferred domesticate (Mukherjee et al. 2008). There is also evidence from the late Neolithic that meat was roasted on the bone (Albarella and Serjeantson 2002, Cummins 2017). However, the majority of faunal assemblages from this period come from large monumental sites and as such may not represent everyday dietary behaviour. While there continues to be a general lack of cereal remains (Cummins 2017) there is evidence of increased reliance on wild plants such as hazelnuts (Corylus avellana) and sloe stones (Prunus spinosa). There is also no apparent change in the relative proportion of domesticated to wild animal species consumed, with domestic species still comprising an overwhelming proportion of the faunal assemblage (Cummins 2017, McClatchie et al. 2014, 2016).
2.3.2.6 Bioarchaeological Evidence from the Neolithic

Unfortunately due to poor preservation there have been relatively few studies of diet among Neolithic individuals in Britain. The majority of the studies available have focused on stable isotope analysis (Richards and Hedges 1999, Richards et al. 2003). These studies report a general shift away from the consumption of marine protein. For instance, an analysis of carbon stable isotopes from 78 individuals, representing 27 coastal and inland sites in England and Wales revealed that all Neolithic individuals analysed had a $\delta^{13}$C close to -20% indicating little or no consumption of marine proteins (Richards and Hedges 1999). Similar findings have been reported by Richards, Schulting and Hedges (2003) and are consistent with the material record in Britain and with other European countries during the Neolithic transition, when humans became increasingly reliant on domesticated animals (Lubell et al. 1994).

One study that did analyse the prevalence of carious lesions among Neolithic British assemblages reported a lower prevalence, compared to later periods. For instance, Lunt et al. (1974) recorded the prevalence of carious lesions among 656 Neolithic teeth from various archaeological sites in Scotland and recorded a prevalence of 1.7%, which is lower than a similar study of Neolithic material from England where a prevalence of 3.1% (n=7000) was recorded (Brothwell and Blake 1966). Similarly a low prevalence of carious lesions has been recorded among Neolithic assemblages from other countries (Scorrano et al. 2018, Lillie and Richards 2000), such as that conducted by Lillie and Richards (2000) of Mesolithic and Neolithic individuals from the Ukraine. This study reported no carious lesions among Neolithic assemblages (309 individuals 3050 dentition). However other studies have recorded a higher prevalence of carious lesions between 8.2 and 12% of dentition being affected by carious lesions (Angel 1944, Fujita 1995, Tayles 1999, Oxenham and Domett 2011, Willis and Oxenham 2013). The comparatively low prevalence of carious lesions among British Neolithic sites has been suggested as evidence that agriculture somewhat ‘failed’ in Britain during this time (Stevens and Fuller 2012, Stevens and Fuller 2015). However these studies failed to record carious lesions by tooth type, location and dental wear, as such the information provided is limited and does not enable comparison.
2.3.3 The British Bronze and Iron Age: Continuity and Change

The forest clearance that dominated the late Neolithic landscape continued through Bronze Age Britain and the floral and faunal assemblages remain fairly similar (Cunliffe 2004b, Dumayne 1993, Fyfe et al. 2003). While the Bronze and Iron Age are obviously associated with the production of new tools made from their namesakes, there is also evidence for significant changes in ritual behaviour and social structures (Barrett 1990, Brück 2004, Cunliffe 2004b, Parker Pearson 2005).


<table>
<thead>
<tr>
<th>Bronze and Iron Age Britain</th>
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<tbody>
<tr>
<td>Early Bronze Age (2500–1500 BCE)</td>
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<td>Middle Bronze Age (1500–1000 BCE)</td>
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<tr>
<td>Late Bronze Age (1000–700 BCE)</td>
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<tr>
<td>Early Iron Age (600–400 BCE)</td>
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<td>Middle Iron Age (400–100 BCE)</td>
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<td>Late Iron Age (100 BC–50 CE)</td>
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2.3.3.1 Possible Ritual, Cultural or Spiritual Behaviours

At the beginning of the Early Bronze Age (EBA), the erection of huge henge monuments continued. The most well-known example being Stonehenge, which was erected in stages between 2800 and 1500 BCE (Barrett 1990, Bradley 1998, Edmonds 1995, Parker Pearson 2016, Parker Pearson et al. 2007). While this is the most well-known example, henge monuments were erected in Britain throughout the EBA and include: Castle Ring, Callanish, Mitchells Ford, Nine Stones and Hurlers Stone Circle. Towards the end of the EBA, there is evidence that ritual and spiritual behaviour changed; multi-burial ancestral tombs were blocked and ceased to be used, along with the creation of huge henge monuments (Cunliffe et al. 2004). The practice of single burials appears to be one of the most wide spread practices that first occurred during the Bronze Age (Brück 1995, 2004). Often these single burials would be arranged in linear cemeteries (Cunliffe et al. 2004, Watson 2001). Grave goods also became more frequent and included knives, arrow heads and jewellery (Barrett 1990, Edmonds 1995).
Fauna

2.3.3.2 Fauna

Bronze and Iron Age faunal assemblages are fairly similar to those from the late Neolithic, mostly consisting of domesticated animals with porcine remains being the most frequent (Cunliffe et al. 2004, Jay and Richards 2006, Redfern et al. 2010 Serjeantson 2007, 2011). The high proportion of meat and dairy consumed is considered to be similar to modern contemporaneous British populations (Copley et al. 2003, Evans et al. 2006, Stevens et al. 2010). This is supported by isotope analysis of individuals from Normanton Down and Stonehenge which had a meat/dairy content comparable to modern UK diet (Evans et al. 2006). Analysis of insect remains also provide support for large quantities of fodder potentially for feeding of livestock. During excavation of the Wilsford Shaft in Normanton Gorse, Wiltshire, the abundance of ‘Click Beetle’ (Adelocera murina) and ‘Garden Chaffer’ (Phyllopertha horticola) which thrive in long meadow grass arguably indicates the presence of large quantities of cut vegetation potentially used as fodder for animals (Osborne 1969).

One change that is evident in the faunal assemblage is the introduction of very small cattle thought to represent a new species introduced to Britain, probably from mainland Europe. During the Bronze Age, the size of cattle in faunal assemblages decreases and during the Iron Age cattle were particularly diminutive in form (Cunliffe 2004b, Jewell 1962). Wild species continued to play a role in the diet of Bronze and Iron Age populations in Britain, including game species, fish, molluscs, crustacea and fowl; however, proportionally these wild species comprised a small role in diet (Dobney and Ervynck 2007). For instance, animal remains deposits believed to be kitchen refuse at an Iron Age site at Micklemoor Hill, West Harling, included ox, sheep, horse, dog, wild boar, beaver, red deer and crane (Clark et al. 1954). While hunting practices continued during the Iron Age, it has been suggested that hunting during this period may have been regarded more as a sport or a rite of passage than strictly food provision, indicated by Celtic warriors decorating their shields with images of wild boar (Renfrew 1985, Rowlett 1994).
2.3.3.3 Flora
There is considerably more evidence of cereal cultivation during the Middle Bronze Age (MBA) and it has been suggested that during the Neolithic agriculture somewhat failed. While domesticated animals made up a substantial proportion of people’s diets and domesticated cereal crops were introduced to Britain, it was not until the MBA that cereal cultivation and consumption were firmly established (Stevens and Fuller 2012). During the Bronze Age in Britain, the predominant cereals crops were wheat, barley and oats (Edwards and Hirons 1984, Hubbard 1976). Barley was the most common find, with emmer being the most frequently occurring wheat species (Applebaum 1955, Brück 2006b, Parker Pearson 2009). A notable characteristic of the Early Iron Age (EIA) was the introduction of spelt wheat into Britain, suggested to have been the predominate grain during this period (Applebaum 1955, Dennell 1976, Newton 2018, Parker Pearson et al. 2018, Powell 2017, Treasure and Church 2017). This is a matter of some contention as the analysis of pottery impressions suggests that emmer wheat was the most frequent cereal, followed by spelt wheat and barley which were of equal use (Applebaum 1955, Palmer and Jones 1991, Pelling 2012).

Crop changes from the Bronze Age to the Iron Age indicate a shift from summer (e.g: oats and barley) to winter crops (e.g: wheat and rye) and it has been suggested that during the EIA the climate in Britain deteriorated leading to wheat becoming popular in the Iron Age as it is better adapted to cold and wet climates compared to barley (Applebaum 1955, Haselgrove 2009, van der Veen and Palmer 1997). Both wild and cultivated oats were also present during the Iron Age although oats may not have been intentionally cultivated until the Roman period (Applebaum 1958, Bird 2017, Curwen 1937, Murphy 2016). Rye and beans also appeared in the archaeological record, although evidence of rye was sporadic among EIA sites and evidence of beans is restricted to archaeological sites in Somerset (Applebaum 1955, Monk and Fasham 1980, Parker Pearson 1999).

2.3.3.4 Material Culture
The earliest Bronze Age period is known as the Beaker period, for the pottery tradition of the same name (Evans et al. 2006). The Beaker tradition spread rapidly through Britain, suggesting increased contact between regions and
indicating well established trade and communication networks linking communities together (Brück 2004, Cunliffe et al. 2004). As the name suggests the use of copper, and later bronze, spread during the Bronze Age increasing demand for the raw components copper and tin. The demand for these materials is also thought to have brought about the increased development of trade networks and communication (Bradley 1998). It was not just copper and bronze that made their first appearances during this time, as items made from other rare materials such as amber, jet and shale have been excavated from Bronze Age burials (Bradley 1998, Brück 2004). Faience, a decorative material predominantly used in beads, made from heating ashes and minerals together, is the first artificial material uncovered from British archaeological sites (Cunliffe et al. 2004, Sheridan et al. 2004). It is suggested that the increased demand for these rare and manufactured materials would have acted to further intensify trade and communication routes (Brück 2006a, 2006b, Sharples 1991).

At Bronze Age sites there is also greater evidence of an increase in status and regional differences illustrated by elaborate bronzes (Brück 2006a, 2006b, Sharples 1991). In Wessex, a number of individuals thought to be of high social status were interred with intricate grave goods and rare materials including gold and amber jewellery (Armbruster 2013, Piggott 1938, Woodward 2002). While there are a number of problems with relating grave goods with the associated human remains, the variation in number, material and quality of grave goods does suggest increased social stratification (Barrett 1980, Brück 1995, 2004, 2006, Gilman et al. 1981).

During the Late Bronze Age (LBA), a number of widespread changes to the socio-cultural environment are evident in the archaeological record. This includes the increased regionality in goods produced by different settlements (Bradley 1998, Crawford 1912, Parker Pearson 2009). While during the MBA there is little variation in the material cultures from settlements (Parker Pearson 2009), throughout the LBA different settlement types produced a large number and range of artefacts and material culture varied between settlements (Bradley 1998, Crawford 1912, Parker Pearson 2009). Metalwork artefacts were found among a greater proportion of LBA settlements (43%) compared to MBA settlements (33%), and there was also a greater variation in types of metal objects among the LBA (76%) compared to the MBA (55%) (Brück 2012). Additionally,
major changes in pottery manufacturing occurred during the Bronze and Iron Age. Between the MBA and LBA there was an emphasis on local pottery, which gradually declined as the consumption of regionally manufactured pottery became more popular (Moore 2007). In the Middle Iron Age (MIA) there is evidence that a larger variety of different pottery types were widely distributed and in the LIA both pottery and querns were exchanged over long distances - up to 80km (Moore 2007). Despite the technological developments that occurred during the Bronze and Iron Ages, flint tools were still in use during the EIA and included primary flakes, cores, scrapers and hammer stones (Humphrey and Young 2016, Powell 2017).

**Weapons and Defence**

In the LBA weapons are more frequent in the archaeological record, alongside a rise in enclosed settlements it is thought that this may be related to increased social stress in Britain (Dent 1983, Hill 1995, Sharples 1991). While in the Bronze Age there is evidence for increased use and production of weapons, during the Iron Age there is little evidence of weaponry. It is thought that the earlier requirements for weaponry may have been replaced by distinctive class settlements and hillforts (Sharples 1991). Evidence for the emergence of hierarchy and kin groups in the EIA are thought to have been brought about in response to increased warfare. However, two centuries before the Roman conquests, swords and spears returned to the archaeological record and hillforts were abandoned (Clarke 1939, Cunliffe 2004b, Cunliffe et al. 2004, Sharples 1991).

**Trade**

Throughout the Bronze Age extensive trade routes are thought to have linked southern England, Britany, Ireland and Iberia. However, in the Early Iron Age (EIA), increased use of iron is thought to have undermined previous trade routes and led to the collapse of the Western Europe seaboard trade (Cunliffe et al. 2014, Sharples 1991). Grain storage structures also become increasingly common and it has been suggested that storing large quantities of grain was essential due to societal changes associated with the collapse of reciprocal trade networks (Cunliffe 1992, Cunliffe et al. 2004, Sharples 1991). Despite the arguments for collapses in reciprocal trade networks there is still evidence for
movement of material culture across long distances (Harding 2017, Osborne 2017).

Cooking and food processing
Developments in cooking and food processing in the LBA are evidenced in an increase in the frequency of ovens, kilns and furnaces, while there are only a few cases of such structures among MBA sites (Brück 1999, Brück 2006a, Cunliffe et al. 2004, McOmish 1996). Querns continue to have a significant role in Iron Age communities based on their inclusion in deposits (Moore 2007). However these querns differed from the previous periods with the introduction of the more efficient rotary querns (Clark and Fell 1953). Clay lined cooking pits have also been found among LBA and MIA roundhouses in Britain. These pits were filled with burnt sand and stone cobbles and are thought to have been used for heating water or food (Webley 2007). There is also evidence for the widespread consumption of beer in the LIA in South East Britain based on the analysis of pottery fragments thought to have been used for the storage and transport of beer (Pitts 2005). Additionally a relatively small amount of wine amphorae entered Britain during the LIA (Cunliffe 2004b, Pitts 2005) as contact with the Roman empire increased with several Roman transition events taking place including Julius Caesar’s campaigns, invasion by Claudius and the Boudican revolt (Conybeare 2018, Jones et al. 2015, Millett et al. 2016, Phipps 2016, Rawlings 2017).

2.3.3.5 Settlements
It was during the Middle Bronze Age (MBA) that significant changes in human settlement occurred. MBA settlements typically comprised of enclosed clusters of roundhouses, with “ponds, granaries and storage pits” (Brück 2007, 2) probably occupied by single households or family groups. The pattern of enclosing settlements and the division of land started around 1500 BCE and rapidly spread across Britain. Towards the end of the MBA and throughout the LBA the continued division of land transformed the landscape in Britain with fields becoming more organised and agricultural practices developing with evidence that fields were manured to increase yield (Cunliffe 2004b, Cunliffe et al. 2004, Haselgrove 2009).
During the LBA there was an increase in the range of settlement types in Britain, a departure from the relatively uniform settlements from the MBA. As with MBA sites, the majority of LBA sites appear to have been occupied by single households or small family groups (Cunliffe 2004b, Cunliffe et al. 2004). There are, however, some LBA sites where evidence indicates a considerable increase in the size of the community who utilised the site. Midden sites suggest a small population of permanent residents while large numbers of people likely congregated for particular events (Brück 2006a, 2006b, 2012, McOmish 1996). This is evidenced by midden deposits including material which originated or utilised resources from a wide area. For instance, the Bronze Age midden at Runnymede, Surrey, contained pottery that was manufactured using clay from sources not present in the local region (Barrett 1980). Faunal remains at Runnymede have been interpreted as indicative of feasting activities (Barrett 1980, Morris 1994). Evidence from MBA sites indicates that houses and enclosures were relatively short-lived, with little evidence of repairs being made to structures (Brück 1999, Cunliffe 2004b). While many LBA sites appear to have followed a similar pattern, there are several LBA sites where evidence of rebuilding indicates the site was inhabited for an extended period of time (Cunliffe 2004b, Cunliffe et al. 2004). While typically associated with the Iron Age during the LBA there is evidence for the increased defence of settlements with early examples of hillforts occurring towards the end of the LBA, although these early examples are considered unlikely to represent continuous habitation.

An important feature of EIA settlements are hillforts which were a well-known feature in southern England (Cunliffe 2004b, Cunliffe et al. 2004, Stead et al. 1969). During the beginning of the EIA there was considerable variation in the type of fortified sites which are collectively referred to as hillforts. Some of this variation is illustrated in figure 2.3.5. However, after around 500 BCE hillforts became more consistent and typically took the form of 0.05km² contour fortifications which spread across the landscape in Britain (Harding 2012, Hawkes 1931, Ralston 1996, Waddington et al. 2012). By the MIA the majority of settlements across western Britain were small and enclosed, although archaeobotanical evidence indicates that these enclosed settlements were not necessarily agriculturally independent (Moore 2007). A number of theories have been proposed to account for the development and spread of increasingly
defensive settlements (Creighton 2004, Harding 2012, Hawkes 1931). The control of agricultural production and trade routes is argued to be the focus of Iron Age warfare which led to increasingly fortified settlements. It has been suggested that corporate leadership, communal defences of hillforts and more rigid hierarchy were established to give greater control of trade and manufacturing industries (Sharples 1991). However, around 300 BCE, towards the end of the MIA early hillforts in Britain appear to have been largely abandoned, although a few do show evidence of continued use and increased fortification such as that of Maiden Castle in Dorset (Cunliffe 2004b, Cunliffe et al. 2004, Sharples 1991).

During the LIA a new form of settlement appeared in Britain referred to as an oppidum (Lodwick 2018, Moore 2017, Jackson 2017). These began in the south of Britain at the time when hillforts were being abandoned. Similar to hillforts early oppida were enclosed settlements typically defended by banks and ditches. However, oppida differed from hillforts in both size and location, being typically larger than hillforts, these oppida were rarely built on hilltops and instead were located at transport links such as river crossings (Lodwick 2018, Moore 2017, Jackson 2017). It has been theorised that this shift in settlement during the LIA reflects increasing intensification of trade networks. However, oppida generally only occurred in southern Britain and in the north hillforts continued to be used during the LIA and even into the Roman period (Cunliffe 2004a, 2004b, Cunliffe et al. 2004).
Figure 2.3.5: Hillforts during the Early Iron Age. a) Oswestry, Shropshire, b) Maiden Castle, Dorchester, c) Barbury Castle, Wiltshire, d) Old Sarum, Winchester, e) Cadbury castle, f) Bradbury Rings.
2.3.3.6 Bioarchaeological Evidence from the Bronze and Iron Age

There is an increase in the number of bioarchaeological studies among Bronze and Iron Age assemblages in Britain; these studies indicate an increase in the consumption of cariogenic foods -such as cereals (Brothwell 1959, Hardwick 1960, Lunt 1974, Moore and Corbett 1975). Lunt (1974) reported a significant increase in the prevalence of carious lesions from Bronze age (1.8%, n=1306) to the Iron Age (6.6% n=301). Similar increases in carious lesions were recorded by Brothwell (1959) who reported a prevalence of carious lesions of 2% among Bronze Age individuals, which increased to 10% among Iron Age individuals.

Stable isotope studies from Bronze and Iron Age sites continue to indicate a diet high in terrestrial protein with little consumption of marine resources (Jay 2008, Jay and Richards 2006). For instance, at the Iron Age site of Wetwang Slack in East Yorkshire, $\delta^{13}$C and $\delta^{15}$N both indicate a diet high in terrestrial protein, findings which are supported by the lack of zooarchaeological evidence of marine resources at the site. Stable isotope analysis from British Iron Age sites also indicates a similar diet and support archaeological evidence that animal protein continued to form an important component of diet, with little variation between sites (Jay and Richards 2007). Furthermore, stable isotope analysis from 77 individuals a Late Iron Age site in Dorset reported no evidence of sex related differences in diet based on carbon and nitrogen stable isotopes (Redfern et al. 2010). Some of the earliest evidence for dietary deficiency diseases are also reported, with Mays (2008) suggesting a diagnosis of infantile scurvy from remains dated to 2200-1970 BCE, although it was not until 1870 CE that scurvy became a regular occurrence in Britain (Mays 2008).
2.3.4 Roman Britain: Amphora, Flavour, Roads and Trade

Rome’s first direct encounter with Britain occurred in 55 BCE when Julius Caesar first set foot on British soil, during his second invasion in 54 BCE demands for annual payment were made and hostages taken (Dargie 2018, Krebs 2018, Kim 2016, Pitts 2008, Wiseman 2018). While there is evidence of close contact between Rome and Britain after the first invasions in 55-54 BCE, it was not until 43 CE nearly 100 years later that Roman occupation of Britain began (Dargie 2018, Madgwick et al. 2019, Pitts 2008). There has been a tendency to oversimplify the cultural effect of the Roman invasion of Britain, whereby Roman culture was transferred to native British populations instead of an exchange of culture taking place (Pitts 2008). Anthropological analysis of modern cases of invasion and occupation, however, have argued against the archaic view of the invading culture simply replacing native culture arguing instead for a homogenous cultural exchange (Pitts 2008).

Table 2.3.3: Roman Britain. Table illustrating the key dates and periods relating to the Roman occupation of Britain (Dargie 2018, Pitts 2008).

<table>
<thead>
<tr>
<th>Roman Britain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Invasion (55 BCE)</td>
</tr>
<tr>
<td>2nd Invasion (54 BCE)</td>
</tr>
<tr>
<td>Roman Occupation (43 CE – CE)</td>
</tr>
<tr>
<td>Trade with Roman Empire starts to decrease (250 CE)</td>
</tr>
<tr>
<td>Britain no longer protected by Roman Empire (410 CE)</td>
</tr>
</tbody>
</table>

Settlements and Trade
Roman settlements can be broadly divided into urban, rural and military settlements and evidence of material culture and the flora and fauna records for these sites show significant differences between them, therefore when considering archaeological evidence during this period it is necessary to discuss these settlement types separately. Urbanisation increased in Britain during the Roman period, which was typically based around Iron Age settlements and forts (Jones 1961). There was also increased regional variation in Britain, for instance Wales became more Romanised early on while there is little evidence of

2.3.4.2 Romano British Diet

Written evidence suggests that most of the food in Roman Britain was consumed in the form of stews and porridge (Alcock 2001, Cool 2006). However in regions in the north and west of Britain, diet appears to have remained largely unchanged from previous periods, perhaps due to lack of trade routes and anti-Roman sentiments (Alcock 2001). Roman recipes and other written accounts show the increased importance of honey and other sweet ingredients such as a syrup made from boiling grape juice. Beverages were also very high in sugar as alcohol was safer to drink compared to water (Eckardt et al. 2016, Mudd 2015, Renfrew 2003, Rogers 2013, Singleton 2003). Therefore the majority of beverages consumed are considered to have been alcoholic, such as wine, cider made from a variety of fruits, and beer - all of which were consumed in large quantities (Cool 2006, Rohnbogner and Lewis 2016, van der Veen 2008, van der Veen et al. 2008).

More evidence concerning diet and lifestyle from written accounts is available during this period, compared to earlier periods, where there are no written records. However many written sources (such as recipes) originate from other regions of the Roman Empire and may not be directly applied to Roman Britain. Even in the capital of the Roman Empire it has been argued that diet has not been thoroughly investigated within archaeology (Alcock 2001, Cool 2006), and instead historical sources are over relied upon to understand Roman diet. One major criticism of this is that these written records were produced by the upper class of Roman society which have been estimated to comprise of less than 2% of the population of Rome. As such these historical reports may not accurately represent the entire or even the majority of the Roman population (Alcock 2001, Cool 2006, Garnsey and Saller 2015, Pitts 2008).

2.3.4.3 Cereals and Grinding

Analysis of charred cereal grains at Romano-British sites revealed three species of wheat were common during this period – emmer, spelt and ‘bread wheat’. Emmer and spelt had been popular in Britain since the Neolithic and Iron Age, while bread wheat - although sporadically present since the Neolithic - only
appears to have become a popular crop during the Roman period (Cool 2006, van der Veen 1989). In Romano-British urban and military sites, larger water or animal powered grinders have been found although evidence suggests that the majority of grains were still ground in households with hand querns (Cool 2006, Hurst 2016, Reniere et al. 2016). Additionally a flat style rotary quern was introduced which slowly replaced the beehive quern that was popular in the LIA (Cool 2006, Cunliffe 2004a). The flour or meal produced appears to have been consumed as both a porridge and bread (Cool 2006, Rohnbogner and Lewis 2016, van der Veen 1989). Recipes in Roman Britain suggest that a variety of breads were eaten and while the benefits of wholemeal bread were known the elite in Roman Britain are thought to have predominantly eaten white bread (Cool 2006, Kyle 2000, Storck and Teague 1952). There is also evidence for regional variation in the bread and cereal consumption with barley - which was considered a punishment ration by the Roman army - remaining more popular in northern Britain (Cool 2006, van der Veen 1989, 2008).

2.3.4.4 Domestic Fauna
The relative proportion of different domesticated animals differs significantly between sites in Roman Britain, cattle and pigs were most prevalent at military sites or urban areas, while sheep were more common among more rural native British sites as was the case in the previous period (Albarella et al. 2008, Alcock 2001). Even among native British sites the prevalence of cattle remains increased, illustrating the effect Roman occupation had on all settlements. The age of sheep deposits also decreased with average age for slaughter becoming the 2nd or 4th year suggesting increased focus on meat compared to wool during the 3rd and 4th century CE (Albarella et al. 2008, Alcock 2001, Applebaum 1958, Redfern et al. 2010, Seetah 2005). It is during the Roman period that there is increased evidence for distinctive breeds of domesticates selectively bred for specific purposes alongside evidence for the introduction of new breeds including larger cattle (Jewell 1962, Redfern et al. 2010). The processing of pork into bacon was another Roman development, and pork was thought to be a particular favourite of the Roman elite alongside venison and poultry (Alcock 2001).
While the earliest evidence for the domestic fowl (*Gallus gallus*) brought into southern Britain by the Romans is dated to the LIA, it was not until the Roman invasion that numbers increase (Maltby 2014, Sykes 2009, 2015). Maltby (1997 cited by Sykes 2009) analysed zooarchaeological remains at several Roman sites and found that domestic fowl were present at all sites, but were less abundant at low status and rural settlements (Maltby 1997 cited by Sykes 2009). Evidence of poultry remains from a number of Roman sites also indicate that a wide variety of species and sizes of both domestic and wild poultry were consumed, and butchery marks indicates these birds may have been cooked whole (Albarella 2005, Davies 1971). Egg shell fragments are also frequent finds although again this is mostly restricted to urban sites with fewer recordings among rural sites. Where identification is possible, hen eggs have been found to be the most common, followed by duck and goose (Albarella 2005, Cool, 2006). It has been suggested that the consumption of both poultry and eggs may have also been somewhat restricted to high status individuals (Albarella 2005, Cool, 2006).

2.3.4.5 Marine Resources
The consumption patterns of fish and other marine sources in the Roman Empire has been shown to vary substantially over time and appears related to a number of contextual factors such as social status and occupation (Crabtree 1990, Pitts 2008). There is limited and sporadic evidence of fish consumption and was mostly restricted to fish sauce or salted or pickled fish imported into Britain in amphorae. Although at large urban sites (such as London) evidence suggests fish played an important part in diet (Orton *et al.* 2017, Redfern *et al.* 2018, Van Neer and Cker 1994). There is also substantial evidence that shellfish consumption - particularly oysters - were wide spread and traded over long distances, and written evidence suggests that British oysters were highly prized, and oyster cultivation was introduced (Davies 1971, Günther 1897, Reece 1988). Unlike other Roman foods, oysters appear to have been consumed at both urban and rural sites. Additionally there is evidence that at some Roman sites fish were farmed. The excavation of two British villa sites Lynch Farm and Shakenoak revealed three ponds dug in the late 2nd century for fish farming - possibly trout (Alcock 2001, Cool 2006).
2.3.4.6 Wild Fauna
Written evidence indicates hunting was a popular pastime in Roman Britain with deer, boars and hares being frequently hunted (Albarella et al. 2008, Allen 2014, Parker 1988). However there is limited zooarchaeological evidence for game consumption, and this is particularly low among urban assemblages such as Colchester where only 5% of the faunal assemblage is attributed to wild species (Albarella et al. 2008, van der Veen 2008). Among military sites there is more variation in the proportion of wild game and other species, with seal bones present at Segontium, and badgers at Caister-on-Sea which bear butchery marks indicating human consumption (Harman 1993, Noddle 1993). Fallow deer remains were identified at Fishbourne Roman palace in Sussex and were radiocarbon dated to 60 and 90± CE. Strontium isotope analysis revealed that the deer dated to 60 CE were imported into Fishbourne, possibly from Italy or southern Gaul, while the deer dated to 90 CE were born and raised at Fishbourne (Cool 2006, Sykes 2009, Sykes et al. 2006).

2.3.4.7 Food Preparation and Cooking Practices
During this period, cooking appears to have become more important socially and culturally with dedicated cooking rooms in urban houses (Alcock 2001, Colquhoun 2008). Hearths continue to be popular, and while the use of ovens does increase, they tend to be restricted to larger houses. The preference of hearths over ovens has been suggested to relate to fire risk considering houses during this time were made predominantly from timber (Cool 2006, Cunliffe 2004a).

Towards the end of the first century CE, the pottery wheel is introduced to Britain leading to an increase in the variation in pottery forms (Cool 2006). Evidence from pottery remains also indicates there were increasing regional differences in pottery and cooking practices that may have related to ethnic differences in the local populations (Briscoe 2015, Cool 2006, Roffett-salque et al. 2017, Swan 2002). Among urban sites there was an increased variation of pottery vessels that would have been used for serving drinks and food that is not seen among the preceding periods or rural sites. For instance in York, pottery vessels dated to 200 CE are similar to those from North Africa which were used to cook food over a brazier, and historical reports indicate that the Roman forces
stationed in York likely included individuals from North Africa (Cool 2006, Swan 2002).

Other new food preparation techniques introduced, were more wide spread. For instance, cheese presses were not found before this time, yet they are commonly found at Roman military sites and provide the first evidence of cheese making in Britain. These cheese presses increased in the archaeological record and remained popular after Roman occupation ended (Alcock 2001, Cool 2006). There is also increased evidence of metal cookware during the Roman period, with metal frying pans dated to around 300-400 CE (Cramp et al. 2011, Cool 2006, Davies 1971). However, many of the metal tools which may bear morphological similarities to modern cookware are considered to have had other functions such as for bathing and hygiene. While metal cookware at Roman sites in Britain is rare, unlike pottery once broken metal objects can be melted and reused therefore the archaeological record may not reflect proportions used. There is also evidence for a wider range of metal knives used for animal butchery (Cool 2006).

2.3.4.8 Introduction of New Foods
The introduction of new plants and animals into Britain during the LIA/Romano British transition altered the landscape of Britain creating horticultural spaces and wild animal reserves not present before 43 CE (Sykes 2009). While several new species and foods were introduced during the LIA, it has been suggested that these early ingredients did not greatly influence cooking or dining practices until Roman occupation (Cool 2006). Prior to the Roman occupation, crops which were actively cultivated in Britain were mostly restricted to cereal grains. The Romans increased the variety of cultigens including parsnips, radishes, beets, endive, lettuce, broad beans, turnips, cabbage, and a different type of carrot which replaced the yellow and woodish wild carrot (Alcock 2001, van der Veen 2008, van der Veen et al. 2008). There is also evidence of new fruit trees like mulberry; the fruit is easily damaged and could not have been imported, as such the presence of mulberry seeds at Romano-British sites indicated introduction of the plant (Livarda 2007, Livarda and Orenga 2015, van der Veen 2008, van der Veen et al. 2008). Other flora
introduced by the Romans that became established shortly after their introduction, including plum, pear, walnut, apple and cherry (Alcock 2001).

During the end of the LIA, zooarchaeological evidence also indicates the introduction of new fauna into Britain associated with increased Roman contact (Albarella et al. 2008, Maltby 1997, Sykes 2009, Sykes et al. 2006). Certain sites appear to have had increased engagement with wild fauna before other sites. At Fishbourne, it appears that exotic species were introduced shortly after the conquest, while at less prestigious sites these species were not introduced until much later (Sykes 2009). Among the more exotic species eaten during the Roman British period is the edible dormouse along with the Guinea fowl, mulberries and cherries (O’Connor 1986).

2.3.4.9 Trade and Importing Foods
Trade and communication networks in Britain also changed substantially during the Roman period. The Romans brought a money based market economy and tax system, and developed roads and transports links to form a strong trade system and economy in Britain (Alcock 2001). The development of trade systems also acted to expand pre-existing industries. For instance, the salt industries established during the LIA continued to expand. Additionally, a large number of products were imported into Britain (Cunliffe 2004b, Cunliffe et al. 2004). Around 43 CE archaeobotanical data indicate that several exotic flora arrived in Britain, and quickly became widely distributed but were not grown locally. These species included figs, grapes, olives, lentils, and pine nuts (van der Veen 2008, van der Veen et al. 2008). Figs were a common import into Britain as the trees, but not the fruit, can grow here. Figs are thought to have been dried and imported from the Mediterranean. There is evidence that figs as well as grapes were consumed in large amounts even at non-Romanised settlements during the beginning of the Roman period. Additionally, cherries both native (Prunus avium) and the imported sour cherry (P. cerasus) were eaten. A number of nuts were also imported, including pine nuts, walnuts and almonds, although these are infrequent finds, and there is more evidence for the consumption of native hazelnuts (Davies 2011, Redfern et al. 2018, van der Veen 2008). Moreover, lentils first occur in the archaeological record during the Roman
period and while they can grow in Britain it is thought that the majority were imported (van der Veen 2008, van der Veen et al. 2008, Willcox 1977).

The analysis of Roman amphora is a valuable resource for reconstructing diet in Roman Britain with the amphora shape being used to identify imported products and where they were consumed (Alcock 2001, Cool 2006, Peacock 1977, van der Veen 2007, van der Veen et al. 2008). For instance, both dates and olives appear to have been imported via amphorae and eaten in the main military and urban sites, but do not appear to have been commonly eaten in rural areas. There is also a greater level of evidence for the flavouring of foods in Roman Britain, such as a fish sauce - or garum - that was made from fermented fish and herbs and included in many Roman recipes. Amphora containing fish sauce were mainly imported from Iberia although there is some evidence for local production in York (Cool 2006, Locker 2007). Fish sauce was imported into Britain from the LIA, but this increased during Roman occupation. However, after 200 CE pottery fragments from these fish sauce amphora decline throughout the Romano-British period, and by 300 CE are no longer present in the archaeological record. Prior to the introduction of fish sauce, olive oil - a staple of Roman life - was imported during the LIA and after the Roman conquest remained widespread (Cool 2006, Locker 2007, Redfern et al. 2010).

2.3.4.10 Bioarchaeological Evidence from Romano-Britain

Several early studies have reported an increase in the prevalence of carious lesions among Romano-British assemblages (e.g. Moore and Corbett 1971, 1973, O’Sullivan et al. 1993, Brothwell 1959, 1963, Peck, 2009, Redfern and DeWitte 2011). For instance, analysis of dental pathology from the Romano-British assemblage from Baldock, Hertfordshire, conducted by Thornton (1991) reported that 70% (n= 87) of individuals had carious teeth, while 14.3% (n=1375) of teeth had carious lesions. This high prevalence of carious lesions could reflect the increased reliance on cariogenic cereals and sweet foods and drinks (Bonsall 2013). Bioarchaeological evidence of increased consumption of cariogenic foods is supported by archaeological evidence which indicates increased consumption of sweet foods, such as wine and honey (Cool 2006). Additionally, Bronsall (2014) recorded a similar prevalence of carious lesions
among males and females indicating that there was no significant sex difference in the cariogenic diet (Bronsall 2014).

Stable isotope analysis continues to indicate a reliance on terrestrial protein although among urban sites there was an increased consumption of marine protein. Cummings (2009) reports enriched nitrogen isotopes levels among the Romano-British assemblages of Cirencester, Alchester and Stanton Harcourt. Nitrogen levels indicate a diet high in animal protein including omnivores, as well as increased consumption of marine protein at the urban Roman site of Cirencester (Cummings 2009). Sex differences have also been reported, stable isotope analysis from a Romano-British assemblage in Dorset, indicates that among females there was an increased consumption of marine resources (Redfern et al. 2010). These results are supported by similar findings from Cheung et al. (2012).

Skeletal pathology can also indicate some aspects of Roman diet. During this period there is argued to be the first evidence for diseases associated with particularly rich diets in Britain such as gout and Diffuse Idiopathic Skeletal Hypertrophy (DISH) at urban sites (Alcock 2001, Roberts and Cox 2004). Among Roman military cemeteries, a high prevalence of osteomalacia is thought to reflect an increase in cereal based diet because cereal grains are high in phytate which interferes with absorption of calcium (Alcock 2001). This is supported by archaeobotanical evidence which suggests that before the 3rd and 4th century CE Roman military forces mostly ate cereals while later in the period meat was increasingly eaten (Alcock 2001, Ford et al. 1977). Additionally, the use of lead pipes introduced at Cirencester Poundbury are linked to the high lead content in bones (Alcock 2001, Montgomery et al. 2010), while the comparatively high levels of tuberculosis in Roman sites are thought to be related to infected milk and dairy consumption (Alcock 2001, Lewis 2011).

2.3.4.11 The End of Roman Britain
The end of Roman occupation was a gradual process beginning around 300 CE. Around this time, the military presence declined, there was a rapid devaluation of Roman currency and a decrease in trade with the Roman empire. In 410 CE, Britain was no longer officially protected by the Roman empire (Cunliffe et al. 2004) and by the end of the 5th century CE towns and villas were abandoned
(Cunliffe et al. 2004, Gerrard 2013). Scorch marks on the tessellated floors of Roman villas at the end of the Roman period indicates that Roman villas once abandoned may have been inhabited by native British groups who did not value Roman traditions (Alcock 2001).

2.3.5 The Early Middle Ages: Formation of England, Scotland, and Wales

After the Roman occupation of Britain ended, the appearance of pagan Scandinavian raiders caused disruption, and social unrest and warfare were endemic. While it is generally considered that the social and cultural upheaval caused by the end of Roman occupation were felt more strongly in the south and east where Roman culture had been more entrenched, this upheaval affected all of Britain (Cunliffe 1992). However, this section will primarily discuss the changes which occurred in England both because social and cultural changes were most evident here due to Romanisation and there is also a greater amount of archaeological and written evidence for this period. While considered part of the Middle Ages, the Early Middle Ages in Britain known as the Anglo-Saxon period in England (410-1066 CE) will be considered separately due to the high number of archaeological sites which categorised human remains during this period.

2.3.5.1 De-Romanisation

In 410CE, Honorius sent a message to the Romano-British population that Britain was no longer under the protection of the Roman Empire, with historical reports suggesting this subsequently led to the Roman military and Roman elite leaving England, taking with them with many features brought by the Roman empire such as currency, cuisine, and bath houses (Cunliffe et al. 2004). It is frequently stated that shortly after aspects of Roman civilisation left, Britain was quickly plunged in to the ‘pagan squalor’ of the Dark Ages (O'Connor 2014). However, the widely held assumption and historical reports that suggest Roman elite and culture left Britain shortly after Honorius recalled the protection of the Roman Empire have not always been supported by archaeological evidence (Cunliffe et al. 2004, Fleming 2011, O'Connor 2014).
While Anglo-Saxon is a general term used for England during this period, it does not sufficiently describe the variation in people who settled in Britain then, which included the Angles from Southern Denmark, Saxons from Germany, Jutes from Northern Denmark, Frisians from the Netherlands and the Franks from Gaul. During the early Middle Ages England became a series of polyglot kingdoms thought to arise from the social and political vacuum resulting from the end of Roman rule (Cunliffe et al. 2004, Loyn 1991, Stenton 1971).

**Table 2.3.4: Anglo-Saxon England.** Time ranges for the Anglo-Saxon period in England (Cunliffe et al. 2004, Geake 1994, Karkov 1999, Poole 2013)

<table>
<thead>
<tr>
<th>Anglo-Saxon England</th>
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</thead>
<tbody>
<tr>
<td>Early Anglo-Saxon (410-600)</td>
</tr>
<tr>
<td>Middle Anglo-Saxon (600-800)</td>
</tr>
<tr>
<td>Late Anglo-Saxon (800-1066)</td>
</tr>
</tbody>
</table>

Kingdoms in the South and East of England were of Germanic origin while the North and West were of Celtic origin. These migrants and invaders brought with them new technologies, culture, and burial practices. Kingdoms during this time often had a strong monastic links beginning in 587 CE with Augustine’s mission to England (Meens 1994, Wood 1994). Following the English settlement, there were four main cultural zones in Britain, the English-speaking Anglo-Saxons to the East, the Celts in the North, the Britannic speaking ancestral Welsh to the West, and in Ireland and some parts of Western Scotland the Gaelic speaking Dal Riata (Cunliffe et al. 2004, Stenton 1971, Weale et al. 2002).

It is during the Anglo-Saxon period where the roots of modern England with respect to its geographical boundaries as well as language and some cultural aspects were founded. Towards the end of the middle Anglo-Saxon period, small tribal regions amalgamated into Kingdoms and by 700 CE there were seven principal Kingdoms in England: the “West Saxons, South Saxons, Kent, East Saxons, East Anglia, Mercia and Northumbria” (Arnold 1997, xvii). These kingdoms were formed through a series of migrations during the preceding two centuries. The relationship between these competing and often warring Kingdoms was predominantly unstable (Arnold 1997, Cunliffe et al. 2004).
Throughout the middle Anglo-Saxon period, prosperity in England increased and is associated with the development of more elaborate social hierarchies evidenced by a number of elite and royal residences. This increased social stratification is also evident in diet which has been found to vary among Anglo-Saxon assemblages based on differences in sex, wealth and status which was inferred from grave goods (Cunliffe et al. 2004, Godden 1990, Härke 1990, Privat et al. 2002). For instance, Anglo-Saxon males buried with weapons - suggested to be a signifier of wealth and status - were generally taller than males buried without weapons perhaps reflecting a better diet (Härke 1990). Additionally, stable isotope analysis of Anglo-Saxon burials indicates different dietary patterns among males, females and children, with males consuming higher levels of protein (Montgomery et al. 2004, Privat et al. 2002). This prosperity also attracted Viking raiding parties from Scandinavia and the Late Anglo-Saxon England was marked by significant violence and warfare with frequent attacks from Norwegians and Danes who in time conquered the majority of Anglo-Saxon England. Eventually only the kingdom of Wessex was outside of Viking control. Viking warfare had a significant economic impact on Anglo-Saxon life and in response trade systems moved to former Roman towns which were considered to be more secure (Cunliffe et al. 2004).

In 871 CE, King Alfred the Great of Wessex began to regain territory from the Danes which led to the unification of England into one Kingdom. However, Danish influence in England was still evident and areas north of the Thames were still subject to Danish law. During this time goods such as pottery and textiles were manufactured on an industrial level (Hall 1989, Ulmschneider 2000, Vince 2005). Urbanisation also continued to increase with the Danes developing urban areas such as York and Nottingham while the Anglo-Saxons recommissioned Roman towns with new fortified settlements. The Late Anglo-Saxon period also saw a number of legal, social, cultural and political changes and both schooling and literacy was more widely encouraged and no longer restricted to the elite (Cunliffe et al. 2004, Loyn 1991, Stenton 1971).
2.3.5.3 The Impact of Christianity
While there is evidence of Christianity reaching England during the late Roman period, until the 7th century CE Anglo-Saxons were largely pagan. It was Augustine’s famous mission to England in 597 CE to King Aethelbert of Kent that brought Christianity to England in force and created an alliance between Christianity and Kingship (Hall 2017, Meens 1994, Wood 1994). After this mission Christianity appears to have been readily incorporated into existing religious systems and quickly became a part of everyday life (Anlezark 2006, Chaney 1960, Edwards 2017, Forbes 2016). Towards the end of the Early Anglo-Saxon period the process of Christianisation was well underway based on written records. As it developed, highly powerful monastic communities arose which had a major impact on diet, with fast days taking up more than two-thirds of the year (Chaney 1960, Crawford 2009, Forbes 2016). During fasting days meat could not be eaten although fish was allowed - these new restrictions acted to rapidly grow the herring industry in England (Crawford 2009).

2.3.5.4 Flora
There appears to have been some continuity in farming practices from the Roman period at least around the Thames Valley area where no dramatic change in pollen, insects or seeds is evident. However, in some areas there is evidence for a reduced level of farming, with pastures and arable land returned to scrub which suggests a lower population density post-Roman occupation (Cunliffe et al. 2004, Hamerow 2012). Although, the number of families that could be supported by an area of land appears to have increased during the Anglo-Saxon period which may indicate increased intensification of farming practices (Cunliffe et al. 2004, Loyn 1991, Venning 2013). Cereal remains from Anglo-Saxon sites include spelt, rye, wheat, barley and oats, the presence of spelt decreased from the Roman period and by the Middle Anglo-Saxon period there is little evidence of spelt. Barley once again became the most important crop in England while evidence for oats is sparse and it is considered unlikely that this crop was actively cultivated (Arnold 1997, Fowler 1980, Loyn 1991, Moore and Corbett 1971, Van Der Veen et al. 2013).

Bread became a staple of Anglo-Saxon diet and the modern English word for Lord and Lady stem from the Old English words ‘hlaford’ and ‘hlafðig’ which
incorporate the word loaf (*hlaf*) (Frantzen 2014, Gautier 2012, Moore and Corbett 1971). While large industrial millstones are present at urban sites, the number of small hand querns in Anglo-Saxon sites indicates that grain was still frequently processed within the household (Bateman *et al.* 2003, Burghart and Wareham 2008, McKerracher 2018). Status differences are also evident in the stones used for the querns, in York lava stones from Germany, which would have produced a finer grain flour, were present among certain households (Frantzen 2014). However, by the Late Anglo-Saxon period, mills powered by oxen or water became more common (Burghart and Wareham 2008, McKerracher 2018). In addition to the crops grown in England there is evidence for a wide range of imported goods including lavender, aniseed, cinnamon, cloves, cumin, cardamom, ginger, liquorice and pepper (Frantzen 2014, Gautier 2012).

### 2.3.5.5 Fauna
Zooarchaeological evidence of Anglo-Saxon archaeological sites indicates very low species diversity compared to Roman periods. For instance, analysis of the Middle Saxon towns revealed that three taxa were overwhelmingly predominate: cattle, caprine (sheep/goat), and pig, with very few bird (like chicken or geese) or small mammal remains identified (Crabtree 1996, O'Connor 2014). Sheep and goats appear to be the predominate species, with higher levels of caprine remains recorded among Anglo-Saxon sites compared to other domesticates (Crabtree 1990). However, while the zooarchaeological evidence for porcine remains is scarce, isotopic analysis of human remains from Anglo-Saxon burials suggests that pigs played an important role in their diet which is also supported by historical sources indicating the importance of pork in the diet (Crawford, 2009). Fish also appear to have been an important part of diet and is linked to the increased Christianisation of England. Evidence of fishing and fish consumption comes from archaeological remains of fishing equipment, such as fish traps, iron fish hooks, net sinkers and line sinkers, as well as place names such as Fiskerton and Fishwick. By the end of the Anglo-Saxon period, a large fishing industry had established with 68,000 herring from one town, based on recordings in the Domesday book (Crawford 2009, Frantzen 2014).
2.3.5.6 Other Dietary Components
Anglo-Saxon ovens are present in the archaeological record from the 6th century CE onwards. The mainstay meal, however, was a stew made in a kettle or cauldron and cooked over an open fire which was an economical cooking style, while wealthier households may have roasted their meat (Albarella 2004, Crawford 2009, Gautier 2012, Hagen 1992). Illustrations from tapestries from this period show the use of spits for roasting meats (Crawford 2009). In addition to wine, beer and ale mead made from honey were the main alcoholic beverages consumed and appear to have been frequently consumed at feasts (Crawford 2009, Pollington 2003). Compared to the Roman period there was less access to sugars in Anglo-Saxon England which is reflected in the prevalence of carious lesions which decreased among Anglo-Saxon assemblages compared to Roman (Moore and Corbett 1971).

2.3.5.7 Burials and Grave Goods
The emergence of elite groups is evidenced in grave goods, with some high-status individuals buried with immense wealth. These high-status burials were not confined to men as some women were also buried with gold and garnet jewellery such as the individual buried in Desborough, Northamptonshire (Arnold 1997, Crawford 2009). Both cremations and burials took place during the Early Anglo-Saxon period. The decision as to which appears to have followed a regional pattern with cremation being more common in the Anglian regions of north and east England and inhumations common in the Saxon regions to the South (Crawford 2009). Among inhumations, grave goods were common and have been excavated from over 50% of Anglo-Saxon burials during the Early Anglo-Saxon period (Loyn 1991). However around 700 CE, burial rituals appear to change, with grave goods becoming less common and by 1000 CE the majority of inhumations do not include burial goods (Arnold 1997, Crawford 2009).

2.3.5.8 Settlements
The building materials employed in the Late Roman period - including tile, stone, brick and glass - were largely abandoned by the late 5th century and were replaced by biodegradable materials such as wood, thatch, earth and turf (Crawford 2009, Hamerow 2012, Williams 1998). Settlements were built from wood until the
Norman conquest, due to the biodegradable nature of wood the majority of information available regarding Anglo-Saxon settlements comes from the location of postholes and pits. While enclosed settlements were common in the preceding period, Anglo-Saxon settlements were sprawling and largely unbound by fences and ditches. As the majority of modern British towns can trace their origin back to the Anglo-Saxon period much of the information concerning these settlements is lost due to continuing development (Blair 1996, Crawford 2009, Hamerow 2012, Williams 1998).

During the Middle Anglo-Saxon period changes in social structures took place with the development of more elite social groups which is reflected in settlement types, with large timber buildings often two stories high with some surrounded by fences (Hamerow 2011, 2012). At sites such as Yeavering, Northumbria or Cheddar, Somerset, ‘palace’ sites are present with large timber buildings that at Yeavering measured 25 meters by 12 meters (Crawford 2009, Hamerow 2012). By the 8th century there is evidence for the increased specialisation of food production at some rural sites such as Hurst Park in East Molesey, Surrey, which is suggested to have developed as a grain processing site based on the organisation of the buildings, presence of grains and rotary querns (McKarracher 2018, Powell 2015). Place names can also illustrate agricultural patterns with sites such as Barton stemming from barley growing, and Beeston from bee-keeping (Crawford 2009, Hamerow 2012, Stenton 1971).

Shortly after the Roman occupation ended, towns established during that period were largely abandoned. However, around 900CE a second urbanisation phase is recorded in England (Laughton 2008). Excavations from Late Anglo-Saxon urban sites indicate a wide variety of occupations including fishmongers, wine merchants and smiths. During the 10th century urbanisation continued, however the majority of the population still lived in rural settlements. While these sites were dispersed and sprawling during the early Anglo-Saxon period by the Late Anglo-Saxon period the sites became nucleated and are considered to be the fore-runner of modern villages (Crawford 2009, Jones 1961).
3.5.9 Trade
While trade rapidly declined and became fragmented at the end of Roman occupation this did not remain the case for all of Anglo-Saxon England (Stenton 1971). Roads inherited from the Roman period continued to be used and developed and were utilised both for long-distance trade as well as pilgrimages (Brookes 2007, Howe 2005, Reynolds and Langlands 2011). Trade also developed which included local, regional and overseas trade systems as well as specialised manufacturing and trade centres using Anglo-Saxon coinage. By the 6th century CE, there are also examples of grave goods which had been imported into England (Arnold 2005, Crawford 2009, Hirst and Biek 1981, Huggett 1988, Loveluck 1998, Yorke 1990). For instance, in Sewerby, Yorkshire, 679 beads were excavated from 19 graves; these beads were of mixed materials but included crystal and glass which were not manufactured in England at this time and indicate overseas trade (Hirst and Biek 1981). Other imported Anglo-Saxon grave goods include glass vessels imported from France, lava quern stones from Germany, and elephant ivory from east Africa and India (Crawford 2009, Loveluck 1998).

2.3.5.10 Scotland and Wales
During the Early Middle Ages, Scotland - like England - was divided into a series of smaller Kingdoms. The four main Kingdoms to emerge were the Picts, the Anglican Kingdom of Bernicia, the Scots of Dal Riata and the Britons of Alt Cult (Cunliffe et al. 2004). At the end of Roman Britain and prior to Viking invasions there was a period of equilibrium between the different groups occupying Scotland. During this time Scotland also converted to Christianity with evidence of monasteries built in Scotland from the 5th century CE (Edwards 2017, Yeoman 2009). In the late 8th century raids by Vikings upset the balance between these Kingdoms and by the 9th century the Angles and the Picts had been destroyed and the Scots were left to rule these combined regions while the rest of modern day Scotland was ruled by the Vikings (Cunliffe et al. 2004, Macquarrie 2004).

Unlike England there was less Roman influence beyond Hadrian’s wall where Iron Age forts continued to be occupied during the Early Middle Ages. As Scotland lacked the urban centres built by the Roman, sites in Scotland during
the Early Middle Ages were predominantly agricultural (Cunliffe et al. 2004, Foster et al. 2006, Macquarrie 2004, Moffat 2015). Cattle and pigs, followed by sheep and goat were the predominant domesticated animals while domesticated fowl were rare in the Scottish zooarchaeological record (Arnold 2005, Macquarrie 2004, Moffat 2015). As with England, the quality and amount of food consumed varied substantially within Scotland with clear socioeconomic differences in diet. Porridge was a daily staple, made by boiling cereal grains with milk and salt. Meat was eaten on rarely by the majority of the population with the majority of protein coming from domesticates (Macquarrie 2004, Moffat 2015). However at coastal sites there is evidence that wild foods still formed an important part of the diet including sea birds, crustaceans, fish, molluses and algae (Macquarrie 2004).

Like Scotland, Wales was largely rural in the Early Middle Ages, during which times there was a gradual consolidation of power among increasingly hierarchical Kingdoms (Arnold 1997, Jones 1953, Walker 1990). Unlike Scotland, Wales had a legacy of Romanisation consisting of roads, villas and forts. The most common cereals crops in Wales were rye, barley and oats and as was the case in England, bread was a staple food, although bread in Wales was made from barley fermented with beer barm to make the mixture lighter (Davies 2000, Niles 2017, Hornsey 2003). Pottage was also frequently eaten in Wales, and while in England this rarely included meat, in Wales pottage typically included meat along with cereals and wild greens (Davies 2000).

2.3.5.11 Bioarchaeological Evidence from Early Medieval Britain

The Early Middle Ages is a relatively short period and underrepresented in the bioarchaeological literature (Mays and Beavan 2012). The studies that are available suggest a similar diet to the Iron Age assemblages being high in terrestrial proteins with a lower consumption of cariogenic foods compared to the Roman period (Hardwick 1960, Moore and Corbett 1971). Analysis of 102 individuals from the Early Medieval period between 500-1000 CE revealed Nitrogen and Carbon isotope values consistent with a diet high in terrestrial protein with little marine consumption even at coastal sites (Hemer et al. 2016). Similar results have been reported by Mays and Beavan (2012) who analysed stable isotope levels for 76 high status (determined based on the presence of
grave goods) individuals from 18 Anglo-Saxon sites. Nitrogen and Carbon isotope values indicate a reliance on terrestrial protein that was fairly consistent across all sites, although elevated carbon levels at coastal sites and Nitrogen levels among river sites is argued to indicate consumption of marine and freshwater resources (Mays and Beavan 2012).

As discussed, Anglo-Saxon burials vary in regard to their grave goods used to infer social and economic status of the deceased (Bayliss et al. 2013, Loyn 1991). Several studies have analysed dietary differences based on the prevalence of carious lesions (Jay and Richards 2006, Peck 2013, Privat et al. 2002) or from isotopic analysis to determine how these perceived status differences influenced diet. Peck (2013) and Jay and Richards (2006) reported no significant difference in the prevalence of carious lesions or stable isotope results and perceived social status. However contrasting results have been reported by Privat et al. (2002) who analysed stable isotope from an Early Anglo-Saxon cemetery at Berinsfield, Oxfordshire and compared results to age, sex and grave goods. Results from this study indicate dietary differences occurred between status/grave goods groups, while little difference was reported between males and females, indicating that status had a greater influence on diet compared to sex differences (Privat et al. 2002).

2.3.5.12 The Beginning of High Middle Ages
At the beginning of 1066 Edward ‘The Confessor’ (1042-1066) died leaving no direct heir to the English throne and Harold Godwinson was elected King. However, his succession was challenged by William, Duke of Normandy and Harold III of Norway who both invaded England on different fronts, at the same time Tostig Godwinson, Harold’s exiled brother raided south eastern England. Tostig and Harold III were both defeated in York at the Battle of Stamford Bridge (in September 1066) leaving Harold Godwinson’s armies depleted yet forced to, march south where William and his Norman forces had gathered at Hastings (Barlow 2014, Brown 2017, Cunliffe et al. 2004, Hughes 1988, Morillo 1999). During the ensuing battle Harold was killed marking the end of both Anglo-Saxon England and the Early Middle Ages (Barlow 2014, Brown 2017, Cunliffe et al. 2004, Golding 2013, Ormrod 1995).
2.3.6 Medieval Britain: Conflicts, Plagues, Famines and More Conflicts

The Medieval period in Britain began in 1066 after the battle of Hastings where the Normans were victorious and William ‘The Conqueror’ was crowned King (Barlow 2014, Cunliffe et al. 2004, Golding 2013, Ormrod 1995). The Norman invasion resulted in upheaval in the social organisation of Britain with many of the Anglo-Saxon gentry replaced by Normans. By 1086 only four members of the old English ruling class still possessed lands and the church had been re-organised. The Normans also fortified the existing wooden churches with stone, many of which still survive today (Carpenter 2003, Golding 2013).

Table 2.3.5: Time periods of Medieval Britain (Barras 2016, Ellis 2018, Goodman 2002, Hughes 1998, Spencer 2015, Thornton 2015).

<table>
<thead>
<tr>
<th>Medieval Britain</th>
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<tr>
<td>High Middle Ages (1066-1272)</td>
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<td>Norman Rule (1066-1154)</td>
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<tr>
<td>Plantagenet Rule (1154-1399)</td>
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<tr>
<td>Late Middle Ages (1272-1485)</td>
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<tr>
<td>Plantagenet Rule (1154-1399)</td>
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<tr>
<td>Lancaster Rule (1399-1461)</td>
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<td>York Rule (1461-1485)</td>
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After the initial upheaval the Norman period (1066-1154 CE) is characterised by increased social and economic stability (Golding 2013). This was in part brought about by the emerging feudal system and developing economy. England changed greatly as a series of rebellions between 1066 and 1069 CE led to the imposition of greater control to ensure law and order. This resulted in the creation of large mounted armed forces, continental style castles, and the introduction of the feudal system to England. It is estimated that by the reign of Henry I (1100-1135 CE) approximately 1,000 castles had been built in England (Brown 1969, Green 2006, Pounds 1993). During the High Middle Ages, Viking raids declined before ceasing altogether, and during the 11th and 12th century the population in Britain grew, and this was generally regarded as a time of prosperity (Cunliffe et al. 2004, Dyer 1989).
The following several hundred years towards the end of the High Middle Ages and throughout the Late Middle Age, are marked by further invasions, international and civil wars (1642-1651) and rebellions (Dyer 1989, Keen 2005). One of the bloodiest and well-known conflicts was the War of the Roses between 1455-1485 CE at the end of the Middle Ages (Goodman 2002). It was also during this period that Wales came under English rule with the first English Prince of Wales during the late 14th century. In Scotland there was a period of peace with England, however after 1286 this ended and was replaced with successive conquest and attempts by England to incorporate Scotland under English rule (Cunliffe et al. 2004).

2.3.6.1 Religion
In Medieval Britain the church dictated almost every aspect of life with the majority of the population belonging to the Roman Catholic church. Religious protocols restricted meat eating so that for the majority of the Middle Ages meat could not be eaten on Fridays, Saturdays, Wednesdays, or during Lent, instead dairy and eggs were proscribed. As a result of these meat restrictions fish consumption rose considerably (Adamson 2004, Breverton 2016, Newman 2001). Fish typically came in the form of salted and pickled herrings as well as a few dried fish. The rich and royalty had access to a large variety of fresh fish and shellfish and many estates and monasteries had their own fish ponds (Adkins et al. 2008). Conveniently, other animals were classed as fish and could be eaten on fast days including seals, whales and porpoises which seem understandable classification, others however required more of a stretch such as barnacle geese, puffins and beavers. Examples of these Medieval ‘fish’ are illustrated in figure 2.3.6 (Adamson 2004). Within English monasteries consumption of meat was abstained from between 960-1216 CE however there is evidence to suggest this was not always strictly adhered to (Müldner and Richards 2005, Spencer, 2011).
Figure 2.3.6: Tastes just like fish: Photograph of puffins (top left) and barnacle geese (top right), bearded seal (bottom left) and humpback whales (bottom right) all considered fish during the Middle Ages in Britain and as such could be eaten when meat was prohibited, illustrating the reaches that were made in classifying these species as fish (Hirst 2019).

2.3.6.2 Flora
Historical evidence indicates that for the majority of the population during the Late Middle Ages there was a dietary shift away from a more protein based diet to a more cereal based diet with a focus on wheat compared to the Early Middle Ages (Müldner and Richards 2005). Cereals were the principal foods for all, with the possible exception of the very wealthy, and were consumed principally in the form of bread but also as beer and ale. Ale appears to have been consumed in large amounts (Adkins et al. 2008, Qin 2017, Woolgar 2016). As an example, a monk had a basic allowance of one gallon of ale a day, and at Framlingham Castle 78 gallons of ale were consumed by the occupants every day (Adkins et al. 2008). Bread was also consumed in huge quantities in Late Medieval England (Adkins et al. 2008, Campbell and Atchley 1981, Miller and Hatcher 2014, Qin
White bread was increasingly preferred and was eaten in large amounts by those who could afford it. In London in 1304 CE there were 53 bakers, 32 for brown bread and 21 white bread; in 1574 CE this rose to 98 bakers with 62 making white bread and only 36 brown (Spencer 2011). As commercial bakeries become common in urban areas more advanced milling technology was developed, however the scale and demand for flour meant that corners were often skipped. During the late 14th century millers and bakers who cut corners and produced poor meal or bread faced expulsion from the craft (Mennell 1996, Sharp 2016, Stone 2006, Woolgar et al. 2006, Woolgar 2016). There was also a greater variety of types of bread, and while white bread was preferred, the most commonly eaten bread during this period was Maslin which was one of the cheapest breads available made with a combination of wheat and rye flour (Stone, 2006). There was however regional variation in bread consumed and in the north and west barley bread and oat cakes were more common. There is little evidence for the consumption of fruits and vegetables during this period although it is known that gardens were common amongst wealthier landowners who would have had the means to grow, and therefore consume fruits and vegetables (Adkins et al. 2008).

2.3.6.3 Fauna
Sheep became the most popular domesticate, with mutton predominating in the diet although beef was still preferred among those who could afford it, this shift was the result of economic demands as sheep were easier and cheaper to manage (Adamson 2004, Cunliffe et al. 2004, Stone 2003). Roasting meat was a popular cooking technique and veal and lamb became less popular meat choices because they did not roast as well as the older meats (Adamson 2004, Cunliffe et al. 2004). Larger cattle with a stature equal to Neolithic oxen became the dominant form and the diminutive cattle popular in the Iron Age appear to have been bred out (Jewell 1962). Pigs became the meat of the poor as they required little management and could forage on their own for the majority of the year (Adamson 2004).

During the Middle Ages, hunting became restricted to landowners and poaching was a serious crime punished by mutilation, as a result domesticates made up an even larger proportion of the protein consumed (Woolgar, 2016). Poultry were
consumed across the social-economic classes and especially with the clergy who were banned from eating meat from animals with four legs but not two. Among the more affluent classes there was more variation in the birds that were eaten compared to modern times and included: swans, peacock, crane, heron, blackbird, egret, gull and thrush (Adamson 2004). Additionally milk from sheep, goats and cows was used throughout the Middle Ages although by the 1500’s cow’s milk was the primary milk produced, due to the reduced milking time compared to sheep and goats (Adamson 2004, Wilson 2002). Milk was used for making cheese, cream and butter. Although among the wealthy milk as a beverage was not frequently drunk as it was considered the drink of children and invalids, instead it was eaten as a dessert cooked and sweetened (Adamson 2004, Wilson 2002). Peasants however, relied on these dairy products as a staple which included curds, whey, butter and cheese (Adamson 2004)

2.3.6.4 Diet
The Normans brought with them an increased variety of food items from other countries and during the Crusades (1095-1270 CE) contact between England and the rest of Europe and other continents influenced not only ingredients but also cooking styles (Woolgar 2016). However, for the majority of the population this had little effect and a diet mainly based on cereal crops remained largely unchanged by this increased contact. During the Late Middle Ages diet varied more substantially between different social groups (Müldner and Richards 2005). There also starts to be more written record of food with the earliest surviving English recipe book dated to around 1390. However surviving cookery books from this period only represent diets of the higher socio-economic groups and royalty (Bickham 2008, Colquhoun 2008, Kernan 2016, Mennell 1996).

Among lower class individuals the diet mainly comprised of cereal grains and pulses. Agriculture in Britain became more intensified with the most common grains being rye, oats, barley and buckwheat, with wheat - the most nutritious and prestigious grain - typically too expensive for individuals from low-socio economic groups (Adamson 2004). The primary source of protein among the lower class was milk, cheese, and eggs until the late 14th century when meat became a more affordable source of protein. However, even after this time dairy
and eggs as a source of protein was still common due to the religious abstinence of meat (Müldner and Richards 2005, Parker Parker Pearson 1997).

Pottage was a staple food that appears to have transcended the social classes similar to a stew this was made from a broth with vegetables, meat, cereals and pulses added as they were available. The ingredients however differed between social groups with the poor typically eating pottage made from vegetables and pulses with meat only added on occasion while the pottage consumed by the wealthy more frequently contained meat (Colquhoun 2008, Müldner and Richards 2005, Woolgar 2016). By the Late Medieval period there was a steady rise in the consumption of meat which was fairly consistent across socioeconomic groups. Isotopic analysis of skeletal assemblages from this period indicate that dietary differences were most prominent between geographic regions and/or monastic association rather than social status (Müldner and Richards 2005).

Sugars in the form of honey and syrups were popular at least among those who could afford it. Cane sugar was rare and expensive even in the Late Medieval period and was treated more as a spice used by the wealthy (Adamson 2004, Colquhoun 2008, Van Der Veen et al. 2013). Disparity in the ingredients accessible to different economic groups also influenced cooking methods. Boiling was the main cooking method with food cooked in pots and cauldrons over fire while for those who could afford joints of meat these would have been roasted on a spit (Adamson 2004, Colquhoun 2008).

2.3.6.5 Settlements and Urbanisation
Britain in the 1300’s was still predominantly rural with approximately 80% of the population living in rural settlements (Holt and Rosser 2014, Laughton, 2008). Most towns are thought to have had a population of around 5,000 however major cities had a much higher population. For instance in the 1300’s Winchester is thought to have had around 10,000 inhabitants while London may have had between 80,000-100,000 people (Laughton 2008). Growth during the Medieval period was concentrated in urban centres and transport links were considerably improved. Additionally, there were increased differences between rural and urban populations with regards to their access to resources. Towns became increasingly wealthy during the 14th and 15th centuries and occupational
diversity was well established with over 70 different occupations recorded in large towns while those in rural settlements mainly worked the land (Dyer 1989, Laughton 2008, Miller and Hatcher 1978).

2.3.6.6 Famines and Plagues
Successive years of failed harvests accompanied by floods beginning in 1293 CE led to food shortages and an inevitable rise in food prices, with grain and livestock prices nearly doubling between 1305 and 1310 CE. These food shortages and the resulting rise in food prices increased the socio-economic divide in diet and also contributed to the reliance on low quality food by the vast majority of the population (Adamson 2004, Kershaw 1973, Woolgar 2016). This was further impacted by livestock plagues in 1313 CE which together with the previous years of food shortages contributed towards the Great Famine (1315-1317 CE), during which 10-15% of the population in England died. Shortly after the famine bubonic plague, or the Black Death, spread along trade routes from central Asia arriving in the south of England in 1348 CE. The plague was active in England for about 18 months. During this time around half of the population succumbed and in some places the mortality rate was 60-70% (Adamson 2004, DeWitte 2010, 2014, Platt 1997, Woolgar 2016). Later plague outbreaks occurred in 1361 CE and 1369 CE and although it has been suggested that nutrition improved in England after this, many people still lived below the breadline (Adamson 2004, Woolgar 2016). Instability, famine and conflict followed the Black Death and contributed to the Peasant’s Revolt in 1381 CE (Adamson 2004, Woolgar 2016).

2.3.6.7 Bioarchaeological Evidence from the Middle Ages
Multiple studies have reported an increase in the prevalence of carious lesions among Medieval assemblages from Britain (Arce 2007, Hardwick 1960, Lukacs and Thompson 2008, Lunt 1974, O'Sullivan et al. 1993, Watt et al. 1997). Arce (2007) compared the prevalence of carious lesions among Romano-British, Early Medieval and Late Medieval sites and reported that among the Late Medieval assemblage the prevalence of carious lesions was greater than both the Roman and Early Medieval assemblages. However a study by Kerr et al (1988) indicates that in Scotland there was a lower prevalence of carious lesions compared to
English sites (Kerr et al. 1988) indicating that regional differences were present in the diet at least in regards to the cariogenic properties of food.

Isotope analysis of human remains from York indicate that during the Late Medieval period there was an increased consumption of marine protein (Müldner and Richards 2005, 2007). This is consistent with the historical and additional archaeological evidence indicating an increased reliance on marine protein brought about by stricter religious dietary restrictions (Hoffmann 2004) and the increased consumption of marine protein among monastic communities. Analysis of stable isotopes ratios from the third molar and rib was undertaken to analyse dietary changes from adolescence among individuals from two Medieval friaries (Kancle et al. 2018). Results indicate that there was an increase in the consumption of animal and marine protein during the individuals life suggested to support historical evidence of a ‘religious diet’ high in marine protein (Kancle et al. 2018).

2.3.6.8 The End of the Middle Ages
By the last century of the Late Middle Ages England was in financial difficulties with the gentry opposing increased taxation - in order to pay for the French wars - leading to a popular revolt in 1450 CE (Hughes 1998, Ormrod 1995, Wood 2007). Tensions continued to increase along with the deteriorating mental state of Henry VI (1422-1461 CE) and the lack of a direct heir which led to a series of conflicts known as the Wars of the Roses (1455-1487) during which time there was succession of short reigns ending with Henry VII (1485-1509) the first Tudor king of England who was then able to restore power and stability to the monarchy through marriage with Elizabeth of York ending the internal conflicts across Britain, at least temporarily (Goodman 2002, Hughes 1998).
2.3.7 Post-Medieval Britain: Urbanisation and Industrialisation…and more Conflicts

Unlike the preceding periods which are marked either by innovations, invasions or conflicts there is no firm boundary or distinction between the Medieval and Post-Medieval periods. As a result there are differing views as to when the Post-Medieval period begins, although it is generally considered to have started between 1500-1550 (Cunliffe et al. 2004, Gaimster and Gilchrist 2003). The most marked changes during this transition period occur in 1540 CE with the Reformation introduced by King Henry VIII (Cunliffe et al. 2004, Hall 2018) and the break from the Roman Catholic Church. Following the Reformation there continued to be a period of upheavals in the 17th century including a series of conflicts in Britain. The execution of Charles I, another civil war, and a decade of puritanical commonwealth government followed by the Restoration with a constitutional monarchy - all had a considerable effect on everyday life (Coates 2004, Purkiss 2007, Worden 2009).

Table 2.3.6: Post-Medieval Britain. Table illustrating the different time periods that make up the Post-Medieval period (Altick 1973, Lockyear and Gaunt 2018, Seaman 2003, Simms and Riotte 2007, Smith 1984b)

<table>
<thead>
<tr>
<th>Post-Medieval Britain</th>
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<tr>
<td>Tudor Period (1485-1603 CE)</td>
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<tr>
<td>Stuart Period (1603-1714 CE)</td>
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<td>Georgian Period (1714-1837 CE)</td>
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<td>Victorian Period (1837-1901 CE)</td>
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During the Post-Medieval period, Britain as it is today was formed with the union of England and Wales in 1536 and Scotland in 1707 (Davies 1999, Grant and Stringer 2003). Key trends which define the Post-Medieval period include large scale population growth with further movement towards urbanisation and an increasing number of the population living in cities and towns while the countryside was transformed through increasingly intensified and commercialised agriculture (Barker and Cranstone 2004, Burnette 2014, Cunliffe et al. 2004, Evans 2013).
2.3.7.1 Industrialisation

Mass loss of life as a result of the Black Death in 1348-1369 resulted in labour shortages all around Britain, which acted as a driving force for increased mechanisation and industrialisation (Barker and Cranstone 2004). This period saw rapid expansions of industry between 1750 and 1830 and is commonly referred to as the Industrial Revolution. Although rather than a single revolution this process is generally considered to have been long and drawn out with stages of economic and social changes starting from the 16th century onwards. This process of increased industrialisation was tied to urban growth and the intensification of farming practices. Additionally, these developing industries required fuel which led to the increased management and coppicing of woodland (Barker and Cranstone 2004, Clark and Cummins 2014, Evans 2013). Growth in industries ranging from iron, steel, pottery, glass and textiles typically relied on coal as a source of power (Clark and Cummins 2014) resulting in the increased burning of coal which substantially changed the environment in Britain.

The Industrial Revolution further intensified urban growth and dramatically changed the lives of people during this period. Industrialisation is associated with increased prevalence of certain diseases related to both population density but also environmental pollutants from the intense burning of coal and long periods of time spent working inside (Allen 2010, Justman and Gradstein 1999, Nef 1934, Wrigley 1998). Industrialisation is also known to have significantly changed people diets as working hours were long and arduous and workers needed to consume large amounts of calories quickly and cheaply to sustain them through a day of intensive labour (Barker and Cranstone 2004, Clark and Cummins 2014, Evans 2013).

2.3.7.2 Agricultural Revolution

The rapid population increases in the Post-Medieval period altered the demand for agricultural products not just in respect to the scale of these products but also their form. As a result agriculture was intensified and there was a movement towards farming strategies that increased both yields and income to support the growing urban population (Burnette 2014, Evans 2013, Lewis 2002, Rippon 2009). This was accomplished through the introduction of new crops and
breeds, adding lime as a fertiliser, and creating extensive system of drains and - in some areas – establishing water meadows (Burnette 2014, Evans 2013). This increased demand also influenced livestock. Increased bone size for cattle and sheep at a number of sites indicates selective breeding of livestock to produce large, more meat productive species (Davies 1999, Thomas 2005, Thomas et al. 2013). Additionally, shifts in the use of domesticates are evidenced in the mid-16th to mid-17th century suggesting an increased focus on dairying based on the increased consumption of veal compared to older cows as demonstrated from the age profiles of zooarchaeological remains (Barker and Cranstone 2004).

2.3.7.3 Urbanisation
There were massive population increases in the Post-Medieval period with the population trebling between the 16th and 19th century. This increase in population further drove commercialisation of agriculture and growth of towns and cities (Barker and Cranstone 2004, Shaw-Taylor and Wrigley 2014). By the early 19th century, mechanisation and industrialisation had transformed Britain from a predominantly rural population to an urban one (Barker and Cranstone 2004, Cunliffe et al. 2004). In 1500 CE around 10% of the population lived in major towns, in 1700 this had increased to 20% and by 1841 CE over half the population lived in towns or cities making Britain the first European country with a predominantly urban population (Adkins et al. 2008, Barker and Cranstone 2004).

The majority of this urban population growth was concentrated in London which in the mid-19th century had a population of over two million. Other cities that saw the bulk of population growth were the growing industrial centres of Manchester, Sheffield, Leeds and Birmingham as well as the majority ports such as Bristol, Liverpool and Glasgow (Adkins et al. 2003). These growing cities were overcrowded and lacked proper sanitation, resulting in frequent outbreaks of contagious diseases often focussed at city ports and trade centres. Poor nutrition and food shortages acted to further exacerbate these outbreaks (Adkins et al. 2008, Barker and Cranstone 2004, Lewis 2002).
2.3.7.4 Religion
The Protestant Reformation in England initiated by King Henry VIII in 1534 saw wide ranging reforms with the dissolution of the monasteries in England and Wales between 1536 and 1540. Protestantism in the form of the Church of England was the majority religion until a brief return to Catholicism between 1553-1558 under the reign of Mary I, before returning to Protestantism with the ascension of Elizabeth I in 1558 (Lee 2006, Picton 2015, Richards 2014). During this time a number of rebellions, conflicts and executions occurred in Britain and religious persecution was rife. In 1560 Catholicism was rejected in Scotland and eventually Britain became a religiously stable Protestant country (Adkins et al. 2008, Cunliffe et al. 2004, Gaimster and Gilchrist 2003). The Post-Medieval period also saw large scale immigrations of different ethnic and religious groups, especially in London and other large cities (Cunliffe et al. 2004).

2.3.7.5 Diet
During the early Post-Medieval period and the Tudor times (1485-1603 CE), diet was very similar to the Middle Ages consisting of pottage and when available roasted or boiled meat, poultry and salted, pickled or dried fish (Pennel 2016, Woolgar 2016). While fruit was generally considered unhealthy during the Middle Ages and early Post-Medieval period, the suspicion of raw fruit and vegetables gradually subsided during the 17th century (McKee 1995, Woolgar 2016). Later in the Post-Medieval period the British Empire expanded, and new ingredients and manufactured goods were imported. During the mid-sixteenth century tomatoes, kidney beans and potatoes were introduced. Initially treated as an unusual delicacy and it was not until was centuries later that they were incorporated into day to day diet (Mack 2001, Mennell 1996). In the 1540s, the turkey was introduced from the Americas and unlike some of the other exotic imports turkey quickly became popular (Cunliffe et al. 2004, Woolgar 2016). Beverages also changed substantially with tea and coffee imported from China and Arabia. At the beginning of the 17th century the majority of foods presently in Britain had already arrived (Cunliffe et al. 2004, Marshall 1998). Meat was consumed in increasingly large amounts during the Post-Medieval period and it has been estimated that three quarters of food consumed by all but the very poorest consisted of meat (Albarella 2004, Cunliffe et al. 2004, Perren 1978, Thomas 2009). Hunting continued it was more of a sport/fashion of the landed
gentry and the wealthy, as such the vast majority of meat came from domesticates (Sadler and Jones 2007, Taylor 2002, Thomas 2005, 2007).

Sugar was the most significant change in Tudor England; while once treated as a spice sugar grew in popularity and increased quantities of sugar were imported (Adkins et al. 2008, Brooks 2016, Wilson 1973). In Elizabethan times (1558-1603) sugar refining began in Britain and groceries stocked sugar in the form of loaves of 100lbs which could be broken or chipped for sale (Bickham 2008, Brooks 1983, 2016, Spencer 2011). Colonies in Barbados produced sugar cane which was exported to Britain, massively increasing the quantity of sugar consumed with preserved confectionaries and syrups being popular. Still the majority of sugar was consumed by the wealthy during the early Post-Medieval period (Bickham 2008, Spencer, 2011, Woolgar et al. 2006). At the beginning of the 16th century the price of sugar had decreased to 4d to 10d a pound, which today would be equivalent to £11.10-£27.75, equal to one days labour for a skilled workman. This rose to between 1 s and 1 s 6d by the end of the century, however rapid inflation occurred in the mid-16th century, so this would have been the equivalent of £6.89-10.34 (Spencer, 2011, Weale 2000). Bakery products also changed greatly during this time and cakes made from enriched dough sweetened with sugar and heavily spiced were popular alongside gingerbread and biscuits (Brooks 2016, Broomfield 2007, Mintz 1985, Spencer 2011, Wilson 1973, Woolgar 2016). Consumption of sugar continued to rise in Britain and it is estimated that in the 1840’s 30lb of sugar was consumed per person with this figure rising to 80lb by the end of the century (Spencer 2011).

The English Civil War in conjunction with the Puritan movement both acted to improve the diets and lives of the poorer populace, particularly for women. Prior to the English Civil War, the divide between the rich and poor became even more pronounced, a divide that was particularly evident in both the diet and the culture of food and dining (Spencer 2011). During the Stuart reign, issues with land and monopolies became the cause of social unrest when the government introduced heavy regulations on many industries through the creation of guilds and monopolies. These monopolies controlled almost all foodstuff including

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8 old English pence, with 240 pence equivalent to one pound
9 shilling, 20 shillings equivalent to one pound
butter, salmon, salt, pepper, wine and currants and in 1621 there were over 700 monopolies in England (Churchill 1925, Peck 2004, Spencer 2011, Weston and Greenberg 2003).

### 2.3.7.6 Cooking and Dining
The technological developments brought about by the Industrial Revolution influenced cooking technology although these innovations were slow to roll out into kitchens across Britain (Spencer 2011). Tin plate rolling machines allowed the large scale production of baking trays and tins needed for a range of pies, tarts and all assortments of baked goods (Gibbs 1950, Pennel 2016, Spencer 2011). One of the most significant changes during the 17th century in dining occurred with the introduction of the fork. Although forks had been used among royalty and nobility for the consumption of sweetmeats since the 14th century, it was not until the 1660's when knife and fork cutlery became popular in Britain (Cunliffe et al. 2004, Wilson 1973). Other technological advances occurred during this period, for instance advances in milling resulted in the production of finer flour and softer more refined bread. Cooking methods however did not change greatly during the 17th century and mostly centred around boiling which was one of the most economical cooking methods whilst the bee hive oven was the only other frequently used means of cooking (Cunliffe et al. 2004, Drummond and Wilbraham 1957, Wilson 1973). Cook books in the 17th century began to resemble meals that would not be considered out of place in a 21st century kitchen, such as plaice poached in white wine seasoned with herbs and spices or chicken pie seasoned with nutmeg (Cunliffe et al. 2004, Driver 1984, Drummond and Wilbraham 1957, Wilson 1973). It was not until the 18th century that kitchen equipment evolved on a wider scale and there was huge variety in the forms of pots, pans and dishes available and roasting surpassed boiling as the favoured cooking technique. Ranges developed in Britain during 19th century and made cooking easier and the popularity of modern ranges also marked the end of spit roasted meats as the vast majority of homes lacked an open range (Broomfield 2007).
2.3.7.7 Bioarchaeological Evidence from Post-Medieval Britain

Among Post-Medieval assemblages the prevalence of carious lesions has been reported to be higher compared to the previous periods (Moore and Corbett 1975, Moore and Corbett 1976, O'Sullivan et al. 1993). This is associated with the increased consumption of sugar and refined carbohydrates (Corbett and Moore 1975, Moore 1993). The lack of status and sex differences in the prevalence of carious lesions reported among Post-Medieval sites suggests that a diet high in cariogenic foods was accessible regardless of status. Analysis of 168 individuals from the Post-Medieval cemeteries of Chelsea Old Church (n=78) and St Brides Lower Churchyard (n=90) in London revealed a high prevalence of carious lesions among males and females with the molar dentition being the most frequently affected (39.0% and 37.8%) while the lowest prevalence of carious lesions occurred among the incisors (8.6% and 20.6%) (Mant and Roberts 2015). Statistically significant sex differences were only recorded among the molars, where females had a significantly higher prevalence of carious lesions for both sites compared to males (Mant and Roberts 2015).

Although the two cemeteries represent different socio-economic groups, significant differences in the prevalence of carious lesions were only recorded among the incisors indicating that individuals from both cemeteries were consuming similar cariogenic diets. Similar results were reported by Brickley et al. (2006) who analysed the prevalence of carious lesions among high and low socioeconomic sites London.

Isotope analysis from Post-Medieval sites, suggest little change in protein consumption (Müldner and Richards 2007, Nitsch et al. 2010, Trickett 2006). Analysis of the 17th-19th century site of All-Saints in York indicate continued consumption of marine protein (Müldner and Richards 2007, Müldner and Richards 2005). These results were unexpected as religious restrictions regarding the consumption of animal protein declined sharply after the Reformation (Spencer 2011).
2.3.8 Britain Since the Neolithic - a Summary

As detailed in this chapter the social, cultural, political, religious and technological developments that have occurred in Britain since the Neolithic are numerous and many of these changes have had a profound influence on people’s relationship with food, both what they ate and how they ate it. To illustrate the vast array of changes that have occurred during the time period covered in this study figure 2.3.9 gives a summary timeline which shows the key socio-cultural, technological and dietary changes in Britain.

Dietary changes similar to those that have occurred in Britain since the Neolithic are suggested to have reduced masticatory strain over the course of human evolution, as diet became softer and increasingly more processed (Katz et al. 2017, Lieberman 2008, von Cramon-Taubadel 2011). This reduced masticatory strain is suggested to have played a key role in the evolution of human craniofacial morphology (Galland et al. 2016, Katz et al. 2017, Pinhasi et al. 2007, Rudney and Greene 1982, von Cramon-Taubadel 2011, Varrela 1992, Watson et al. 2018), with a number of theories relating diet to an increasingly gracile cranial morphology among anatomically modern humans which are discussed further in chapter 3 (Brace 1964, Brace et al. 1987, Calcagno and Gibson 1988, Cieri et al. 2014, Frayer 1980, Larsen 1995, Lieberman 2008, y’Edynak 1989).
Figure 2.3.7: Britain Since the Neolithic a Summary. In order to illustrate the numerous changes, developments, innovations and introductions that have occurred in Britain since the Neolithic these are shown in a condensed timeline (authors own image).
Chapter 3
Craniofacial Evolution and Bone Remodelling

Since the emergence of Anatomically Modern Humans (AMH) approximately 200 – 300 kya (Lamb et al. 2018, Neubauer Hublin et al. 2018, Stringer and Calway-Witham 2017), the cranium has become increasingly gracile with the dimensions of the facial bones decreasing in size and the cranial vault becoming more rounded and globular. While a number of different theories have been proposed to explain these changes, one of the most prominent is the Masticatory Functional Hypothesis (MFH) (Carlson 1974, von Cramon-Taubadel 2017, Katz et al. 2017). The MFH suggests that mastication stimulates the growth and development of the craniofacial bones (Pinhasi et al. 2007, Varrela 1992). Changes in masticatory behaviours (dietary changes) therefore are considered to influence the shape/form of the skull. As subsistence strategies and food processing techniques have changed dramatically over the course of human history it has been suggested that this has resulted in a reduction in masticatory stress, which has reduced and altered the craniofacial complex. This chapter will first detail the craniofacial changes that have occurred since the emergence of AMH and the theories proposed to explain these changes. Following this, bone remodelling theory will be discussed to detail how biomechanical forces can influence bone morphology.
Table 3.1: Human Cranial Features. Diagnostic features of Anatomically Modern Human Crania, information from Lieberman et al. (2002).

<table>
<thead>
<tr>
<th>Diagnostic Feature of Anatomically Modern Humans Crania</th>
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<tbody>
<tr>
<td>Short high cranial vault</td>
</tr>
<tr>
<td>Parietals long and curved in mid-sagittal plane</td>
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<tr>
<td>Parietal arch high and wide in coronal plane</td>
</tr>
<tr>
<td>Occipital bone long, narrow, not markedly projecting</td>
</tr>
<tr>
<td>High frontal angle</td>
</tr>
<tr>
<td>Weak, noncontinuous supraorbital torus divided into medial and lateral portions</td>
</tr>
<tr>
<td>Canine fossa present</td>
</tr>
<tr>
<td>Globular cranium – a rounded cranial vault in the sagittal, coronal, and transverse planes</td>
</tr>
<tr>
<td>Retracted face – refers to the anteroposterior position of the face relative to the anterior cranial base and neurocranium</td>
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3.1 Anatomically Modern Human Evolution

Since the emergence of AMH, the skull has undergone significant reductions in overall size and the degree of robusticity, or ‘gracilization’ (Baab 2018, Godinho et al. 2018, Katz et al. 2017, Lahr 1996, Lieberman 1998, Lieberman et al. 2002). The cranial morphology of early AMH fossils differs considerably from that of the majority of living human populations (see Table 3.1 for typical AMH features). Early human fossil crania have been recorded to be as much as 10-30% larger and more robust (Kidder et al. 1992). The cranial morphology of early modern *Homo sapiens* from the Palaeolithic include: a long cranial vault, robust features such as a large mental eminence, large external occipital protuberance, projecting mastoid process, marked glabella, projecting lower face and a broad upper face (Hublin et al. 2017, Lahr et al. 1996, Lahr 1996, Reiner et al. 2017, Trinkaus 2005). Similarly the mandible morphology of these early human fossils is large and robust, complemented with large dentition (Lahr et al. 1996, Lahr 1996, Liu et al. 2010, Trinkaus 2005, Trinkaus et al. 2003). For instance the earliest known AMH fossil evidence dates to 315±34 kya from Jebel Irhoud, Morocco where a minimum of five individuals were excavated (Hublin et al. 2017). The Jebel Irhoud fossils had a tucked under face, a long cranial vault, although this is more globular than archaic *Homo sapiens* (AH), as well as robust brow ridges and very large teeth which are more consistent with more AH as illustrated in figure 3.1.1.
Figure 3.1.1: Early AMH cranial morphology compared to Recent Modern Humans. Diagram illustrating the cranial and mandibular outline for the reconstructed cranial remains from Jebel Irhoud, Morocco (left). This is compared to a generalised modern human (right) based on a photograph of a modern human skull. This diagram illustrates the reduction in robust superstructures such as the brow ridge and external occipital protuberance as well as the increased globularity of the cranial vault, gracilisation of the mandible and reduced prognathism of modern human populations.

During the Middle and Upper Palaeolithic (200-10kya), the robusticity of the cranial superstructures decreased, the skull shortened and levels of sexual dimorphism decreased while ‘facial retraction’ and ‘globularity’ of the cranial vault increased (Brace et al. 1987, Lieberman et al. 2002, Smith et al. 1982, y’Edynak and Iscan 1993). Middle Palaeolithic (200-50 kya) fossils continue to exhibit a suite of both archaic and anatomically modern features. For example, Omo-Kibish (dated to 195-150 kya) has a number of robust features and muscle attachments such as the mastoid process, occipital torus, temporal ridge and supra-mastoid crest while also having a higher, more rounded cranial vault more similar to that of modern humans (Day 1969, Trinkaus 2005). Early modern human fossils from the Upper Palaeolithic (50-10 kya) such as those from Maldeč, Czech Republic dated to approximately 35 kya exhibit more gracile features consistent with AMH. Although some more robust features including a
broad upper face and large molars remain (Trinkaus et al. 2003). In addition to
the craniofacial reduction that occurred during the Palaeolithic, there has also
been a decrease in tooth size recorded at the rate of approximately 1% every
2000 years between 100,000 and 10,000 years BP (Brace et al. 1987).

It is not, however, until the Mesolithic (9,000 – 4,000 BCE) and Neolithic (4,000
– 2,500 BCE) periods when significant cranial reductions are recorded in the
fossil record. Over the last 10,000 years further decreases in sexual dimorphism
have been recorded, while cranial gracilisation became more pronounced
moving towards the gracile globular shape observed among living populations.
Similarly the reduction in dentition doubles, with teeth reducing 1% every 1000
years (Brace et al. 1987, Frayer 1980, González-José et al. 2005, Henneberg 1988,
Larsen 1995). These reductions have been recorded across the globe, with
human remains from Africa, Asia, Europe and to some extent Australasia,
showing similar levels of gracilisation (Kallen and Gans 1972, Lieberman,
Krovitz et al. 2004, Pinhasi et al. 2007). This gracilisation has been argued to
primarily effect the masticatory complex with significant reductions in the size
and robusticity of the mandible. As such these changes are thought to be
associated with marked changes in subsistence strategies and diet (Richards
2002, Sardi et al. 2004). Several theories have been proposed for the rapid change
in craniofacial morphology that occurred during the Mesolithic and Neolithic
periods, which will now be explored.
3.1.1 Theories for craniofacial reduction

There are a number of different theories for why the craniofacial complex has reduced, with several suggesting a link between human behaviour (dietary or cultural) and biological changes (Frayer 1980, Larsen 1995, Lieberman 2008). This section will briefly discuss five of the more commonly cited theories, the proposed evidence that underpins them, and whether this evidence explains the observed reductions.

3.1.1.1 Cognition, Brain Shape and Cranial Morphology

A number of models have been proposed that relate changes in cranial morphology over human evolution to evidence of cognitive evolution such as the appearance of more complex technologies from upper Palaeolithic AMH sites (Lieberman 2008). These models have linked archaeological evidence such a development in stone tool industries, with increased cognitive capabilities, and the increase in overall brain size or changes in specific regions of the brain. These theories typically suggest that changes to the face and jaws were secondary to cognitive development (Ambrose 2001, Lieberman 2008). For instance, Ambrose (2001) associated developments in stone tool technology in the Middle Palaeolithic with increased cranial capacity. However both the absolute and relative brain size are approximately equal between AMH and AH (Holloway 1985, Ruff et al. 1997). Furthermore the majority of evidence for this model is in fact the absence of evidence for Upper Palaeolithic technologies or symbolic artwork recorded at AH sites (Lieberman 2008).

Other theories related to the cognition of AMH suggest that cranial changes may relate to increases in the relative size of specific regions of the brain, such as a larger frontal lobe thought to relate to social cognition (Deacon 1997, Dunbar 2003) and an enlargement of the surface of the parietal lobes thought to relation to increased importance of spatial recognition (Bruner 2010). However these theories have been rejected based on evidence from comparative studies of hominoids and extant primates that demonstrated that the relative size of the frontal, parietal and occipital lobes are similar compared to AMH (Lieberman 2008, Semendeferi et al. 2001). There is however evidence that cranial morphology of AMH may be related to the size of the temporal lobe which is up to 25% proportionally larger than extant apes (Holloway et al. 2004).
temporal lobe is involved in the organisation of sensory input which is necessary for language and memory (Binder et al. 1997, Simons and Spiers 2003). A geometric morphometric analysis comparing AH and AMH cranial morphology determined that the region of the crania which contains the temporal lobes is 15-20% longer and 20% wider relative to cranial size in AMH (Lieberman 2008, Lieberman et al. 2004, 2002). These changes in cranial morphology have also been suggested to account for the reduction in the facial morphology and the resulting tucked under appearance of AMH faces which is illustrated in figure 3.1.2 (Lieberman 2008). However as previously discussed the Jebel Irhoud fossils demonstrate that facial reductions and developments of a ‘tucked under’ facial form predated changes in the cranial vault at least at this site (Hublin et al. 2017).

Figure 3.1.2: Diagram showing the changes in facial morphology that have resulted in a ‘tucked under’ facial appearance among modern humans. Photographs of hominin fossils illustrating a retraction of the facial features to be positioned under the cranial vault among modern humans (d)12, with Upper Palaeolithic individuals from Mladeč ~31 ka (c)13, compared to the more pronounced and prognathic features of early modern Homo sapiens from Quafzeh ~95ka (b)14 and Jebel Irhoud ~300 ka (a)15.

12 Image from: Stringer and Calway-Witham 2017, 212, Figure 1
13 Image from: Wild et al. 2005, 33, Figure 1
14 Image from: Scerri et al. 2018, 583, Figure 1
15 Image from: Stringer and Calway-Witham 2017, 212, Figure 1
3.1.1.2 Probable Mutation Effect

One theory proposed to account for the reductions in tooth size recorded among the past 40,000 years and documented worldwide, is the probable mutation effect (Brace 1964, Brace et al. 1987, Calcagno and Gibson 1988). The Probable Mutation Effect (PME) states that selection pressures relax when structures are no longer functionally required. When these selection pressures relax it allows for mutations to accumulate within the population reducing the size of the structures that are no longer functionally required (Brace 1964). A proposed example of the PME model includes the loss of eyesight and pigmentation among cave fish that live in near total darkness (Holloway 1966). In humans it has been suggested that craniofacial reduction is the result of technological advances in food processing, which have reduced the functional masticatory requirements (Calcagno and Gibson 1988). This reduction in functional requirement of the masticatory apparatus led to a relaxation of the pressure for large dentition allowing for an accumulation of mutations causing a reduction of the craniofacial structures and in the dentition itself (Brace 1964, Calcagno and Gibson 1988). However there are several strong criticisms against the PME model as it is not supported by bioarchaeological, genetic and dental evidence (Bailit and Friedlaender 1966, Calcagno and Gibson 1988, Holloway 1966, Ritter et al. 2009). For example, the PME model makes several genetic assumptions which Calcagno and Gibson (1988) argue are invalid. The PME model requires high levels of mutations per generation, around $2 \times 10^{-5}$, however estimates of the average mutation rate in humans is around 20 to 200 times smaller than this (Awadalla et al. 2010, Calcagno and Gibson 1988, 1000 genome consortium 2010, Lynch et al. 2016). Furthermore if these changes result from the accumulation of a large number of mutations within populations in the absence of selection pressures, it is argued that this would result in an increase in variability within populations and does not account for the consistent trend in dental reduction seen over time among AMH (Bailit and Friedlaender 1966). Moreover rather than the argument that larger teeth are no longer advantageous and therefore selective pressure is reduced Calcagno and Gibson (1988) argued instead that natural selection is more likely to account for this reduction as proportionally larger teeth have been found to have a deleterious effect on human health (Quek et al. 2003, Saglam and Tuzum 2003). As such, it is argued
that large teeth may have been selected against after a reduction in mandible morphology (Calcagno and Gibson 1988).

3.1.1.3 Selection for reduced body-size in males
An alternative explanation for the reduction in dentition and increased gracilisation of the crania is that this was the result of changes in the sexual division of labour between the Palaeolithic, Mesolithic and Neolithic periods (Frayer 1980). This theory states that advancements in hunting technologies are related to a decrease in robustness among males (Frayer and Wolpoff 1985, Frayer 1980). It is hypothesised that during the Upper Palaeolithic hunting required more robust phenotypes among males to compensate for limited hunting technologies. When hunting technologies became more advanced during the Mesolithic, this arguably reduced the selective advantage of increased robusticity among males (Frayer 1980, Hill et al. 2017). Therefore, this observed decrease in sexual dimorphism is argued to be evidence that the activities performed by males and females overlapped. This theory was supported by an ethnographic study which found that among hunter gather populations there was a greater degree of sexual dimorphism compared to agriculturalists (Murdock and Provost 1973). However there are several problems with this theory. The first is that it has been suggested that the greatest decrease in sexual dimorphism occurred between the Upper Palaeolithic and Mesolithic (Frayer and Wolpoff 1985, Stulp and Barrett 2014, Vick 2005), and that modern levels of sexual dimorphism were reached at least 150 kya (Ruff 2002). While technological developments occurred between these periods there is no evidence for significant changes in subsistence strategies. A review of 50 different subsistence behaviours among 185 human populations reported that the activities most consistently shared among males and females were associated with agriculturalist populations such as crop planting, harvesting and milking (Murdock and Provost 1973). As such it would be expected that during the Neolithic when subsistence strategies changed from hunter-gathering to agriculture one would expect to see the most marked reductions in sexual dimorphism, but this was not observed. Additionally sexual dimorphism has been demonstrated to be influenced by other environmental as well as genetic factors (Perez and Monteiro 2009, Silventoinen 2003, Steyn et al. 1999, Ubelaker and DeGaglia 2017), such as nutrition (Frayer and Wolpoff 1985, Gray and

3.1.1.4 Masticatory-functional hypothesis
When considered in the coronal plane, the modern human face is between 30-50% smaller than that of AH. Some proportion of this reduction is said to be epigenetic and attributable to the reduction in masticatory strain brought about by a softer more processed diet (Lieberman 2008). These changes in craniofacial and dental morphology among the Homo lineage have also been associated with a reduction in masticatory demands brought about by changes in diet as well as cooking and food processing methods (e.g. Robinson 1954, Brace 1991, Wrangham et al. 1999, Lieberman et al. 2004, Ungar et al. 2006, Zink and Lieberman 2016). During the Palaeolithic when gradual facial reductions were recorded there is the earliest evidence of cooking in the form of hearths (Goldberg et al. 2001, James 1989, Lieberman 2008), and the Mesolithic and Neolithic when craniofacial reductions became more pronounced is associated with the advent and increased development of agriculture which is considered to have resulted in a significantly softer and more processed diet (Katz et al. 2017, von Cramon-Taubadel 2011).

The Masticatory-Functional Hypothesis (MFH) proposed by Carlson (1974) states that advancements in food processing technologies resulted in a softer diet which did not require as much time or force to masticate (Carlson and Van Gerven 1977, Varrella 1990). Mandible growth and morphology has been demonstrated in several clinical and animal studies to be associated with masticatory activity – this is discussed further in section 4.4.1 and 4.4.2 (Barber et al. 1963, Enomoto et al. 2010, Mays 2013, Watt and Williams 1951). The MFH therefore argues that by reducing this strain over time through technological development, the size of the masticatory apparatus decreased and that this resulted in the other cranial changes that typify modern humans since the Upper Palaeolithic. Dental reduction is considered by the MFH to be a secondary or tertiary development, related to the reduction of the dimensions of the masticatory apparatus. There is considerable archaeological, animal and clinical support for the role of masticatory strain in the gracilisation of the modern

The MFH was originally developed based on the observation of significant craniofacial differences between Nubian populations over time, which represent hunter-gatherer, incipient agricultural and fully agricultural populations (Carlson and Van Gerven 1977, Carlson 1974). Of the 16 craniofacial measurements taken from the sample, 11 were found to be significantly different among the subsistence groups. Nine of the significant measurements represent cranial structures considered to be directly related to masticatory function (Carlson and Van Gerven 1977). Although there are a number of criticisms associated with the earlier studies that provide support for the MFH, including: the low Mesolithic sample size, reliance on just 16 cranial and mandibular linear measurements, or the assumption that the samples employed by Carlson and Van Gerven (1977) represent a biologically continuous population. Despite this, recent studies continue to provide support for an association between diet, mastication and cranial morphology (Katz et al. 2017, Rudney and Greene 1982, von Cramon-Taubadel 2011, Galland et al. 2016, Watson et al. 2018). During human evolution widespread dietary changes have been recorded that are generally considered to have reduced masticatory strain which are consistent with the craniofacial reductions present in the fossil record.

While there is considerable support for MFH with regard to reductions in the masticatory complex among modern human populations (Rando et al. 2014, Stansfield et al. 2018, Varrela 1992, von Cramon-Taubadel 2011) other studies have also suggested that the human masticatory apparatus has evolved for increased mechanical efficiency allowing for the production of high bite forces with low muscular effort among modern humans (Spencer and Demes 1993, O’Connor et al 2005, Lieberman 2008, 2011, Wroe et al. 2010, Eng et al. 2013, Ledoga et al. 2016). For instance, Wroe et al. (2010) argued that the human cranium has adapted to produce higher masticatory forces based on finite element analysis of modern human, extant ape and fossil Australopithecine crania. Wroe et al. (2010) reported that modern humans had a more efficient feeding apparatus. This high bite force leverage among humans contrasts with
theories that there has been a relaxation of the selection forces that favour high bite force (e.g. Brace 1991, Lieberman et al. 2004, Ungar et al. 2006). However, results from a study by Stansfield et al. (2018) did not support the notion that the mandible of modern human populations are better adapted to generate and withstand mechanical loading. Instead they argue that facial reduction and retraction resulted in increased biting efficiency and was not driven by the need for increased bite forces. The reduction in size and robusticity of the mandibles of modern populations is suggested to reflect underdevelopment rather than adaptation to dietary changes (Stansfield et al. 2018). Finally, this model fails to fully explain the selective forces that resulted in a reduction in size of dentition among individuals with a smaller craniofacial dimension - a gap which the Mixed Model attempts to explain.

3.1.1.5 Mixed Model: biomechanical and natural selection
An adaptation or development of the MFH is the Mixed Model which combines the biomechanical aspects of the MFH with natural selection (y'Edynak 1989). This theory states that technological advancements with regards to food processing led to a softer diet that required lower masticatory strain levels which subsequently reduced the size and robusticity of the mandible. However, the Mixed Model then diverges from the MFH by arguing it is this decrease in mandibular dimensions increases the prevalence of malocclusions because the teeth are too large to fit the jaws. The over-crowding of the dentition is suggested to result in an increased prevalence in dental pathology which due to the negative affect on human health selects for smaller dentition (y'Edynak 1989, y'Edynak and Fleisch 1983). As discussed in the section 3.1.1.4 above there is considerable evidence to suggest that a reduction in biomechanical demands may be associated with a reduction in the dimensions of the masticatory apparatus (Kiliaridis et al. 1995, 1989, Odman and Kiliaridis 1989, Sella-Tunis et al. 2018, Toro-Ibacache et al. 2016), and a correlation has been recorded in the prevalence of dental impaction and mandibular dimensions (Kaya et al. 2010). However, there is little evidence in favour of selection pressure for smaller dentition being related to increased malocclusion and/or dental pathology (y'Edynak 1989). Furthermore, this model ignores the prominent role of dietary composition in the prevalence of dental pathology. Although the prevalence of both malocclusion and dental pathology have increased since the advent of
agriculture, substantial changes in dietary composition have also been recorded. Increased reliance on dietary carbohydrates occurred during this transition, which are well documented to be associated with the development of carious lesions (Green and Hartles 1966, Touger-Decker and van Loveren 2003). Moreover, if the driving force for a decrease in tooth size was the deleterious effect of dental pathology (such as carious lesions) on human health it is argued that teeth which are morphologically less complex would be more advantageous than smaller teeth (Carlson and Van Gerven 1977). Dental impaction however, has been argued to result in infection (Adeyemi et al. 2016, Al-Hansabu et al. 2011, Frazee 2008, Quek et al. 2003, Renton and Wilson 2016, Saglam and Tuzum 2003), and has been suggested to be associated with dental crowding resulting from a mismatch between jaw and tooth size (Normando et al. 2016). A high prevalence of dental crowding has been recorded among modern humans (Dachi and Howell 1961, De Souza et al. 2008, Disha et al. 2017, Normando et al. 2016). Comparatively, among fossil ancestors malocclusion and dental crowding has been rarely recorded (Brace 1963, Brace and Mahler 1971), with prevalence of malocclusion increasing during the Holocene among agriculturalists (Gibson and Calcagno 1993). Moreover dental crowding has been suggested as an evolutionary force in the agenesis of third molars and individuals with agenesis of the M3 were found to have less crowding and a lower prevalence of dental pathology (Esan and Schepartz 2017, Keene 1964, Trakiniene et al. 2018). Agenesis in turn is argued to be related to a reduction in general tooth size (Abu-Hussein et al. 2015, Azzaldeen et al. 2017, Garn et al. 1963, Higashihori et al. 2018, Wright et al. 2016).

These are just a few of the models proposed to account for the craniofacial evolution among AMH, with new theories still being proposed. A more recent theory argues that craniofacial gracilisation among AMH is related to behavioural modernity and social cooperation necessary for increases in population density (Cieri et al. 2014). This theory proposes that the gracilisation of the craniofacial region is the result of feminisation brought about by a decrease in testosterone or androgen reactivity is argued to relate to higher levels of social tolerance (Cieri et al. 2014). As the morphology of the crania is critical for several functions including “cognition, vocalisation, respiration, diet and thermoregulation” (Lieberman 2008, 55) the lack of consensus regarding the
gracilisation of modern human craniofacial structures is hardly unexpected. There is however, sufficient evidence for at least the partial role of reduced masticatory strain in reduction of the masticatory apparatus over human evolution (von Cramon-Taubadel 2011, 2014, 2017, Moore et al. 1968, Rando et al. 2014, Varrela 1992). Furthermore, among more recent archaeological assemblages – Medieval and Post-Medieval periods - there is evidence for a continued reduction associated with large dietary transitions such as industrialisation (Moore et al. 1968, Rando et al. 2014). As such the morphology of the masticatory apparatus may be used to infer changes in masticatory strain and dietary consistency. While the MFH relates large dietary transitions and innovations with the increasingly gracile craniofacial complex among modern humans, smaller dietary changes recorded in recent British history discussed in Chapter 2 may also result in sufficient alterations in masticatory behaviours to influence morphological changes in the craniofacial complex, specifically the mandible through bone remodelling. In order to further consider how mandible morphology is altered by masticatory forces it is necessary to first consider how bone remodel in response to mechanical stimuli.
3.2 Bone Remodelling

Over the course of a person’s lifespan bones are subjected to mechanical forces and physiological influences (Katsimbri 2017). In order to prevent microdamage or fractures associated with this mechanical strain the skeleton needs to adapt in terms of bone mass, trabecular architecture and bone morphology (Katsimbri 2017, Lanyon 1992b). Bone remodelling facilitates adaptation in bone structure, strengthening bones against mechanical strain and preventing damage from occurring as a result of loading strain (Katsimbri 2017, Martin and Seeman 2008). While the general shape of each bone is genetically determined and will form in the absence of functional mechanical strain and pathological conditions, bone architecture is influenced by the skeleton’s response to functional load bearing and will not form fully without this strain (Carter 1987, Lanyon 1992a, 1992b, 1996). An understanding of the influence of mechanical strain on bone morphology can be traced back to the 17th century when Galileo inferred a relationship between mechanical strain and bone morphology noting that body weight and physical activity were related to skeletal size (Carter 1984, Stolk et al. 2001). During the 19th century a number of researchers developed theories regarding the relationship between form and function with regards to the skeleton and these are discussed further in section 3.2.3.1 (Carter 1984, Stolk et al. 2001).

This section is divided into four sub-sections. Section 3.2.1 provides a brief background of skeletal anatomy and bone cells which are necessary to provide a foundation for bone remodelling theory. Section 3.2.2 details bone remodelling including the history of bone remodelling theory which examines how research has progressed over time. The bone remodelling process is then discussed on a cellular and macroscopic level in section 3.2.3 followed by a discussion of the factors which have been demonstrated to influence bone remodelling and which needs to be considered as extraneous factors when inferring behaviour/activity from bone remodelling. Finally, section 3.2.4 examines how bone remodelling is stimulated by activity and reviews previous studies which have examined this relationship and how this research has progressed over time detailing why this present study uses analysis of 3D GMM variation of macroscopic bone morphology.
3.2.1 Skeletal Anatomy

The skeletal system has two primary functions: structure and metabolism. The structural function of the skeletal system includes the support and protection of internal organs and muscle attachment for locomotion (Carter 1984). The metabolic function of the skeletal system involves providing a reserve for calcium and phosphate required for homeostasis (Hadjidakis and Androulakis 2006, Henriksen et al. 2009, Sherman 2012). Remodelling is a vital process for both these functions by repairing injuries to the bone, modifying structure and morphology to maintain support as well as a means of releasing the calcium and phosphorus stored in the skeletal system (Hadjidakis and Androulakis 2006).

When considering bone remodelling in response to mechanical strain it is necessary to first briefly discuss skeletal anatomy, specifically the different bone cells and tissues that comprise the adult human skeleton. This section will discuss the cellular components of bone and different bone tissue in relation to bone remodelling.

3.2.1.1 Bone Cells

Bone is a mineralised connective tissue comprised of four types of cell which are involved in bone remodelling. The main cells are osteoclasts and osteoblasts, although osteocytes and bone lining cells are also involved in this process as illustrated in figure 3.2.1 (Florenceio-Silva et al. 2015, Katsimbri 2017).

Osteoclasts

Osteoclasts are large multinucleated cells which are derived from mononuclear precursor cells of the macrophages/monocytes lineage and are the only known cell which is capable of resorbing bone (Florenceio-Silva et al. 2015, Katsimbri 2017). Due to the role of osteoclasts in bone resorption, an abnormal increase in either osteoclast activity or formation leads to bone diseases such as osteoporosis where a decrease in bone density results from bone resorption exceeding formation (Andersen et al. 2013, Crane and Cao 2014, Florenceio-Silva et al. 2015). Osteoclasts are regulated through their lifespan which is approximately 12.5 days (Katsimbri 2017). Cases where the lifespan of osteoclasts is extended increases the number of osteoclasts and pathological conditions such as Pagets disease occur (Katsimbri 2017).
Osteoblasts

Osteoblasts are specialised bone forming cells which are derived from mesenchymal stem cells (Florence-Silva et al. 2015, Katsimbri 2017). Osteoblasts are located along the bones surface and 4-6% of the bone surface is comprised of osteoblasts (Florence-Silva et al. 2015). The primary function of osteoblasts is to form new bone through the synthesis and secretion of Type I collagen which comprises the major bone matrix protein (Katsimbri 2017, Kenkre and Bassett 2018). Additionally osteoblasts mineralise newly formed bone osteoid through the excretion of phosphates from osteoblast-derived matrix vesicles within the osteoid (Katsimbri 2017).

Osteocytes

Osteocytes are the most abundant bone cell and comprise 90-95% of the total number of bone cells (Florence-Silva et al. 2015, Katsimbri 2017). While osteoblasts and osteoclasts are defined by their function osteocytes are defined by their location and morphology (Florence-Silva et al. 2015). Osteoclasts are located in the lacunae within mineralised bone and are derived from osteoblasts which have undergone terminal differentiation and have been engulfed by un-mineralised osteoid during bone formation (Katsimbri 2017). Osteocytes also have the longest lifespan of any other bone cell of up to 25 years (Florence-Silva et al. 2015). After being engulfed in the bone matrix osteocytes lose over 70% of their organelles and cytoplasm and acquire long dendritic processes resulting in a star shaped appearance which is significantly different from osteoblasts (Katsimbri 2017). It is these dendritic processes that extend into the canaliculi of the bone matrix and interact with other osteocytes and osteoblasts on the bone surface forming a lacunar-canicular network which detects mechanical strain on the bone (Katsimbri 2017, Kenkre and Bassett 2018, Prideaux et al. 2016). Osteocytes regulate osteoblast activity and as such can stimulates bone remodelling in response to increased mechanical strain (Katsimbri 2017, Prideaux Findlay et al. 2016). Osteocytes also respond to metabolic signals which are suggested to be associated with increased bone remodelling and reduced bone mass in response to aging (Katsimbri 2017, Manolagas and Parfitt 2010).
**Bone lining cells**

Bone lining cells are flat shaped osteoblasts located in the bone surface. When viewed under an electron microscope they appear as a thin seam of non-mineralised matrix. This thin layer of bone lining cells are thought to act as a membrane that separates bone from the interstitial fluids preventing the direct activity between osteoclasts and bone matrix when bone resorption should not occur (Florencio-Silva et al. 2015, Wein 2017). Additionally bone lining cells are also involved in osteoclast differentiation (Florencio-Silva et al. 2015).

![Diagram illustrating the different bone cells and their precursor cells.](image)

**Figure 3.2.1: Bone remodelling.** Diagram illustrating the different bone cells and their precursor cells. The interaction of these cells with each other during bone remodelling is shown illustrating the role of each cell and the scale illustrates the size of osteoclasts relative to the other bone cells (Hirst 2019).

### 3.2.1.2 Bone Tissue

In the mature skeleton there are two types of bone: trabecular and cortical. While these tissues are identical in their chemical composition they differ both macro- and microscopically (Hadjidakis and Androulakis 2006). Approximately 80% of bone mass is comprised of cortical bone which is dense and compact. Cortical bone forms the external ‘shell’ of bones that surrounds the marrow space (Clarke 2008). The function of cortical bone is to provide structure and strength to the bone; it has a slow turnover rate and high resistance to bending and torsion.
remaining 20% of the adult human skeleton is composed of trabecular bone which is a honeycomb-like network of trabecular plates (Clarke 2008). Trabecular bone is located on the inside of long bones and vertebral bodies as well as other irregular bones or large flat bones. Compared to cortical bone, trabecular bones are comparatively less dense and more elastic with a higher turnover rate. The primary function of trabecular bone is metabolic although trabecular bone still contributes to the mechanical support of the skeletal system (Hadjidakis and Androulakis 2006). When considering the external morphology of bone, it is the cortical bone that is being analysed, and as such it is important to understand how biomechanical forces interact with cortical bone.

**Muscle and Bone Interaction**

In addition to providing support and stability, the musculoskeletal system allows organised movement through the interaction of bone, muscles, cartilage, tendons and ligaments. Skeletal muscles act on bone via connective tissues such as tendons and ligaments which attach to bone at insertion sites called entheses (Asahara et al. 2017, Zatsiorsky and Prilutsky 2012, Zelzer et al. 2014). Entheses allow for the transmission of contractile forces generated in muscles to the respective skeletal attachment site and may be divided into fibrous and fibrocartilaginous entheses illustrated in figure 3.2.2. A fibrous enthesis may either be a bony attachment where the tendons insert directly into the bone or periosteal where tendons insert into the periosteum (Asahara et al. 2017, Rabey et al. 2015, Zatsiorsky and Prilutsky 2012). Fibrocartilaginous insertion sites are the most common form of enthesis and are characterised by fibrocartilage at the tendon bone interface (Apostolakos et al. 2014). Skeletal muscles therefore impart forces on bones and changes to the force producing capacity of muscles have been demonstrated in several studies to correspond to changes in the properties of bone (Avin et al. 2015, Sartori and Sandri 2015).
3.2.2 Bone Remodelling

The skeleton undergoes continuous remodelling which is necessary to repair damaged bone and maintain mineral homeostasis, and the same bone remodelling process occurs in response to biomechanical stimuli (Boskey and Posner 2018, Chen et al. 2015). This section will discuss bone remodelling from a cellular level and will then focus on biomechanically stimulated bone remodelling and the historical and current theories regarding this.

3.2.2.1 Bone Remodelling Process

Bones are constantly being remodelled through the coupled action of osteoclasts and osteoblasts with old bone being resorbed and replaced with new bone (Hill and Orth 1998, Sims and Gooi 2008). Bone remodelling occurs throughout life asynchronously at anatomically distinct sites throughout the skeleton in Basic Multicellular Units (BMU) sometimes referred to as Bone Structural Units (BSU) or Bone Remodelling Compartments (BRC) (Andersen et al. 2014, Kular et al. 2012, Sherman 2012). The BMU consists of four units: osteoclasts resorbing bone, osteoblasts replacing bone, osteocytes within the bone matrix and bone lining cells which cover the bone surface (Hadjidakis and Androulakis 2006,
Kular et al. 2012, Martin and Sims 2005, Sims and Gooi 2008, Wang and Seeman 2008). At any one-point c20% of bone is undergoing remodelling. Individual BMUs are suggested to be locally controlled as they are geographically and chronologically separated from each other (Hill and Orth 1998, Sims and Martin 2014). Bone remodelling consists of a four stage process: the resorption, reversal, formation and termination/resting phases (Hill and Orth 1998, Katsimbri 2017). It is important to understand the phases of bone remodelling as each stage is influenced by different factors some of which are related to mechanical loading and others which are the result of extraneous factors.

Resorption Phase

The bone resorption phase - illustrated in figure 3.2.3 - involves the removal of both the mineral and organic constituents of bone matrix through the action of osteoclasts which are aided by osteoblasts (Katsimbri 2017, Kenkre and Bassett 2018, Rabey et al. 2015). This phase begins with the dissemination of osteoclast progenitors from hemopoietic tissue in the bone. The osteoclast progenitors then differentiate into osteoclasts through interaction with osteoblast stromal cells (Katsimbri 2017, Prideaux et al. 2016, Rabey et al. 2015). The bone lining cells which prevent osteoclast activity are removed from the mineralised osteoid layer through the production of proteolytic enzymes including matrix metalloproteinases, collagenase and gelatinase (Katsimbri 2017, Kenkre and Bassett 2018, Prideaux et al. 2016, Rabey et al. 2015). The removal of these bone lining cells allows the osteoclasts access to the underlying mineralised bone. The osteoclasts are then activated by osteoblasts, the activated osteoclasts resorb the bone through the production of hydrogen ions and proteolytic ions (Hill and Orth 1998, Kenkre and Bassett 2018, Rabey et al. 2015). The resorption phases is terminated when the osteoclasts ultimately undergo apoptosis (Hill and Orth 1998, Katsimbri 2017).
Figure 3.2.3: Bone Resorption. Diagram illustrating the removal of bone lining cells and proliferation of osteoclasts for bone resorption. This illustrates the process by which osteoclasts remove bone through the production of different proteolytic enzymes (Hirst 2019).

Reversal Phase
After the maximum depth of bone resorption has been achieved during the resorption phase there is a reversal phase which lasts approximately nine days (Hill and Orth 1998, Katsimbri 2017, Raggatt and Partridge 2010). During this phase osteoclasts disappear from the bone surface and macrophage-like cells are present (Abdelgawad et al. 2016, Hill and Orth 1998, Katsimbri 2017). The mechanism which arrests osteoclast activity and stimulates osteoblast activity is poorly understood, but it has been suggested that these macrophage-like cells may release factors which inhibit osteoclasts and stimulate osteoblasts (Hill and Orth 1998, Katsimbri 2017, Kenkre and Bassett 2018, Raggatt and Partridge 2010).

Formation Phase
Bone formation – illustrated in figure 3.2.4 - results from the proliferation of mesenchymal cells. Although the process is not yet fully understood, it is suggested that the process which attracts the osteoblasts precursor cells to the site of the defect results from a chemostatic reaction mediated by local factors.
produced during the resorption phase (Dempster and Raisz 2014, Hill and Orth 1998, Katsimbri 2017, Raggatt and Partridge 2010, Siddiqui and Partridge 2016). Osteoblast precursor cells then differentiate into mature osteoblasts. The differentiation of osteoblast precursors may be controlled through a number of bone-derived growth factors although the precise growth factors involved has not been determined (Hill and Orth 1998, Katsimbri 2017, Siddiqui and Partridge 2016). The osteoblasts then secrete osteoid, an unmineralized bone matrix for which Type 1 Collagen comprises 94% (Boskey and Posner 2018, Brickley and Ives 2008, Kular et al. 2012).

**Figure 3.2.4: Bone formation.** Diagram illustrating the differentiation of osteoblasts from osteoblast precursor cells, which then secrete unmineralized bone matrix (Hirst 2019).

**Termination/Resting Phase**

The termination phase – illustrated in figure 3.2.5 - begins about 30 days after the formation of new osteoid and lasts for approximately 90 days for trabecular bone and 130 days for cortical bone (Katsimbri 2017, Raggatt and Partridge 2010). During the termination phase, newly formed osteoid is mineralised which requires calcium and phosphorus in the extracellular fluid and occurs within 10-15 days (Boskey and Posner 2018, Brickley and Ives 2008, Katsimbri 2017). After mineralisation the bone returns to a dormant phase when osteoblasts undergo apoptosis and are either embedded in the newly mineralised matrix or remain on the surface as bone lining cells (Boskey and Posner 2018, Katsimbri 2017, Raggatt and Partridge 2010).
Figure 3.2.5: Bone resting phase. Diagram illustrating the mineralisation of osteoid through the addition of calcium and phosphorus from the extracellular fluid. The osteoblasts are then either imbedded in the newly mineralised matrix (a) undergo apoptosis (b) or remain as bone lining cells on the surface of the bone (c) (Hirst 2019).

3.2.3 Bone Remodelling and Physical Stimuli

Bone remodelling occurs for several reasons: in response to trauma, to maintain homeostasis and in response to biomechanical stimuli. For the purposes of this thesis, bone remodelling will refer to biomechanically stimulated changes in normal bone turnover resulting in either hypertrophy or atrophy and significant alterations to bone mass, morphology, size and the internal architecture of bone (Carter 1984, Stolk et al. 2001). Mechanically adaptive bone remodelling is a homeostatic mechanism which regulates functional bone strains at each location throughout individual bones and the skeleton as the functional demands of a bone vary throughout the element (Lanyon 1996). This form of bone remodelling is influenced by a feedback mechanism which maintains bone strain levels at an optimum level by increasing bone mass when bone strain is increased and reducing bone mass when strain levels are decreased (Bassett 1968, Lanyon et al. 1982, Lanyon et al. 1976, Pauwels 1973). A number of terms relevant to bone remodelling theory are defined in table 3.2.1.

3.2.3.1 Bone Remodelling Theory
The association between bone morphology and biomechanical activity can be dated back to the 17th century with Galileo, and later in 1741 when Nicolas André stated that bone morphology may be altered by external forces (André 1741, Lee and Taylor 1999). However, it was not until the late 19th century that these theories really took form. While the theory of bone remodelling is generally
attributed to Julius Wolff who coined the term bone remodelling in 1870, the internal and external morphology of bone in relation to mechanical loading was described by Ward (1838), Meyer (1866) and Culmann (1867). In 1838 Ward investigated the mechanical properties of bone and described the morphology of trabecular bone in the head of the femur and related this to its mechanical function. This work was continued by Meyer in 1866 and Culmann in 1867. Meyer (1867) observed that trabeculae within bone aligns with the principal direction that mechanical stress is placed upon the bone. Meyer’s (1867) observations led Wolff to develop his theory of the ‘law of bone transformation’ (Koch 1917, Pauwels 1954, Roux 1885, Turner 1992, Wolff 1870). However, it was Culmann’s Crane Model illustrated in figure 3.2.6 that Wolff largely based the law of bone remodelling upon which states:

"alterations of the internal architecture clearly observed and following mathematical rules, as well as secondary alterations of the external form of the bones following the same mathematical rules, occur as a consequence of primary changes in the shape and stressing ... of the bones.” (Wolff 1986, 1).

**Table 3.2.1: Bone remodelling terms.** Definitions for terms relevant to bone remodelling theory.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone stress/strain</td>
<td>The mechanical stimuli applied to bone from the muscles or external environment resulting in deformation of the bone (Commissio et al. 2018, Turner and Burr 1993).</td>
</tr>
<tr>
<td>Strain/loading cycles</td>
<td>The repeated mechanical strains or loading placed on bone during repetitive movements or stimuli (Lanyon 1987), for instance during mastication one cycle would be the strain exerted during the opening and closing of the jaw (Comissio et al. 2018)</td>
</tr>
<tr>
<td>Dynamic strain</td>
<td>Strain or stress placed on bone that changes in either the force, position or direction or the strain, such as walking or chewing</td>
</tr>
<tr>
<td>Static strain</td>
<td>A constant strain placed on bone, for instance weight bearing without motion</td>
</tr>
<tr>
<td>Microstrain</td>
<td>The unit used to express strain calculated as the change in length of a material as a ration to the unaffected length (Turner and Burr 1993).</td>
</tr>
<tr>
<td>Mechanotransduction</td>
<td>The process by which cells convert mechanical stimuli into electrochemical activity (McNamara and Prendergast 2007, Parker Parker Pearson and Lieberman 2004).</td>
</tr>
</tbody>
</table>
The law of bone remodelling as described by Wolff however is significantly different from our current understanding of the process by which bones remodel in response to biomechanical forces (Lee and Taylor 1999). For instance, Wolff focussed on static loading and rejected the notion that bone resorption played a role in bone remodelling. From a strict mathematical sense Wolff’s Law has largely been discredited (Ruff et al. 2006). Over time, however, a more general interpretation of Wolff’s Law has been accepted: that a bone’s form is influenced by responses to mechanical strain (Parker Parker Pearson and Lieberman 2004). It has been argued that the modern concept of Wolff’s Law is due to the work of Wilhelm Roux who introduced the concept of functional adaptation in to Wolff’s static loading bone remodelling theory. In 1885, Roux argued that dynamic functional stimuli shaped bones through bone remodelling and it is Roux’s work that is more in keeping with our modern understanding of bone remodelling theory. Significant advances in molecular, cellular and the systemic biology of skeletal tissue have occurred since these theories were developed and bone remodelling theories were later further refined by the Mechanostat Hypothesis introduced by Frost in 1960 (Andersen et al. 2014, Frost 1987, 2001, 2004, Marcian et al. 2014, Martin and Burr 1989). The Mechanostat Hypothesis assumes that osteoblasts are the principal bone cell which is sensitive to bone strain and that osteoblasts possess an absolute strain set point which differs depending on their location allowing a localised response to bone strain (Lanyon 1996). The Mechanostat Hypothesis states that there is an upper and lower threshold for mechanical loading and that if the physical strain on a bone is above the upper threshold then bone mass is increased through remodelling. When physical strain on bone is below the lower threshold bone mass decreases - whereby 1000με16 results in a change in bone length of 0.1% (Marcian et al. 2014). In between these two thresholds there is the ‘lazy zone’ or ‘dead zone’ whereby bone remodelling is not influenced and bone mass is maintained (Christen et al. 2014). These theories however have continued to develop and it is now generally considered that osteocytes are the bone cells that respond to mechanical strain and stimulate bone remodelling.

16 Microstrain (με) is the unit commonly used for measuring the elastic deformation of bone in response physical forces (Marcian et al. 2014)
3.2.3.2 How mechanical loading stimulates bone remodelling

While it is well known and supported that bone remodelling is influenced by physical loading on the bones, there is considerable debate and uncertainty regarding how mechanical loading stimulates bone remodelling. Several theories have been proposed but none universally accepted. Mechanical strain stimulates bone remodelling through the process of mechanotransduction - the process by which cells convert mechanical stimuli into electrochemical activity (McNamara and Prendergast 2007, Parker Parker Pearson and Lieberman 2004). Mechanotransduction has been suggested to occur through multiple stimuli and mechanisms involving the interactions of cytokines, hormones, growth factors and physical load bearing (Lanyon 1996, Parker Parker Pearson and Lieberman 2004). Previous studies which have attempted to determine the mechanical stimuli which mechanosensitive osteogenic cells respond to have investigated possible influence of fluid flow, matrix strain and matrix damage (McNamara and Prendergast 2007). It has however generally agreed that osteocytes are the best candidate for detecting mechanical strain and microdamage in the bone (García-Aznar et al. 2005). It has been hypothesised that “osteocytes act as strain receptors and transducers” (Marotti 1996, 68). The osteocytes have canaliculi which are long processes that radiate approximately 15μm from the osteocyte in every direction creating a connected cellular network and communicate via

**Figure 3.2.6: Culmann’s crane.** Culmann’s Crane illustrations in which the morphology of trabecular bone in the proximal femur is compared to the structure of a crane or support beams for a street light (Lee and Taylor 1999, 102, Figure 1).
transmitter proteins with adjacent osteocytes in the periosteal and endosteal membranes (Lanyon 1993, Parker Pearson and Lieberman 2004). The osteocyte canaliculi are filled with a fluid that is displaced during bone deformation creating a change in fluid pressure which stimulates prostaglandin and nitric oxide production (Parker Pearson and Lieberman 2004). Several studies have investigated how changes in fluid flow and pressure may stimulate bone remodelling (Hambli and Kourta 2015, Klein-Nulend et al. 2015, Parker Pearson and Lieberman 2004). An in vitro study of osteoblast activity found that osteocytes producing a pulsatile or steady fluid flow resulted in a greater osteoblast response compared an oscillating flow (Jacobs et al. 1998). While the process of mechanotransduction remains incompletely understood, there is considerable research investigating the relationship between strain and bone remodelling response (Jacobs et al. 1998, Parker Pearson and Lieberman 2004).

3.2.3.3 Strain Type

When considering the potential for bone remodelling to reflect biomechanical activity it is necessary to consider how variations in mechanical stimuli influence the bone remodelling process. The influence of mechanical strain on bone remodelling has been demonstrated to vary between skeletal elements (Carter 1984, Stolk et al. 2001). While the reason for these discrepancies are multifactorial, it has been suggested that the type of mechanical strain bones are subjected to influences bone remodelling (Qin et al. 1996, Turner 1998). It is therefore important to consider the variation in the mechanical loading of bones in order to understand the skeletal response to activity. Physical strain on bone can be broken down into a number of components which have each been suggested based on experimental animal studies to differentially influence bone remodelling; these are strain distribution, strain magnitude, strain rate and strain change (Lanyon 1996, Rubin and Lanyon 1987). This section will discuss these aspects of strain in relation to the mandible and mastication.

*Dynamic vs Static Strain*

While Wolff’s bone remodelling theory focussed on static strain (Ruff et al. 2006), Turner argued that bone remodelling is governed by dynamic strain instead of static loading (Turner 1998). The importance of dynamic strain in bone remodelling is supported by several animals and human studies (Lanyon
1987, Lanyon and Rubin 1984, 1985, Robling et al. 2001, Rubin Lanyon 1984, Sugiyama 2018). When bone was exposed in vivo to a short period of dynamic mechanical strain a proportional increase in the metabolism of osteocytes and periosteal cells was recorded (Skerry et al. 1989). Furthermore, static loads have been found to have no or a minimal effect on bone remodelling while dynamic loads stimulates bone remodelling (Lanyon 1992b). For instance, bone formation in rabbits was found to be stimulated by dynamic loads instead of static loads (Liskova and Hert 1971, Turner 1998). When considering mastication, it is clear that this results in dynamic strain and as such is more likely to result in bone remodelling and morphological changes compared to static strain (Shimada et al. 2012, 2015).

Strain Frequency/Rate

When mechanical loads and the number of strain cycles are constant, the frequency of strain cycles has been found to significantly influence bone remodelling. When strain frequency increased from 1-30 Hz the threshold for bone remodelling was found to decrease from 1,200 to 100 με (Cullen et al. 2001, Qin et al. 1998). Furthermore, studies have argued that even very low levels of mechanical strain (<10 microstrain) are sufficient to stimulate bone formation at high strain frequencies (Judex and Rubin 2010, Lad et al. 2016 Rubin et al. 2001). High strain rates have also been argued to be more effective in stimulating bone remodelling compared to low strain rates in animals studies (Skerry 1997). During mastication, strain frequency has been recorded at around 1.57Hz (Po et al. 2011), for a comparison a humans walking stride 2.0Hz, while a cheetah’s (Acinonyx jubatus) sprinting stride has been recorded at four Hz (Hudson et al. 2012, Pachi and Ji 2005).

Strain magnitude

Strain magnitude and rate have been suggested as the primary mechanical variables influencing bone remodelling response to activity (Bloomfield et al. 2004). In human studies, bone mass has been found to be greater among athletes competing in high power sports such as power lifting and gymnastics where

\[^{17}\text{hertz}\]

\[^{18}\text{microstrain}\]
these activities result in higher levels of force on the skeleton which results in a higher level of bone formation (Cullen et al. 2001). This is supported by experimental animal studies which have found that a force applied to bone showed a positive correlation with increase in bone mass (Cullen et al. 2001, Rubin and Lanyon 1985, 1987). For instance, periosteal bone formation was found to be greater among rabbits subjected to 30N\(^{19}\) of strain compared to 25N, with mineral apposition 60% greater among individuals with 30N strain magnitude (Cullen et al. 2001). Furthermore studies have argued that above 30N bone formation increases linearly with strain magnitude (Cullen et al. 2001, Rubin and Lanyon 1985). During mastication strain magnitudes of around 300N have been recorded (Koc et al. 2010) as such while previous studies have typically focussed on activity of the limb bones the force produced during mastication is clearly sufficient to result in bone remodelling.

*Duration and Strain Cycles*

Several studies have also found that both the number of loading cycles and the stress magnitude significantly influenced bone mass although stress magnitude was argued to be of greater influence compared to number of loading cycles (Whalen et al. 1988). It was argued by Lanyon and Rubin (1984) that cyclic loading was essential for maintaining bone mass (Lanyon 1984). The number of strain cycles has been found to influence bone remodelling when strain magnitude remained constant and above the minimum strain threshold (Cullen et al. 2001). For instance, rabbit tibiae were loaded with 25N or 30N for the same time and cycle speed; periosteal bone formation observed to increase with strain cycles greater than 40 for both strain magnitudes. Although with a higher strain magnitude (30N) there was a greater increase in bone formation with strain cycles (Cullen et al. 2001). However beyond a certain point the increased duration or number of strain cycles has been found not to yield a proportional increase in bone density. Instead bone formation tends to saturate with increased strain cycles as bone cells lose responsiveness to repetitive mechanical stimuli (Turner 1998). Rubin and Lanyon (1984) found that at a high strain magnitude a low number of loading cycles was sufficient to optimise osteogenic response while

\(^{19}\) newtons
increasing loading cycles as much as ten times was not determined to increase the osteogenic response (Bloomfield et al. 2004, Rubin and Lanyon 1984). This is supported by an experimental animal study involving rats jumping 40cm down five times a day which was shown to result in increased bone mass. Increasing the loading cycle to ten jumps a day was not found to greatly increase bone mass above that produced by 5 jumps (Umemura et al. 1997). Research has suggested that because bone cells lose sensitivity to mechanical strain, a recovery period is required between exercises in order to restore mechanical sensitivity (Robling et al. 2001). Studies have found that rats subjected to mechanical strain in multiple sessions during the day showed a greater increase in bone mass compared to rats who experienced the same magnitude of strain and number of cycles in a single session (Turner and Robling 2003). Mastication changes resulting from dietary consistency have been shown to significantly influence the number of chewing cycles (van der Bilt and Abbink 2017) and as such dietary changes that increase the number of chewing cycles will arguably result in changes in bone remodelling.

The majority of previous studies investigating bone remodelling in response to activity have focussed on high strain magnitude activities, and have therefore focussed on the lower and upper limbs (eg: Cardoso and Henderson 2010, Hagihara and Nara 2016, Hawkey and Merbs 1995, Lai and Lovell 1992, Lam et al. 2016, Maggiano et al. 2008, Mays 1999, Meyer et al. 2011, Nikita et al. 2011, Rabey et al. 2015, Rhodes and Knüsel 2005, Shaw and Stock 2009, Stock and Macintosh 2016, Stock and Pfeiffer 2001, 2004, Weiss 2003a, 2003b, 2005, Wescott 2006, Wescott and Cunningham 2006). When considering the biomechanical strain that occurs during mastication it is clear that this strain is dynamic (Sun et al. 2004) with a high frequency (Stanford and Brand 1999) and number of strain cycle (Sun et al. 2004). Therefore although the strain magnitude is lower compared to previous research which have principally investigated weight bearing activities there is considerable evidence to suggest that changes in masticatory forces will influence bone remodelling and result in macroscopic morphological changes, this is discussed further in Chapter 4.
3.2.3.4 Factors Influencing Bone Remodelling

Bone remodelling is a complex process which is influenced by a number of extraneous factors including systemic hormones and locally produced growth factors. These factors influence bone remodelling and the ability for bones to respond to mechanical stimuli (Hill and Orth 1998, Wozney et al. 1990). While in experimental animal studies some of these factors may be controlled, in archaeological studies this is not possible and instead it is necessary to discuss these factors and consider their potential influence. This section will discuss the extraneous factors which directly influence the process of bone remodelling on a cellular level.

Hormones

Hormones may influence bone remodelling through their action on osteoblasts, osteoclasts, or cell differentiation. Hormones which have been found to influence bone remodelling include polypeptide, steroid and thyroid hormones (Matsuo and Irie 2008). Oestrogen has been suggested to regulate osteoclastogenesis and oestrogen deficiency increases bone remodelling (Deckers et al. 2000, Rosendahl et al. 2017). It has been suggested that among post-menopausal or amenorrhoeic women weight bearing exercise do not significantly increase bone mass (Kirk et al. 1989, Rodan 1991, Sinaki et al. 1989). In experimental animal studies rats were found to have decreased activity related bone remodelling after an oophorectomy compared to control cases (Hume et al. 1989, Rodan 1991). Clinical studies have found that bone mass among post-menopausal women has been found to decrease by 20-25% (Martin and Sims 2005, Schiessl et al. 1998). Furthermore, blocking the oestrogen receptor has been shown to diminish the bone remodelling response to mechanical strain (Bloomfield et al. 2004). Additionally growth factors, which are polypeptides that regulate the replication and the differentiated function of cells, are present in the bone matrix at significant quantities, and have been demonstrated to influence the growth properties and function of bone cells in vitro (Crane and Cao 2014, Wozney et al. 1990). When the production of growth factors is inhibited this has

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20 Surgical removal of one (unilateral) or both (bilateral) ovaries, the ovaries produce oestrogen and individuals who undergo a bilateral oophorectomy will no longer produce oestrogen, while a unilateral oophorectomy has been associated with an earlier age of menopause (Rosendahl et al. 2017)
been directly linked to bone remodelling. For instance, vascular endothelial growth factors (VEGF) are associated with bone remodelling and mice with limited expression of VEGF’s develop multiple skeletal irregularities such as reduced bone mineralisation, defects in osteoblast proliferation and activity (Deckers et al. 2000).

**Nutrition / Vitamins**

Several vitamins are critical for skeletal homeostasis and nutritional deficiency has been associated with a reduction in bone remodelling (Kenkre and Bassett 2018, Williamson et al. 2017). Calcium insufficiency reduced the effectiveness of mechanical strain to stimulate bone remodelling increasing bone mass (Bloomfield et al. 2004). Moreover Vitamin D³ deficiency has been demonstrated to have a detrimental effect on bone remodelling (Williamson et al. 2017). Additionally several metabolic bone diseases may influence bone remodelling including: osteomalacia, hypophosphataemic syndromes, hyperparathyroidism, renal osteodystrophy, osteoporosis and Paget’s disease (Sherman 2012).

**Age**

While the osteogenic response to bone strain is maintained into old age, studies have suggested that the bones responsiveness to strain declines (Forwood and Burr 1993, Lanyon 1996). Muscle mass has also been demonstrated to decrease with aging, which has been suggested to account for the reduction in bone mass and mineral density (Burr 1997). However it has been claimed that age related bone mass occurs prior to a decline in muscle mass and strength (Marcus 1995). Other theories have argued that the mechaniosensitivity of bone decreases over time with older individuals requiring high strain magnitudes to initiate the same bone remodelling response as younger individuals (Saxon et al. 2005). For instance, at 19 months of age rats were found to be less responsive to mechanical strain compared to nine month old rats (Duan et al. 2003). Despite this, the analysis of cultured human bone cells found no evidence that mechanosensitivity to mechanical strains decreased over time (Ahlborg et al. 2003). Furthermore, other studies have found contrasting results with older individuals having either an increased, decreased or no significant change in bone responsiveness between old and young individuals (Saxon et al. 2005). Bone remodelling in response to activity is suggested to be more responsive during childhood and adolescence.
and provides a protective function against bone loss later in life (Parker Pearson and Lieberman 2004). Furthermore exercise related bone mass acquired during childhood has been argued to be maintained into adulthood (Bloomfield et al. 2004). Exercise has been shown to increase bone mass among young individuals, and maintain or reduce bone loss among elderly individuals (Mosekilde 1995).

### 3.2.4 Bone Remodelling Response

When mechanical strain placed upon bone exceeds the upper threshold bone remodelling is stimulated resulting in an increase in bone production and subsequently cortical thickness and overall strength of the bone (Frost 1987, Hillam and Skerry 1995, Rando et al. 2014). This is illustrated by numerous clinical and experimental animal studies. These studies have found that when levels of mechanical loading are altered this results in changes in bone mass, mineralisation and morphology (Akhter et al. 1998, Lambers et al. 2011, Schulte et al. 2013). For example, when Zebra fish are subjected to physical exercise using a swim tunnel, an increase in bone mineralisation and mass after four weeks was observed (Akhter et al. 1998, Suniaga et al. 2018). Similarly five minutes of mechanical strain on the caudal vertebrae of a juvenile rat was found to result in a significant increase in bone formation (Chow et al. 1998). Moreover, Woo et al. (1981) recorded a 17% increase in femur thickness among exercised compared to unexercised pigs (Woo et al. 1981). Furthermore, athletes who experience high-intensity mechanical loading have higher muscle mass and increased bone mass, mineralisation and robusticity (Jürimäe et al. 2018, Lambert et al. 2017, Xiong and Yu 2017, Yingling et al. 2017).

In contrast, when strain placed upon the bone drops below the lower threshold this mechanism stimulates bone resorption, reducing cortical bone thickness and as such the overall strength of bone (Frost 1987, Rando et al. 2014). The importance of functional loading on the final form of these skeletal elements can be seen among individuals where injury or disease has prevented functional loading (Lanyon 1992a). These studies illustrate that the osteogenic response to mechanical stimuli is vital in load-bearing bones attaining their normal form. In order for bones to remodel and adapt to functional loading, bone cells require a
mechanism for assessing direct and indirect functional strains upon the tissue (Lanyon 1987).

### 3.2.4.1 Analysing Bone Remodelling in Archaeology

Due to this relationship between muscle activity and bone remodelling, bone morphology has been used in archaeological research as a means of inferring activity and behaviour among past populations since the late 20th century (Amtmann 1971, Brock and Ruff 1988, Ruff 1987). Previous investigations of the relationship between physical activity and bone remodelling has taken several different approaches, either focussing on changes in bone mass or density in relation to loading/activity, microscopic analysis of trabecular and cancellous bone, morphology of muscle insertion sites, cross section geometry and macroscopic cortical bone morphology (Hawkey and Merbs 1995, Lieberman et al. 2004, Nicholson and Harvarti 2006, Parker Pearson and Lieberman 2004, Whalen et al. 1988). This section will compare these methods and detail why this study is employing 3D GMM.

**Bone Mass and Mineralisation**

Activity and exercise have been argued to be the predominate factor in determining the bone mass and density of weight bearing or heavy loading bones (Lanyon 1996, Whalen et al. 1988). Human and animal studies have consistently demonstrated that functional loading is positively associated with location specific changes in bone mass (Lanyon 1996). Moreover extreme inactivity and reduction of mechanical strain has been shown to result in up to 40% loss of bone mass and increase in bone mass by up to 40% is associated with increases in athletic activity (Smith and Gilligan 1991). Bone mass was found to be significantly higher among adults who jogged >9 times a month compared to cohorts who jogged less frequently (Bloomfield et al. 2004, Mussolino et al. 2001). Furthermore, several studies have determined that 3-24 months of moderate to high resistance training was associated with a significant increase in bone mass (Bloomfield et al. 2004). Conversely long-term immobilisation has also been linked to a reduction in bone mass and mineralisation. For instance when normal load bearing of the calcanei of animals is prevented for a 12 week period 25% of bone mass was lost (Skerry 1997). Decreases in bone mass or mineralisation have been reported among humans who have been immobilised during

Bone mass and mineralisation have been employed in archaeological studies as a means of inferring behaviour (Bloomfield et al. 2004). For example, among agriculturist and hunter-gatherers from the Holocene the potentially more sedentary agriculturalists had a lower bone density compared to the more active hunter-gatherers (Chirchir et al. 2017, Macintosh et al. 2014, Marchi et al. 2011). In other cases, significant reduction in bone density of individual or specific bones have been used to infer injury or illness which compromises mechanical function (Battles 2009). Two individuals from the Medieval Croatian sites of Zadar and Virje were found with atrophy and shortening of the limbs thought to indicate that they lived with triplegia and hemiplegia for several years before their death (Novak et al. 2014). Bone mass or bone mineralisation however, provide a limited means of inferring activity among past populations and it is difficult to relate these changes to specific activity. Additionally the microstructure of cortical and trabecular bone is considered to adapt to mechanical strain, and as such has used to infer behaviour/activity (Ferretti et al. 2003, Skedros et al. 1999). For instance the distribution of bone mass within trabecular bone has been found to be associated with physical stressors on the bone (Hayes and Snyder 1981). This however, requires either destructive analysis of skeletal remains, or the use of expensive imaging equipment such as micro CT scanning.

Muscular skeletal markers

One of the methods employed to infer specific behaviour and activities among past populations is the use of muscular skeletal markers (MSM) which are sites on the skeleton where a muscle, tendon or ligament inserts into the periosteum. Bone remodelling in response to biomechanical strain is said to result in pronounced hypertrophy at these sites. Because these markers are muscle specific it is argued that the analysis of the robusticity of MSM can be used to infer habitual activities based on which muscle experienced the greatest biomechanical strain (Hawkey and Merbs 1995, Peterson 1998). Hawkey and Merbs (1995) used MSM as a means of inferring habitual activity among two archaeological First Nation assemblages in Hudson Bay, Canada. They observed that significant changes to MSMs occurred over time and between the sexes,
arguably indicating sexual division of labour and changes in subsistence strategies over time. Other studies have gone further to infer very specific activities such as the use of hand held projectile weapons and rowing (Molnar 2005). However serious concerns regarding the validity of MSMs have been raised (Godde et al. 2018). For instance, the scoring of muscle markings is known to be highly subjective and influenced by both the researcher and the general robusticity and size of the skeletal remains (Wileczak 1998). Furthermore, inferring specific activities from MSMs have been criticised as muscles work in complex groups and inferring specific behaviours is arguably reductionist (Kennedy 1998, Robb 1998, Stirland 1998). Also factors such as age (al-Oumaoui et al. 1987, Niinimaki and Sotos 2012, Weiss 2003b), sex, genetics, hormones, body size (Weiss 2007, Weiss et al. 2012, Wileczak 1998) and pathological conditions - such as diffuse idiopathic skeletal hyperostosis and osteoarthritis (Eshed et al. 2004, Lieverse et al. 2013, Lieverse et al. 2009, Milella et al. 2012) have been demonstrated to influence MSM. The use of MSM to infer habitual activity among past populations appears to have declined over recent years although despite this there are still a number of recent studies continuing to infer specific behaviours such as horse riding (Djukic et al. 2018) and archery (Tihanyi et al. 2015). When considering mastication there are very few MSMs on the mandible, and those muscle markings which are present are regions used for sex estimation and may not be an appropriate method for inferring changes in masticatory strain.

Cortical Thickness/Cross Sectional Morphology

Several bone remodelling studies have focussed on changes in cortical bone, and traditionally this has focussed on cortical bone thickness or cross-sectional morphology of long bones in relation to activity (Whalen et al. 1988). The diaphyseal cross-section morphology of load-bearing long bones has been found to be influenced by mechanical strain (Rittweger et al. 2000). For instance, the dominant arm of tennis players undergo greater hypertrophy compared to their non-dominant arm (Buskirk et al. 1956, Jones et al. 1977). Jones et al. (1977) found that diaphyseal cortical thickness was significantly greater on the dominant humerus of professional tennis players by 34.9% among males and 28.4% among females (Jones et al. 1977). Cross-sectional geometric morphometric properties have been used for several years as a means of making inferences regarding the
mechanical adaptation of long bones. Early archaeological studies typically focussed on investigating potential differences in cross-sectional geometry between assemblages (Ruff 2000). For example, Ruff and Hayes (1983) analysed cross-sectional geometry of the tibia and femora from 119 individuals from Pecos Pueblo, New Mexico. When compared to studies of modern samples the cross-sectional shape of the tibia and femur were significantly different among the Pecos sample, thought to reflect the increased biomechanical strain experienced by individuals from the Pecos Pueblo site (Ruff and Hayes 1983). A study conducted by Trinkaus (1999) analysed cross-sectional geometry of tibial remains from the Near Eastern Middle Palaeolithic which indicated a reduction in mobility between late archaic humans and early anatomically modern humans (Trinkaus 1999). Furthermore, an analysis of tibial cross-sectional morphology revealed significant differences between nomadic pastoralists and sedentary agriculturalists from Sudan (Hackner 2017).

More recent studies have compared cross-sectional geometry of archaeological assemblages with modern populations of known assemblages. Macintosh et al. (2018) compared the humeral and tibial cross-sections from Central European female agriculturists and modern living females where habitual behaviour was recorded. Results from this study indicated that during the first 5500 years of agriculture humeral rigidity among females was greater than that among modern athletes, arguably indicating that manual labour was an important component of the behaviour of prehistoric females (Macintosh et al. 2017). The relationship between mechanical strain and the morphology of long bone diaphyseal cross sections, however, is not simple (Parker Pearson and Lieberman 2004). In addition to activity, body mass and shape has been demonstrated to influence mechanical loading and weight bearing of skeletal elements and body mass has been shown to significantly influence diaphyseal cross-section of long bones (Ruff 2000). Therefore studies which infer activity from the morphometric analysis of diaphyseal cross-sections of long bones need to take into account the influence of body size (Ruff 2000). While there have been some studies which have analysed cross-sectional geometry of the mandible (Daegling and Grine 1991), these have only analysed the mandibular body which has been demonstrated to be less influenced by masticatory strain compared to the gonial angle, condyle or coronoid process.
As discussed there are problems associated with inferring mechanical strain or specific behaviour from the cross-sectional geometry, bone density and MSMs, specifically when considering the mandible and masticatory behaviour (Parker Pearson and Lieberman 2004). Other methods have focused on macroscopic analysis of cortical bone morphology, traditionally this involved taking linear measurements although this later included three-dimensional geometric morphometrics (3D GMM) analysis of bone morphology. Methods for measuring and analyzing the interaction between mechanical loading and bone remodelling and morphology have subsequently improved greatly advancing the field of study (Bertram and Swartz 1991). Technological advancements increasing the precision and availability of 3D surface scanners as well as statistical advancements has led to a large number of studies (Errickson et al. 2017, Hackner 2017, Haruda 2017, White 2015) investigating 3D morphological variation in skeletal elements. While principally this developed for the craniometric analysis of modern human variation or evolution, these methods are being increasingly utilised for a wider range of studies including the analysis of biomechanics and bone remodelling (Perez-Criado et al. 2017). One of the benefits of GMM is that analysis focuses on shape, which may be defined as “the geometrical properties of an object that are invariant to effects of translation, scaling and rotation” (Monteiro et al. 2000, 217). As such geometric morphometric analysis has advantages over traditional morphometrics which are heavily influenced by size (Rosas and Bastir 2004). Additionally, the reconstruction of missing or distorted elements of the human skeleton is a challenge which is shared by the fields of bioarchaeology, palaeoanthropology, forensics, orthodontics and medicine (Benazzi and Senck 2011, Gunz et al. 2009). Another benefit of GMM is that it is possible to reconstruct or estimate missing landmarks in GMM studies (Benazzi and Senck 2011).

As discussed in Chapter 2 diet in Britain has changed over time, with a gradual increased in food processing and the consumption of softer stickier foods resulting in a reduction in masticatory stress. Furthermore, among anatomically
modern human history similar dietary changes are implicated in the craniofacial reductions evident in the human lineage. This study aims to fill in the gap in current research focussing a GMM analysis of human mandible morphology. It is therefore necessary to consider next mandible morphology and masticatory muscles, as well as the previous literature that has investigated changes in mandible morphology in relation to diet.
Chapter 4
The Mandible

As demonstrated in Chapter 3, biomechanical stressors influence bone remodelling and subsequently bone morphology. In order to determine to what extent masticatory stressors influence mandible morphology, it is first necessary to consider mandible morphology and mastication. The first two sections of this chapter will discuss the form and function of the mandible detailing the different regions of the mandible and the masticatory muscles. This is important to consider as bone remodelling is stimulated by muscle activity and principally affects mandible morphology at these muscle attachment sites. The third section of this chapter will discuss the animal, clinical and archaeological evidence for a relationship between mandible morphology, masticatory muscles and dietary changes. The following two sections will detail the factors which have been found to influence mastication, as well as those which may influence mandible morphology directly, including population history, as this is necessary in order to understand how large-scale migrations and occupations may have influenced mandible morphology in Britain.

4.1 Mandible Form and Function

The mandible is both the largest and strongest facial bone and can be broadly divided into two portions, the curved horizontal body and two perpendicular vertically ascending rami (Angelopoulos and Scarfe 2018, Vadgama and Patel 2017, White and Folkens 2005). The mandibular body, also known as the corpus and horizontal ramus, is a thick U-shaped portion of the mandible which houses the lower dentition. At the anterior aspect of the mandibular body located along the sagittal plane is the mental protuberance which varies in size and robusticity and is an identifying feature of AMH (Hall et al. 2010, Vadgama and Patel 2017, White and Folkens 2005). The ascending ramus is a thinner portion of bone that rises vertically from the mandibular body, above the line of the dental arcade and articulates with the cranial base (Hall et al. 2010, White and Folkens 2005). Two projections extend vertically from the ramus, the coronoid process to the anterior and the condyle to the posterior. The coronoid process is a thin triangular bony projection which varies individually, and between males and
females, with regards to the shape and robusticity (Hall et al. 2010, White and Folkens 2005). The mandibular condyle is a large, rounded articular prominence and forms the lower component of the temporomandibular joint (Hall et al. 2010, Langley and Tersigni-Tarrant 2017, Sakul et al. 2018, White and Folkens 2005). The gonial angle or mandibular angle is the rounded intersection between the mandibular body and the ascending ramus at the posterior-inferior border of the mandible.

The primary function of the mandible is mastication, which is facilitated by four muscles: the masseter, medial pterygoid, lateral pterygoid and temporalis, described further in section 4.2. These muscles work in combination to move the jaw up and down, pivoting at the condyle and side to side in both a hinge and sliding action (Ginszt et al. 2017, Nishi et al. 2017, Stone and Stone 2012, Van Eijden et al. 1997). The main components and landmarks of the mandible, as well as the attachments sites for the four masticatory muscles are illustrated in figures 4.1.1 and 4.1.2 below.

Figure 4.1.1: Line drawing of the lateral view of the mandible illustrating the mandibular body, ascending ramus, gonial angle and the condyle and coronoid processes. The attachment for the temporalis muscle on the lateral surface of the coronoid process and the masseter muscle on the lateral surface of the ascending ramus and the gonial angle are outlined in red (Gray 1918, Figure 167, image taken from: https://www.bartleby.com/107/44.html).
Figure 4.1.2: Line drawing of the medial view of the mandible illustrating the mandibular body, ascending ramus, gonial angle and the condyle and coronoid processes. The attachment for the temporalis muscle on the medial surface of the coronoid process and lateral pterygoid on the coronoid neck and medial pterygoid on the medial surface of the gonial angle are outlined in red (Gray 1918, Figure 177, image taken from: https://www.bartleby.com/107/44.html).

The movement of the mandible during mastication occurs at the temporomandibular joint (TMJ) a bilateral synovial joint where the mandible articulates with the cranium (Alomar et al. 2007, Carpenier et al. 1988, Fujita et al. 2001, Hinton and Carlson 1979). A dense fibrocartilaginous disc separates the TMJ into the superior and inferior cavity, and acts to cushion the joint and absorb stress. The TMJ is a ginglymoarthrodial joint which means that is moves in both rotation as a hinge action and translation as a sliding action (Alomar et al. 2007, Carpenier et al. 1988, Fujita et al. 2001, Stockstill and Mohl 2015). Both TMJs function together in a coordinated movement of the jaw, and neither can act independently of the other. Rotation at the TMJ allows for the opening and closing of the mouth, a movement which typically results in a 20-25mm opening (figure 4.1.3) (Helland 1980, Sakul et al. 2019, Stockstill and Mohl 2015). During larger movements of the mouth a sliding (translation) movement is also required, where the condyle slides out of the glenoid fossa anteriorly to the articular eminence, as such two joint system are involved in this movement (figure 4.1.4) (Nagata et al. 2001, Sakul et al. 2019). The TMJ is also protected by three functional and two accessory ligaments which act to restrain movement of the
joint to prevent damage discussed further in section 4.3.1 (Helland 1980, Sakul et al. 2019).

**Figure 4.1.3: Hinge movement of the TMJ.** Diagram illustrating the TMJ from the lateral view with the anterior of the mandible towards the right showing the position of the condyle, articular disc and glenoid cavity during the hinge -rotation- movement of the TMJ that allows the mouth to open 20-25mm. The articular disc a dense fibrocartilaginous disc which separates the mandibular condyle from the glenoid fossa is shown in purple (Hirst 2019).

**Figure 4.1.4: Sliding action of the TMJ.** Diagram illustrating TMJ from the lateral view with the anterior of the mandible towards the right showing the position of the condyle, articular disc and glenoid cavity during the sliding -translation- movement of the TMJ which allows the mouth to open ≥25mm, the articular disc is shown in purple (Hirst 2019).
4.2 Masticatory Muscles
When investigating dietary adaptations of the mandible it is important to consider the biomechanical function during mastication, and the muscles involved. There are four major muscles involved in mastication: the temporalis, the masseter, and the medial and lateral pterygoid muscles (Ginszt et al. 2017, Nishi et al. 2017, Ulrich 1959, van Eijden et al. 1997). In addition to the masticatory muscles that move the mandible, the muscles that form the tongue are also involved in the oral processing of food (Abd-El-Malek 1955, Lowe and Johnston 1979, Sanders and Mu 2013, Sauerland and Mitchell 1975). This section will discuss the insertion and attachment sites of these muscles and their role in mastication.
4.2.1 Temporalis
The temporalis muscle, also known as the temporal muscle, is a broad fan shaped muscle on the lateral side of the crania. The temporalis muscle arises from the temporal fossa and descends through the zygomatic arch before forming a thick tendon that inserts at the coronoid process on the mandible (figure 4.2.1) (Alomar 2007, Stone and Stone 2012, van Eijden et al. 1996, Washburn 1947). The function of the temporalis muscle can be divided into the anterior and posterior portions (Stone and Stone 2012). The anterior portion acts to move the mandible anteriorly in protrusion, while the posterior part of the muscle moves the mandible posteriorly in retraction. The action of both portions together moves the mandible dorsi-cranially; as such the strength of the temporalis muscle is associated with a strong jaw closure (Alomar 2007, van Eijden et al. 1997).

Figure 4.2.1: Temporal Muscle. Diagram illustrating the anatomy of the temporalis muscle and insertion into the coronoid process of the mandible, image taken from: https://www.kenhub.com/en/videos/temporal-muscle
4.2.2 Masseter
The masseter muscle originates at the zygomatic arch and inserts on the mandible. The masseter consists of two portions: the superficial and the deep portion. The superficial portion of the masseter muscle inserts at the masseteric tuberosity on the lateral surface of the gonial angle (Stone and Stone 2012). The deep portion of the masseter muscle inserts on the lateral surface of the mandibular ramus and into the TMJ (figure 4.2.2) (Stone and Stone 2012, Hannam and Wood 1989, van Eijden et al. 1997). As with the temporalis muscle the masseter muscle functions to move the mandible dorsi-cranially to close the jaw; it also acts to stabilise the articular capsule of the TMJ (Bakke et al. 1992, Stone and Stone 2012, Vitti and Basmajian 1977).

Figure 4.2.2: The Masseter Muscle. Diagram illustrating the masseter (shown in green) from the lateral view (above) posterior view (below), showing the superficial portion on the left and the deep portion on the right, image taken from: https://www.kenhub.com/en/videos/masseter-muscle
4.2.3 Medial Pterygoid

The medial pterygoid muscle originates from the sphenoid at the pterygoid fossa and pterygoid process and inserts at the pterygoid tuberosity on the medial surface of the gonial angle as illustrated in figure 4.2.3 (Carpentier et al. 1988, Stone and Stone 2012). In combination with the masseter muscle, the medial pterygoid forms a sling around the posterior and inferior of the mandible (Carpentier et al. 1988, Stone and Stone 2012, Wilkinson and Chan 1989). Contraction of the medial pterygoid moves the mandible dorsi-cranially, and anteriorly in protrusion (van Eijden et al. 1997, Vitti and Basmajian 1977).

Figure 4.2.3: The Medial Pterygoid. Diagram illustrating the medial pterygoid (shown in green) from the lateral view (above) and the posterior view (below) showing the deep head on the left and the superficial head on the right, image taken from: https://www.kenhub.com/en/videos/medial-pterygoid-muscle
4.2.4 Lateral Pterygoid

The lateral pterygoid has two origin points and can be divided into the large and small head. The small head of the lateral pterygoid originates from the intra-temporal crest of the sphenoid and inserts at the articular disc of the TMJ (Carpentier et al. 1988, McNamara 1973, Stone and Stone 2012). The large head of the lateral pterygoid originates from the pterygoid process of the sphenoid and inserts at the lateral portion of the mandibular condyle as illustrated in figure 4.2.4 (Carpentier et al. 1988, Fujita et al. 2001, McNamara 1973, Stone and Stone 2012, Widmalm et al. 1987). The function of the lateral pterygoid differs from that of the other muscles of mastication as it acts to open the jaw. Additionally, the unilateral activation of the lateral pterygoid also acts to move the mandible laterally during mastication (Vitti and Basmajian 1977, Wood et al. 1986, Mahan et al. 1983).

Figure 4.2.4: Lateral Pterygoid. Diagram illustrating the lateral pterygoid (shown in green) from the posterior view above with the superior head on the left and the inferior head on the right. Below are the same muscles from the lateral view with the superior head on the left and the inferior head on the right. Image taken from: https://www.kenhub.com/en/videos/lateral-pterygoid-muscle.
4.2.5 The Tongue

One of the most important muscle groups involved in mastication, and yet least understood, are the muscles of the tongue, which consists of the intrinsic and extrinsic muscles as illustrated in figure 4.2.5 (Abd-El-Malek 1955, Sanders and Mu 2013, Takemoto 2001). The tongue is attached to the mandible at the superior surface of the mental spine (Abd-El-Malek 1955, Gerard et al. 2003). The size and development of the tongue has been demonstrated to be associated with mandible morphology. The tongue is also argued to be elemental in the development and maintenance of normal mandibular ontogeny and post-natal growth and development (Hutchinson et al. 2014, Hutchinson 2017). For instance, mandibular growth between 20 weeks and two years of age has been found to be directed by the growth of the tongue (Hutchinson 2017). Furthermore, a geometric morphometric study of the tongues and mandibles from cadavers, determined that the mandible and tongue are intrinsically linked with regards to size and shape (Hutchinson et al. 2014). There has however been limited research concerning the activity of the tongue in mastication and mandible morphology among adults, and previous studies have failed to quantify which regions of the mandible are influenced by the development and function of the tongue.

Figure 4.2.5: The tongue. Diagram of the muscles of the tongue and attachment to the mental spine on the mandible (Gilbert et al. 2008, 4071, Figure 2).
4.3 Growth, development and the influence of the muscles
Postnatal growth of the mandible occurs through a process of displacement, whereby bone is resorbed and deposited at opposing sides of growth centres. It was Hunter (1771) who first reported that growth of the mandible occurs in a posterior direction towards the base of the skull, as opposed to growth through the elongation at the mental eminence as illustrated in figure 4.3.1 (Enlow and Hans 1996). This theory was proved nearly 200 year later in an experimental animal study conducted by Humphrey in 1964 where metal rings were placed on the anterior and posterior margins of the mandible of growing pigs. The rings that were placed on the posterior of the ramus became more deeply embedded in the mandible over time, while those in the anterior of the mandible at the mental eminence were released during growth (Humphrey 1964).

Figure 4.3.1: Growth of the Mandible. Diagram illustrating regional growth and remodelling in the mandible through bone resorption and deposition. Black arrows indicate of bone resorption and white arrows areas of deposition (Enlow and Hans 1964, 43, Figure 17).
The mandible is a complex morphological structure that is composed of different developmental units, which share a morphological function, as such each unit is constrained, in part, by the others (Rosas and Bastir 2004). There are six functional matrixes in the mandible which determine growth and development. These regions function individually and include: the body, alveolar process, coronoid process, gonial or mandibular angle, condyles and mental eminence. Each of these regions have their own influencing factor that determines growth (Moss and Rankow 1968). The influencing factor of the alveolar process is the dentition, this relationship is most clearly demonstrated in cases of antemortem tooth loss which has been shown to result in significant morphological changes and bone resorption at the alveolar process (Margvelashvili et al. 2013, Mays 2014, Parr et al. 2017). The condyles exhibit a more complicated growth pattern through proliferation of the condylar cartilage the mandible grows longer higher and wider (Sicher 1945). For the other regions, the influencing factors are primarily the muscles. The coronoid process is influenced by the temporalis muscle and the gonial/mandibular angle is influenced by the masseter and medial pterygoid muscle (Moss and Rankow 1968). Finally, the mental eminence is influenced by the digastric muscles which attach at the mental spine on the posterior surface of the mental eminence, while not one of the principal masticatory muscles, the digastric muscle is involved in movement of the mandible and hyoid when swallowing (Shinozaki et al. 2017, Sporns et al. 2017).

These functional matrixes have been recorded to be more greatly influenced by masticatory demands and bite force, compared to other regions. For instance, in experimental human and cadaver studies the ascending ramus and mandibular (gonial) angle were determined to be the regions which were most associated with increased development of the masticatory muscles (Hannam and Wood 1989, Kasai et al. 1994, Mays 2013, Raadsheer et al. 1999, Sasaki et al. 1989, Throckmorton and Dechow 1994). Therefore, in order to investigate mandible morphology in relation to mastication and diet it is necessary to further consider the function of these regions, along with the alveolar process, coronoid process, condyles and mental eminence, and how function is reflected in form.
4.3.1 Mandibular Condyle

The mandibular condyle articulates with the inferior surface of the articular disc that rests in the glenoid fossa of the temporal bone, together forming the moveable osseous portion of the temporomandibular joint (TMJ) (Miyawaki et al. 2001). Five ligaments attached to the mandibular condyle act to protect and support the TMJ. These ligaments act to limit movement of the joint in order to prevent damage (Alomar 2007, Yatabe et al. 1997, Osborn 1995). In addition to these ligaments, the inferior and superior lateral pterygoid muscles attach to the mandibular condyles. The function and morphology of these muscles are discussed in section 4.2. The mandibular condyle is subjected to significant mechanical strain during mastication (Kufley et al. 2017, Smith et al. 1983). As such the morphology of the mandibular condyle and the TMJ is influenced by mastication and diet (Kurusu et al. 2009, Owen et al. 1991, Throckmorton and Dechow 1994, Watt and Williams, 1951). As dietary consistency influences the mechanical strain placed upon the mandibular condyles this arguably influences bone remodelling.

Several animal studies have recorded significant variation in condylar morphology between species, this variation has been attributed directly to variation in diet and masticatory strategy (Anthwal et al. 2013, Anthwal and Tucker 2012, Bouvier 1986, Osborn 1987, Michaux et al. 2007, Ross et al. 2012). Furthermore, studies have recorded remodelling and alterations to the morphology of the mandibular condyle associated with dental attrition within species (Kufley et al. 2017). Moreover, the condylar morphology of 40 human females demonstrated a significant association with occlusal force, whereby low occlusal force individuals had smaller condyles (Alexis 2018, Enomoto et al. 2010, Kurusu et al. 2009, Yonemitsu et al. 2007). Additionally rats provided with a soft diet had a decreased bone volume and length of the condyle neck, while hard diet rats showed an increased volume and length (Denes et al. 2018).

Evolutionary changes in the mandibular condyle among extinct hominoids are considered to reflect changes in diet and food processing behaviours (Osborn 1987). Additionally, previous studies have recorded changes in the morphology of the mandibular condyle over time among modern humans, which is suggested to be the result of significant dietary transitions (Bejdova et al. 2013, Hinton and Carlson 1979, Kranjčić et al. 2012, Rando et al. 2014, Sardi et al. 2006, Trinkaus...
et al. 2003). For instance, morphological differences in the mandible of Mesolithic and Post-Mesolithic Nubians were recorded by Galland et al. (2016). Hunter-gatherer Nubians from the Mesolithic had a longer mandibular condyle, compared to Post-Mesolithic agricultural populations, these morphological differences are suggested to relate to subsistence changes. This is supported by previous studies which have illustrated a relationship between TMJ morphology and diet (Koppe et al. 2007, Mongini, 1974, Osborn and Baragar 1992). Due to the previous literature supporting a relationship between morphology of the mandibular condyle and masticatory stress this study will utilise four landmarks on the mandibular condyle, these landmarks are illustrated in section 5.5.5 table 5.5.2.

4.3.2 The Coronoid Process
Compared to the condyle there has been very limited research regarding the relationship between the morphology of the coronoid process and diet/masticatory behaviour. While it is known that the coronoid process and mandibular notch experiences high levels of strain (Pérez-Barbería and Gordon 1999), and that morphology of the coronoid process varies between species in relation to dietary adaptations (Nogueira et al. 2009), this is normally treated as an extension of analysis of the condyle. There are however a few studies which have detailed changes in the coronoid process in relation to known dietary transitions. For instance a taller and more angled coronoid process was recorded among agriculturalists compared to hunter-gathers who had a comparatively short process (von Cramon-Taubadel 2011). Moreover, Neanderthals who are generally considered to have produced a greater bite force compared to AMH also had a comparatively taller coronoid process (Nicholson and Harvati 2006). Furthermore, an experimental animal study analysed ten cats who had their right temporal muscle removed at 6-weeks-old. The cats were fed a normal diet until 16 months of age when they were sacrificed, and morphology of the coronoid process was examined (Avis 1959). It was found that on the right hand side, in the absence of mechanical strain from the temporalis muscle the coronoid process was slightly shorter, and the shape was significantly different (Avis 1959).
4.3.3 Mandibular/Gonial Angle
The mandibular angle is formed by the posterior border of the mandibular ramus and the inferior border of the mandibular body (Oettlé et al. 2009). The size of the mandibular angle has been suggested to relate to masticatory stressors, due to the location of masticatory muscle attachments (section 4.2). This is supported by several experimental animal studies that have directly related the morphology of the mandibular angle with the biomechanical functions of the superficial masseter and the internal pterygoid muscle (Avis 1961, Hichijo et al. 2015, Lee et al. 2017). These studies reported that a smaller, less robust mandibular angle was associated with reduced masticatory forces (Oettlé et al. 2019. For instance, the removal of the superficial masseter and internal pterygoid muscles of 30 rats, resulted in significant morphological reductions in the mandibular angle after 8-43 days (Avis 1961). This is further supported by clinical studies of individuals with myotonic dystrophy21 of the masticatory muscles. Patients with myotonic dystrophy were found to have a less prominent mandibular angle, and reduced mandibular ramus and condyles compared to the control group (Kiliaridis et al. 1989, Lee et al. 1972). Moreover, an analysis of a 15th century Finish and Norwegian human skeletal assemblages found that individuals with marked tooth wear had a smaller more acute mandibular angle (Krogstad and Dahl 1985, Varrella 1990). While there is extensive support for the relationship between the mandibular angle and mastication, the lack of distinct landmarks on the gonial angle makes 3D GMM of the mandible difficult. Despite this, three landmarks on the gonial angle will be utilised in this study, see section 5.5.5.

4.3.4 Mental Eminence Region
It has been suggested that the protruding morphology of the mental eminence of the human mandible is also influenced by masticatory stress, related to dietary consistency (Coquerelle et al. 2012, 2013, Daegling 1993, Tuominen et al. 1993). However, there remains a number of unresolved questions concerning the mental region of the human mandible, and there is a lack of previous research concerning its growth, development and evolution (Coquerelle et al. 2013,

21 a genetic disorder that results in pronounced atrophy of the muscles
Stringer et al. 1984). Despite this, research conducted by Coquerelle et al. (2012) did indicate that the development of the mental prominence/eminence is influenced by the activity of masticatory muscles. Additionally, the mental eminence is a frequently used feature for sex estimation, with males having a larger more robust mental eminence compared to females as shown in figure 4.3.2 (Buikstra and Ubelaker 1994, Durić et al. 2005). As males have been found to on average have a higher bite force (discussed further in section 4.5.2) (Koc et al. 2013, Modesto de Abreu et al. 2014, Peyron et al. 2004, Tamut et al. 2012, Youssef et al. 1997), the sexually dimorphic nature of this feature may provide further support to the role of masticatory muscles in the development of the mental eminence. Evolutionary research potentially provides further support for this, as research (discussed in Chapter 3) indicates that a reduction in tooth size has influenced the morphology of the mental eminence over human evolution (Coquerelle et al. 2013, Riesenfield 1969). Considering the purported relationships between masticatory stress, mandible morphology and tooth size (section 3.1.1), more research is necessary to understand the relationship between the morphology of the mental region both in terms of adaptation and evolution.

![Figure 4.3.2: Sex estimation from the mental eminence.](image)

4.3.5 Mandibular body
It has been suggested that the morphology of the mandibular body is influenced by dietary changes (Galland et al. 2016, Katz et al. 2017, Martin and Danforth 2009, Rando et al. 2014). Both the width and breadth of the human mandible has been observed to change significantly over time, with a decrease in width and an increase in length resulting in a longer thinner more gracile mandible, which is arguably the result of reductions in masticatory strain (Kaifu 1997, Lavelle 1972,
Martin and Danforth 2009, Rando et al. 2014). While masticatory stress is directly applied to the mandibular body via the teeth, during normal mastication this stress is distributed across the dental arcade. Therefore, compared to the other regions where force is applied via muscle insertion sites, masticatory stress is thought to be more distributed across the mandibular body (Lee et al. 2017). Furthermore, an experimental animal study observed that morphological differences resulting from changes in dietary consistency were less marked in the mandibular body compared to other regions such as the gonial angle (Yamada and Kimmel 1991). This study however, analysed microscopic changes in bone remodelling and as such results may not apply to macroscopic analysis of mandibular morphology (Yamada and Kimmel, 1991). Several landmarks along the mandible body were utilised in order to investigate how width, breadth and height has changed over time in Britain.

4.4 Mastication and Bone Remodelling
Mechanical strain placed on the mandible influences growth and development (Jahan et al. 2010, Mao and Nah, 2004). As the masticatory muscles are the strongest muscles in the skull, they are the primary muscles which create in mechanical strain on the mandible, and consequently stimulate bone remodelling and morphological changes to the mandible (Rando et al. 2014). Animal and human studies have demonstrated a relationship between higher bite force or size of the masticatory muscles and increased mandibular robusticity (Hutchinson et al. 2014, Mays 2013, Kiliaridis et al. 1995, Kiliaridis et al. 1989, Odman and Kiliaridis 1989, Toro-Ibacache et al. 2016). These studies further determined that increased robusticity was most prominent at the posterior part of the mandible and that a smaller mandibular angle; more angular coronoid and condylar processes as well as an anterior growth rotation pattern were all associated with increased bite force (Kiliaridis et al. 1995, Mays 2013, Ringqvist 1973, Sondang et al. 2003, Throckmorton et al. 2000, Tircoveluri et al. 2013, Yonemitsu et al. 2007). In order to understand the relationship between diet, masticatory behaviour and human mandibular morphology, this section will discuss experimental animal studies which have investigated this relationship. This will then be built upon by clinical human studies which have recorded a correlation between masticatory behaviour and masticatory muscles as well as
between masticatory muscles and mandible morphology. Finally, previous archaeological studies which have investigated changes in mandible morphology among past population associated with dietary transitions will be discussed.

4.4.1 Animal Studies
Cranial and mandibular morphology varies substantially between mammalian species due to the requirements imposed by their diet. Carnivores and herbivores, for instance, have vastly different masticatory requirements which is reflected in both their masticatory muscles and mandible morphology (Hanken and Hall 1993, Watson et al. 2018). Carnivores require jaws with a fast closing capacity, reduced lateral movements and high levels of force directed posteriorly in order to resist anterior forces of struggling prey. As such, they have large temporalis muscles, a high coronoid process and low mandibular condyles. Conversely herbivores require large lateral masticatory movements in order to efficiently break down tough cellulose. These lateral movements require a large masseter and pterygoideus muscles, and a high mandibular condyle (Anthwal et al. 2013, Anthwal and Tucker 2012, Hanken and Hall 1993, Watson et al. 2018). Furthermore, variation in masticatory stress and mechanical loads has arguably resulted in significant morphological variation even among closely related species (Anapol and Lee 1994, Daegling and McGraw 2007, Meloro et al. 2017, Ray and Kim 2015). Among eight species of closely related platyrrhine monkeys significant differences were reported in mandible and dental morphology occur in relation to observed dietary differences (Anapol and Lee 1994). Furthermore, significant differences present in the mandible morphology between Bornean orangutans (Pongo pygmaeus wurmbii) and Sumatran orangutans (Pongo abelii) are suggested to be the result of differences in diet. While both species consume similar diets, the Bornean orangutans spends a larger proportion of time-consuming hard foods including bark, seeds and vegetation (Taylor 2006, Vogel et al. 2014).

In addition to between species differences, experimental animal studies have consistently observed that among non-human animals including mice, rats, and monkeys, changes in dietary consistency have resulted in significant changes to mandible morphology, as well as reduced bone mineral density. Such
morphological changes are arguably the result of the reduction in masticatory stress brought about by this dietary change (Barber et al. 1963, Denes et al. 2018, Ito et al. 1988, Kikuta 1985, Kiliaridis et al. 1988, Kufley et al. 2017, McFadden et al. 1986, Watt and Williams 1951, Yamada and Kimmel 1991). For example, among studies where rats were fed soft or hard diets, the soft diet group were found to have reduced bone mass as well as thinner cortical bone in the mandibular condyles, ramus and alveolar process based on radiographic analysis (Bresin et al. 1999, Tsai et al. 2011). Similar results have been recorded among non-human primates. For instance, forty-three squirrel monkeys was found to vary significantly between hard and soft dietary groups, with the hard diet monkeys having a more robust mandible compared to the soft diet group (Beecher et al. 1983). These results are further supported by a 3D geometric morphometric study which investigated mandibular shape change among rats (Kono et al. 2017). It was reported that rats fed either a soft powdered diet or a hard diet, had significant differences in the posterior of the mandibular body and the coronoid and condyle after six weeks based on analysis of micro-CT scans (Kono et al. 2017).

Additionally in cases where animals have been artificially prevented from normal masticatory activity a reduction in bone mineral density, masticatory muscle size and significant changes in mandible morphology have all been recorded. For example, Sato et al. (2005) prevented rats from biting through the surgically insertion of a metal plate into their jaw between the maxillary and mandibular incisors. After four weeks a decline of bone mineral density was recorded, compared to a control group (Sato et al. 2005). After six weeks of masticatory hypofunction bone mineral destiny had declined significantly, with a 11.6% decrease in bone density on the buccal side and 16.7% on the lingual. The greatest decline in bone mineral density occurred at the root apex (38.1%) (Sato et al. 2005). Moreover, studies have reported that injections of botulinum\textsuperscript{22} into the lower jaw of rats, resulted in a reduction in muscle volume as well as cortical bone thickness, specifically at attachment sites for the masticatory muscles, as well as alterations to the overall morphology of the craniofacial bone structure compared to the control group (Matic et al. 2007, Moon et al. 2015, Tsai et al.

\textsuperscript{22} which prevents muscle activity
2009, 2010a, 2010b, 2015). These studies indicate that among non-human animals alterations in both dietary consistency and masticatory muscle function can result in significant changes in craniofacial morphology within a relatively short time period.

4.4.2 Clinical Studies
Among humans there are several studies which have demonstrated a relationship between bite force and mandible morphology (Sella-Tunis et al. 2018, Toro-Ibacache et al. 2016). Toro-Ibacache et al. (2016) analysed the craniofacial morphology of 20 adult humans, 11 female and nine males, and compared this to the cross-sectional area (CSA) of the masticatory muscles. A large CSA for the temporalis muscles was found to correlate with an elongated mandibular ramus and low set coronoid process. This study however, focussed on the craniofacial morphology and only four landmarks were placed on the mandible, as the posterior and inferior portion of the mandible were frequently absent from the CT scans (Toro-Ibacache et al. 2016). A study conducted by Sella-Tunis et al. (2018) analysed CT scans of sixty-two human mandibles, mandibular morphology was analysed using landmark based GMM analysis. Analysis revealed a significant association between mandible morphology and the CSA of the masticatory muscles. Larger masticatory muscles were associated with a wider ramus, larger coronoid and a more rectangular body. Moreover little correlation was reported between linear mandible measurements and masticatory muscle size, illustrating that the relationship between mandible morphology and masticatory activity is not readily identified through linear measurements, and the relative superiority of landmark GMM methods (Sella-Tunis et al. 2018).

Clinical human studies have also demonstrated that increased masticatory activity resulted in an increased bite force, which in turn was associated with increased masticatory muscle size (Hutchinson et al. 2014, Toro-Ibacache et al. 2016, Kiliaridis et al. 1995, Odman and Kiliaridis, 1989, Kiliaridis et al. 1989). For instance, young adults following a regime of systematic masticatory activities involving a hard-chewing gum showed an increase in maximal bite force after one month of exercise (Kiliaridis et al. 1995). The use of similar masticatory training exercises was also suggested to have a positive effect on patients who
presented with an anterior open bite\(^\text{23}\) illustrating that these increases in masticatory strain are associated with changes in mandible morphology (Ingervall and Bitsanis 1987, Spyropoulos 1985). Additionally, patients with myotonic dystrophy have lower maximal bite forces and higher rates of malocclusion, and their craniofacial and mandible morphology was found to differ from the control sample (Kiliaridis et al. 1989, Odman and Kiliaridis 1989). These studies therefore suggest both that masticatory activity influences development of the muscles of mastication, and that the size of these muscles correlate with specific craniofacial and mandibular morphological differences.

4.4.3 Archaeological Studies
As demonstrated, there is substantial evidence supporting the relationship between masticatory behaviour, size of the masticatory muscles and mandible morphology among human and non-human animals. These studies, however, have looked at the extremes in masticatory changes and as such results are not necessarily representative of natural dietary changes, such as those that have occurred in human history. However, previous archaeological investigations have demonstrated significant changes in mandible morphology associated with major dietary transitions - such as the Agricultural and Industrial Revolution. This section will detail some of the previous studies that have analysed morphological differences in the mandible as a means of investigating dietary changes, an overview of these studies are provided in table 4.4.1.

4.4.3.1 The Advent of Agriculture
Paschetta et al. (2010) analysed craniofacial variation among 357 individuals from archaeological assemblages during the agricultural transition in the Ohio Valley. Significant difference were recorded in the morphology of the mandibular corpus and ramus between hunter-gatherer and agriculturists (Paschetta et al. 2010). Unfortunately, due to the preservation of the mandible, this study primarily utilised landmarks on the craniofacial bones. Furthermore, morphological differences between the groups were not described. Similar

\(^{23}\) a form of malocclusion where the front teeth do not touch and there is not overlap between the upper and lower incisors
findings have been recorded by Carlson and Van Gerven (1977) among ancient Nubians, suggesting that the transition to agriculture corresponded with a significant decrease in the robusticity of the craniofacial complex, specifically the mandible (Carlson and Van Gerven 1977b). Among hunter gatherers and agriculturalists in the Levant a similar reduction in the masticatory functional complex has been recorded by Pinhasi et al. (2007). While overall mandible size was not significantly different, the ramus breadth and anterior height of the mandibular body were both significantly reduced among agriculturalists (Pinhasi et al. 2007). Furthermore, an analysis of human mandibular morphology during the terminal Pleistocene period in the Levant revealed a significant reduction in the size of the mandible over time, suggested to be related to dietary changes which occurred during this period and resulted in reduced masticatory stress (May et al. 2018). These studies however, relied on linear measurements and as such represent changes in size of the mandible rather than necessarily reflecting shape changes (Sardi et al. 2006, González-José et al. 2005).

4.4.3.2 3D Geometric Morphometrics
A few studies have utilised 3D geometric morphometric analysis – which explores shape rather than size - to investigate changes in mandible morphology during the agricultural transition (Galland et al. 2016, von Cramon-Taubadel 2011, Katz et al. 2017). For instance, when comparing hunter-gatherer populations with different agriculturists, significant morphological changes were detected in the craniofacial complex (von Cramon-Taubadel 2011, Katz et al. 2017). Among the agricultural groups individuals had a taller coronoid process, narrower ramus and lower projecting mental eminence. These differences were found to be more pronounced among the dairy agriculturists as opposed to cereal farmers which was argued to be the result of a more pronounced reduction in masticatory stress among dairying populations (Katz et al. 2017).

Furthermore, a global analysis of mandibular shape and subsistence economy, determined that while morphological variation in the cranium did not reflect dietary changes, significant changes did occur between subsistence groups in mandible morphology. Hunter-gatherer and agricultural archaeological assemblages were compared among 11 populations and mandibular and cranial morphology were analysed using landmark GMM. Results determined that agriculturalists typically had a relatively short and broad mandible, with a tall
mandibular ramus and coronoid process, and wide gonial angle. In comparison the hunter-gatherer populations had a low and narrow mandible with a short ramus and coronoid process, and narrow gonial angle (von Cramon-Taubadel 2011). These shape differences are similar - albeit less extreme - to the morphological changes which have been reported in the clinical and experimental animal studies discussed in section 4.4.1, supporting previous claims that diet among pre-agricultural populations was harder requiring stronger masticatory muscles compared to the agriculturalists.

4.4.3.3 Industrialisation
While clear changes were observed across the transition to agriculture, another notable dietary shift that has been previously studied is the Industrial Revolution (Bosman 2016, Rando et al. 2014). These studies have recorded significant differences in mandible morphology between Medieval and Post-Medieval skeletal assemblages. A 3D geometric morphometrics analysis of mandible morphology which compared individuals from archaeological sites of Alkmaar (1484-1574AD) and Middenbeemster (1829-1866AD) reported that Medieval individuals had significantly larger mandibles. However, morphological differences were only recorded among males in this study (Bosman 2016). Similar analysis has been conducted on British archaeological assemblages from Medieval and Post-Medieval periods in London. Rando and Hillson et al. (2014) analysed 279 mandibles and determined a significant reduction in several mandibular measurements among Post-Medieval individuals. This reduction in size was more prominent in areas of the mandible associated with masticatory muscle attachments, such as the gonial angle, ramus height, ramus width as well as bi-gonial and bi-condylar breadth (Rando et al. 2014). These studies support the archaeological and historical evidence that the diet consumed during the Post-Medieval period was softer, requiring less mastication. Additionally, more recent changes in mandible morphology have been recorded in a comparison between early 20th century individuals from the Terry and Hamann Todd collection and later 20th century individuals from the Forensic Anthropology Database in Tennessee (Martin and Danforth 2009). Analysis revealed that there were statistically significant differences in the width and length of the mandibular body and bigonial breadth, supporting previous research that over time
mandible morphology has become longer, narrower and more gracile (Martin and Danforth 2009).

4.4.3.4 Multi-Period Analysis
While many previous studies have only compared two time periods thereby focusing on a single dietary transition, there have been two previous studies which have investigated changes in mandible morphology across multiple time periods in Britain. Moore et al. (1968) analysed changes in mandible morphology - based on linear measurements - between Neolithic, Bronze Age, Romano-British, Anglo-Saxon, Medieval, 17th and 19th century assemblages (n = 571). The most significant changes between assemblages were found to occur in the mandibular ramus (Moore et al. 1968). Similarly, Lavelle (1972) recorded significant differences in mandible morphology between Romano-British, Anglo-Saxon and 19th century British assemblages. While it was determined in this study that Romano-British and Anglo-Saxon mandibles both showed significant separation from nineteenth century assemblages, it could not be determined if these changes were the result of short-term dietary changes or long-term evolutionary factors. While these studies provide evidence for long-term morphological changes in Britain, they failed to describe in detail the morphological changes which occurred or the regions of the mandible which were principally affected. Furthermore, since these studies morphometrics has advanced considerably and 3D geometric morphometric analysis has been shown to be superior to linear measurements, revealing more information (Cardini 2013).

As discussed there is evidence supporting the link between masticatory behaviour and mandible morphology both among experimental animal studies (section 4.4.1) and human clinical studies (section 4.4.2). Furthermore multiple bioarchaeological studies have reported significant morphological changes occurring in the mandible that are associated with major dietary transitions. Despite this, other studies have found a comparatively weak relationship between mandible morphology and diet, arguing that mandible morphology cannot be used to infer diet (Grine and Daegling 2017). Moreover, many of these previous studies have typically relied on small sample sizes (eg: Frake and Goose (1997) n = 36, Bosman (2016) n= 87, Galland et al. (2016) n = 97, representing
five assemblages) and linear measurements (eg: Kaifu 1997, Martin and Danforth 2009, Mays 2015, May et al. 2018, Moore et al. 1968) and have not investigated how smaller dietary changes may influence mandible morphology. As such larger longitudinal studies incorporating several time periods and utilising 3D geometric morphometric analysis is required in order to understand the sensitivity of the mandible to dietary changes.
Table 4.4.1: Previous Studies- Mandible morphology and Diet  
Table detailing the previous studies which have compared mandible morphology among two or more human archaeological assemblages in order to investigate how dietary differences may have influenced morphology, of the 14 studies only five of these were 3D GMM studies, none of which had more that 33 landmarks and the largest sample was 534 individuals.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sample</th>
<th>Method</th>
<th>Key Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Bosman 2016, Bosman et al. 2017)</td>
<td>Medieval (n=37) and Post-Medieval from the Netherlands (n=51) assemblages</td>
<td>3D GMM study, 27 landmarks and nine curves of semi landmarks</td>
<td>Medieval individuals were found to have larger more robust mandibles among males, with no significant differences recorded among females</td>
</tr>
<tr>
<td>(Katz et al. 2017)</td>
<td>Global sample of 24 groups of preindustrial forager and farmer (n=534) these populations were divided based on their diet, the dietary groups studies were dairy, cereals and mixed</td>
<td>3D GMM, 22 landmarks on the mandible</td>
<td>Cranial and mandibular differences between the subsistence groups indicate a reduction in masticatory stress as indicated by a reduction in mandibular size among the agricultural assemblages</td>
</tr>
<tr>
<td>(Galland et al. 2016)</td>
<td>5 periods in Lower Nubia (n=97), Mesolithic (11,000-8,000 BCE) n=18, A-group (3,300-2,800 BCE) n=21, C-group (2,300-1,800 BCE) n=27, Pharanoic (1,550-1,070 BCE) n=23 and Meroitic (100 BCE -350 CE) n=8.</td>
<td>3D GMM, 33 landmarks on the mandible, crania also included</td>
<td>Significant morphological differences recorded between hunter-gatherer and agricultural groups. Mesolithic Nubians had a larger and more robust mandible compared to later groups</td>
</tr>
<tr>
<td>(Bejdova et al. 2013)</td>
<td>Analysis of Czech populations over time, including Early (n=81) and High Middle Ages (n=53), early modern ages (n=64) and Modern (21st century) Czech populations (n=92)</td>
<td>3D GMM, 27 landmarks</td>
<td>Sexual dimorphism in mandible size increased over time, no clear pattern in morphology. Size changes in female mandibles were thought to better reflect environmental conditions. While not the focus of this research temporal changes were evident, modern individuals did appear to have a more gracile mandible, although statistics are no available for this.</td>
</tr>
<tr>
<td>Study</td>
<td>Sample Description</td>
<td>Methodology</td>
<td>Findings</td>
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<td>------------------------------</td>
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<tr>
<td>(von Cramon-Taubadel 2011)</td>
<td>295 mandibles from a global sample of 11 populations of agricultural and hunter-gatherer populations</td>
<td>3D GMM, 33 landmarks</td>
<td>Compared to the crania mandible morphology reflected substance economy more than neutral genetic patterns. Hunter gatherers had a longer narrower mandible compared to agriculturalists.</td>
</tr>
<tr>
<td>(Paschetta et al. 2010)</td>
<td>Hunter gatherer and agricultural assemblages from the Ohio Valley n= 357</td>
<td>3D geometric morphometric analysis</td>
<td>Significant differences in the mandible corpus and ramus. Only described the amount of variation between groups and majority of landmarks were located on the crania.</td>
</tr>
<tr>
<td>(May et al. 2018)</td>
<td>Comparison of assemblages from the Pleistocene and Holocene in the Levant, n=41 Natufian hunter-gatherers, n=28 pre-pottery Neolithic, n=13 Chalcolithic farmers and a modern control sample n=61</td>
<td>15 linear measurements and cross-sectional areas and four angular measurements</td>
<td>Reduction in mandible size over time, with an ongoing reduction between the Chalcolithic and modern sample.</td>
</tr>
<tr>
<td>(Hoover and Williams 2016)</td>
<td>165 individuals Jomon period in Japan including foraging, fisher-gatherers and maritime foragers</td>
<td>7 mandible measurements</td>
<td>Mandible morphology varied between regional diets, subsistence patterns were found to better explain variation compared to temporal trends or biological sex.</td>
</tr>
<tr>
<td>(Mays 2015)</td>
<td>Post-Medieval comparison of n=64 individuals from Zwolle Netherlands 19th C and Wharram Percy, England 10th-19th C</td>
<td>9 linear measurements and the gonial angle</td>
<td>Mandibles from Zwolle were smaller than the Wharram Percy particularly in the gonial and ramus region.</td>
</tr>
<tr>
<td>(Rando et al. 2014)</td>
<td>279 Medieval (n=135) and Post-Medieval (n=144) British skeletons</td>
<td>11 mandible measurements</td>
<td>Significant reduction in the majority of mandible measurements among the Post-Medieval assemblage.</td>
</tr>
<tr>
<td>(Martin and Danforth 2009)</td>
<td>407 mandibles from the Terry Collection, Smithsonian and Hamann-Todd, Cleveland Museum of Natural History compared to 595</td>
<td>9 mandible measurements</td>
<td>Significant decrease in mandible body width and bi-gonial breadth and an increase in body length over time.</td>
</tr>
<tr>
<td>Study</td>
<td>Sample Description</td>
<td>Measurements</td>
<td>Findings</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------------------------------------------------------------------</td>
<td>--------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>(Kaifu 1997)</td>
<td>284 individuals from eight time periods in Eastern Japan between 4000 BCE to 1950 CE</td>
<td>21 mandible</td>
<td>Mandibular differences recorded over time, pre-modern and modern groups showed a significant reduction in the areas associated with masticatory muscles</td>
</tr>
<tr>
<td>(Frake and Goose 1997)</td>
<td>36 mandibles medieval and modern (17th-18th century) British assemblages</td>
<td>5 linear mandible dimensions</td>
<td>Medieval individuals from Liverpool and Scarborough were similar in size and larger than 17th-18th century individuals</td>
</tr>
<tr>
<td>(Lavelle 1972)</td>
<td>Romano-British, Anglo-Saxon and 19th century British assemblages (n=210)</td>
<td>10 mandible</td>
<td>There was a reduction in the majority of mandibular dimensions, while the mandibular angle increased over time. Although CVA showed no significant differences between Roman and Anglo-Saxon samples while both differed significantly with the 19th century sample</td>
</tr>
<tr>
<td>(Moore et al. 1968)</td>
<td>517 mandibles from Neolithic, Bronze Age, Romano British, Anglo-Saxon, Medieval, 17th and 19th century England</td>
<td>Linear and angular measurements of the mandible</td>
<td>Mandible size decreased over time, suggested to relate to dietary changes such as the replacement of rye with wheat as a key staple and refinement of cooking processes</td>
</tr>
<tr>
<td>(Pinhasi et al. 2007)</td>
<td>242 individuals across six periods in the Levant, Early, Middle and Late Middle Agricultural and Pre-pottery Neolithic A, B and C</td>
<td>9 mandibular dimensions</td>
<td>Significant reduction in ramus breadth and anterior height of the mandible as well as a reduction in the dentition.</td>
</tr>
<tr>
<td>(Carlson and Van Gerven 1977b)</td>
<td>Hunter gatherer (n=12), transitional agriculture (n=52) and fully agricultural assemblages (n=188)</td>
<td>16 craniofacial measurements</td>
<td>Reductions in the size and robusticity of the maxilla-mandible complex</td>
</tr>
<tr>
<td>Study</td>
<td>Sample Size</td>
<td>Measurements</td>
<td>Methods</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------</td>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>(Rock et al. 2006)</td>
<td>30 individuals from a Black Death cemetery in London, 54 individuals from the Mary Rose and 31 modern individuals</td>
<td>20 measurements from cephalometric radiograms</td>
<td>Reductions in the dimensions of the cranial and mandibular measurements</td>
</tr>
<tr>
<td>(Luther 1993)</td>
<td>31 medieval individuals from a black death cemetery in London and 32 modern individuals</td>
<td>4 2D indices based on radiographs</td>
<td>A more gracile mandible morphology and more obtuse gonial angle was associated with modern individuals</td>
</tr>
</tbody>
</table>
4.5 Factors Influencing Mastication

Masticatory patterns are known to vary between individuals, and several intrinsic and extrinsic factors, beyond simply the length of chewing and the relative hardness of the food source are known to influence mastication (Koc et al. 2013, Mioche et al. 2004b, Mioche et al. 2004a, Rey et al. 2007, Van der Bilt 2002, Vinyard et al. 2008). Therefore, in order to understand temporal changes in mandible morphology, the external and internal factors which may influence masticatory patterns need to be considered. Masticatory efficiency (ME) and masticatory performance (MP) relates to the ability to reduce food into small particles for consumption. ME and MP have been suggested to influence mandible morphology and subsequently factors influencing ME and MP need to be considered for their potential impact on mandibular morphological variation (Helkimo 1978). Several interconnecting factors are known to influence ME and MP including: bite force, occlusion, salivary activity, tongue movement and mandibular kinematics (Felicio et al. 2008, Farias Gomes et al. 2010, Helkimo et al. 1978, Modesto de Abreu et al. 2014). Hatch et al. (2000) analysed the MP of 631 individuals between 37 and 80 years of age. MP was analysed by weighing the macerated food that will pass through a screen after a standardised amount of time chewing. These results supported the notion that “…masticatory performance is the outcome of complex simultaneous interrelationships among physiological and contextual variables” (Hatch et al. 2000, 645). This section will discuss some of the factors identified in Hatch et al. (2000) study, as well as other studies which have been found to influence mastication.

4.5.1 Food texture

The material properties of food have been demonstrated to alter the way food is processed within the oral cavity (Foster et al. 2006, Koc et al. 2013). Texture as it relates to mastication has been highly studied, and food hardness is arguably the most frequently studied aspect. Increased hardness of food has been found to result in an increased chewing time, muscle activity and jaw movement (Foster et al. 2006, Koc et al. 2013, Peyron et al. 2002). Other factors relating to texture such as moisture release, cohesiveness, adhesiveness, particle size and
factorability have all been shown to influence masticatory activity (Koc et al. 2013). While it is not possible to estimate these different food textures among archaeological assemblages it is important to realise that dietary changes in masticatory patterns do not simply relate to the relative hardness of food.

4.5.2 Sex Differences
Hatch et al. (2000) noted that sex was the predominate influencing factor affecting bite force, with females having a lower maximum bite force (MBF) compared to males. The influence of sex on mastication is further supported by the results obtained from a clinical study conducted by Tamut et al. (2012). ME was assessed among males and females based on the amount of masticated test food which passed through a sieve (Tmut et al. 2012). It was determined that males had a significantly higher MBF but lower ME compared to females. Similar findings have been reported by Modesto de Abreu et al. (2014) who analysed the ME and MBF among 27 men and 28 women with normal occlusion. Moreover, electromyography activity and larger vertical movements were also reported among males compared to females during mastication (Koc et al. 2013, Peyron et al. 2004, Youssef et al. 1997). This indicates that the activity of the masticatory muscles may vary both in force and pattern between males and females.

4.5.3 Age
Age has also been argued to influence oral physiology and neuromuscular activity during mastication, which results in changes in masticatory patterns (Mioche et al. 2004b). An individual’s age has been shown to influence masticatory patterns, even when controlling for ante-mortem tooth loss. Peyron et al. (2004) analysed the mastication of 67 individuals aged between 25 and 75; all had complete dentition and were regarded as having no influencing dental pathology. The number and frequency of masticatory cycles, as well as the electromyography activity from the right and left masseter and temporalis muscles were analysed while the subjects chewed food models of varying hardness. A positive correlation between the subject’s age and the number of masticatory cycles was reported. Overall, Peyron et al. (2004) found a mean
increase of 0.3 cycles per year of life. In addition to this, the frequency of masticatory cycles was found to decrease with age (Peyron et al. 2004). It cannot be determined, however, if the frequency and duration of chewing has a significant effect on mandible morphology, as this increased frequency has been suggested to compensate for reduced masticatory force (Mioche et al. 2004b). As older individuals have a decreased total muscle mass and muscle force, as well as a reduction in chewing velocity and smaller amplitude of vertical masticatory movements. It is therefore argued that to compensate for these reductions in masticatory force, older individuals have an increased number of chewing cycles (Koc et al. 2013, Mioche et al. 2004b, Mioche et al. 2004a, Peyron et al. 2004). However, Hatch et al. (2000) found conflicting results arguing that age does not have a statistically significant effect on MP.

4.5.4 Occlusal Area and Antemortem Tooth Loss
The amount of dentition present and the degree of occlusal contact has been reported to influence chewing patterns and efficiency. A loss of occlusal contact either as a result of antemortem tooth loss (AMTL) or malocclusion has been found to alter chewing patterns and decrease masticatory efficiency (English et al. 2002, Ikebe et al. 2006, 2011, Koc et al. 2013). AMTL has consistently been found to have a significant influence on ME in clinical studies (Manly 1951, Manly and Braley 1950, Schutz 1922). An experimental study which raised the bite of individuals through the insertion of an on-lay apparatus resulted in a reduction to both the occlusal area and MP when chewing (Schutz 1922). These results are further corroborated by Manly (1951) who conducted chewing tests using peanuts and carrots and assessed MP with a sieve method similar to Hatch et al. (2000). Results suggested that occlusal area was the most significant factor affecting MP (Manly 1951).

Furthermore, it was argued by Schutz (1922) that the occlusal surface of a tooth was the principal factor relating to the value of that tooth in mastication. The influence of AMTL therefore varies depending on the missing tooth (Manly 1951, Schutz 1922). The first and second molar have been determined in experimental studies to be of equivalent value in MP but are twice as effective as premolars (Manly 1951, Schutz 1922). A clinical study which measured ME
when chewing raw peanuts found that individuals with all molar dentition present had an average performance of 88%, while performance dropped to 78% among individuals missing their third molars. Individuals with only their first molar in occlusion average performance was only 55% (Manly and Braley 1950). The effect of AMTL upon ME however, varies between type of food items consumed. Therefore studies which analyse ME based on one type of food provides limited information, and results may not be applicable to normal dietary behaviour (Sheiham et al. 1999). Moreover AMTL has been shown among modern populations to influence dietary choices (Hung et al. 2003, 2005).

4.5.5 Pathology
The presence of certain pathological conditions affecting the dentition may influence masticatory patterns, due to associated pain during mastication (Harper et al. 2000). An experimental study conducted by Svensson et al. (1997) found that pain in the masseter muscles induced by bilateral injections of hypertonic saline resulted in statistically significant changes in masticatory patterns, with reduced EMG activity when closing the jaws, and increased EMG activity when opening the jaws during mastication (Svensson et al. 1997). Pain associated with TMJ wear has also been found to result in a reduced range of masticatory movement; when pain was alleviated during treatment the range of movement was found to increase (Mazzetto et al. 2010). These findings are further supported by Hansdottir and Bakke (2004) who determined that long-standing TMJ pain was associated with impaired masticatory function, which affected the duration of masticatory cycles, closing velocity and maximum bite force (MBF) (Hansdottir and Bakke 2004). Furthermore, among children with juvenile rheumatoid arthritis, patients compromised their MP to avoid pain during mastication (Harper et al. 2000). This was determined based on reduced MP among patients with rheumatoid arthritis compared to a control group, when chewing a test material for 20 masticatory cycles. Unfortunately, this study did not analyse masticatory patterns or bite force and as such it could not be determined in what way MP was compromised (Harper et al. 2000).

Additionally, the presence of dental pathology, including carious lesions, may alter masticatory behaviour and food selection. A clinical study conducted by
Decerle et al. (2013), suggested that among individuals with multiple untreated caries, masticatory performance was reduced (Decerle et al. 2013, Hixon et al. 1962). While previous studies have not established a relationship between pain associated with oral pathology and mandible morphology, alteration in masticatory patterns in response to pain associated with pathology may influence mandible morphology (Hatch et al. 2000).

It has been made clear in the previous literature that a number of intrinsic and extrinsic factors may influence mastication, and subsequently mandible morphology. Where possible these influencing factors will be taken into considering during this research and are discussed in the sample requirements in section 5.1. While it is not possible to account for all of these influencing factors among archaeological studies, it is necessary to consider the potential influence of these factors when interpreting results.
4.6 Factors Influencing Mandible Morphology
As with all bones, the morphology of the mandible is influenced by a complex web of interlinking factors and morphological variation cannot be reduced down to simply genetics or biomechanical/masticatory factors. It is therefore important to consider the factors which have been determined in previously published literature to significantly influence mandible morphology and consider the potential effect of these factors on the current study.

4.6.1 Dental Pathology
Dental pathology is known to influence the formation and resorption of bone in the mandible, either directly or indirectly by influencing masticatory behaviour. Pathological conditions which are known to affect bone morphology include: dental abscesses, osteosarcomas and osteoarthritis of the TMJ (Chang et al. 2015, Martinón-Torres et al. 2011, Smith and Farman 1977, Yamada et al. 2004).

4.6.2 Sex Differences
Sex differences present in the skeleton are controlled by hormonal and endocrine growth regulators, which develop fully during puberty (Bejdova et al. 2013, Loth and Henneberg 1996, Vodanovic et al. 2006). In the mandible, sexually dimorphic changes are predominantly associated with size differences as well as specific muscular differences, resulting in males having larger mandibles with more prominent muscle attachments, while females have a smaller, smoother, more gracile mandible (Bejdova et al. 2013, Sikka and Jain 2016, Veleminska et al. 2012, Vodanovic et al. 2006). These differences are argued to be most prominent in the attachment sites of the coronoid process and gonion region (Bejdova et al. 2013, Rosas et al. 2002, Vodanovic et al. 2006). Forensic and archaeological sex estimation techniques often involve the assessment of several mandibular landmarks due to the sexual dimorphic nature of the mandible (Bejdova et al. 2013, Franklin et al. 2006a, 2006b, 2007, Hunter and Garn 1972, Schmittbuhl et al. 2002, Steyn and Iscan 1998). Sex estimation methods involving the mandible have been estimated to be accurate up to 97.1% of the time (Schmittbuhl et al. 2001, 2002). Furthermore, sexual dimorphic variation in the mandible has been shown to vary over time (Bejdova et al. 2013, Garvin and Ruff 2012). For example, Bejdova et al. (2013) conducted a geometric morphometric analysis of human mandibular variation, analysing sexual
dimorphism in the mandible between four time periods (Early Middle Ages, High Middle Ages, early modern ages and modern 21st century Czech populations) and noted that sexual dimorphism increased over time (Bejdova et al. 2013). While the variation in degree of sexual dimorphism recorded may be influenced by dietary changes over time. Moreover sexual dimorphic variation is arguably expressed more strongly among populations with better nutrition, health and living conditions (Oetlé et al. 2009). It is important to consider the potential sexual dimorphic influence within this study, as well as how sexual dimorphism may change over time.

4.6.3 Antemortem Tooth Loss
Antemortem tooth loss (AMTL) is a common occurrence among archaeological assemblages, and the prevalence of AMTL has been found to increase over time, and is associated with the increased consumption of sugars and complex carbohydrates (Mays 2013, Cohen and Krane-Cramer 2007). AMTL reduces the available occlusal surface, and as such reduces the mechanical strain placed on the mandible during mastication (Mays 2013). As a result, AMTL may result in substantial remodelling of the mandible, and significant morphological changes. The extent of bone remodelling has been found to vary between individuals, with some people experiencing slight bone resorption and others extensive resorption and osteoporosis after loss of dentition (Kingsmill and Boyde 1998). Moreover, the degree of bone remodelling and morphological changes associated with AMTL has been found to vary depending on the dentition lost (Helkimo et al. 1977, Mays 2013). For instance, molar dentition which generates high MBF among humans has been associated with the most significant morphological change after AMTL (Kingsmill and Boyde 1998). As such both the presence and location of the AMTL need to be considered when analysing mandible morphology.
4.6.4 Geographic variation in mandible variation
While mandible morphology has largely been argued to reflect biomechanical rather than genetic factors (Cleaver 1937, Hrdlička 1940a, von Cramon-Taubadel 2011), some studies have maintained that significant geographical patterning occurs in mandible variation within species. It is suggested that geographic variation in mandible morphology is related to climatic and cultural variation influencing diet and masticatory behaviour of these populations, and as such only weakly reflects population history (Kangas et al. 2017, Nicholson and Harvati 2006). For instance, Kangas et al. (2017) analysed the mandible morphology of moose (Alces alces) across different geographic regions. Results from a landmark based GMM analysis revealed significant geographic changes in mandible morphology. Such changes were consistent between males and females, and principally affected regions associated with the attachment of masticatory muscles. There was only a weak association between morphological variation and population genetics, and as such morphological variation was thought to be associated with tougher diets consumed by higher latitude populations (Kangas et al. 2017). Furthermore, a GMM analysis of the skull and mandible of the punaré rat (Thrichomys apereoides), found that mandible morphology varied significantly with latitude, this variation is suggested to result from differences in vegetation in these regions, and subsequently the diet of the punaré rat (Monteiro et al. 2003).

Similarly, geographic variation in mandible morphology have also been recorded among humans (Hylander 1977, Humphrey et al. 1999, Nicholson and Harvati 2006). Among humans, there have been several studies which have recorded significant differences in mandible morphology between populations (Humphrey et al. 1999, Smith 2008, von Cramon-Taubadel 2011). For instance, the analysis of 13 linear mandibular measurements from 317 European and Zulu modern humans conducted by Humphrey et al. (1999) determined that 74.3% of individuals could be correctly classified into one of ten population categories based on discriminant function analysis of the 13 measured variables. However, when these results are compared to similar studies of cranial morphology less intraspecific variation was recorded in the mandible (Humphrey et al. 1999). In contrast to previous work a 3D GMM study of nine mandibular landmarks among a sample representing nine modern human populations determined no
significant correlation between mandible morphology and population history (Smith 2008).

Genetic differences have also been suggested to influence the response of the mandible to dietary changes. A study conducted by Corruccini et al. (1985) suggested that the consumption of soft processed foods associated with modern diets are related to a decrease in facial width, among white North Americans. These differences, however, were not consistent among other populations experiencing the same dietary shift, such as Northern Indian and Chinese Populations. Therefore, skeletal morphological changes associated with dietary variation may not be consistent among different populations, and the potential influences of migrations needs to be considered within this study. It is possible however, that these results reflect differences in dietary transitions between these populations (Corruccini et al. 1985). Several studies which reported significant geographical patterns in modern human mandibular variation, argued that as with non-human animals, such variation reflects climatic and functional dietary specialisation, while only weakly reflecting population history (Nicholson and Harvarti 2006, von Cramon-Taubadel 2011). For instance, distinct facial features and mandibular morphology of North American arctic populations are thought to reflect functional demands of a tougher diet as well as para-masticatory dental activity (Antón 1996a, Hylander 1977, Nicholson and Harvati 2006). Mandibular morphology among Arctic populations is described as being large and robust with a large gonial angle and wide bicondylar breadth. These morphological features have been associated with generating exceedingly large vertical bite forces, and support the notion that morphological differences result from functional masticatory specialisation (Anderson 1998, Antón 1996b, Hylander 1977). These inferences are supported by studies which have recorded a greater bite force among Arctic populations compared to American or Scandinavian populations (Hylander 1977, Waugh 1937). Furthermore studies have found that the anterior temporalis muscle, which is associated with increased molar biting force, is more developed among Arctic populations when compared to other populations (Antón, 1996b). As such, it is argued that geographic variation in human mandible morphology is associated with climatic and dietary factors and may not strongly reflect population history. However, Nicholson and Harvati (2006) conducted a 3D GMM study investigating modern human mandible
variation, results revealed significant geographic variation in mandible morphology, suggested to relatively weakly reflect both population history as well as climate (Nicholson and Harvati 2006). When analysing dietary changes in mandible morphology, these climatic factors can be mitigated by employing a sample from a restricted geographic region, such as British archaeological assemblages (Bejdova et al. 2013).

All of these factors need to be considered when investigating how diet may influence mandibular morphology in relation to dietary changes. The next chapter will incorporate the background research detailed in chapters 2 to 4 when discussing the materials and methods that will be utilised for this research in order to address the research questions posed in section 1.1.
Chapter 5
Materials and Methods

To address the research questions discussed in chapter 1 section 1.1 and to investigate the relationship between mandible morphology and dietary changes in Britain, a variety of analytical methods were employed and a large sample of skeletal assemblages spanning the periods from the Neolithic to Post-Medieval Britain was utilised. This chapter will first discuss the sample requirements for this study based on the research questions posed. Following this the skeletal assemblages will be discussed as well as the sex estimation and dental wear analysis. Finally, the data collection and analytical methods for the both the linear metric and 3D geometric morphometric analysis shall be discussed.

5.1 Material Requirements
Each question was evaluated to determine the material and methodological requirements, previous research that has approached similar topics was utilised for the purposes of methodological comparison.

How has mandible morphology changed over time in Britain?
In order to understand how mandibular morphology has changed over time in Britain it is important to include a large sample of mandibles from British archaeological assemblages. However, it was necessary to compromise the sample size with time and financial constraints as well as considering the preservation and availability of archaeological material from these periods. Fewer skeletal assemblages are available for the earlier time periods, additionally access to this material is also more restricted; due to the preservation and availability making it both in more demand and subject to stricter constraints regarding handling and research. Previous research analysing mandible morphology between periods has ranged substantially in the sample sizes employed with some as low as eight individuals for earlier time periods while studies of modern forensic collections have included up to 407-595 individuals from each collection (studies detailed further in chapter 4 section 4.4 table 4.4.1).
Has sexual dimorphism in the mandible changed over time in Britain?

In order to analyse sexual dimorphism in Britain and compare dimorphism over time it will be necessary to estimate sex among the skeletal assemblages employed. Sex estimation methods employed will include previously published methods for estimating sex based on the morphology of the crania, pelvis and long bone measurements discussed in section 5.2.8. While methods are available for estimating sex from mandibular morphology this will not be included to avoid tautology. Due to the preservation requirements for the mandible, having sex estimation a requirement would greatly limit the sample size and analytical potential of this research. Previous studies which have compared mandible morphology between temporal periods have not restricted this analysis to between sex estimation groups (e.g: Galland et al. 2016, May et al. 2018, von Cramon-Taubadel 2011). Von Cramon-Taubadel (2011), for instance, reported that significant sex differences were not present in shape-only PCA and therefore did not conduct separate analysis of sex estimation groups when comparing subsistence groups. It was decided that in order to maintain a sufficient sample for the primary research question a similar approach would be taken. Whereby for temporal analysis sex estimation groups will be combined after confirming there are no significant differences between them.

Does mandible morphology vary in relation to social status?

In order to analyse social status difference in mandible morphology known status assemblages were required. The skeletal assemblage of St Gregory’s priory and cemetery is known to represent two socioeconomic groups, with high status groups buried in the priory and low status from the cemetery (Hicks and Hicks 2001, Miszkiewicz 2015, Miszkiewicz and Mahoney 2016). The social status sample is detailed further in section 5.2.3.

What is the relationship between dental wear and mandible morphology among British assemblages?

In order to determine if mandible morphology varies in relation to dental wear it is necessary to create dental wear groups to allow for statistical comparison. Dental wear groups were calculated based on the mean wear of the M1 and grouped into three categories: low wear, moderate wear and high wear. As with
sex estimation dental wear was not a sample requirement, this is discussed further in section 5.3.

How does the variation in mandible morphology in Britain over time compare with geographic variation?
In addition to the British archaeological assemblage a larger global sample of skeletal remains are required in order to compare the morphological variation that has occurred over time in Britain with that of a global geographic sample detailed in section 5.2.2.

5.1.1 Specimen Requirements
As discussed in chapter 4 section 4.5 and 4.6 there are several factors which have been shown to influence mandible morphology and masticatory function, such factors need to be considered when determining the sample requirements and exclusion criteria for the material used here. Therefore when determining which individuals were included the following factors were considered:

5.1.1.1 Antemortem tooth loss
Antemortem tooth loss (AMTL) reduces dental occlusion which results in an alteration in the biomechanical forces acting upon the mandible. This alteration to masticatory forces and behaviour is particularly important when occlusion is reduced in the molar region of the mandible where maximum bite forces are generated (Helkimo et al. 1977, Mays 2013). Among archaeological material a high prevalence of antemortem tooth loss has been recorded especially among older adult individuals and more recent archaeological assemblages (Brothwell 1963, Cohen and Krane-Cramer 2007, Mays 2013, Steckel and Rose 2002, Roberts and Cox 2003). Due to the high prevalence of AMTL among archaeological assemblages it was determined that it would not be possible to exclude all mandibles with missing dentition from the study, as this would markedly decrease the number of potential specimens available. Instead it was decided, based on previous research (Jonasson et al. 2018, Parr et al. 2017, Small et al. 2016), that mandibles should not be included in the study if there were more than two cases of AMTL, or any cases of consecutive AMTL. Individuals with congenitally missing teeth were not included in the sample as it is unknown how
this may influence mandible morphology and several of the landmarks utilised in this study were dependant on the location of the dentition.

5.1.1.2 Age
Upon maturity, there is little or no significant change to the overall morphology of bone unless subject to changes in muscular activity (Bastir et al. 2006, Goose and Appleton 1982, Humphrey 1998, O'Connor and Lanyon 1982). Therefore, only adult individuals were included in this study. Individuals determined to be juvenile, based on open or incomplete fusion of the epiphyses of the post-cranial skeleton (Buckberry 2018, Cunningham et al. 2016, Rogers 2016) were excluded. The absence of M3 was not considered to be sufficient evidence that the individual was a juvenile, as the congenital absence of M3 has increased over time among modern human populations (Carter 2016, Guatelli-Steinberg 2016). Beyond confirming individuals are adults, age will not be estimated due to generally poor preservation of the skeletal elements utilised in age estimation methods among adults. Moreover the sample requirements for AMTL already acted to restrict the age range of individuals with a preference to young adults.

5.1.1.3 Sex Estimation
Mandibular morphology is known to vary between males and females, a point which is illustrated by the inclusion of mandibular morphological features such as the mental eminence and gonial angle in sex estimation methods (Giles 1964, Steyn and Iscan 1998). This is detailed further in section 4.5.2. Therefore when analysing morphological changes in the mandible over time it is necessary to account for the potential influence of sexual dimorphism as an increase in the proportion of males in a time period could present as an increase in mandibular robusticity and incorrectly be interpreted as a change in diet or masticatory behaviour. Sex was estimated from macroscopic visual analysis of the cranial and post-cranial skeleton (see section 5.2.3), the mandible was not included in sex estimation methods in order to avoid tautological results as differences in sexual dimorphism as well as dietary differences may influence sex estimation from the mandible. However, it was not always possible to make a confident sex estimation of individuals due to skeletal preservation, and so in order to achieve a sufficiently large sample size individuals of unknown or indeterminate sex were also included in the sample.
### 5.1.1.4 Dental Pathology

Any individuals that exhibited pathological lesions which may have affected the form or function of the mandible were excluded from this study. This primarily included individuals with abscesses. In addition, remains which exhibited antemortem fractures to the mandible or osteoarthritis of the temporomandibular joint (TMJ) were removed from the study. Even if one side of the mandible was unaffected by the pathology, the mandible was excluded because such injuries may alter dietary behaviour which would affect results (discussed further in section 4.5.5). Exclusionary pathology was defined by the criteria outlined in table 5.1.1 below. Additionally, individuals who had a cranium present, evidence of trauma or pathological lesions on the facial bones were also excluded.

### Table 5.1.1: Pathological conditions which alter mandible morphology.

Table detailing the pathology excluded from this study, including a description of the pathological lesions.

<table>
<thead>
<tr>
<th>Pathology</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abscess</td>
<td>The presence of a smooth walled cavity which results from chronic infections with an accompanying fistula and inflammatory bone reaction (Hillson 2002).</td>
</tr>
<tr>
<td>Mandibular Fracture</td>
<td>A discontinuity in the form of the mandible where evidence of bone remodelling is present (Waldron 2008).</td>
</tr>
<tr>
<td>Osteoarthritis TMJ</td>
<td>The primary defining criteria for OA of the TMJ are eburnation, marginal or joint surface osteophytes and porosity/pitting and alterations to the joint contour. Although porosity/pitting on its own should not be considered indicative of OA. Eburnation while indicative of OA is rare in cases in the TMJ. In the absence of eburnation both porosity and joint surface or marginal osteophytes should be present for a diagnosis of OA. Finally, only marked alteration to the joint contour at the condyle and/or articular eminence should be considered indicative of OA, slight changes to the joint contour should not be considered diagnostic of OA (Rando and Waldron 2012).</td>
</tr>
<tr>
<td>Cleft Palate</td>
<td>A congenital condition that results in incomplete fusion of the palate resulting in partial or complete separation of the maxilla (Anderson 1994, Coccia et al. 1969).</td>
</tr>
</tbody>
</table>
5.2 Skeletal Assemblages
In total, 991 specimens were analysed for the purposes of this project. These can be divided into two sub-groups (British Archaeological and Geographical) and are described in full below.

5.2.1 British Archaeological Material
To investigate the relationship between changing dietary behaviour over time, British archaeological assemblages dated to between the Neolithic and Post-Medieval period were utilised. Palaeolithic and Mesolithic material were not included due to the low number of individuals excavated in Britain and the poor preservation of the remains from these periods (Ashton 2016, Charlton et al. 2016, Cummings 2017, Orschiedt 2018). Archaeological assemblages were chosen based on the number of individuals, preservation of remains and the amount of information available from both historical texts and previously published archaeological research. An opportunistic sample strategy was employed with skeletal assemblages included from all known archaeological collections were at least ten individuals could be accessed or in the case of Neolithic assemblages three individuals. Because many archaeological assemblages do not advertise their human remains collections in order to achieve a sufficient sample size specialist museums, county museums, archaeological trusts and universities in Britain that teach courses on biological archaeology/anthropology courses were contacted via email to determine presence of skeletal collections. All sites that responded to requests and indicated the presence of skeletal assemblages that met the minimum requirements for study were included in this research were accessed. One exception to this was the Museum of Manchester where preservation of material upon arrival was found to be lower than expected and only one individual was included from this site. It was not possible to access any more skeletal material for inclusion in this study either due to the limited preservation, lack of site information or cases where access was not granted by curators/ collection managers.

A total of 911 archaeological mandibles were analysed which were from 150 different archaeological sites, these sites are detailed further in appendix 3. To aid later analysis the material was grouped into six periods: Neolithic, Bronze and Iron Age, Roman, Anglo-Saxon, Medieval, and Post-Medieval (see Chapter
2 for further details of these time periods) detailed in table 5.2.1. The archaeological assemblages were dated prior to this research, dating methods when known are discussed in the site overview in appendix 3. As methods for dating varied between sites and in many cases were unknown, Bronze and Iron age individuals were grouped together. This was due to multiple sites which were only dated to between these two periods, and without further information regarding dating methods as well as many sites being active between these two periods it was not possible to separate these two periods during analysis. For the assemblages where dating was provided in years or as a range these assemblages were allocated to a period based on the dates detailed in table 5.2.1. An overview of the skeletal assemblages utilised during this study and a more detailed site summary are shown in table 5.2.2 and figure 5.2.1 below.


<table>
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<tr>
<td>Anglo-Saxon</td>
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<tr>
<td>Post-Medieval</td>
<td>1540-1901 AD</td>
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Figure 5.2.1: British archaeological skeletal assemblages by period. Bar Graph illustrating the archaeological number of individuals from each time period in Britain which were included in this study. This graph illustrates the increase in skeletal assemblages which were utilised over time, with the highest number of individuals from the Medieval and Post-Medieval periods.

As the material analysed in this study was acquired from a variety of archaeological sites it is important to also consider potential geographic variation in the material analysed. Table 5.2.2 and figure 5.2.2 below illustrates the locations of the archaeological sites included in the analysis.
Table 5.2: British archaeological sites and locations. Archaeological collections, site and location information from the skeletal assemblages included in this study.

| Site Name                      | Site                          | Location                  | Period               | Number of
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<td>Pontefract, West Yorkshire</td>
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<td>Hereford</td>
<td>Hereford, Herefordshire</td>
<td></td>
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<td>Towton</td>
<td>Tourtont, North Yorkshire</td>
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<td>North shields, Yorkshire</td>
<td>Post-Medieval</td>
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<td>London</td>
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<td>St Brides</td>
<td>London</td>
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<td>Sheffield University</td>
<td>Coronation Street</td>
<td>South Shields, Durham</td>
<td></td>
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<td></td>
<td>Carver Street</td>
<td>Sheffield, Yorkshire</td>
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<td>2</td>
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<tr>
<td>Bournemouth University</td>
<td>Quaker Burial, Kingstone</td>
<td>Kingston-upon-Thames, London</td>
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<td>Chichester</td>
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<td>Eyemouth</td>
<td>Eyemouth, Scotland</td>
<td>Unknown</td>
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</tr>
</tbody>
</table>
Figure 5.2.2: Map of British archaeological sites. This map illustrates the location of each British archaeological site - where location could be reasonably pinpointed - where skeletal remains utilised in this study were excavated.
5.2.2 Geographical Analysis Sample
During British history there has been a number of invasions and large-scale migrations many of which have altered culture and diet in Britain which may in turn have influenced mandible morphology. Therefore, it is necessary to consider the potential genetic influence of such population movements. Multiple studies have reported geographic variation in cranial morphology (von Cramon-Taubadel 2017, Herrera et al. 2017, Noback and Harvati 2015), while these studies report less geographic influence on mandible morphology (Cleaver 1937, Cramon-Taubadel 2011, Hrdlička 1940a) the influence of migration into Britain at the sites analysed in this study needs to be considered. The morphological variation occurring within Britain over time shall therefore be compared to geographic variation in mandible morphology from a global sample. Sample sizes for the geographical analysis were chosen based on previously published studies of modern human variation (1000 Genomes Project Consortium 2010, 2015, Cramon-Taubadel 2014), whereby larger sample sizes were taken from continents with higher levels of recorded genetic and craniometric variation. Unfortunately, it was not possible to obtain larger numbers from either Oceania or the Americas as many collections had repatriated individuals from these areas. The geographical material was mostly accessed from the Duckworth Laboratory in Cambridge, although two individuals from the Manchester Museum were also included. In total 80 individuals from outside of Britain were scanned for this research. An overview of the geographic material is detailed in table 5.2.3, while table 5.2.4 provides further information concerning the geographic location for each individual, which are also illustrated in figure 5.2.3.

Table 5.2.3: Geographic sample overview by continent. Overview of geographic material illustrating a higher proportion of individuals from Africa and Asia

<table>
<thead>
<tr>
<th>Continent</th>
<th>Number of Individuals</th>
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<tbody>
<tr>
<td>Europe</td>
<td>7</td>
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<tr>
<td>Africa</td>
<td>26</td>
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<tr>
<td>North America</td>
<td>6</td>
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<tr>
<td>South America</td>
<td>3</td>
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<tr>
<td>Asia</td>
<td>21</td>
</tr>
<tr>
<td>Oceania</td>
<td>17</td>
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</table>
Table 5.2.4: Geographic Sample Detailed. Table detailing the geographical material analysed in this study.

<table>
<thead>
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<th>Collection</th>
<th>Continent</th>
<th>Location/Population</th>
<th>#</th>
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<td>Somalia</td>
<td>1</td>
</tr>
<tr>
<td>Duckworth</td>
<td>Africa</td>
<td>African Bantu, Upper Mobankhi</td>
<td>1</td>
</tr>
<tr>
<td>Duckworth</td>
<td>Africa</td>
<td>African Guinea</td>
<td>1</td>
</tr>
<tr>
<td>Duckworth</td>
<td>Africa</td>
<td>African Surinam</td>
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</tr>
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<td>Ashanti</td>
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<td>Bantu</td>
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<td>Peru</td>
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Figure 5.2.3: Geographic sample map. Map illustrating the location of the geographical material analysed.
5.2.3 Sex Estimation Methods

Sex was estimated using standard osteological methods which included the analysis of the pelvis and crania as well as measurements taken from the long bones. These methods are detailed in tables 5.2.5, 5.3.6 and 5.2.7 below. Sex was estimated for all individuals with sufficient preservation of the crania and pelvis, when cranial or pelvic features were ambiguous or indeterminate measurements of the long bones (table 5.2.6) were used. Results of sex estimation for the entire sample is detailed for each period in table 5.2.8 with a site break down provided in table 5.2.9.

Table 5.2.5: Sex estimation from the pelvis. Pelvis sex estimation description information obtained from (Ferembach et al. 1980, Krogman and Iscan 1986, Phenice 1969, Schwartz 1995).

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<th>Landmark</th>
<th>Female Description</th>
<th>Male Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall Shape/Structure</strong></td>
<td>Female - slight muscle attachments, low and broad</td>
<td>Male - large muscle attachments, tall and narrow</td>
</tr>
<tr>
<td>Greater Sciatic Notch</td>
<td>Female - Wide angle and symmetrical</td>
<td>Male - Sharp angle and asymmetrical</td>
</tr>
<tr>
<td><strong>Ventral Arch</strong></td>
<td>Female - Present</td>
<td>Male - Absent</td>
</tr>
<tr>
<td>Subpubic Concavity</td>
<td>Female - Present</td>
<td>Male - Absent</td>
</tr>
<tr>
<td>Inferior Ramus</td>
<td>Female - Ridge present</td>
<td>Male - ridge absent</td>
</tr>
</tbody>
</table>

Table 5.2.6: Sex estimation from the articular measurements. Table demonstrates articular sex estimation method. Information obtained from Ferembach et al. (1980) and Krogman and Iscan (1986).

<table>
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<tr>
<th>Measurement</th>
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<th>Female</th>
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<tr>
<td>Distal Femur Diameter</td>
<td>&gt;78mm</td>
<td>&lt;72mm</td>
</tr>
<tr>
<td>Distal Radius Diameter</td>
<td>&gt;36mm</td>
<td>&lt;33mm</td>
</tr>
<tr>
<td>Femoral Head Diameter</td>
<td>&gt;48mm</td>
<td>&lt;43mm</td>
</tr>
<tr>
<td>Humerus head diameter</td>
<td>&gt;47mm</td>
<td>&lt;43mm</td>
</tr>
<tr>
<td>Radial Head Diameter</td>
<td>&gt;21mm</td>
<td>&lt;21mm</td>
</tr>
<tr>
<td>Scapula- Diameter of Glenoid fossa</td>
<td>&gt;28mm</td>
<td>&lt;26mm</td>
</tr>
</tbody>
</table>
Table 5.2.7: **Sex estimation from the crania.** Sex estimation characteristics of the cranium excluding the mandible, information obtained from Krogman and Iscan (1986), Ferembach *et al.* (1980) and Schwartz (1995).

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Male Description</th>
<th>Female Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Shape/Structure</td>
<td>Robust and angular</td>
<td>Gracile and rounded</td>
</tr>
<tr>
<td>Glabella Profile</td>
<td>Prominent</td>
<td>Smooth and gracile</td>
</tr>
<tr>
<td>Orbital Margin</td>
<td>Rectangular with thick edges</td>
<td>Rounded with sharp edges</td>
</tr>
<tr>
<td>Mastoid prominence and breadth</td>
<td>Larger and extends inferiorly</td>
<td>Smaller and more rounded</td>
</tr>
<tr>
<td>Nuchal Lines</td>
<td>Robust and prominent</td>
<td>Smooth</td>
</tr>
<tr>
<td>Occipital Protuberance</td>
<td>Large and protruding, may be hooked</td>
<td>Small and gracile</td>
</tr>
<tr>
<td>Temporal Line</td>
<td>Prominent</td>
<td>Smooth and gracile</td>
</tr>
</tbody>
</table>

Table 5.2.8: **Period summary of sex estimation results.** Summary of the number of individuals and sex ratio organised by archaeological period.

<table>
<thead>
<tr>
<th>Period</th>
<th>Total Number</th>
<th>Males</th>
<th>Females</th>
<th>Unknown Sex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neolithic</td>
<td>19</td>
<td>5</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Bronze and Iron Age</td>
<td>90</td>
<td>38</td>
<td>24</td>
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<td></td>
<td>Eccles</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Raunds</td>
<td>32</td>
<td>23</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
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<td>10</td>
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<td>2</td>
<td>5</td>
</tr>
<tr>
<td></td>
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<td>8</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Stocklund</td>
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<td>0</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>St Andrews</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Brighton Hill South</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
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<td></td>
<td>Selbourne Priory</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Church Close</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>St Guthlac's Priory</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fishergate House</td>
<td>22</td>
<td>15</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>York Barbican</td>
<td>22</td>
<td>12</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>George Street</td>
<td>35</td>
<td>14</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Llandough</td>
<td>17</td>
<td>8</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Medieval Guildhall Yard</td>
<td>23</td>
<td>12</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Guildford Friary</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Wetwang Slack</td>
<td>24</td>
<td>9</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Blackfriars</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Boxlane</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Hereford</td>
<td>17</td>
<td>10</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Towton</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Post-median</td>
<td>Coach Lane</td>
<td>41</td>
<td>20</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>PAY05</td>
<td>19</td>
<td>0</td>
<td>1</td>
<td>18</td>
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<tr>
<td></td>
<td>St Brides</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Chelsea Old Church</td>
<td>15</td>
<td>6</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Coronation Street</td>
<td>51</td>
<td>30</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Carver Street</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Kingston</td>
<td>17</td>
<td>6</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>BPP08</td>
<td>16</td>
<td>7</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>GW85</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Hickleton</td>
<td>10</td>
<td>4</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Helmsley</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Chichester</td>
<td>56</td>
<td>20</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>Unknown</td>
<td>Eyemouth</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
5.2.4 Social Status
Skeletal collections curated by the University of Kent, Canterbury from St Gregory’s Cemetery and Priory were included to allow for the analysis of morphological variation in relation to social status. This collection was included due to the high preservation of the material as well as the socio-economical division between the cemetery and priory collections – known from historical evidence (Hicks and Hicks 2001, Miszkiewicz 2015, Miszkiewicz and Mahoney 2016). This sample is illustrated in table 5.2.10.

Table 5.2.10: Social status sample. Table detailing the individuals from St Gregory’s cemetery and priory used for social status comparison.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Male</th>
<th>Female</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priory</td>
<td>10</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Cemetery</td>
<td>40</td>
<td>8</td>
<td>19</td>
<td>13</td>
</tr>
</tbody>
</table>
5.3 Dental Wear

Dental wear is created via tooth on tooth contact during normal masticatory movement as well as para-masticatory behaviours (Alt et al. 1998). It is well known that dental wear is influenced by diet; rough, hard fibrous diets are associated with high levels of dental wear (Esclassan et al. 2009, Scott and Turner 1988, Watson et al. 2011). For most of human history, high levels of dental wear have been a common feature (Eshed et al. 2005, Kaifu et al. 2003, Smith 1984a). For instance high levels of dental attrition have been recorded among hunter-gather populations, suggested to be related to the consumption of fibrous plants and food processing techniques be which introduce grit into the diet (Eshed et al. 2005, Haas and Llave, 2015, Sarig et al. 2016). Conversely a soft, highly processed diet tends to result in low levels of wear (Esclassan et al. 2009, Scott and Turner 1988, Watson et al. 2011). For instance post-industrial populations with soft processed diets are associated with reduced levels of wear when compared to earlier agricultural populations (Kaifu et al. 2003, Molnar 1972).

Although dental wear has been used to infer dietary change it is also significantly influenced by the age of an individual, as illustrated in the inclusion of dental wear for age estimation methods (Hillson 2002). Moreover, dental wear is greatly influenced by the presence of abrasive material in the diet, which may result from grit introduced into food during food processing rather than solely the intended dietary constituents (Jaworskim et al. 2017, Fiorenza et al. 2018).

In addition to macroscopic dental wear, microwear has been used in reconstructing diet in archaeology. Microscopic pits and scratches on the dental enamel have been used to infer broad diet and subsistence patterns (DeSantis 2016, Grine and Kay 1988). For instance, analysis of microwear has been used to distinguish grazers and browsers (Rivals et al. 2012). However, microwear has typically been used to investigate dietary differences between species and there have been few dental microwear studies among modern human assemblages (DeSantis 2016).

Dental wear is therefore included in this study as an indicator of behavioural differences between groups. Dental wear was recorded using a macroscopic visual analysis method (Smith, 1984), where dental wear is assigned a numerical value between one and eight based on written descriptions outlined in table 5.3.1 and diagrams which are illustrated in figure 5.3.1 (Smith 1984a). This
method was utilised due to both the standardisation provided by written and visual descriptions of stages and the efficiency of the method. Furthermore, this method has been widely used in bioarchaeological research which allows for potential comparisons with previous studies.

**Figure 5.3.1: Dental wear visual descriptions.** Images illustrating tooth wear stages 1-8 for different tooth form (Smith 1984a, 46, Figure 3) ‘Diagrams of crown surfaces used to score tooth wear. Bars between outlines connect common variants of patterns and degree of wear allowed in a stage’.
Table 5.3.1: Dental wear descriptions. Wear descriptions for stages 1-8 incisor/canine, premolars and molars. Taken from Table 2 (Smith 1984a, 45) ‘Descriptions of stage of occlusal surface wear’.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Incisors and Canine</th>
<th>Premolar</th>
<th>Molars</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Tooth is missing/ cannot be coded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>No visible wear to slightly polished surface, dentin is not visible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Small dentin exposure - point of hairline</td>
<td>Cusps moderately worn with a blunting effect</td>
<td>Cusps moderately worn no more than two pinpoint cases of dentine exposure</td>
</tr>
<tr>
<td>3</td>
<td>Thick line of dentine is exposed</td>
<td>Cusps removed and potential moderate dentin exposure in patches</td>
<td>Cusps removed and pinpoint-moderate dentine exposure</td>
</tr>
<tr>
<td>4</td>
<td>Moderate dentine exposed does not appear as a line</td>
<td>A large patch of dentine exposure on at least one cusp</td>
<td>Several large dentine patches</td>
</tr>
<tr>
<td>5</td>
<td>Significant dentine exposure, complete enamel rim</td>
<td>Two large patches of dentine exposure</td>
<td>At least two dentine patches on the cusps have merged</td>
</tr>
<tr>
<td>6</td>
<td>Significant dentine exposure, 50% loss of enamel ring</td>
<td>Dentine patches merged together, enamel ring intact</td>
<td>Three- four dentine patches merged, enamel island present in the centre</td>
</tr>
<tr>
<td>7</td>
<td>Majority of enamel ring lost, significant dentine exposure</td>
<td>Dentine fully exposed and enamel ring is lost on at least one side</td>
<td>Dentine is fully exposed and the enamel ring is largely intact</td>
</tr>
<tr>
<td>8</td>
<td>Crown surface is lost, no enamel present and the crown surface takes on the root shape</td>
<td>Crown height significantly reduced, and the crown surface takes on the root shape</td>
<td></td>
</tr>
</tbody>
</table>
5.3.1 Dental Wear Groups

In order to analyse the relationship between mandible morphology and dental wear it is necessary to group individuals by dental wear in order to preserve statistically viable group sizes for analysis. Dental wear of the M1 was used to group individuals into three categories low wear, moderate wear and high wear. Low wear included individuals in stages 1-3, moderate wear stages 4-6 and high wear groups were individuals with M1 wear in stages 7-8. Results from this grouping are detailed in table 5.3.2 and figure 5.3.2 below. This demonstrates a low percentage of individuals in the high wear group (11%) with the majority of individuals being in the moderate wear group (52%). Significant difference was reported in dental wear between the time periods analysed (appendix 4 table 4.3.5 and 4.36), as such CV scores were analysed to determine possible influence from dental wear, in all sex and period comparisons were reported in CVA results.

<p>| Table 5.3.2: Dental wear groups and sex estimation. Table detailing the number of people in each dental wear group separated by time period and sex estimation. |</p>
<table>
<thead>
<tr>
<th>Period</th>
<th>Sex</th>
<th>Low Wear</th>
<th>Moderate Wear</th>
<th>High Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neolithic</td>
<td>Male</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bronze and Iron Age</td>
<td>Male</td>
<td>8</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>15</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Roman</td>
<td>Male</td>
<td>10</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>17</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td>Male</td>
<td>9</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>10</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Medieval</td>
<td>Male</td>
<td>20</td>
<td>41</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>22</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>Male</td>
<td>47</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>34</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>197</td>
<td>278</td>
<td>59</td>
</tr>
</tbody>
</table>
Figure 5.3.2: **Dental wear groups.** Stacked bar graph illustrating the percentage of individuals with an M1 present in each dental wear group for all time periods analysed.
5.3.2 Dental Wear Ratio
As discussed, masticatory behaviour has been shown to influence the masticatory muscles and subsequently mandible morphology (Hutchinson et al. 2014, Mays 2013, Kiliaridis et al. 1995, Kiliaridis et al. 1989, Odman and Kiliaridis 1989, Toro-Ibacache et al. 2016). It is therefore necessary when comparing mandible morphology over such a long time period to consider any changes in masticatory patterns - in terms of the way in which people use their teeth - which may influence results. Dental wear patterns were analysed to determine if significant differences occurred over time in Britain, in terms of the relative use of different teeth during mastication. Any significant changes in dental wear pattern may indicate a behavioural or dietary change that altered masticatory patterns which may influence mandible morphology. Because of the dental eruption sequence on dental wear, tooth wear as a proportion of the wear of the M1 will be analysed. The wear ratio will be calculated as (tooth wear ÷ M1 wear)x100. Whereby teeth that have a wear ratio score of one have the equivalent wear as the first molar while teeth which are less worn will have a wear ratio <1 and teeth which are more worn than the M1 will have a wear ratio >1 (Clement 2007, Clement et al. 2009).

No significant asymmetry in dental wear was recorded and as such left and right mandibular dentition were combined for analysis. Overall the results were consistent with the expected pattern of dental wear, with dental wear ratio score correlating with eruption sequence. Dental wear ratio was then analysed to determine how this varied among time periods and between sex estimation groups reflecting dietary differences between these assemblages.

For dental wear analysis data were collected and input into a Microsoft Excel spreadsheet, the data was then coded and transferred to an SPSS document for statistical analysis. The following functions in SPSS (IBM SPSS statistics 24) were used: crosstabs, frequencies, ANOVA, cluster analysis and t-test. These statistical tests are detailed further in table 5.3.3. To analyse variation in dental wear ratios among the sample box plots were produced in PAST. Results from the dental wear ratio analysis is detailed below. The mean was utilised for statistical comparison after a Shapiro-Wilk test and Q-Q graphs indicated these data were normally distributed and could therefore be treated as a ‘population’. Difference in mean was analysed using an independent sample t-
test and, where applicable, ANOVA and Bonferroni tests. The aim of these analyses was to determine if dental wear ratio was significantly different between periods or sex estimation. A statistically significant difference was reported when the p-value was less than 0.05 (<5%), which is the generally accepted value for significant results.

Table 5.3.3: Statistical functions. Statistical functions used in SPSS for dental wear ratio analysis.

<table>
<thead>
<tr>
<th>Test</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>ANOVA</em></td>
<td>A one-way analysis of variance (ANOVA) determines if there are significant differences between the means of three or more independent groups. Requires the sample to be normally distributed</td>
</tr>
<tr>
<td><em>t-test</em></td>
<td>Compares the means a continuous variable between two independent groups. Requires the sample to be normally distributed</td>
</tr>
<tr>
<td><em>Bonferroni</em></td>
<td>An extension of the ANOVA a Bonferroni test compares each of the independent groups from an ANOVA to determine among which groups significant differences in means occur.</td>
</tr>
</tbody>
</table>

5.3.2.1 Sex estimation: how dental wear ratio vary between males and females, within each time period?

There were not enough individuals of identified sex with dentition present to include Neolithic individuals in this analysis. Among the Bronze and Iron Age individuals, there was a similar pattern in dental wear ratios between sex estimation groups with an increase in the wear of the anterior dentition relative to the M3 (figure 5.3.3 and 5.3.4). Among males however there was a slight difference with PM4 having a lower wear ratio, although this was not significant.

In general, among Roman, Anglo-Saxon, Medieval and Post-medieval individuals males appear to have less variation in tooth wear ratios between anterior and posterior dentition (figure 5.3.5-5.3.12). Among females, while the anterior dentition and premolars typically had similar dental wear ratios, there was a greater decline in wear ratios for the molar dentition. Post-medieval males had both I1 and canine wear ratios that were higher than among females. Because it was difficult to discern clear differences in the dental wear ratio between males and females based on the Box and Whisker plots, statistical
analysis was conducted in SPSS to investigate if the mean dental wear ratio for each tooth varied significantly between males and females. Mean dental wear ratios were analysed between males and females for each time period with the exception of the Neolithic, and independent sample t-test (Table 5.3.4) revealed that statistically significant sex differences were only present among the Anglo-Saxons for the third molar, Medieval for first incisors and among Post-medieval individuals for fourth premolar, canines and first incisors.

![Dental wear ratio Bronze and Iron Age females](image)

**Figure 5.3.3: Dental wear ratio Bronze and Iron Age females.** Box plot illustrating the dental wear ratio for mandibular dentition among Bronze and Iron Age females. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.
Figure 5.3.4: Dental wear ratio Bronze and Iron Age males. Box plot illustrating the dental wear ratio for mandibular dentition among Bronze and Iron Age males. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.

Figure 5.3.5: Dental wear ratio Roman females. Box plot illustrating the dental wear ratio for mandibular dentition among Roman females. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.
Figure 5.3.6: Dental wear ratio Roman males. Box plot illustrating the dental wear ratio for mandibular dentition among Roman males. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.

Figure 5.3.7: Dental wear ratio Anglo-Saxon females. Box plot illustrating the dental wear ratio for mandibular dentition among Anglo-Saxon females. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.
Figure 5.3.8: **Dental wear ratio Anglo-Saxon males.** Box plot illustrating the dental wear ratio for mandibular dentition among Anglo-Saxon males. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.

Figure 5.3.9: **Dental wear ratio Medieval females.** Box plot illustrating the dental wear ratio for mandibular dentition among Medieval females. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.
Figure 5.3.10: Dental wear ratio Medieval males. Box plot illustrating the dental wear ratio for mandibular dentition among Medieval males. The purple line illustrates the wear level of M1, the mean wear for the I1 was therefore found to be similar to the wear of M1. Whiskers illustrate the standard error in dental wear ratio.

Figure 5.3.11: Dental wear ratio Post-Medieval females. Box plot illustrating the dental wear ratio for mandibular dentition among Post-Medieval females. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.
Figure 5.3.12: Dental wear ratio Post-Medieval males. Box plot illustrating the dental wear ratio for mandibular dentition among Post-Medieval males. The purple line illustrates the wear level of M1, I1, I2 and the canines were therefore found to have a wear score similar or higher to that of the M1. Whiskers illustrate the standard error in dental wear ratio.
Table 5.3.4: *t*-test for sex difference in dental wear ratio by period.* Independent samples *t*-test showing the significant differences recorded in mean dental wear ratios between males and females for each time period analysed.

<table>
<thead>
<tr>
<th>Period</th>
<th>Levene's Test for Equality of Variances</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>Sig.</td>
<td>t</td>
<td>df</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td></td>
<td>13.25</td>
<td>.001</td>
<td>2.85</td>
<td>42</td>
</tr>
<tr>
<td>m3</td>
<td>Equal variances assumed</td>
<td>7.40</td>
<td>.008</td>
<td>-2.43</td>
<td>86</td>
</tr>
<tr>
<td>Medieval i1</td>
<td>Equal variances assumed</td>
<td>5.03</td>
<td>.027</td>
<td>-2.36</td>
<td>119</td>
</tr>
<tr>
<td>Post-Medieval pm4</td>
<td>Equal variances assumed</td>
<td>9.09</td>
<td>.003</td>
<td>-3.37</td>
<td>97</td>
</tr>
<tr>
<td>Post-Medieval i1</td>
<td>Equal variances assumed</td>
<td>8.79</td>
<td>.004</td>
<td>-2.97</td>
<td>90</td>
</tr>
</tbody>
</table>
5.3.2.2 Sex estimation: how does dental wear ratios vary among males and females over time?

When dental wear ratios were analysed over time, there were more apparent differences in wear patterns among males compared to females. An ANOVA (table 5.3.5) was conducted which further supported this as among females there were only significant differences reported for M3 and pm3 between periods. While among males significant differences were present in M3, M2, canines and I1. A Bonferroni test was conducted to determine among which time periods significant difference were present for both females and males. Among females there were only significant differences recorded in dental wear ratios among M3s between females from the Roman and Anglo-Saxon periods. However, among males there were significant differences recorded in individual period comparisons for canines and M2s. For canines there were significant differences in dental wear ratios among Post-Medieval males and Bronze/Iron Age, Roman, Anglo-Saxon and Medieval males. Among the dental wear ratios for the second molar, significant differences were recorded between Post-Medieval males and Bronze/Iron Age, Roman and Anglo-Saxon males, as well as between Medieval males and Roman and Anglo-Saxon males.
Table 5.3.5: ANOVA differences in dental wear ratio over time for males and females. ANOVA illustrating that among males there was a greater number of dentition showing significant differences in dental wear ratios between time periods (m3, m2, canine and first incisor) compared to females (m3 and third premolar).

<table>
<thead>
<tr>
<th>Sex Estimation</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females m3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>.21</td>
<td>5</td>
<td>0.04</td>
<td>2.31</td>
<td>0.05</td>
</tr>
<tr>
<td>Within Groups</td>
<td>1.94</td>
<td>109</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2.15</td>
<td>114</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pm3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>0.45</td>
<td>5</td>
<td>0.09</td>
<td>2.53</td>
<td>0.03</td>
</tr>
<tr>
<td>Within Groups</td>
<td>6.58</td>
<td>184</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7.03</td>
<td>189</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Males m3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>1.57</td>
<td>5</td>
<td>0.31</td>
<td>25.09</td>
<td>0.00</td>
</tr>
<tr>
<td>Within Groups</td>
<td>2.10</td>
<td>168</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3.67</td>
<td>173</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>1.66</td>
<td>5</td>
<td>0.33</td>
<td>13.84</td>
<td>0.00</td>
</tr>
<tr>
<td>Within Groups</td>
<td>5.45</td>
<td>227</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7.11</td>
<td>232</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>2.12</td>
<td>5</td>
<td>0.43</td>
<td>3.74</td>
<td>0.00</td>
</tr>
<tr>
<td>Within Groups</td>
<td>22.50</td>
<td>198</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>24.61</td>
<td>203</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>1.87</td>
<td>5</td>
<td>0.37</td>
<td>2.43</td>
<td>0.04</td>
</tr>
<tr>
<td>Within Groups</td>
<td>27.14</td>
<td>176</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>29.01</td>
<td>181</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3.2.3 Time period: how do dental wear ratios vary over time among all individuals?

Dental wear ratios were then analysed over time combining both males and females. By combining males and females as well as including un-sexed individuals it was possible to include the Neolithic period in this analysis.

Among Neolithic individuals there was greater wear on the first incisor. While mean wear was similar to the M1, the range in dental wear ratio for this tooth was greater and exceeded the wear of M1, suggesting increased use of the anterior dentition. The third molar still had the lowest level of wear which is expected as it is the last tooth to come into occlusion (figure 5.3.13). Among Bronze and Iron Age individuals dental wear ratios for the anterior dentition were similar for incisors, canines and premolars, although there was a large difference in dental wear ratios for PM3 and PM4 and both M2 and M3 had a significantly lower dental wear ratio compared to the other dentitions (figure 5.3.14). Among Roman individuals there was a similar pattern in dental wear ratios although there was no significant difference in M2 and PM4 as was also the case with Anglo-Saxon and Medieval individuals (figure 5.3.15-17). Among the Post-Medieval individuals there is once again increased wear on the first incisor (figure 5.3.18).

The mean dental wear ratios were further analysed to determine if significant differences occurred over time and an ANOVA revealed that there were significant differences in dental wear ratio between periods for the molars, canines and first incisors. A Bonferroni test was conducted which shows that for the M3s significant differences in wear ratio occurred between the Post-Medieval period and the Bronze/Iron Age, Roman and Anglo-Saxon periods, as well as between Medieval individuals and the Roman and Anglo-Saxon individuals. For the M2 significant differences were recorded between Post-Medieval individuals and the Romans, as well as between the Romans and the Neolithic individuals. Finally, among the first incisor there were only significant differences between the Post-Medieval and Medieval individuals.
Figure 5.3.13: Dental wear ratio Neolithic. Box plot illustrating the dental wear ratio for mandibular dentition among Neolithic individuals. The purple line illustrates the wear level of M1, the mean wear for the I1 was therefore found to be similar to the wear of M1. Whiskers illustrate the standard error in dental wear ratio.

Figure 5.3.14: Dental wear Bronze and Iron Age. Box plot illustrating the dental wear ratio for mandibular dentition among Bronze and Iron Age individuals. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.
**Figure 5.3.15: Dental wear ratio Roman.** Box plot illustrating the dental wear ratio for mandibular dentition among Roman individuals. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.

**Figure 5.3.16: Dental wear ratio Anglo-Saxon.** Box plot illustrating the dental wear ratio for mandibular dentition among Anglo-Saxon individuals. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.
Figure 5.3.17: Dental wear ratio Medieval. Box plot illustrating the dental wear ratio for mandibular dentition among Medieval individuals. The purple line illustrates the wear level of M1, as such in general the M1 was the most worn tooth among this group. Whiskers illustrate the standard error in dental wear ratio.

Figure 5.3.18: Dental wear ratio Post-medieval. Box plot illustrating the dental wear ratio for mandibular dentition among Post-Medieval individuals. The purple line illustrates the wear level of M1, the mean wear for the I1 was therefore found to be similar to the wear of M1. Whiskers illustrate the standard error in dental wear ratio.
Table 5.3.6: ANOVA differences in dental wear ratio over time. Results from an ANOVA illustrating that over time there were significant differences between periods in mean tooth wear ratio for M3, M2, canines, and I1.

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>m3</td>
<td>Between Groups</td>
<td>0.82</td>
<td>5</td>
<td>.16</td>
<td>9.05</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>6.47</td>
<td>359</td>
<td>.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>7.29</td>
<td>364</td>
<td></td>
<td></td>
</tr>
<tr>
<td>m2</td>
<td>Between Groups</td>
<td>0.55</td>
<td>5</td>
<td>.11</td>
<td>4.43</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>14.56</td>
<td>590</td>
<td>.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>15.10</td>
<td>595</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Between Groups</td>
<td>0.98</td>
<td>5</td>
<td>.20</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>42.25</td>
<td>501</td>
<td>.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>43.23</td>
<td>506</td>
<td></td>
<td></td>
</tr>
<tr>
<td>i1</td>
<td>Between Groups</td>
<td>1.28</td>
<td>5</td>
<td>.26</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>48.05</td>
<td>456</td>
<td>.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>49.33</td>
<td>461</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It was determined that there were no abnormal dental wear ratio patterns recorded over time in Britain, as such it is concluded that masticatory patterns did not differ significantly between periods, as such mandible morphology can be analysed among time periods without further consideration of dental wear ratios.
5.4 Methods: Mandible Measurements

Previous studies have typically relied on measurements of the mandible to analyse changes in mandibular morphology between assemblages. To allow for comparisons between the results from this research and previously published studies, it was deemed necessary to include some standard measurements in the analysis. These measurements will additionally be used to compare the efficacy of linear measurements with 3D GMM. Seven measurements were taken using sliding callipers, these measurements are described in table 5.4 and illustrated in figure 5.4 below, results were then input and analysed in SPSS. To ensure results were consistent and accurate all measurements were taken three times to the nearest 0.1 millimetre and the mean measurement was recorded.

An intra-observer error study was conducted where three mandibles were measured five times. Mean intra-observer error was recorded between 0.1-1mm (see appendix 4 figure 4.3.1). An inter-observer error study was also conducted, five archaeology PhD students with a background in osteology were provided with written descriptions and were asked to measure three mandibles. Mean inter-observer error was determined to be between 0.5 – 2.8 mm (see appendix 4 figure 4.3.2). Both the inter and intra-observer error was considered acceptable. The mean was utilised for statistical comparison after a Shapiro-Wilk test and Q-Q graphs indicated these data were normally distributed and could therefore be treated as a ‘population’. Difference in mean was analysed using an independent sample t-test and where applicable ANOVA and Bonferroni tests (see table 5.3.3). The aim of these analyses was to determine if mandible measurements were significantly different between comparison groups. As discussed, a statistically significant difference was reported when the p-value was less than 0.05 (<5%).
**Table 5.4: Mandible measurements.** Table describing the measurements taken in this study (Arsdale and Lordkipanidze 2012, Franklin *et al.* 2008, Freidline *et al.* 2017, Lopez *et al.* 2017, McNamara and Bryan 1987, Trinkaus 2003).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandibular Length 1</td>
<td>Distance from the posterior superior surface of the mandibular condyle and infradentale - the superior point on the alveolar bone at the interdental space between the 1st incisors (McNamara <em>et al.</em> 1987, Trinkaus 2003)</td>
</tr>
<tr>
<td>Mandibular Length 2</td>
<td>Distance from the posterior superior point on the coronoid process and infradentale (Arsdale and Lordkipanidze 2012, Freidline <em>et al.</em> 2017)</td>
</tr>
<tr>
<td>Body Length</td>
<td>Distance from the posterior inferior point where the mandibular body joins the ramus and infradentale (Lopez <em>et al.</em> 2017)</td>
</tr>
<tr>
<td>Bicondylar Breadth</td>
<td>Distance between the superior lateral point on the mandibular condyles (Lopez <em>et al.</em> 2017)</td>
</tr>
<tr>
<td>Bicoronoid Breadth</td>
<td>Distance between the superior point on the coronoid processes (Lopez <em>et al.</em> 2017)</td>
</tr>
<tr>
<td>Ramus Height</td>
<td>Distance between the gonial angle and the superior most point on the mandibular condyle (Franklin <em>et al.</em> 2008, Lopez <em>et al.</em> 2017)</td>
</tr>
<tr>
<td>Body Height</td>
<td>Distance between the infradentale and the inferior most point of the mandibular ramus along the sagittal plane (Franklin <em>et al.</em> 2008)</td>
</tr>
</tbody>
</table>
Figure 5.4 Mandible measurements. Diagrams illustrating the linear measurements taken on the mandible with calipers, the left image shows a mandible from lateral position with the L1, L2, Bl and Rh measurements and on the right the mandible from anterior view showing the CorB, ConB and Bh measurements.
**5.5 Methods: 3D Geometric Morphometrics**

Geometric morphometrics is the study of size and shape through the multivariate analysis of Cartesian coordinates. This allows for groups and individual shape differences to be visualised providing a superior representation of the shape of a specimen compared to more traditional measurements (Nicholson and Havarti 2006, O’Higgins 2001). There are several types of geometric morphometrics, however this research will focus on landmark based geometric morphometrics. Landmark based geometric morphometrics employs either 2D or 3D Cartesian landmark coordinates in order to summarise biological shapes (Bookstein 1997, Dryden and Mardia 1998, Webster and Sheets 2010). A benefit of landmark based geometric morphometrics is that the resulting graphical representations of special differences are visually appealing, intuitive and allows for complex changes in biological shapes to be visualised.

The following steps are required when conducting a landmark based geometric morphometric study, which will be discussed in this section:

~ Data acquisition 1: Scanning the specimen ([section 5.5.3](#)) ~ 40 minutes per mandible

~ Data acquisition 2: Clean and align scans ([section 5.5.4](#)) ~ 15 minutes per mandible

~ Data acquisition 3: Landmarks placed on a computer model of the specimen and coordinate data extracted ([section 5.5.5](#)) ~ ten minutes per mandible

~ Estimate missing landmarks ([section 5.5.2.4](#))

~ Format the coordinate data for the entire sample into a script that can be read in R ([section 5.5.6](#))

~ Data registration: Perform Generalised Procrustes Analysis (GPA) to isolate the shape data ([section 5.5.6](#))

~ Data reduction of the GPA coordinate matrix, this is done through either Principal Component analysis and Canonical Variate Analysis ([section 5.5.6](#))

~ Analyse data using multivariate statistics and visualise shape changes using Evan Toolbox ([section 5.5.6](#)).
5.5.1 Landmark Requirements

Landmark based GMM involves the simplification of a biological shape in terms of “a constellation of discrete anatomical loci, each described by 2- or 3-dimensional Cartesian coordinates” (Webster and Sheets 2010, 164). This requires the placement of consistent and reliable landmarks to generate a discrete representation of the 3D object. Landmarks are homologous points that must be present among all samples and consistent between samples while at the same time landmarks must be relevant to the area of study (Bookstein 1997, Souter et al. 2010).

Despite the recent expansion of 3D GMM research there has been a dearth of studies investigating mandible morphology (Enomoto et al. 2010). The relative lack of 3D GMM studies investigating mandible morphology may in part be due to the nature of GMM which relies on the consistent placement of homologous landmarks on all individuals in the study (Webster and Sheets 2010). Compared to the cranium, for which there is an overwhelming number of GMM studies, the mandible has very few true biological landmarks. The three GMM studies with the largest sample size which analysed the mandible only included 22, 27, and 33 landmarks respectively (Katz et al. 2017, Bejdova et al. 2013, von Cramon-Trabadel 2011). Previous studies which have analysed morphological changes in the mandible are further detailed in section 4.4.3. Conversely craniofacial studies frequently include semi-landmarks and may have over 100 landmarks, with Mitteroecker et al. (2005) having 191 anatomical and semi-landmarks. In this present study it was deemed highly important to incorporate a large number of landmarks and to ensure these landmarks fitted the requirements of GMM analysis which are:

- Consider the ‘biological question’ when choosing the landmarks (Webster and Sheets 2010).

- Landmarks need to be placed reliably and consistently on the entire sample, which can be tested through an intra-observer error study (Webster and Sheets 2010).

- Landmarks need to be able to be placed consistently on the entire sample, if an individual is missing just one landmark, they cannot be included in the study (Webster and Sheets 2010).
5.5.1.1 The Biological Question
When deciding landmarks for a GMM study it is first necessary to consider the biological question that is being asked (Souter et al. 2010). After considering the relevant background literature it was noted that the key areas where morphological variation should occur are the condyles, ramus and gonial angle, this is discussed further in section 4.2. This was considered when deciding the landmarks to include within this current analysis. However, due to their nature these areas were also the regions where the majority of variation occurred, which makes the placement of consistent homologous landmarks problematic.

5.5.1.2 Reliable and consistent placement of landmarks
To determine if landmarks could be consistently and reliably placed among the specimens, intra and inter observer error studies were conducted. Only landmarks which could be consistently placed with <3 mm of error were utilised. In order to determine if the landmarks chosen were reliable an inter and intra observer error study was conducted (section 5.5.2)

5.5.1.3 Landmark Consistency
One limitation of landmark based GMM is that all the data used in the analysis must have the same set of landmarks. Therefore, specimens with missing landmarks - either the result of taphonomic damage or problems arising during data acquisition - must be excluded from the analysis (Adams et al. 2004). To determine if the landmarks chosen would likely be present on a large enough sample to allow for valuable statistical analysis, a mini study was conducted. Full details of this study are detailed in section 5.5.2.1. It was determined based on results from this study that preservation of the archaeological mandibles would not be sufficient to achieve a large enough sample size when requiring all 46 landmarks to be present. However missing landmarks can be reconstructed bilaterally across the plane of symmetry which allows for a larger sample size to be achieved. This study demonstrated the need for such methods especially for time periods with lower levels of preservation, these methods are discussed further in section 5.5.2.4.
5.5.2 Method Development Studies

To ensure that the landmarks chosen, fit the requirements of GMM analysis a number of method development studies were conducted. Originally 52 landmarks were chosen and tested for their repeatability and reliability, after analysis 46 landmarks were determined to fit the requirements detailed in section 5.5.1 and were used in this research.

5.5.2.1 Method development study: Preservation Analysis I

A limitation of landmark based GMM is that all the landmarks must be present on the entire sample. Therefore, specimens with missing landmarks, either from the result of physical taphonomic damage to the specimen or during the data acquisition stage, must be excluded from this study (Adams et al. 2004). To determine if the landmarks utilised would be present on a large enough sample, an initial presence/absence study was conducted. 50 mandibles from the Duckworth collection and 50 mandibles from the St Gregory priory and cemetery were utilised for this study. Midline landmarks were recorded as present or absent, and the bilateral landmarks were recorded as present 1, present 2 or absent.

Results from this mini study – shown in **Table 5.5.1** - indicated that among 91% of mandibles the minimum number of required landmarks were present, although only on 55% of mandibles were all symmetrical landmarks present. Preservation of the archaeological material from St. Gregory’s Priory and Cemetery was significantly lower compared to the Duckworth collection, with only nine mandibles having all landmarks present and 28 mandibles having the minimum landmark requirements for inclusion.

**Table 5.5.1: Landmark presence/absence.** Table detailing the mandibles which are complete, posses the minimum number of landmarks and which have less than the minimum number of landmarks

<table>
<thead>
<tr>
<th></th>
<th>Complete</th>
<th>Minimum</th>
<th>Absent</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duckworth</strong></td>
<td>21</td>
<td>29</td>
<td>6</td>
<td>50</td>
</tr>
<tr>
<td><strong>St. Gregory’s</strong></td>
<td>9</td>
<td>28</td>
<td>13</td>
<td>50</td>
</tr>
</tbody>
</table>
It was determined from this study that the chosen landmarks would be present on enough mandibles, however, some missing landmarks must be estimated/reconstructed using methods discussed in section 5.5.2.4 in order to achieve an adequate sample size.

5.5.2.2 Method development study: Intra-observer error
To ensure landmarks are placed consistently an intra-observer error study was conducted. The sample included 3D scans from 20 mandibles from the Duckworth collection where all landmarks were present. Mandibles were chosen from different continents in order to increase morphological variation for this analysis. Landmarks were placed on scans of each mandible once a week for ten weeks, descriptions and diagrams illustrated in section 5.5.5 were used when placing landmarks, to ensure consistency.

Before considering the results of the intra-observer error study it is first necessary to briefly discuss the problems with investigating observer error in geometric morphometric studies. There are currently no standardised methods for calculating error or suggested thresholds for the acceptable level of error (Hirst et al. 2018, von Cramon-Taubadel et al. 2007, White et al. 2018). Furthermore, the level of observer error reported by some published papers is unfeasibly low (eg: Fuessinger et al. 2018, Guyomarc'h et al. 2012). For instance, Fuessinger et al. (2018) reported measurement error as low as 0.001mm for some landmarks with a mean error of 0.3mm. Further research is necessary in order to establish methods for estimating observer error and determine an acceptable level of error. Until then it was determined for this study to take two approaches.

The first was to analyse the coordinate data after GPA registration and PCA. While there are numerous issues with investigating error in PCA aligned coordinates (Chapman 1990, von Cramon-Taubadel et al. 2007, Zelditch et al. 2012) this approach is frequently taken by previous papers (eg: Franklin et al. 2006a, 2007, Kranioi et al. 2009, Lockwood et al. 2002, Terhune et al. 2007).

The first level of analysis determined that when analysed through GPA and PCA the mean Procrustes distance between the repeated sampling was less than the Procrustes distance between individuals. Intra-observer error for the raw landmark coordinates was then analysed individually in SPSS. The mean standard deviation in X Y and Z coordinates and the combined error in
millimetres was evaluated. The results from this second analysis showed that 15 of the landmarks had higher levels of error associated with them (>2mm).

![Intra-Observer Error](image)

**Figure 5.5.1: Intra-observer error results.** Bar graph illustrating the mean intra-observer error in mm for each landmark.

Because of this analysis it was determined necessary to remove 13 landmarks from the study and alter two landmarks. This resulted in a lack of data which reflected mandibular shape in the gonial angle and inferior border of the mandibular body. To compensate for this three new landmarks were introduced. These were tested using the same method as before (illustrated in figure 5.5.1) and it was determined that error levels were sufficiently low (<1.6mm), allowing these landmarks to be incorporated.

### 5.5.2.3 Method development study: Inter-Observer Error

A study was also conducted to determine if these landmarks could be placed consistently by other researchers, while these results do not impact the validity of the current study it is important for future research as a low inter-observer error would allow the same methodology to be employed for future studies allowing direct comparisons with the landmark data collected in this study. For the inter-observer error study five PhD students from the archaeology department at UCL with a background in osteology were selected. The participants were given a brief tutorial on how to use the Landmark Editor software (Wiley et al. ND) and provided with written descriptions (table 5.5.2) and diagrams (figure 5.5.17 and 5.5.18) of the landmarks employed in this study.
Additionally, a previously landmarked mandible was included for comparison as some of landmarks are difficult to interpret on 2D images. Participants placed landmarks on scans from three complete mandibles from the Duckworth collection and the raw landmark coordinates were extracted for comparison, as with the intra-observer error study landmark accuracy was analysed based on Procrustes aligned coordinates and raw landmark data.

Landmarks had to all be placed in the same order which led to confusion among the participants, as such prior to analysis all landmarks were checked and the order of landmark placement but not the position was changed in these cases. This type of error is immediately evident when conducting GPA and PCA. As expected, inter-observer error was higher than the intra-observer error study however standard deviation did not exceed 3mm – for accumulated error between X,Y and Z coordinates - for any of the landmarks as illustrated in figure 5.5.2. Furthermore, Procrustes distance between mandibles was greater than the variation in participant error for each individual.

![Inter-Observer Error](image)

**Figure 5.5.2: Inter-observer landmark error.** Bar graph illustrating the amount of mean standard deviation (mm) for each of the landmarks in this study.
5.5.2.4 Method development study: Reconstruction Study
As discussed in section 5.5.3.1 preservation of the mandibles from British archaeological assemblages was not sufficient to acquire a large enough sample for each period if only complete mandibles could be included. As such methods for reconstructing/estimating missing landmarks were evaluated for their efficacy for this sample. The following five methods were compared in this study:

R1: Manual simplistic mirroring across a bilateral mid-plane

A plane of bilateral symmetry is estimated from the mean X value of the midsagittal landmarks, the missing landmarks are then reconstructed using the Y and Z coordinates from the corresponding original landmarks, and the X coordinate for the missing landmarks are estimated by calculating the distance along the X axis between the original landmark and the midsagittal plane and reflecting this distance across the midsagittal plane to get the X value for the missing landmark.

R2: TPS reconstruction in geomorph (estimate.missing(TPS))

Missing landmarks are estimated by using TPS to interpolate specimens on a reference specimen to estimate the locations of missing landmark. Here, a reference specimen is obtained from the set of specimens for which all landmarks common to both are present. Finally, the TPS is used to estimate the location for the missing landmarks in the target specimen.

R3: Multivariate regression method in geomorph (estimate.missing(Reg))

Missing landmarks are estimated for incomplete specimens, for the multivariate regression method each landmark is regressed on all other landmarks for the set of complete specimens, and the missing landmark values are then predicted by this linear regression model. Because the number of variables can exceed the number of specimens, the regression is implemented on scores along the first set of PLS axes for the complete and incomplete blocks of landmarks.
R4: Mirroring across an empirical midplane in *morpho* (fixLMmirror)

For this method, the configurations are mirrored and the relabelled version is matched onto the original, using a thin-plate spline deformation. The missing landmark is then estimated using its bilateral counterpart.

R5: TPS reconstruction in *morpho* (fixLMtps)

Missing landmarks are estimated by deforming the sample average or a weighted of the configurations most similar onto the deficient configuration. The deformation is performed by a Thin-plate-spline interpolation calculated by the available landmarks.

Preservation Study II

While the results from the previous preservation study indicated that reconstruction of incomplete mandibles would be required, it is necessary to further understand the pattern of preservation in the scanned mandibles. When considering reconstruction methods, it is important that the proposed methods have high rates of accuracy among the landmarks which are most frequently missing.

Analysis of the entire sample revealed that 41.731% of mandibles were complete while only 2.3184% had the minimum number of landmarks for inclusion in the study, and the remaining 55.796% mandibles were incomplete but had at least 25 landmarks present. Further analysis was conducted to determine the mean number of missing landmarks for the total sample and among the different regions of the mandible, the results from this analysis is included in figure 5.5.3 and 5.5.4 below. It was determined that the most frequently absent landmarks were 35-40 and 43-48, which are the landmarks located on the condyle and coronoid. These results are consistent with expectations, as these are the regions of the mandible which project from the body of the mandible, and as such are more susceptible to taphonomic factors.
Figure 5.5.3: Percentage of missing landmarks. Bar graph illustrating the percentage of missing landmarks.

Six landmarks had a significantly higher percentage of absence, these were the superior, lateral and medial points on the condyle, the condylar neck and the superior and anterior points on the coronoid were absent from over 14% of the sample, the majority of the other bilateral landmarks were only absent from approximately 6% of the population.

Figure 5.5.4: Frequency of missing landmarks. Bar chart illustrating the frequency of missing landmarks among the sample.
It is clear from these results that the condyle and coronoid are the most frequently missing landmarks and therefore it is important that reconstruction methods are accurate for these landmarks. Additionally, as the mean number of missing landmarks is 4.5, reconstruction methods need to be capable of reconstructing at least five landmarks with a high degree of accuracy, which would allow the reconstruction of 55.6% of the incomplete mandibles.

Raw landmark error, the numerical difference between the original (O) and reconstructed (R) coordinates for methods R1-R5 were directly compared. The mean error was calculated to analyse the efficacy of each method. For the first level of analysis 50% of the bilateral landmarks were reconstructed, which involved reconstructing the entire left hemisphere of the mandible. However as only 2.31% of the mandibles in this study were missing an entire hemisphere further analysis will be conducted to analyse the efficacy of these methods for only reconstructing the most frequently missing landmarks. This second analysis will only involved R2-R5 reconstruction methods as the results from the R1 method were determined not to be influenced by the number of missing landmarks.

![Figure 5.5.5: Mean error for estimating missing landmarks R1-R5. Mean difference between reconstructed and original coordinates for each landmark, method R3 is not included due to extreme levels of error which warranted its exclusion.](image_url)
A significantly greater level of error was produced in the R3 (Multivariate Regression) method as such this method was not included for further analysis. The R4 and R5 reconstructions, while lower in error than R3 is still greater than the R1 and R2 reconstructions. To evaluate the error of the R4 and R5 methods it is therefore necessary to analyse them separately from the high error R2 and R3 methods. It was decided from this study that that mandibles would not be included if only half of all bilateral landmarks were present.

**Figure 5.5.6: Mean error for estimating missing landmarks R1-R2.** Mean error in R1 and R2 methods, showing that it varied between landmarks as to which method is the most accurate.
Comparison R2-5 for the most frequently missing landmarks

When reconstructing only the most frequently missing landmarks methods R4 and R5 had the lowest level of error. Method R2 still resulted in the reconstruction of the present bilateral landmarks and produced the highest level of error after R3 (figure 5.5.7). Methods R4 and R5 had the lowest level of error were compared separately (figure 5.5.8). Both R4 and R5 reconstruction methods had under 3.5mm of error for all landmarks. The R4 reconstruction method was more accurate, with error not exceeding 2mm for any of the reconstructed landmarks.

![Error in estimating most frequently missing landmarks R2-R5](image1)

**Figure 5.5.7: Error in estimating most frequently missing landmarks R2-R5.** Bar graph illustrating the error between reconstructed landmarks using the R2, R4 and R5 methods compared to the original landmark values. Method R3 was excluded from the comparison due to very high levels of error.

![Mean error R4-R5](image2)

**Figure 5.5.8: Mean error R4-R5 frequently missing landmarks.** Error in estimating most frequently missing landmarks R4-R5. Bar graph illustrating the error between reconstructed landmarks using the R4 and R5 methods compared to the original landmark values.
Levels of error were low enough that it was determined individuals with eight missing landmarks would be reconstructed using method R4, however any individuals with more than eight missing landmarks would not be reconstructed. While further research would be valuable to determine how landmark position influenced error when reconstructing a lower number of landmarks. These ‘frequently missing landmarks’ were also the landmarks associated with the highest level of error when reconstructing all bilateral landmarks and error level was still under 3mm, therefore for the purposes of this study this method was determined acceptable.

Reconstruction and estimation methods are frequently used in GMM studies as the nature of the requirements of GMM combined with the preservation of archaeological materials can greatly reduce sample sizes and hinder analysis (Arbour & Brown 2013, Hirst et al. 2018). These methods typically rely on exploiting bilateral symmetry and as such when large numbers of missing landmarks are estimated, these methods may act to reduce the asymmetry of a data set. As such estimation methods should not be utilised in studies which focus on the analysis of asymmetry among the sample. However, in this study with a maximum of eight missing landmarks being estimated per individual and error levels associated with these methods being lower than inter-observer error studies it is unlikely that such methods will have any influence on these results.
5.5.3 Scanning Method
The quality and definition of the scan needs to be considered for GMM studies as consistent placement of landmarks is unlikely to be achievable among poor quality scans (Webster and Sheets 2010). Therefore, to ensure adequate coverage of the mandible three scans were taken for each specimen. This allows the full form of the mandible to be captured while limiting the total number of scans, thus both reducing the amount of time taken per mandible as well as reducing the amount of processing required to align the scans which reduces the potential error created in this process. All together the scanning process took approximately 40 minutes per mandible, for the entire sample of 911 mandibles this meant a scanning time of around 607 hours.

Figure 5.5.9: Next Engine Scanner. Photograph of a Next Engine HD scanner conducting a 360º scan of a human crania using the turntable (White 2015, 42, Figure 1).

Mandibles were scanned using a Next Engine HD scanner (illustrated in figure 5.5.9) using the high definition setting. The first scan was a 360º scan with the mandible positioned at an angle with the posterior inferior surface of the mandibular body and gonial angle on a polystyrene block approximately 1 ½ inches in height and five inches in length so that both gonial angles are positioned on the block shown in figure 5.5.10 and 5.5.11.
The second scan was a three-sided bracket scan designed to capture the morphology of the inferior surface and the anterior lingual surface of the mandibular body as well as the posterior inferior surface of the mandibular ramus. This involved positioning the mandible with the incisal surface of the incisors and canines placed on top of a 3-inch-high by 1-inch wide block so that the superior surface of the mandibular condyles is supporting the mandible on the turntable shown in figure 5.5.11 and 5.5.13.
The third scan taken was a single scan designed to capture the superior surface of the dentition, retro-molar space, superior surface of the mandibular condyles and the coronoid process. For this scan the mandible was positioned at a steep angle resting on the inferior anterior surface of the body at the mandibular symphysis and the posterior inferior surface of the mandibular angle positioned against the vertical place of a large block approximately two inches high and five inches wide, so that the mandible is at an approximate angle of $45^\circ$ shown in figure 5.5.12.

![Diagram for single scan](https://www.bartleby.com/107/44.html)

**Figure 5.5.12: Diagram for single scan.** Diagram illustrating the positioning of the mandible for the 3rd single scan, image modified from Gray 1918, Figure 167, https://www.bartleby.com/107/44.html).
5.5.4 Data Processing Methods

Once the three different scans were complete, they were combined to form a single 3D model using the ‘align’ process in Scan Studio and extraneous material such as the positioning props were removed from the scan. This process is illustrated in figure 5.5.14 and 5.5.15, with the final scan shown in figure 5.5.16. It took approximately 15 minutes per mandible to complete the cleaning and aligning process taking over 227 hours for the entire sample. The 3D models once complete were exported as a PLY file.
Figure 5.5.14: Scan studio cleaning scans. Screenshot illustrating the process of removing the props used to support the mandibles and hold them in position.

Figure 5.5.15: Scan Studio align models. Screen shots of the alignment process, alignment could be conducted in either the blue model view (top) which was better for identifying surface detail or in the full colour view (bottom left) which was particularly useful in cases were the mandibles had writing on them, although in some instances the colour was not successfully captured in the scan as shown (bottom right).
Figure 5.5.16: Final complete scan in Scan Studio. Screen shot of a final completed scan for mandible in both blue surface detail views (left and middle) and colour detail (right).

5.5.5 Landmarks

Landmarks were then placed using the free software Landmark Editor (Wiley et al. ND) (as illustrated below in figure 5.5.19), the coordinates were then extracted as text files. Based on the results from the method development studies (section 5.5.3), 46 landmarks were chosen to include in analysis, these are described in table 5.5.3 and illustrated in figure 5.5.17 and 5.5.18 below. When landmark data were missing these coordinates were estimated in R as per the reconstruction study detailed in section 5.3.3. The landmark process took approximately ten minutes per mandible totalling 152 hours.
<table>
<thead>
<tr>
<th>#</th>
<th>Landmark</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1st incisor labial surface</td>
<td>Superior position on the alveolar bone at the labial surface below the interproximal surface between the 1st incisor</td>
</tr>
<tr>
<td>2</td>
<td>1st incisor lingual surface</td>
<td>Superior position on the alveolar bone at the lingual surface below the interproximal surface between the 1st incisor</td>
</tr>
<tr>
<td>3-4</td>
<td>Canine labial surface</td>
<td>Superior position on the alveolar bone at the central labial surface below the canine</td>
</tr>
<tr>
<td>5-6</td>
<td>Lingual surface 1st premolar</td>
<td>Superior position on the alveolar bone at the central lingual surface below the 1st premolar</td>
</tr>
<tr>
<td>7</td>
<td>Mental eminence</td>
<td>Most anterior point of the mental eminence along the mandibular symphysis</td>
</tr>
<tr>
<td>8</td>
<td>Superior to mental eminence</td>
<td>Most posterior depressed point on the anterior surface of the mandible body along the mandibular symphysis</td>
</tr>
<tr>
<td>9-10</td>
<td>Mental Foramen</td>
<td>Mental foramen</td>
</tr>
<tr>
<td>11-12</td>
<td>Buccal surface M1 and PM4</td>
<td>Point on the alveolar bone on the buccal surface between the M1 and PM4</td>
</tr>
<tr>
<td>13-14</td>
<td>Buccal surface M1 and M2</td>
<td>Point on the alveolar bone on the buccal surface between the M1 and M2</td>
</tr>
<tr>
<td>15-16</td>
<td>Buccal surface M2 and M3</td>
<td>Point on the alveolar bone on the buccal surface between the M2 and M3</td>
</tr>
<tr>
<td>17-18</td>
<td>Lingual surface M1 and PM4</td>
<td>Point on the alveolar bone on the lingual surface between the M1 and PM4</td>
</tr>
<tr>
<td>19-20</td>
<td>Lingual surface M1 and M2</td>
<td>Point on the alveolar bone on the lingual surface between the M1 and M2</td>
</tr>
<tr>
<td>21-22</td>
<td>Lingual surface M2 and M3</td>
<td>Point on the alveolar bone on the lingual surface between the M2 and M3</td>
</tr>
<tr>
<td>23-24</td>
<td>Inferior mandibular body parallel with point 20 and 23</td>
<td>Along the inferior-most lateral surface of the mandibular body inferior to point 15 and 16</td>
</tr>
<tr>
<td>25-26</td>
<td>Inferior mandible body parallel with mandibular notch</td>
<td>Point along the inferior surface of the mandibular body, directly inferior to the mandibular notch and symmetrically bisecting the ramus</td>
</tr>
<tr>
<td>27-28</td>
<td>Superior to gonial angle on posterior ramus</td>
<td>The most anterior point along posterior edge of the mandibular ramus, superior to the gonial angle and inferior to the mandibular condyle</td>
</tr>
<tr>
<td>29-30</td>
<td>Posterior condyle neck</td>
<td>Neck of the condyle on the posterior surface</td>
</tr>
<tr>
<td>31-32</td>
<td>Superior condyle</td>
<td>Most superior point on the mandibular condyle</td>
</tr>
<tr>
<td>33-34</td>
<td>Lateral condyle</td>
<td>Most lateral point on the mandibular condyle</td>
</tr>
<tr>
<td>35-36</td>
<td>Medial condyle</td>
<td>Most medial point on the mandibular condyle</td>
</tr>
<tr>
<td>37-38</td>
<td>Mandibular notch</td>
<td>Most inferior point along the superior edge of the mandibular ramus between the mandibular condyle and the coronoid process</td>
</tr>
<tr>
<td>39-40</td>
<td>Superior coronoid</td>
<td>The superior point of the coronoid process</td>
</tr>
<tr>
<td>41-42</td>
<td>Anterior coronoid</td>
<td>Most anterior point along the anterior edge of the mandibular ramus inferior to the coronoid process and superior to the retromolar space</td>
</tr>
<tr>
<td>43-44</td>
<td>Anterior Inferior ramus</td>
<td>Most posterior point along the anterior edge of the mandibular ramus inferior to point 29 and superior to the retromolar space</td>
</tr>
<tr>
<td>45-46</td>
<td>Gonial Angle</td>
<td>Gonial angle</td>
</tr>
</tbody>
</table>
Figure 5.5.17: Mandible landmarks lateral view, image modified from Gray 1918, Figure 167, [https://www.bartleby.com/107/44.html](https://www.bartleby.com/107/44.html).

Figure 5.5.18: Mandible landmarks medial view, image modified from Gray 1918, Figure 177, [https://www.bartleby.com/107/44.html](https://www.bartleby.com/107/44.html).
During the landmarking and reconstruction process several individuals were removed – due to either error in processing scans or resolution of the scans being insufficient for confident landmark placement – from the sample. The final GMM sample is detailed in Table 5.5.3.

Table 5.5.3: Final sample for 3D geometric morphometric analysis. Table detailing the number of individuals where landmark data were available for 3D geometric morphometric analysis.

<table>
<thead>
<tr>
<th>Period</th>
<th>Total</th>
<th>Males</th>
<th>Females</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neolithic</td>
<td>14</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Bronze and Iron Age</td>
<td>84</td>
<td>29</td>
<td>36</td>
<td>19</td>
</tr>
<tr>
<td>Roman</td>
<td>94</td>
<td>37</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td>153</td>
<td>54</td>
<td>39</td>
<td>67</td>
</tr>
<tr>
<td>Medieval</td>
<td>215</td>
<td>67</td>
<td>92</td>
<td>56</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>217</td>
<td>88</td>
<td>99</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>777</td>
<td>280</td>
<td>308</td>
<td>196</td>
</tr>
</tbody>
</table>
5.5.6 Geometric Morphometrics: Statistical Analysis

Once landmarks were placed on all of the mandible scans these data were exported for analysis in R. In order to analyse shape variation the coordinate data had to be registered (section 5.5.6.1) and reduced (section 5.6.5) using for GPA and PCA/CVA analysis. This analysis was conducted in R, the functions used for these analyses are detailed in table 5.5.4, the R script used for this analysis is provided in Appendix 6. As with dental wear analysis and mandible measurements the mean was utilised for statistical comparison after a Shapiro-Wilk test and Q-Q graphs indicated these data were normally distributed and could therefore be treated as a ‘population’. Difference in mean was analysed using an independent sample t-test and where applicable ANOVA and Bonferroni tests. The aim of these analysis was to determine if centroid size or canonical variates significant differed between comparison groups. As previously discussed, a statistically significant difference was reported when the p-value was less than 0.05 (<5%).
Table 5.5.4: R packages and functions used in GMM analysis

<table>
<thead>
<tr>
<th>Package</th>
<th>Function</th>
<th>Description</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGL</td>
<td>deformGrid3d</td>
<td>Adds a reference grid to a RGL plot</td>
<td>Used to subset specimen data</td>
</tr>
<tr>
<td>-</td>
<td>substr</td>
<td>Extract or replace substrings in a character vector</td>
<td></td>
</tr>
<tr>
<td>Morpho</td>
<td>CVA</td>
<td>Performs Canonical Variate Analysis</td>
<td>Leave-one-out cross validation analysis</td>
</tr>
<tr>
<td>-</td>
<td>class</td>
<td>Classification results based on posterior probabilities. Leave-one-out cross validation analysis</td>
<td></td>
</tr>
<tr>
<td>geomorph</td>
<td>plotRefToTarget</td>
<td>Plot shape differences between a reference and a target specimen</td>
<td>Illustrate shape differences between PCA, CVA and group means</td>
</tr>
<tr>
<td>-</td>
<td>read.morphologika</td>
<td>Obtains 3D landmark data and specimen information from a Morphologika file</td>
<td>Import data into R</td>
</tr>
<tr>
<td>-</td>
<td>gpagen</td>
<td>Performs Procrustes analysis of 3D landmark data</td>
<td>GPA</td>
</tr>
<tr>
<td>-</td>
<td>coords.subset</td>
<td>Subset landmark coordinates via a grouping factor</td>
<td>Used to subset coordinate data so that groups can be analysed separately</td>
</tr>
<tr>
<td>-</td>
<td>plotTangentSpace</td>
<td>Plots Procrustes aligned specimens in tangent space along their principal component axes</td>
<td>Principal component analysis</td>
</tr>
</tbody>
</table>

5.5.6.1 Data Registration: Generalised Procrustes Analysis (GPA)
In order to compare shape differences between specimens, landmark configurations need to be registered into a common coordinate system (Slice 2005, von Cramon-Taubadel et al. 2007). Procrustes analysis is the most common registration method which removes non-shape data (Mitteroecker and Gunz 2009, O’Higgins 2000, Rohlf 1999). The term Procrustes comes from the Greek myth of Procrustes - a bandit in Attica who had an iron bed which he made his victims lie on. If the victim was shorter than the bed Procrustes would stretch them by hammering or raking their body to make them fit, and if they were longer than the bed Procrustes would cut off their legs (Encyclopaedia Britannica N.D , Gower 1975). Procrustes analysis acts in a similar way to the
Attican bandit, whereby size and rotation effects of landmark data are removed allowing shape to be directly compared. Generalised Procrustes Analysis (GPA) is argued to be the most valuable and frequently used data registration method for shape correspondence (Goodall 1991). GPA allows analysis of variation in shape by aligning shapes through isometric scaling, translation and rotation while preserving the actual shape of elements (Mitteroecker and Gunz 2009, Monteiro et al. 2000, Rohlf 1999). After GPA was performed using the geomorph package in R the registered coordinates are referred to as Procrustes shape coordinates. Procrustes coordinates and centroid size was exported, and these data were used in subsequent statistical analysis such as principal component analysis (PCA) and canonical variate analysis (CVA) (see below).

5.5.6.2 Data Reduction: Principal Component Analysis (PCA)

After registration of the raw coordinate data, the Procrustes coordinates were analysed using two different data reduction techniques, the first of which is the most commonly found statistical process in geometric morphometrics: principal component analysis (PCA) (Mitteroecker and Gunz 2009, O’Higgins 2000, Slice 2005). PCA converts the GPA covariance matrix into eigenvectors, referred to as Principal Components (PC’s) and eigenvalues, through eigen decomposition (Mitteroecker and Gunz 2009). PCA is particularly useful in 3D GMM analysis because it reduces large data sets into the dimensions which represent the greatest variation or principal components. This allows shape variation among specimens to be plotted on a few dimensions and illustrates the amount of variation explained by each principal component. However, such shape changes may not necessarily correspond to biologically meaningful changes and it is necessary to visualise the shape variation explained by each PC in order to determine if this is a meaningful difference. Typically, studies will focus on the first few PC’s as these represent the most shape variation between specimens, however the cut-off point varies between studies and there is as yet no standardised approach (von Cramon-Taubadel 2007, Hirst et al. 2018). For the

24 Shape refers to the geometrical attributes which are unchanged when the figure is translated, rotated and scaled
purposes of this research, when using PCA all principal components which explain >5% of total variation will be investigated. This is because in this study mandible morphological variation was found to be represented by a large number of PC’s, each only account for a relatively small proportion of variation in the sample. While previous studies have principally utilised PCA it was determined during a pilot study that PCA produced a large number of PC scores that represented each representing a low percentage of group shape variation, which combined with little discernible difference between groups for the first five PC scores it was concluded that PCA would not be sufficient to analyse morphological variation in the mandible for this study. As such PCA analysis was only used to compare the amount of morphological variation that occurs in the geographic sample to the British archaeological sample.

5.5.6.3 Canonical Variate Analysis (CVA)
Canonical Variate Analysis (CVA) is the second data reduction technique that is included in this study. The purpose of (CVA) is to simplify the differences between groups (Campbell and Atchley 1981, Zelditch et al. 2012). There are a number of similarities between PCA and CVA, in that a new coordinate system is constructed however in the case of CVA these are canonical variates (Zelditch et al. 2012). While PCA is used to describe the differences between individuals, CVA is used to describe differences between group means. Furthermore CVA utilises the patterns of within-group variation to scale the axes for the CVA coordinate system, as such distances in CVA are not equivalent to distances in PCA or the original coordinate system (Zelditch et al. 2012). The major benefit of CVA compared to PCA is the ability to determine the number of significant dimensions between two or more groups and to calculate the 95% confidence intervals for each group. For the majority of analysis CVA will be used as this research focusses on investigating group differences.

5.5.6.4 Analysing GMM
In addition to convex hull and box plots to illustrate group differences in PCA and CVA, these data will be analysed in SPSS. Centroid size is the measure of size used in GMM, this is calculated as the square root of the sum of squared distances for all landmarks from their centroid. Centroid size will be analysed in SPSS, after it was confirmed that centroid size was normally distributed these
differences in means were analysed using t-tests, ANOVA and Bonferroni (see table 5.4.3). In addition to centroid size, CVs were analysed in SPSS to confirm that no significant differences were present between sex estimation or dental wear groups (t-test and ANOVA) provided in appendix 5.

5.5.7 Data Presentation
Finally, to illustrate these data PAST was used to create scatter graphs and convex hulls for the PCA and CVA results. This software was utilised because it allows for the creation of coloured convex hulls to illustrate group differences. Additionally, box and whisker graphs were also used to compare groups when analysing a single CV. This was both in cases where only one CV showed significant differences between the groups analysed as well as to clarify morphometric variation in cases with multiple CV’s. Finally, Evan Tool Box was used to create 3D illustrations to show exaggerated shape variation represented by the principal components and canonical variates. These visualisations are created by warping the 3D model of a mandible to a set of landmark coordinates which represent chosen canonical variate scores (eg: +5 CV and -5 CV), the landmark configurations are produced in R using the package morpho and the function cvvis.
Chapter 6
Results

This chapter details the results from the geometric morphometric analysis conducted to investigate how human mandibular morphology has changed in Britain from the Neolithic to the Post-Medieval period. Mandible measurements (section 6.1) and 3D geometric morphometric results (section 6.2) will be discussed separately to answer the research questions posed in chapter 1 section 1.1. For the purpose of these results it will be necessary to use abbreviations in tables and graphs; these are detailed below in table 6.1.

### Table 6.1: Abbreviation for discussion of results

Table detailing the abbreviations and descriptions that will be used in graphs and tables throughout the results section.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Code</th>
<th>Description</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Neolithic</td>
<td>NF</td>
<td>Neolithic females</td>
<td>NM</td>
<td>Neolithic males</td>
</tr>
<tr>
<td>I</td>
<td>Iron/Bronze Age</td>
<td>IF</td>
<td>Iron/Bronze Age females</td>
<td>IM</td>
<td>Iron/Bronze Age males</td>
</tr>
<tr>
<td>R</td>
<td>Roman</td>
<td>RF</td>
<td>Roman females</td>
<td>RM</td>
<td>Roman males</td>
</tr>
<tr>
<td>A</td>
<td>Anglo-Saxon</td>
<td>AF</td>
<td>Anglo-Saxon females</td>
<td>AM</td>
<td>Anglo-Saxon males</td>
</tr>
<tr>
<td>M</td>
<td>Medieval</td>
<td>MF</td>
<td>Medieval females</td>
<td>MM</td>
<td>Medieval males</td>
</tr>
<tr>
<td>P</td>
<td>Post-Medieval</td>
<td>PF</td>
<td>Post-Medieval females</td>
<td>PM</td>
<td>Post-Medieval males</td>
</tr>
</tbody>
</table>

6.1 Mandible Measurements

Previous studies which have recorded significant differences in mandible morphology have mostly focussed on size differences, and calliper measurements. To allow for comparisons with these previously published studies - as well as to compare the analytical potential of 3D GMM with low cost and time methods such as calliper measurements - seven mandible measurements were taken with manual callipers. Based on a Shapiro-Wilk test and Q-Q plots it was determined that mandible measurements were normally distributed and as such using the mean for these measurements was considered appropriate for analysis (Appendix 4). Among the total sample, condylar breadth had the largest mean measurement, followed by mandible length 1, while body height was the smallest mandible measurement. Mandible measurements were analysed among sex estimation groups, chronological periods and dental wear.
6.1 Time period: how do mandible measurements vary over time among males and females?
Mandible measurements were analysed to determine how measurements changed over time among males and females, as calliper measurements have been found in previous studies as well as in this present study to vary significantly between sex estimation groups it is not possible to investigate differences in mandible form over time without considering males and females separately.

6.1.1 Females
Among females mandible measurements were found to be normally distributed (appendix 4 table 4.2.1). An ANOVA was conducted to determine if significant differences were present over time among females from this sample, which determined that there were only significant differences for body length. Mandibular body length was lowest among the Post-Medieval period and highest among Roman individuals (table 6.1.1, figure 6.1.1. and appendix 4 table 4.2.2). A Bonferroni post-hoc test revealed that there were only significant differences in body length between Post-Medieval and the Roman, Anglo-Saxon and Medieval individuals (see appendix 4, table 4.2.4 and table 4.2.5). There were also nearly significant differences (p=0.052) in body height over time, but no significant differences or nearly significant differences in body height occurred between individual period comparisons.

Table 6.1.1: ANOVA differences between time periods for females. ANOVA table detailing the comparison of mean body length among females over time, showing that there is a significant difference (p <0.00) in body length between time periods.

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td>Body length</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>756.01</td>
<td>5</td>
<td>151.20</td>
<td>5.55</td>
<td>.000</td>
</tr>
<tr>
<td>Within Groups</td>
<td>6743.09</td>
<td>247</td>
<td>27.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7499.10</td>
<td>252</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.1.1: Body length among females over time. Bar graph illustrating that while significant differences were recorded among females over time for body length based on an ANOVA, there is still a considerable overlap in standard error for most of the periods. Results were compared among each time period N (Neolithic), IB (Iron and Bronze Age), R (Roman), AS (Anglo-Saxon), M (Medieval) and PM (Post-Medieval, the error bars illustrate the standard error.

6.1.1.2 Males
Among males mandible measurements were also found to be normally distributed (appendix 4 table 4.2.1). An ANOVA was conducted to determine if significant differences were present over time among males from this sample, which illustrated that there were significant differences for coronoid breadth, condylar breadth, body length and body height (table 6.1.2, figure 6.1.2-5 and appendix 4 table 4.2.4). However, these measurements did not display a similar pattern over time; while mean condylar breadth increased over time from the Neolithic through to the Roman period, there was then a rapid decrease in size among Anglo-Saxon and Medieval individuals. Mean coronoid breadth however was lowest among the Bronze and Iron Age males and greatest among the Roman males, after the Roman period coronoid breadth decreased, and among Post-Medieval males mean coronoid breadth was very similar to among Bronze and Iron Age males. Mean body height and body length however did show a similar trend over time generally decreasing from the Neolithic through to the Medieval period before increasing slightly among the Post-Medieval males (appendix 4 table 4.2.2).

A Bonferroni post-hoc test revealed that there were significant differences in coronoid breadth between the Roman and the Bronze and Iron Age and Post-
Medieval males. In body length significant differences were only recorded among Medieval and Bronze and Iron Age individuals, and for body height between Medieval and Anglo-Saxon individuals while for condylar breadth there were no significant differences between individual periods (appendix 4 table 4.2.5).

Table 6.1.2: ANOVA differences between time periods for females. Results from an ANOVA detailing that among males there were significant differences (p<0.05) over time in the mean measurement for Coronoid Breadth, Condylar Breadth, Body Length and Ramus Height.

<table>
<thead>
<tr>
<th>Sex estimation</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CorB</td>
<td>Between Groups</td>
<td>1093.69</td>
<td>5</td>
<td>218.74</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>10437.09</td>
<td>155</td>
<td>67.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>11530.78</td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ConB</td>
<td>Between Groups</td>
<td>712.82</td>
<td>5</td>
<td>142.56</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>8199.84</td>
<td>146</td>
<td>56.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>8912.67</td>
<td>151</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bl</td>
<td>Between Groups</td>
<td>401.02</td>
<td>5</td>
<td>80.20</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>9338.31</td>
<td>311</td>
<td>30.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9739.33</td>
<td>316</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bh</td>
<td>Between Groups</td>
<td>208.78</td>
<td>5</td>
<td>41.76</td>
<td>3.61</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>3664.68</td>
<td>317</td>
<td>11.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>3873.42</td>
<td>322</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.1.2: Coronoid breadth among males over time. Bar graph illustrating the differences recorded among males between time periods for coronoid breadth. Results were compared among each time period N (Neolithic), IB (Iron and Bronze Age), R (Roman), AS (Anglo-Saxon), M (Medieval) and PM (Post-Medieval), whiskers illustrate the standard error.

Figure 6.1.3: Condyle breadth among males over time. Bar graph illustrating the differences recorded among males between time periods for condyle breadth. Results were compared among each time period N (Neolithic), IB (Iron and Bronze Age), R (Roman), AS (Anglo-Saxon), M (Medieval) and PM (Post-Medieval), whiskers illustrate the standard error.
Figure 6.1.4: **Body length among males over time.** Bar graph illustrating the differences recorded among males between time periods for body length. Results were compared among each time period N (Neolithic), IB (Iron and Bronze Age), R (Roman), AS (Anglo-Saxon), M (Medieval) and PM (Post-Medieval), whiskers illustrate the standard error.

![Body length over time among males](image)

Figure 6.1.5: **Ramus height among males over time.** Bar graph illustrating the differences recorded among males between time periods for ramus height. Results were compared among each time period N (Neolithic), IB (Iron and Bronze Age), R (Roman), AS (Anglo-Saxon), M (Medieval) and PM (Post-Medieval), whiskers illustrate the standard error.

![Ramus height over time among males](image)
6.1.2 Sex estimation: how do mandible measurements vary between males and females, within each time period?

Overall females had a lower mean compared to males for all mandibular measurements and this was consistent across all time periods (appendix 4 table 4.1.2 and 4.2.2). However, there was considerable variation between periods as to the significance of this difference. In general, it was found that over time the number of mandible measurements which were significantly different between males and females increased.

6.1.2.1 Neolithic

Among individuals from the Neolithic, males had a higher mean for all mandible measurements compared to females, however an independent samples t-test revealed that there were only significant differences in mandible measurements between males (mean = 66.9, SD= 4.7) and females (mean = 60.1, SD= 2.25) for ramus height (t(10)—3.24, p= 0.009) (figure 6.1.6 and appendix 4 table 4.2.3). Despite the lack of significant differences in mandible measurements a cluster analysis revealed that sex estimation could be correctly classified 81.8% of the time. The sample size for the Neolithic however was very small, particularly for certain mandible measurements that were more prone to taphonomy damage such as the condyles and coronoids. To illustrate the distribution of males and females for each mandible measurement histograms were produced which are shown in figure 6.1.7.

Figure 6.1.6: Sex differences in Ramus Height among Neolithic individuals. Bar graph illustrating the differences in ramus height between males and females among individuals from the Neolithic. Whiskers illustrate the standard error.
Figure 6.1.7: Neolithic mandible measurements histograms. Males are shown in green and females in blue for coronoid breadth (CorB), length 1 (L1), body height (Bh), length 2 (L2), condyle breadth (ConB), ramus height (Rh) and body length (Bl)
6.1.2.2 Bronze and Iron Age
Among individuals from Bronze and Iron Age assemblages an independent samples t-test revealed that there were only significant differences in mandible measurements between males and females for condylar breadth ($t(27)=-2.22$, $p=0.35$), body length ($t(61)=-3.773$, $p=<0.00$) and ramus height ($t(60)=-3.532$, $p=0.01$) (appendix 4 table 4.2.3), with males having a larger mean measurement compared to females (table 6.1.3 and figure 6.1.8). While more measurements were significantly different between males and females compared to the Neolithic individuals, classification accuracy for the Bronze and Iron Age period was lower, with only 58.1% of the individuals being correctly classified as either male or female. As such, for Bronze and Iron Age individual’s mandible measurements were found to be only slightly better than chance for estimating sex. To illustrate the distribution of males and females for each mandible measurement histograms were produced which are shown in figure 6.1.9.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sex Estimation</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>ConB</td>
<td>Female</td>
<td>11</td>
<td>114.75</td>
<td>12.36</td>
<td>3.73</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>18</td>
<td>123.82</td>
<td>9.54</td>
<td>2.25</td>
</tr>
<tr>
<td>Bl</td>
<td>Female</td>
<td>25</td>
<td>82.52</td>
<td>5.12</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>38</td>
<td>88.34</td>
<td>6.50</td>
<td>1.05</td>
</tr>
<tr>
<td>Rh</td>
<td>Female</td>
<td>26</td>
<td>60.80</td>
<td>5.99</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>36</td>
<td>66.69</td>
<td>6.81</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Table 6.1.3: Mean measurements with significant sexual dimorphism for Bronze and Iron Age individuals. Table describing the mean measurements and standard deviation for mandible measurements that were found to be significantly different between males and females, showing that the mean for these measurements were higher among males compared to females.
Figure 6.1.8: Sex differences in mandible measurements among Bronze and Iron Age individuals. Bar graph illustrating the significant differences recorded between males and females for condyle length, body length and ramus height. Whiskers illustrate the standard error.
Figure 6.1.9: Bronze and Iron Age mandible measurements histograms. Males are shown in green and females in blue for coronoid breadth (CorB), length 1 (L1), body height (Bh), length 2 (L2), condyle breadth (ConB), ramus height (Rh) and body length (Bl).
6.1.2.3 Roman
Among Roman individuals all mandible measurements, with the exception of condylar breadth, were found to be significantly different between males and females, based on an independent t-test illustrated in table 6.1.5. Males again had a higher mean for all measurements (table 6.1.4 and figure 6.1.10). Males and females were also found to be correctly classified for 65% of cases, while this is higher than Bronze and Iron Age, this classification accuracy is still lower than accepted standards for estimating biological sex. To illustrate the distribution of males and females for each mandible measurement histograms were produced which are shown in figure 6.1.11.

Table 6.1.4: Mean measurements with significant sexual dimorphism for Roman individuals. Table detailing the mean and standard deviation for the mandible measurements that were found to be statistically significant, showing that mean measurements were higher among males for all measurements.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sex Estimation</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CorB</td>
<td>Female</td>
<td>28</td>
<td>98.44</td>
<td>8.666</td>
<td>1.638</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>21</td>
<td>106.91</td>
<td>10.128</td>
<td>2.210</td>
</tr>
<tr>
<td>L1</td>
<td>Female</td>
<td>39</td>
<td>107.00</td>
<td>7.209</td>
<td>1.154</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>41</td>
<td>112.78</td>
<td>9.108</td>
<td>1.422</td>
</tr>
<tr>
<td>Bl</td>
<td>Female</td>
<td>40</td>
<td>83.64</td>
<td>6.935</td>
<td>1.096</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>41</td>
<td>86.77</td>
<td>5.145</td>
<td>.803</td>
</tr>
<tr>
<td>Bh</td>
<td>Female</td>
<td>46</td>
<td>31.26</td>
<td>3.432</td>
<td>.506</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>43</td>
<td>32.90</td>
<td>3.229</td>
<td>.492</td>
</tr>
<tr>
<td>Rh</td>
<td>Female</td>
<td>38</td>
<td>62.85</td>
<td>6.572</td>
<td>1.066</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>39</td>
<td>66.37</td>
<td>5.771</td>
<td>.924</td>
</tr>
<tr>
<td>L2</td>
<td>Female</td>
<td>42</td>
<td>79.17</td>
<td>8.055</td>
<td>1.243</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>42</td>
<td>84.46</td>
<td>7.682</td>
<td>1.185</td>
</tr>
</tbody>
</table>
Table 6.1.5: t-test results for Roman sex differences. Results from an independent samples t-test showing that only Length I did not have equal variance, and that for all measurements (with the exception of condylar breadth which are not included in the table) there was a significant difference between males and females (p<0.05).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Levene's Test for Equality of Variances</th>
<th>F</th>
<th>Sig.</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CorB</td>
<td>Equal variances assumed</td>
<td>.09</td>
<td>.76</td>
<td>-3.15</td>
<td>47</td>
<td>.003</td>
</tr>
<tr>
<td>L1</td>
<td>Equal variances assumed</td>
<td>7.60</td>
<td>.01</td>
<td>-3.14</td>
<td>78</td>
<td>.002</td>
</tr>
<tr>
<td></td>
<td>Equal variances not assumed</td>
<td></td>
<td></td>
<td>-3.16</td>
<td>75.55</td>
<td>.002</td>
</tr>
<tr>
<td>Bl</td>
<td>Equal variances assumed</td>
<td>2.08</td>
<td>.15</td>
<td>-2.31</td>
<td>79</td>
<td>.023</td>
</tr>
<tr>
<td>Bh</td>
<td>Equal variances assumed</td>
<td>.21</td>
<td>.65</td>
<td>-2.33</td>
<td>87</td>
<td>.022</td>
</tr>
<tr>
<td>Rh</td>
<td>Equal variances assumed</td>
<td>.33</td>
<td>.57</td>
<td>-2.50</td>
<td>75</td>
<td>.014</td>
</tr>
<tr>
<td>L2</td>
<td>Equal variances assumed</td>
<td>.08</td>
<td>.78</td>
<td>-3.08</td>
<td>82</td>
<td>.003</td>
</tr>
</tbody>
</table>

Figure 6.1.10: Sex differences in mandible measurements among Roman individuals. Bar graph for Roman individuals showing differences between males and females which are statistically significant based on an independent sample t-test, whiskers illustrate the standard error.
Figure 6.11: Roman mandible measurements histograms. Males are shown in green and females in blue for coronoid breadth (CorB), length 1 (L1), body height (Bh), length 2 (L2), condyle breadth (ConB), ramus height (Rh) and body length (Bl)
6.1.2.4 Early Medieval/ Anglo Saxon

Mean mandible measurements were higher among males for the Anglo-Saxon/ Early Medieval individuals as illustrated in figure 6.12 and table 6.1.6. Length I, body length, body height, ramus height and length II were all found to be significantly different between males and females from Anglo-Saxon sites, based on an independent sample t-test illustrated in table 6.1.7. Individuals were correctly classified for 69.7% of cases. As with the proceeding periods. To illustrate the distribution of males and females for each mandible measurement histograms were produced which are shown in figure 6.1.3.

Table 6.1.6: Mean measurements with significant sexual dimorphism for Anglo-Saxon individuals. Table detailing the mean mandible measurements for the measurements which were found to be statistically significant between males and females.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sex</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Female</td>
<td>36</td>
<td>106.29</td>
<td>10.21</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>45</td>
<td>113.04</td>
<td>8.62</td>
<td>1.29</td>
</tr>
<tr>
<td>B1</td>
<td>Female</td>
<td>37</td>
<td>83.44</td>
<td>4.58</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>48</td>
<td>86.62</td>
<td>4.59</td>
<td>0.66</td>
</tr>
<tr>
<td>B2</td>
<td>Female</td>
<td>37</td>
<td>30.66</td>
<td>3.66</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>48</td>
<td>33.39</td>
<td>3.29</td>
<td>0.48</td>
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<tr>
<td>R1</td>
<td>Female</td>
<td>35</td>
<td>63.10</td>
<td>5.25</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>50</td>
<td>67.96</td>
<td>4.87</td>
<td>0.69</td>
</tr>
<tr>
<td>L2</td>
<td>Female</td>
<td>35</td>
<td>79.91</td>
<td>6.12</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>45</td>
<td>83.13</td>
<td>6.05</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Table 6.1.7: **t-test results for Anglo-Saxon sex differences.** Independent sample t-test for the mandible measurements that were significantly different between males and females.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>F</th>
<th>Sig.</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.29</td>
<td>.59</td>
<td>-3.2379.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>0.31</td>
<td>.58</td>
<td>-3.1783.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bh</td>
<td>0.47</td>
<td>.49</td>
<td>-3.6183.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rh</td>
<td>0.54</td>
<td>.46</td>
<td>-4.3983.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>0.13</td>
<td>.72</td>
<td>-2.3578.021</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6.1.12: Sex differences in mandible measurements among Anglo-Saxon individuals.** Bar graph illustrating the quartiles for mandible measurements determined to vary significantly between males and females for the Anglo-Saxon/Early Medieval period, whiskers illustrate the standard error.
Figure 6.1.13: Anglo-Saxon mandible measurements histograms. Males are shown in green and females in blue for coronoid breadth (CorB), length 1 (L1), body height (Bh), length 2 (L2), condyle breadth (ConB), ramus height (Rh) and body length (Bl)
6.1.2.5 Medieval
As with the Anglo-Saxon individuals among the medieval individuals from this sample, length I, body length, body height, ramus height and length II were all found to be significantly higher among males compared to females (table 6.1.8, table 6.1.9 and figure 6.1.14). Classification accuracy of these mandible measurements was also similar among Medieval individuals with 62.8% of individuals correctly classified as either male or female. To illustrate the distribution of males and females for each mandible measurement histograms were produced which are shown in figure 6.1.15.

Table 6.1.8: Mean measurements with significant sexual dimorphism for Medieval individuals. Table detailing the mean and standard deviation for mandible measurements among males and females from Medieval sites.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sex</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Female</td>
<td>59</td>
<td>106.62</td>
<td>6.07</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>84</td>
<td>111.13</td>
<td>8.49</td>
<td>0.93</td>
</tr>
<tr>
<td>Bl</td>
<td>Female</td>
<td>61</td>
<td>82.04</td>
<td>4.76</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>87</td>
<td>84.90</td>
<td>5.01</td>
<td>0.54</td>
</tr>
<tr>
<td>Bh</td>
<td>Female</td>
<td>61</td>
<td>29.92</td>
<td>2.96</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>91</td>
<td>31.37</td>
<td>3.46</td>
<td>0.36</td>
</tr>
<tr>
<td>Rh</td>
<td>Female</td>
<td>58</td>
<td>63.07</td>
<td>5.79</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>87</td>
<td>66.29</td>
<td>5.71</td>
<td>0.61</td>
</tr>
<tr>
<td>L2</td>
<td>Female</td>
<td>61</td>
<td>79.63</td>
<td>4.87</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>85</td>
<td>83.12</td>
<td>6.19</td>
<td>0.67</td>
</tr>
</tbody>
</table>
Table 6.1.9: t-test results for Medieval sex differences. Table showing the results from an independent samples t-test illustrating that for Length I, body length, body height, ramus height and length II.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Levene's Test for Equality of Variances</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Equal variances assumed</td>
<td>6.37</td>
<td>.01</td>
<td>-3.49</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td>Equal variances not assumed</td>
<td>-3.70</td>
<td>140.94</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>Bl</td>
<td>Equal variances assumed</td>
<td>0.11</td>
<td>.74</td>
<td>-3.49</td>
<td>146</td>
</tr>
<tr>
<td>Bh</td>
<td>Equal variances assumed</td>
<td>2.24</td>
<td>.14</td>
<td>-2.68</td>
<td>150</td>
</tr>
<tr>
<td>Rh</td>
<td>Equal variances assumed</td>
<td>0.46</td>
<td>.50</td>
<td>-3.30</td>
<td>143</td>
</tr>
<tr>
<td>L2</td>
<td>Equal variances assumed</td>
<td>0.80</td>
<td>.37</td>
<td>-3.66</td>
<td>144</td>
</tr>
</tbody>
</table>

Figure 6.14: Sex differences in mandible measurements among Medieval individuals. Bar graph illustrating the difference in range for mandible measurements determined to be significantly different based on an independent sample t-test, whiskers illustrate the standard error.
Figure 6.1.15: Medieval mandible measurements histograms. Males are shown in green and females in blue for coronoid breadth (CorB), length 1 (L1), body height (Bh), length 2 (L2), condyle breadth (ConB), ramus height (Rh) and body length (Bl).
6.1.2.6 Post-Medieval

Mandible measurements among Post-Medieval individuals were as with all preceding periods greater than the mean measurements for females, as illustrated in table 6.1.10 and figure 6.1.16. For Post-Medieval individuals all measurements were found to be statistically significant with the exception of condylar breadth between males and females based on the results of an independent sample t-test table 6.1.11. Classification accuracy among Post-Medieval individuals was higher than all other periods, with the exception of the Neolithic individuals where sample size was very low, with 75.9% of individuals correctly classified as either male or female. To illustrate the distribution of males and females for each mandible measurement histograms were produced which are shown in figure 6.1.17.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sex</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CorB</td>
<td>Female</td>
<td>50</td>
<td>97.16</td>
<td>8.08</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>55</td>
<td>101.04</td>
<td>8.05</td>
<td>1.09</td>
</tr>
<tr>
<td>ConB</td>
<td>Female</td>
<td>45</td>
<td>117.08</td>
<td>9.29</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>49</td>
<td>120.17</td>
<td>7.65</td>
<td>1.09</td>
</tr>
<tr>
<td>L1</td>
<td>Female</td>
<td>84</td>
<td>104.22</td>
<td>6.13</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>87</td>
<td>109.58</td>
<td>7.73</td>
<td>0.83</td>
</tr>
<tr>
<td>Bl</td>
<td>Female</td>
<td>83</td>
<td>79.35</td>
<td>4.92</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>87</td>
<td>85.28</td>
<td>5.93</td>
<td>0.64</td>
</tr>
<tr>
<td>Bh</td>
<td>Female</td>
<td>84</td>
<td>29.66</td>
<td>2.87</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>87</td>
<td>32.56</td>
<td>3.42</td>
<td>0.37</td>
</tr>
<tr>
<td>Rh</td>
<td>Female</td>
<td>84</td>
<td>62.64</td>
<td>5.21</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>89</td>
<td>67.67</td>
<td>5.92</td>
<td>0.63</td>
</tr>
<tr>
<td>L2</td>
<td>Female</td>
<td>80</td>
<td>79.33</td>
<td>5.97</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>86</td>
<td>83.93</td>
<td>6.63</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Table 6.1.10: Mean measurements with significant sexual dimorphism for Post-Medieval individuals. Table illustrating the mean mandible measurements and standard deviation for males and females at Post-Medieval sites in Britain.
Table 6.1.11: t-test results for Post-Medieval sex differences. Independent samples t-test showing that between males and females mean differences in mandible measurements were significantly different.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>F</th>
<th>Sig.</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
<th>(2-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CorB</td>
<td>0.01</td>
<td>.94</td>
<td>-2.46</td>
<td>103</td>
<td>.016</td>
<td></td>
</tr>
<tr>
<td>L1 Equal variances assumed</td>
<td>6.52</td>
<td>.01</td>
<td>-5.01</td>
<td>169</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>L1 Equal variances not assumed</td>
<td></td>
<td></td>
<td>-5.03</td>
<td>162.86</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>Bl Equal variances assumed</td>
<td>1.29</td>
<td>.26</td>
<td>-7.08</td>
<td>168</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>Bh Equal variances assumed</td>
<td>2.67</td>
<td>.10</td>
<td>-5.99</td>
<td>169</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>Rh Equal variances assumed</td>
<td>0.47</td>
<td>.49</td>
<td>-5.92</td>
<td>171</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>L2 Equal variances assumed</td>
<td>0.06</td>
<td>.81</td>
<td>-4.69</td>
<td>164</td>
<td>.000</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.1.16: Sex differences in mandible measurements among Post-Medieval individuals. Bar graph illustrating the difference in range for mandible measurements. Whiskers illustrate the standard error.
Figure 6.1.17: Post-Medieval mandible measurements histograms. Males are shown in green and females in blue for coronoid breadth (CorB), length 1 (L1), body height (Bh), length 2 (L2), condyle breadth (ConB), ramus height (Rh) and body length (Bl).
6.1.2 7. Sexual Dimorphism
Sexual dimorphism was calculated as a percentage using the formula shown in figure 6.1.18 below. It was determined that among the entire sample ramus height and body height were the most sexually dimorphic measurements (figure 6.1.19). When sexual dimorphism in mandible measurements was compared across time periods considerable variation was apparent (figure 6.1.20). Neolithic measurements showed the greatest amount of variation in sexual dimorphism between measurements, which was expected due to the low sample size of sexed Neolithic mandibles. There was no obvious pattern between the measurements with any one period having consistently higher or lower sexual dimorphism for all measurements. Instead it is apparent that sexual dimorphism varied considerably over time.

\[
\frac{\text{male mean} - \text{female mean}}{\text{female mean}} \times 100
\]

**Figure 6.1.18:** Calculation used for sexual dimorphism (S Hillson, personal communication 2018)

**Figure 6.1.19:** Sexual Dimorphism mandible measurements. This graph illustrates that the highest sexual dimorphism was recorded in ramus and body height and the lowest sexual dimorphism in condyle breadth.
Figure 6.1.20: Sexual Dimorphism in mandible measurements for each time period. This graph illustrates that sexual dimorphism varied over time and between measurements.
6.1.3 How do mandible measurements vary between dental wear groups? Mean mandible measurements were found to vary significantly between dental wear groups (appendix 4.3.1 – 4.3.4), however this is likely heavily influenced by the decrease in dental wear over time which was recorded among the periods analysed. As such further analysis was conducted to determine if mandible measurements differed significantly between dental wear groups when analysed by period and sex estimation group.

An ANOVA (table 6.1.12) determined that there were significant differences in wear groups within the Roman, Medieval and Post-Medieval periods for both males and females. It was found that it was not the same mandible measurements that varied significantly with wear group, for instance among Roman females Length I and ramus height were significantly different between wear groups, while for Roman males condylar breadth, coronoid breadth, ramus height and Length I were all significantly different. Among Medieval individuals condylar breadth for females and Length I for males varied significantly between different wear groups. While for Post-Medieval individuals coronoid breadth for females and condylar breadth for males differed significantly with wear group.
Table 6.1.12: ANOVA dental wear groups and mandible measurements. ANOVA table detailing the mandible measurements which were found to be significantly different between dental wear groups when analysed within time periods and sex estimation groups (p<0.05).

<table>
<thead>
<tr>
<th>Period</th>
<th>Sex</th>
<th>Measurement</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roman</td>
<td>Female</td>
<td>L1</td>
<td>Between Groups</td>
<td>962.79</td>
<td>8</td>
<td>120.35</td>
<td>3.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>928.16</td>
<td>26</td>
<td>35.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1890.96</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rh</td>
<td></td>
<td></td>
<td>Between Groups</td>
<td>644.65</td>
<td>8</td>
<td>80.58</td>
<td>3.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>691.72</td>
<td>26</td>
<td>26.61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1336.36</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>CorB</td>
<td>Rh</td>
<td>Between Groups</td>
<td>1373.07</td>
<td>8</td>
<td>171.63</td>
<td>4.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>376.92</td>
<td>9</td>
<td>41.88</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1749.99</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rh</td>
<td></td>
<td></td>
<td>Between Groups</td>
<td>483.89</td>
<td>8</td>
<td>60.49</td>
<td>3.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>459.92</td>
<td>23</td>
<td>19.99</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>943.82</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ConB</td>
<td></td>
<td></td>
<td>Between Groups</td>
<td>893.54</td>
<td>7</td>
<td>127.65</td>
<td>3.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>606.66</td>
<td>16</td>
<td>37.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1500.19</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td></td>
<td>ConB</td>
<td>Between Groups</td>
<td>1710.88</td>
<td>10</td>
<td>171.09</td>
<td>3.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>2658.17</td>
<td>50</td>
<td>53.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>4369.05</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medieval</td>
<td>Females</td>
<td>ConB</td>
<td>Between Groups</td>
<td>893.540</td>
<td>7</td>
<td>127.65</td>
<td>3.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>606.66</td>
<td>16</td>
<td>37.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1500.19</td>
<td>23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

276
<table>
<thead>
<tr>
<th>Period</th>
<th>Sex</th>
<th>Measurement</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Males</td>
<td>L1</td>
<td>Between Groups</td>
<td>1710.88</td>
<td>10</td>
<td>171.09</td>
<td>3.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>2658.17</td>
<td>50</td>
<td>53.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>4369.05</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td>CorB</td>
<td>Between Groups</td>
<td>1100.45</td>
<td>7</td>
<td>157.21</td>
<td>2.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>1759.73</td>
<td>29</td>
<td>60.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>2860.17</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ConB</td>
<td>Males</td>
<td></td>
<td>Between Groups</td>
<td>746.98</td>
<td>9</td>
<td>82.99</td>
<td>2.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Within Groups</td>
<td>1222.90</td>
<td>37</td>
<td>33.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1969.89</td>
<td>46</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2 3D Geometric Morphometrics
As the previous sections have illustrated there is evidence of dietary change in Britain over time. Additionally, traditional measurements have shown that there were significant changes in mandible size over time.

3D geometric morphometric analysis was conducted to determine if these results further support evidence that mandible morphology has changed over time in Britain. This analysis is separated into size determined by centroid size, and shape which will be analysed by Canonical Variate Analysis (CVA). While the majority of previous geometric morphometric studies only utilise Principal Component Analysis (PCA) when analysing more complex shape changes and when investigating group differences CVA has been suggested to be more valuable (MacLeod 2018). When PCA and CVA were analysed in this present study PCA was found to be ineffective at investigating shape differences in the mandible, producing a large number of principal components each representing minimal shape changes that were difficult to observe and qualify.

6.2.1 Time period: how does mandible morphology vary over time among males and females?
Among females centroid size was found to vary significantly between time periods, however among males there was no such significant difference in centroid size shown in table 6.2.1 (appendix 5 table 5.1.1-5.1.3). A Bonferroni post hoc test was conducted to determine among which periods there was significant variation in centroid size (table 6.2.2). This revealed that Post-Medieval females had a significantly smaller centroid size compared with females from the Neolithic, Roman and Anglo-Saxon sites (appendix 5 table 5.1.4-5.17). Despite the lack of significant differences in centroid size, a leave-one-out cross validation analysis showed a high accuracy rate for classifying time period among both males and females as shown in table 6.2.3 and 6.2.4.
Table 6.2.1: ANOVA illustrating female differences over time. ANOVA table illustrating that among females there was a significant difference in centroid size between time periods ($p<0.00$).

<table>
<thead>
<tr>
<th>Sex</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>6016.39</td>
<td>9</td>
<td>1203.28</td>
<td>4.91</td>
<td>.000</td>
</tr>
<tr>
<td>Between Groups</td>
<td>65306.23</td>
<td>259</td>
<td>245.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>69522.62</td>
<td>264</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2.2: Bonferroni illustrating female differences over time. Results from a Bonferroni test showing that significant differences in centroid size occurred between females from the Post-Medieval period and females from the Neolithic, Roman and Anglo-Saxon periods.

<table>
<thead>
<tr>
<th>(I) Period</th>
<th>(J) Period</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error (I-J)</th>
<th>Sig.</th>
<th>95% Confidence Interval Lower Bound</th>
<th>95% Confidence Interval Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Medieval</td>
<td>Neolithic</td>
<td>-25.84</td>
<td>7.99</td>
<td>.02</td>
<td>-49.54 -2.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roman</td>
<td>-10.79</td>
<td>3.05</td>
<td>.01</td>
<td>-19.83 -1.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anglo-Saxon</td>
<td>-9.30</td>
<td>3.02</td>
<td>.04</td>
<td>-18.26 -3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medieval</td>
<td>-4.99</td>
<td>2.55</td>
<td>.78</td>
<td>-12.56 2.58</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2.3: Leave-one-out cross validation analysis time periods for males. Results from a leave-one-out cross validation analysis with an overall classification accuracy: 84.5% for centroid size among males from different time periods.

<table>
<thead>
<tr>
<th>Neolithic</th>
<th>Bronze/Iron Age</th>
<th>Roman</th>
<th>Anglo-Saxon</th>
<th>Medieval</th>
<th>Post-Medieval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neolithic</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bronze/Iron Age</td>
<td>0</td>
<td>34</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Roman</td>
<td>0</td>
<td>0</td>
<td>34</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>39</td>
<td>2</td>
</tr>
<tr>
<td>Medieval</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>73</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 6.2.4: Leave-one-out cross validation analysis time periods for females. Results from a leave-one-out cross validation analysis with an overall classification accuracy: 87.9% for centroid size among females from different time periods.

<table>
<thead>
<tr>
<th>Neolithic</th>
<th>Bronze/Iron Age</th>
<th>Roman</th>
<th>Anglo-Saxon</th>
<th>Medieval</th>
<th>Post-Medieval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neolithic</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bronze/Iron Age</td>
<td>0</td>
<td>25</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Roman</td>
<td>0</td>
<td>0</td>
<td>36</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td>0</td>
<td>0</td>
<td>33</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Medieval</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>57</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>4</td>
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CVA was conducted to analyse morphological differences between time periods for males and females separately. Among males CV1 decreases from the Neolithic through to the Roman males, before increasing again among Anglo-Saxon males, Post-Medieval males had the highest CV1 score, which was significantly greater than the Bronze and Iron Age, Roman and Anglo-Saxon males (figure 6.2.1 and figure 6.2.3). CV2 score shows a gradual increase over time apart from the Roman period which has the highest CV2 scores and is significantly higher than all other periods (figure 6.2.1. and figure 6.2.4).

CV3 mostly acts to separate out the Neolithic males, while Bronze and Iron Age and Medieval individuals have a very similar CV3 score and Roman and Post-Medieval males having a similar CV3 score (figure 6.2.2 and figure 6.2.5). There was less variation in CV4 score between males from different time periods with the highest score among Neolithic and Bronze and Iron Age individuals, followed by Post-Medieval males, while Roman, Anglo-Saxon and Medieval males had a very similar CV4 score (figure 6.2.2 and figure 6.2.6).

Finally, CV5 mostly separates out males from the Neolithic which have the highest CV5 score, significantly greater than all other periods, and Anglo-Saxon males which had the lowest CV5 score which was also significantly different (figure 6.2.7).
Figure 6.2.1: CVA for males over time (CV1 and CV2). Convex hull graph illustrating CV1 (representing 30.8% of total variation) and CV2 (representing 19.2% of total variation) among males for each time period analysed. This shows that among males, Roman individuals showed the greatest separation for CV1 and CV2. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates (Neolithic = red, Bronze and Iron Age = orange, Roman = yellow, Anglo-Saxon = green, Medieval = blue, Post-Medieval = purple/indigo).
Figure 6.2.2: CVA for males over time (CV3 and CV4). Convex hull graph illustrating CV3 (representing 18.7% of total variation) and CV4 (representing 15.7% of total variation) among males for each time period analysed. This shows that among males, Neolithic individuals showed the greatest separation for CV3 and CV4. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates (Neolithic = red, Bronze and Iron Age = orange, Roman = yellow, Anglo-Saxon = green, Medieval = blue, Post-Medieval = purple/indigo).
Figure 6.2.3: CV1 for males over time. Box and Whisker graph illustrating the CV1 score (representing 30.8% of total variation) among males from each time period, with Post-Medieval males having the highest CV1 score and Roman males the lowest. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

A high CV1 score such as that of the Post-Medieval males was associated with a more gracile mandible, a wider gonial angle, shorter mandibular body, taller ramus, deeper mandibular notch and a less curved anterior and posterior border of the ramus. Conversely a negative CV1 score is associated with a more robust mandible with a taller mandibular body, more prominent gonial angle, shorter and wide ramus, shallow mandibular notch and curved anterior and posterior border of the ramus (figure 6.2.3).
Figure 6.2.4: CV2 for males over time. Box and Whisker graph illustrating the CV2 score (representing 19.2% of total variation) among males from each time period, with Roman males having the highest CV2 score and Neolithic males the lowest. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

Roman males with a high CV2 score generally had a mandible which had a wider gonial angle, more prominent mental eminence, taller coronoid and narrower ramus, with Neolithic males with a low CV2 score typically had a shorter mandibular body, wider ramus more anteriorly projecting coronoid process and taller condyle (figure 6.2.4).
Figure 6.2.5: CV3 for males over time. Box and Whisker graph illustrating the CV3 score (representing 18.8% of total variation) among males from each time period, Neolithic males had the highest CV3 score while Medieval and Bronze/Iron Age males had the lowest. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

A low CV3 score is associated with a more gracile mandible, that has a shorter mandibular body, wider although still prominent gonial angle, shorter and wider ramus which flares laterally. While a high CV3 scores of the Neolithic males is associated with a more robust mandible, with a deeper mandibular body, taller and straighter ramus, narrower gonial angle, and deeper mandibular notch (figure 6.2.5).
Figure 6.2.6: CV4 for males over time. Box and Whisker graph illustrating the CV4 score (representing 15.7% of total variation) among males from each time period, Bronze/Iron Age males had the highest CV4 score and Medieval males had the lowest score. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

A low CV4 score corresponds to a wider mandible, which a narrower gonial angle, wider ramus, wider coronoid process and a prominent gonial angle. A low CV4 score such as the Bronze and Iron Age males had a wider gonial angle, narrower mandible, narrower and more gracile ramus and deep mandibular notch (figure 6.2.6).
Figure 6.2.7: CV5 for males over time. Box and Whisker graph illustrating the CV5 (representing 15.4% of total variation) score among males from each time period. Neolithic males had the highest CV5 score while Anglo-Saxon males had the lowest. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

A low CV5 score corresponded to a mandible shape where the coronoid process projects anteriorly away from the condyle creating an increased distance between these two landmarks, small condyles and generally a wide mandible while high CV5 score is associated with a narrow more angular mandible, wide condyles and smaller distance between the coronoid and condyle (figure 6.2.7).
Figure 6.2.8: CVA for females over time (CV1-CV2). Convex hull graph illustrating CV1 (representing 29.2% of total variance) and CV2 (representing 25.1% of total variance) among females for each time period analysed. This shows that among females, Neolithic individuals showed the greatest separation for CV1 and CV2. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates (Neolithic= red, Bronze and Iron Age = orange, Roman = yellow, Anglo-Saxon = green, Medieval = blue, Post-Medieval = purple/indigo).

When mandible morphology was analysed over time among the females from this study there is less of a clear pattern in convex hulls for CV1 and CV2 (figure 6.2.8). Among females CV1 decreases over time, with Neolithic individuals having the highest CV1 score, significantly different from all of the other periods. From the Bronze and Iron Age CV1 decreases gradually over time, with no significant differences between adjacent periods however there are significant differences in CV1 score between non-adjacent time periods (figure 6.2.10). For instance, the CV1 score for Bronze and Iron Age females is significantly different from Anglo-Saxon and later periods, but not from the Roman females. CV2 shows significant differences occurred between Anglo-Saxon and Medieval

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females, and Bronze and Iron Age, Roman and Post-Medieval (figure 6.2.11). CV3 mostly acts to separate out the Neolithic females which have a high CV3 score followed by Anglo-Saxon and then Post-Medieval females, while Bronze and Iron Age, Roman and Medieval females show no significant differences females (figure 6.2.9 and figure 6.2.12). CV 4 illustrates Bronze and Iron Age females had the lowest CV4 score, significantly lower than all other periods, followed by Anglo-Saxon, Medieval, and Post-Medieval individuals which showed little variation between them. CV4 score was highest among Neolithic and Roman females and this was significantly higher than most other periods (figure 6.2.9 and figure 6.2.13). Finally, CV5 score is lowest among Neolithic, Medieval and Post-Medieval females (figure 6.2.14).

Figure 6.2.9: CVA for females over time (CV3-CV4). CVA graph illustrating CV3 (representing 15.2% of total variance) and CV4 (representing 12.5% of total variance) among females for each time period analysed. This shows that among females Neolithic individuals showed the greatest separation for CV3 and CV4. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates (Neolithic= red, Bronze and Iron Age = orange, Roman = yellow, Anglo-Saxon = green, Medieval = blue, Post-Medieval = purple/indigo).
Figure 6.2.10: CV1 for females over time. Box and Whisker graph illustrating the CV1 score (representing 29.1% of total variance) among females from each time period, showing Neolithic females had the highest CV1 score and Post-Medieval females had the lowest. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

CV1 score decreases over time illustrating a progression to a more gracile mandible form, with Neolithic individuals having a higher CV1 score which is associated with a more robust mandible with taller mandibular body, narrower and more prominent gonial angle, wider and shorter ramus and a wider coronoid process. Over time as CV1 score decreases mandible form becomes more gracile, with a thinner mandibular body, narrower and taller ramus that flares laterally and wider gonial angle (figure 6.2.10).
Figure 6.2.11: CV2 for females over time. Box and Whisker graph illustrating the CV2 score (representing 25.11% of total variance) among females from each time period, showing significant fluctuation between time periods. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

CV2 fluctuates between time periods, with a high CV2 score such as Bronze and Iron Age and Post-Medieval females has a more gracile, narrower appearance with a wider gonial, shorter mandibular body, narrower ramus. While a low CV2 such as Medieval and Anglo-Saxon females denote a more robust, wider mandible with a more prominent and narrower gonial angle tall mandibular body and wide ramus (figure 6.2.11).
Figure 6.2.12: CV3 for females over time. Box and Whisker graph illustrating the CV3 score (representing 17.9% of total variance) among females from each time period, showing Neolithic females had the highest CV3 score. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

There are fewer clear differences in mandible morphology between a high and low CV3 score. A low CV3 score results in a wider mandible, both in the body of the mandible and the ramus, with the rami flaring laterally, creating a greater bicondylar width. While the body of the ramus is not wider (anterior to posterior), the distance between the coronoid process and the condyle is greater, with the condyle projecting posteriorly and the coronoid anteriorly. Conversely a high CV3 score such as that of Neolithic females is associated with a narrower mandible, and smaller distance between the coronoid process and condyle (figure 6.2.12).
**Figure 6.2.13: CV4 for females over time.** Box and Whisker graph illustrating the CV4 score (representing 15.2% of total variance) among females from each time period, with the lowest CV4 score among Bronze and Iron Age females. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

A high CV4 score is associated with a wider mandible, smaller distance between the coronoid process and condyle and a less prominent gonial angle. While a low CV4 score such as Bronze and Iron Age females is associated with a more prominent gonial angle, anterior projecting coronoid and posterior condyle creating a wider distance between the coronoid process and the mandibular condyle (**figure 6.2.13**).
Figure 6.2.14: CV5 for females over time. Box and Whisker graph illustrating the CV5 score (representing 12.5% of total variance) among females from each time period, with the lowest score among Neolithic females. Visualisations are superimposed on the scatter graphs which show mandible morphology at +15 and -15 for the Canonical Variates and whiskers illustrate the standard error in CV score.

A low CV5 score corresponds to a wider mandible, with a lower mandibular body, more oblique gonial angle, and a greater distance between the coronoid process and condyle. Conversely a high CV5 score results in a taller mandibular body and narrower gonial angle (figure 6.2.14).
6.2.2 Time period: how does mandible morphology vary over time?
While centroid size and mandibular measurements need to be analysed among sex estimation and dental groups, the nature of CVA in explaining differences between groups allows for analysis of differences between time periods for males, females and individuals of uncertain sex combined. CVA was first conducted to analyse how mandible morphology varied between all time periods, while later analysis worked to compare just two time periods. The canonical variates which accounted for temporal variation were analysed among known sex estimation groups. It was determined that there was no significant difference in CV score and sex estimation groups (appendix 5 table 5.2.1 and 5.2.2). As such it was determined acceptable to analyse all sex estimation groups together.

CVA analysis was conducted to investigate how mandible morphology changes over time in Britain (figure 6.2.15-17). Analysis revealed that these shape differences could be explained by five Canonical Variates. CV1 and CV2 (figure 6.2.15) show that among the Post-Medieval (purple/indigo) sample there was a greater level of variation compared to the other time periods, although this variation may well be influenced by the larger sample size. While there is considerable overlapping between the other periods some clear trends are present, for instance the Anglo Saxon and Medieval individuals show similarities in their distribution, while there is less similarity between the distribution of Roman and Anglo-Saxon individuals, with more similarity between Anglo-Saxon and Bronze and Iron Age individuals.

When considering the shape differences explained by the Canonical Variates and illustrated in the superimposed visualisations, the +5 CV1 visualisations show a mandible which has a more angular arcade compared to -5 CV1 where the arcade is a wider U-shape. +5 CV1 also has a more prominent mental eminence, lower condyle, higher coronoid, more prominent gonial angle and taller mandibular body compared to -5 CV1. The +5 CV2 visualisation shows a more prominent but also more acute gonial angle resulting in a ramus that is tilted anteriorly, compared to -5 CV2 where the gonial angle is oblique resulting in a ramus that projects anteriorly and a mandible that has a long stretched out appearance. +5 CV2 also shows a mandible with a wider ramus, more curved coronoid,
shallower mandibular notch and a taller mandibular body that is shorter in antero-posterior length compared to the -5 CV2 image.

Figure 6.2.15: CVA over time (CV1-CV2). Scatter graph with convex hulls showing the variation between time periods for CV1 (representing 33.4% of total variance) and CV2 (representing 24.8% of total variance) (Neolithic= red, Bronze and Iron Age = orange, Roman = yellow, Anglo-Saxon = green, Medieval = blue, Post-Medieval = purple/indigo). Visualisations are superimposed on the scatter graphs which show mandible morphology at +5 and -5 for the Canonical Variates. Sex estimation is also depicted by the symbols (x= male, o= females and ● = unknown).

When considering how CV3 and CV4 (figure 6.2.16) explain shape differences between periods there is considerable overlap among periods along the CV4 axis with little variation between the centroid for all of these periods. The greatest variation appears to be in the Anglo-Saxon period but this is due to just one individual. It was considered that this individual may reflect an error in the landmarking or estimation of missing landmarks process however this was investigated by visualising the scan and landmarks for this individual and no error could be detected leading to the assumption that this just represents an outlier. CV3 acts to separate the Neolithic individuals from all other periods.
which group closely along this axis, while there is little overlap between Neolithic individuals and all other periods.

The visualisations show that for -5 CV3 the mandibular body was shorter both in height and anterior-posteriorly, the ramus is narrower anterior-posteriorly and the anterior border of the ramus and coronoid process is more curved compared to +5 CV3. +5 CV4 which shows a mandible with a narrower more angular dental arcade, longer more obtuse gonial angle and shorter mandibular body, compared to the -5 CV4 where the dental arcade is wider and more U-shaped, the ramus is wider anterior-posteriorly, the gonial angle is more robust and prominent, the mandibular notch is shallower, and the anterior surface of the ramus and coronoid process is more curved.

Figure 6.2.16: CVA over time (CV3-CV4). Scatter graph with convex hulls showing the variation between time periods for CV3 (representing 15.3% of total variance) and CV4 (representing 14.4% of total variance) (Neolithic= red, Bronze and Iron Age = orange, Roman = yellow, Anglo-Saxon = green, Medieval = blue, Post-Medieval = purple/indigo). Visualisations are superimposed on the scatter graphs which show mandible morphology at +5 and -5 for the Canonical Variates. Sex estimation is also depicted by the symbols (x= male, o= females and ● = unknown).
Figure 6.2.17: CVA over time (CV4-CV5). Scatter graph with convex hulls showing the variation between time periods for CV4 (representing 14.4% of total variance) and CV5 (representing 12.1% of total variance) (Neolithic= red, Bronze and Iron Age = orange, Roman = yellow, Anglo-Saxon = green, Medieval = blue, Post-Medieval = purple/indigo). Visualisations are superimposed on the scatter graphs which show mandible morphology at +5 and -5 for the Canonical Variates. Sex estimation is also depicted by the symbols (x= male, o= females and ● = unknown).
**Figure 6.2.18: CV1 over time.** Box and Whisker plot showing the CV1 score which explains 33.4% of the variation over time, this is illustrated for each time period analysed with super imposed visualisations illustrating the shape changes at +5 and -5 CV1. Whiskers illustrate the standard error in CV score.

In order to better understand the shape changes between periods, each CV was analysed separately in a Box and Whisker plot (figure 6.2.18 -6.2.22). These results illustrate that for CV1 there is a decrease over time from Neolithic through to Post-Medieval with a significant decrease between Neolithic and Bronze/Iron Age individuals, after which there is no significant difference between Bronze/Iron Age, Roman and Anglo-Saxon individuals, followed by a slight decrease to Medieval and Post-Medieval individuals. A high CV1 score corresponds to a narrower more acute gonial angle, taller mandibular body and wider ramus resulting in a mandible which generally appears more robust. While a low CV1 score results in a more acute mandible, with a more oblique gonial angle, shorter mandibular body and narrower ramus.
Figure 6.2.19: CV2 over time. Box and Whisker plot showing the CV2 score which explains 24.8% of the variation over time, this is illustrated for each time period analysed with super imposed visualisations illustrating the shape changes at +5 and -5 CV2. Whiskers illustrate the standard error in CV score.

Results show that there were similarities among Neolithic, Anglo-Saxon and Medieval individuals for CV2 with Bronze and Iron Age, Roman and Post-Medieval individuals having a significantly higher CV2 score. A high CV2 score is associated with a mandible with a taller mandibular body and a coronoid that projects superiorly rather than anteriorly, while a low CV2 mandible is more likely to have a reduced height of the mandibular body and a more anteriorly projecting coronoid process.
Figure 6.2.20: CV3 over time. Box and Whisker plot showing the CV3 score which explains 15.3% of the variation over time, this is illustrated for each time period analysed with super imposed visualisations illustrating the shape changes at +5 and -5 CV3. Whiskers illustrate the standard error in CV score.

CV3 score was found to fluctuate between each of the periods, being lower among the Neolithic, Roman and Medieval individuals. There are similarities in the shape associated with CV2 and that CV3. A high CV3 score is associated with a mandible with a taller mandibular body, lower condyle and a coronoid that projects superiorly rather than anteriorly, while a low CV2 mandible is more likely to have a reduced height of the mandibular body and a more anteriorly projecting coronoid process.
Figure 6.2.21: CV4 over time. Box and Whisker plot showing the CV4 score which explains 14.4% of the variation over time, this is illustrated for each time period analysed with super imposed visualisations illustrating the shape changes at +5 and -5 CV4. Whiskers illustrate the standard error in CV score.

Among CV4 there was only a significant difference in the Neolithic individuals and the other periods. There is little obvious variation between the high and low CV4 visualisation with a high CV4 score generally corresponding to a narrower mandible with a smaller bicondylar breadth, while mandibles with a low CV4 score are wider with a greater bi-condylar breadth.
Figure 6.2.22: CV5 over time. Box and Whisker plot showing the CV5 score which explains 12.1% of the variation over time, this is illustrated for each time period analysed with super imposed visualisations illustrating the shape changes at +5 and -5 CV5. Whiskers illustrate the standard error in CV score.

There were less clear differences between CV5 scores, although CV5 was lowest among Roman and Anglo-Saxon individuals, this was slightly higher among Medieval and Post-Medieval and significantly higher among Neolithic and Bronze and Iron Age individuals. Regarding shape changes a low CV5 score corresponds to a taller mandible body and ramus, while a high CV5 scores is associated with a more laterally flared ramus which appears shorter.
6.2.2.1 Individual Period Comparisons
Because CVA works by investigating group differences, in order to more precisely compare individual periods it is necessary to conduct separate CVA for each period comparison. Each period was compared with males, females and unknown sex individuals grouped together. Visualisation were created at +15 and -15 CV1 for all comparisons to ensure consistency in the visualisations, this resulted in more dramatic shape differences for some periods comparisons while for comparisons between adjacent periods shape differences from these visualisation were not as prominent. It was determined that the CV score which acted to separate the temporal periods did not significantly differ from between males and females (appendix 5 table 5.2.3-5.2.16)

*Neolithic and Iron and Bronze Age Comparisons*

Figure 6.2.23: CVA Neolithic and Bronze and Iron Age comparison. Box and Whisker plot showing the differences between Neolithic (N) and Bronze and Iron Age (I) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.
CVA was conducted to determine how mandible morphology varies between individual periods, Box and Whisker plots were created to illustrate these results and in each case visualisations were created to show exaggerated shape changes at +15 and -15 CV1. When comparing Neolithic and Bronze and Iron Age individuals clear morphological differences are evident in the visualisations for +15 and -15 CV1 (figure 6.2.23). Neolithic individuals with a negative CV1 score have a deeper mandibular body, larger more prominent gonial angle that is more acute so that the posterior of the mandibular ramus is tilted anteriorly. The mandibular ramus among Neolithic individuals is also wider anteriorly-posteriorly and has a wider dental arcade. Conversely Bronze and Iron Age individuals had a shorter mandibular body, narrower ramus more oblique gonial angle and narrower dental arcade.
Neolithic and Roman Comparisons

Figure 6.24: CVA Neolithic and Roman comparison. Box and Whisker plot showing the differences between Neolithic (N) and Roman (R) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

The comparison between Neolithic and Roman individuals showed similar morphological differences as between Neolithic and Bronze and Iron Age individuals, although these differences were less pronounced. Neolithic individuals with a negative CV1 score have a deeper mandibular body, larger more prominent gonial angle that is more acute so that the posterior of the mandibular ramus is tilted anteriorly. The mandibular ramus among Neolithic individuals is also wider anteriorly-posteriorly and has a wider dental arcade. Conversely Roman individuals had a shorter mandibular body, narrower ramus, more oblique gonial angle and narrower dental arcade (figure 6.2.24).
Figure 6.2.25: CVA Neolithic and Anglo-Saxon comparison. Box and Whisker plot showing the differences between Neolithic (N) and Anglo-Saxon (A) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

When analysing the differences in mandible morphology between Neolithic and Anglo-Saxon individuals this differs from the previous Neolithic comparisons. Among Anglo-Saxon individuals the mandibular body was shorter and ramus narrower, with a condyle higher than the coronoid process, reduced gonial angle, and a deep mandibular notch. In comparison the Neolithic individuals have a taller mandibular body, the ramus is wider anterior to posterior, the condyle is also lower compared to the coronoid process, the mandibular notch is slightly shallower and wider and the gonial angle is more pronounced (figure 6.2.25).
When analysing the differences in mandible morphology between Neolithic and Medieval individuals morphological variation between these periods were similar to that of the Bronze and Iron Age and Roman. Neolithic individuals with a negative CV1 score have a deeper mandibular body, a larger more prominent gonial angle that is more acute so that the posterior of the mandibular ramus is tilted anteriorly. The mandibular ramus among Neolithic individuals is also wider anteriorly-posteriorly and has a longer anterior to posterior dental arcade. Conversely Anglo-Saxon individuals had a shorter mandibular body, narrower ramus more oblique gonial angle and shorter anterior to posterior dental arcade (figure 6.2.26).
When analysing the differences in mandible morphology between Neolithic and Post-Medieval individuals, variation is similar to previous periods but more pronounced. Neolithic individuals with a negative CV1 score have a deeper mandibular body, larger more prominent gonial angle that is more acute so that the posterior of the mandibular ramus is tilted anteriorly. The mandibular ramus among Neolithic individuals is also wider anteriorly-posteriorly, more curved along the anterior of the ramus and coronoid process and has a longer anterior to posterior dental arcade. Conversely Post-Medieval individuals had a shorter mandibular body, narrower ramus, more oblique gonial angle and shorter anterior to posterior dental arcade (figure 6.2.27).
When analysing the differences in mandible morphology between Bronze and Iron Age and Roman individuals it was found that Roman individuals had a more robust mandible. In addition to a wider more robust mandible, Romans had a taller mandibular body, and wider ramus, low condyle and comparatively higher coronoid process, and robust gonial angle, while Bronze and Iron Age individuals had a narrower more gracile mandible, with a shorter and longer mandibular body, narrower and taller mandibular ramus, with a coronoid that was low compared to the condyle (figure 6.2.28).
Figure 6.29: CVA Bronze and Iron Age and Anglo-Saxon comparison. Box and Whisker plot showing the differences between Bronze and Iron Age (I) and Anglo-Saxon (A) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

A comparison between Bronze and Iron Age individuals revealed that compared to Bronze and Iron Age individuals. Anglo-Saxon individuals had a wider more U-shaped and gracile mandible, while the Bronze and Iron Age individuals had a more robust angular V-shaped dental arcade. The Anglo-Saxon individuals also had a more curved inferior border, so that the base of the mandible is almost convex. The mandibular ramus is narrower anterior to posterior, and the mandibular condyle is slightly taller than the coronoid and a gonial angle that is less pronounced. Bronze and Iron Age individuals conversely have a pronounced mental eminence, wider and shorter ramus and taller mandibular ramus (figure 6.2.29).
Figure 6.2.3: CVA Bronze and Iron Age and Medieval comparison. Box and Whisker plot showing the differences between Bronze and Iron Age (I) and Medieval (M) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

When Bronze and Iron Age and Medieval individuals were compared, Medieval individuals had a more gracile and wider U-shaped mandible, while Bronze and Iron Age individuals had a more robust and angular V-shaped mandible. Medieval individuals had a taller and narrower ramus anterior to posterior, shallow mandibular notch, oblique gonial angle, and a shorter mandibular body. In comparison, Bronze and Iron Age individuals had a tall mandibular body, short and wide mandibular ramus and deep mandibular notch (figure 6.2.30).
Bronze and Iron Age and Post-Medieval Comparisons

Figure 6.2.31: CVA Bronze and Iron Age and Post-Medieval comparison. Box and Whisker plot showing the differences between Bronze and Iron Age (I) and Post-Medieval (P) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

There were pronounced differences between the visualisations for CV1 for Bronze and Iron Age and Post-Medieval individuals, with Post-Medieval individuals having a more gracile mandible compared to the more robust Bronze and Iron Age individuals. The Post-Medieval individuals had a shorter mandible body, narrower and taller ramus, wider gonial angle, shallower mandibular notch, straighter anterior ramus/coronoid with very little curvature along the anterior border. In comparison the Bronze and Iron Age individuals had a taller mandibular body with a shorter and wider ramus, pronounced gonial angle with a more acute angle compared to the Post-Medieval individuals, the anterior border of the ramus and coronoid process was also more curved with a strong anterior and posterior curve forming an S-shape (figure 6.2.31).
Roman and Anglo-Saxon Comparisons

**Figure 6.2.32: CVA Roman and Anglo-Saxon comparison.** Box and Whisker plot showing the differences between Roman (R) and Anglo-Saxon (A) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

The Roman mandibles were more robust compared to the Anglo-Saxon, although the most obvious morphological differences were in the ramus, condyle and coronoids. Roman individuals typically had a taller mandibular body, more pronounced gonial angle and wider and short ramus, the condyles are lower than the coronoid process and an anterior border is curved. The Anglo-Saxon mandible compared to the Roman have a shorter mandibular, reduced gonial angle, a narrower and taller mandibular ramus with a condyle which is taller than the coronoid process which is angled slightly anterior and towards the inferior (figure 6.2.32).
Roman and Medieval Comparisons

**Figure 6.2.33: CVA Roman and Medieval comparison.** Box and whisker plot showing the differences between Roman (R) and Medieval (M) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

Compared to the Medieval individuals, Romans again had a more robust mandible with a taller mandibular body, wider and short ramus, pronounced gonial angle, short condyles comparative to the coronoid process. While the Medieval individuals had a wide mandibular body, that was shorter, a narrow ramus, wide condyles which were taller than the coronoid process, the coronoid process was narrow and angular and tilted slightly to the anterior and inferior (figure 6.2.33).
**Figure 6.2.34: CVA Roman and Post-Medieval comparison.** Box and Whisker plot showing the differences between Roman (R) and Post-Medieval (P) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

There were pronounced differences between the Roman and Post-Medieval individuals with Romans once again having a more robust mandible and Post-Medieval having a very gracile mandible. The Roman mandibles typically had a taller mandibular ramus with a comparatively short but wide mandibular ramus and pronounced gonial angle. The condyles and coronoid process were similar in height with both the anterior and posterior border of the ramus being greatly curved. In comparison the Post-Medieval mandibles had a very thin mandibular body, with a tall and narrow ramus and diminished gonial angle, which was more oblique and created a mandible that appeared more elongated. The condyle and coronoid were again of similar height, although the condyles were more rounded and there was little curvature on either the anterior or posterior border of the mandibular ramus (**figure 6.2.34**).
When comparing the Medieval and Anglo-Saxon mandibles there is no obviously more robust or gracile group. Among the Medieval individuals the mandibular body was shorter although the ramus was wide and there was a prominent gonial angle. The ramus flares laterally among the Medieval individuals creating a wide bicondylar length, which is further emphasised by wide mandibular condyles. Among the Anglo-Saxon individuals there is a tall robust mandibular body, fairly gracile gonial angle compared to the Medieval individuals and the ramus flares slightly towards the medial at both the superior and inferior ends, created a smaller bi-condylar length (figure 6.2.35).
Figure 6.2.36: CVA Medieval and Post-Medieval comparison. Box and Whisker plot showing the differences between Medieval (M) and Post-Medieval (P) individuals including superimposed visualisations illustrating the shape changes represented by CV1 at +15 CV and -15CV. Whiskers illustrate the standard error in CV score.

Post-Medieval individuals had a more gracile mandible with a short mandibular body with an oblique gonial angle creating an elongated or stretched appearance to the mandible. There was also little curvature on either the anterior or posterior borders of the ramus with both the condyle and coronoid processes appearing almost as if they were stretched superiorly. In comparison, the Medieval individuals had a more robust mandible, with a mandibular body that appears slightly taller, and a more pronounced gonial angle that is narrower, the mandibular ramus is wider and shorter, with a wide mandibular notch and coronoid process that stretches anteriorly and is heavily curved on the anterior border of the ramus but only slightly curved on the period border of the ramus (figure 6.2.36).
6.2.3 Sex estimation: how does mandible morphology vary between males and females among the entire sample?

Due to the nature of CVA it is possible to investigate how mandible morphology varies between males and females for the entire population, by understanding general morphological differences that occur between males and females, this allows for greater comparison with period specific sex differences in mandible morphology. To determine if these results were influenced by differences between time periods or sites further analysis was conducted, including independent sample t-test and ANOVA which revealed that there are no significant differences in CV1 between time periods or archaeological sites.

Figure 6.2.37: CVA analysis for sex differences. Box and Whisker plot illustrating the CV1 score for males and females among the entire sample analysed, visuals illustrating the mandibular form for -5 CV1 and + 5 CV1 show exaggerated male and female mandible morphologies. Females (F) are shown on the left with a negative CV score and males (M) on right with a positive CV score. Whiskers illustrate the standard error in CV score.
The difference between males and females from the entire sample could be described by one Canonical Variate as illustrated in figure 6.2.37. Female mandibles tended to have a shorter mandibular body, and a shorter ramus which was rotated laterally, condyles which were smaller and more rounded, and a less prominent gonial angle. Conversely males had a straighter more robust ramus, with larger more angular condyles and more prominent gonial angle, the mandibular body is taller and there is a deeper narrower mandibular notch compared to the female. While significant differences were recorded in the mean CV1 for males and females overall, there was considerable overlap in the ranges for CV1.

6.2.4 Sex estimation: how does mandible morphology vary between males and females, within each time period?
Among all periods, males had a greater mean centroid size, with mean centroid size varying significantly between males and females for all periods, with the exception of the Neolithic, although this is likely to be an effect of a small sample size (table 6.2.5). The mean difference between males and females was lowest among the Roman sites and greatest among the Bronze and Iron Age sites. A leave-one-out cross validation analysis was conducted to determine how accurately centroid can be used to identify males and females for each period, results found that in general classification accuracy was very high with all periods after the Neolithic, with >90% classification accuracy, and the Medieval period having 100% classification accuracy for males and females, the results from this analysis are illustrated in table 6.2.6.
Table 6.2.5: t-test for sex differences in centroid size among time periods. Results from an independent sample t-test illustrating sex differences in centroid size for each time period. Significant sex differences were present in all time periods with the exception of Neolithic assemblages.

<table>
<thead>
<tr>
<th>Period</th>
<th>F</th>
<th>Sig.</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron/Bronze Age</td>
<td>.29</td>
<td>.59</td>
<td>-4.31</td>
<td>66</td>
<td>.000</td>
</tr>
<tr>
<td>Roman</td>
<td>.02</td>
<td>.88</td>
<td>-2.29</td>
<td>75</td>
<td>.025</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td>.82</td>
<td>.37</td>
<td>-3.08</td>
<td>87</td>
<td>.003</td>
</tr>
<tr>
<td>Medieval</td>
<td>.33</td>
<td>.57</td>
<td>-6.88</td>
<td>155,000</td>
<td>.000</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>1.65</td>
<td>.20</td>
<td>-8.22</td>
<td>183,000</td>
<td>.000</td>
</tr>
</tbody>
</table>

Table 6.2.6: Classification for sex estimation based on centroid size. Table detailing the classification accuracy of distinguishing between males and females for each period based on centroid size.

<table>
<thead>
<tr>
<th>Period</th>
<th>Classification Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neolithic</td>
<td>77.8%</td>
</tr>
<tr>
<td>Bronze and Iron Age</td>
<td>92.3%</td>
</tr>
<tr>
<td>Roman</td>
<td>94.7%</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td>97.7%</td>
</tr>
<tr>
<td>Medieval</td>
<td>100%</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>95.2%</td>
</tr>
</tbody>
</table>
Figure 6.2.38: CVA for sex differences among the Neolithic. Box plot illustrating the CV1 score for males and females among the Neolithic sites analysed, visuals illustrating the mandibular form for -5 CV1 and +5 CV1 show exaggerated male and female mandible morphologies. Neolithic females (NF) are shown on the left and Neolithic males (NM) on the right, no whiskers were produced for this analysis because the sample size was too small to analyse standard error.

Further analysis was conducted to investigate the morphological differences between males and females for each time period. Among the Neolithic individuals there was little obvious shape change between +5 CV1 and -5 CV1 (figure 6.2.38). Although there were significant differences recorded in CV1 between males and females there is a very small sample size of sexed Neolithic mandibles in the study. Among the observable differences, the mandibular condyles were more rounded among the females and angular among the males. The gonial angle is also more reduced and oblique among females compared to the more robust and prominent gonial angle of the males.
As with the Neolithic samples there was little obvious shape change between +5 CV1 and -5 CV1. Among the observable differences the mandibular condyles were more rounded among the females, and angular among the males. The gonial angle is more reduced and oblique among females, compared to the more robust and prominent gonial angle of the males. The ramus is also narrower anterior to posterior, and the mandibular body is slightly shorter in both height and anterior to posterior length (figure 6.2.39).
6.2.4.3 CVA- Roman

Figure 6.2.40: CVA for sex differences among the Roman. Box and Whisker plot illustrating the CV1 score for males and females among the Roman sites analysed, visuals illustrating the mandibular form for -5 CV1 and +5 CV1 show exaggerated male and female mandible morphologies. Roman females (RF) are shown on the left and Roman males (RM) on the right. Whiskers illustrate the standard error in CV score.

Among the Roman sample there begins to be increased morphological differences between +5 CV1 and -5 CV1 visualisations, the ramus is both shorter, and narrower anterior to posterior, the coronoid process is also smaller and straighter among females while among males the coronoid projects more anteriorly. Among females the ramus flares slightly laterally while among males this is straight. The gonial angle continues to be more pronounced and robust among males and the mandibular body is shorter. While there are some increased sex differences in the Roman sample, some of the sex differences present in the previous periods such as the more angular condyles among males are less apparent in the Roman samples (figure 6.2.40).
6.2.4.4 CVA- Anglo-Saxon

Figure 6.2.41: CVA for sex differences among the Anglo-Saxon. Box and Whisker plot illustrating the CV1 score for males and females among the Anglo-Saxon sites analysed, visuals illustrating the mandibular form for -5 CV1 and + 5 CV 1 show exaggerated male and female mandible morphologies. Anglo-Saxon females (ASF) are shown on the left and Anglo-Saxon males (ASM) on the right. Whiskers illustrate the standard error in CV score.

Among Anglo-Saxon individuals there is a greater difference between the range for CV1 for males and females and there is no overlap in ranges. When considering the visualisations, the mandibular ramus is slightly more flared laterally among females compared to males but this is not as prominent as among the Roman individuals. The ramus is also shorter among females and the mandibular notch is shallower compared to males. The mandibular body is again shorter in both height and anterior-posterior length. As with all other periods the gonial angle is more prominent among males (figure 6.2.41).
6.2.4.5 CVA- Medieval

Figure 6.2.42: CVA for sex differences among the Medieval. Box and Whisker plot illustrating the CV1 score for males and females among the Medieval sites analysed, visuals illustrating the mandibular form for -5 CV1 and + 5 CV 1 show exaggerated male and female mandible morphologies. Medieval females (MF) are shown on the left and Medieval males (MM) on the right. Whiskers illustrate the standard error in CV score.

In the Medieval sample there is once again only slight differences in mandibular condyle morphology between males and females, with males having a slightly more angular condyle compared to females. The ramus also continues to flare slightly laterally among females while among males this is straighter. As with the preceding periods the mandibular body and ramus are both shorter both in height and anterior-posterior length. As with the Anglo-Saxon sample there is no overlap in the ranges for CV1 for Medieval males and females (figure 6.2.42).
6.2.4.6 CVA- Post-Medieval

Among Post-Medieval individuals there is little overlap in the ranges of CV1. When considering the visuals, the flaring of the mandibular ramus among females in comparison with the straighter more vertical ramus of males is more prominent. The mandibular condyles are wider among the males, although not necessarily more angular. The gonial angle continues to differ between males and females, among females the gonial angle is more oblique resulting in a mandible shape that is more stretched and elongated and a ramus that projects more posteriorly. The mandibular notch is also shallower and longer anterior to posterior among females, while among males this is deeper. The mandibular body continues to be shorter in height among females compared to males (figure 6.2.43).
How does mandible morphology vary between individuals of low and high-status burials from the same assemblage?

Centroid size was found not to vary significantly among males and females from high or low status burials at St Gregory’s Cemetery and Priory, although results from a CVA did reveal significant differences in CV1 between males and females illustrated in figure 6.2.44. Low status individuals had a narrower mandible with a high mandibular body, tall ramus, curved inferior border of the mandible, deep mandibular notch, tall and wide coronoid process. Comparatively the high-status individuals had a prominent gonial angle, wider gonial angle, shallow and wide mandibular notch, more anterior positioned coronoid process and a wider U-shaped mandible.

Figure 6.2.44: CVA for status differences at St Gregory’s. Box and Whisker plot for CV1 showing the high (H) and low status (L) individuals with visualisations for +10 CV1 and -10 CV1. Whiskers illustrate the standard error in CV score.
When CVA was conducted for males and females among high and low status individuals the greatest separation occurred between high status males and females, with high status males being separated from all other groups along CV1 which high status females lie closer to low status females (figure 6.2.45). Box and Whisker plots for individual CV scores were created to focus on specific shape changes.

CV1 showed that among females there were no significant differences between high and low status individuals, while among males there was a significant differences. Shape differences associated with CV1 were subtle, high status males had a higher ramus with a taller coronoid process, more prominent gonial angle, deeper mandibular notch and slightly shorter mandibular body, as well as a wider U-shaped mandible (figure 6.2.46). CV2 separates out high and low status individuals among both males and females, a negative CV2 such as that of high-status females is associated with a shorter mandibular body and ramus. A positive CV2 such as that of the low status males is associated with a narrower mandible, taller ramus and mandibular body and more prominent gonial angle. CV3 acts to separate high and low status females and is associated with a more prominent shape change with a negative CV3 having a narrower mandibular ramus anterior-posteriorly, taller ramus, more oblique gonial angle and taller condyle (figure 6.2.48).
Figure 6.2.45: CVA for status and sex differences at St Gregory’s (CV1-CV2). CVA graph showing males and females from high and low status groups from St Gregory’s Cemetery and Priory for CV1 (representing 60.8% of total variation) and CV2 (representing 20.8% of the total variation). This graph shows that high status females grouped more closely with low status males and females. High status individuals are shown in purple with high status females (FH) on the right and high status males (MH) on the left. Low status individuals from the priory are shown in light blue with males (ML) with a higher CV2 compared to females (FL). Visualisations created show the shape changes associate with CV1 and CV2 at -5 and +5.
Figure 6.2.46: CV1 for status and sex differences at St Gregory’s. Box and Whisker plot for CV1 showing the high and low status males and females with visualisations for +5 CV1 and -5 CV1. Whiskers illustrate the standard error in CV1 score. Low and high-status females (FL and FH) and low status males (ML) have a higher CV1 score compared to high status males (MH) who have a negative CV1 score. Whiskers illustrate the standard error in CV score.
Figure 6.2.47: CV2 for status and sex differences at St Gregory’s. Box and Whisker plot for CV2 showing the high and low status males and females with visualisations for +5 CV2 and -5 CV2. Whiskers illustrates the standard error in CV2 score. High status females (FH) had the lowest CV2 score and low status males the highest CV2 score (ML). However mean CV2 score only varied as much as between -1.5 and +1.5.
Figure 6.2.48: CV3 for status and sex differences at St Gregory’s. Box and Whisker plot for CV3 showing the high and low status males and females with visualisations for +5 CV1 and -5 CV1. Whiskers illustrates the standard error in CV3 score. High status females (FH) had the lowest CV3 score while a high CV3 score was recorded among all other groups.
6.2.6 How does mandible morphology vary between dental wear groups? Similar to mandible measurements, centroid size was found to vary significantly between wear groups in general, however when analysed within period and sex estimation groups significant differences only occurred among females within the Post-Medieval period and among males with the Bronze and Iron Age period. Table 6.2.7. CVA was conducted and figure 6.2.49 illustrates morphological differences between wear groups. CVA analysis was also conducted to determine how mandible morphology differed between the different dental wear groups. CVA was then repeated for analysis of within period and sex estimation groups.

Table 6.2.7: ANOVA dental wear and centroid size. ANOVA table illustrating that within sex and period groups significant differences in centroid size were only recorded between dental wear groups for females in the Post-Medieval period and males in the Bronze and Iron Age.

<table>
<thead>
<tr>
<th>Sex</th>
<th>Period</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>Post-medieval</td>
<td>4361.19</td>
<td>9</td>
<td>484.58</td>
<td>2.30</td>
<td>.029</td>
</tr>
<tr>
<td></td>
<td>Between Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>11180.46</td>
<td>53</td>
<td>210.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>15541.65</td>
<td>62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Males</td>
<td>Iron/Bronze Age</td>
<td>4643.65</td>
<td>9</td>
<td>515.96</td>
<td>2.94</td>
<td>.018</td>
</tr>
<tr>
<td></td>
<td>Between Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>4034.02</td>
<td>23</td>
<td>175.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>8677.67</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.2.49: CVA dental wear groups (CV1 and CV2). Convex hull graph for CV1 and CV2 for dental wear groups 1/low (light blue), 2/moderate (purple) and 3/high (light green) with visualisations for produced for +10 CV1 and CV2 and for -10 CV1 and CV2.

Canonical Variate Analysis was conducted to determine how mandible morphology varied between dental wear groups. The scatter graph and visualisations suggest that individuals from wear group one had a more negative CV1 and positive CV2 with a more gracile mandible, a more oblique gonial angle, shorter mandibular body and narrower ramus. Wear group two and three had more robust mandibles, with wear group 2 having a more negative CV2 score with a taller mandibular body, wider ramus and more prominent gonial angle. While wear group three had a positive CV2 score, the CV1 score was also positive indicating a mandible that is also more robust with a more prominent gonial angle, prominent mental eminence, and wider ramus.
6.2.7 How does the amount of mandible morphology that occurs over time in Britain compare with geographic variation?

Previous studies have reported that mandible morphology is primarily influenced by environment including masticatory behaviour compared with population differences. However other studies have argued for a significant influence of genetic variation on mandible morphology. As such it was important to compare the amount of variation present across a geographic sample compared with over time in Britain. For this analysis PCA as opposed to CVA was used for GMM analysis. PCA was used because the amount of morphological variation within groups was of importance rather than how the groups differed in their morphology.

Figure 6.2.50: PC1 and PC2 for geographic and temporal mandible variation. PC1 accounts for 20% of total variance and PC 2 11% of total variance. Convex hulls show the group variation for Neolithic (red), Bronze and Iron Age (orange), Roman (yellow), Anglo-Saxon (green), Medieval (blue), post medieval (indigo) and the geographic sample (purple).
Figure 6.2.51: PC3 and PC4 for geographic and temporal mandible variation. PC3 accounts for 7% of total variance and PC4 6% of total variance. Convex hulls show the group variation for Neolithic (red), Bronze and Iron Age (orange), Roman (yellow), Anglo-Saxon (green), Medieval (blue), post medieval (indigo) and the geographic sample (purple).

Results from PCA shown in figure 6.2.50 and figure 6.2.51 illustrate that the amount of variation for PC1-PC4 was greater over time among British archaeological assemblages compared to global geographic assemblages. Moreover geographic variation was found to be lower than the later time periods in Britain including Post-Medieval, Medieval, Anglo-Saxon and Roman periods.
6.3 Summary of Results

Before considering the research questions further, the results from this study will be briefly summarised highlighting key findings. These results will then be discussed in chapter 7 in relation to previous clinical, archaeological and historical research, to discuss how these results relate to the archaeological context.

6.3.1 Over time mandible morphology became more gracile, significant changes in morphology were associated with periods or large-scale dietary changes

Among the entire sample mandible morphology became more gracile over time with a narrower mandibular body and ramus, a wider gonial angle and a deeper mandibular notch among the later periods. When considering all individuals together there was little difference in CV1 between Bronze/Iron Age, Roman and Anglo-Saxon individuals with significant differences only occurring between Neolithic and Bronze/Iron Age, Anglo-Saxon and the Medieval period and between the Medieval period and the Post-Medieval period. CV2-CV5 fluctuated between periods with no clear temporal trend. Among females there was a clearer temporal trend in mandible morphology, while among males mandible morphology fluctuated more between periods with no clear trend. Individual period comparisons further revealed what was generally an increased gracility over time, however, there were a few exceptions to this. The comparison between Roman and Bronze/Iron Age individuals showed that the Roman individuals were actually more robust compared to the Bronze/Iron Age individuals.

6.3.2 During the Roman period there was a significant change in mandible morphology for males that was not present among females

Roman mandibles were significantly more robust compared to other periods, based on a significantly lower CV1, and higher CV2 both representing more robust mandible morphologies with a deeper mandibular body, more prominent gonial angle and mental eminence, wider ramus and narrower gonial angle. Compared to males, among females significant differences were not reported among females from the Roman period individuals were similar to the adjacent periods based on CVA results. The more robust mandibles among Roman males are consistent with a higher strain diet.
6.3.3 **3D geometric morphometric analysis shows a greater level of variation between time periods compared to measurement data.**
For mandible measurements among females only body length was reported to differ between time periods and among males body length, condylar breath and body height differed between these groups. In comparison CVA revealed significant shape differences occurring over time, additionally the visualisations produced from CVA allows for a greater understanding of relative shape changes compared to the metric data. In general results from this study demonstrated the value of 3D geometric morphometrics when analysing mandible morphology and the relative inaccuracy of 3D linear measurements of the mandible. As such while studies which have focussed on linear measurements may provide evidence for differences between groups, a lack of significant differences in these measurements should not be taken as a lack of significant differences in mandible morphology between groups.

6.3.4 **Sex differences were present for every period however degree of sexual dimorphism and expression varied between periods**
Significant differences between males and females for each time period could be described by one canonical variate and for all periods females typically had a more gracile mandible compared to males. The degree of separation between sex estimation groups varied over time and generally increased over time, although there was a greater mean difference in CV1 among the Anglo-Saxon individuals followed by Medieval and among Post-Medieval individuals there was some overlap in the ranges for CV1 among males and females. Visualisations produced to illustrate morphology for +5 and -5 CV1 for all time periods show similarity in morphological differences represented by CV1 for the first four time periods. However, for the Medieval and Post-Medieval periods CV1 denotes different morphological variations. Mean difference in centroid size was also found to differ between the time periods, with the greatest mean difference in centroid size present among the Bronze and Iron Age individuals and the lowest among the Roman, with significant sex differences recorded for all periods, with the exception of the Neolithic likely due to low sample sizes.
6.3.5 Significant differences in mandible morphology were present between individuals from the cemetery and priory at St. Gregory’s in Canterbury. Among individuals from St Gregory’s cemetery and priory there were distinct differences between the two burial grounds. Additionally, sex differences were noted in the reported status groups, with more prominent status differences recorded among males, and low status males were found to be similar to both high and low status females. Visualisations produced at +5 and -5 for CV1 and CV2 however did not illustrate clear differences in the mandible morphologies.

6.3.6 Significant morphological differences were associated with M1 dental wear groups, although this was not linear. Dental wear group one was associated with a more gracile mandible, with a wider gonial angle and narrower mandibular body and ramus. The moderate wear group typically had a more robust mandible with a more prominent narrower gonial angle, deeper mandibular body and wider ramus. The high wear group had a more complex morphology with a combination of robust and gracile features.
Chapter 7
Discussion

Results from this study revealed significant and complex changes in mandible morphology over time, as well as between sex estimation and dental wear groups. Following a detailed discussion of these results in section 7.1, the limitations of this study and requirements for future research are explored in section 7.2 and 7.3 respectively.

7.1 Discussion of Results

Having presented the results from this study in chapter 6 each of the research questions posed in chapter 1 section 1.1 will be discussed fully with reference to the material covered in the archaeological and clinical background in chapters 2-4.

7.1.1 Research Question: How has mandible morphology changed over time in Britain?

When considering males and females together, significant changes in mandible morphology were recorded over time. In general the mandible became more gracile with more notable changes occurring between the Neolithic and the Iron and Bronze Age, as well as between the Anglo-Saxon and Medieval, and the Medieval and the Post-Medieval periods. Earlier periods had a narrower more acute gonial angle, taller mandibular body and wider ramus resulting in a mandible which generally appears more robust, while later periods are associated with an increasingly gracile mandible, with a more oblique gonial angle, shorter mandibular body and narrower ramus, these changes are illustrated in figure 7.1.1 below.

Figure 7.1.1: Comparison of robust and gracile mandible morphology occurring over time in Britain. The diagram on the left shows the more robust mandible morphology that is associated with the earlier time periods and the diagram on the right the more gracile morphology of later time periods, these visualisations are based on the results of a CVA and illustrate the shape differences represented by CV1.
These results are consistent with the morphological changes reported in experimental animal and clinical studies, when dietary consistency or masticatory force was decreased (Barber et al. 1963, Denes et al. 2018, Ito et al. 1988, Kikuta 1985, Kiliaridis et al. 1988, Kufley et al. 2017, McFadden et al. 1986, Watt and Williams 1951, Yamada and Kimmel 1991). The majority of these studies however, have focussed on single regions of the mandible (Bresin et al. 1999, Tsai et al. 2009, Denes et al. 2018), bone density (Barber et al. 1963, Bresin et al. 1999, Tsai et al. 2010b, Sato et al. 2005, Yamada and Kimmel 1991) or cortical thickness (Bresin et al. 1999, Ito et al. 1988, Tsai et al. 2010b) which limits comparison with these results. One study where comparisons may be made was conducted by Sella-Tunis et al. (2018) who analysed human mandibular morphology in relation to the cross-sectional area (CSA) of the masticatory muscles. Head and neck CT scans - from a medical centre in Cleveland Ohio - of 382 individuals (193 males and 189 females) aged between 18 and 80 years of age were analysed to compare mandible morphology with the CSA of the masseter and temporalis muscles. Mandible morphology was analysed using landmark 3D GMM methods. Results showed an increase in CSA was associated with an increase in ramus width, body height, and coronoid height, as well as a larger more robust gonial angle and vertically aligned ramus. The morphological differences reported by Sella-Tunis et al. (2018) in relation to changes in the CSA of the masticatory muscles are remarkably similar to the gracilisation that occurred over time in Britain, as illustrated in figure 7.1.2.
Figure 7.1.2: Morphological changes associated with the cross-sectional area of the masticatory muscles reported by Sella-Tunis et al. (2018) compared to morphological changes reported over time in Britain. Illustrations at the top left show the more gracile mandible morphology reported among individuals with small masticatory muscle CSA compared to the robust morphology (top right) of individuals with a large CSA (Sella-Tunis et al. 2018, 7, figure 6). Similar morphological changes were reported in this study over time in Britain with a more robust morphology among earlier time periods (bottom right) compared to the gracile morphology of later time periods (bottom left).

The results from this study therefore support the hypothesis that the mandible has become increasingly gracile over time in Britain likely due to a reduction in the size of the masticatory muscles reflecting dietary changes, based on similarities with the morphological changes reported by Sella-Tunis et al. (2018). The morphological changes recorded over time in Britain are also consistent with previously published archaeological studies which have reported an increased gracilisation of the masticatory structures associated with the development and intensification of agriculture and the Industrial Revolution (Bejdova et al. 2013, Bosman 2016, Bosman et al. 2017, Carlson and Van Gerven 1977b, Galland et al. 2016, Katz et al. 2017, May et al. 2018, Paschetta et al. 2010, von Cramon-Taubadel 2011). For instance, von Cramon-Taubadel (2011), analysed craniofacial morphology among 11 populations worldwide comparing hunter-gatherer and agricultural subsistence economies. Hunter-gatherer populations had a relatively long and narrow mandible with a short ramus and coronoid process as well as a more acute and prominent gonial angle. Conversely
agriculturalists were found to have a relatively short and broad mandible with a
taller coronoid process and ramus, as well as a more elongated and obtuse gonial
angle. Similarly, Rando et al. (2011) recorded a significant difference in mandible
morphology between Medieval and Post-Medieval Londoners. Post-Medieval
males and females exhibited a significant reduction in ramus breadth, as well as
an increase in the length of the mandibular body and gonial angle. However,
other morphological changes recorded over time in Britain in this present study
were inconsistent with the results from previous archaeological studies, such as
the increased bicondylar breadth, shorter ramus, and taller mandibular body. A
comparison of the morphological changes reported over time in previous studies
with the morphological changes recorded in this study are shown in table 7.1.1.
However, these differences may be the result of methodological disparities due
to the lack of consistency in methods, as such the potential for comparisons are
limited.

In addition to this general trend in mandible morphology, three significant
reductions in mandibular robusticity were recorded over time in Britain, which
may indicate periods of significant dietary changes. Such dietary changes may
represent alterations in the dietary constituents or the processing of food, both
resulting in a softer diet requiring less masticatory strain. These individual period
comparisons are discussed further in sections 7.1.1.1 – 7.1.1.6.
Table 7.1.1: Comparison with archaeological studies. This table compares the morphological changes recorded over time in Britain with morphological changes reported over time in previous archaeological studies (discussed in this chapter and chapter 4) which investigated morphological changes associated with dietary transitions that are considered to have reduced masticatory stress. A ✓ indicates similar results were reported, a ✗ that the opposite morphological change was reported and a – indicates no change reported in this region or the feature was not discussed. It needs to be noted that the studies discussed in this table have not analysed the same time periods or geographic regions, however they have all reported similarities in mandibular gracilization occurring over time among humans.

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<td>Wider more obtuse gonial angle</td>
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<tr>
<td>Smaller body height</td>
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7.1.1.1 Neolithic and Bronze and Iron Age

While the Neolithic sample was small, significant morphological differences were reported between Neolithic and the Bronze / Iron Age individuals. In the overall period comparison, Neolithic individuals had a significantly higher CV1 and CV4 score (associated with a more robust mandible morphology) compared to all other periods. When Neolithic and Bronze / Iron Age assemblages were compared directly, mandible morphology was found to become increasingly gracile between these periods, based on results from a CVA illustrated in figure 7.1.3. These morphological changes are similar to those associated with smaller masticatory muscles and a softer more processed diet (Sella-Tunis et al. 2018). It is therefore suggested that between the Neolithic and Bronze / Iron Age in Britain significant dietary changes occurred which resulted in a reduction in masticatory strain.

As discussed in chapter 2 it has been proposed that the Neolithic Revolution in Britain did not include transmission of all components of the ‘Neolithic package’ equally (Stevens and Fuller 2012, 2015). The domestication of animals is considered to have been rapidly incorporated into Britain, supported by the extensive zooarchaeological evidence of domesticated animals at Neolithic sites and the significant reduction in the relative proportion of wild species compared

Figure 7.1.3: Morphological differences between Neolithic and Bronze / Iron Age individuals. This diagram shows the increased gracilisation reported between Neolithic (left) and Iron and Bronze Age (right) individuals, these visualisations are based on the results of a CVA and the shape differences which are represented by CV1.
to the Mesolithic period (Cummings 2017, Cummings and Harris 2011, Renfrew 1985, Thomas 1988, Thomas and McFadyen 2010). However, it has been argued that arable agriculture was not widely adopted into Britain until the later Neolithic and Early Bronze Age (Stevens and Fuller 2012, 2015). With the exception of the potential increased consumption of domestic plants presenting as a softer more homogenous diet high in carbohydrates, there is a lack of evidence for other significant dietary changes between these periods (Cunliffe et al. 2004, Jay and Richards 2006, Redfern et al. 2010 Serjeantson 2007, 2011). Whereas evidence for other dietary changes may be missing from the archaeological record, the increased gracility reported is consistent with the increased consumption of cereal crops, due to the morphological similarities with previous studies that have investigated the changes associated with the development of agriculture (Katz et al. 2017, Lieberman 2008, von Cramon-Taubadel 2011). Previously, the evidence for the theory that domesticated plants were not fully incorporated into the British Neolithic has been based on a lack of evidence of arable agriculture from the Neolithic. However, the significant reduction in mandibular robusticity between the Neolithic and the Bronze / Iron Ages may provide evidence for the theory that arable agriculture did not fully develop in Britain until the Bronze / Iron Age.

The Agricultural Revolution is one of the most frequently studied dietary transitions in archaeology, and numerous studies exist which have analysed morphological changes associated with this transition. These studies have frequently compared two periods on either side of the dietary transition, however by only analysing two time periods it cannot be determined if the associated morphological changes which have been reported are rapid or gradual. In the absence of comparative data, it is not possible to determine if the reduction in mandible robusticity after the Neolithic is unique to Britain and therefore represents the delayed adoption of arable agriculture. One previous study which analysed mandible morphology among agricultural transition periods was conducted by Carlson and van Gerven (1977) who analysed craniofacial morphology among three periods in Nubia known to represent the transition from hunter-gather to agriculturalism. Mesolithic hunter-gather populations (n=12) who are considered to have relied on large game hunting, the A-C group (n=52) dated to between 3,400-1,000 BCE considered to
represent the transition from hunter-gatherer to agricultural substance strategies and the Meroitic-Christian (n=188) period known to be a fully agricultural subsistence group were compared. Sixteen linear measurement of the crania and mandible were analysed among these three substance groups. Over time there was a general decrease in both the size and robusticity of the mandible and nine of the 11 variables which were found to significantly decrease in size were directly related to masticatory function. It was reported that between the hunter-gatherer and transitional periods there was complete separation of the populations based on a discriminant classification matrix. However, between transitional and later agricultural assemblages there was considerable morphological overlap reported, although these groups were still found to be significantly different (Carlson and van Gerven 1977). Results from this study therefore indicate that the most prominent morphological changes in the mandible occurred immediately after the introduction of agricultural technologies.

Unfortunately, due to the lack of available Mesolithic skeletal assemblages in Britain it was not possible to analyse morphological changes during the Mesolithic-Neolithic transition. Thus it cannot be determined if significant reductions in mandible morphology between the Neolithic and Bronze and Iron Age represent a continuous trend towards a more gracile mandible morphology originating in the Mesolithic. Additionally, due to sample size restriction as well as limitations in dating accuracy and the presence of multi-period burial grounds, it was necessary to combine the Iron and Bronze Ages into one sample, therefore the two periods Neolithic and Bronze and Iron Age each represent very long-time range; just under 2000 years whereas later periods only cover around 500 years on average. As such the significant reduction in mandible robusticity recorded may be influenced by the length of time period and accumulated dietary and subsequently morphological changes.

Despite the limitation of the materials of this study, these results provide evidence for a reduction in dietary consistency between the Neolithic and Bronze / Iron Age in Britain which may arguably provide evidence for domesticated crops only making up a large proportion of the diet during the later time period. While not evidence in itself of a so called ‘failure’ of the Agricultural Revolution in Britain during the Neolithic, it does provide evidence for dietary

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changes consistent with the increased consumption of domesticated plants. Further research is needed to compare British Post Neolithic morphological variation with that of other regions where it is suggested arable agriculture was more readily adopted with other elements of the ‘Neolithic package’.

7.1.1.2. Before and after Roman Britain
In the overall comparison between time periods there were no significant differences reported in CV1 between Bronze/Iron Age and Roman individuals or between Roman individuals and Anglo-Saxons. However, significant differences were present in CV2 between Roman and Bronze/Iron Age as well as more prominent differences between Roman and Anglo-Saxon individuals with Romans having a higher CV2 score. Furthermore, Roman individuals had a significantly lower CV5 score compared to Bronze / Iron Age individuals. Individual period analysis using CVA was conducted allowing direct comparison of the significant morphological differences that occurred between the Roman and Bronze / Iron Ages and the Roman and Anglo-Saxon individuals.

Unlike the other morphological changes reported over time in Britain, between the Bronze / Iron Age and Roman periods in Britain mandible morphology became more robust. The gonial angle became more prominent and acute and the ramus wider and shorter with a taller and wider mandible body, illustrated in figure 7.1.4. These changes are the reverse of to the general pattern reported over time from the Neolithic through to the Post-Medieval periods and the morphological changes reported by previous archaeological, animal and clinical studies that are associated with a softer diet or reduced masticatory strain. These results are therefore consistent with an increase in masticatory activity occurring in Roman Britain.
Figure 7.1.4: Morphological changes reported between the Bronze / Iron Age to the Roman period. This diagram shows increase in robusticity that was reported between the Bronze/Iron Age and the Roman period in Britain these visualisations are based on the results of CVA and illustrate the shape differences represented by CV1.

In Roman-Britain there is historical and archaeological evidence for the introduction of new plants and animals. In addition to the newly introduced flora and fauna, widespread cultural and technological changes (Alcock 2001, Briscoe 2015, Colquhoun 2008, Cool 2006, Roffett-salque et al. 2017, Swan 2002), including food processing technologies are associated with the Roman occupation. Despite the plethora of evidence for dietary changes during this period it is not clear which factors may have increased masticatory demands, as the majority of foods introduced to Britain would have been soft and unlikely to have increased masticatory demands. While a number of fauna were introduced to Britain by the Romans, animal protein is considered to have also been eaten in large quantities in the Bronze/Iron Age so these increased masticatory demands are unlikely to have been the result of the increased consumption of animal protein (Albarella et al. 2008, Allen 2014, Parker 1988). Other dietary changes known from the Roman period include the increased consumption of bread and changes in cooking methods and equipment which require further discussion.

Bread is known to have been consumed in large quantities in Roman Britain, while the elite in the Roman empire are reported as preferring softer white bread most of the bread consumed is considered to have been very hard and dry (Cool
It is therefore possible that this increased consumption of bread would be associated with an increase in masticatory stress. However, bread was also consumed in large amounts during the Anglo-Saxon period, forming a dietary staple (Frantzen 2014, Gautier 2012, Moore and Corbett 1971). Between the Roman and Anglo-Saxon period mandible morphology did become more gracile, although this gracilisation differed in form from the general gracilisation reported over time. This would not be expected if the increased robusticity reported in Roman Britain was principally related with bread consumption.

Another masticatory behaviour associated with the Roman empire is the chewing of mastic gum, derived from the bark of the mastic tree (*Pistacia lentiscus*) (Chadzopulu *et al.* 2011, Fischman 2000, Howes 1950, Paraschos *et al.* 2012). One of the earliest written references of mastic is dated to the 5th century BCE and attributed to Herodotus who describes the “chewing … of the dried resinous fluid secreted by the bark of the mastic tree” (Paraschos *et al.* 2012, 2294). However, it is not known if the chewing of mastic gum was a common feature of the Roman period in Britain, an as a luxury product unlikely to have been widely available or account for the morphological changes reported in this study.

In addition to the changes in dietary components that are associated with Roman Britain the archaeological and historical record details changes in cooking practices and technologies which may have influenced the texture of foods and therefore masticatory behaviours (Alcock 2001, Briscoe 2015, Colquhoun 2008, Cool 2006, Roffett-salque *et al.* 2017, Swan 2002). Ovens were more frequent at Roman sites as well as metal cookware alongside the presence of dedicated rooms for cooking and food preparation (Alcock 2001, Colquhoun 2008), this arguably indicates the increased importance placed on food. However, technological improvements in food processing are typically associated with a softer diet (Paschetta *et al.* 2010, Wollstonecroft 2011). Moreover, historical reports from the Roman Empire suggest a preference for a soft, sweeter diet (Rohnbogner and Lewis 2016, Semchuk 2016). Therefore, it is unexpected that the technological advances which occurred would have resulted in the increased dietary hardness if a soft diet was preferred.

In addition to the dietary changes, the Romanisation of Britain is associated with widespread cultural changes as well as migration. While mandible morphology
has been found to be more greatly influenced by environmental factors as opposed to population history (Cleaver 1937, Hrdlička 1940a Nicholson and Harvarti 2006, von Cramon-Taubadel 2011), some genetic influence on mandible morphology has been reported (von Cramon-Taubadel 2017, Herrera et al. 2017, Noback and Harvati 2015, Nicholson and Harvati 2006). However, the large-scale migrations that occurred during the Roman period would be expected to differentially affect Roman military and urban sites. While data is unavailable for some of the Roman sites utilised in this study, due to both the number of sites analysed and available archaeological context (discussed further in section 7.1.1.5 and appendix 3) it is considered unlikely that these results are significantly influenced by population history.

Results from a CVA conducted to compare the Roman and Anglo-Saxon assemblages illustrated that Anglo-Saxon individuals had a slightly more gracile mandible with a shorter mandible body and ramus, and thinner more gracile coronoid process. One of the most prominent morphological differences between these periods is the relative height of the coronoid and condyle, among Roman individuals the coronoid is higher than the mandibular condyle while the converse is true among Anglo-Saxons, illustrated in figure 7.1.5.

![Figure 7.1.5: Morphological changes from the Roman to the Anglo-Saxon period](image)

Figure 7.1.5: Morphological changes from the Roman to the Anglo-Saxon period. This diagram shows the morphological variation reported between the Roman and Anglo-Saxon individuals in Britain these visualisations are based on the results of a CVA and the shape differences represented by CV1.
When interpreting the morphological changes reported between the Roman and Anglo-Saxon assemblages it is interesting to consider the general mandible morphology of carnivores and herbivores. Carnivores have a larger more prominent coronoid process, a dietary adaptation that facilitates strong jaw closure. Herbivores on the other hand have a larger more superior mandibular condyle which allows for increased lateral movements which more efficiently breaks down tough cellulose during mastication (Anthwal et al. 2013, Anthwal and Tucker 2012, Hanken and Hall 1993, Watson et al. 2018). Some comparisons may be drawn between carnivores and herbivores and the morphological variation reported among Roman and Anglo-Saxon individuals from this study. Dietary changes between these periods may therefore have resulted in an increase in lateral masticatory movements among Anglo-Saxons. Two documented dietary changes which may account for the increased lateral movement is the increased consumption and reliance on bread and the prohibition of meat on certain days of the week related to the spread of Christianity (Chaney 1960, Crawford 2009, Forbes 2016). Unfortunately, there is a lack of human comparative data which has analysed mandibular morphology among meat eating or vegetarian groups. Without such research it is not possible to determine if human mandibular morphology would respond similarly to a plant-based diet compared to other species. Furthermore, the morphological differences shown in the comparison of individual periods are an exaggerated form therefore it is necessary to remember that this does not reflect the extent of the true morphological variation which is subtler.
7.1.1.3. Industrialisation and Urbanisation - Medieval and Post-Medieval Britain

Results from the multi-period CVA revealed significant differences in CV1 (which represents the main trend for increased gracilisation over time) between Medieval and Post-Medieval assemblages. These results are consistent with previous research which has investigated morphological changes in the mandible that may result from dietary changes associated with the Industrial Revolution. When Medieval and Post-Medieval assemblages were directly compared using CVA the significant morphological differences reported between these periods differed slightly from the gracilisation reported between the Neolithic and Bronze / Iron Age, with a more pronounced narrowing of the mandibular ramus as illustrated in figure 7.1.6.

![Figure 7.1.6: Morphological differences between the Medieval and Post-Medieval periods. Illustrations showing the morphological variation and gracilisation that was reported between the Medieval and Post-Medieval assemblages in Britain, these visualisations are based on the results of a CVA and the shape differences represented by CV1.](image)

For much of the Post-Medieval period diet is thought to have been similar to the Middle Ages, at least for a large proportion of the population whose diet primarily consisted of pottage. Industrialisation and urbanisation in Britain are considered to have resulted in a softer more homogenous and highly processed diet. With most of the population living in urban settlements people were no longer growing their own foods, instead they relied on the foods which were readily available and convenient (Pennel 2016, Woolgar 2016). These foods were frequently highly processed, soft and sweet. The increase in highly processed
complex carbohydrates and sugars during the Post-Medieval period is one of the most studied dietary change in bioarchaeology, with several studies reporting a significantly higher prevalence of dental caries (Broomfield 2007, Mintz 1985, Moore and Corbett 1975, 1976, O'Sullivan et al. 1993, Spencer 2011, Wilson 1973, Woolgar 2016). However, previous studies which have investigated the effects of industrialisation on mandible morphology have either restricted comparison to Medieval and Post-Medieval assemblages (Bosman 2016, Rando et al. 2014), or Medieval, Post-Medieval and Modern assemblages (Martin and Danforth 2009). By analysing earlier time periods this study also identified a significant increase in gracilisation between the Anglo-Saxon and Medieval periods.
7.1.1.4 Anglo-Saxon and Medieval Britain
In addition to the expected increase in gracilisation recorded between the Medieval and Post-Medieval periods, significant gracilisation occurred between the Anglo-Saxon and Medieval assemblages. Results from the CVA revealed that the morphological changes which occurred between these two periods differed from the typical gracilisation reported among previous studies and over time in Britain. Compared to Anglo-Saxon individuals, Medieval individuals had a wider mandible with a lower mandibular body, wider ramus and shallower mandibular notch. The gonial angle while more obtuse is also more prominent among Medieval individuals, illustrated in figure 7.1.7. Due to a lack of previous research regarding the type of dietary changes and mandible morphology - previous studies have typically focussed on the relative hardness of diet - it is not possible to infer specific masticatory behaviours from these morphological changes. Instead the significant increase in typical gracilisation reported in the overall period comparison will be the focus of this discussion.

Figure 7.1.7: Morphological differences between the Anglo-Saxon and Medieval assemblages. Illustrations showing the morphological variation reported between the Anglo-Saxon and Medieval individuals in Britain, these visualisations are based on the results of a CVA and the shape differences represented by CV1.

Several dietary changes occurred in Britain between the Anglo-Saxon and Medieval periods that may have reduced masticatory strain and resulted in the morphological changes reported. Christianity became increasingly widespread which is related to dietary restrictions, which principally reduced the consumption of animal protein (Chaney 1960, Crawford 2009, Forbes 2016). While these dietary restrictions did fluctuate during this period, historical and
archaeological evidence provides support that for much of the population the consumption of animal protein decreased (Müldner and Richards 2005, Spencer, 2011). Animal protein was substituted by increased dairy and fish with everyday meals typically consisting of pottage which required little masticatory strain. The reduction in animal protein is a continued trend from the Anglo-Saxon period into Medieval Britain, and as such it might be expected to result in a similar morphological pattern to that reported between the Roman and Anglo-Saxon assemblages in section 7.1.1.2. However, results from a CVA is influenced by the groups which are compared. When Roman and Medieval assemblages were compared directly a very similar morphological change to the Roman and Anglo-Saxon comparison was reported. As such the morphological changes reported may well indicate a continuation and intensification of the dietary changes that occurred between the Roman and Anglo-Saxon period.
7.1.1.5. Males over-time: The problem with Roman males
When males and females were considered separately different patterns were recorded in mandible morphology over time. Among males the most notable change is associated with the Roman periods. Roman males had a significantly lower CV1 and higher CV2 compared to all other periods. CV1 is associated with a more robust mandible, a taller mandibular body, more prominent gonial angle, shorter and wide ramus, shallow mandibular notch and curved anterior and posterior border of the ramus. CV2 is associated with a taller ramus with a more prominent coronoid process compared to the mandibular condyle. Such differences were not present among females for the multi-period comparison illustrated in figure 7.1.8.

![Morphological changes in CV1 and CV2 that separate Roman males from all other time periods.](image)

Figure 7.1.8: Morphological changes in CV1 and CV2 that separate Roman males from all other time periods. Illustrations depicting the results from CVA and the morphological changes associated with low CV1 (top right) and high CV2 (bottom right) which are associated with Roman males and compared to the males from the other periods in Britain (left).

These results indicate that, while among females a more consistent and gradual gracilisation was reported. The Roman period was of course a time of invasion and migration into Britain, with numerous social, cultural and dietary changes recorded. In addition to the possible environmental factors that may have influenced male mandibular morphology, it is necessary to also consider the potential genetic influence.

During the Roman occupation armed forces were stationed all over Southern Britain and many forces would have included men from mainland Europe,
North Africa and the Middle East. This would mean the increased influence of genetic variation known to influence mandible morphology; albeit to a lesser extent than environmental factors. Furthermore, these military forces were known to have brought with them dietary and cooking practices from their countries of origin such as the braziers found in York where the Roman military forces are thought to have originated from North Africa (Cool 2006, Swan 2002). If such morphological differences in the mandible resulted from these genetic or cultural behaviours it would be expected that the majority of males would have been excavated at Roman military or urban sites.

When considering the Roman sample employed in this study which are illustrated in figure 5.2.10 chapter 5, the majority of the roman males (n=21) were excavated from the Romano-British site of Kempston, Bedfordshire. Of the 35 individuals included from Kempston 60% were male, while 34% were female, and the rest were unidentified. Kempston however was a rural settlement, with no evidence of military occupation, although the settlement is thought to have had a Romanised appearance (Dawson 2004). While there is limited published bioarchaeological data from the inhumations at Kempston, the available bioarchaeological and material remains indicate that Kempston was an agricultural community, evidenced by the presence of quern stones and cereal remains indicating the processing of spelt, wheat, emmer bread wheat and rye (Dawson 2004). The other two sites where multiple Roman males were included are Baldock near St Albans, Bedfordshire and Kingsholm, Gloucester. The Roman fortress of Kingsholm is thought to have been established 49 CE as part of a military campaign to supress the Silures tribe in South Wales (BARC 2007). However, only four of the 51 Roman males were excavated from Kingsholm. The Roman cemetery at Baldock is a late Romano British cemetery with no evidence of military occupation. Apart from the Romano-British site at Kempston there were no Roman sites with a significantly higher proportion of males. Combined with the lack of genetic influence in mandible morphology it is considered unlikely that the morphological differences among Roman males reflects genetic variation resulting from migration of Roman military and elite individuals. Rather, it is suggested that males at Romano-British sites may have consumed different diets compared to females. There is a however, a lack of bioarchaeological evidence to suggest significant dietary differences based on
isotope analysis, dental wear or carious lesions among Roman-British sites (Bonsall 2013, Cheung et al. 2012, Redfern et al. 2010). Unfortunately without further evidence, it is not possible to determine the cause of the increase in mandibular robusticity among Roman males.

7.1.1.6. Females over-time: Increased gracilisation
In comparison, results for females from CVA revealed a linear progression over time towards a more gracile mandible morphology, with significant reductions in robusticity occurring between each period. The most significant difference was reported between the Neolithic and the Bronze / Iron Age however, these results are likely influenced by the low number of Neolithic individuals estimated as female. While significant differences occurred between CV2-CV5 the total proportion of variance explained by these canonical variates make these results largely insignificant and as such they will not be discussed further.

It is interesting to note that when females are analysed on their own the increased gracility over time does not follow the same step-like pattern that occurs when analysing the total sample. For instance, the significant morphological changes associated with the Medieval and Post-Medieval period are much less prominent. As such dietary shifts do not appear to have had as significant an impact among females compared to males. This may be due to cultural factors buffering females, as such dietary transitions may not have been experienced as profoundly among females. However, such sex differences in diet and other aspects of social and cultural life are known to vary over time. It would therefore seem unlikely that sex differences in diet would act to consistently buffer females from significant dietary changes over time. Another possible theory that may account for these results is that the bite force produced by females is lower than males (Tamut et al. 2012) and as such dietary changes may have a reduced capacity to produce morphological changes in the mandible. There has however been little research focussing on sex differences in response to masticatory forces in which to compare with these results. Despite this, results do indicate that it should not necessarily be assumed that males and females will respond to dietary changes in the same way, or to the same extent, as males.
7.1.2. Research Question: Has sexual dimorphism in the mandible changed over time in Britain?

The results from mandible measurements, centroid size and canonical variate analysis revealed that as expected sex differences were present in the size and morphology of the mandible for all periods analysed. The specific sex differences identified were generally consistent with previously published research whereby males had larger more robust mandibles, while females had smaller and more gracile mandibles illustrated in figure 7.1.9.

![Mandible Images]

**Figure 7.1.9: Morphological differences reported between males and females for the entire sample.** Male (top) mandible morphology has a more prominent gonial angle and square appearance with a taller straighter ramus and taller mandible body. Females (bottom) have a more gracile mandible with a lower mandible body, wider gonial angle and angled ramus that flares laterally. These visualisations are based on the results of a CVA and the shape differences represented by CV1.

Over time it was reported that sexual dimorphism increased, with more prominent sex differences in size and shape evident among the Medieval and Post-Medieval populations. Similar findings have been reported by Bejdová et al. (2013) who reported an increase over time in the mean difference in centroid size between males and females. There are three key theories as to why sex differences may change between time periods including: improved nutrition which may result in more pronounced sexual dimorphism, socio-cultural changes altering sexual selection, and finally dietary differences between males and females may have changed over time. Each theory will be discussed in relation to the results from this study, previously published research and evidence from the archaeological and historical record.
7.1.2.1 Nutritional Status
Previous studies have recorded a reduction in sexual dimorphism among populations and assemblages affected by malnutrition (Greulich 1951, Stini 1971, 1972). Males are thought to be more susceptible to malnutrition, while females with a smaller body size and higher storage of subcutaneous fat are thought to be better able to tolerate periods of malnutrition. One of the earliest studies that reported a greater susceptibility of males to reduced nutritional quality was conducted by Greulich in 1951. Greulich (1951) analysed the growth and development of children from Guam who after World War II experienced dietary deficiency. It was reported that male children exhibited greater deficits compared to females for height, weight and skeletal maturation, when compared with children from Cleveland, USA (Greulich 1951). Moreover a reduced sexual dimorphism in arm muscle circumference has been recorded among undernourished populations (Stini 1972), although others have not found any reduction (Stinson 1985). However, these studies have typically relied on stature or limb measurements and may not be applicable to the mandible. Moreover, these studies fail to sufficiently describe the nutritional deficits associated with reductions in sexual dimorphism, instead these studies frequently refer simply to ‘nutritional stress’, as such it is not known if it is a reduction in calorie consumptions or specific nutrients that is associated with a reduction in sexual dimorphism. If nutritional status was influencing sexual dimorphism in the mandible between time periods it would be expected that a similar pattern in sexual dimorphism would be reported in stature and long bone measurements. Roberts and Cox (2003) analysed stature among males and females from assemblages dated to between the Neolithic and Post-Medieval periods and reported an increase in mean stature difference between sexes illustrated in table 7.1.2. However, there were still considerable fluctuations between periods with Bronze Age individuals having a lower mean difference in stature than the preceding or subsequent period, while the highest mean stature dimorphism was recorded among the Medieval period. When stature, as reported by Roberts and Cox (2003) were compared to the results from this study some similarities are evident in the ranking of sexual dimorphism in stature, centroid size and CV1 as illustrated in table 7.1.3.
Table 7.1.2: Table illustrating the mean stature for males and females from each time periods analysed by Roberts and Cox (2003). Additionally, the mean difference between males and females was calculated and is shown in the right-hand column. These results show that over time there was a general increase in mean difference in stature, data from Roberts and Cox (2003, 396, Table 8.1).

<table>
<thead>
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<th>Male Stature cm (N)</th>
<th>Female Stature cm (N)</th>
<th>Mean Difference</th>
</tr>
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<tbody>
<tr>
<td>Neolithic</td>
<td>165.0 (71)</td>
<td>157.0 (36)</td>
<td>8</td>
</tr>
<tr>
<td>Iron Age</td>
<td>172 (61)</td>
<td>161.0 (20)</td>
<td>11</td>
</tr>
<tr>
<td>Bronze Age</td>
<td>168.0 (113)</td>
<td>162.0 (72)</td>
<td>6</td>
</tr>
<tr>
<td>Roman</td>
<td>169.0 (1296)</td>
<td>159.0 (1043)</td>
<td>10</td>
</tr>
<tr>
<td>Anglo-Saxon</td>
<td>172.0 (996)</td>
<td>161.0 (751)</td>
<td>11</td>
</tr>
<tr>
<td>Medieval</td>
<td>171.0 (8494)</td>
<td>159.0 (7929)</td>
<td>12</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>171.0 (558)</td>
<td>160.0 (540)</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 7.1.3: Ranking of sexual dimorphism over time for statute, CV1 and centroid size. Ranking of centroid size and CV1 from mandible morphology in this study, compared with stature data from Roberts and Cox (2003).

<table>
<thead>
<tr>
<th>Period</th>
<th>Stature</th>
<th>Centroid Size</th>
<th>CV1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neolithic</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Iron Age and Bronze Age</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Roman</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Early Middle Ages/ Anglo-Saxon</td>
<td>4/5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Medieval</td>
<td>6</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Post-Medieval</td>
<td>4/5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Other methods of investigating nutritional stress in bioarchaeology typically rely on the analysis of nutritional deficiency diseases (Cook 2018, Gowlang et al., 2018, Mays 2014, Moes and Blatt 2018, Van der Merwe and Steyn 2010), while other studies have analysed so-called ‘stress markers’ such as enamel hypoplasia, cribra orbitalis and porotic hyperostosis (Novak et al. 2018, Scott and Hoppa 2018, Nagaoka et al. 2018). However, the specificity and efficacy of these lesions have been called into question with two main areas of concern highlighted. The
first is that stress is a general term, it may refer to psychological, nutritional, mechanical or environmental conditions. Furthermore, it is necessary to consider the osteological paradox, these are after-all the individuals who survived (DeWitte and Stojanowski 2015, Milner and Boldsen 2018). These skeletal lesions may therefore indicate survival during a ‘stressor’ when other individuals may have perished and as such are not a good indicator of individual ‘stress’ burdens.

In addition to the bioarchaeological evidence available, a review of the archaeological and historical evidence can reveal information regarding food scarcity and nutritional stress in Britain. Historical evidence indicates a high number of livestock and crop plagues as well as droughts that resulted in widespread famines during the Anglo-Saxon and Medieval periods (Adamson 2004, DeWitte 2010, 2014, Platt 1997, Woolgar 2016). If sexual dimorphism in the mandible is significantly influenced by nutritional stress, sexual dimorphism would have been expected to be particularly low during these periods.

7.1.2.2 Sexual Selection
Another factor known to influence sexual dimorphism among humans are changes in sexual selection which are known to vary between cultures and over time (Marcinkowska et al., 2014). For instance, waist-to-hip ratio (WHR) is an indicator of female fecundity and a significant correlate with reported female attractiveness. Preferential WHR has been found to vary between populations; in North America, the UK and Germany males were found to prefer a low WHR (Furnham et al. 1997, Henss 2000, Singh 1993a, 1993b) while in other populations such as the Hadza of Tanzania (Wetsman and Marlowe 1999) or the Matsigenka in Peru a high WHR of 0.9 was preferred (Yu and Shepard 1998). In this study the periods where the greatest sexual dimorphism in mandible morphology was reported may reflect culturally specific mate preferences with males preferring more gracile highly feminised faces and/or females selecting for the more robust masculine facial form. For instance, several studies have found that males with a more robust and wider jaw were considered more attractive and that jaw morphology was associated with other traits such as perceived strength (Dixson et al. 2018, Thornhill and Gangestad 1993, Johnston et al 2001, Perrett et al. 2000). Additionally, mandible morphology is influenced
by the size of the masticatory muscles which are in turn related to the production of sex hormones. Therefore, these sex specific preferences may not relate to facial form and instead may be a bi-product of selecting for other characteristics, both behavioural and physical, that are associated with sex hormones. The effect of sex hormones on mandible morphology is evident from studies of castrated animals, for instance Wang et al. (2015) compared the mandible morphology of castrated and non-castrated rhesus monkeys (Macaca mulatta); castrated males were found to have a narrower mandible with a shorter distance between the mandibular rami (Wang et al 2015).

Unfortunately, little is known about mate selection in Britain prior to the Medieval period, although it has been argued that behavioural equality is linked to sexual dimorphism in mate selection criteria (Conroy-Beam et al. 2015). For example, Conroy-Beam et al. (2015) compared female sexual selection criteria across 33 countries (n= 5,389) which were compared to an analysis of gender equality. The 1995 gender empowerment measure was utilised as an index of gender equality for each country. It was reported that sex differences in the overall pattern of mate preference correlated with equality in gender empowerment with a negative correlation between sex differences in mate selection and equality (Conroy-Beam et al. 2015). Furthermore, an analysis of sexual dimorphism in stature was compared with female status and food security among 28 societies. It was reported that a lower sexual dimorphism was associated with higher female status (Gleeson and Kushnick 2018).

A review of the material record looking at sex differences in burial pattern and written records may be used to inform on gender equality in the past and subsequently mate choice. If mandible morphology were to reflect changes in sexual preference, it would be expected that other craniofacial features would exhibit similar reductions in sexual dimorphism. However there have been relatively few studies analysing sexual dimorphism in the craniofacial skeletons of individuals from the time periods of this study, with most studies of sexual dimorphism focussed on other characteristics such as height which is known to be influenced by nutritional status as discussed in section 7.1.2.1. As such without further research it is not possible to determine if the changes in sexual dimorphism reported over time are related to sexual selection or other factors.
7.1.2.3 Dietary Differences

Finally, as demonstrated extensively in the background chapters of this thesis it has been well documented that masticatory activity can affect bone remodelling and subsequently mandible morphology. As such morphological differences in the mandible may be associated with sex specific differences in masticatory activity, diet and dietary consistency. To evaluate this theory, it is necessary to look at other historical and archaeological data that may reveal sex specific differences in diet over time in Britain. Unfortunately, in the written recorded this is difficult to analyse as sources typically refer to the community as a whole and the ‘invisible’ members of a society such as women and children are infrequently mentioned (Moore and Scott 1997, Redfern 2005). Moreover, many bioarchaeological indicators of diet are thought to be influenced by biological sex, such as gout (Dong et al. 2018, Roubenoff 1990) and DISH (Fornaciari et al. 2018, Holgate and Steyn 2016, Kuo et al. 2015). Isotopic analysis, dental caries and dental wear are left as the key means of inferring dietary differences between sex estimation groups, as other archaeological evidence of diet such as the archaeobotanical, zooarchaeological and material record cannot reveal within-group dietary differences. However, the majority of studies which have analysed bioarchaeological indicators of diet among archaeological assemblages in Britain have reported no significant differences between sex estimation groups (Adamson 2004, Bronsall 2014, DeWitte 2010, 2014, Mant and Roberts 2015, Platt 1997, Privat et al. 2002, Redfern et al. 2010, Woolgar 2016), including those among the later time period. Among these later time periods dietary differences between males and females would be expected if the increased sexual dimorphism in this study were related to dietary differences. However as discussed, methods for investigating diet among past populations focuses on the key components of diet such as protein or carbohydrate source or the relative proposition of cariogenic foods consumed. Therefore, these studies ignore many aspects of diet such as food texture which may influence mandible morphology. As such the lack of sex differences in previously published bioarchaeological research does not necessarily rule out the potential of a dietary influence. Without further research it is not possible to determine if the increase in sexual dimorphism over time in Britain is influenced by nutritional stress, sexual selection or dietary differences and may well result from a complex interaction of these factors and others which are unidentified.
7.1.3 Research Question: Does mandible morphology vary in relation to social status?

Social status has been suggested in numerous archaeological studies to be associated with differential access to resources including diet (Colquhoun 2008, Müldner and Richards 2005, Privat et al. 2002, Woolgar 2016). Unfortunately, in this study there was only one sample from the Medieval cemetery and priory at St. Gregory’s in Canterbury, known to include both high and low social status individuals (Hicks and Hicks 2001, Miszkiewicz 2015, Miszkiewicz and Mahoney 2016). Results from this study did suggest that in mandible morphology there were some slight but statistically significant differences between high and low status individuals. Low status individuals had a narrower mandible with a high mandibular body, tall ramus, curved inferior border of the mandible, deep mandibular notch, tall and wide coronoid process whilst in comparison high-status individuals had a prominent and wider gonial angle, shallow and wide mandibular notch, more anterior positioned coronoid process and a wider U-shaped mandible as illustrated in figure 7.1.10. Additionally, when considering sex differences in this sample results from a CVA revealed that in CV1 and CV2 high status females grouped closely with low status females, while there was significant separation between high and low status males. Furthermore, low status males grouped more closely with the high and low status females.

Figure 7.1.10: Morphological differences between high and low social status groups from St Gregory’s Cemetery and Priory. Illustrations showing the morphological differences and slightly more gracile mandible morphology which was reported between high (right) and low (left) social status groups these visualisations are based on the results of CVA and the shape differences represented by CV1.

During the Medieval period it has been extensively documented that individuals of high social status had preferential access to food items, particularly animal protein despite well documented religious restrictions on diet (Adamson 2004,
Breverton 2016, Newman 2001). However, there is bioarchaeological evidence that these restrictions may not have been strictly adhered to, particularly among the wealthy and monastic populations (Adkins et al. 2008, Mülldner and Richards 2005, Spencer 2011). For instance, a high prevalence of Diffuse Idiopathic Skeletal Hyperostosis (DISH) has been recorded among monastic assemblages in Britain and mainland Europe, including St Gregory’s Priory. Although the aetiology of DISH is thought to be multifactorial and poorly understood it is associated with a rich diet and clinically DISH occurs more frequently among individuals with obesity and diabetes (Rogers and Waldron 2001).

Additionally, among the lower classes such as those who would have been buried in St. Gregory’s Cemetery diet in late Medieval Brittan is thought to have been generally made up of cereals in the form of boiled pottage. Pottage would have required minimal masticatory stress. The more gracile mandible morphology recorded among the Cemetery populations therefore is consistent with this form of soft highly processed diet. When animal protein was consumed by the lower classes this would have been in much smaller quantities and poorer cuts of meat which were typically added to the pottage cooked for long periods of time until they were broken down. Higher class individuals however could afford the prime cuts of meat and as the fashion during this period was for large cuts that were roasted, this would have been comparatively a much more demanding diet in regard to masticatory requirements.

There are several possible explanations for the status and sex differences recorded among the St-Gregory’s Priory and Cemetery. As discussed in the previous research questions, sexual dimorphism may be amplified among populations with improved nutritional status. As such the greater difference in mandible morphology between males and females from the high-status Priory burials may reflect consumption of a better-quality diet. Improved nutrition among the high-status individuals may have allowed for the expression of the more masculine morphological traits to be exhibited. This theory may also account for the lack of variation between high and low status females.
7.1.4 Research Question: What is the relationship between dental wear and mandible morphology in British assemblages?

Results from a CVA revealed separation of the three dental wear groups based on CV1 and CV2. As expected, the low dental wear group was typically associated with a more gracile mandible, with a shorter mandibular body, thinner ramus and more oblique gonial angle. and the moderate wear group was associated with a more robust mandible morphology, while the high wear group was associated with a combination of robust and gracile features.

There are several possible explanations for the mixed gracile and robust features of the high dental wear group. Dental wear increases with age, furthermore older individuals typically have lower masticatory force and efficiency (Koc et al. 2013, Mioche et al. 2004b, Mioche et al. 2004a, Peyron et al. 2004). Therefore, these results may reflect the disparity between a mandible which has undergone higher levels of accumulated masticatory force, but a reduction in masticatory efficiency in the years before death. A decrease in masticatory force may result in a reduction in these skeletal stressors and a change to a more gracile mandible in certain features, while retaining some robust features. Analysis showed that as expected and consistent with previous research, individuals from the older periods typically had a higher dental wear score table 5.3.2, and as such the morphological differences between these wear groups may be affected by the dietary behaviours of these different periods. Unfortunately, without an independent age estimation method it is not possible to determine if the individuals in the high wear group represent older individuals, and therefore if mandible morphology or masticatory force is influenced by aging among these individuals.
7.1.5 Research Question: How do linear mandible measurements compare with 3D Geometric morphometric for investigating morphological changes in the mandible

One of the most obvious benefits of 3D GMM analysis is that the effect of size is removed allowing males and females to be analysed together and individuals of unknown sex estimation to be included therefore increasing the sample sizes. Furthermore, the creation of 3D shape visualisations better allows for understanding and illustrating morphological changes. However, beyond the obvious benefits it should be considered if the morphological differences revealed in the 3D GMM analysis were also evident from linear mandible measurements. The linear mandible measurements detailed in chapter 5 section 4 were analysed and compared to the results from the 3D GMM analysis.

Among females over time, only body length was significantly different showing a general decrease over time with Post-Medieval individuals having the lowest body length. Among males four measurements were found to vary significantly between periods. Both coronoid breadth and condyle breadth was highest among Roman males which may relate to the morphological changes illustrated in the 3D GMM analysis. Body length among males also decreased over time although this was slightly lower among Medieval individuals compared to Post-Medieval. Considering the lack of significant differences reported from analysis of mandible measurements it is considered that if only mandible measurements were utilised very little could be inferred about morphological changes in the mandible over time in Britain.

When considering analysis of sexual dimorphism an increase in sexual dimorphism was recorded over time, both in terms of the number of measurements where significant differences were reported and sexual dimorphism percentage. These results are expected as sexual dimorphism is known to significantly influence the size of the mandible and therefore measurements are expected to better reflect sexual dimorphism rather than temporal changes in mandible morphology which are considered to primarily influence the shape of the mandible. Based on these results it is argued that mandible measurements should not be relied upon for analysing morphological differences in the human mandible although measurements are more suitable for sexual dimorphism.
7.1.6 Research Question: How does the level of variation in mandible morphology over time in Britain compare to global geographic variation in mandible morphology?

As illustrated in the results from the PCA, for PC1-PC4 variation was greater among the British archaeological assemblages compared to the geographic sample in Britain. Additionally, the geographic variation was exceeded by the amount of variation reported for most periods. While this amount of variation may be related to sample sizes, as the later periods had larger sample size and only 80 individuals were analysed for the geographic sample. The geographic variation in mandible morphology was also exceeded by the morphological variation reported among the Bronze and Iron Age assemblages where only 84 mandibles were included. As such these results are unlikely to solely reflect sample size. These results are supported by previous studies which have argued that population history does not significantly influence mandible morphology (Cleaver 1937, Hrdlička 1940a, Nicholson and Harvarti 2006, von Cramon-Taubadel 2011). As this was only a minor research question to confirm that morphological variation resulting from genetic influences from migrations and invasions into Britain would not significantly influence results therefore these data will not be discussed further for the purposes of this research.
7.2 Limitations
There are several limitations and criticisms that can be made of this study, the majority of which relate to limitations in time and the nature of the archaeological material with variable preservation and at times limited site information.

7.2.1 Genetic Influence
Pronounced morphological differences were recorded among Roman males, however it is not possible with current evidence to determine if such changes were the influence of diet and behaviour or if they reflect genetic influence associated with the influx of Roman armed forces from a wider geographic region. Comparisons with a geographic sample show that in general there are greater differences present in mandible morphology in Britain compared to the geographic sample, however that does not discount the potential impact of genetic factors.

7.2.2 Pathology
There are a number of pathological conditions that affect the hard and soft tissue which may have influenced masticatory behaviour or mandible morphology. While cases of concurrent AMTL, abscess or other pathological lesions effecting the mandible were excluded from this study there is always the possibility of pathological conditions which do not result in skeletal changes to the mandible. For instance, there are several neurological conditions which can result in loss of strength or control over the skeletal muscles and may influence masticatory behaviour. While there may have been evidence for some of these conditions in cranial and post-cranial skeletal remains, due to constraints in time and the preservation of the skeletal remains it was not possible to consider evidence for pathological conditions other than those affecting the mandible, or where available maxilla.

7.2.4 CVA Vs PCA
While CVA is a valuable analytical tool for comparing group differences, it fails to describe the variation in shape within groups. However, as illustrated in section 6.2.6 PCA results are largely incoherent due to the large sample size and high number of PC’s, each representing little of the total variance in the sample. Similar results were found in previous research by Rando (2011) who reported no significant separation of Medieval and Post-Medieval mandibles based on
PCA. As such neither analytical approach is ideal when considering the sample and research questions of this study. Perhaps with fewer landmarks allowing a simplification of the mandible morphology it may be possible to utilise PCA, however this would require compromising specificity for clarity.

7.2.5 Sample Size and Differential Preservation
It was necessary to make compromises with the sample requirements of this study as when analysing human remains from a wide time period there are different preservation factors to consider. For instance, among Neolithic individuals there is both a low number of excavated remains as well as generally very poor preservation of the skeletal elements. However, when mandibles were intact there were not many cases of pathology or antemortem tooth loss that would have resulted in exclusion of the individuals from this study. On the other-hand with Post-Medieval individuals there are a large number of densely populated sites and preservation of the skeletal remains was generally good. However, prevalence of dental caries, abscesses and antemortem tooth loss was high which made it difficult to find individuals who fit the requirements of the study despite the large number of remains excavated. These preservation factors as well as changes in the population density in Britain during these periods had to be considered and had a significant influence on the available sample size, although for the time periods and geographic regions covered by this study the sample size (777 individuals for 3D GMM analysis) is considered generous for an archaeological study. However, by covering a wide range of periods the ability to focus analysis on a single period and analyse mandible morphology by, for instance geographic region or settlement type is very limited, and only among the Medieval and Post-Medieval assemblages is the sample large enough to potentially allow for this level of analysis in the future.

7.2.6 Age Estimation
After the pilot study it was apparent that preservation of the skeletal elements necessary for an accurate age estimation of adult remains was not going to be present among a sufficiently high proportion of the sample to allow for meaningful analysis and as such age estimates were not included in the methods. However, as has been demonstrated by several studies and discussed in the previous chapters of this thesis, age is known to affect both activity of the skeletal muscles including maximum bite force as well as bone remodelling
response to physical stimuli. Furthermore, as discussed previously dietary changes have been shown to result in rapid morphological alterations to the mandible, and as such analysis of mandibular morphology may only be informing us of dietary behaviours during the last few years or months of an individual's lifespan. Therefore, by not including an age estimation this study cannot reveal any dietary differences between age groups. That said, the restrictions placed on the sample for this study - both the presence of the M3 or alternately sufficient wear on the M2 to determine adulthood (due to increasing prevalence of M3 agenesis over time) as well as not allowing more than two cases or consecutive cases of antemortem tooth loss - acts to restrict the potential age range of the individuals in this study. Combined with the low accuracy and specificity of age estimation methods among adults it is unlikely the inclusion of age estimations into analysis would have allowed meaningful analysis to be conducted.

7.2.7 Sex Estimation
As discussed, acquiring a sufficiently high sample size was one of the main constraints of this study, while originally a confident sex estimation was planned to be a sample requirement it was soon made clear during the pilot study that this would not result in a large enough sample, particularly for the earlier periods where preservation of the skeletal remains was typically poor. As such analysis of sex differences in measurements, dental wear or mandible morphology could only be conducted on a much smaller sample which differentially affected the earlier time periods and may have influenced the results.

7.2.8 Estimating missing landmarks - Reconstruction Error
As detailed in the chapter 5 the error in estimating missing landmarks was carefully considered however there was still some level of error in estimating these landmarks, which may have influenced results. There has been a lack of previous research and standards for interpreting the error associated with such methods. Further research is therefore needed to create a standardised approach for investigating error and determining the acceptable level of error with such methods.

7.2.9 Visualisations
The creation of 3D visualisations to illustrate the shape differences represented by the canonical variates allowed for the statistical analysis to be considered in
terms of biological meaningfulness. While there were several benefits of these visualisations not all canonical variates could be viewed on the same terms, for some visualisations much more obvious shape differences were illustrated and others were very subtle. In the end it was decided that for each question the same \(-/+\) CV would be used for all comparisons. This posed some problems which are evident in the results in chapter 6. For instance, among some comparisons the visualisations represent a much more exaggerated shape change which is not representative of the actual sample, whereas for other comparisons the visualisation produced whilst still slightly exaggerated did at times overlap with the CV1 score of the actual individuals. It is a concern that representing the results in this manner may lead to the data being misconstrued and could mislead readers that these visualisations were accurate of the sample. Furthermore, when analysing sex differences for each time period all visualisations were created and \(+5\) and \(-5\) CV1 which allowed for consistency. However, while the mean differences in CV1 was greater among the Medieval periods compared to the Post-Medieval periods it is apparent in the visualisations produced that the CV1 for the Post-Medieval individuals represents a much more obvious shape difference, these factors all needed to be considered in the interpretation of results.

7.2.10 Before Agriculture
The introduction of domesticated plants and animals in the Neolithic has been found in other studies to be associated with an increase in dental caries and reduction in mandibular robusticity. However, due to availability and preservation Palaeolithic individuals were not included in this present study therefore it was not possible to fully investigate the influence of agriculture on skeletal morphology.
7.3 Future Research
Considering the results and discussion from this study and the limitations discussed in section 7.2 it is apparent that lack of previous research has limited interpretation of results and as such areas for future research need to be considered. Some of this research can be conducted from data collected during this research, others are areas where future research is needed in order to further interpret the morphological changes reported.

7.3.1 Mandible Morphology and Malocclusion
In order to further investigate the effect of a changing mandible morphology of the dental arcade future work will compare morphological changes in the mandible over time with the prevalence and type of intra-dental arcade malocclusions. Malocclusion within the dental arcade was recorded during data collection, unfortunately due to time and word count restrictions it was not possible to include this analysis in the final thesis. Furthermore, it would be good to compare these results with the prevalence of dental caries among the mandibular dentition to further investigate the potential impact changes in mandible morphology and malocclusion may be having on dental health.

7.3.2 Looking to the Future: Living Populations
Future research would benefit from the inclusion of data from modern living populations to determine if the trend in mandible morphology is continuing today and investigate the potential impact which smaller and more gracile mandibles may have on the prevalence of dental pathology and malocclusion among living populations.

7.3.3 Comparing the Development of Agriculture in Britain with Mainland Europe
There has been considerable debate regarding the introduction of agriculture into Britain, as such it would be interesting for future research to investigate this further, by including Palaeolithic Neolithic and Bronze / Iron Age individuals from different sites in other countries. This research should compare both the prevalence of dental caries and changes to mandible morphology to determine if the skeletal and dental evidence support a slower adoption of agriculture in Britain compared to mainland Europe.
7.3.4 Romanisation: The North and South Divide
While present among all periods geographic variation in Britain is likely to have been pronounced during the Roman period, as the spread of Roman troops and Romanisation of Britain was staggered South to North and with Northern Scotland remaining independent and never falling under Roman control. Unfortunately, in this present study restrictions in preservation and sample sizes limited the potential to analyse the impact of differential Romanisation in Britain. Future research would benefit from a larger Romano British sample and include individuals from the North of Britain including sites around the Romano British and Scottish border. This research would also benefit from a continuation of this level of detail among the later periods in order to investigate the continued effect differential Romanisation had on diet, culture and behaviour.

7.3.5 Diet and Social Status in Medieval Britain
As demonstrated among the St Gregory site in Canterbury, morphological differences were present among high and low status individuals, with increased sex differences among the high-status groups. The sample size for this research however was small, and further research particularly among Medieval sites in Britain where there are known, and recorded status differences would be valuable to further explore this relationship. Furthermore, the St Gregory’s assemblages are also associated with monastic differences between the individuals. Further research would benefit from exploring social differences and monastic differences in diet and mandible morphology separately in order to further investigate the effect of monastic dietary restrictions separated from strictly economic influences on diet.
Chapter 8
Conclusion

The purpose of this research was to determine how dietary changes which occurred over time in Britain may influence mandible morphology through bone remodelling and alterations in masticatory behaviour. Previous research has typically restricted comparison to two time periods and utilised linear measurement. By conducting a longitudinal analysis of multiple periods in Britain accompanied by more advanced 3D GMM analysis this research provides a greater insight into how mandible morphology has changed over time in Britain. The key findings of this study are:

How has mandible morphology changed over time in Britain?
- Mandible morphology had become more gracile over time. This is consistent with the majority of the previous literature showing overall an increased height and width of the ramus, lower mandibular body, wider and less prominent gonial angle.
- An increase in gracilisation occurred between specific periods. Reported morphological changes were most pronounced between Neolithic and Bronze and Iron Age assemblages and between the Anglo-Saxon, Medieval and Post-Medieval assemblages.
- Individual period comparisons showed that morphological changes were not always consistent between periods.
- Between the Bronze/Iron Age and Roman period mandibles became more robust - this was most evident among males.

Has sexual variation in the mandible changed over time in Britain?
- Sexual dimorphism increased over time in Britain.
- Sexual dimorphism was evident in 3D GMM, centroid size and linear mandible measurements.

Does mandible morphology vary in relation to social status?
- High status individuals from St Gregory’s Priory had more robust mandibles compared to the low status individuals in the cemetery.
Status differences were more prominent among males compared to females.

What is the relationship between dental wear and mandible morphology in British assemblages?

- Mandible morphology became more robust between low and moderate dental wear groups although high wear groups had a combination of robust and gracile features.

Has sexual dimorphism in the mandible changed over time in Britain?

- 3D GMM analysis is better at analysing morphological changes in the mandible over time compared to linear measurements. Although measurements were valuable in the analysis of sexual dimorphism, 3D GMM analysis still provided more detailed results and visual analysis.

How does the level of variation in mandible morphology over time in Britain compare to global geographic variation in mandible morphology?

- A lower level of morphological variation was reported globally compared to over time in Britain.

The methods and materials employed in this study have provided a novel insight into how mandibular morphology responds to changes in masticatory behaviour and diet, as well as how diet has changed over time in Britain. Results from this study provide a substantial contribution to the growing literature which has investigated how changes in human behaviour can influence skeletal morphology. Considering the results, it is suggested that further research should employ 3D geometric morphometric methods in the analysis of human mandibular morphology, and that future research should not be restricted to the comparison of two time periods/assemblages, or solely focus on major dietary transitions. Results also demonstrate that further work is required to understand how dietary changes influence mandible morphology beyond simply being more robust or gracile.
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## Appendix 1: Publication Plan

Table 1.1: Publication Plan. Table detailing the order and descriptions for publications that are planned from research conducted as part of this thesis, these are shaded in three stages for publication.

<table>
<thead>
<tr>
<th>Title</th>
<th>Brief Description</th>
<th>Suggested Publication</th>
<th>Suggested Submission Date</th>
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</thead>
<tbody>
<tr>
<td>Considerations for the Geometric Morphometric analysis of human mandibular morphology</td>
<td>Details the methods and observer error studies for scanning and landmarking a mandible as well as including key results from the method development studies such as preservation of archaeological mandible and comparison of reconstruction methods. This will be useful for others wanting to analyse mandible morphology should include online access to the landmark coordinates from this study if possible.</td>
<td>Archaeological Science</td>
<td>June 2019</td>
</tr>
<tr>
<td>Masticating in Britain: A geometric morphometric analysis of human mandibular variation over time in Britain</td>
<td>This will provide an overview of the study demonstrating that it was not just the ‘key’ dietary transitions when mandible morphology has changed. Discuss the susceptibility of the mandible to smaller and less well documented dietary changes.</td>
<td>AJPA</td>
<td>July 2019</td>
</tr>
<tr>
<td>Error in landmark based geometric morphometric studies and the lack of standards</td>
<td>Discussion of error in landmark based geometric morphometric studies, threshold for GMM studies, make suggestions for error threshold and how to record and present error.</td>
<td>Archaeological Science</td>
<td>October 2019</td>
</tr>
<tr>
<td>Was arable agriculture in Britain delayed? Morphological changes in the human mandible during the Neolithic and Bronze and Iron Age Periods</td>
<td>Neolithic to Iron Age Britain and investigation of evidence for increased agricultural development during this period including a more in-depth geographical analysis, comparing to results from other studies which investigated agricultural development during the Mesolithic/Neolithic transition.</td>
<td>AJHB</td>
<td>August 2019</td>
</tr>
<tr>
<td>Title</td>
<td>Brief Description</td>
<td>Suggested Publication</td>
<td>Suggested Submission Date</td>
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<tr>
<td>They came, they saw, they masticated: How Roman diet influenced mandible morphology in Britain</td>
<td>Roman Britain in depth analysis a geographical sampling, including urban and rural analysis as well as known military sites to compare diets from differentially ‘Romanised’ assemblages as well as potential genetic factors.</td>
<td>AJPH</td>
<td>October 2019</td>
</tr>
<tr>
<td>Masticating during the British Industrial Revolution: A geometric morphometric analysis of human mandibular variation in Britain</td>
<td>Analysis of morphological changes that occurred during the industrial revolution. As previous studies investigating this have typically focussed on just comparing the medieval and post-medieval periods this study demonstrated that a significant reduction in mandible robusticity was occurring from the Anglo-Saxon period in Britain. Investigate this further including geographical analysis and urban rural comparisons</td>
<td>PNAS</td>
<td>September 2019</td>
</tr>
<tr>
<td>Mandible morphology environment or genetic: A comparison of geographic and temporal variation</td>
<td>Pilot study analysis of geographic sample from the Duckworth and British temporal sample to compare the degree of variation that occurs over time in Britain with geographic variation, also analysis geographic variation to determine if more related populations have similar mandible morphologies</td>
<td>HOMO</td>
<td>March 2020</td>
</tr>
<tr>
<td>Mastication and Malocclusion: Investigating the relationship between mandible morphology and malocclusion</td>
<td>Detail results of a geometric morphometric analysis of mandibular morphology and the prevalence and type of malocclusion within the mandibular dental arcade. These results will be important both for theories of mandible reduction in AMH but also regarding the increased prevalence of malocclusion and orthodontic requirements which is a current health crisis. Malocclusion was recorded for each tooth and included rotation, displacement, spacing and crowding etc.</td>
<td>Archives of Oral Biology</td>
<td>November 2019</td>
</tr>
<tr>
<td>Mandible Morphology and Carious Lesions: Investigating the relationship between mandible morphology and carious lesions</td>
<td>This would relate to the theories for the reduction in mandible robusticity and investigate if as mandibles became more gracile this resulted in an increase in the prevalence of dental caries. Carious lesions on the crown, CEJ and root were recorded</td>
<td>IJPP</td>
<td>December 2019</td>
</tr>
</tbody>
</table>
as part of the secondary data for this thesis but could not be included in the final thesis due to limitations in the word count and timing.

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<tbody>
<tr>
<td>Sex differences in mandible morphology over time in Britain: Diet, environment or sexual selection?</td>
<td>Sexual dimorphism in the human mandible was demonstrated to vary between time periods, further research and discussion is needed to investigate potential environmental or sexual selection pressures</td>
<td>AJHB</td>
<td>February 2020</td>
</tr>
<tr>
<td>Asymmetry in the mandible: Chewing side preference or environmental stressors</td>
<td>An analysis of asymmetry in the mandible over time and between populations, relate this to suggestions that higher levels of fluctuating asymmetry may be related to environmental stressors</td>
<td>Archives of Oral Biology</td>
<td></td>
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</tbody>
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