A Dental Revolution? The intriguing effects of the profound social and dietary changes of the 18/19th centuries on the masticatory system

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Declaration

I, Christopher Martin Silvester 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

Developments in milling technology and an influx of new commodities from the 18th-19th centuries AD transformed the composition of the British diet, foreshadowing the soft hyper-nutritive diets of many 21st century populations. Jaw development is highly plastic and depends on the functional demands placed on the masticatory system, particularly during chewing. A reduction in jaw dimensions and an increase in poor occlusion among modern groups has, therefore, been attributed to the softer diet that emerged during the Industrial Revolution. Consequently, it has been hypothesised that underlying these changes are differences in masticatory behaviour when compared to pre-industrial groups.

This thesis aims to test this hypothesis in order to assess whether a dental revolution, a radical transformation in masticatory behaviours, occurred in the Industrial Period. A method of 3D dental wear pattern analysis called Occlusal Fingerprint Analysis (OFA) was utilized to reconstruct masticatory behaviours from the wear facets of the molar teeth. Dental wear facets reflect the pathways of mandibular movement that occur during the chewing cycle. The facet patterns of the lower second molars of individuals from the Industrial period (n=104; 1700-1900AD) were compared to a pre-industrial sample dating to the Mediaeval and Early Post-Mediaeval periods (n=130; 1100-1700AD). Dynamic virtual simulations of the chewing stroke were also undertaken for a subset of individuals from each period (n=32).

Significant differences in dental wear facet patterns between the two groups indicated that masticatory behaviours were altered in response to changing dietary composition; there was a shift to a more vertically directed chewing action as foods became softer and more heavily processed during the Industrial era. The research confirms the fundamental role food properties play in shaping mastication and, consequently, addresses the underlying mechanism responsible for the changes in occlusion and jaw morphology that have occurred over the past three centuries.

Impact Statement

Dentistry is confronted with the functional and aesthetic consequences that result from problems in dental occlusion, how the teeth fit together. Individuals from industrialised societies are characterised by higher levels of poor dental occlusion than their pre-industrial antecedents. The aetiological factors responsible for this increase have been a concern of dentists and dental anthropologists since the early 20th century. The current research provides evidence that changes in chewing behaviour were responsible for the reduction in jaw size in modern groups as dietary content became softer. This may inform orthodontic and oral rehabilitation treatments aimed at improving masticatory function by highlighting the foundational role the physical properties of the foods consumed play in the development of the masticatory system. The public's perception of any occlusal problems they might have may also be altered by placing them in the context of malocclusion becoming the norm in modern times as dietary composition has shifted.

Previous research has highlighted the impact of transformed working practices, urbanisation and overcrowding on the state of health of Industrial-era British populations. The research provides further insights into the physiological ramifications of industrialisation and highlights how this process not only remade the socioeconomic fabric of society but also had biological consequences.

The fragmentary and distorted condition of skeletal and fossil material often prevents the characterisation of dental occlusion using methods from dentistry. The current research has indicated that the 3D analysis of occlusal wear facet patterns can be used to reconstruct both static and dynamic occlusion in a bioarchaeological context and could provide a method suitable for the investigation of changes in patterns of occlusion through time.

The variability in dental wear facet patterns in anatomically modern humans has not been extensively assessed. As such, the current research will provide useful comparative material that will add to the growing scholarly work interested in using dental wear facet patterns to make inferences about dietary content. The skeletal assemblages examined have detailed historical and archaeological records of the foods they consumed and can be used to make inferences about groups that are less well documented. The current research has showcased the potential for using OFA as a method to complement other techniques more commonly employed to reconstruct diet in the past.

The generation of high resolution virtual three-dimensional models of teeth was an essential component of the current research. A rigorous methodological assessment of structure-from-motion photogrammetry, a technique of 3D model generation that only requires access to a conventional camera and appropriate software, was performed to determine whether this cheaper and more widely available method provided a suitable alternative to a high-resolution structured light 3D scanner. Photogrammetry did not result in satisfactory virtual model quality for the current research, however, the overall geometry of the teeth was effectively reconstructed. This methodological assessment may be of relevance to other researchers interested in generating 3D models of small topographically complex objects. These results were presented in the American Journal of Physical Anthropology alongside the workflow used and examples of the 3D models generated.

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1 Introduction

Food satisfies the nutritional requirements of human existence. Humans can eat a variety of foods so can adapt their dietary regimes to whatever is available. On the other hand, as humans have certain minimum dietary requirements, a minimum of dietary variability needs to be maintained. This has been called the 'omnivore's paradox'. An oscillation occurs between an interest in new foods, which may be essential to survival, and a conservative distrust of unknown foods, which may be potentially dangerous (Fischler 1988; Rozin 1999).

The production, distribution and consumption of food are not solely a biological concern. They are essential and active in the creation and maintenance of social groups and their boundaries (Appadurai 1981; Mintz and Du Bois 2002). In the human past, major transitions in diet and food production practices have been associated with marked transformations in the social, political, economic and physiological characteristics of societies and the people that make up those societies (Goody 1982; Mintz 1985). Two major periods of change characterise the story of human eating over the past 10,000 years. The first is the transition between the Mesolithic (9500-4000 BC) and Neolithic periods (4000-2300 BC). A dramatic change in subsistence economy took place in Britain. Hunted and foraged resources were gradually replaced by domesticates, comprising new plant and animal resources. An agricultural mode of subsistence became dominant (Gron *et al.* 2020; Richards and Hedges 1999; Schulting 2015).

It has been estimated that this dietary shift resulted in a reduction in the nutritional diversity of the foods consumed and the emergence of a heavy reliance on starches for dietary calories (an estimated 50-70%) (Luca *et al.* 2010). The "Age of Starch" (S Hillson 2020, personal communication) persisted from the Neolithic period into the Post-Mediaeval period (AD 1550 to present). Despite this overarching reliance on starches, spatial and temporal variation in the technologies of food production and the types of foods consumed were apparent. The dietary patterns of agriculturalists have been associated with changes in the dentition and masticatory system when compared to hunter-gatherers, who often consumed tougher and more fibrous foods (Kaifu 1999; Smith 1984).

A second dietary revolution swept across Europe during the 18th and 19th centuries AD alongside revolutions in industry, agriculture and transportation

(Knapp 1988). The English diet had been remade by the close of the 19th century (Mintz 1985). Food production had been transformed into a highly mechanised and large-scale industry producing increasingly heavily processed and standardised foods (Burnett 1989; Drummond and Wilbraham 1957). New transport networks and technologies enabled the development of national and global networks of food production and consumption. This largely supplanted the localised regimes of production that characterised earlier periods. An influx of new commodities, embedded within an emerging colonial world system, were incorporated within the British diet (Goody 1982; Mintz 1985). Sugar, tea, potatoes and heavily processed white bread became essential dietary staples (Burnett 1989; Collins 1975). Sugar, in particular, became a major source of calories. The cultivation of sugar cane in the Caribbean and South America and its refining and export encouraged the growth of global corporations equivalent to the enormous 20th Century development of commodities, such as bananas, which to this day has profound social, economic and political consequences (Mintz 1985; Striffler and Moberg 2003).

These dietary changes had profound implications for how people experienced food and how food was mobilised to realise social identities and define group boundaries (Bickham 2008; Hastorf 2017). Modern eaters are often reduced to mere consumers with much of the preparation of food occurring outside the household. The origin and methods of production of these foods are largely unknown. Economic and technical changes in food preparation occurred concurrently with shifts in lifestyle that altered the social conditions in which foods were eaten and the ways in which culinary systems were used to define social groups (Fischler 1988). This can be considered the age of sugar and processed foods, which continues into the 21st century where soft hyper-nutritive diets are consumed by industrialised groups (Burnett 1989; Cordain et al. 2005; Kaidonis et al. 2014).

The radical dietary changes that occurred in the 18th and 19th centuries were inscribed upon the masticatory system. Craniofacial development and facial dimensions are partly dependent on the action and function of the jaw muscles during mastication (Kiliaridis 2006; Weijs and Hillen 1986; Yamada and Kimmel 1991). Heavily processed diets reduced the biomechanical demands placed on the masticatory system during oral processing and had implications for its growth and development. A reduction in the dimensions of the jaws occurred (Corruccini 1984; 1999; Rando et al. 2014). In addition, rising sugar consumption and greater access to cariogenic white bread have been associated with higher prevalence rates of dental caries (Corbett and Moore 1976; Mant and Roberts 2015; Whittaker and Molleson 1996). The human dentition is arguably evolved and adapted to function under the premise of heavy attritional tooth wear over the course of an individual's lifetime (Kaifu *et al.* 2003). The retention of relatively unworn tooth morphology late into life in early industrial and modern groups means that the compensatory mechanisms that adapt the physiological function of the dentition as dental wear occurs are not as active as they were during the bulk of human evolution (Kaidonis *et al.* 2014). The bone of the jaws remodels in response to the forces acting on it and the less energetic dental function has led to a mismatch between jaw size and tooth size which results in poorly fitting and functioning dentitions.

Greater occlusal variability, including the misalignment and overcrowding of the dental arches, has been associated with modern industrialised populations and their 18th-19th century antecedents (Begg 1954; Corruccini 1984; Corruccini 1999; Hunt 1961). An 'epidemiological transition' in patterns of dental occlusion has been intimately linked to the adoption of more heavily processed diets (Corruccini 1984). Among modern groups transitioning to industrialised dietary regimes, the crowded and misaligned dental arches of the industrialised component are in marked contrast to the predominantly well-aligned occlusal relationships of those retaining more traditional dietary practices (Corruccini and Whitley 1981; Corruccini *et al.* 1983). These changes cannot be principally explained by genetic factors given the rapid increase in the prevalence of malocclusion over one or two generations. Changes to environmental stimuli are critical to the increased prevalence of occlusal variability in industrialised groups (Corruccini 1999).

The phenotypic changes that have affected the masticatory system as a result of the adoption of a more heavily processed diet during and following industrialisation can be summarised as changes in mandibular morphology, retention of unworn dental forms late into life and an increase in occlusal variability (Corruccini 1999; Kaidonis *et al.* 2014). The mechanisms underpinning these phenotypic changes are largely related to shifts in masticatory function, which have been explored using clinical and animal studies of masticatory development and behaviour (Kiliaridis 2006; Yamada and Kimmel 1991). Human feeding studies have also identified variability in masticatory behaviours in response to changing food properties (Woda *et al.* 2006). Identifying how human oral processing behaviours have changed in response to the dietary transitions that have occurred over the course of human history is fundamental in explaining the changes in the masticatory system that have been reported by previous studies (Hanihara *et al.* 1981; Hirst 2019; Shiono *et al.* 1982; Rando *et al.* 2014). It is also important in explaining the epidemic of occlusal problems seen in the 21st Century. This thesis proposes methods for identifying these changes and attempts to contrast masticatory function in people eating industrialised food products with people for whom such products were not available.

The overarching hypothesis to be tested is that the profound dietary transition that occurred in Britain during the Industrial period (AD 1700-1900) impacted masticatory behaviours. This critical period forms one of the key dietary transitions in the story of human eating over the past 10,000 years. The project aims to discover whether the dramatic changes in dietary content and consistency in the Industrial period were accompanied by a Dental Revolution, defined as a radical shift in the functional use and demands placed on the dentition. Furthermore, this investigation should provide insights into the impact of contemporary heavily processed diets on the masticatory system.

The impact of this transition could only be highlighted by comparing archaeological assemblages from the Industrial period, including people with low wear rates, with assemblages containing people whose diet came from traditional agricultural subsistence practices. Mediaeval and early Post-Mediaeval groups (AD1100-1700) are temporally the most proximate traditional agriculturalists to the Industrial period. Consequently, assemblages from these periods made the best comparative material against which to compare later assemblages from urban contexts whose heavily processed diet came from industrial sources. This choice is supported by published arguments that mediaeval individuals present less frequent and less marked occlusal variability than industrial groups alongside higher rates of dental wear (Evensen and Øgaard 2007; Hanihara *et al.* 1981) and have jaws that are more robust (Rando *et al.* 2014).

The current research used a method of 3D dental wear pattern analysis, called Occlusal Fingerprint Analysis (OFA) (Kullmer *et al.* 2009; Kullmer *et al.* 2020), to make a quantitative comparison of occlusal contact and jaw movement between the Mediaeval and early Post-Mediaeval periods (AD 1100-1700) and the Industrial period (AD 1700-1900). Repeated patterns of jaw movement and contact create highly polished planar wear areas called dental wear facets. The jaw movements responsible for creating them during the chewing cycle can be reconstructed from their orientation and inclination (Kullmer *et al.* 2012). Wear facets have been used to infer the inclination and orientation of the chewing cycles of extinct and extant mammals (Koenigswald *et al.* 2013), to reconstruct occlusal relationships (Benazzi *et al.* 2013a; Kullmer *et al.* 2013) and to compare the dietary and masticatory behaviours of hominids (Benazzi *et al.* 2013b; 2016; Fiorenza *et al.* 2011a; Fiorenza *et al.* 2018; Zanolii *et al.* 2019). Dental wear facet analysis was expected, therefore, to provide an effective method for addressing functional shifts in use of the dentition during the key dietary transition being studied here.

Previous studies that have utilised OFA have mainly focused on larger scale or otherwise prominent dietary contrasts, which would result in more marked modifications of masticatory behaviour. This has included comparisons between modern hunter-gatherers, eating either meat-based or more mixed diets, agriculturalists from the early Neolithic, and Neanderthals and early anatomically modern humans from different geographic regions (Fiorenza *et al.* 2011a; Fiorenza *et al.* 2018). The potential for OFA to be used as a tool to reveal variation in dietary content and masticatory behaviours at a smaller scale, such as within skeletal assemblages, has not yet been extensively explored. The richness of historical and archaeological evidence for different dietary practices in the Mediaeval, Post-Mediaeval and Industrial periods holds the potential to explore less marked yet historically described differences in food consumption within each period. The project will also offer comparative data sets which will contribute to assessing the variability in modern human dental wear patterns by providing a larger sample than has been typical of previous studies that have utilised OFA (e.g. Fiorenza *et al.* 2011a; n=73).

To address the research questions, this thesis is structured as follows: Chapter 2 begins by discussing how food and eating provide the foundation of many of the social encounters that occur each day as well as satisfying nutritional needs. The ways in which these perspectives can be applied to bioarchaeological investigations of dietary change are considered. The nature of the dietary changes that occurred during the Mediaeval, early Post-Mediaeval and Industrial periods are then explored. Shifts in the physical composition of the foods eaten are considered alongside how they were mobilised to negotiate social status, adhere to religious proscriptions and define household and national communities. The anatomy and function of the masticatory system, chewing cycles, occlusion and dental morphology are described in chapter 3. The mechanisms responsible for the formation of dental wear are considered and the utility of using dental wear facets to reconstruct masticatory behaviours presented. Following the literature summary, chapter 4 presents the research questions of the thesis. The material and methods used in the thesis are detailed in chapter 5. A description of the composition and historical context of each skeletal assemblage included in the current study is given. OFA requires the generation of high-quality 3D models of teeth. Structure-from-motion photogrammetry, a method of producing a digital surface scan of an object using conventional photography, was critically assessed as a cheaper and more widely available alternative to the high-resolution structured light scanning systems conventionally used in OFA studies. The results of this methodological assessment are provided in this chapter. Chapter 6 presents the results of the thesis structured using the research questions. These results are then discussed in chapter 7 and a final conclusion and synthesis are presented in chapter 8.

2 The Remaking of the English Diet

2.1 Beyond Feeding: Theoretical Framework

An understanding of food as socially active is an essential component of any exploration of dietary change in an archaeological context (Holtzman 2006). Foods are more than simply the nutritional basis of existence (Richards 1932; Rozin 1999). The types of food eaten, the context in which they are eaten, and the persons they are eaten with shape social encounters and the human, and even non-human, relationships that emerge from them (Fischler 1988; Holtzman 2006; Meigs 1988; Rozin and Vollmecke 1986; Strathern 2012; Yates-Doerr and Mol 2012).

The acquisition, processing, distribution and eating of food create interdependence as well as division within communities and households (Malinowski 1929; Radcliffe-Brown 1922; Robertson Smith 1889). Culinary etiquette and the perceived appropriateness of foods for consumption can create and reinforce particular social and gender roles and actively establish social boundaries between humans and their wider social worlds (Douglas 1972; Levi-Strauss 1965; Richards 1939). Among the Southern Bantu of Central Africa, Richards (1932) observed that the socialization of children within communal life, and the experience of the relationships between age-sets and the sexes, was inextricably embedded within the distribution of food. The sharing of meals and the distribution of meat occurred according to strict kinship principles as well as forming crucial elements of marriage contracts and religious activities. How a meal is structured, who it is eaten with and how it is eaten will determine the social exchanges associated with it (Douglas 1972; 1982). As such, the foods eaten may transform how an eater is identified and recognised within society more broadly and associate them with particular social groups and gender identities (Meigs 1987; Mol 2008; Strathern 2012).

The foods consumed can be one of the strongest markers of social status, class and ethnicity. The primary value of food items as nourishment may be subsidiary to their role as objects of social ambition, rivalry and emotion (Evans-Pritchard 1969; Richards 1932; Weismantel 1988). Food avoidance centred upon the repulsive sensory qualities, the anticipated harm of ingestion or the perceived negative attributes of a potential food can also feature prominently in the articulation of class identity (Rozin and Fallon 1987; Simoons 1994). Appadurai (1981) described the conflict and competition that emerge from social transactions around food as 'gastro-politics'. The terms of this gastronomic competition are largely defined by the availability of resources, the time and energy required to prepare the foodstuff, the context of its consumption, the social groups it is customarily associated with, and the history and geography of its production and consumption (Fraser 2016; Goody 1982; Mintz 1985; Mintz 1996; Robb 2007). For example, Northern Ghana became involved in a global system of exchange from the 1830s onwards. During this time, methods of cooking and food defined as 'European' became associated with formal occasions and were involved in the definition of a new elite political class responsible for the administration of the emerging nation state of Ghana (Goody 1982). As new foods and processing methods are introduced, the ways in which foods are used to define different social groups and the hierarchical relationships between them frequently changes (Sutton 2001).

Food can also be important and active in the experience of national life. The nation can be defined, following Anderson (2006), as an imagined political community comprising members that, despite not knowing each other directly, share a sense of communion. Food frequently plays an active part in this shared communion. Individual feelings about certain foods must be mobilised to create a national cuisine when eaten with sufficient frequency that the eaters regard themselves as experts on them (Hobsbawn 2012; Mintz 1996). Access to new supplies of cheap cod from the North Sea, which could be transported inland by the extensive rail network, enabled the widespread consumption of fish and chips across Britain by the close of the 19^{th} century (Burnett 1989). This overcame previous dietary regionalism to provide a dish that allowed disparate communities to experience a unity of national consciousness when eaten. Food permeates most aspects of social life and has been theorized as constitutive of group membership, class aspiration, gender, nationhood, and ethnicity (Appadurai 1981; Mintz and du Bois 2002).

Anthropological approaches can inform bioarchaeological perspectives on feeding and eating (Figure 1). Food as material culture is predominantly destroyed as it is incorporated into the body during the transformative process of ingestion, therefore, human remains provide an important data source when investigating the types of and manners in which food was consumed in the past (Dietler 2010; Gumerman 1997). Attempts can be made to interpret the roles foods might have had within the social existence of the communities studied and to discuss how culinary and food producing activities may have been active in the creation and demarcation of different social groups (Hastorf 2017). Within bioarchaeology, the resolution to which different types of eater within a given skeletal assemblage can be identified varies depending on the methods used.

The skeletal and dental tissues of the eater are formed by the foods they have consumed over the course of their lives. Stable isotopic ratios of carbon (δ13C) and nitrogen (δ15N) reflect the isotopic ratios of the foods ingested and have been utilised to reconstruct the diets of past groups (Lee-Thorp 2008, Schoeninger 2014), identify dietary transitions (Guo *et al.* 2018; Homes Hogue and Melsheimer 2008) and identify dietary differences within skeletal assemblages (Ambrose *et al.* 2003; Dhaliwal *et al.* 2020). Isotopic ratios of carbon (δ13C) reflect the proportions of plants with a C_3 photosynthetic pathway and a C_4 photosynthetic pathway that an individual consumes. Most plants utilise a C_3 pathway, however, several grasses adapted to hot and arid environments, such as maize or millet, use a C_4 pathway. This has been used to track the uptake of maize cultivation across North America (Makarewicz and Sealy 2015; Vogel and Van Der Merwe 1977). Isotopic ratios of carbon may also indicate differences in the quantities of marine foods eaten. C_4 plants were not widely used in Europe or Asia so differences in isotopic values observed between and within archaeological groups are typically limited in a European context to discussions of the quantities of meat and marine resources being consumed (Schwarcz *et al.* 2010). Variation in δ15N is largely dependent on the number of steps from the start of the food chain, the trophic level effect. Thus, δ15N values are greater in carnivores than herbivores and in marine rather than terrestrial species, as marine environments typically incorporate a greater number of trophic levels.

The teeth and mouth are at the forefront of eating. The mouth is the threshold by which persons incorporate the world around them and are continually transformed by it (Falk 1991; Rozin 1999). Acts of eating are, therefore, inscribed upon dental surfaces. The imprint of the foods eaten are visible in macroscopic and microscopic wear patterns across the enamel and, where exposed, the dentine (Ungar 2015). The masticatory system also changes plastically in response to the demands placed upon it during chewing and non-masticatory tooth use (Corruccini 1999; Sofaer 2006). The distribution of dental pathology may also reflect dietary content, such as the increase in the prevalence of dental caries associated with the increased sugar consumption characteristic of industrialised groups from the 19th century onwards (Hillson 2001; Mintz 1985). Consequently, dental evidence can be utilised to reconstruct the kinds of eaters present within and between groups. Dental evidence not only attests to the mechanical qualities of the food eaten but also reflects the confluence of technologies of production, regional, national and global identities, social competition and aspiration.

In the current research, dental evidence was used to examine how the process and experience of eating was altered by the dietary changes that occurred during the Industrial period in Britain (1700-1900AD), the implications this had for the masticatory system more widely, and whether dental evidence can be used to identify the different eaters present within and between skeletal assemblages (Figure 1). Historical and archaeological evidence describing the foods eaten in the Industrial period, and the Mediaeval period used as a comparator, are extensive. This provided an opportunity to examine whether the historically and archaeologically described ways in which food socially differentiated individuals in each period could be identified and further elaborated using dental evidence.

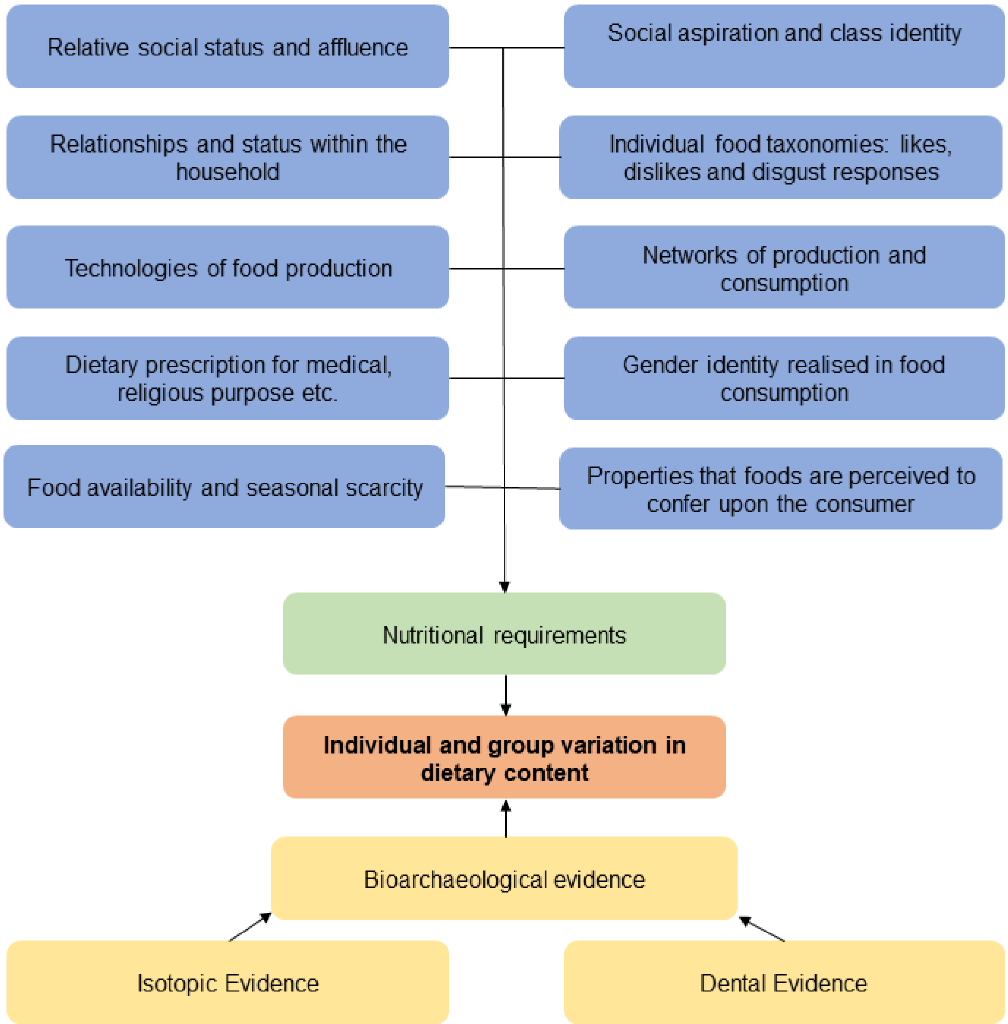


Figure 1: Factors that may influence dietary composition and experiences of eating in human groups and bioarchaeological evidence that can be used to make inferences about individual and group differences in eating practices in the past.

2.2 Eating and Dietary Change in the Mediaeval and Post-Mediaeval periods

The consumption of increasingly processed foods and a growing reliance on sugar for dietary calories characterised the transition between the Mediaeval and the Industrial periods (Drummond and Wilbraham 1957). Despite this, commonalities existed in many of the dietary staples consumed. Underlying changes, however, did occur in the social experience of eating these foodstuffs (Fischler 1988; Mennell 1996; Mintz 2009). Consumers became enmeshed in broadening networks of production (Goody 1982). These changes anticipated the soft hyper-nutritive diets of 20th and 21st century industrialised groups and reflected a key turning point in the history of eating for anatomically modern humans. This is in stark contrast to the diets that predominated for the majority of hominin evolution, which were determined by local resource availability and were rich in non-cereal plant resources (Cordain *et al.* 2005; Kaidonis *et al.* 2014).

2.2.1 Mediaeval and early Post-Mediaeval periods (AD1100-1700)

2.2.1.1 Dietary staples: cereals and milling technology

The bulk of the mediaeval diet was constituted by field crops. Between AD 1250-1540, it has been estimated that 80% of a harvest labourer's calorific intake, 78% of a soldier's and 65-70% of the lay nobility's diet was made up of cereals (Murphy 1998). Consumption was principally in the form of bread of highly variable quality and composition and ale. Among poorer sections of society, this was also in the form of pottage; a thick soup (Stone 2006). The social and religious centrality of bread was inculcated within Christian religious practices, such as the call for daily bread within the Lord's Prayer and the transubstantiation of bread into the body of Christ during the Eucharist (Rubin 1991; Woolgar 2016).

The status of the eater was reified by the types of bread consumed, whilst the hierarchy of bread flours was simultaneously reified during every act of eating (Keene 1998; Woolgar 2016). Wheat was regarded as the premier grain and was typically consumed by great lay and ecclesiastical lords. Wheat was considered the most digestible flour and, therefore, was the most appropriate for the upper classes (Mennel 2010). Different qualities of wheaten bread could be produced depending on the extent to which the flour had been sieved and the amount of bran discarded (Stone 2006). The proverb 'good service will receive paindemaine', the fine white wheaten loaf of great households, further illustrated the social value and aspirational qualities with which luxury loaves were imbued within Mediaeval consciousness (Woolgar 2016). Among the lower classes, darker and coarser loaves were predominant. Rye and maslin, a mixture of rye and wheat, produced bread of a darker hue and inferior value. A still coarser and cheaper bread was made from the milling and baking of oats, barley and occasionally peas (Stone 2006). Coarser and denser barley loaves were more commonly eaten by the poor and often distributed as alms (Woolgar 2011).

From the 13th century until the 19th century, the Assize of Bread regulated the sale of bread. The price of each kind of loaf was fixed and therefore, as the price of grain rose, the weight of the loaf was reduced. The size of each loaf was inversely proportional to the price of grain (Stone 2006). The operation of the Assize was variable between regions as inspection was conducted by individual municipalities. The prices of grains at the corn market were set annually after the Feast of St Michael (Ross 1956).

Furthermore, in urban contexts fraudulent practices were relatively common, chiefly involving the modification of the content, weight and price of loaves, particularly in times of dearth. This fraud was dealt with under the Assize of Bread. The Londoner John de Strode in 1323, for example, was consigned to the stocks for using sweepings and dirt from his boulting house for making bread. In 14th century London, a demand for better quality 'wastel' (white) loaves grew and regulations in 1378 ordered the bakers of wheaten loaves to bolt their flour twice through successively smaller sieves as poor milling otherwise left small particles of grit in the grain (Rawcliffe 2013). Fraudulent practices may have further increased the coarseness of the mediaeval loaf and also rendered the composition of the bread consumed highly variable.

During times of poor harvest and when the price of grain was high, less affluent families would use inferior grains and maximise their use of seasonally available foods (Dyer 2006). Beans, peas and acorns were used to make the cheapest bread in times of dearth (Briers *et al.* 1993). In *Piers Plowman*, an allegorical narrative poem written in the 14th century, Piers lamented the dearth of food before the harvest. He was reduced to two loaves of beans and bran for his infants and green cheeses and an oatcake without any meat (Langland and Pearsall 1978). Archaeobotanical evidence indicates regional differences in cereal cultivation, with variable proportions of wheat, barley, oats and rye, likely pertaining to variation in soil geology and growing conditions (Rippon *et al.* 2014). In northern counties, the main crop was oats. Milk was more readily available in rural areas and often used to make pottages (Drummond and Wilbraham 1957).

Access to finer and more prestigious loaves was increased for many survivors of the Black Death in the 14th century. In 1346, the labourers and permanent manorial staff of the demesne farms at Cuxham, Oxfordshire, received the poorest part of the threshed wheat, barley and peas as their allowance. Following the Black Death from 1347, the provision of wheaten bread for the labourers expanded, and the use of peas ceased and there was a relative decline in the cultivation of cheaper bread grains (Keane 2012). Similarly, at Sedgeford, in 1256 harvest workers received 2.8 pints of ale a day and mainly barley bread. This had increased to 6.4 pints of ale a day and bread almost entirely of wheat in 1424 (Stone 2006).

Mediaeval milling produced a coarser and less absorbent flour with a comparatively lower water content than that of later periods (Stone 2006). Grains were pulverised to form a coarse mixture containing all parts of the grain, including a good deal of finely ground bran and most of the germ (Drummond and Wilbraham 1957; Perren 1990). Manorial mills would have been either water or wind powered during this period (Watts 2002). Millstone fabrics were highly variable but were commonly composed of sedimentary rock with a high silica content. Until the 18th century, mill stones were typically monolithic and cut and shaped in one piece at a quarry (Tucker 1977). The most widely used native millstone fabrics included “Welsh Stone”, a sandstone conglomerate from the Lower Wye Valley commonly used in western England, and “Millstone Grit”, a coarse sandstone derived from the Pennines more typically used in the Midlands and the North of England. “Penna” millstones cut from greensand from a quarry likely located in Pensel Wood, Somerset, were also frequently used in Southern England (Farmer 1992). Stones imported in quantity from the continent were commonly cut in one piece from basaltic lava in the Niedermendig district of Western Germany. These stones were exported from Cologne and got their nickname 'cullens' for this reason. They were widely used in the East and North of England (Farmer 1992; Watts 2002). A study reported higher quantities of detrital quartz and feldspars in Millstone Grit relative to sandstones from the Wye valley and greensand from Somerset, which may influence the quantities of exogenous abrasives incorporated within the final bread produced (Hawkins and Mcconnell 1992). The stones listed were probably restricted to use in manorial demesne mills rather than peasant mills; peasant mills would have likely relied upon cheaper local stone for milling (Farmer 1992).

Following grinding, the meal was shaken through a *teme*, a hand-held sieve made from either wool or linen. Many of the coarser particles, however, were retained in the flour. Hand sieving persisted until the close of the 17th century when automatic bolters were introduced to the mill machinery (Petersen and Jenkins 1995).

The use of querns was controlled in the late Mediaeval period to protect manorial incomes, as demesne farmers would have to pay for the privilege of using manorial mills. Despite this, it is estimated that 20% of milling in 14th century England was still performed using hand mills and confiscation of quern stones was common. In the early 14th century, Abbot Richard of St Alban's had confiscated enough quern stones to pave the parlour floor. Many of the hand mills used were pot-querns, introduced in the Middle Ages, which consisted of a lower stone with a cylindrical recess into which the upper stone was fitted. The querns were often dressed with a pattern of furrows and the ground flour was ejected through the central spout (Briers *et al.* 1993; Watts 2002).

Mediaeval loaves would have had a harder and firmer crumb and included greater quantities of abrasive particles from the milling process than the loaves produced following technological changes in milling during the Post-Mediaeval period (Schmiele *et al.* 2012). This is inferred by the more extensive dental wear that has been reported among assemblages dating to the Mediaeval period relative to assemblages dating to the Industrial and modern era in a global context (Evensen and Øgaard 2007; Kaifu 2000; Moore and Corbett 1973). A decrease in masticatory activity has also been inferred from the Mediaeval to the Industrial period from a narrowing of the mandibular body and a reduction in the robusticity of the attachment sites of the major muscles of mastication (Kaifu 1997; Rando *et al.* 2014).

2.2.1.2 Garden produce and wild foods

The dietary habits of the Mediaeval period were embedded within localised regimes of production. Gardens were a crucial part of the Mediaeval English economy and reified the social hierarchy; the well-stocked and managed gardens of the aristocracy were in marked contrast to the small parcels of land used by the peasantry for their subsistence needs. Peasants supplemented their diets with onions, peas and leeks grown on small garden plots. (Dyer 2006). The majority of individuals would probably have had access to such a plot, but the contribution of garden produce was not sufficient to overcome periods of dearth in dietary staples.

Pottage was eaten daily by all classes and was a mainstay of the mediaeval diet. Many were just a broth or stock in which meat or vegetables had been boiled.

The commonest pottages involved only vegetables such as onion, leek and cabbages (Brears *et al.* 1993). Lipid analysis of pottery fragments from Raunds, Northamptonshire, associated with a small mediaeval manor and hamlet dating from the 12th-14th centuries, yielded residues indicative of the stewing of brassicas. The residues co-occurred alongside ruminant carcass products suggesting the use of pottery vessels for the production of stews and pottages. Cereals were likely also included in these pottages; however, they are poorly represented in residue analysis due to their meagre lipid content (Dunne *et al.* 2019).

Larger institutions, such as monasteries and cathedrals, also obtained dietary supplements from gardens. The Blackfriars of Gloucester, for example, had access to a garden for producing fruit and vegetables (Palmer 1892). A 15th century cellarer's account of Durham Cathedral priory garden detailed regular payments for the purchase of seed, which was most frequently onion seed. A pig garden, rabbit warren, fishpond and orchard in the grounds were also referenced. Apples and pears from orchards were frequently used in their culinary preparations (Keene 2012; Woolgar 2016). Access to vegetables and fruit would have been possible for the bulk the population during the Mediaeval period and would have been most readily available during the summer and autumn (Dyer 2006). Excessive consumption of green vegetable and salad foods, however, was discouraged. John Russell's *Boke of Nurture* warns that a sensitive stomach may result from eating salad and green foods (Woolgar 2016). Aristocratic households shunned vegetables that were regarded as foods of the poor, such as onions and leeks. These foods were, however, included in the ascetic diets of the elite during the season of Lent (Dyer 1994).

All social strata were subject to periods of seasonal scarcity and experienced fragility of food resources during the Mediaeval period (Mennell 1996). Despite this, the lower ranks of society experienced these periods of dearth more strongly than the upper echelons of society. Wild foods were used as fall-back foods in times of scarcity and formed an important resource within demotic cuisine (Dyer 2006; Woolgar 2016). The hungriest time was typically from May to June prior to the harvest during which the poor would likely pick green peas in open fields to supplement their diets (Dyer 2006). Peasants collected nuts, such as hazelnuts and chestnuts, as a supplementary food during autumn and winter (Moffett 2006; Woolgar 2016).

2.2.1.3 Meat and dairy consumption: seasonal abundance and elite excess

Acts of eating formed a principal axis along which the capacities of eaters as social actors were recognised and negotiated. In addition to the importance of the types of loaves consumed, the quantities of meat and fish consumed differentiated elite eaters (Mennell 1996).

The diets of the upper classes were characterised by exorbitant meat consumption compared to the sporadic, often seasonal consumption of bacon by the peasantry (Keene 1998; Woolgar 2016). In October 1420, an ordinary member of the Earl of Warwick's household consumed approximately 1.84lb of beef and 1.28lb of mutton during the two meals of the day (Woolgar 2006). The exclusivity of meat consumption was codified in AD1363 by legislation restricting individuals of the rank of groom or below to one meal of meat or fish a day; allowance of foodstuffs such as milk, cheese and butter were given according to an individual's estate. Individuals worth less than 40 shillings were expected to not eat excessively and consume foods appropriate to their means (Drummond and Wilbraham 1957). Feasts were a prominent site of conflict and competition centred on food in the Middle Ages. Attending a feast consolidated the communal and social bonds of those that ate together. Simultaneously, opportunities were engendered for the negotiation of social hierarchies through the seating arrangement and the types of, and manner in which, the food was served (Kjær and Watson 2010).

The hunting, killing and eating of certain wild animals were restricted to certain social classes from AD1066. The household book of the Earl of Northumberland (c.AD1512) indicated that only the Earl was permitted to eat cranes, herons, mallards, woodcocks and seagulls. Only those at his table could eat plovers (Woolgar 2016). Meat was a key foodstuff in the consumption behaviours used to concretise the identities of mediaeval elites to the exclusion of the peasantry (Mennell 1996).

In contrast, peasant households often reared pigs as a 'live savings bank' (Burnett 1989; Woolgar 2006). Pig remains from Mediaeval York typically belong to younger individuals and probably represent animals kept in backyards and open areas in the city (O'Connor 2000). In London, animals were brought to the city from across the country in complex exchange networks. Many animals likely came from at least 100km from the city. Faunal remains indicated that meat from cattle was predominantly consumed in the city rather than that of sheep/goat or pigs (Keene 2012). The availability of meat was highly seasonal. Autumn slaughter was typically associated with the feast of St Martin (November 11th) which corresponded with the peak in livestock fattening (Walsh 2000). The oscillation between feasting and fasting adhered to the seasonal rhythms of relative abundance and scarcity (Woolgar 2016). Accounts of the possessions of peasants from the period often list the salted meat and bacon stored in the house which represented the meat preserved following the autumn slaughter (Dyer 1998; Harvey 1976).

High proportions of sheep are common within faunal assemblages from the Mediaeval period highlighting the vital role wool production played in the economy. Animal remains from rural contexts are typically mature specimens and were likely consumed once no longer useful for wool production in contrast to the younger individuals more characteristic of higher status and urban contexts (Grant 1989). At the small mediaeval manor at Raunds, Northamptonshire, the faunal assemblage dating from AD1250–1450 was dominated by sheep, forming approximately 60% of the material, highlighting that they were often important within the economy of meat and wool production in a rural setting (Albarella and Davis 2010). Following the Black Death and the associated decline in the human population, it has been argued that the quantities of meat available to peasant households increased (Dyer 1994; Mennell 1996).

Ceramic vessels encountered in rural locations emphasized boiling and stewing rather than frying; peasants did not have access to the oils and fats necessary for frying (Woolgar 2016). A high proportion of cooking vessel sherds from Raunds (c.60%) yielded ruminant processing products indicating the consumption of these animals in pottages stewed alongside brassicas (Dunne *et al.* 2019). Dripping trays and spits became more common in peasant contexts in the late 14th-15th centuries suggesting that meat was more regularly available for roasting (Gerrard and Gutiérrez 2018).

Approximately a quarter to a half of peasant households would have had access to livestock for the acquisition of dairy products. Dairy products would have been more widely and regularly available than eggs and meat and formed an important protein source (Woolgar 2006). Dairy products were sometimes referred to as ‘white meats’ of the poor (Adamson 2004). Faunal remains recovered from Mediaeval York are commonly dominated by cattle bones (constituting approximately 70-80% of the material recovered). The age-at-death profile and season of slaughter suggested by the faunal remains were consistent with them being the by-product of dairy, wool, dung and traction demands. Meat was likely a by-product of the surrounding dairying economy with animals being slaughtered when they were no longer needed (O’Connor 2000). A quarter of the vessels sampled from Raunds, Northamptonshire, contained lipid residues consistent with the processing of dairy products, such as butter and cheese for consumption by the local peasantry (Dunne *et al.* 2019). Dairy products were an increasingly active element within the formulation of elite identities in the 15th century. Aristocratic consumption regularly featured milk, cheese and butter in dishes that might be classed as desserts (Woolgar 2006).

In late mediaeval towns, the artisans that shared crowded lodgings often lacked access to even rudimentary cooking facilities, so they were dependent upon hot foods from cookshops. In Norwich between 1275 to 1348, 73 cookshops are known, however, it is likely that a half penny pie was an extravagance and eating only bread, cheese and water would have been the norm. Many pies were filled with substandard meat, frequently also offal, and were continually reheated (Rawcliffe 2013). It has been suggested that the urban poor would have had more regular access to meat and fish than their rural counterparts (Drummond and Wilbraham 1957), although the meat available was frequently corrupted or rancid (Rawcliffe 2013).

2.2.1.4 Fish and dietary abstinence

Christianity vilified the eating of flesh and the vices of carnality associated with it (Bynum 1988; Serjeanston and Woolgar 2006). Spiritual virtue and the potency of one’s prayers were associated with the practice of abstinence. From at least the 11th century onwards, abstinence from meat was often associated with preparation for spiritual acts, such as communion, and fish was often substituted for meat on Wednesdays, Fridays and Saturdays and during the season of Lent, Advent and the days preceding Saints' feast days (Woolgar 2016). The *Summa Predicantum*, a manual for preachers written by the Dominican Friar John Bromyard, highlighted a mediaeval concern with the dangers of overindulgence. The kitchen of Gluttony in the Devil's castle was said to be a place where people became intoxicated and were more likely to die from food than the sword (1586). In contrast, saints were often described as subsisting only on wild foods, bread, and water (Bynum 1988).

Emphasis on the avoidance of meat by the church increased demand for fish, which acted as an expensive dietary substitute. Meat within Mediaeval Christian European thought typically referred to the flesh of 'Quadrupeds', created by God on the sixth day and believed to be more likely to incite passions in the consumer, rather than fish and fowl, which were created on the fifth day (Bazell 1997). Within a few decades of AD 1000, the trade in preserved cod had begun predominantly in the eastern towns of York, Norwich and London. Prior to this, fish were drawn from a range of local sources and consequently came from a narrower range of habitats and species. An analysis of fish remains from approximately 120 assemblages across 50 sites indicate that cod and herring provided the bulk of the fish eaten. Haddock, ling and conger eel were also featured (Serjeanston and Woolgar 2006). Freshwater fish, such as carp, tench and eels, were also drawn from local rivers, brooks and ponds (Drummond and Wilbraham 1957).

Most fish were prohibitively expensive for all but the upper echelons of society; in AD 1402 Bishop Mitford of Salisbury paid up to twice the wages of a skilled labourer for a single trout (Woolgar 2010). Isotopic evidence from mediaeval York supports high levels of marine protein consumption, especially within monastic contexts (Müldner and Richards 2007a, 2007b). Manorial custumals, which documented the particulars of social, economic and political life at a manor, indicate that harvest workers and ploughmen were provisioned with fish, principally herring, at Sedgeford in Norfolk. During the harvest, 5% of a worker's daily calories were likely constituted by fish, indicating seasonal access to fish for the poorer echelons of society (Serjeanston and Woolgar 2006). Estuarine resources, particularly shellfish, were widely eaten by those in proximity to the seashore as a supplementary dietary resource. Oysters were eaten throughout the year whilst mussels, whelks, razorfish, cockles and limpets were eaten in more restrictive periods, especially during Lent (Woolgar 2016).

The abstemious diet of the poor is highlighted in Chaucer's poem the Nun's Priest's Tale. The widow is described as possessing three cows, a sheep and formerly three sows. She is described as never sick from overeating and has only the milk and coarse dark bread (probably of rye or maslin) with occasional broiled bacon or an egg that her farm produced (Chaucer 1986). This scarce and simple diet was regarded as morally virtuous in mediaeval thought. In a fable by Odo of Cheriton, a field mouse is invited to eat choice morsels by a house mouse, however, the mice are almost eaten by a cat in the process. The fable highlighted the perils of supping on luxuries with the devil (the cat) when good barley bread could be eaten in good conscience (Woolgar 2016).

Dispensation from the observance of abstinence was permitted to the elderly, the pregnant, pilgrims, the poor, the sick or those involved in hard manual labour. Omission of abstinence rested on the individual's conscience and failure to uphold dietary observances would be scrutinised at confession (Woolgar 2006). Bynum (1988) argued that abstinence from food had greater moral and symbolic potency for women given their close association with food production and preparation. The hagiography of female saints more frequently described prolonged periods of fasting as a means to emulate the piety and vulnerability of Christ. Gender and age boundaries were reinforced and defined by these exceptions from fasting while men and women who did not fall within these categories were equally beholden to the rules of fasting.

2.2.1.5 Institutional eating: monasteries and hospitals

The diets of monastic institutions were an arena of both social and moral conflict. Among the upper ranks of the ecclesiastical order a tendency towards the emulation of aristocratic consumption was evident. Conversely, the quantity and composition of monastic diets was embedded within a mediaeval ontology in which excess and indulgence were regarded as morally reprehensible. Monastic diets were expected to reflect and perpetuate this morality of abstinence. The monastic diet was generally focused on cereal products, vegetables, fish, dairy foods and honey. Among the Cistercian order, periods of abstinence were marked by the exclusion of dairy foods and eggs (Woolgar 2006). Many monasteries often had fishponds and access to freshwater fish (Serjeanston and Woolgar 2006).

Monastic orders each had specific codes of dietary practice derived from the original dietary model of St Benedict centred on vegetarianism. These dietary codes were continually renegotiated and from the 14th century meat dishes were more common within the Benedictine order (Bazell 1997). Cistercian spiritual rigour was marked by the absence of dietary indulgence. At Beaulieu Abbey in AD1269, financial records indicated that Cistercian monks were permitted meat only during infirmity. Augustinian Canons ate meat to an extent more consistent with the habits of the upper levels of secular society. Monastic records suggested that protein and calorific intake at Augustinian monasteries was high and likely lead to obesity in some cases (Woolgar 2016). Gifts to monastic institutions were common and reified the moral worth of the giver. This involved provisions of extra wine, ale and fish from benefactors. Eleanor of Castile, for example, gave the Oxford Dominicans salmon baked in pastry in 1290AD and cash contributions for the purchase of food (Woolgar 2011).

Mediaeval hospitals fulfilled a range of important social functions, the foremost of which was the care of the poor, old and sick (Rofffey 2012). Some institutions, such as the two London hospitals of St Anthony and St Bartholomew, had reputations as educational establishments while others provided accommodation for wayfarers. In principle, this succour was provided for free, however, in practice pressing economic circumstances restricted the provisioning of the hospital inhabitants. The purchase of corrodies, which assured board and lodging for an individual for a specific sum of money, was commonly practised to supplement hospital income (Rawcliffe 1984).

It was understood that the sick and feeble required a special diet, however, a combination of poverty, maladministration and occasional dishonest practices frequently required economization on the quality and quantity of food for the infirm. Hence, the dietary provisioning at hospitals was highly variable. For example, the affluent hospital of St Anthony in London was known for its lavish provisioning of meat, particularly on high days and holidays, due to the profitability of its educational establishment (Rawcliffe 1984).

Certain hospitals focused on the care of particular groups, such as lepers, the insane or the terminally ill. Most of England's 300 documented mediaeval leper hospitals, known as leprosaria, were founded prior to the 14th century. Many of these institutions may have served small rural communities, while others were typically located on the boundaries of towns. In the 15th century, the majority of leprosaria took on a more general use as accommodation for the ill, sick and poor (Roffey 2012).

Institutional diets in the Mediaeval period were highly variable. The quantities of meat consumed in monastic houses differed markedly between religious orders, however, records suggest that consumption of meat, particularly among higher ranking order members, emulated the high consumption levels of nobles. Hospital diets were largely dependent on the affluence of the institution and the dietary prescriptions believed to be beneficial to the inmates.

2.2.1.6 Lepromatous leprosy and mediaeval leprosy hospitals (leprosaria): an example of institutional eating.

Leprosy (Hansen’s disease) is a chronic disease caused by *Mycobacterium leprae*, which typically involves the nervous system and the skin. The effects of the disease are closely related to the host’s immunological response. Skeletal involvement is often associated with lepromatous leprosy and can be identified skeletally based on the presence of rhino-maxillary syndrome: resorption and loss of the central portion of the maxilla, destruction of the nasal aperture and modification of the nasal aperture (Waldron 2008).

Clinically, orofacial lesions are commonly reported among individuals with lepromatous leprosy (Manjunath Shenoy *et al.* 2007; Rodrigues *et al.* 2017). The loss of the central maxillary incisors is a frequent consequence of resorption of the alveolar process and associated involvement of the hard palate (Waldron 2008). Chronic gingivitis may also occur. The tongue is involved in up to 25% of cases. Ulceration and repair of the perioral tissues may result in microstomia, contracture of the mouth (Naik *et al.* 2011). More uncommonly, affecting 21% of a clinical group, the maxillary and mandibular branches of the trigeminal nerve and buccal and mandibular branches of the facial nerve may be involved resulting in a sensation of anaesthesia on the affected side, which may impact masticatory behaviours and speech. Oral hygiene practices may also be impeded by reduced functionality in the hands (Dave and Bedi 2013). Orofacial manifestations of lepromatous leprosy may modify the masticatory behaviours of those affected through tooth loss, nervous involvement and soft tissue lesions in the oral cavity.

Furthermore, leprosy in the Mediaeval period was regarded as a humoral imbalance and dietary measures were considered a key element of restoring balance (Radcliffe 2008). The lay staff at the leprosaria would have been able to assist with the care of the lepers. The lepers were encouraged to eat mild and moist foodstuffs, such as eggs, milk, poultry, good pork and fresh fish. These foods were regarded as easily digestible and capable of cooling the overheated digestive system of lepers. Leprosaria frequently had fishing rights and reared dairy cattle, pigs and hens to fulfil their dietary requirements (Brenner 2010; Radcliffe 2008). In addition, it was commonly believed that the sick poor, especially the leprous, could eat contaminated and substandard meat without negative effects. In the Late Mediaeval period, for example in 14th century York, bad meat was often donated to the local leprosaria. Similarly, in Norwich, the assembly ruled in 1473 that individuals that brought rancid meat to the leprosaria had to touch other food in the market with a stick rather than their hands (Rawcliffe 2013). At Maldon, Essex, inmates could claim ‘unsound’ bread, ale and fish as it was believed that their digestive systems could process the food. They also had access to fresh food (Roffey 2012).

Among leprosaria, it is possible that the leprous inmates would have consumed greater quantities of meat than the lower classes of the period; both in donations of substandard meat to the institution and meat foods recommended as part of the provision of care for lepers. In addition, orofacial manifestations of lepromatous leprosy may have influenced masticatory behaviours due to perioral tissue and hard palate involvement, gingivitis, tooth loss and involvement of the trigeminal nerve and buccal and mandibular branches of the facial nerve.

2.2.1.7 Sugar and spice: elite luxuries

‘War without fire is not worth anything, as worthless as sausages (‘andouilles’) without mustard.’ Henry V at the Siege of Meaux, AD1421-2 (Woolgar 2016: 236).

Highly flavoured sauces and spices were regarded as stimulants of the appetite and provided a locus for competitive emulation of elite practices and class aspiration. All levels of society were permeated by a passion for acidic sauces and spices, however, their great expense rendered them unaffordable for the majority of the population (Freedman 2005). During the 12th century, pepper, cumin and saffron were available to London households. By the 14th-15th centuries, the variety of spices available had increased to include anise, capers, caraway, cassia bark, cloves, cubebs, fenugreek, galingale, mace, nutmeg and sanders. The social value placed on sauce is exemplified by sumptuary legislation produced by Edward III in 1336-7 to fund his war against France via the taxation of elite spending on sauces. Inexpensive sauces could be produced by modest households enabling the imitation of elite forms of dining (Woolgar 2016).

In 11th and 12th century Europe, the use of sugar was limited to medicinal contexts (Laurioux 1985). Sugar was perceived as exotic, being associated with Babylon, Cyprus or Alexandria. It was transported from the Mediterranean to England in the late 13th century. Honey was the most readily accessible sweetener and beekeeping was commonly practiced in the countryside and gardens prior to the 14th century (Woolgar 2016). The rise of Atlantic Island production in the 14th century stabilised supply and sugar became entangled within the reification of elite social status through acts of eating (Mintz 1985). Sugar, sold by the loaf and unaffordable for all but the wealthiest of households, began to replace honey in elite circles as a highly desirable flavouring. Increased desire for sugar was fuelled by a passion for exotic tastes, which contrasted with native foodstuffs. Sugar linked the individuals that consumed it to wider networks of circulating global commodities beyond the local regimes of production upon which most of the Mediaeval population depended (Woolgar 2016).

In the 15th century, sugar had become more plentiful and became an important aspect of the visual and edible displays of the affluent. The marriage feast of Henry IV and Joan of Navarre, in 1403, for example, was accompanied by subtleties (sugar sculptures) in the form of animals, objects and buildings. By the 1660s, Robert May, a professional cook employed from the reign of Elizabeth I until Charles II, reported that vast and elaborate subtleties accompanied every royal feast and wealthy households had begun to imitate these practices often using marzipan as a substitute for sculptures made entirely of sugar. It was not until sugar became cheaper and more plentiful that the symbolic importance of sugar among the upper classes declined. A transformation of its symbolic power began in the Post-Mediaeval period as the mass consumption of sugar rendered its production more profitable (Mintz 1985). The elite accentuated their embodied difference by consuming foods that involved elaborate preparation, presentation, and ingredients, such as spices, beyond the reach of individuals of lower socioeconomic status (Hastorf 2017).

2.2.1.8 Mediaeval and Early Post-Mediaeval summary

Food and eating were important aspects of the fabric of mediaeval personhood. Food was a sphere in which an individual negotiated their social and moral value. Within Christian thought, gluttony and overindulgence were regarded as morally reprehensible, demanding regular periods of abstinence and fasting. The rhythms of daily eating were embedded within the preparation for religious observances, the seasonal availability of foodstuffs and the mobilization of food as a medium for social emulation and aspiration. Production was often on a local scale, however, exclusive and high-status commodities, such as sugar, involved distribution networks across large geographical distances.

The mediaeval diet was dominated by the consumption of cereals in the form of bread or pottages. Mediaeval milling practices retained greater quantities of abrasive particles and yielded a coarser and tougher loaf. The dietary supplements available to the peasantry varied seasonally and would have formed as little as 20% of the total calories consumed. In the autumn, a peak in meat availability occurred, however, some salted meat and bacon would have been available throughout the year; dairy products acted as the 'white meat' of the poor. Gardens provided brassicas and alliums and wild foods would have been foraged during periods of scarcity. In contrast, the diets of the upper classes were supplemented daily by either meat or fish. Sugar was frequently consumed by the elite from the 14th century onwards but remained beyond the budgets of most households. The dietary regimes of monasteries and hospitals depended markedly on the relative affluence of the institution. Dietary prescriptions were often recommended for the inmates of hospitals and varied depending upon their physical and mental conditions.

2.2.2 Industrial Ingestion (AD1700-1900)

Food production was arguably the last major trade in Britain to experience an industrial revolution but, by the end of the 19th century, it had been transformed into a large-scale and highly mechanised concern (Burnett 1989). Major shifts in the types and quantities of foods consumed, however, had already occurred earlier in the Post-Mediaeval period. The British diet was remade by new commodities associated with Empire, developments in preservation and mass transportation, and shifts in food processing methods.

2.2.2.1 Dietary staples: cereals, milling technology and potatoes

Field crops remained the principal dietary staple into the 19th century (Mennel 1996). Petersen and Jenkins (1995) argued that bread dependency existed to such an extent in the 18th century that the price of bread regulated the entire economy. The relative affluence of workers was dictated by fluctuations in the price of bread (Burnett 1989). The prominence of bread in the post-mediaeval consciousness of the labouring classes is evident in instances of popular protest during times of scarcity and paralleled its importance within mediaeval thought. In the 1816 Bread Riots, calls for 'Bread or Blood' went up in Suffolk, Norfolk and Cambridge (Burnett 1989). In 1838, a band of disillusioned labourers marched under the traditional banner of protest, a loaf of bread on a pole, before they were massacred at Bossendon Wood, Kent (Reay 1988). Bread was the 'staff of life' for both the urban and rural poor and was the final bastion against the threat of scarcity and starvation (Davies 1828).

From 1750 onwards, Collins (1975) argued that a wheat eating revolution occurred, underwritten by a fashion for consuming white bread which emanated from London and spread to larger towns during the 18th century. A preference for wheaten bread was established among many rural and urban working communities by the late 18th century (Davies 1795). Coarser household flour was supplanted by fine white flour (Fay 1923). The increasing detachment of the miller, as producer, from the consumer in the 18th and 19th centuries led to the systematic adulteration of foods with inferior and cheaper substitutes in order to produce highly desirable white bread. Alum was almost universally used to produce whiter loaves (Odling 1857). In London, damaged foreign wheat, common garden beans, peas and potatoes were used as adulterants. In 1818, reports existed of large quantities of white Derbyshire stone being finely ground and combined with flour to produce loaves (Burnett 1989). During the 19th century there was a shift in diet, as urbanization progressed, from the home-made to the store-bought and ready-cooked. Emphasis was placed upon white loaves, tea and sugar (Horrell and Oxley 2012).

Whilst bread remained an active element of gastro-politics into the 19th century with the whitest wheaten bread remaining the most desirable loaf (Table 1), changes in milling technologies altered the qualities of flour available and the terms of that competition (Burnet 1989). Archaeological evidence for more efficient composite millstones, built up from segments of quartzite quarried from the Seine basin east of Paris, are found from the 17th century onwards (Farmer 1992). The introduction of an automatic boulter into the mill machinery at the close of the 17th century eliminated the need for hand sieving and transformed millers into manufacturers capable of producing ready-made flours to an established standard. Finer grades of flour were produced with the introduction of the double grinding technique and burrstones from France in the second half of the 18th century (Petersen and Jenkin 1995).

Table 1: List of different grades of flour according to the Bread Act of 1757. In London, it is estimated that a sixth of bakers in operation produced bread using whites and firsts for the middle and upper classes. Approximately two thirds of the bakers sold either white bread made using seconds or poorer quality bread using thirds whitened with alum. The remaining sixth of bakers were cut-price bakers using a combination of the lowest grades of flour available (Petersen and Jenkins 1995).

Grade of flour	Composition of Flour	Common Usage
Whites	Finest extraction of best quality	Pastries and bread rolls Parliamentary White Loaves from 1708-58.
Firsts or best households	Fine extractions (70% or less) of good quality wheat	Wheaten (white) bread.
Seconds or second households	Medium extractions (75%) of good quality wheat mixed with firsts	Wheaten bread Standard Wheaten Bread specified in 1772 Act.
Thirds, fine middlings or third households	Coarse extraction up to 80% of good quality wheat or medium extractions of middling qualities	Household bread Ship's biscuits Mixed with seconds or first to make Standard Wheaten bread.
Fourths, coarse middlings, sharps	Usually flinty particles left after flour proper extracted	Mixed with seconds or thirds to make: Economical versions of Standard Wheaten or Household bread Ship's biscuits.
Wheat meal or millstone	Undressed meal of the whole grain after bran and pollards removed.	Coarsest brown loaves, otherwise biscuits or animal feed
Whole meal	Undressed meal of whole grain with bran and pollards ground in.	

Further refinement occurred during the 19th century. Silken gauze enabled greater removal of the bran, any quartz sand derived from the millstone and other silt sized particles from the meal than their woollen and linen predecessors. From the 1870s, porcelain and steel roller mills revolutionised milling by facilitating the production of highly standardised and heavily refined grades of flour. In earlier stone milling, the wheat grains were pulverized together forming a coarse wheat meal with all of the parts of the grain mixed together. In roller mills, the flour passed through a series of rollers after each of which the material was sifted and the coarser material progressively removed. Faster working speeds were enabled by the replacement of wooden gears with more efficient iron gear wheels from 1800 onwards. Furthermore, the addition of steam power in 1880 to the milling industry liberated millers from the constraints of wind and water power enabling the concentration of milling at specialised industrial sites (Perren 1990).

By the close of the 19th century, the loaves consumed had become more standardised and the aspiration to consume white wheaten bread had become a potential reality for the majority of the population (Burnett 1989). The increasing removal of the more nutrient rich portions of the grain from the flour, including the germ and bran leaving only endosperm of uniform size, arguably diminished the nutritional properties of the bread consumed in the 19th century (Cordain *et al.* 2005).

Urban workers were largely dependent on shop bought commodities of which bread was the foremost convenience food (Burnett 1989). Bread was entwined within the urbanisation process and wheaten bread was a materialization of the social aspiration and competition of the urban poor. Wholemeal bread initially diffused down the income scale followed by bread made using sifted white flour (Collins 1975). Potatoes formed an additional source of carbohydrate. The limited cooking facilities in tenement houses confined households to either boiling or roasting potatoes on an open fire (Burnett 1989). The diet of rural workers was little changed from the Mediaeval period, beyond the changes in bread composition and the addition of potatoes. The Agricultural Committee of 1824 reported the diet of Thomas Smart, an agricultural labourer, who was supporting his 7 living children out of the 13 that were born. He subsisted almost entirely on cheese and bread and often had no meat or milk for months at a time (Burnett 1989).

2.2.2.2 Regionalism: The North and South divide.

The regional variation in the types of cereals consumed persisted from the Mediaeval period into the 19th century. Wheat remained the most socially prestigious flour and was considered the most digestible (Mennel 2010), but regionalism existed in the prevalence of wheat eating especially in rural areas. The uptake of white wheaten bread was less rapid in the north (Drummond and Wilbraham 1957) where it was regarded as a 'dainty' for more 'respectable' tables. Instead, the bread of the northern poor was typically of a mixed cereal composition, often of barley, oats and rye (Collins 1975). Communal baking ovens persisted in some northern towns until the 20th century, whereas they had largely decayed and disappeared in southern counties by the 19th century (Burnett 1989).

Eden's The State of the Poor in 1795, which examined the diets of 42 counties, found that groups in southern counties subsisted almost exclusively on wheaten bread, tea, potatoes and cheese whereas households in northern counties often ate barley bread, oatmeal, milk, butter, potatoes, and occasional meat (Table 2: 1795). Collins (1975) estimated that wheat constituted up to 97% of the cereals consumed in Southeast England, whereas, in northern cities, such as in Manchester, labourers consumed oatcakes, oatmeal and milk.

At the start of the 18th century, the potato was still rarely cultivated in England but during the century cultivation expanded rapidly in the north. By 1770, potatoes had become a mainstay of the diets of the poor in the north but were still not taken up in quantity by the southern poor. The differences between the diets of the north and south were heightened by the close of the 18th century. The southern rural poor were more heavily impacted by enclosure, depriving them of land for grazing livestock, producing milk and cultivating vegetables (Drummond and Wilbraham 1957). Eden (1795) in the State of the Poor (Table 2), described how meat and milk were rare in the majority of southern households and bread with a little cheese or butter was typically the main dietary constituent. The northern poor had greater varieties of food available, typically in the form of milk and potatoes for those in more rural locations. The diets of many agricultural labourers in northern of England remained consistent throughout the Post-Mediaeval period with continued consumption of oatmeal, milk and vegetable broths (Burnett 1989; Drummond and Wilbraham 1957).

Table 2: Household weekly expenditure and dietary intake. Comparison of household weekly expenditure and dietary intake between regions as described by Eden (1795) during his survey of parishes at the close of the 18th century. The higher income of the spectacle frame maker from Wolverhampton is reflected in the greater quantity of meat consumed per week. A quartern loaf weighed 4lb and 15oz following the Assize of Bread. In Ealing, milk and potatoes were provided from the landowner's farm.

Region	South	London	Midlands	North
Town	Portsmouth	Ealing	Wolverhampton	Sunderland
Occupation	Dockyard labourer	Farm Labourer	Spectacle Frame Maker	Coal Miner
Family Size	Wife and 3 children	Wife and 4 children	Wife and 4 children	Wife and 3 children
Annual Household Income	£36 3s	£38 12s	£50 7s	£35 3s
Flour or loaves a week	9-10 Quartern wheaten loaves	7 Quartern wheaten loaves	Wheat 25lb	Bread meal of wheat, rye and barley 35lb
Meat	A joint per week	4lb	12lb	4lb
Milk	0 litres	7.7 litres	3.4 litres	8 litres
Cheese	Small amount with bread	Small amount with bread	2lb	N/A
Butter	Unspecified	Unspecified	2lb	Unspecified
Oatmeal	0	0	0	9lb
Sugar	Unspecified	2lb or 18 pence worth	Unspecified	1 shilling
Potatoes	0	Allowance from master's garden	25lb	5.25lb
Barley to boil with milk	0	0	0	1lb

2.2.2.3 Meat and fish consumption and other luxuries: a reflection of income and social status

Meat and fish remained active foods in the negotiation of class aspiration in the Industrial period and were key indicators of household wealth. Poorer households typically only had access to bacon as a periodic dietary addition because it was cheap and kept well (Burnett 1989; Knapp1987; Mennell 1996). Engels, describing the state of the poor in Manchester during the early 19th century, highlighted that death by starvation was a constant threat and that the meat available to the poor was often rancid or derived from old and diseased animals and any vegetables were wilted. The quantity of meat consumed decreased with decreasing household income. Daily bacon and cheese with supper was available to workers on a higher income. In contrast, the lowest paid labourer's diet was limited to bread, cheese, porridge and potatoes (Engels 1844).

Daily living standards were embedded in regionalism and the differences between rural and urban life. Agriculture remained the single largest occupation throughout the Industrial period, however, its decline in importance was steady throughout the Industrial Revolution. Expenditure on food required a large proportion of household income and remained the case from 1750-1850 with little overall change in dietary content or quality (Griffin 2018). Among agricultural workers, 52.5% of income was spent on bread leaving little money to spend on supplementary dietary items. Miners and industrial workers spent a slightly smaller proportion of their income on bread, 40 and 36% of income, respectively (Griffin 2018). Low-paid textile workers in Northern England were spending 12% of their take-home pay on meat, mostly bacon (Neild 1841). David Davies (1795), writing in the late 18th century, described how the majority of the poor could not afford meat, cheese or butter except in the smallest quantities due to the expense of wheaten bread. Pigs were still occasionally kept where space and income permitted to give greater access to affordable meat. Unlike in the Mediaeval period, garden areas traditionally used for vegetable cultivation, which provided a source of food in times of scarcity, had been engulfed by growing large-scale farms curtailing an important element of local production. Common land for grazing a household cow to produce milk was also seldom available and the milk that was available in Southern England was frequently of inadequate quality for consumption (Davies 1795).

Gender identity and class aspiration were negotiated and reinforced through the distribution of food within the household. Horrell and Oxley (2012) forwarded a male 'breadwinner model' for patterns of consumption in the early 19th century. Men and individuals that contributed most to household income received the largest share of any meat and cheese (Griffin 2018; Horrell and Oxley 2012). Dr. Edward Smith stated in 1863 that any meat was almost exclusively eaten by the father and that his wife regarded this arrangement as morally right (Mintz 1985). Women and children were the chief casualties of the poor living standards of many labourers. They often subsisted solely on bread, potatoes and weak sweetened tea (Burnett 1989). Engels (1844) described how children sometimes survived the whole day upon a penny worth of bread or just potatoes with salt and never any meat. The practice of giving children spirits and even opium was also lamented as detrimental to their bodily development (Ibid.).

It was not until the latter half of the 19th century that meat and fish began to enter British working-class diets more regularly (Knapp 1988). Developments in mass transportation radically changed the availability of consumables in this period. During the early 18th century, food was transported to towns via often poorly maintained roads and frequently reached them in an unfit state for consumption, either stinking or rancid (Drummond and Wilbraham 1957). Canals slightly eased the transportation of food across the country in the later 18th century. Railways later revolutionized the food supplies of large towns opening up a national food market from the 1830s onwards. Regional variation in food supply and differences between the diets of urban and rural groups began to diminish following these developments (Mennell 1996). Periods of local scarcity could be more readily ameliorated by the national supply. In addition, the salt tax was abolished in 1825 encouraging the preservation of fish by salting and increasing the inland circulation of fish. Ice packing of fish and new supplies of cheap cod from the North Sea, transported inland by rail, appear to coincide with the rise of fish and chips at the close of the 19th century (Burnett 1989).

The railway boom laid the foundation for mass markets in preserved and processed foods to develop (Goody 1982). Cheaper lean meat from huge meat canning firms in Chicago and Cincinnati started being imported from 1868 and corned beef became popular among the working classes from 1876 (Burnet 1989). Frozen meat from America also started to arrive in Britain from the 1870s, however, carcass meat remained largely unaffordable for the working-class until the 1890s (Burnett 1989; Knapp 1988). These processed and preserved foods were more widely available to all social classes and reduced some of the contrasts between their patterns of consumption. Furthermore, global networks of transportation enabled the consumption of foods previously restricted to a certain season (Mennell 1996).

The middle classes expanded in tandem with the managerial and clerical occupations associated with industrial growth as the British consumer became entangled in a broadening world system and national market of food consumption

(Burnett 1989; Goody 1982). The foods eaten, manner of service and time of eating were integral to their accumulation of social prestige within the arena of gastro-politics. The dinner party became the ultimate space within which the host could demonstrate their affluence and good taste. Meat consumption was daily and might amount to 1/2lb per household member. Fish, milk, butter, vegetables and fat were also very frequent dietary components (Burnett 1989). Isotopic evidence from the post-mediaeval churchyard of All Saints, Pavement in York, associated with a wealthy parish, suggested that fish consumption in the city from the late 17th to early 19th century remained high, and comparable to the Mediaeval period (Müldner and Richards 2007b).

As new commodities became more accessible, the social emulation of the elite became increasingly feasible for the emergent middle classes. The character of conflict and competition embodied in eating practices shifted in this period. The excess and conspicuous consumption of the elite mediaeval table was superseded by elite consumption that emphasized refined and delicate foods that maintained culinary exclusivity. The emergence of haute cuisine in the Post-Mediaeval period among the upper classes can be construed as a means of continuing to achieve social differentiation through eating (Mennell 1996).

Furthermore, within the arena of gastro-politics, the status of foods as prestigious or ignominious are continually negotiated and defined within eating practices and discourse. It is in the context of the detachment of the urban upper and middle classes from the slaughter of animals and meat production that Mennell situated the emergence of vegetarianism in the 18th century. In contrast, the lower classes often had differing attitudes to animal cruelty with bull baiting remaining popular. Culinary explanations were added to these activities with some asserting that the meat became more tender if the animal was tormented before its death. Another example of shifting attitudes to the consumption of certain animal products was the avoidance of tripe by those with elite aspirations due to its adoption by the lower classes, although the food was once associated with the upper classes (Mennell 1996).

2.2.2.4 Imperial eating: sugar and tea

New commodities entered the field of mass consumption and became important elements of daily consumption (Burnett 1989). Localized networks of food consumption and production and relative self-sufficiency were gradually replaced by the influx of industrially produced foods and a growing dependence on the products of Empire during the 19th century (Goody 1982). The most significant of which were two interrelated items, tea and sugar. Sweetened tea began to replace alcoholic beverages as the drink of preference and the working classes often ate their bread and porridge with treacle (Engels 1844; Mintz 1985). The amount of tea imported increased from 20,000 pounds per year at the end of the 17th century to 20,000,000 pounds per year by the close of the 18th century (Drummond and Wilbraham 1957). Mintz (1985) argued that the first sweetened cup of tea to be drunk by an English worker anticipated the remaking of the social and economic basis of English society. The increasingly widespread uptake of tea began to imbue and ritualise tea consumption as part of the reconfiguration of British identity.

The types of tea and way in which they were consumed was far from uniform, however, and reflected household income. The cleric David Davies (1795), observing rural life in the late 18th century, described the tea of the poor as a few leaves in hot water sweetened with brown sugar compared to the fine hyson tea of the upper classes with refined white sugar. The poor would moisten their bread with tea as a meal; the alternative was just bread and water. Individuals such as John Hanaway (1767), an 18th century social reformer, lamented the consumption of tea by even the poorest beggar when in many instances they were stricken by poverty to the extent that they lacked the means to buy bread. Up to 10% of the household income of the English poor was spent on sugar and tea (Bickham 2008).

During the 18th and 19th centuries, sugar was transformed from the prestigious foodstuff of the elite to a commonplace luxury, and later staple, of the commoner (Mintz 1985). Sugar diffused rapidly down the social hierarchy as it became cheaper and more widely available against a background of African slavery, New World plantations and colonial expansion (Mintz 1996). Per capita sugar consumption increased rapidly, especially during the second half of the 19th century. By the end of the 19th century, it is estimated that sugar contributed nearly one-sixth of total calorific intake. Sugar consumption by the poor was not limited to sweetened tea. It was also used to make complex carbohydrates more palatable and calorific. Treacle was often spread on bread or mixed with porridge and hasty pudding, an oatmeal porridge. Mintz (1985) argued that the rapid uptake of sugar by the labouring classes may have reflected their displeasure with their pre-existing dietary provision.

Among the emergent middle classes in the late 18th century, hot and cold puddings and pastries were taken up with increasing frequency, sometimes forming the second or third course of meals. Sugar became inculcated within the rhythms of daily life. The norms and configuration of its consumption were practised differently across class and gender boundaries. Although sweet foods retained a ritualised importance in festival situations, more consistent with their prestigious position within mediaeval usage, the consumption of sugar by the poorer echelons of society also imbued sugar with an everyday quality (Mintz 1985).

Sugar and tea formed the principal medium through which empire was experienced within the rhythms of daily life in England and enmeshed the consumer within a global network of production and consumption (Bickham 2008). The sensory qualities of foods render their consumption highly emotive and serve as powerful repositories of memory. Acts of eating can be invested with both subjective recollections of individual experiences and wider regional, national, and global narratives (Sutton 2001). The abolition of slavery movement in the late 18th century promoted the notion that faraway suffering was incorporated into the sphere of domestic consumers by colonial products, such as sugar. They challenged the discourse forwarded by supporters of the sugar trade that described sugar not as a sensuous luxury but a physical necessity and instead argued that eating sugar was tantamount to accepting the practices of slavery (Sussman 1994).

Bickham (2008) argued that the foreignness of imperial products enabled them to transcend social and geographic boundaries enabling sugar and tea to emerge as important national foods. Trade cards, used by grocers to advertise imperial commodities, reified the association between the acquisition and safeguarding of these new valued commodities and imperial pursuits. Examples of these cards depicted Britannia receiving imperial foods as tribute and images depicting African slaves working under the plantation system in North America. The consumption of products of Empire were crucial to the integration of individuals within wider narratives of colonial production and consumption.

The increased prevalence of dental caries among Industrial groups reflected the role of imperial foodstuffs, particularly sugar, in providing the primary experience of Empire for the bulk of the population of England. Rising sugar consumption and greater access to white bread resulted in a more highly cariogenic diet (Mant and Roberts 2014; Whittaker and Molleson 1996). Corbett and Moore (1973; 1975; 1976) argued that a long-term trend is evident in the prevalence of dental caries from the Mediaeval period into the 19th century. Two meta-analyses using skeletal assemblages from across Europe found an increase in caries prevalence between assemblages dating from the 10th-17th centuries when compared to those from the 18th-19th centuries. Ante-mortem tooth loss also became more frequent in Industrial-era assemblages, which may reflect an increase in tooth extraction by dentists during the 18th century as developments in dental medicine occurred (Müller and Hussein 2017; Witwer-Backofen and Engel 2018). During the 19th century, the tooth positions and sites most commonly affected by carious attack began to resemble modern distributions. The portion of an assemblage from Lancashire dating to after 1850 showed a marked increase in caries prevalence when compared to the pre-1850 portion of the same assemblage. This may reflect the impact the removal of import duties on sugar had in the 1840s on levels of sugar consumption (Corbett and Moore 1976).

In addition, DNA extracted from dental calculus, which is mineralised dental plaque, indicated a shift in oral microbiota between the Mediaeval period and Industrialised groups (Adler *et al.* 2013). There was a reduction in the biodiversity in the modern plaques examined and an increase in the domination of potentially cariogenic bacteria This matches the increased consumption in Industrialised groups of refined grain and processed sugar, which are the main substrates of bacterial fermentation resulting in the lowering of the pH of the plaque in dental caries.

2.2.2.5 Industrial summary

Bread remained the principal dietary staple for the lower classes during both periods (Table 3). Urban workers in the 19th century typically subsisted on a monotonous diet of bread, potatoes and weak sweetened tea (Burnett 1989).

Technological changes in milling dramatically altered the composition of the loaves consumed resulting in a wheaten bread revolution (Collins 1975). The consumption of softer and more heavily processed dietary staples resulted in a reduction in abrasive dental wear and the biomechanical loading of the masticatory system during chewing (Kaidonis *et al.* 2014; Kaifu *et al.* 2003). Sugar shifted from a luxurious rarity in the Mediaeval period to an essential of everyday consumption by the close of the 19th century (Mintz 1985) engendering higher prevalence rates of dental caries in Industrial groups (Corbett and Moore 1976). This enmeshed the consumer within a global colonial system of production and consumption. Conspicuous patterns of elite mediaeval consumption were replaced by a more abstemious model that involved more delicate and exclusive foodstuffs (Mennell 1996). Acts of eating were explicitly implicated in the negotiation of the moral and social worth of the eater in the Mediaeval period. This moral dimension became less explicit in the Industrial period (Bynum 1988; Woolgar 2016). The increasingly processed and cariogenic diets that emerged during the 19th century foreshadowed the soft-hyper-nutritive diets that characterise contemporary industrialised groups (Corruccini 1999).

Table 3: Comparison of dietary content in the Mediaeval, early Post-Mediaeval and Industrial periods

Dietary Element	Mediaeval and Early Post-Mediaeval Periods (AD1100-1700)	Industrial Period (AD1700-1900)
Dietary Staples	Cereals were the primary dietary staple Mostly oats, barley, rye, and peas rather than wheat.	Cereals remained crucial dietary staples Wheat became increasingly predominant as the period progressed. Sugar and potatoes became important sources of calories.
Milling Technology	Loaves were coarse as flour contained more bran, other components of the grain and exogenous abrasives. The composition of loaves formed a key aspect of social differentiation.	Changes in milling technology resulted in more heavily refined flour. White wheaten bread became increasingly widespread.
Meat	A rare dietary addition for the lower classes. The upper classes consumed large quantities of meat.	Quantities of meat consumed were closely associated with wages. The poorest echelons of society rarely ate meat.
Eating Practices	Rhythms of eating were embedded within the religious observation of abstinence and seasonal availability. Food was mobilised as a medium of social emulation and aspiration.	Consumer embedded within wider networks of global production and consumption. Eating often at the forefront of the daily experience of Empire. Social status was reified by the consumption of exclusive foodstuffs.
Production	Production was often on a local scale Garden plots provided supplementary foodstuffs, such as vegetables. Access to common land enable the pasturing of livestock and access to dairy products, especially in rural areas.	A national market for foods developed alongside the railways. A dependence upon shop bought commodities developed, especially among urban groups. Producers became increasingly detached from consumers as the scale of food production increased.
Regional Diets	Diets varied between the North and South of England. Oats were the main crop in the North and milk was more readily available to make pottages.	The uptake of white wheaten bread was slower in northern counties. Northern diets were more varied often including oatmeal, potatoes, and dairy products.
Social Identity	Gender and age categories were reified by dispensation from abstinence.	Gender identities were differentiated by access to meat. Males consumed the majority.

3 The Dentition in Function: morphology, occlusion, mastication and dental wear

The main proposition of this research is that humans adapt their chewing cycles to the physical and mechanical properties of the foods they consume. If there was a method by which mastication could be reconstructed in skeletal material, inferences could be made regarding likely dietary composition and the changing ways in which foods were eaten in the past. Research into a wide range of mammals, both extinct and extant, has shown that the pattern and orientation of tooth wear can be used to reconstruct chewing cycles (Koenigswald *et al.* 2013; Kullmer *et al.* 2009). The location, size and orientation of highly polished dental wear facets, produced by wear on the enamel of teeth, reflect not only the anatomy of the teeth and jaws but also the sequence of jaw movements involved in chewing cycles and the physical and chemical properties of the food consumed. Understanding how the dietary changes that occurred during the Industrial period impacted chewing behaviour is essential in explaining the accompanying modifications to the function, development and morphology of the teeth and jaws that have been observed in modern industrialised groups by previous researchers (Corruccini 1999; Kaidonis *et al.* 2014).

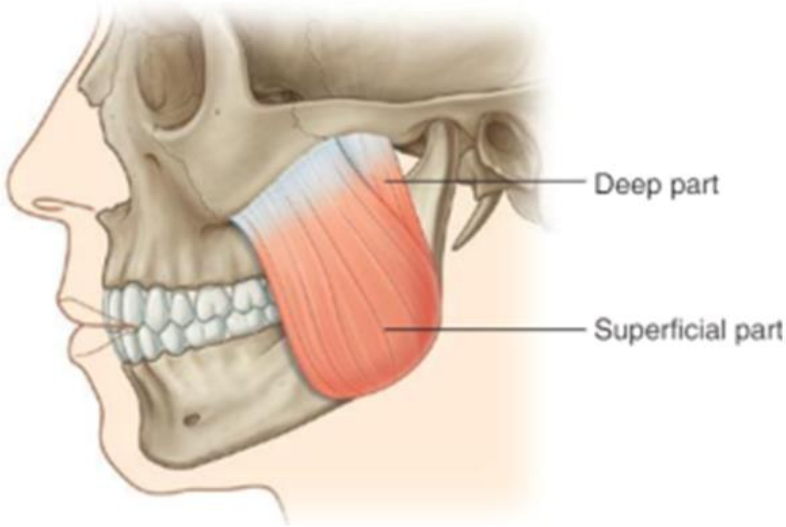
The purpose of this chapter is to introduce the dental concepts that are foundational to the reconstruction of masticatory behaviours using dental wear. These concepts were also used to develop the hypotheses that will be tested in this thesis.

3.1 The chewing cycle and power stroke

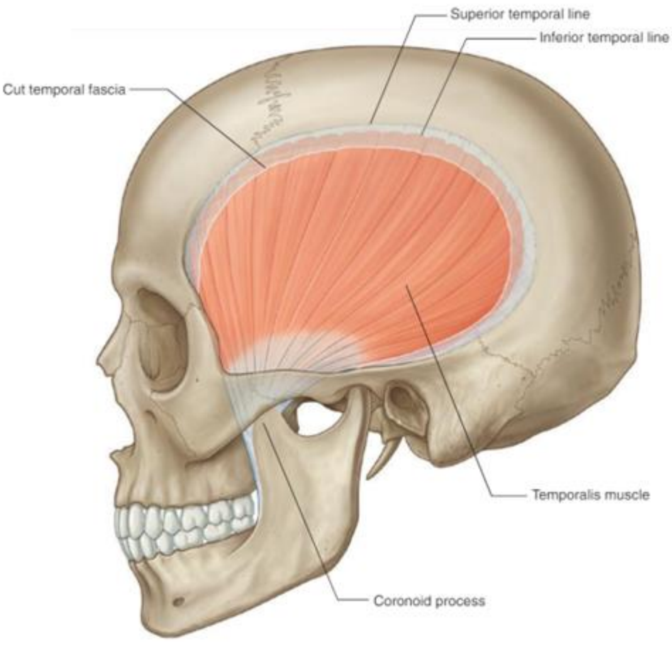
The purpose of mastication is principally to reduce food size to facilitate swallowing and digestion (Berthaume 2016; Bornhorst and Singh 2012). Mastication also acts to initiate various digestive and metabolic processes, such as the breakdown of starch by salivary amylase (Peyron *et al.* 2017). A certain threshold of food particle size and food bolus lubrication must be reached to enable swallowing (Mishellany-Dutour *et al.* 2008; Woda, Mishellany, *et al.* 2006). The process involves food particles being aggregated through the incorporation of saliva (Mosca and Chen 2017).

Mastication is hypothesized to be controlled by a central pattern generator in the brainstem and to be modulated both by conscious control and feedback from muscle spindles and periodontal mechanoreceptors (Lund and Kolta 2006; Sessle 2016; Türker *et al.* 2007). During mastication, jaw movement is achieved by the action of the muscles of mastication, typically operating as either couplets or triplets (Figure 2) (Herring 2007; Weijs 1994). During jaw closing, triplet I, comprising the balancing side superficial masseter, balancing side medial pterygoid and working side posterior temporalis, draw the molar teeth on the chewing side laterally and upwards. The working side molars are then drawn back towards the midline of the dentition by the activation of triplet II, the working side superficial masseter and working side medial pterygoid and balancing side posterior temporalis. Jaw opening is then commenced by the relaxation of the jaw adductor muscles and the activation of the depressor group, including the mylohyoid and digastric muscles. During jaw opening, the working side of the mandible continues to move towards the balancing side (Crompton *et al.* 2010; Hylander 2006; Weijs 1994; Williams *et al.* 2011).

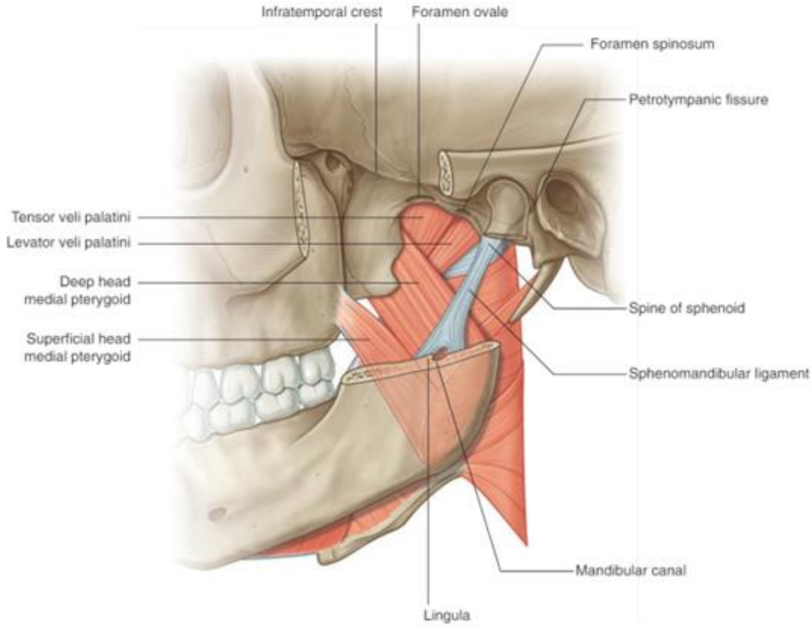
Masseter Muscle



Temporalis Muscle



Medial Pterygoid



Lateral Pterygoid

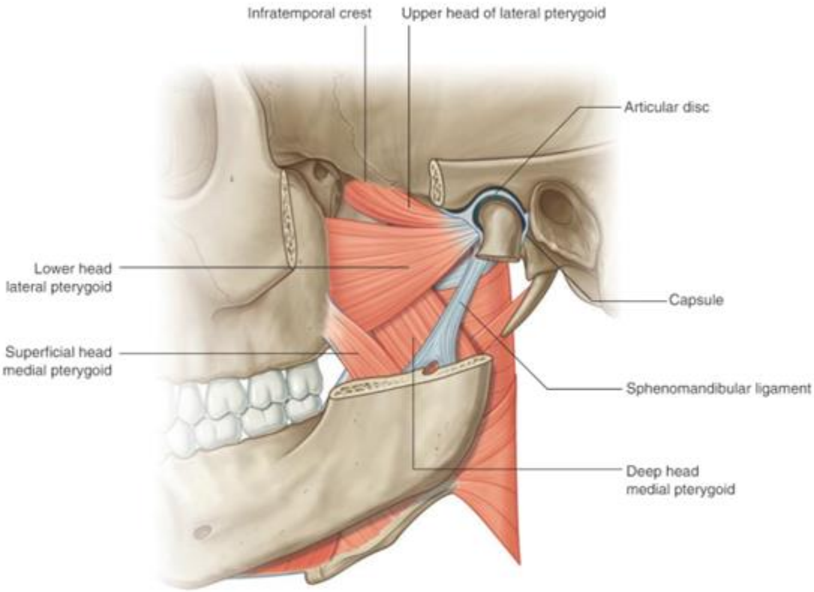
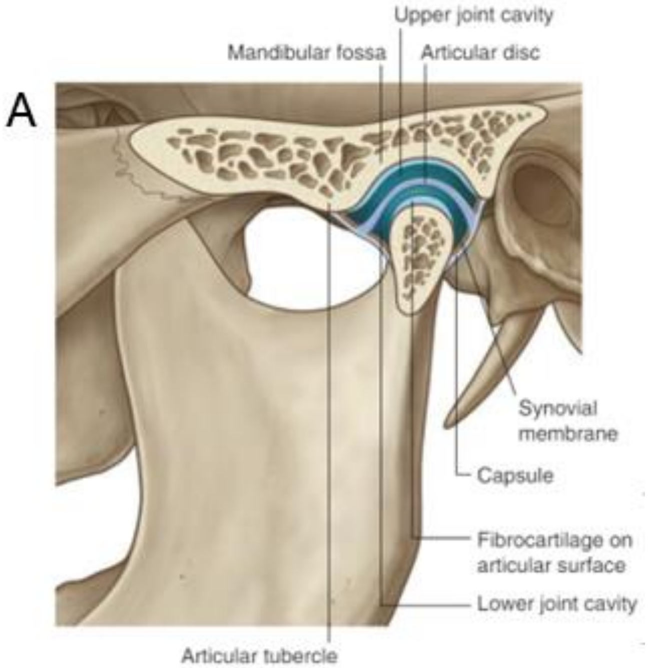
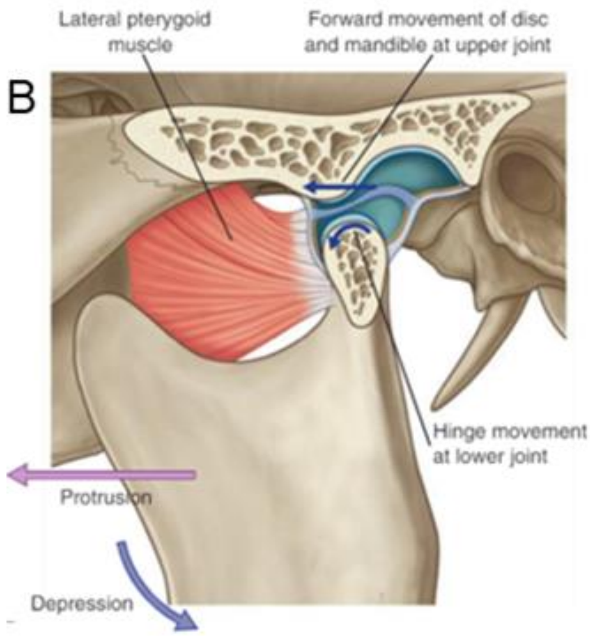
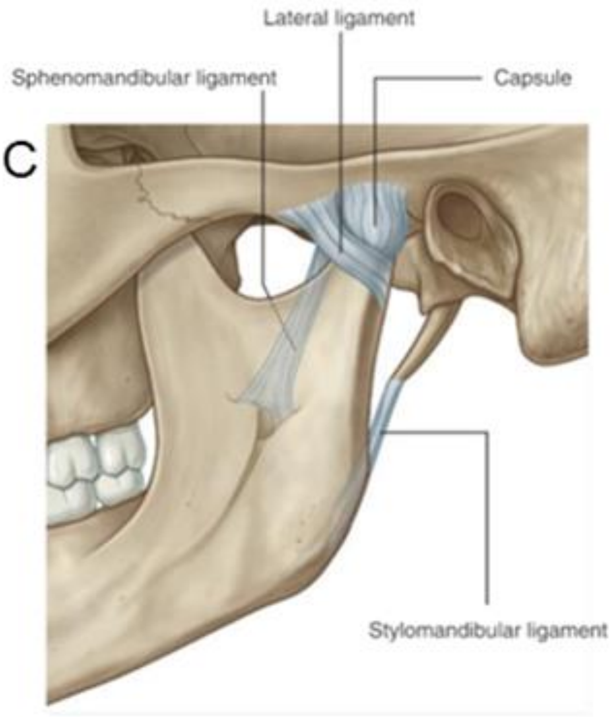


Figure 2: Diagrams showing the location of the jaw adductor muscles in anatomically modern humans. Reprinted from Drake et al. *Gray's Anatomy for Students. Chapter 8 The Head and Neck. Figures 8.141 p.966, 8.143 p.968, 8.146 p.971 and 8.147 p.972. Copyright (2020) with permission from Elsevier.*

The range of possible jaw movements of a species is largely dictated by the anatomy of the temporomandibular joint (TMJ) (Koenigswald *et al.* 2013). In anatomically modern humans, the TMJ is divided into two compartments (Figure 3). They are delineated by an articular disc of dense fibrous connective tissue interposed between the mandibular condyle and the squamous portion of the temporal bone. The upper compartment primarily facilitates gliding translation movements whereas the lower compartment principally acts as a hinge or rotary joint. Consequently, the TMJ is often considered a hinge joint with a translatable socket (Hylander 2006).




Lateral pterygoid muscle
Forward movement of disc and mandible at upper joint
B
Hinge movement at lower joint
Protrusion
Depression


Lateral ligament
Sphenomandibular ligament
Capsule
C
Stylomandibular ligament

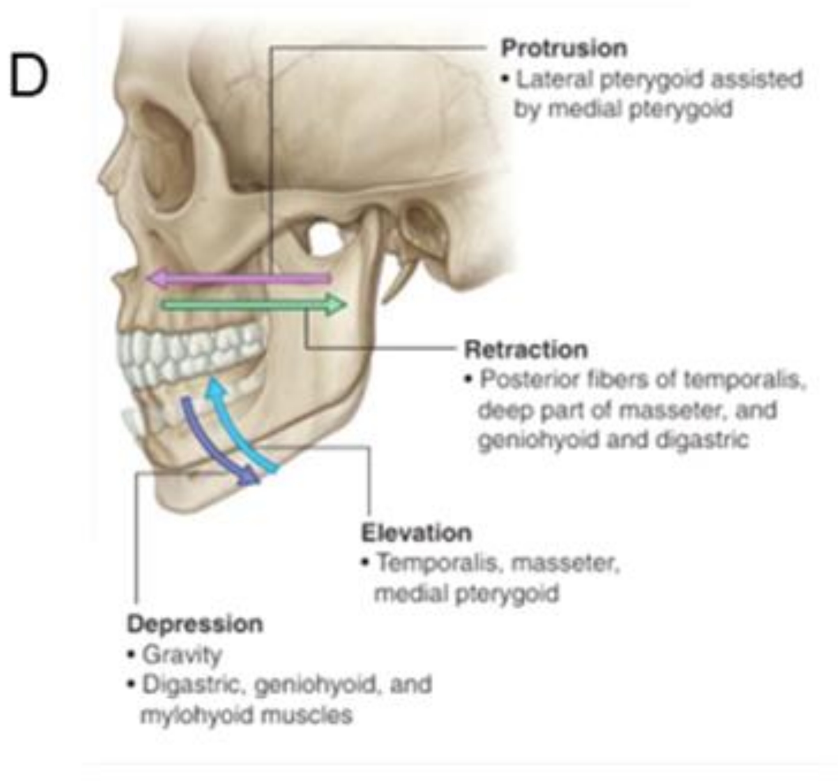


Figure 3: Anatomy of the temporomandibular joint (TMJ) and the movement of the mandible. The TMJ is divided into an upper and lower joint capsule by an articular disc (A). Combined action of upper and lower components of the articular disc produce a translational movement and hinge action (B). The ligaments associated with the TMJ (C). The muscles of mastication involved in producing the major movements of the mandible (D). Reprinted from Drake et al. Gray's Anatomy for Students. Chapter 8 The Head and Neck. Figures 8.138 p.964, 8.139 p.965, 8.140 p.965. Copyright (2020) with permission from Elsevier.

The complete feeding sequence in humans can be divided into a series of stages (Figure 4) (Crompton and Hiiemae 1970; Hiiemae *et al.* 1996; Hiiemae and Palmer 1999). Humans typically share a comparable general movement profile during the oral processing stage of the feeding sequence. A characteristic teardrop profile is formed when viewed in the frontal plane (Figure 4). Their duration and amplitude, however, are highly variable within a single feeding sequence (Hiiemae 1978).

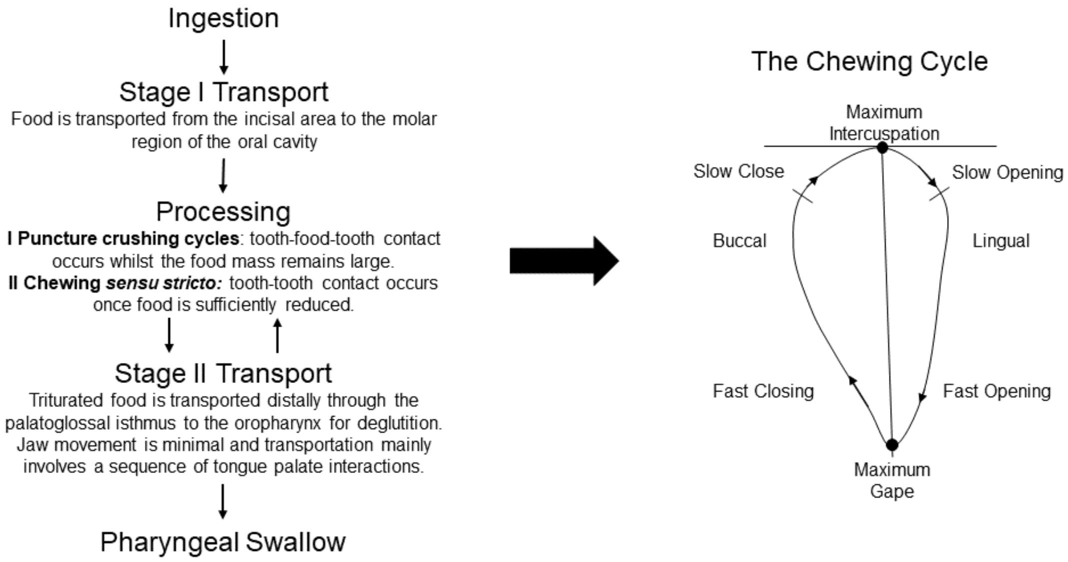


Figure 4: The complete feeding sequence in humans. Stage II transport and processing have been observed to occur simultaneously. The regular cyclical jaw and tongue movements associated with the feeding sequence may be briefly replaced by irregular movements before a swallow occurs (Hiiemae and Palmer 1999).

Firstly, ingested food is transported to the molar region of the oral cavity by the action of the tongue in order for oral processing to occur. The initial phase of oral processing is frequently characterised by puncture crushing cycles (Hiiemae 1978). In anatomically modern humans, the protocone of the upper molars and the relatively large talonid basin of the antagonistic lower molar provide an effective mechanism for the puncturing and crushing of food; this has been compared to the action of a pestle and mortar (Crompton 1971; Kay and Hiiemae 1974; Spears and Crompton 1996). In these cycles, the lower jaw moves upwards from maximum gape until tooth-food-tooth contact occurs. The transition between the fast closing and the slow closing phase of the chewing cycle ensues at this moment of first contact (Figure 4). Puncture-crushing cycles have general movement profiles comparable to later chewing cycles (*sensu stricto*) in the feeding sequence, however, they are characterised by a greater vertical amplitude and reduced transverse component (Hiiemae 1978; Maier 1984). They are also characterised by more erratic jaw movement profiles relative to later chewing strokes and often comprise a series of predominantly vertically directed up-and-down strokes as repeated tooth-food contact occurs. Jaw muscle activity is often chiefly synchronous during this time (Hylander 2006; Wall *et al.* 2006).

Following the reduction of a large food mass to a homogenised state by puncture crushing, chewing (*sensu stricto*) occurs (Crompton and Hiiemae 1970). This phase of oral processing involves tooth-tooth contact mediated by the partially reduced food mass and saliva interposed between the antagonistic teeth (Kay and Hiiemae 1974). Saliva acts to lubricate oral tissues during this process (Mosca and Chen 2017). The complementary planes and crests of the upper and lower molars produce shearing forces as they move past each other which further reduce food particle size (Maier 1984).

The sequence of tooth-tooth contacts that happens during chewing cycles (*sensu stricto*) is referred to as the power stroke (Figure 5) (Hiiemae 2004). The power stroke has two phases in anatomically modern humans (Kay and Hiiemae 1974; Kullmer *et al.* 2009). During phase I, the lower molars on the working side move from a lateral position following an upward, anteriorly and medially directed movement (Figure 5). This terminates in maximum intercuspation as the protocone of the maxillary molar enters the talonid basin. The lower molars on the working side follow an anterior, medially and slightly downward directed pathway during the phase II movement, which is followed by jaw opening (Schultz and Martin 2014).

Once adequately triturated, the bolus is moved distally in the oral cavity by a sequence of tongue-palate interactions referred to as stage II transport in preparation for swallowing (Hiiemae 2004). Stage II transport can be ongoing whilst the food is still being processed and reduced by the molariform teeth. Alternation between processing, stage II transport and pharyngeal swallows occurs in most chewing cycles forming several sub-sequences within the overall chewing sequence. This process is repeated until the terminal swallow takes place, when all food has been cleared from the oral cavity (Hiiemae and Palmer 1996).

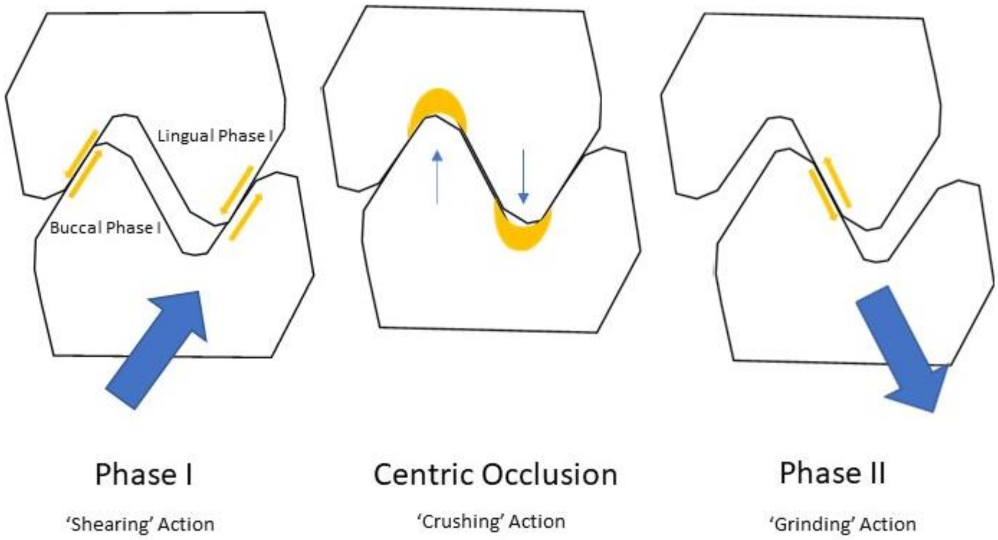


Figure 5: Diagram illustrating the masticatory power stroke (Cross-section across the buccolingual axis of two antagonistic molars). The phases depicted correspond to those described by Kay and Hiiemae (1974) and Janis (1990). Figure created by author.

3.2 Adaptation of mastication in response to food properties and individual factors

3.2.1 Adaptation to Food Properties

Masticatory behaviours adapt to food properties and continue to be modified as food properties change during a chewing sequence. Food properties can be defined in terms of intrinsic mechanical properties, such as toughness and hardness, and extrinsic surface characteristics, such as stickiness, particle size and roughness (Table 4) (Agrawal et al. 1998; Hiiemae 2004; Koç et al. 2013; Thiery 2017). Two intrinsic mechanical factors, hardness and toughness are integral to the breakdown mechanics of food in the mouth (Chen 2009; Koç *et al.* 2013). Different hardness and toughness properties require different types of jaw movement and tooth-tooth interactions to effect fracture (Hua *et al.* 2015).

Table 4: Definitions of the food properties described in the current research.

Food Property	Definition
Hardness	The force required to fracture a food under initial loading conditions (Agrawal et al. 1998; Chen 2009; Koç et al. 2013; Thiery 2017).
Toughness	The resistance of a food to further crack propagation once an initial crack has been created (Agrawal et al. 1998; Chen 2009; Koç et al. 2013; Thiery 2017).
Stickiness	The tendency for a food to adhere to a contact surface, such as the teeth, during oral processing. Represents a combination of the adhesive and cohesive properties of the food (Adhikara *et al.* 2001).
Plasticity	Plastic foods do not return to their original shape when the stress is removed and are instead deformed (Foster *et al.* 2006).
Elasticity	Elastic foods return to their original shape once the stress is removed and the strain disappears (Foster *et al.* 2006).
Roughness	Roughness refers to the surface morphology and topography of a food item. The roughness of the surface will depend upon the magnification at which it is examined. Rougher foods have more complex surface topography (Quevedo and Aguilera 2004).
Brittleness	A food is classed as brittle if it lacks ductility and cannot be easily bent or stretched. It lacks tensile strength. There are, however, many different concepts of brittleness within tribology (Hucka and Das 1974).

Periodontal receptors and muscle spindle afferents detect the intrinsic mechanical properties of foods during mastication and modify masticatory parameters accordingly (Bakke 1993). The capacity to adapt to food properties develops early in life. Animals raised on a soft diet during the critical period of masticatory maturation, in which the motor pattern used for oral processing develops, exhibit underdeveloped sensory feedback mechanisms resulting in limited efficiency when attempting to triturate harder food items (Fujishita *et al.* 2015). Similarly, the capacity to modify oral behaviours in response to food properties has been observed in humans older than 18 months (Wilson and Green 2009).

Within a single chewing sequence, a process of oral adaptation occurs to the changing mechanical and rheological properties of the ingested food (Chen 2009; Iriarte-Díaz et al. 2011). This involves the continual modification of the relative lateral and vertical component of jaw movement and jaw adductor muscle activity as the food is reduced and saliva incorporated (Hiiemae *et al.* 1996; van der Glas *et al.* 2018).

In human feeding studies, tougher and harder foods are more frequently chewed with a greater vertical amplitude and a larger lateral component of jaw movement (Agrawal *et al.* 2000; Bakke 1993; Neill and Howell 1986). Jaw movements are characterised by a slim drop shaped pattern when processing softer foods (Figure 6; Pröschel and Hofmann 1988). In a feeding study of 11 individuals, a more vertically directed squashing action was more frequently observed during the comminution of softer foods whereas more resistive foods required a greater transverse grinding component to mandibular movements when conducting oral processing (Hiiemae *et al.* 1996). Chewing rates also vary depending on the plasticity, stickiness, elasticity and brittleness of the foods ingested. More plastic foods are typically chewed at lower frequencies (van der Bilt and Abbink 2017). Plastic foods are also chewed with greater lateral and vertical amplitudes than elastic foods indicating that rheological factors, alongside food hardness, also influence chewing stroke profiles (Foster *et al.* 2006).

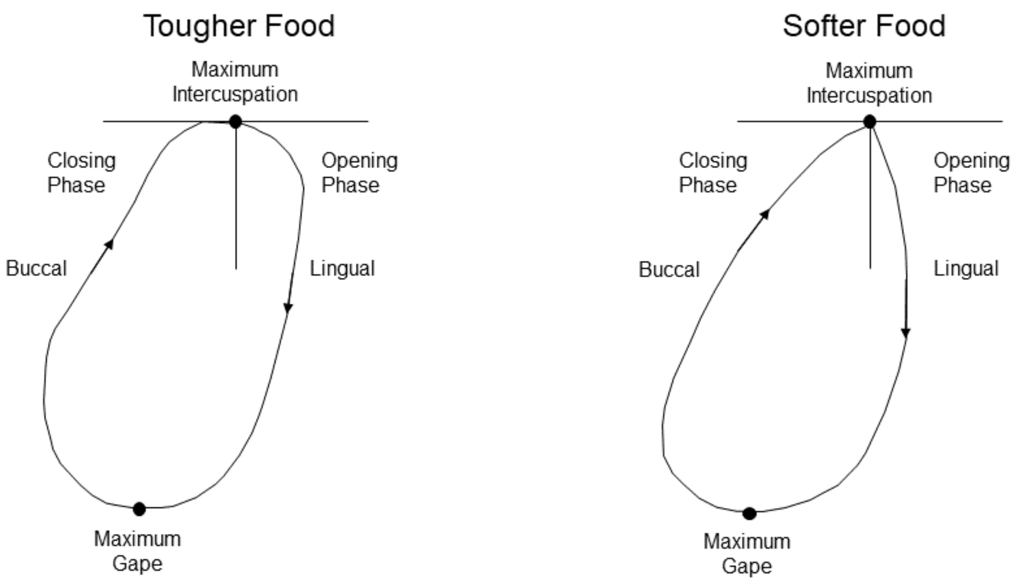


Figure 6: Comparison of jaw movement profiles viewed in the frontal plane when chewing tougher and softer foods. Chewing profiles when consuming tougher foods typically exhibit a more angulated profile and involve a greater lateral component during the latter part of jaw closing and the early part of jaw opening. A tear drop shape pattern is more commonly observed when consuming softer foods in which jaw closing and opening are more strongly vertically directed. Figure is based on Pröschel and Hofmann 1988; figure 1, p.618.

Greater feeding sequence duration and an increase in interindividual variation in feeding behaviours have been observed when eating harder food items (Hiiemae and Palmer 1999, Peyron *et al.* 2002). In addition, significantly greater electromyographic (EMG) activity has been found in the jaw adductor muscles and greater numbers of chewing cycles per sequence have been reported in response to harder foods, indicating that neuromuscular output is modified by food properties (Agrawal *et al.* 1998, Peyron *et al.* 2002; Peyron *et al.* 2004).

Dietary staples likely became softer and less biomechanically demanding to orally process following changes in food production techniques during the Industrial period (Burnett 1989; Collins 1975). As such, a reduction in the number of chewing cycles per sequence might be anticipated and the more vertically directed tear drop shaped pattern of jaw movement might be expected to dominate chewing cycles (Figure 6).

3.2.2 Intrinsic Factors influencing Mastication

Despite similarities in the response of individuals to changing food properties, considerable variability in sequence profile and chewing frequency have been reported amongst individuals chewing the same type of food who share highly comparable dental statuses (Murray 2016). It is likely that each individual exhibits a highly individualised relationship between muscle, teeth and bone that leads to high levels of variability in masticatory behaviours within a group. A similar level of comminution has been observed when preparing a given food for swallowing between different individuals, however, suggesting that individuals adapt their physiological parameters to achieve similar masticatory outcomes in diverse ways (Woda, Mishellany, *et al.* 2006).

Within a feeding sequence, humans commonly chew unilaterality, particularly when processing harder foods (Martinez-Gomis *et al.* 2009; Zamanlu *et al.* 2012). Variation in preferred chewing side has been observed in most clinical feeding studies of humans (Neill and Howell 1988; Zamanlu *et al.* 2012). The right-side of the dentition is the side most commonly favoured (in up to 78% of individuals; Neill and Howell 1988), however, bilateral chewing during feeding sequences is also regularly reported (Martinez-Gomis *et al.* 2009; Nissan *et al.* 2004). Some studies have indicated that chewing efficiency may be greater on the preferred chewing side indicating that, for a given individual, masticatory performance may differ between the sides of the dentition (Haralur *et al.* 2019; Martinez-Gomis *et al.* 2009; Rovira-Lastra *et al.* 2014).

Clinical studies have identified significant differences between the sexes in their mastication parameters (Woda, Foster, *et al.* 2006). The chewing envelope of women has been found to be slightly smaller than that of men (Bakke 1993). In a series of feeding studies, involving a range of foods of different consistencies, men typically had a wider lateral movement and greater vertical opening of the jaw during oral processing, irrespective of the food being chewed (Kiliaridis *et al.* 1991; Neill and Howell 1986; 1988; Tamura and Shiga 2014). Jaw opening and closing velocity was also found to be greater in men irrespective of test food, whereas women spent longer in intercuspal position during each chewing cycle (Figure 7). As a result, male chewing cycles were of a shorter duration (Nagasawa et al. 1997; Neill and Howell 1988; Scudine *et al.* 2016; Youssef *et al.* 1997). Significant differences between the sexes in the amplitude of muscle activity within a chewing cycle have not been consistently found in clinical feeding studies (Khamnei *et al.* 2016; Youssef *et al.* 1997). Men have been shown to exhibit greater EMG activity over a chewing sequence, however, and slightly higher occlusal force (Peyron *et al.* 2004; Shiga *et al.* 2012). Greater chewing frequencies and efficiency have also been reported in males (Khamnei *et al.* 2016; Shiga *et al.* 2012). No significant differences in the stability of the masticatory pathway or rhythm have been reported between the sexes (Tamura and Shiga 2014).

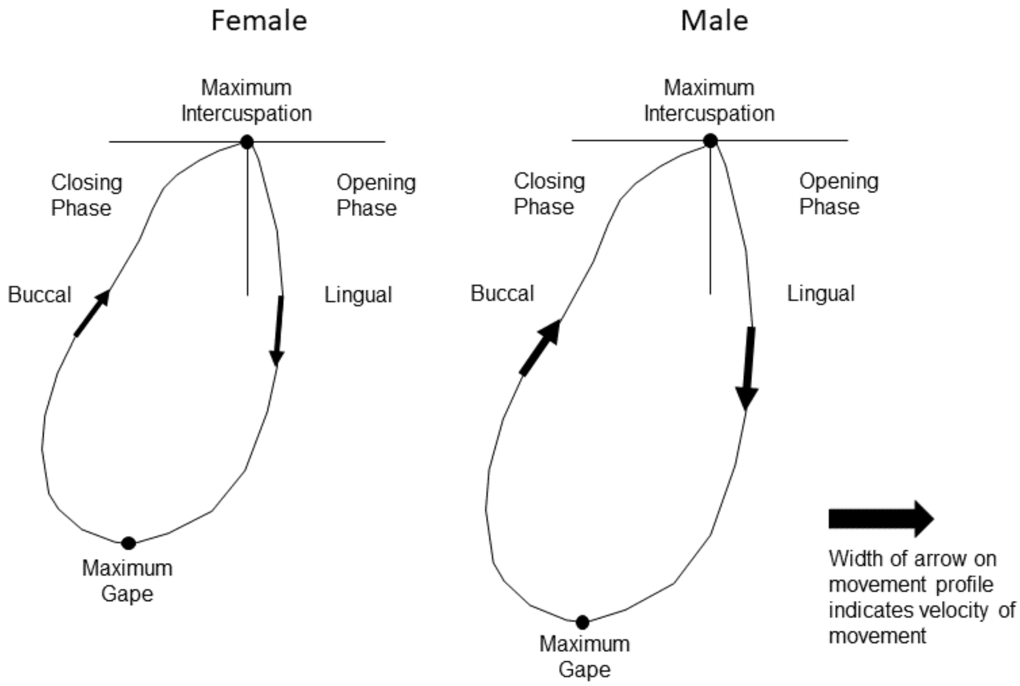


Figure 7: Comparison of male and female movement profiles viewed in the frontal plane during the chewing cycle. The movement profiles of males are characterised by larger vertical and lateral amplitudes. In addition, jaw closing and opening velocity is typically greater in males.

Ageing has some influence on masticatory parameters. These effects are moderate, however, and do not markedly impair mastication when extracted from those associated with increased tooth loss and other confounding factors, such as motor impairment (Mioche *et al.* 2004; Peyron *et al.* 2017; Woda, Foster, *et al.* 2006). Older individuals have been shown to retain the capacity to adapt chewing cycles to changing food properties by modifying the vertical and lateral amplitude of chewing strokes and adjusting EMG activity in response to food hardness (Karlsson and Carlsson 1990; Peyron *et al.* 2004; Peyron *et al.* 2017). The cross-sectional area and density of the masseter and pterygoid muscles decreases with increasing age alongside overall jaw muscle activity (Mioche *et al.* 2004; Newton *et al.* 1987; Newton *et al.* 1993). The vertical displacement and movement velocity of the mandible generally decreases with age whilst the number of chewing cycles and chewing duration required to produce a bolus that can be swallowed increases (Feldman *et al.* 1980; Karlsson and Carlsson 1990; Ketel *et al.* 2020; Koyama *et al.* 2002; Mioche *et al.* 2004; Peyron *et al.* 2004;). The increase in chewing cycles per sequence increases the EMG activity required for older individuals to orally process a given food, irrespective of its hardness (Peyron *et al.* 2004).

Tooth loss and the number of dental contacts across the dentition has a considerable impact on masticatory efficiency and performance (Feldman *et al.* 1980; Ikebe *et al.* 2012; Kosaka *et al.* 2018; Woda, Foster, *et al.* 2006). Since tooth loss typically becomes more frequent with increasing age, these two factors often act concurrently to alter masticatory performance. Clinically, a greater number of chewing strokes have been observed to be required to prepare a bolus that can be swallowed among individuals with increasing levels of edentulousness. A slight decrease in jaw closing velocity and masticatory frequency has also been noted (Slagter *et al.* 1993; Wayler and Chauncey 1983; Woda, Foster *et al.* 2006). Many clinical examinations of the effects of tooth loss on masticatory behaviours and performance are not appropriate analogues for archaeological groups as they consider the mitigating influence of the wearing of partial and complete dentures.

In summary, the parameters of chewing cycles and the overall chewing sequence are modified in response to food properties but are also influenced by underlying individual factors (Table 5). In the current research, these intrinsic factors, including sex, age and tooth loss should be considered as variables that may potentially contribute to the overall variability in the dental wear facet patterns observed and the chewing behaviours inferred from them.

Table 5: A summary of the effects of food properties and intrinsic individual factors on chewing sequence and chewing stroke parameters. Factors either increase (+), decrease (-) or have no or limited effect (=) on the chewing parameter. Table modified from Woda, Foster et al. (2006, table 1, p.32).

Factors influencing chewing sequence and cycle parameters		Chewing Sequence Parameters			Chewing Stroke Parameters			
		Number of strokes to prepare bolus	Chewing sequence duration	Chewing frequency	EMG activity per stroke	Vertical amplitude	Lateral amplitude	Jaw closing velocity
Food Properties	Hardness (soft to hard)	+	+	=	+	+	+	-
	Physical properties (elastic to plastic)	=	=	-	=	+	+	+
Intrinsic Individual Factors	Sex (from female to male)	=	-	+	=	+	+	+
	Age (with increasing)	+	+	=	+	=	=	-
	Tooth Loss (with increasing)	+	+	-	+	?	?	-

3.3 Dental Wear Mechanisms

Dental enamel is an almost wholly mineral biological composite, comprising approximately 90% hydroxyapatite crystals which are arranged into bundles that vary in orientation. The remaining 10%, the space between the crystals, is filled with a matrix of mainly water and low molecular weight proteins (Hillson 2005; van Casteren and Crofts 2019).

Dental wear, the gradual loss of tooth substance, results from the complex interaction of physical and chemical mechanisms (Table 6) (Addis and Shellis 2006; d'Incau et al. 2012; Kaidonis 2008; Shellis and Addis 2014). The explanation of dental wear mechanisms is complicated by discordance in the literature between researchers who utilise concepts developed within dentistry and those that employ concepts from engineering tribology (Lewis and Dwyer-Jones 2005). During mastication, most of the physical wear that occurs will be three-body abrasion due to the action of intervening freely moving particles between the teeth. Although each mechanism of tooth wear can occur in isolation, multiple wear mechanisms may occur simultaneously or in tandem to produce additive and synergistic effects. Erosive wear interacts with physical wear mechanisms but can also directly remove dental hard tissue by complete dissolution. Areas of softened enamel are created by erosive wear through the removal of mineral content a few micrometres below the surface (Addis and Shelley 2006). These softened areas are more susceptible to subsequent mechanical wear (Ruben *et al.* 2019).

Table 6: Dental wear mechanisms

Wear Mechanism	Description
Attrition or Two-body Abrasion	It has been argued that dental attrition results principally from tooth-tooth contact and has been equated with the concept of two-body abrasion in tribology (Kaidonis 2008; d'Incau et al. 2012). In tribology, two-body abrasion is poorly defined. Two contrasting definitions exist. The predominant view is that two-body abrasion occurs when the first body is cut into by asperities rigidly attached to a moving second body, such as a hard metal file abrading a softer metal body. Alternatively, it may be the action of loose abrasive particles (the second body) moving across a solid surface (the first body), such as loose abrasive material moving down a chute (Gates 1998). During any interaction between opposing teeth, there will be an intervening layer of particles suspended in saliva, which may include detached enamel chips, exogenous abrasive and/or food particles (Lewis and Dwyer-Joyce 2005). Consequently, dental attrition define as two-body abrasion cannot occur mechanistically as an intervening third body will always be present between the two interacting teeth (Addy and Shellis 2006; Shellis and Addy 2014). The value of differentiating two-body from three-body abrasion in tribology has been questioned (Gates 1998). As such, it is perhaps preferable to refer to all physical wear effecting the teeth as abrasion (as defined below) as a situation in which two-body abrasion occurs between the teeth arguably seldom happens.
Abrasion or Three-body Abrasion	Abrasive wear (three-body abrasion) involves the displacement of two bodies across each other with the interposition of abrasive particles between them. These intervening particles constitute the third-body (d'Incau *et al.* 2012). The friction of exogenous material over the tooth surface results in the loss of tooth substance. The action of abrasive food particles can produce both generalised wear areas across the tooth crown, as well as, specific wear facets depending on the action of the teeth and jaws (Figure 8) (Lewis and Dwyer-Joyce 2005). In practices, it is useful to differentiate between effects that produce generalised wear across the tooth surface and those that produces dental wear facets.
Erosion	Erosion can be defined as the progressive loss of tooth substance due to the action of corrosive agents. Different patterns of erosive wear will depend on whether the source of acids is intrinsic or extrinsic (Kaidonis 2008). Following sustained exposure to acidic conditions in the oral environment, defects develop on the tooth typically characterised by shallow concavities (Ganss 2006).
Abfraction	Abfraction is the cracking and the subsequent breaking away and loss of tooth substance. Fracture is likely to occur along the boundaries of the hydroxyapatite crystals that make up the dental enamel. This most commonly occurs in areas where stress is concentrated during the occlusal loading of the teeth, such as the cervical region. Abfraction lesions often present in clinical dentistry as a crescent shaped area of lost enamel along the cervical line (Grippo *et al.* 2004; Lewis and Dwyer-Joyce 2005).

Mechanisms of dental wear may also differ between cycles of the chewing sequence. Puncture-crushing cycles result in generalised abrasion as the food slurry, containing any suspended abrasive particles, may move freely between the teeth since the occlusal surfaces are not brought as closely together as during power stroke (Butler 1981; Kaidonis 2008; Lewis and Dwyer-Joyce 2005). During puncture-crushing, the friction of exogenous material over the tooth surface produces generalised wear and gradually obliterates the occlusal topography (Figure 8) (Lewis and Dwyer-Joyce 2005; Kaidonis 2008; Shellis and Addy 2014). During chewing *sensu stricto*, the opposing surfaces of the teeth are in closer proximity as the power stroke occurs (Figure 8). A layer of particles suspended in saliva, likely including food particles, abrasives and detached enamel, is present between the tooth surfaces. This results in the development of dental wear facets at areas of the occlusal surface against which abrasive particles are repeatedly trapped and moved across as the dental surfaces slide past one another during the power stroke. Dental wear facets are shiny planar surfaces with well-defined edges. Each facet that develops as a result of the masticatory power stroke has a corresponding wear facet in the teeth of the opposing dental arch (Butler 1981; Lewis and Dwyer-Joyce 2005).

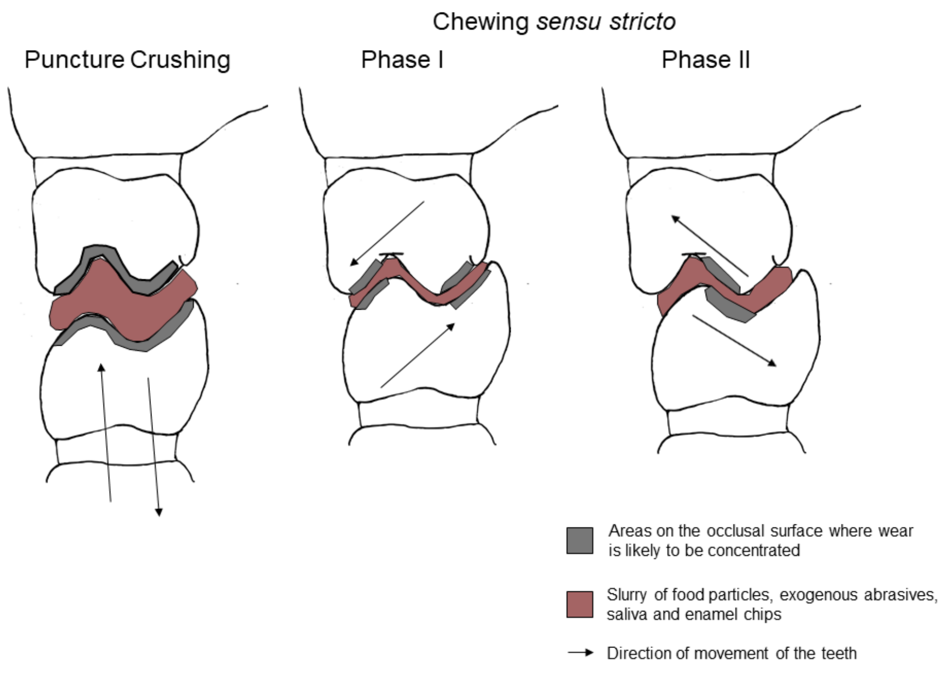


Figure 8: Diagram showing the interaction between opposing teeth during puncture crushing cycles and chewing sensu stricto. During both phases of oral processing, the predominant dental wear mechanism is dental abrasion or three-body abrasion mediated by dental erosion (Lewis and Dwyer-Joyce 2005). In puncture-crushing, the larger quantity of food particles and more vertically directed chewing action will result in more generalised wear across the entire occlusal surface. During chewing sensu stricto, the intervening slurry of particles is reduced, there is a greater lateral component of jaw movement and the distance between opposing dental surfaces is reduced. As such, trapped particles abrade the dental surfaces as they slide past each other as the teeth move into and out of maximum intercuspation. This results in specific areas of focused wear at which dental wear facets develop. Figure created by the author.

In addition to wear on the occlusal surface, interproximal tooth wear occurs due to the movement of the crowns during chewing and results in tooth wear between adjacent teeth in the dental arcade. This process acts to remove tooth substance from the mesial and distal portions of the crowns involved and produces dental wear facets in these regions (Begg 1954; Benazzi *et al.* 2011).

At a microscopic level, the capabilities of a particle in the oral cavity to inflict wear upon dental tissues are determined by its hardness, the angle of interaction between the particle and tooth surface and the occlusal load applied to it (Arsecularatne and Hoffman 2010; Borrero-Lopez *et al.* 2014). In abrasion, ribbons or chips of enamel are broken away by the movement of the particle across the enamel surface (Lucas *et al.* 2016; Xia *et al.* 2015). Some studies have indicated that siliceous plant phytoliths, softer than enamel, may be active in the wear of teeth at a microscopic level (Fox *et al.* 1994; Gügel *et al.* 2001; Lucas *et al.* 2013; Lucas *et al.* 2016; Lucas and van Casteren 2015; Sánchez-Hernández *et al.* 2016; van Casteren and Crofts 2019; van Casteren *et al.* 2020). Abrasion, however, has been principally attributed to the ingestion of grit. Quartz grains, for example, can remove enamel tissues with only a limited application of force when they have the right angle of attack (Ungar 2015). If abrasion results in the removal of enamel chips, these chips will likely be further involved in the abrasion of the parent enamel surface during the chewing sequence (Lucas *et al.* 2013).

A recent experiment (van Carstern *et al.* 2020) examining the interaction between the densest woody plant tissues and enamel at a nanoscopic scale indicated that plant tissues are not capable of producing the microwear features characteristic of a highly complex worn surface. This would suggest that microwear textures may reflect the manner in which particles interact with and move across dental surfaces during mastication, especially grit and to a lesser extent phytoliths, rather than the hardness and toughness of the ingested food itself (Ibid.). Another recent study of microwear formation in a controlled feeding experiment of capuchin monkeys found that new microwear features were not readily formed within a single feeding bout on brazil nuts and that interindividual variation in microwear features was substantial. These *in vivo* and *in vitro* studies highlight current deficiencies in understanding the formation processes underpinning dental microwear features and highlight the complex interplay between food and grit particle properties, their size and shape, and individual chewing behaviours in the formation of these features (Teaford *et al.* 2020). Although the relative contribution of food particles to the abrasiveness of dietary content is still debated, the grit ingested plays a clear role in the abrasion of dental surfaces. Developments in milling practices during the Industrial period reduced the quantities of abrasive particles, such as quartz derived from millstones, within the flour consumed (Burnett 1989). The abrasive load placed on the dentition during mastication was therefore reduced when compared to their Mediaeval antecedents.

The predominant mechanisms of dental wear from prehistoric to recent times shifted due to the decrease in the quantity of abrasive particles within the foods consumed as food processing technologies changed. In a study of individuals from six different temporal groups in Japan from the Jomon period (4000-300BC) through to the 20th century, a steady decrease in the extent of abrasive wear in the posterior dentition was apparent (Kaifu 1999; 2000). Modern dentitions are typified by the predominance of erosive wear rather than abrasive wear, due to the inclusion of a variety of extrinsic acids within the diet (Ganss *et al.* 2002; Kaidonis 2008; D'incau *et al.* 2012). The retention of relatively unworn teeth into adulthood in these contemporary groups continues to concentrate occlusal loading stresses in the buccal cervical region of the tooth in lower post-canine teeth increasing the likelihood of abfraction and the development of non-carious cervical lesions (Benazzi *et al.* 2013b). Similarly, in the Industrial period, more unworn occlusal forms were likely retained later into life than in the Mediaeval period.

3.4 Dietary inference, masticatory behaviours and dental wear

Dental evidence across a range of scales provides insight into dietary behaviours and adaptations. The morphology of the mammalian dentition, including the arrangement of cusps across the molar crown, reflects the evolution of tooth function in response to food properties (Crompton 1971; Crompton and Sita-Lumsden 1970; Fortelius and Solounias 2000; Hillson 2005; Lucas 2004). The orientation and topography of tooth surfaces determine the mode and duration of the application of stresses to food items. Opposing crests can exert shearing forces on food items. Paired blunt and concave or convex surfaces can apply crushing loads to ingested food. Selective pressures will favour the acquisition of occlusal morphology better adapted to the oral processing of important habitual dietary items or the crucial fall-back food resources of a species (Simpson 1933; Spears and Crompton 1996).

The analysis of the three-dimensional characteristics of occlusal form, prior to its modification by dental wear, can be performed using dental topographic analysis (Ungar and Williamson 2000). Morphological features, such as shearing crest length across the crown and topographic complexity, have been used to differentiate primate species pursuing different subsistence strategies. Folivores are often characterised by more prominent shearing crests when compared to frugivores (Allen *et al.* 2015; Bunn and Ungar 2009; Kay and Hiiemae 1974; Klukkert *et al.* 2012; M'Kirera and Ungar 2003; Ungar *et al.* 2016). Overall tooth shape has also been used to establish functional similarities between the dentitions of carnivora and rodents (Evans *et al.* 2007).

Dental morphology prior to its modification by wear provides an indication of the dietary items a species is capable of eating and is more useful when making higher-order taxonomic comparisons, particularly when considering evolutionary timescales. Discrepancies can exist between the dietary regime indicated by gross dental morphology and the actual dietary content of a group, however, when considering shorter temporal scales, actual dietary preference, and within and between species comparisons (Calandra and Merceron 2016; Teaford 2007; Ungar 2015). Liem's paradox (1980) highlighted that many species with highly specialised teeth actively avoid the foods that they are adapted to process in favour of more easily processed or readily available foodstuffs. This limits the dietary inferences that can be made based on dental morphology alone. Tooth form may indicate potential diet rather than preferred diet (Ungar 2015). In addition, overall dental form may indicate other aspects of behaviour. For example, the canine/premolar complex, present in most nonhuman anthropoid primates, is used in threatening displays and occasionally actual fighting. Selection likely shaped their use as a weapon (Delezene 2015; Galbany *et al.* 2015; McGraw *et al.* 2002).

Furthermore, teeth can be divided into two classes. Some species have occlusal surfaces that are sufficiently functional in their unmodified form immediately after eruption, such as bunodont molars. On the other hand, others require a phase of initial wear to obtain full functionality through the reshaping of the occlusal surface. The exposed cross-section of the molar teeth of many herbivores combine faster wearing dentine with harder wearing enamel resulting in the development of enamel ridges that act as shearing blades when consuming coarse vegetation. Specialised facets develop on the carnassial teeth of carnivores for the shearing of meat (Koenigswald 2018; Ungar 2015).

Dental wear indicates the way the teeth were used. It can be considered primarily at two scales when inferring actual tooth use and dietary composition: dental macrowear and dental microwear (Table 7) (Fortelius and Solounias 2000; Janis 1990; Smith 1984; Teaford and Walker 1984; Ungar 2015).

Table 7: Description of methods that have been used to make inferences about diet and other aspects of behaviour using dental wear.

Scale of Analysis	Method	Examples of research that has used the method
Overall Dental Morphology	Comparison of cusp size and shape in three-dimensions.	Evans *et al.* 2007; Kay and Hiiemae 1974.
Dental Macrowear	Gross dental wear analysis using ordinal schemes to rank extent of dental wear.	Scott 1979a, Smith 1984.
	Quantitative assessment of dentine exposure of a tooth as a proportion of the occlusal surface.	Clement and Hillson 2012
	Dental wear facet analysis, such as Occlusal Fingerprint Analysis (OFA), measuring the size, orientation and steepness of dental wear facets.	Fiorenza *et al.* 2011a; Zanolli *et al.* 2019.
	Dental mesowear assessing occlusal relief and cusp shape after modification by wear.	Fortelius and Solounias 2000; Joomun et al. 2008.
Dental Microwear	Assessment of the distribution of pits and scratches across dental wear facets using a scanning electron microscope	Gordon 1984; Teaford and Walker 1984.
	Dental microwear texture analysis quantifying the distribution and profile of microwear features in three-dimensions across areas of dental wear facets.	Scott *et al.* 2006; Ungar et *al.* 2007

3.4.1 Dental Macrowear Analysis

The analysis of dental macrowear can involve quantitative, semi-quantitative and qualitative approaches to the analysis of the pattern of wear across the occlusal surface of the tooth visible to the naked eye or under low powered magnification. In anatomically modern humans, ordinal approaches to scoring the extent and pattern of dentine exposure across the worn occlusal surface have been used to compare the relative abrasiveness of different dietary regimes, food processing techniques and the use of teeth as tools (Miles 1963; Molnar 1972; Scott 1979a; Smith 1984). In addition, quantitative methods, such as expressing the area of dentine exposed as a proportion of the total occlusal area when measured from photographs, have been used as alternatives to these ordinal schemes (Clement *et al.* 2012; Clement and Hillson 2012).

Dental mesowear analysis has typically been applied to the teeth of extant and extinct herbivores and considers the modification of the occlusal surface over the course of an individual's lifetime. It relies upon the gradient between tooth wear that blunts occlusal relief and that which produces sharp wear facets (Figure 9). In browsers, dental wear typically creates steeper and sharper occlusal relief with well-defined wear facets. Heavier dental abrasion is more typical of grazers and species consuming foods covered in grit and dust, which results in more heavily blunted and rounded occlusal topography (Ackersmans 2020; Fortelius and Solounias 2000; Joomun *et al.* 2008; Kaiser and Solounias 2003; Schubert 2007).

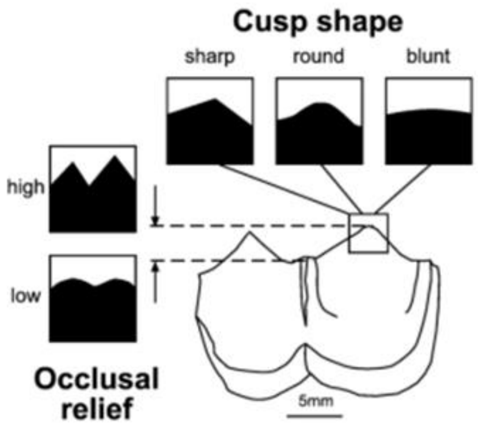


Figure 9: Diagram showing the method used to perform dental mesowear analysis by Joomun et al. (2008) in herbivorous mammals. The occlusal relief and shape of the cusps are assessed using an ordinal scale. Reprinted from Palaeogeography, Palaeoclimatology, Palaeoecology, Vol 263 (3-4), Joomun et al.*, p94, Copyright (2008), with permission from Elsevier.*

Dental wear facet patterns, also visible to the naked eye, reflect the cumulative outcome of tooth use over a substantial portion of an individual's lifetime (Fiorenza *et al.* 2020; Janis 1990; Kullmer *et al.* 2009). Whereas dental mesowear and gross wear analysis provide an overview of wear across the occlusal surface, dental wear facets reflect the habitual jaw movement pathways utilised during feeding in mammals (Koenigswald *et al.* 2013; Kullmer *et al.* 2012). Most wear facets represent a specific moment of contact during the power stroke. Within this process, a particular antagonistic area will fit perfectly into the topography of the opposing tooth to create a specific wear facet (Ulhaas *et al.* 2007). Dental wear facets in anatomically modern humans are restricted to the enamel and are, therefore, obliterated as dental wear progresses into the dentine of the tooth so only relatively unworn teeth are appropriate for performing dental wear facet analysis (Fiorenza *et al.* 2018). The size, orientation and type of wear facets distributed across the occlusal surface have been used to infer dietary behaviours in multiple mammalian species (Butler 1952; Fiorenza *et al.* 2011a; Janis 1990).

Wear facets can be associated with either a shearing or crushing function (Table 8). The size and development of wear facets across the occlusal surface reflect the processing pathways used to reduce habitual dietary components (Janis 1990). It has been argued that the relative wear facet area associated with each phase of the power stroke is the most important parameter in reconstructing diet using wear facets as this is more likely to reflect differences in masticatory behaviours in response to different food properties (Fiorenza *et al.* 2020). The mode of formation of tip crushing facets is still debated and it is unclear whether they can be attributed to the regular power stroke within the chewing cycle (Fiorenza *et al.* 2018). Consequently, they are typically not considered alongside phase I and phase II facets when conducting dietary inferences based on dental wear facet patterns (Fiorenza *et al.* 2011a; Fiorenza 2015).

Table 8: Food processing mechanisms and dental wear facet areas.

Wear Facet Type	Reduction Mechanism	Description	Dietary composition associated with enlargement of facet areas
Buccal Phase I (BPI)	Shearing	Contact between the crests and leading edges of the post-canine teeth during phase I.	Tough and fibrous foods. High meat consumption (Fiorenza et al. 2011a) and/or coarse vegetable foods (Janis 1990)
Lingual Phase I (LPI)	Crushing	Food is crushed in the fossae of the molar teeth by the tips of cusps as the teeth move into maximum intercuspation during the latter part of phase I.	Associated with foods that require pulping and crushing: roots, seeds, gums, fruit and fungi etc. (Janis 1990).
Phase II (and/or Terminal Phase I) (PII)	Shearing/ Crushing	Low-force hypothesis: Possibly involved in crushing during the terminal part of phase I and maximum intercuspation. Food breakdown during actual phase II movement is limited (Hylander *et al*. 1987). High-force hypothesis: Significant food breakdown occurs during phase II of the power stroke combining both a shearing and crushing function (Kay and Hiiemae 1974).	Less clear dietary association. In herbivores, enlarged phase II areas were associated with the ingestion of large quantities of fruit in contrast to more folivorous species (Janis 1990).
Tip Crushing (TC)	Crushing	Crushing wear is formed principally on the cusps of the teeth during the puncture-crushing phase of oral processing.	Amplified in processing cycles used to reduce anisotropic hard and brittle items, such as nuts and seeds, or for the pulping of softer items, such as fruit (Janis 1990).

Variation in the pattern, size, inclination and orientation of dental wear facets has been associated with dietary composition, both at interspecies (Janis 1990; Kay and Hiiemae 1974) and intraspecies levels (Fiorenza *et al.* 2011a; Fiorenza *et al.* 2018). The relative facet area associated with buccal phase I, lingual phase I and phase II of the power stroke have been shown to differentiate modern hunter-gatherer groups, Neanderthals from different ecogeographic regions (Fiorenza *et al.* 2011a) and early agriculturalists (Fiorenza *et al.* 2018). Modern hunter-gatherers consuming large quantities of meat had larger buccal phase I and phase II facets and less-developed lingual phase I facets. This indicates a prominent shearing action in individuals that consume meat as a chief dietary component. Groups with a more mixed diet exhibited large lingual phase I facets, small phase II facets and less developed buccal phase I facets (Fiorenza *et al.* 2011a). More horizontally inclined wear plane angles have been reported in the teeth of hunter-gatherers, likely consuming a coarser diet, when compared to agriculturalists (Fiorenza *et al.* 2018; Smith 1984;).

The interpretation of phase II wear facets is complicated by their potential involvement in both puncture-crushing cycles and chewing *sensu stricto* (Hiiemae 1978)*.* Kay and Hiiemae (1974) proposed that phase II facets are involved in a relatively significant proportion of food breakdown during phase II of the power stroke. This has been termed the 'high-force hypothesis' (Wall *et al.* 2006). In contrast, experimental observation of mandibular bone strain and electromyographic activity in long-tailed macaque and Anubis baboon indicated that peak bone strain and jaw adductor activity occurred prior to maximum intercuspation and that bone strain was rapidly unloaded prior to phase II of the power stroke (Hylander *et al.* 1987; Wall *et al.* 2006). The mastication of softer foods in macaques, however, was potentially associated with significant masticatory forces during the early portion of phase II movements (Hylander and Crompton 1980; Hylander *et al.* 1987). These studies support the 'low-force hypothesis', in which phase II facets may act predominantly as guiding contacts during the phase II movement itself and likely principally develop and function during the terminal part of phase I, when food is compressed between cusp tips and their opposing basins. Phase II wear facets would also likely be active during puncture-crushing cycles (Hylander and Crompton 1980; Teaford 1985; Wall *et al.* 2006). Phase II wear facets may, therefore, be more appropriately considered terminal phase I/phase II facets.

Differences in dental wear facet patterns cannot be attributed solely to dietary composition and food processing methods, however. The progress of dental wear and the development of dental macrowear patterns can be attributed to several exogenous and endogenous factors (Fiorenza *et al.* 2018). The developmental sequence of the dentition, non-masticatory tooth use, enamel thickness, occlusal variability, tooth inclination and the biomechanics of craniofacial shape can all contribute to the occlusal wear pattern (Fiorenza *et al.* 2010; Fiorenza *et al.* 2011b; McKee and Molnar 1988; Oxilia *et al.* 2018).

Dental wear facets develop and are continually modified through tooth use and, therefore, attempts must be made to compare individuals at similar states of dental wear (Kaiser *et al.* 2013). A longitudinal study of wear facet inclination in Milne-Edwards's Sifaka, a type of lemur from Ranomafana National Park, indicated that the orientation and inclination of wear facets showed considerable variability over short time periods (1-3 years). A long-term trend for inclination to decrease with age was observed (Blatch *et al.* 2011). In addition, significant differences were found in the wear facet inclination of modern-hunter gatherers exhibiting different Smith wear scores (Fiorenza 2009).

Occlusal variability, such as the presence of supernumerary teeth and misaligned dental arches, can negatively affect masticatory efficiency and result in the development of distinctive wear facet patterns associated with often restricted masticatory pathways as the movement of the mandible adapts to the occlusal conditions as far as possible (Fiorenza and Kullmer 2016). Differences in tooth inclination and asymmetry in the masticatory system have been forwarded as factors contributing to differences in dental macrowear patterns. In the Yuendumu longitudinal growth study, increased buccal inclination of the lower teeth was associated with larger lingual phase I areas, whereas lingual inclination tended to increase buccal phase I wear (Oxilia *et al.* 2018). In addition, habitual non-masticatory tooth use can create wear facets which exhibit an unusual orientation and often lack an antagonist in the opposing dental arcade (Fiorenza and Kullmer 2013, 2015).

Bruxism, parafunctional activity involving the repetitive grinding or clenching of the teeth, can also produce atypical patterns of dental wear (Lobbezoo *et al.* 2006; Lobbezoo *et al.* 2013). Clinically, irregular patterns of dental wear occupying larger areas of the crown have been reported in bruxing individuals (Restrepo *et al.* 2006). The mandibular excursions of individuals who brux are often associated with a repeated pathway of jaw movement. Consequently, the pattern of contacts that develop are commonly highly specific and frequently only effect one side of the dental arcade or a few teeth (Sameera *et al.* 2017). A lack of differentiation between the direction and inclination of wear facets associated with incursive and excursive movements may indicate the presence of bruxing behaviour (Fiorenza and Kullmer 2016). To model and interpret the occlusal wear pattern in a particular assemblage, all the mechanisms contributing to the development of dental wear facets should be considered where possible (Oxilia *et al.* 2018). This is very difficult to achieve in the fragmentary and often poorly represented archaeological dentitions which also require the making of untestable assumptions about unknown life histories.

3.4.2 Dental Microwear Analysis

The distribution, orientation and density of microscopic scratches and pits found across dental wear facets can also be utilised for dietary reconstruction (Figure 10) (Ungar 2015). These dental microwear features have a relatively high turnover rate, referred to as the 'Last Supper' phenomenon, so represent the food consumed over a short period, as little as a few weeks, prior to death or the recording of the dental impression (El Zaatari *et al.* 2011; Fortelius and Solounias 2000; Grine 1986; Mahoney *et al.* 2016). Any direct association between macrowear and microwear patterns is weak (Schmidt 2010).

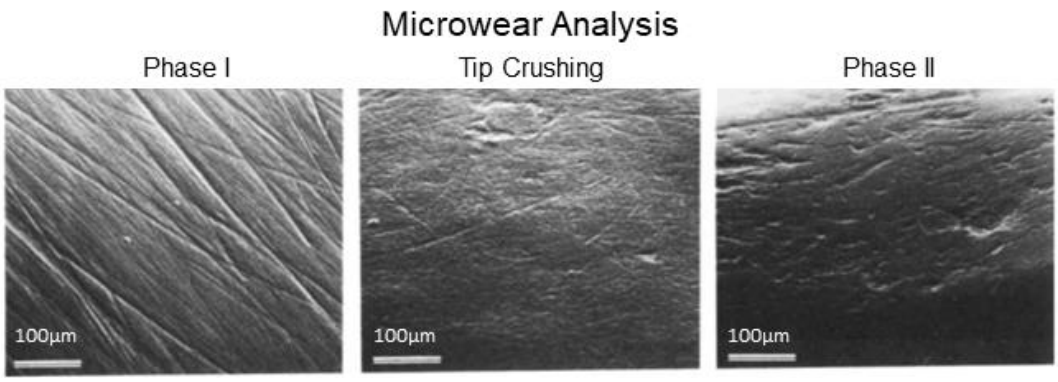


Figure 10: Diagram showing the dental microwear features visible across the wear facets on a single molar specimen from a chimpanzee. Note higher frequencies of scratching on the phase I wear facet and more pitting on the phase II wear facet (Figure 5 p.204 from Gordon 1982). Copyright © 1982 Wiley-Liss, Inc., A Wiley Company.

Early assessments of dental microwear features attempted to interpret jaw movement pathways in extant and extinct species based on the orientation of the striations on dental wear facets (Butler 1952; Gordon 1984; Morel *et al.* 1991; Mills 1955; Simpson 1933). The expansion of dental microwear research occurred due to the increased availability of scanning electron microscopes from the 1970s onwards (Ungar 2015). The ratio between pits and scratches was shown to differentiate primates known to differ in dietary content. Hard object feeders had greater numbers of pits on their phase II wear facets whereas species consuming tougher and more fibrous foods, such as folivores, had greater numbers of scratches (Teaford and Walker 1984). More subtle seasonal dietary variation and dietary differences between closely related primate species were also identified (Teaford 1984; 1985; Teaford and Glander 1991; 1996). Laboratory feeding experiments also indicated that dental microwear patterns differed between primates raised on foods with different physical properties (Teaford and Oyen 1989). High levels of interobserver error limited the precision of these earlier studies, however (Grine *et al.* 2002).

The development of dental microwear texture analysis provided an automated alternative to these earlier approaches to microwear analysis (Ungar *et al.* 2003; Ungar *et al.* 2007; Ungar 2015). A 3D point cloud is generated of the target wear surface and the texture of the surface is analysed. A value is generated to describe the complexity of the surface, which is typically larger for heavily pitted surfaces when compared to those dominated by scratches. A value describing the directionality, or anisotropy, of the microwear features that comprise the surface texture is also produced. This is greater on surfaces that are chiefly marked by consistently aligned striations rather than pits (Scott *et al.* 2006; Ungar *et al.* 2007; Ungar 2015). Species that habitually consume hard and brittle foods have been shown to exhibit higher microwear surface texture complexity and lower anisotropy values as their tooth surfaces are dominated by pits. Those that rely upon tougher foods that require shearing typically have higher surface anisotropy and lower complexity values as their tooth surfaces are characterised by larger numbers of closely aligned scratches (Ungar 2015).

Furthermore, differences have been reported in microwear textures between phase I and II facets indicating that these wear facets are likely involved in different tooth-food interactions (Figure 10) (Gordon 1982; 1984; Teaford and Walker 1984; Teaford 1985). In three primate species, higher surface complexity and anisotropy were found on their phase II wear facets when compared to phase I facets. Phase II microwear textures may reflect the compression of food particles against phase II wear facets during the terminal part of phase I of the power stroke and maximum intercuspation. This would likely include any grit and possibly phytoliths in the ingested food. In contrast, phase I wear facets are likely primarily formed during a stage of the masticatory cycle in which fewer abrasive particles have the right angle of attack to produce highly complex dental microwear surfaces and masticatory forces are orientated at an acute angle to the worn surface (Krueger *et al.* 2008).

3.4.3 The Selection of OFA for the Current Research

The analysis of dental morphology, macroscopic wear patterns and dental microwear patterns provide contrasting and complementary scales of resolution when examining masticatory behaviours and performing dietary reconstructions (Fortelius and Solounias 2000; Ungar 2015). The myriad factors underpinning the formation of dental microwear textures require further exploration experimentally to understand the dynamic interplay between food particle properties, grit and chewing behaviours (Teaford *et al.* 2020) so was not deemed an optimal approach for the current analysis, which aimed to reconstruct and compare masticatory behaviours in the Mediaeval and Industrial periods.

OFA, which examines the distribution, size and orientation of dental wear facets, provides an insight into prominent jaw movement pathways, chewing behaviours and para-masticatory tooth use over a substantial portion of an individual's lifetime (Fiorenza *et al.* 2020). This approach, therefore, provides a suitable technique to address the deficiency in knowledge surrounding the impact that the more heavily processed foods associated with industrialisation had on masticatory behaviours. OFA requires the selection of an appropriate system for describing the location of dental wear facets. This is discussed in the following section.

3.5 Dental Wear Facet Labelling Systems

Systems have been devised to label dental wear facets according to their position on the occlusal surface and their role in the functional interaction between upper and lower molar crowns during mastication (Schultz *et al.* 2018). These systems were initially developed as methods of reconstructing the functional jaw movements of extinct mammals and to make comparisons between their dental morphology and function. Mammalian molar crowns can be regarded as being constructed from homologous elements, despite considerable variability in overall appearance (van Valen 1994). Using this concept of homology, cusps and facets can be given the same name provided they occupy similar positions within the overall topographic arrangement of the molar and have approximate functional correspondence when antagonistic teeth are interacting during occlusion. Butler (1952) showed that homologous dental wear facets could be identified on homologous elements of the molars of different species and proposed a system for labelling these facets to enable comparison (Table 9; Figure 11). He identified 10 facets in the Perissodactyla and numbered the facets with reference to the functional relationship between morphological features in the upper and the lower teeth. Later, he identified 12 facets in tertiary North American primates (1973).

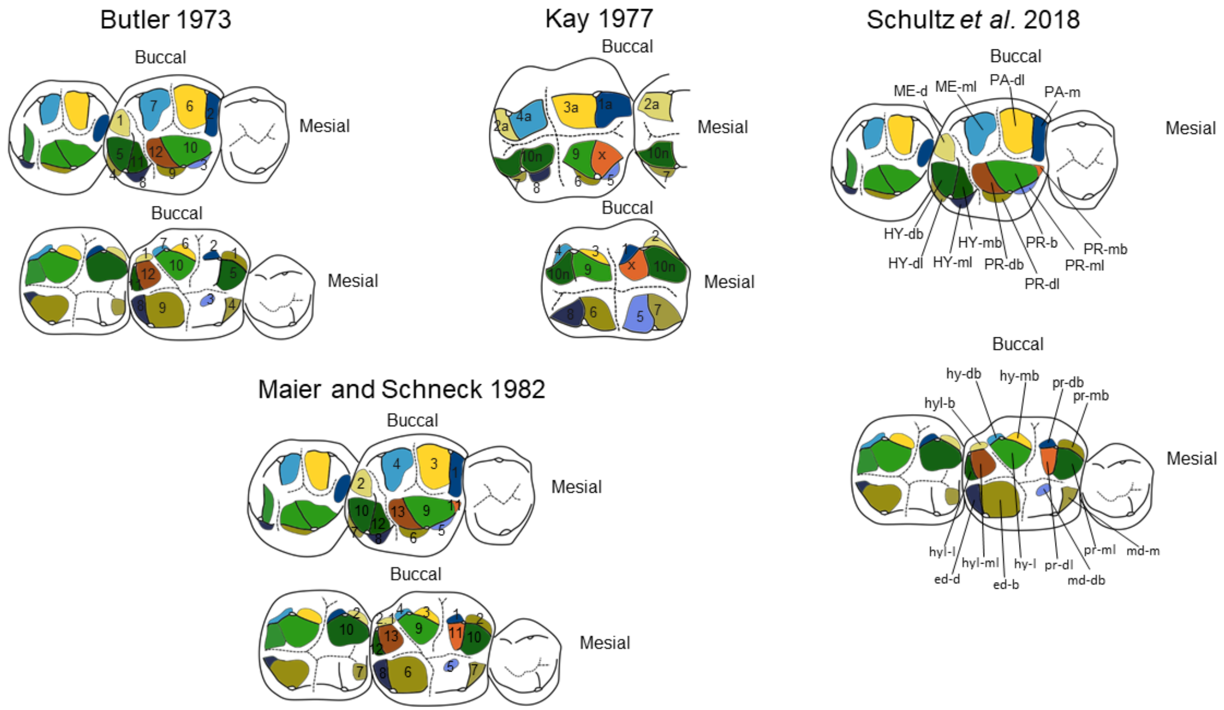


Figure 11:Diagram showing facet labelling systems that have been applied to the study of primate dentitions. Corresponding upper and lower wear facets are the same colour. All illustrations are of hominoid molar teeth except for Kay (1977), which represents a Rhesus macaque. This includes the labelling systems developed by Butler (1973), Kay (1977), Maier and Schenk (1982) and Schultz et al. (2018). Diagrams for Maier and Schneck (1982; figure 1 p.694) and Kay (1977; figure 2 p.330) were redrawn from their original publications. The diagrams to illustrate the Butler (1973) and Schultz et al. (2018) systems are adaptations of the original Maier and Schenk figure (1982; figure 1 p. 694).

Subsequent authors have developed alternative systems of facet labelling (Table 9) (*Schultz et al.* 2018). Mills (1955) did not label the facets identified across the dentitions of primates and instead assigned them to a phase of the power stroke. Crompton (1971) identified six pairs of wear facets that were labelled according to the order in which they were believed to have appeared during the evolution of the tribosphenic molar. This system was also adopted and expanded by Kay and Hiiemae (1974), who identified a maximum of 10 wear facets across the primate species they examined. Kay (1977) described a further two facets in Cercopithecine molars: facets ‘x’ and ‘10n’. Maier and Schenk (1981; 1982) later relabelled these facets as 11 and 12 and identified a facet 13, present only in hominoid molars. Difficulties arise within these numbering systems when attempting to apply them to specimens that deviate from the tribosphenic molar pattern, particularly early mammaliaforms, that require the invention of additional facet nomenclature. In addition, these labelling systems can give facets in different locations the same number increasing the complexity of making comparisons between studies (Schultz *et al.* 2018). Furthermore, multiple wear facets, particularly in the lower molars, can correspond to a single wear facet in the uppers further complicating labelling systems (Fiorenza 2009; Ulhaas *et al.* 2007).

Table 9: Wear facet numbering systems that have been used in the assessment of dental function and occlusion of mammaliaform teeth. Adapted from Schultz et al. (2018; table 1 p.35). For Gingerich (1974), the B prefix indicates phase I wear facets and L indicates phase II wear facets. For Schultz et al. (2018) in the upper teeth the prefix corresponds to the cusps: paracone (PA), metacone (ME), protocone (PA) and hypocone (HY). In the lower teeth the cusp prefixes are for the protoconid (pr), hypoconid (hy), metaconid (md), entoconid (ed) and hypoconulid (hyl). Cusp locations are shown in Figure 12. The suffixes refer to the direction that the wear facet is facing on the slopes of the cusp: mesial (m), distal (d), buccal (b) and lingual (l).

Maier and Schneck (1982); Kullmer *et al.* (2009)	Kay (1977)	Gingerich (1974)	Crompton (1971)	Butler (1952, 1973)	Schultz (*et al.* 2018)	
					Upper teeth	Lower teeth
1	1a, 1b	B1	1a, 1b	2	PA-m	pr-db
2	2a, 2b	B2	2a, 2b	1	ME-d	pr-mb
3	3a,3b	B3	3a, 3b	6	PA-dl	hy-mb
4	4a,4b	B4	4a, 4b	7	ME-ml	hy-d
5	5	B5	5	3	PR-ml	md-db
6	6	B6	6	9	PR-dl	ed-b
7	7			4	HY-dl	md-m
8	8, 8n	B7		8	HY-l	ed-d
9	9, x	L1		10	PR-b	hy-l
10	10	L2		5	HY-db	pr-ml
11	X				PR-mb	pr-dl
12	10n				HY-mb	hyl-l/hy-l
13					PR-db	hyl-ml

More recently a modular system of nomenclature has been developed in an attempt to overcome the lack of clarity and consistency associated with earlier numerical systems. This system is widely applicable to a range of tooth morphologies and better accommodates the comparison of dental wear facet patterns between species. Each facet label is composed of two parts. The first refers to the cusp on which the facet is located. The second part describes the facet's orientation on the cusp in relation to the occlusal plane (Schultz *et al.* 2018).

Wear facets have also been associated with phases of the power stroke. In primates, some were assigned by Mills (1967) to either a medially directed, incursive, upwards and slightly forward movement of the jaw that brought the teeth into centric occlusion. Other facets were associated with the subsequent jaw movement, directed downwards and slightly medially, in which the teeth are discluded (Mills 1967; 1978). Gingerich (1974), using the nomenclature developed by Crompton (1971), assigned each of the nine wear facets identified when describing the dental function of the Palaeocene primate *Plesiadapis* to a phase of the power stroke. Similarly, Kay and Hiiemae (1974) attributed facets 1-8 to phase I of the power stroke, the incursive movement, and facets 9-10 to phase II of the power stroke, the excursive movement, in a series of extinct and extant primates. Maier and Schneck (1982) added facets 11-13 to the wear facet areas involved in phase II of the power stroke in their analysis of hominoid molars. Wear facets involved in phase I of the power stroke were further divided between buccal phase I facets, situated on the buccal cusps of the upper and lower molars, and lingual phase I facets, located on the lingual cusps of the upper and lower molars (Kullmer *et al.* 2009; Fiorenza *et al.* 2011a; Fiorenza *et al.* 2020).

The system developed by Schultz *et al.* (2018) has not been widely used by other researchers using wear facet patterns to reconstruct dietary and masticatory behaviours across hominids, including the studies by Zanolli *et al.* (2019) and Fiorenza *et al.* (2020). The current research, therefore, will utilize the system developed by Maier and Schneck (1981; 1982) to remain consistent with and readily comparable to the facet labelling system used in all other studies that have performed OFA on anatomically modern humans (Table 10; Figure 12 and Figure 13).

Table 10: The numbering system used to describe dental wear facet patterns in the current study after Maier and Schneck (1981; 1982). The analogous codes from the system devised by Schultz et al. (2018) are also given below each facet number from the Maier and Schneck system so that readers can make a comparison between the two. The location of the features described are given in Figure 12 and Figure 13.

Wear Facet	Phase	Upper location	Lower location
1 PA-m/ pr-db	I	On the mesiolingual slope of the paracone between the praeparacrista and entoparacrista.	On the disto-buccal slope of the protoconid situated buccal to the post-protocristid.
2 ME-d/ pr-mb	I	On the mesiolingual slope of the metacone lingual to the postmetacrisa and distal to the entometacrista.	On the mesio-buccal slope of the protoconid located buccal to the praeprotocristid.
3 PA-dl/ hy-mb	I	On the distolingual slope of the paracone distal to the entoparacrista and lingual to the postparacrista.	On the mesio-buccal slope of the hypoconid located buccal to the praehypocristid.
4 ME-ml/ hy-d	I	On the mesiolingual slope of the metacone mesial to the entometacrista and lingual to the praemetacrista.	On the disto-buccal slope of the hypoconid located buccal to the posthypocristid.
5 PR-ml/ md-db	I	On the mesiolingual slope of the protocone lingual to the praeprotocrista.	On the disto-buccal slope of the metaconid distal to the entometacristid and buccal to the postmetacristid.
6 PR-dl/ ed-b	I	On the distolingual slope of the protocone lingual to the postprotocrista.	On the mesio-buccal slope of the entoconid mesial to the ectoentocristid and buccal to the praeentocristid.
7 HY-db/ md-m	I	On the distolingual slope of the hypocone lingual to the posthypocrista.	On the mesio-buccal slope of the metaconid between the praemetacristid and the entometacristid.
8 HY-l/ ed-d	I	On the mesiolingual slope of the hypocone lingual to the praehypocrista.	On the disto-buccal slope of the entoconid between the ectoentocristid and postentocristid.
9 PR-b/ hy-l	II	On the mesiobuccal slope of the protocone between the crista obliqua and the praeprotocrista.	On the lingual slope of the hypoconid lingual to the praehypocristid and posthypocristid.
10 HY-db/ pr-ml	II	On the distobuccal slope of the hypocone between the ectohypocrista and posthypocristid.	On the mesiolingual slope of the protoconid between the entoprotocristid and the praeprotocristid.
11 PR-mb/ pr-dl	II	On the mesiobuccal surface of the protocone in the region of the anterior fovea distal to the praeprotocrista.	On the distolingual slope of the protoconid between entoprotocristid and the postprotocristid.

12 HY-mb/ hyl-l; hy-l	II	On the mesiobuccal surface of the hypocone between the praehypocrista and the ectohypocrista.	On the distolingual slope of the hypoconulid between the entohypocristid and the posthypocristid.
13 PR-db/ hyl-ml	II	On the distobuccal slope of the protocone between the crista obliqua and the postprotocrista.	On the mesiolingual slope of the hypoconulid between the praehypocconulidcristid and the entohypoconulidcristid.

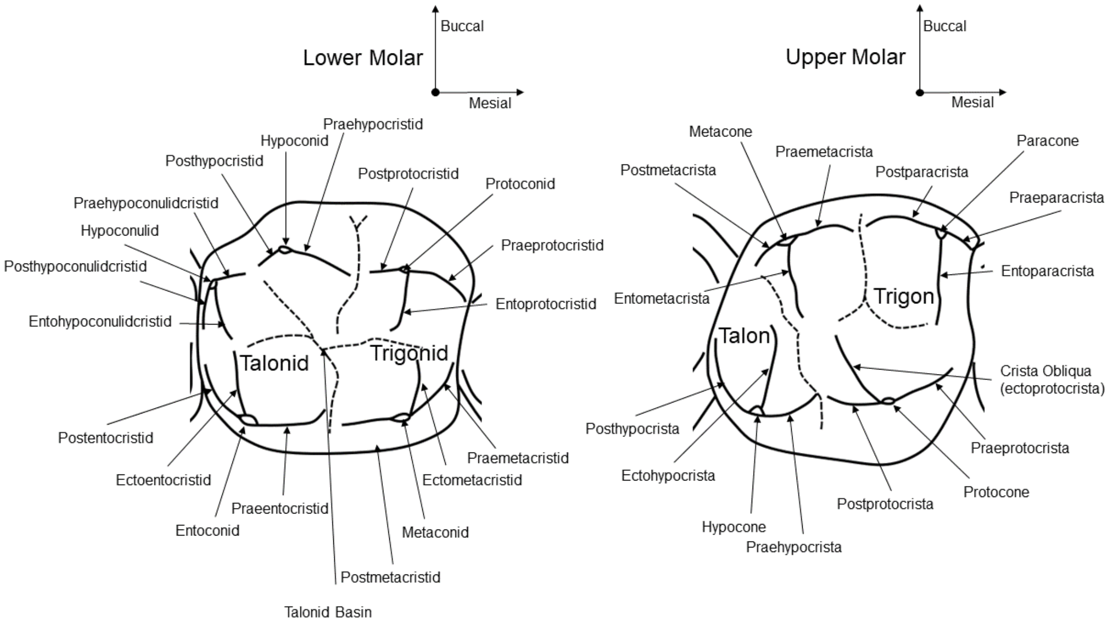


Figure 12: Diagrams of the upper and lower first molars of an anatomically modern human showing the location of the features on the occlusal surface referenced in Table 10 when describing the location of the 13 dental wear facet pairs of Maier and Schneck (1981; 1982). Diagrams redrawn and modified from Maier and Schneck (1981; figure 2, p.132). Human molars are tribosphenic in that the large lingual cusp of the upper molar (protocone) occludes with the distal basin of the lower molar (talonid basin) (Davis 2011).

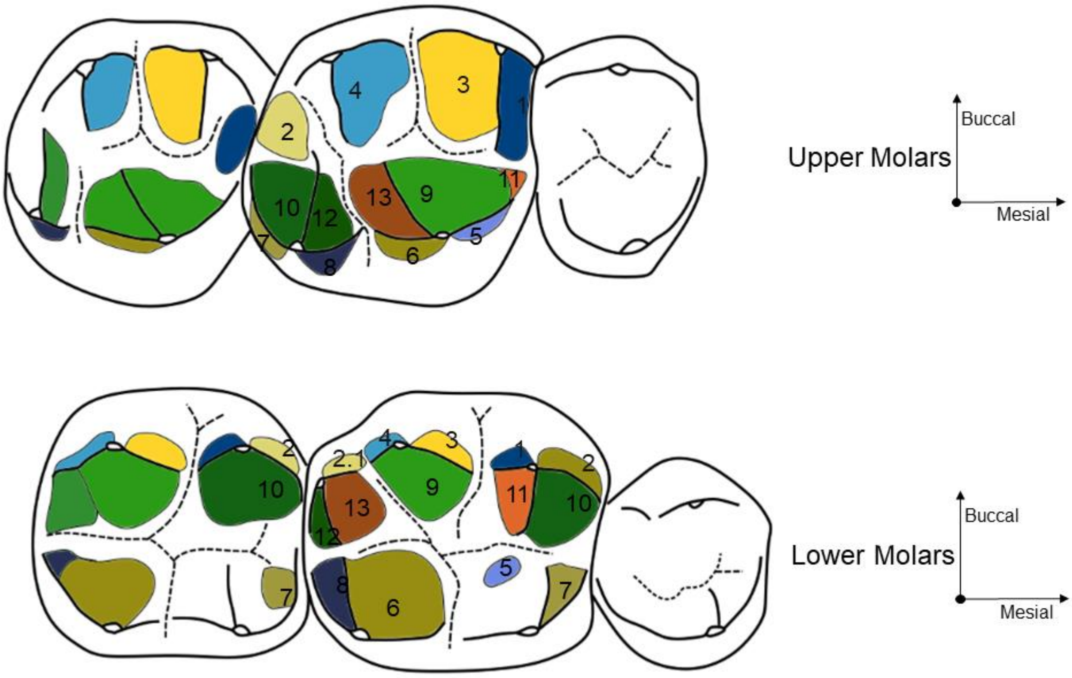


Figure 13: Molar wear facets labelled according to the scheme devised by Maier and Schneck (1981; 1982). For detailed descriptions of their locations refer to Figure 12 and Table 10. Diagrams redrawn and modified from Maier and Schneck (1981; figure 2, p.132).

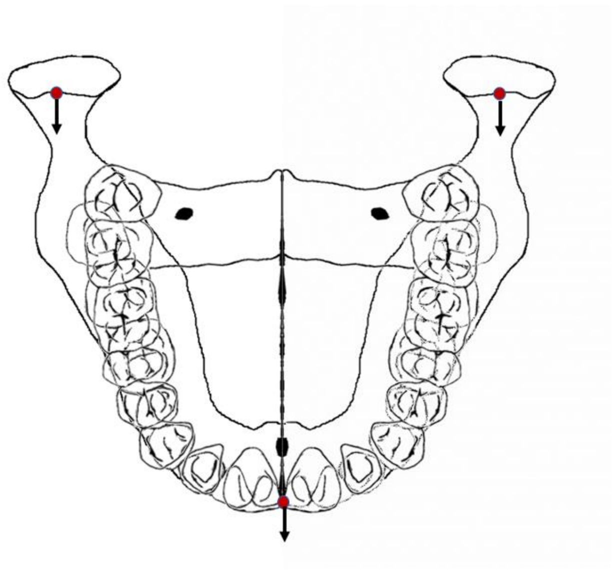
3.6 Occlusal Compass Concept

The presence and position of dental wear facets can be used to infer dominant jaw movement pathways (Butler 1952; Crompton and Hiiemae 1970; Greaves 1973; Mills 1967). Derived from prosthodontics, the occlusal compass concept of Douglass and DeVreugd (1997) provides a means of attributing each dental wear facet pair in the upper and lower molars to a specific direction of jaw movement (Figure 14). The occlusal compass concept was developed to identify whether there are any interferences during the movement of the teeth into and out of maximum intercuspation within a clinical context. Maximum intercuspation, therefore, is treated as the starting point when describing the direction of jaw movement required to bring each wear facet pair into contact (Kullmer *et al.* 2009; Ulhaas *et al.* 2007;). Wear facets have been produced experimentally using dental models and support the association between specific jaw movement pathways and the orientation and position of wear facets (Costa and Greaves 1981; Kullmer *et al.* 2012).

The occlusal compass does not directly describe the chewing motion. Instead, it reflects the decomposition of this motion into its composite elements; the direction and orientation of each wear facet being described in relation to centric occlusion and the pathway of jaw movement required to bring them into contact (Fiorenza and Kullmer 2013). As an example, a lateroprotrusive movement of the lower teeth from intercuspal position would bring facets 2, 3, 6 and 7 into contact (Figure 14 and Figure 15). Wear facets, labelled using the Maier and Schenk system (1982), are typically attributed to the following major directions of jaw movement (Fiorenza and Kullmer 2013):

- Lateroretrusion: wear facets 1, 4, 5 and 8.
- Lateroprotrusion: wear facets 2, 3, 6 and 7.
- Mediotrusion: wear facets 9, 11, 12
- Medioprotrusion: wear facets 10 and 13.

The method used to produce occlusal compass diagrams in the current research is given in section 5.2.2.3.6.



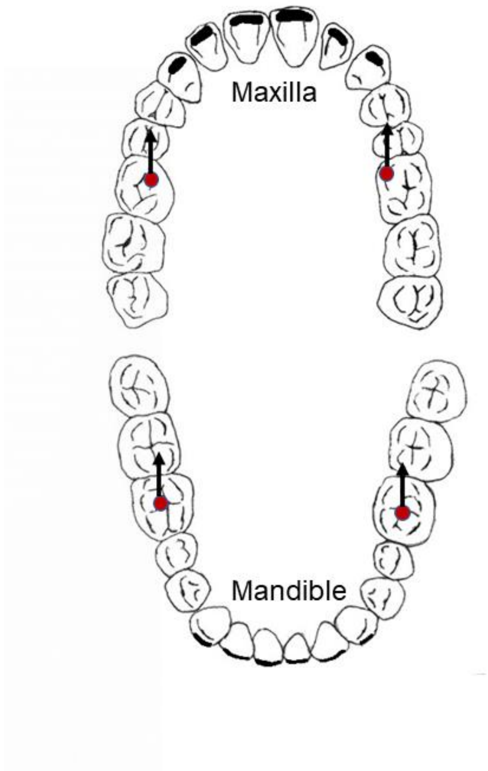


Figure 14a: Protrusion: the mandibular condyles move in parallel as they are thrust forwards (left). This brings the labial surfaces of the anterior mandibular teeth into contact with the lingual surfaces of the maxillary anterior teeth (right). The direction of movement indicated on the teeth is shown in relation to the path the protocone, located on the maxillary first molar, traces across its mandibular antagonist during protrusion. The red dots represent the position of the jaws when in centric occlusion and their subsequent position following movement in the specified direction. Figure created by author.

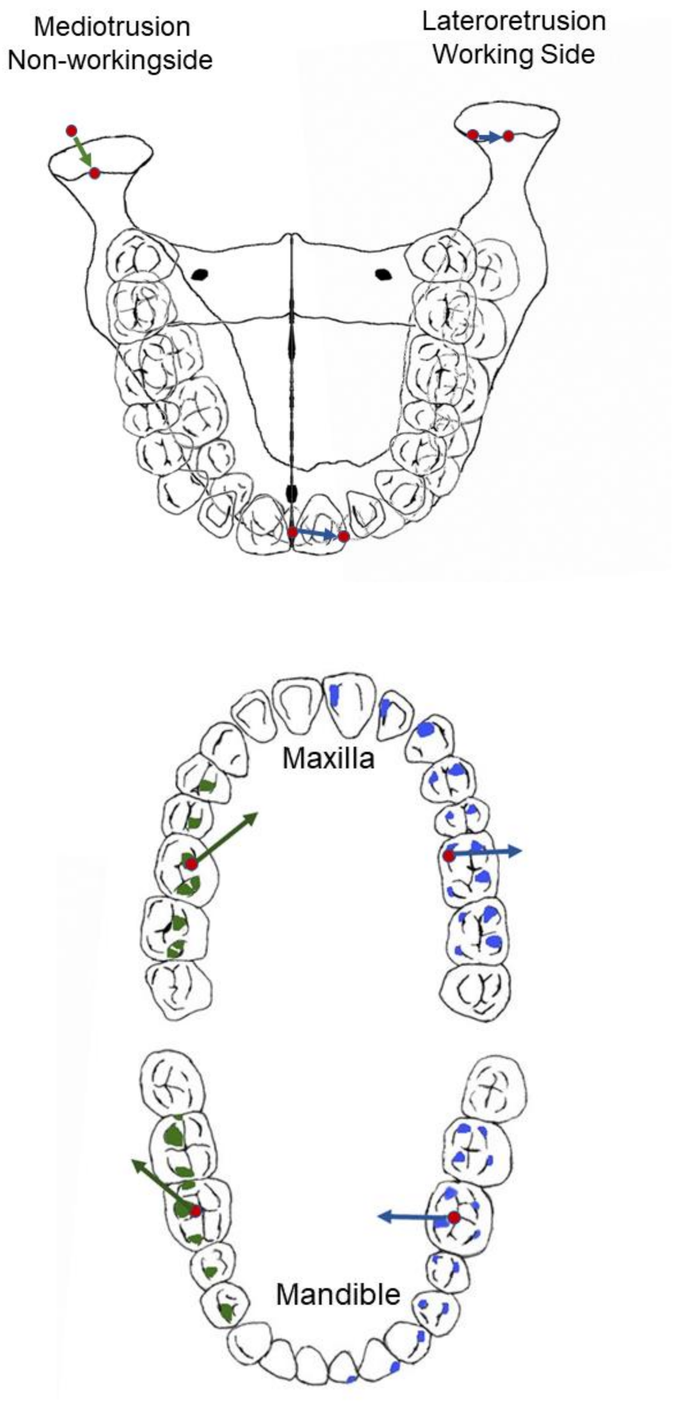


Figure 14b: Mediotrusion (green): medial or inward thrust of the mandible involving the rotation of the mandible around the condyle on the non-working side. Lateroretrusion (blue): lateral or outward projection of the mandible involving the rotation of the mandible around the condyle on the working side (left). Pattern of working side and non-working side contacts are shown across the maxillary and mandibular teeth are coloured according to the direction of jaw movement they are associated with (right). The red dots represent the position of the jaws when in centric occlusion and their subsequent position following movement in the specified direction. Figure created by author.

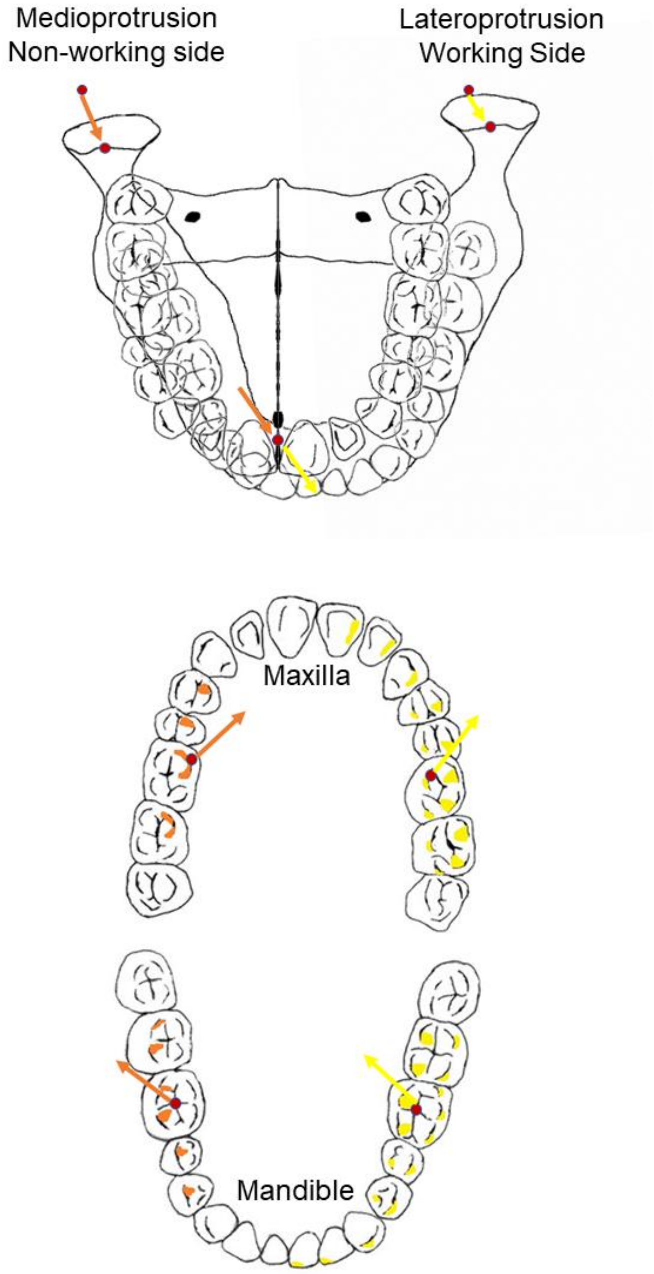


Figure 14c: Lateroprotrusion (Yellow; working side): an outward and forward thrust of the mandible. Medioprotrusion (Orange: non-working side): an inward and forward thrust of the mandible (left). Pattern of working side and non-working side contacts are shown across the maxillary and mandibular teeth and are coloured according to the direction of jaw movement they are associated with (right). The red dots represent the position of the jaws when in centric occlusion and their subsequent position following movement in the specified direction. Figure created by author.

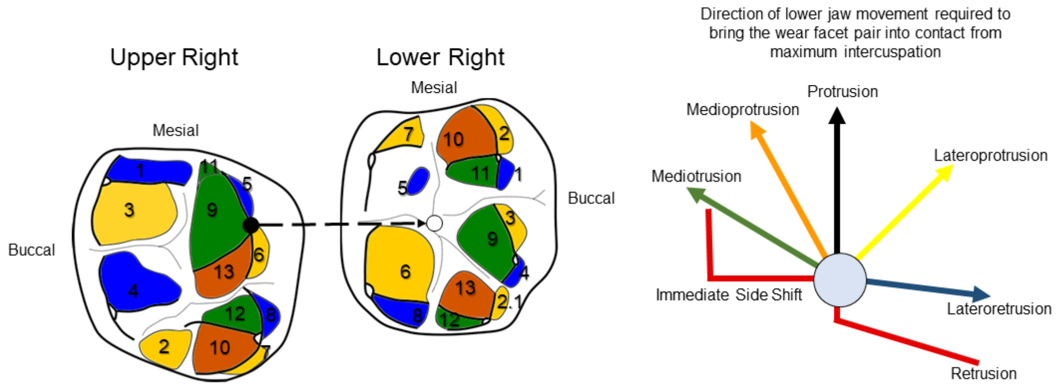


Figure 15: Diagram showing the occlusal compass concept in relation to the wear facets on a pair of upper and lower first molars. In this example, the individual has an Angle Class I molar occlusion (section 3.7.1). The dashed line indicates that the protocone is situated within the talonid basin of the lower molar at maximum intercuspation. Wear facets are numbered using the Maier and Schneck system (1982). The colour of each wear facet corresponds to the direction of mandibular movement required to bring each pair of wear facets into contact when starting from maximum intercuspation (Figure 14): blue corresponds to lateroretrusion, yellow to lateroprotrusion, green to mediotrusion and orange to medioprotrusion. Most masticatory movements occur within the area bounded by the blue lateroretrusive and the green mediotrusive arrows. The red lines represent threshold movements associated with retrusive movements and immediate side shift. Immediate side shift involves a transverse movement in which the condyle shifts medially. During a retrusive movement, the condyles move backwards in a parallel motion into the glenoid fossae of the temporal bone. Figure created by author.

Individual anatomic variation in the movement of the rotating condyle affects the size and variation of the occlusal compass (Douglass and DeVreugd 1997). The temporomandibular joint limits the possible extent of lateral movements made by the mandible. Dental relief guides and predetermines pathways of occlusal contact as teeth move into and out of maximum intercuspation. The fissure pattern on the occlusal surface guides laterotrusive, mediotrusive and protrusive movements. The cusp slopes contribute to the direction of lateroprotrusive and medioprotrusive movements (Ulhaas *et al.* 2007). In most bunodont dentitions, such as the teeth of *H. sapiens*, low tooth relief provides only a minor guide to masticatory movements compared to other taxonomic orders, such as the carnivora with typically have higher occlusal relief. As the tooth relief reduces with progressive wear, the guiding structures also reduce in prominence, which allows less precise movements and higher mobility of the mandible (Koenigswald *et al.* 2013).

Contacts resulting from para-masticatory activity will likely exhibit an orientation and inclination that differ from those associated with the masticatory power stroke and may lack antagonistic wear facets in the opposing dental arcade (Fiorenza *et al.* 2011c; Fiorenza and Kullmer 2013). Para-masticatory tooth use encompasses any activity outside of the use of the teeth to triturate food during the feeding sequence. This includes the use of the teeth as tools (Eshed *et al.* 2006; Littleton 2017; Molnar 1971; 1972; Scott and Winn 2011; Watson and Haas 2017). The Inuit of Canada, Alaska and Greenland, for example, are characterised by extremely heavy wear in the anterior teeth from using their teeth to assist with tasks, such as the preparation of tough walrus and seal hides, and gripping objects (Clement and Hillson 2012). Among a range of pre-historic hunter-gatherers, wear facets on the buccal slopes of the upper molars, found to lack antagonist facets in the lower teeth and presenting an orientation that deviated from the facets associated with the power stroke, have been attributed to the use of the teeth to hold and potentially cut objects (Fiorenza *et al.* 2011c).

The mastication compass concept introduced by Koenigswald *et al.* (2013) provides a means of visualising masticatory pathways in three-dimensions, which builds on and compliments the occlusal compass concept. It simultaneously summarises the direction and inclination of the incursive pathway as the teeth move into centric occlusion. In genera with two phases of occlusal contact during the power stroke, the orientation and inclination of the excursive movement is also summarised. Taken together, the occlusal compass and mastication compass concepts can be used to infer an individual's prominent patterns of tooth use, including masticatory and para-masticatory activity.

3.7 Dental Occlusion

3.7.1 Static and Dynamic Occlusion

The interpretation of dental wear facet patterns is complicated by variability in occlusion between individuals of one species. Dental occlusion is how the teeth fit together (Angle 1907; Hillson 1996). Within dentistry, the study of occlusion is concerned with how the teeth, muscles, the temporomandibular joints and the jaws function together (Johnson *et al.* 2016). As such, an assessment of the relationships between the components of the masticatory system are important in understanding individual variability in dental function and chewing behaviours. In addition, dental occlusion will influence the way dental wear develops as this is highly dependent on the relationship between opposing teeth and how they come together during mastication (Fiorenza *et al.* 2010).

Static occlusion occurs when the teeth are moved into maximum intercuspation. This represents the relationship assumed by the dental arches when an individual closes their teeth together; their habitual bite. The number, distribution and symmetry of dental contacts in maximum intercuspation vary widely between individuals (Mcdevitt and Warreth 1997). Maximum occlusal stability occurs when the teeth are in maximum intercuspation as it reflects the position in which the teeth best fit together. In this position, the location of the mandibular condyles, however, may not be optimal (Glossary of Prosthodontic Terms 2017). The dental contacts that occur during excursive mandibular movements are referred to as dynamic occlusion (Davies and Gray 2001; Douglass and Devreigd 1997). Occlusal contacts commonly occur on both the working and non-working sides of the dentition during lateral excursions of the mandible (Hochman *et al.* 1995; Ingervall *et al.* 1991). Non-working side contacts, usually, do not interfere with working side contacts and if present typically occur in the most posteriorly located functioning teeth (Ingervall 1972).

Dental cusps either serve a supporting or guiding function during dynamic occlusion. Support cusps act as vertical stops to jaw closure and are often arranged to receive the occlusal load down their vertical axes. Guiding cusps have a shearing as well as a guiding function (Douglass and Devreigd 1997). In dentistry, three main occlusal configurations are described (Johnson *et al.* 2016; Kaidonis *et al.* 2014; Klineberg 2016; Rinchuse *et al.* 2007). Group function occlusion involves multiple contacts on the working side during lateral excursions, which act to distribute occlusal forces across the involved teeth (Douglass and Devreigd 1997; Glossary of Prosthodontic Terms 2017; Ingervall 1972;). Alternatively, in canine-guided occlusion only the canines make contact during lateroretrusive movements purportedly protecting the remaining dentition from adverse occlusal forces as the teeth move into and out of maximum intercuspation. This arrangement is often considered optimal within modern orthodontics, however, there is limited evidence to support this view (Glossary of Prosthodontic Terms 2017; Rinchuse *et al.* 2007). Balanced occlusion involves multiple contacts of the anterior and posterior teeth on both the working and nonworking sides during lateral excursions (Kaidonis *et al.* 2014). Pure canine-guided or pure group function are seldom observed in a clinical setting (Woda *et al.* 1979).

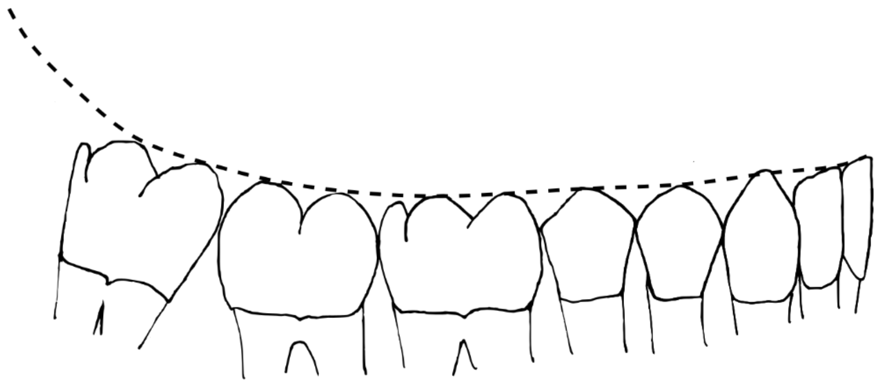


Figure 16: Illustration of the Curve of Spee in anatomically modern humans. Figure created by author.

The variable inclination and arrangement of the teeth in anatomically modern humans produce specific forms of occlusion (Hillson 2005). A smooth curve in an antero-posterior direction, the Curve of Spee (1890), can be traced from the incisal edge of the mandibular incisors along the buccal cusp tips of the posterior teeth up to the anterior border of the mandibular condyle (Figure 16) (Wilson 1911). It has been argued that a correlation exists between the tilt of the posterior molars in the Curve of Spee and the inclination of the superficial masseter muscle among primates, including anatomically modern humans. This enlarges the shearing and crushing forces acting on foods as they are processed by the molar teeth (Osborn 1993).

A mediolateral curve viewed in the frontal plane exists between each pair of posterior teeth in the unworn dentition due to the lingual inclination of the mandibular molars and the buccal inclination of the maxillary molars. This is referred to as the Curve of Wilson (Wilson 1911). The Sphere of Monson considers both the Curve of Spee and Curve of Wilson in three-dimensions (Monson 1922) (Figure 17). In an ideal arrangement, Monson (1920) described the cusps and edges of each tooth as following the circumference of a sphere. These curves appear convex in the mandibular arch and concave in the maxillary arch (Hillson 1996; Osborn 1993).

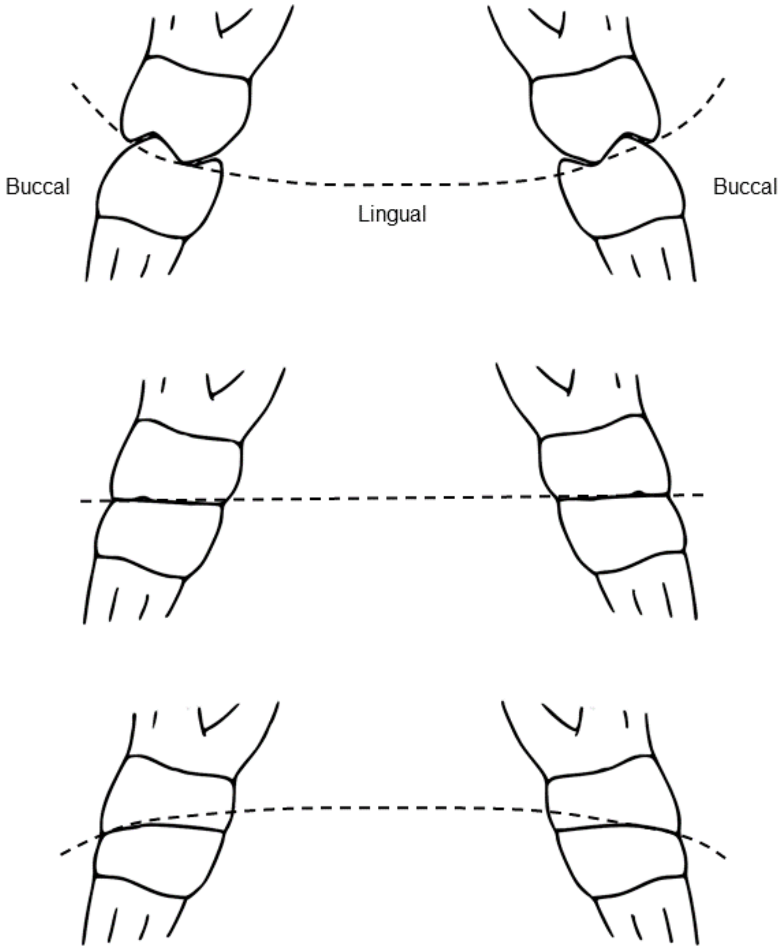


Figure 17: Illustration of the development of the curve of Monson as dental wear progresses. Molar teeth are shown in mesial view. Upper: The curve of Monson in the unworn dentition. Middle: The flat occlusal plane that develops following moderate occlusal wear. Lower: The reversed curve of Monson in more advanced stages of dental wear. Modified from Hillson (1996, Figure 11.4, p.238).

Angle (1899) classified dental occlusion into three classes based on the relative anteroposterior relationship between the first molars (Table 11; Figure 18). Following Angle's scheme, the mesio-buccal cusp of the upper first molar should be located in the buccal groove of the lower first molar during static occlusion in individuals with normal occlusion. Each tooth, apart from the third molar, should receive the support of two antagonists (1907). Clinically, the chewing patterns of individuals with Angle Class III occlusion did not differ significantly in response to the mechanical properties of the foods ingested unlike individuals with Angle Class I and II occlusion (Pröschel and Hofmann 1988).

Table 11: Angle's classification of dental occlusion (1907)

Angle Class	Molar relationship	Condition of the Anterior Teeth
I	The mesio-buccal cusp of the upper 1st molar is usually located in the buccal groove of the lower 1st molar (mesio-distally normal)	Anterior crowding may be possible.
II	The lower molars occlude distal to their normal position relative to the uppers.	Division I: protrusion of the upper incisors and narrowing of the upper arch. Division II: The upper incisors are retroclined.
III	The lower molars occlude mesial to their normal position relative to the uppers.	The lower incisal edges may occlude with the labial edges of the uppers.

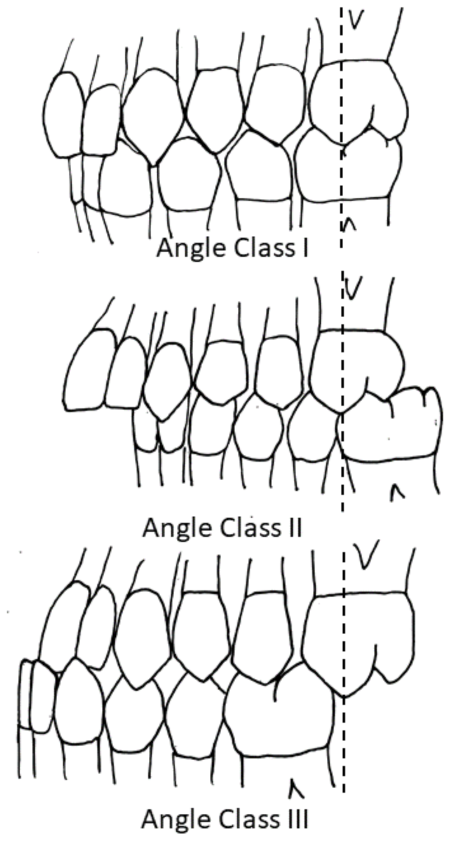


Figure 18: Diagram showing the Angle Class relationships described in Table 11. The dashed line corresponds to the position of the mesio-buccal cusp of the upper first molar. Figure created by author.

The typical wear facet patterns described by Mills (1978) and Maier and Schneck (1982) in humans corresponded to an individual with Angle Class I dental occlusion. Deviation from Angle Class I occlusion may result in the absence of certain contact areas, such as the lack of contact between the posterior-most molar teeth in an Angle Class III occlusion (Fiorenza *et al.* 2010). In contemporary and early modern industrialised human groups, in which occlusal variability has become the norm rather than the exception, it can be anticipated that greater variation in the distribution of wear facets will be evident (Corruccini 1984; Mills 1978). The role of static occlusion is difficult to consider in isolated teeth or specimens where few teeth are present, however, as the reconstruction of the overall occlusal relationship between the dental arcades will not be possible.

3.7.2 Changes in Occlusion in response to Dental Wear

The study of occlusion is further complicated by how occlusion changes over the life history of an individual as part of wider physiological processes. It responds to changes in habit, diet, occlusal relief and pathological conditions, such as dental caries. The morphology of the teeth, their emergence and the development of occlusion reflect a combination of genetic, epigenetic and environmental factors (Corruccini 1999; Kaidonis *et al.* 2016; Peck 2016). The pre-natal development of the mouth jaws and teeth is strongly controlled by genetic factors mediated epigenetically by the maternal environment. Post-natal growth is shaped by the mechanical loads placed on the system, particularly during mastication, demanding biomechanical responses and the modification of growth and development (Peck 2016). Consequently, the majority of cranio-facial phenotypic variation is in a constant state of flux and is highly plastic. The teeth in occlusion are at the centre of this fluctuating system (Garib *et al.* 2020; Varrela 2006).

Prior to the adoption of the heavily processed diets characteristic of industrialised groups, anatomically modern humans experienced higher rates of dental wear because of the incorporation of large quantities of abrasive material within the foods they consumed. Higher wear groups exhibit adaptive mechanisms to the modifications to occlusion that occur following the loss of tooth substance to dental wear. This includes mesial drift, continuous eruption and lingual tipping (Kaifu *et al.* 2003). Interproximal wear and ante-mortem tooth loss create spaces between the remaining teeth. A process of mesial drift occurs in which the remaining teeth migrate within the alveolar bone in a mesial direction acting as a compensatory mechanism to close these gaps (Begg 1954). Evidence for mesial drift has been reported in modern clinical studies of both developing and established dentitions (Roux *et al.* 1990; Teng *et al.* 2019; Weber 1969; Yilmaz *et al.* 1980).

Continuous eruption of the teeth, resulting in a greater distance between the alveolar crest and the occlusal surface of the tooth, also occurs with advancing wear as a mechanism to compensate for loss of tooth substance to dental wear in order to maintain occlusal contact (Begg 1954). This process has been identified in modern clinical settings based on the movement of the teeth in relation to fixed implants (Heij *et al.* 2006; Iseri and Solow 1996). An eruptive movement of the tooth with increasing tooth wear has also been identified in British Roman, Anglo-Saxon and Mediaeval material using radiographs to measure the distance between the root apex and alveolar canal (Levers and Darling 1983; Newman and Levers 1979; Whittaker *et al.* 1982; Whittaker *et al.* 1990; Whittaker 1992). In the absence of an antagonist, supraeruption of a tooth can occur resulting in the eruption of the tooth beyond the occlusal plane (Ainamo and Ainamo 1978; Craddock *et al.* 2007).

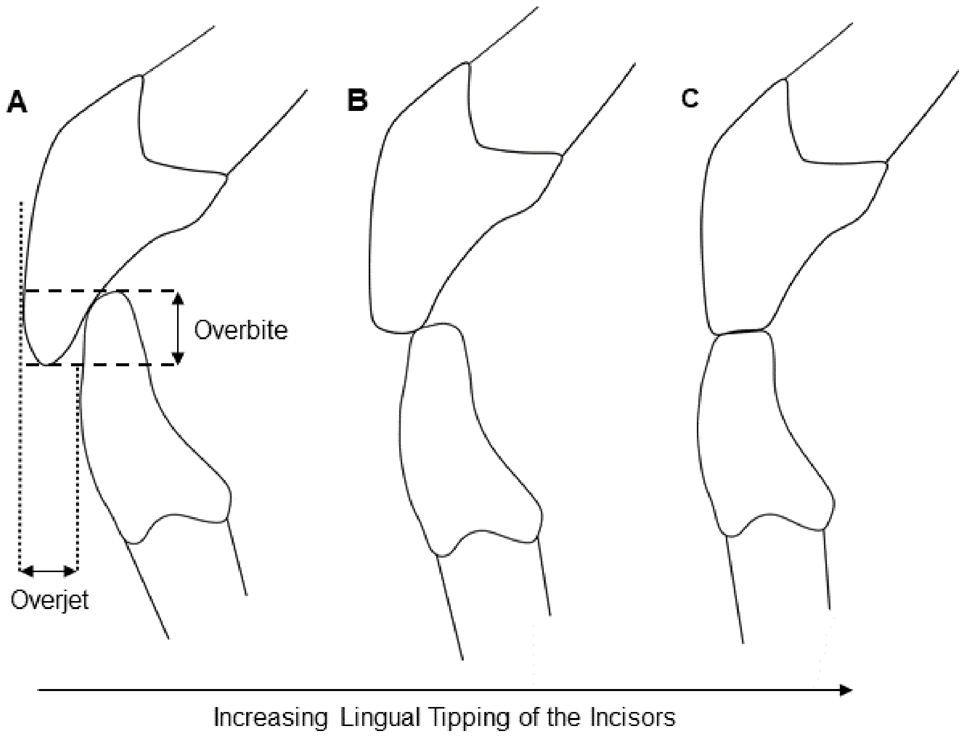


Figure 19: Diagram showing the changes in relationship between the central incisors with increasing wear. A: unworn incisors with an overjet and overbite >0mm resulting in an overlap between the upper and lower incisal edges. B: With increasing wear, lingual tipping of the incisors begins, and overjet and overbite are reduced. C: Edge-to-edge occlusion typically characterises individuals with more advanced stages of incisal wear. Further incisal tipping and wear along the incisal edge reduce overbite and overjet to zero. (After Kaifu et al. 2003, figure 7, p.52).

In relatively unworn dentitions, a pattern of occlusion predominates in which the incisal edge of the maxillary incisors overlaps labially the incisal edge of the mandibular incisors (Figure 19) (Ireland and Yeung 2020). A measure of the vertical and horizontal relationships between the central incisors is provided by overbite and overjet, respectively (Figure 19). Overbite is the vertical distance between the incisal edges of the central incisors, whilst overjet is the horizontal distance between tangents drawn in the facial plane in relation to the labial surfaces of the upper and lower central incisors (Harris and Corruccini 2008). Increased wear across the incisal edge reduces the extent of the overbite between maxillary and mandibular incisors whilst lingual tipping of the incisors acts to reduce the overjet between them. The incisors typically erupt into the mouth with a slight labial incline. Lingual tipping is the physiological process by which the anterior teeth become increasing upright as wear proceeds (Kaifu 2000; Kaifu *et al.* 2003).

Moderate amounts of lingual tipping have been reported in modern industrialised groups with relatively modest amounts of dental wear (Behrents 1985; Bishara *et al.* 1994; Forsberg 1979) and also in mediaeval material from Scandinavia and Japan (Hasund 1965; Kaifu 2000; Lundström and Lysell 1953; Lysell and Fillipson, 1958). This suggests that this compensatory mechanism is inherent within the dentition of anatomically modern humans. This leads to an edge-to-edge pattern of occlusion between the anterior teeth of individuals as they reach more advanced stages of dental wear (Brace 1986; Kaifu *et al.* 2003).

3.7.3 Increase in occlusal variability in industrialised groups

The environmental conditions to which the masticatory system of anatomically modern humans is adapted to are not present in modern industrialised groups, particularly a dietary regime that requires vigorous mastication and is highly abrasive (Hunt 1961; Kaidonis *et al.* 2014). This is central to the debate surrounding the aetiology of increased occlusal variability in contemporary industrialised groups. Misaligned and crowded dental arches have become the norm. An ‘epidemiological transition’ in patterns of occlusion has been proposed by Corruccini (1984) following the adoption of heavily processed diets by industrialised groups.

Occlusal variability is the term adopted in the current study to describe positional variations of the teeth and the variation in the relationship between the dental arches. The term malocclusion is interwoven within the concept of an idealised ‘normal’ occlusion, which stems from the work of Angle and other early 20th century orthodontists (Harris and Corruccini 2008). The form of ‘normal’ dental occlusion defined in modern dentistry is seldom encountered in clinical dentistry in the absence of orthodontic intervention and is extremely rare in pre-Industrial groups and modern hunter-gatherers (Kaidonis *et al.* 2014; Kaifu *et al.* 2003).

Begg (1954) hypothesized that a reduction in dental wear in contemporary groups led to a discordance between the size of the jaws and the amount of tooth substance present. An increase in occlusal variability was the result.

Fundamental to his theory was the presence of excess tooth substance within the dentition to compensate for dental attrition over an individual's lifetime. His theory was supported by his observation of well-aligned dental arcades among Australian Aborigines, who consumed a highly abrasive diet, alongside a large reduction in the mesio-distal dimensions of the teeth due to approximal attrition. Begg (1954, p.311) claimed that a 'very small amount of function' is required to stimulate the growth of the jaws to their 'full hereditary sizes'. This led to his conclusion that the substantial reduction in dental wear in industrialised groups was the primary factor in their increased prevalence of occlusal variability and validated the orthodontic removal of teeth to ease crowding (Begg 1954).

The primacy Begg attributed to the reduction of dental wear in the aetiology of malocclusion has been more recently challenged, however (Corruccini 1990; 1999). Begg's Australian Aboriginal case study has been criticised for utilising a small sample size, likely including individuals selected for unusually large unworn teeth and very small worn teeth, which would better support his hypothesis. The material examined by Begg was a subset of the collection studied by Campbell in 1925 and if the full dataset is used the average mesiodistal reduction across the dental arcade was of a smaller magnitude than was obtained by Begg (Campbell 1925; Dawes 1986). Furthermore, in the longitudinal study of the Yuendumu group in Australia, different occlusal statuses were apparent in individuals with similar mean tooth size indicating that tooth size was not the primary factor in determining the extent of occlusal variability (Corruccini 1990).

Conversely, Corruccini argued that the lack of chewing stresses in individuals consuming a modern processed diet resulted in insufficient growth in the jaws and the development of high levels of occlusal variability (1999). Rats fed a softer diet were found to show localised decreases in osteoblastic activity causing changes in mandibular shape when compared to rats eating a hard food diet (Yamada and Kimmel 1991). In the absence of sufficient alveolar growth, inadequate space for emerging teeth and disharmonious jaw relationships are anticipated (Brown *et al.* 1990). Crowded and misaligned dental arches of settled and acculturated components of populations have been contrasted with the predominantly well-aligned occlusal relationships noted in unindustrialised portions of the same population (Corruccini *et al.* 1983a; Corruccini 1984).

In the Mammoth Cave region of Kentucky, an increase in occlusal variability, quantified using the Treatment Priority Index, occurred following a dietary transition from garden produce and thick-crust cornbread, requiring prolonged and intensive chewing, to a diet dependent upon modern processed components. The genetic composition of the residents remained relatively stable so distortion of occlusal phenotypes by underlying variation in the genotype was minimal (Corruccini and Whitley 1981). In Pima Amerindians, less occlusal variability was apparent in a pre-1950 group raised on garden staples when compared with a post-1950 group consuming processed foods (Corruccini *et al.* 1983b). Furthermore, the offspring of Chinese immigrants raised in Liverpool displayed approximately twice the occlusal variability of their parents raised in rural China (Corruccini 1984). These studies indicate that the high occurrence of considerable occlusal variability can be attributed to the adoption of a more heavily processed and less biomechanically demanding diet. Although several studies have indicated a genetic component may contribute to the development of malocclusion (Normando *et al.* 2011; Corruccini *et al.* 1990), the increase in prevalence rates of malocclusion over one to two generations suggests that this epidemiological transition cannot be explained primarily by genetic factors (Corruccini 1999).

Bioarchaeological studies (Hirst 2019; Rando *et al.* 2014) support changes in jaw morphology and dimensions following the transition to a more heavily processed diet following the changes in dietary composition that occurred during the Industrial period (1700AD onwards) when compared to their Mediaeval equivalents (1100-1550AD). A reduction in mandibular dimensions has been identified between the Mediaeval and Post-Mediaeval periods in British assemblages likely in response to the reduced biomechanical demands of the later post-mediaeval diet. These changes can be summarised as a reduction in the size of the ramus, reduced mandibular width and an increase in the gonial angle (Rando *et al.* 2014). An increase in occlusal variability was reported when comparing Mediaeval Danish material with their modern counterparts (Helm and Prydsö 1979). Discrepancies between the size of the jaws and the amount of tooth substance present became increasingly frequent over the past two millennia in Japan in studies comparing archaeological skeletal material to modern groups (Hanihara *et al.* 1981; Shiono *et al.* 1982). This was accompanied by a decrease in mandibular size and the anterior-posterior length of the upper and lower jaws (Shiono *et al.* 1982). It is, therefore, likely that occlusal conditions differed markedly between the Mediaeval and Industrial periods and this may need to be considered in the current research.

3.7.4 Examples of Occlusal Variability and how they may influence masticatory behaviours

Dynamic shifts in the masticatory system occur in relation to dietary input throughout the lifetime of the individual. Differences in occlusal configuration will have an impact on individual feeding practices. Several types of occlusion have been associated with modern hunter-gatherer groups that habitually engage in vigorous mastication. This includes the development of a helicoidal plane of dental occlusion (Smith 1986) and alternate intercuspation (Barrett 1953; 1958). As wear proceeds more rapidly on the buccal cusps in the mandibular molars and the lingual cusps of the maxillary molars, the Curve of Monson is frequently reversed among individuals with more advanced stages of tooth wear (Figure 17) (Ackermann 1964; Osborn 1982; Smith 1986; Tobias 1980). Within the molar row, the first molars exhibit the most advanced wear as they are the first to erupt in the sequence. The first molar may develop a reversed Curve of Monson in which the tilt of the wear plane is inclined lingually. This reversal of the Monson Curve becomes increasingly likely with the consumption of a more abrasive diet. At later stages of wear, the later erupting second molar may be worn flat and the final molar to erupt, the third molar, may still exhibit the regular Curve of Monson. This arrangement is referred to as the helicoidal plane of dental occlusion (Osborn 1982; Smith 1986).

The pattern of contact between the molars during the power stroke is likely altered following the development of the helicoidal plane. Molar contacts develop sequentially from the first molar to the third molar during phase I of the power stroke. In phase II, this is reversed, and the first molar is the first to come out of occlusion and contacts are retained for longest on the third molar (Osborn 1982). The helicoidal plane has been found in contemporary hunter-gatherer groups, chimpanzees, early specimens of the genus *Homo* and other mammals, such as bears (Campbell 1925; Tobias 1980; Smith 1986).

In other groups, such as Australian Aborigines, that have high rates of dental wear and engage in vigorous mastication, an occlusal pattern known as alternate intercuspation or X-occlusion can develop (Barrett 1953; 1958; Kaidonis *et al.* 2014). In individuals with this occlusal arrangement, maxillary arch breadth exceeds mandibular arch breadth resulting in a large overjet on the non-working side when the posterior teeth on the working side are in maximum intercuspation (Figure 20). This resembles the transverse dental arch relationships of herbivorous mammals and was observed in 70% of males and 40% of females involved in the Yuendumu longitudinal growth study involving an Aboriginal community from 1951-1971. This pattern of occlusion was observed to develop at early ages in this study group and contrasts with the parallel growth of the dental arches more common among Europeans (Brown *et al.* 1987; Brown *et al.* 1990). This pattern of dental occlusion has been reported in other hunter-gatherer groups, such as the Greenland Inuit and South African Bantus (Brown et al. 2011).

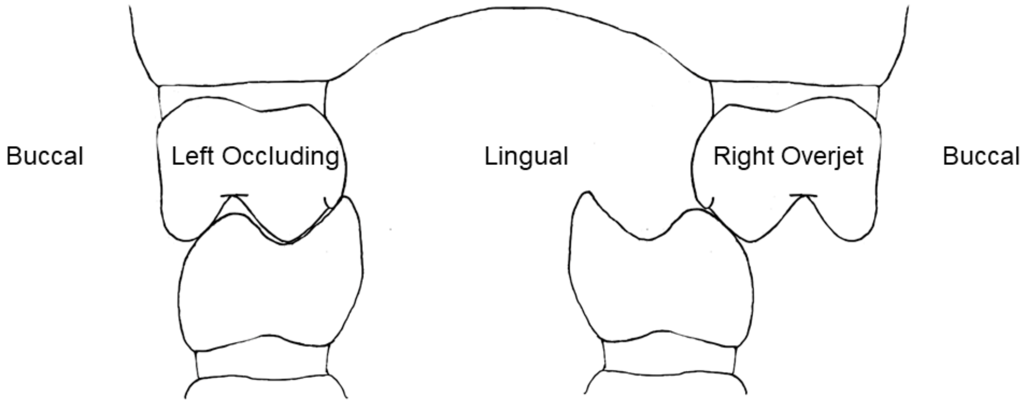


Figure 20: Illustration of teeth in alternate intercuspation. When the left teeth are in maximum intercuspation, there is a marked overjet between the molars on the right side of the dentition. When the molars on the right side of the dentition are in maximum intercuspation the situation is reversed due to the discrepancy between the width of the maxillary and mandibular dental arches. Figure after Kaidonis et al. *2014; Figure 7; p. 167.*

Functionally, the disparity between upper and lower arch breadths may provide greater chewing efficiency when habitually consuming harder and tougher foods (Kaidonis *et al.* 2014). Alternate intercuspation, accompanied by the flattening of the occlusal surface that occurs following heavy tooth wear, may lead to a pattern of mastication comparable to that of herbivorous mammals; chewing stokes with an increased lateral component enable food to be milled between flat tooth surfaces. This contrasts with the more vertically directed and sharp chopping motions, more heavily restrained by cusp morphology, that are more typical of the unworn dentitions of modern Industrialised groups (Brown *et al.* 1987; Brown et al. 2011; Oxilla *et al.* 2018).

Another type of occlusal variability that may impact masticatory behaviours is crossbite (Figure 21). Crossbite describes irregular relationships between the upper and lower dental arcades either in the posterior or anterior portions of the dentition (Piancino and Kyrkanides 2016; Staley and Reske 2011). The buccal cusps of the post-canine maxillary teeth are expected to project laterally over the buccal cusps of the lower molars. Posterior crossbites occur either when the maxillary teeth extend too far laterally beyond their mandibular antagonists (buccal crossbite) or when the buccal cusps of the maxillary teeth occlude lingual to their normal position (lingual crossbite). In the anterior dentition, an anterior crossbite is defined as the lingual positioning of one or several of maxillary incisor relative to the mandibular incisors (Borrie and Bearn 2011; Harris and Corruccini 2008; Tomonari *et al.* 2014).

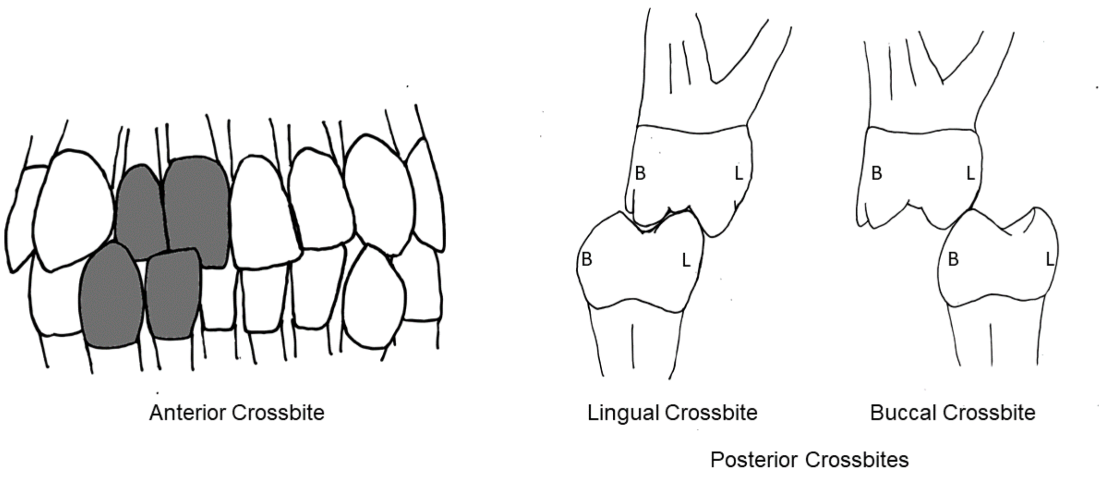


Figure 21: Illustration of the relationship between the anterior teeth in an anterior crossbite (left). The teeth involved in the anterior crossbite are highlighted in grey. Note the positioning of the involved lower teeth labial to the incisal edges of the maxillary teeth. Figure created by author. Diagram showing the mesial aspect of the upper and lower molars on the left side of the dentition with a posterior lingual crossbite and a posterior buccal crossbite (right). Lingual and buccal directions are indicated on the diagram by L and B, respectively. Crossbites can be unilateral or bilateral. Figure after Hillson 1996; Figure 4.3; p. 111).

The location of a crossbite within the dentition will have different functional implications for mastication. Fragmentation of the mandible and maxilla can often lead to difficulties in diagnosing crossbites using criteria derived from dentistry (Vodanovíc et al. 2012). The distribution of dental wear facets across the dentition (Sarig *et al.* 2013) and the reconstruction of occlusal kinematics using OFA (Fiorenza and Kullmer 2016) have been used to infer the presence of occlusal variability and infer its effect on mastication in both full and incomplete dentitions. A method for identifying crossbites in fragmentary dentitions based on the position of dental wear facets is presented and discussed in section 5.2.1.3.

Clinically, individuals with unilateral posterior crossbites exhibit a higher frequency of abnormal chewing cycles often with an associated reduction in dental contacts in the region of the maloccluding teeth (Rilo *et al.* 2007). Reverse chewing cycles, which are characterised by a reverse direction of closure, less lateral displacement, slower jaw closing velocity and unbalanced muscle activation often characterise individuals when chewing on the side of the dentition with a posterior crossbite. Meanwhile, the unaffected side typically exhibits a normal jaw closing direction (Figure 22; Lewin 1985; Piancino *et al.* 2006; 2009; 2010; 2012; Throckmorton *et al.* 2001). The mastication of harder foods was associated with a higher frequency of reversed chewing cycles (72% of individuals) than a softer bolus (55%) in a clinical study of individuals with mixed dentitions and posterior crossbites (Piancino *et al.* 2012) The presence of an anterior crossbite has been associated with steeper incursive and excursive jaw movements during chewing cycles. The lateral component of jaw movement increased during excursions following treatment (Yashiro *et al.* 2004). Reverse chewing cycles are not typically observed clinically in individuals with anterior crossbites (Piancino *et al.* 2012). Differences in occlusal arrangement may have implications for masticatory function and need to be discussed when attempting to reconstruct chewing behaviours using dental wear facets.

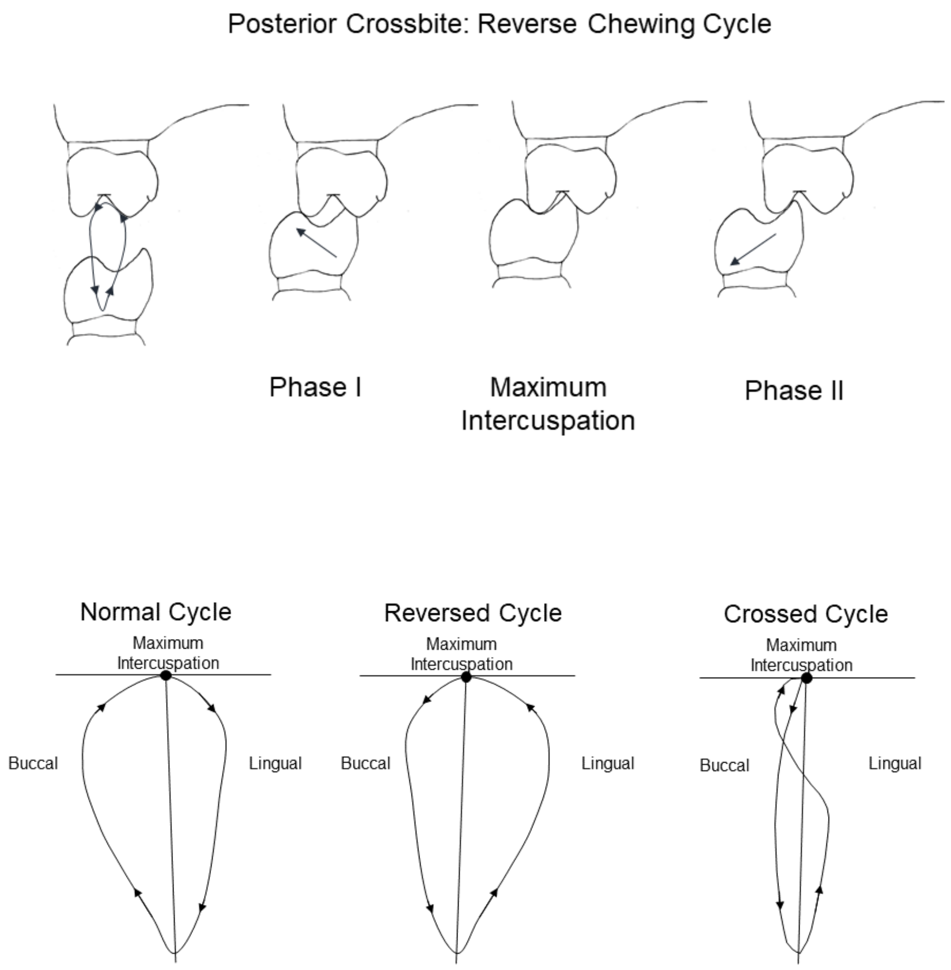


Figure 22: Illustration of a reverse chewing cycle on the left side in an individual with a posterior lingual crossbite (upper). A comparison of the movement of the lower dentition viewed in the frontal plane of a normal chewing cycle, a reversed chewing cycle and a crossed and reversed chewing cycle (lower). Figure created by author.

3.8 A new approach to examining the effects of Industrialisation on masticatory behaviours

Historical and archaeological sources provide a comprehensive insight into the dietary transformations that occurred during the Mediaeval and early Post-Mediaeval periods (1100-1700AD) and Industrial era (1700-1900AD) (Burnett 1989; Woolgar 2016). A radical shift in dietary consistency and the types of food consumed took place. The dietary changes associated with the early stages of European industrialisation reflect the beginnings of the most recent major revolution in subsistence practices for hominins. Food production became increasingly large-scale and globalised whilst the foods eaten became more intensively processed, softer and hyper-nutritive (Corruccini 1984; Reardon and

Timmer 2012). The effects of industrialisation on dental occlusion, rates of pathology, jaw morphology and gross wear have been extensively explored. More frequent occlusal variability, higher rates of dental caries, lower levels of dental wear and gracilisation of the mandible have been identified (Corbett and Moore 1976; Corruccini 1999; Kaifu *et al.* 2003; Rando *et al.* 2014).

Previous studies have confirmed that this is a key dietary transition in terms of the morphology and function of the masticatory system. However, an essential factor within the debate surrounding changes in occlusion, gross wear and jaw morphology during this period has been neglected. Attempts have not been made to examine the impact changes in dietary properties have had on masticatory behaviours during the Industrial Revolution (Figure 23). Chewing behaviours and the biomechanical stimulation of the masticatory system are critical elements in its function, growth and development (Kaidonis *et al.* 2014; 2017). An understanding of masticatory behaviours and how they might have changed during industrialisation, therefore, is pivotal to wider arguments predicated on the hypothesis that the biomechanical demands placed on the masticatory system were reduced during this period.

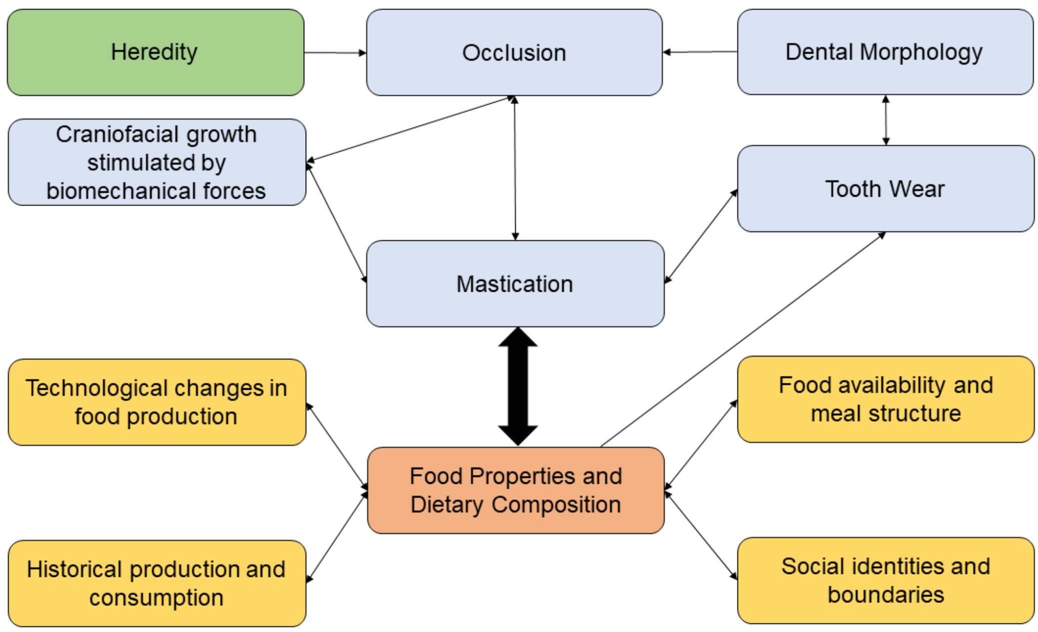


Figure 23: Diagram summarising the relationships between key concepts underpinning the function of the masticatory system and dietary composition.

This research provides a new perspective on the dietary history and dental behaviours of anatomically modern humans in addition to insight into the dental conditions and habits of 21st century industrialised groups by utilising dental wear facet patterns to reconstruct masticatory behaviours and compare them between the Industrial, Mediaeval and early Post-Mediaeval periods. Occlusion, mastication, craniofacial development, diet and dental wear are all closely interwoven in the functioning of the masticatory system. As such, the methods used need to consider differences in occlusal conditions between the two periods where possible that may influence masticatory function as discussed in this chapter. Underlying differences in the rate of dental wear between the two periods should also be assessed as this will have an impact on how occlusion is modified over an individual's lifetime.

Furthermore, previous studies of dental wear facet patterns in hominins have been limited by the small sample sizes typical of pre-Neolithic assemblages (e.g. Fiorenza *et al.* 2011a; 2020). These studies used a selection of contemporary modern hunter-gatherers with established yet variable dietary patterns to provide a comparative dataset for this earlier material (Fiorenza *et al.* 2011a). An analysis of dental wear facet patterns has not been undertaken for Industrial and Mediaeval groups. This current study provides an example of the variability in wear facet expression in anatomically modern humans, which will be of relevance to the interpretation of dental wear facet patterns in individuals from other contexts.

4 Research Questions

A Dental Revolution? Did technological advances in food processing and the introduction of new dietary commodities in the 18/19th centuries bring about significant changes in masticatory behaviours and tooth use?

Do dental wear facet patterns indicate that a change in masticatory behaviours occurred between the Mediaeval and Early Post-Mediaeval periods (AD1100-1700) and the Industrial era (1700-1900AD)?

The following changes in dental wear pattern would be expected in the Industrial Period (AD1700-1900) as a result of the historically documented changes in dietary composition to softer, more heavily processed foods relative to the Mediaeval and Early Post-Mediaeval periods (AD1100-1700):

1. A reduction in the gradient of dental wear between the first and second molars should occur.
2. The occlusal relief across the entire occlusal surface of the lower second molar would be expected to be less heavily reduced in the Industrial period.
3. Greater quantities of tip crushing wear would be anticipated in the pre-industrial group due to the incorporation of larger quantities of abrasive particles in the diet resulting in more extensive cusp removal.
4. The composition of the wear facet area of the lower second molar should indicate a decrease in the lateral component of jaw movement during the power stroke as dietary content became more heavily processed.
5. The wear facets on the lower second molar should be more obliquely inclined due to anticipated differences in the inclination of each phase of the power stroke.
6. There may be slight changes in wear facet orientation suggestive of differences in the directionality of the incursive and excursive components of the power stroke.
7. Higher frequencies of ante-mortem tooth loss are anticipated in the Industrial period, partly due to consumption of a more cariogenic diet, higher levels of dental caries and associated tooth extraction. Clinical evidence suggests that higher levels of ante-mortem tooth loss, particularly of the posterior teeth, will impact masticatory performance.

8. Mesial drift due to tooth loss and the loss of antagonistic teeth will alter occlusal relationships and may impact the dental wear patterns of the teeth involved. It is hypothesised that ante-mortem tooth loss may contribute to the overall differences observed in dental wear patterns between the two periods.
9. There should be a decrease in the lateral component of the movement of the lower molars during dynamic simulations of the power stroke; a power stroke dominated by a more strongly vertically directed chopping action might be anticipated.

Can OFA be used to identify within assemblage and period variation in dietary composition and para-masticatory behaviours that are historically and/or archaeologically described?

The potential for OFA to identify within assemblage and period variability in dietary composition and para-masticatory behaviours is relatively unexplored. The following differences in the assemblages examined might be expected given historically and archaeologically described differences in dietary content related to social identity.

Industrial Period (AD1700-1900)

1. During the Industrial period, the largest share of any meat and cheese was typically consumed by men whilst women and children subsisted almost solely on bread, potatoes and weakened tea. A proportion of buccal phase I wear facets indicative of greater shearing activity and meat consumption would be anticipated if these dietary differences were of sufficient magnitude.
2. A wider range of age groups is anticipated to be includable in OFA for the Industrial period due to an expected lower wear rate when compared to the Mediaeval and early Post-Mediaeval periods. It is anticipated that wear facet expression may change with increasing age-at-death.
3. In the Industrial period, the quantities of meat consumed were highly dependent upon income and it has been asserted that differences in diet were of greater magnitude between, rather than within, social classes (Burnett 1989). Among assemblages with contextual information pertaining to social stratification, greater quantities of buccal phase I

shearing wear might be anticipated among higher status individuals that habitually consumed larger amounts of meat.

4. More heavily processed white wheaten bread was taken up less rapidly in Northern England. Differences in wear facet expression would be expected if the composition of the staple food items consumed differed markedly between the north and south of England.
5. Habitual clay pipe use creates distinctive wear facets on the anterior teeth and premolars. It is expected that these will be accompanied by differences in molar wear facet expression.
6. Dental wear facets attest to the occlusal relationship between opposing molar rows. Malocclusion in the posterior dentition should be identifiable by reconstructing the relationships between antagonistic molar rows using OFA.

Mediaeval and Early Post-Mediaeval Period (AD1100-1700)

1. Historical evidence for marked sexual differences in the diets consumed in the Mediaeval and early Post-Mediaeval periods was not found. Significant differences in dental wear patterns would, therefore, not be expected.
2. In the Mediaeval period, there is historical evidence for differences in dietary practices at institutions such as monasteries and hospitals. Contrasts in lower second molar wear patterns would be expected between the inhabitant of such institutions relative to lay cemeteries.
3. Leprosy often has orofacial manifestations, which may impact masticatory behaviours. In addition, dietary measures were often utilised in the treatment of leprosy in the Mediaeval period. Individuals with lepromatous leprosy might be expected to exhibit dental wear patterns that differ from those unaffected by the pathology.

5 Materials and Methods

5.1 Materials

5.1.1 Inclusion Requirements for Material

5.1.1.1 Power Analysis to determine sample size

A power analysis (Cohen 1988; 1992; Kraemer and Blasey 2016) indicated that a sample size of at least 86 individuals from each period, the Mediaeval and early Post-Mediaeval (AD1100-1700) and the Industrial (AD1700-1900), should be adequate for detecting significant differences in relative wear facet area, whilst maintaining a suitable level of statistical power and alpha risk, if the effect size of period is small to medium (Table 12). Data were taken from the work of Fiorenza *et al.* (2011a) as an example of the magnitude of effect sizes anticipated when comparing relative wear facet areas between groups derived from the same species consuming different diets. The dietary differences between Neanderthals from different ecogeographic regions and modern hunter-gatherers pursuing different subsistence strategies do not provide an optimal analogue for the anticipated differences in dietary composition between the Mediaeval and Industrial periods, which principally relate to technological developments in food processing technologies. A more appropriate analogue was, however, not available. The majority of differences between cemeteries dating to each period and the groups within those cemeteries, if they are of the magnitude described by Fiorenza *et al.* (2011a), should be detectable with a sample size of 20 to 30 individuals per group.

A preliminary analysis comparing the relative wear facet areas of the lower second molars between early post-mediaeval shroud burials (AD1550-1700) from St Michael's Litten cemetery with later Industrial period shroud burials (AD1700-1900) also indicated that a group size of 12 to 20 individuals should be adequate for identifying significant contrasts in dental wear patterns between groups where effect sizes are large. Where effect sizes are smaller, at least 73 individuals should be adequate to determine any significant differences in relative wear facet areas.

Table 12: Table presenting predicted optimal sample size for each assemblage examined. An alpha level of 0.05 and power value of 0.8 was selected (Cohen 1990). Statistical power is the probability of detecting an effect when one exists. Effect size was estimated using the mean differences in relative wear facet areas reported by Fiorenza et al. (2011a) and also using a preliminary analysis of material from St Michael's Litten, Chichester (ESC11).

Power Stroke Phase	**Buccal Phase I**		**Lingual Phase I**		**Phase II**	
Groups Compared	**Effect Size (d) (95% CI)**	**Opt. Sample Size**	**Effect Size (d) (95% CI)**	**Opt. Sample Size**	**Effect Size (d) (95% CI)**	**Opt. Sample Size**
Mixed Diet vs. Meat Eating Modern Hunter-Gatherers (Fiorenza et al. 2011a)	0.7 (-0.05 to 1.44)	34	-1.33 (-2.12 to -0.54)	10	0.83 (0.08 to 1.59)	24
Neanderthal Deciduous Woodland vs. Steppe Group (Fiorenza et al. 2011a)	-1.51 (-2.87 to-0.14)	8	1.86 (0.44 to 3.29)	6	-1.31 (-2.65 to 0.02)	11
Neanderthal Steppe vs. Mediterranean Group (Fiorenza et al. 2011a)	-1.31 (-3.47 to 0.85)	11	2.05 (-0.36 to 4.47)	5	-0.43 (-2.42 to 1.56)	86
Early Post-mediaeval Shroud Burials vs. Late Post-mediaeval Shroud Burials from Chichester, ESC11.	-0.46 (-1.22 to 0.28)	73	-0.93 (-1.70 to -0.15)	20	1.25 (0.46 to 2.04)	12

5.1.1.2 Selection Criteria for assemblages

The assemblages selected for inclusion had to effectively address the research hypotheses being assessed by the current research. The principal research question sought to identify differences in masticatory behaviours following the introduction of more heavily processed and softer dietary staples in the Industrial period. Historical and archaeological evidence indicated that the majority of assemblages selected were largely representative of the average diet and lifestyle in either the Mediaeval, early Post-Mediaeval or Industrial periods. In addition, the project aimed to examine whether OFA could identify more subtle dietary differences within the periods examined. Consequently, in each period a range of socioeconomic groups and regions were represented by the assemblages selected. The following criteria were therefore used for selection:

- The assemblage was dated to either the Mediaeval and Early Post-Mediaeval periods (AD 1100-1700) or the Industrial period (AD 1700-1900). Where inhumations at a single cemetery overlapped both periods, contextual information for each burial had to be adequate to disentangle the earlier from the later burials. The only cemetery selected that required separation into early and later phases was St Michael's Litten, Chichester (ESC11), which dated from AD 1550-1900.
- Sufficient contextual information for each assemblage had to be available to characterise the general profile of the individuals interred at the site. Most of the assemblages included were selected because they were drawn from cemeteries of a substantial size (greater than 100 individuals) and likely reflected the average demographic for the period and region.
- Assemblages in each period were drawn from a range of geographic regions to test whether historically reported regional dietary differences resulted in differences in dental wear patterns.
- If assemblages from approximately the same geographic region were available in the Mediaeval, early Post-Mediaeval and Industrial periods these assemblages were prioritised.
- The assemblage had to be available for examination within a suitable timeframe for data collection to be completed (September 2017 to September 2019).
- At least five individuals within the assemblage had to satisfy the individual selection criteria below. Larger assemblages were prioritised to increase the likelihood that this condition would be met.

5.1.1.3 Selection Criteria for individuals

Individuals chosen as representatives of each skeletal assemblage had to satisfy the selection criteria outlined (Table 13). The wear facet patterns of the mandibular and maxillary molars will differ from anterior to posterior due to subtle differences in dental morphology and their position and inclination in relation to the TMJ (Fiorenza 2009; Spears and Macho 1996). The number and expression of wear facets along the tooth row will also depend upon the position of the molar within dental occlusion; for example, the upper third molar will typically only have one mandibular antagonist in an Angle Class I occlusion whereas the first and second will have two (Fiorenza *et al.* 2010). As such, wear facet patterns can only be compared between a given tooth position when utilising differences in wear facet proportions and inclination to infer underlying differences in diet and masticatory behaviours.

Kay (1973, p.181) argued following a survey of 200 primate taxa that the second molar gives an effective representation of masticatory behaviours in primates and provides an indication of masticatory function across the molar dentition, including shearing, crushing, and grinding potential. In addition, the lower second molar more commonly exhibited a Smith wear stage of 2 in the mediaeval dentitions examined when compared to the first molar and was less frequently lost ante-mortem than the first molar in the Industrial period. The mandibular dentition was frequently better represented in the assemblages examined than the maxillary dentition. Consequently, the lower second molar was targeted for performing dental wear facet analysis. Individuals were selected with a consistent degree of second molar wear as previous studies have indicated that differences in wear stage can strongly influence wear facet inclination (Fiorenza 2009; Knight-Sadler and Fiorenza 2017). In addition, in heavily worn teeth wear facet identification becomes increasingly difficult and wear facets are often merged (Fiorenza *et al.* 2011b). Individuals were not selected if the occlusal surface was partially obliterated by dental caries or substantial post-mortem chipping had occurred.

Table 13: Selection criteria for individuals to be included in the current research.

Primary Selection criterion (Must be present)
At least one lower second molar present with a Smith wear stage of 2 (1984). This was the tooth selected for conducting OFA. This wear stage is characterised by moderate cusp removal and no more than one or two pinpoints of dentine exposure (Smith 1984). Preference was given to the lower right molar.
Secondary Selection criteria (Preference given to those that satisfy the following)
Relatively good representation of the dentition, preferably with some representation of both the upper and lower dental arcades. All permanent teeth are erupted and in wear except for the third molar. Presence of post-cranial skeletal elements to facilitate sex and age-at-death estimates.

5.1.2 Assemblages Included

On this basis, five assemblages from the Mediaeval and early Post-Mediaeval periods and four from the 18^{th}/19^{th} centuries were selected (Table 14). For each chronological period, assemblages were identified from a variety of regions to determine whether historically described regional differences in diet are detectable in dental wear patterns (Figure 24; Figure 25). Several of the assemblages selected had sufficient contextual data available to investigate within assemblage variability in dental wear patterns and dietary composition.

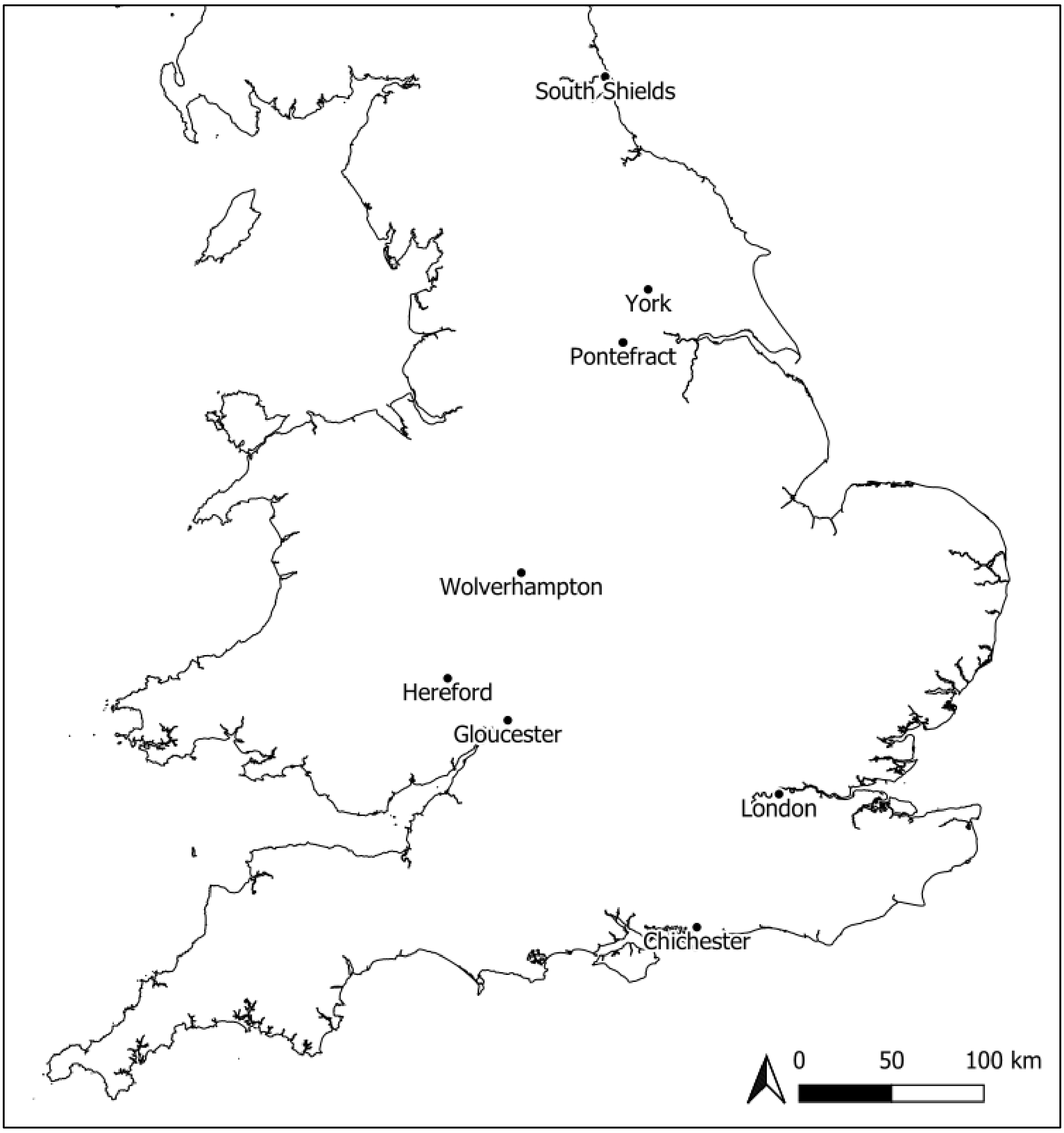


Figure 24: Map of Great Britain showing the towns and cities from which the skeletal assemblages examined were derived. Contains OS data © Crown copyright and database right 2021.

Table 14: Table showing the assemblages included in the current study and giving details of their locations, size, date and the number of individuals from this collection that satisfied the inclusion criteria.

Collection	Code	Location of Collection	Dates Cemetery in Use	Location	Social Class	Number of Individuals in Collection	Type of Group	Number Suitable	Publications in which Assemblage is described
Industrial Assemblages (AD 1700-1900)							**Total**	**104**	
St Michael's Litten, Chichester (Late)	ESC11	UCL	c. AD1700-1900	South (Coastal)	Low to Middle (Coastal)	300	Urban	26	Hart 2012
St Bride's Church, Fleet Street	SB79	St Bride's Church	AD1714-1848	London	Variable but including upper classes	227	Urban parish burial ground	31	Harvey 1967
The Church of St Hilda, Coronation Street, South Shields	CS06	University of Sheffield	AD1816-1856	North (Coastal)	Low	114	Urban working-class group; ship builders	25	Raynor, McCarthy and Clough 2011
St Peter's Wolverhampton	StP	University of Bradford	AD1800-1853	West Midlands	Low to Middle	150	Urban; short burial period	18	Adams and Colls 2007
Pre-Industrial Group: Mediaeval and Early Post-Mediaeval Assemblages (AD 1100-1700)							**Total**	**130**	
St Michael's Litten, Chichester (Early)	ESC11	UCL	c. AD1550-1700	South (Coastal)	Low to Middle (Coastal)	300	Urban	18	Hart 2012
All Saint's Church, Fishergate, York	BARB	University of Sheffield	c. AD1100-1500	North	Various	547	Lay cemetery	32	Macintyre and Bruce 2010
Hereford Cathedral	HE93	University of Bradford	c. AD1100-1600	Midlands	Lower to high status	1200	Lay cemetery including two large plague pits	42	Stone and Appleton-Fox 1996
Box Lane	BL	University of Bradford	c. AD1100-1500	Pontefract, North Yorkshire	Lower to Middle	88	Lay Cemetery	7	Roberts and Burgess 1999
Blackfriars	BF	University of Bradford	AD1246-1539	Gloucester	Variable	192	Friary	9	Atkin 1992
St James and St Mary Magdalene, Chichester, West Sussex	CH86	University of Bradford	c. AD1100-1600	South	Lower to Middle (Coastal)	374	Leprosarium and alms house	24	Magilton *et al.* 2008

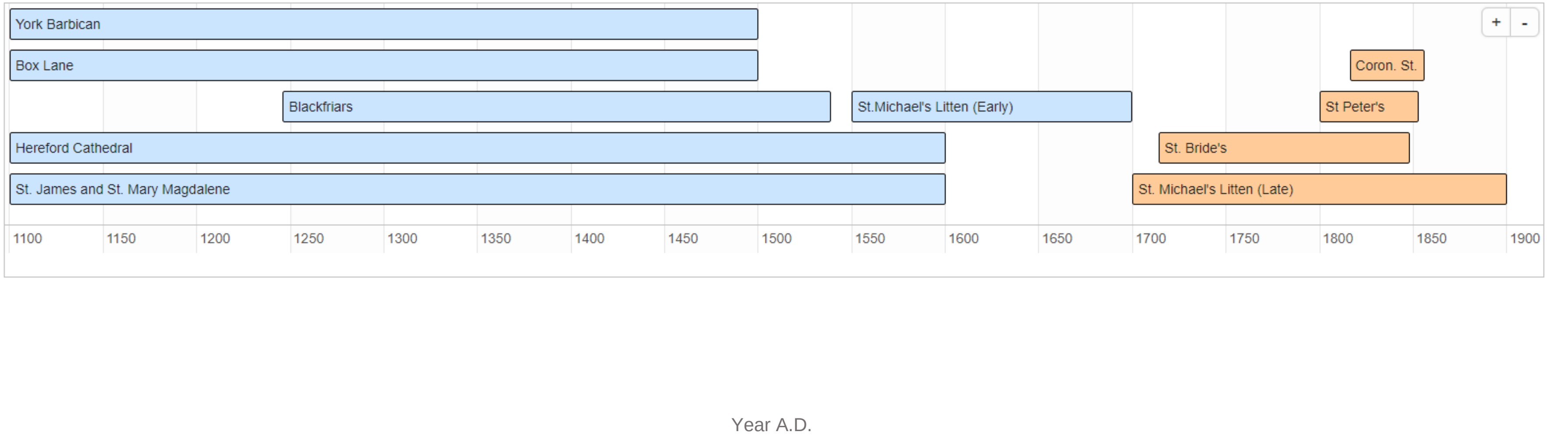


Figure 25: Timeline illustrating the date ranges for inhumations at the cemetery sites examined. Mediaeval and early Post-Mediaeval assemblages are coloured blue and Industrial era assemblages are coloured red. Several of the cemetery assemblages examined spanned from the Mediaeval period into the early Post-Mediaeval period (AD1100-1700). This material formed the comparative material against which the masticatory behaviours of the Industrial period (AD1700-1900), attested to in dental wear patterns, were compared.

5.1.2.1 Background of each Assemblage

5.1.2.1.1 Mediaeval and Early Post-Mediaeval periods (AD1100-1700)

5.1.2.1.1.1 York Barbican, All Saint's Church, Fishergate (BARB)

The assemblage was excavated during fieldwork conducted by On-Site Archaeology from 2007-8 in advance of a new development situated south of the mediaeval city walls in Fishergate on the east side of the River Foss (Figure 26 and Figure 27). Trial excavations at the site conducted in 1987 and 2003 encountered several mediaeval burials. The graveyard was characterised by a high burial density indicating intensive use over a prolonged period. The occupants of the cemetery were likely civilians drawn from a range of socioeconomic groups. The complete length of the foundations of All Saint's Church were contained within the excavation area. It was likely established in the late 11th century and fell out of use shortly after AD1585. The church was closely associated with Whitby Abbey and, consequently, was dissolved during the dissolution of the monasteries. Approximately 550 skeletons were found within the church and to the east, west and north of it (McIntyre and Bruce 2010). Of the individuals recovered, 32 individuals satisfied the inclusion criteria for the current project. Unlike mediaeval Hereford, York did not operate a monopoly on the burial rights of local parishes, therefore, individuals were typically interred in their local parish burial grounds (Forrest 2010).

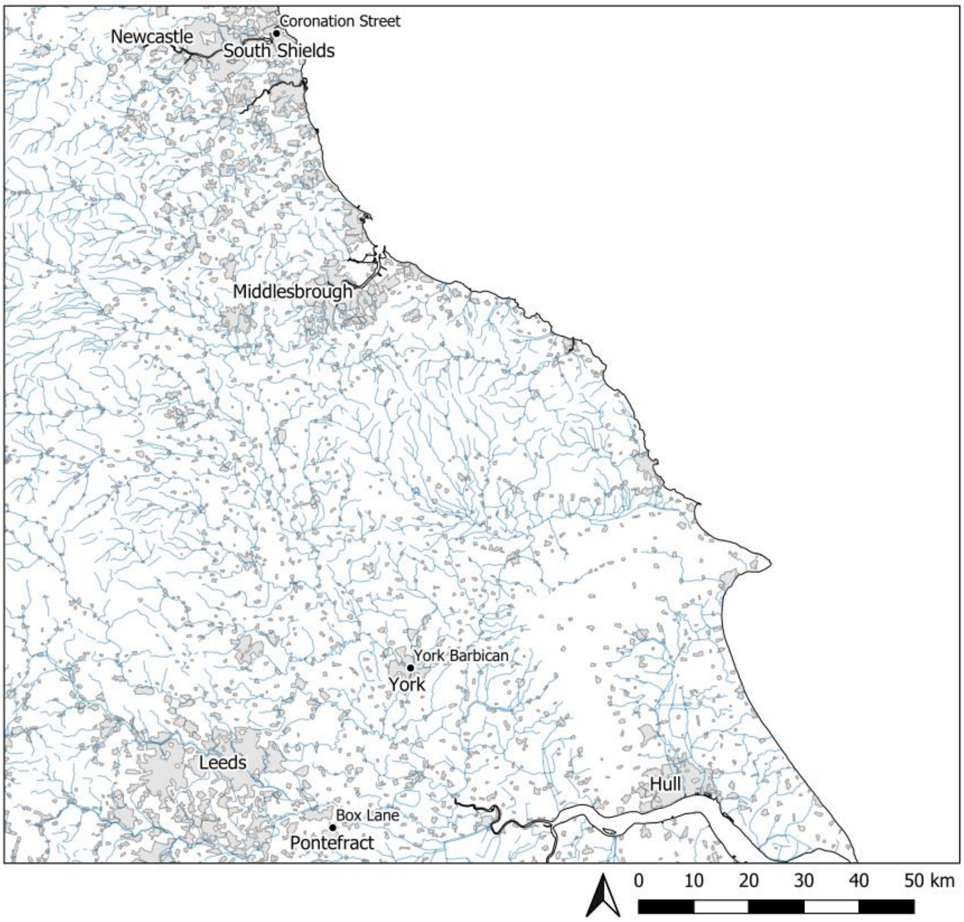


Figure 26: Map showing the location of the Box Lane, York Barbican and Coronation Street cemetery sites in northern England. Contains OS data © Crown copyright and database right 2021.

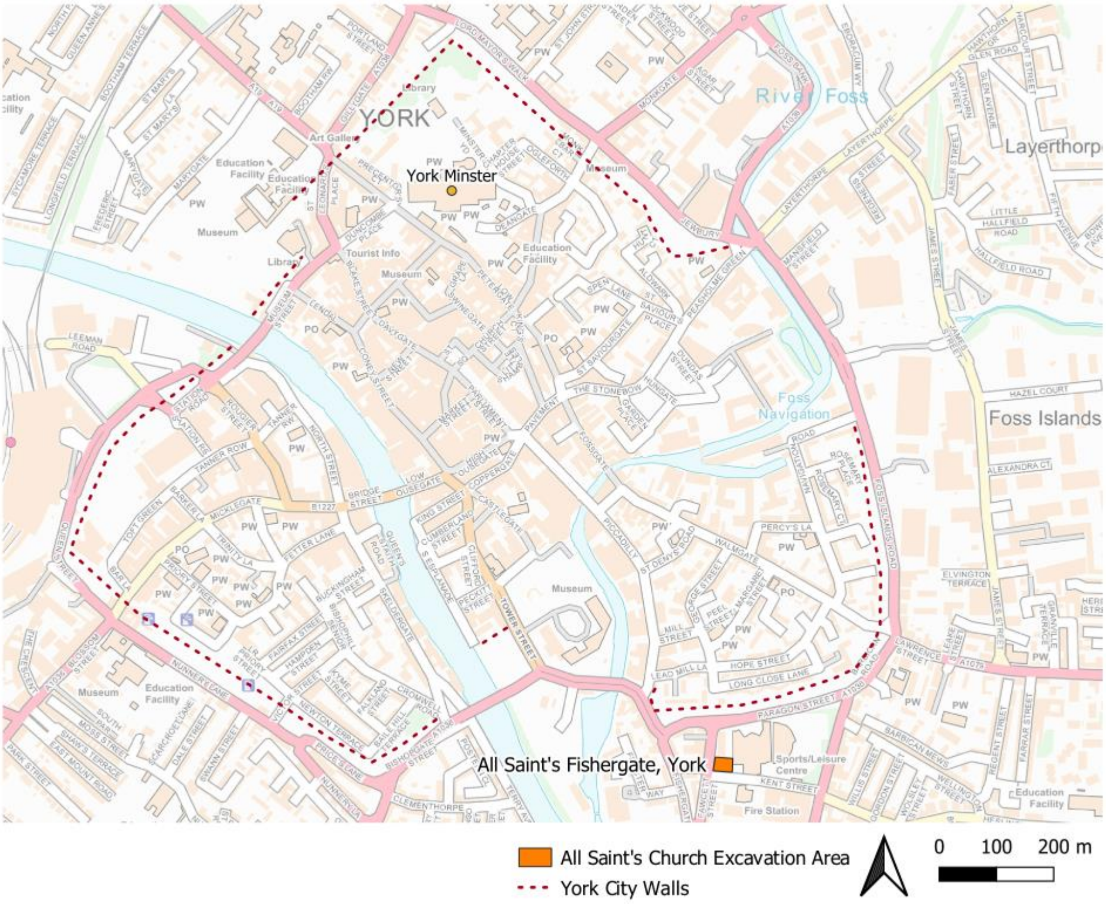


Figure 27: Map showing the location of the York Barbican site excavated from 2007-2008 by On-Site Archaeology, which encompassed the cemetery associated with the Church of All Saint's Fishergate. The location of the Mediaeval city wall is included on the map. Contains OS data © Crown copyright and database right 2021.

Ten mass graves were encountered cutting across the earlier mediaeval burials. They contained between four and eighteen individuals. The mass graves probably dated to the 17th century during which York was besieged by Parliamentary force between April and July AD1644. The domination of the mass graves by male individuals and the proximity of the site to areas of strong Parliamentarian activity suggest that these individuals may have been associated with Oliver Cromwell's army (McIntyre and Bruce 2010). None of the individuals from these mass graves were included in the current analysis.

The City of York is situated on the confluence of the rivers Foss and Ouse (King and Henderson 2014). By AD1377, York was the second largest city in England and was known as a centre for the production and accumulation of wool, which was derived from the surrounding area (Nightingale 2010). In the mid-14th century, following the Black Death, the cloth industry started to develop. The freedom of York was attained by 117 weavers, dyers, fullers and shearers in AD1360 compared to 69 in the preceding decade. In addition, a shift occurred from demesne to peasant farming during this period. The investment of capital was not adequate to maintain both the cloth and the wool industry during the 15th century, resulting in the decline of trade and York was only the eleventh largest city in England by AD1525 (Nightingale 2010).

Stable isotope analysis has suggested a relatively high consumption of marine protein based on enriched $\delta^{15}N$ signatures for many individuals sampled from within the city, however, the quantities consumed would have depended upon social status (Müldner and Richards 2005; 2007a; 2007b). The prominence of marine protein consumption related to the proscription of abstinence from meat on up to half of the days of the year within the Christian calendar (Woolgar 2016). Marine species, principally cod and herring, have been recovered from deposits within the city and likely contributed a greater dietary component than freshwater fish from the 11th-12th centuries onwards (Barrett *et al.* 2004). In addition, high levels of pollution in the waterways from the 11th century onwards have been inferred from the disappearance of freshwater species within fishbone assemblages that require well-oxygenated water, such as grayling (King and Henderson 2014).

Isotopic evidence from the nearby site of the Priory of St Andrew, Fishergate, associated with the Gilbertine order (c.11th-16th century AD), suggested that males were likely consuming greater quantities of marine protein than females. Three male/female double burials, however, had similar isotopic profiles indicating that protein consumption was consistent within a single household and status context. Difficulties distinguishing clergy from lay people within the cemetery contexts at Fishergate limited the inferences that could be made regarding monastic dietary composition (Müldner and Richards 2007b). Children were fully weaned from two years of age and appear to have consumed a diet consistent with adults consuming large amounts of marine protein from an early age (Burt 2013). This contrasts with lower protein consumption and heavy reliance on grains in nearby rural areas, such as Wharram Percy (Mays *et al.* 2002; Richards *et al.* 2002).

Animal bone assemblages from mediaeval York are typically dominated by cattle remains with a smaller component of porcine and ovine material. The age-at-death profiles of cattle and sheep indicated that mainly older individuals were consumed. This suggests that the meat was a by-product of dairy, wool, dung and traction demands and were likely drawn from the surrounding agrarian economy. Pigs were mainly killed as younger individuals and were likely kept within backyard areas and open spaces within the city (O'Connor 2000). Contemporary accounts complain of the accumulation of dunghills and the number of pigsties within the city. Ordinances placing restrictions on pig-keeping were repeated throughout the 14th-16th centuries and highlight the ubiquity of the practice within the city (King and Henderson 2014).

The enriched $\delta^{15}N$ values for mediaeval York have also been associated with high consumption of porcine protein based on the hypothesis that pigs would be eating human refuse containing marine protein (Müldner and Richards 2005). Pigs from Coppergate and Swinegate did not, however, exhibit enriched $\delta^{15}N$ profiles consistent with the consumption of human waste foods, including marine protein. Most pigs probably consumed a predominantly herbivorous diet (Hammond and O'Connor 2013).

Charred plant remains attest to the consumption of free-threshing 'bread' wheats, rye and barley in mediaeval York (Hall 2000). The use of rotary quern stones declined in mediaeval England from the 12th century when prohibitions were placed on their use (Ottoway and Rogers 2002). Millstone fragments recovered from the mediaeval village of Wharram Percy, Yorkshire, indicated that the majority of grinding would have been performed using stones of basaltic lava from the Niedermendig district of Germany. These would have been exported from Cologne (they obtained their nickname of 'cullens' from Cologne) to ports on the eastern coast of England (Farmer 1992) (Table 15).

Recovered leaf epidermis from the genus *Allium* support the cultivation and consumption of both onions and leeks on small plots in the city (Hall 2000). Fruit, such as apples and pears, would have been grown in the city and brought from the surrounding hinterland (Rycraft 2000).

The Priory of St Andrew, Fishergate, showed a higher prevalence of carious lesions in the later phase of the site (13th-16th century). This may indicate access to more refined carbohydrates relative to the earlier Mediaeval period. 56% of the individuals examined showed some irregularity of the teeth and the prevalence of crowding was 29% in males and 39% in females. Where the articulation of jaws was possible, 88.5% were classified as Angle class I, 10.9% as Angle Class II and 0.6% as Angle Class III (defined in section 3.7 Dental Occlusion). 65.1% of incisal relationships were classified as Class I, 4.6%as Class II div I, 16.2% as Class II division II was and 13.9% as Class III (Addyman, Stroud and Kemp 1993).

Table 15: Dietary profile for the York Barbican, All Saint's Church assemblage.

Site	**York Barbican**
Dietary Staples	Wheats, rye, oats, peas and barley consumed as porridges and loaves
Dietary Supplements	Vegetables (Onions and leeks) grown on plots within city Marine protein (Cod and Herring) Animal protein (Beef, pork and mutton) depending on social status.
Milling Technology	Grinding performed in watermills and windmills using stones of basaltic lava from the Niedermendig district of Germany
Social Status	Mainly civilians of variable social status, however, due to scant burial data difficult to distinguish social groups within cemetery.
Sex differences	Isotopic evidence at nearby Fishergate Priory indicated that females were consuming smaller quantities of high trophic level foods.

5.1.2.1.1.2 Box Lane, Pontefract (BL)

The Box Lane assemblage was excavated during a development to the north of the Scheduled monument of St John's Priory, Pontefract, as part of a rescue excavation in 1987 for a commercial development (Figure 26 and Figure 28). The excavation area was located to the southwest of the intersection between Box Lane and Ferrybridge road. The excavation comprised three areas; two of which encompassed portions of a mediaeval cemetery. Pottery recovered suggested that a portion of the burials dated from the 13th-14th centuries. At least 184 individuals were buried across the excavation areas, however, the majority of skeletons were only partially complete (Roberts and Burgess 1999). Of the 88 individuals held at Bradford University, only seven individuals satisfied the inclusion criteria.

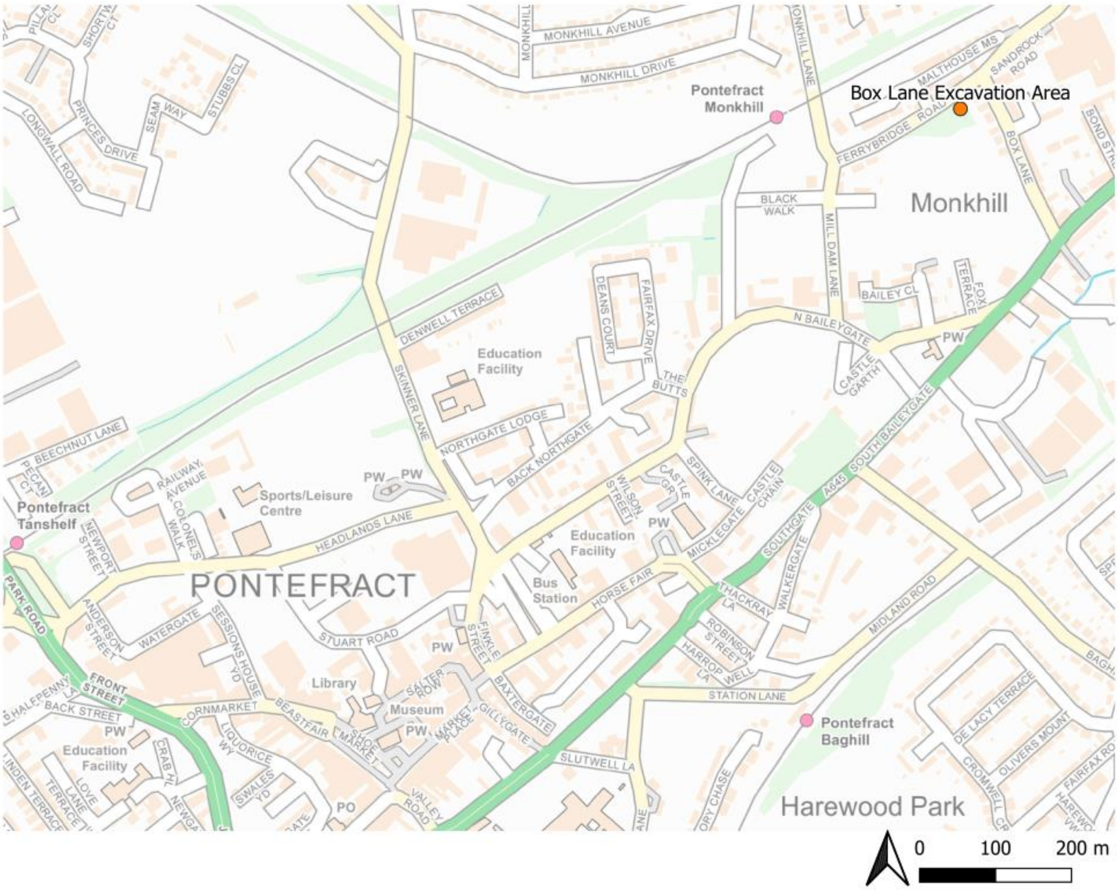


Figure 28: Map showing the location of the areas excavated at Box Lane, Pontefract (NGR SE 4630 2273). Contains OS data © Crown copyright and database right 2021.

The cemetery at Box Lane was likely associated with St John's Priory, which was founded in about AD1090. Pottery recovered supports burial dates from the 13th to the 14th century. It is uncertain, however, whether the cemetery served the Cluniac monks themselves or the lay population of the monastery and the community of nearby settlements. The cemetery included both women and men, with relatively few children, infants and adolescents, supporting the latter interpretation. Burials were modest and bodies were likely placed in shrouds without the use of coffins. Grave positions were probably marked, given evidence for secondary interments at shallower depths within the primary grave cuts. The arrangement of graves did not appear to reflect differences in age and sex (Roberts and Burgess 1999).

Pontefract was one of the most important mediaeval towns in Yorkshire located to the Southeast of York. In the 11th and 12th century, the earliest earthwork castle was constructed alongside domestic and industrial tenements centred on All Saint's church. At least three pre-conquest ecclesiastical sites existed prior to the establishment of St John's Priory in AD1090. High status ecclesiastical establishments provided the stimulus for the growth of the town. The town flourished from the 12th-13th centuries and expanded westward. It functioned as the administrative centre of the de Lacy and Lancastrian lands in the north. There was evidence for iron working, tanning and skinning and livestock dealing in the 12th century town, however, by the 14th century the biggest employer was the textile industry. Pontefract merchants were licensed to export wool by sea, via Knottingley on the River Aire and Humber estuary. Textile manufacture declined in the 16th century (Roberts and Whittick 2013).

An isotopic study comparing several individuals from Box Lane with those interred at the rural hospital of St Giles at Brough found that the isotopic profile of the Box Lane individuals was consistent with a typical mediaeval diet in which some meat was eaten fairly regularly and fish were occasionally consumed (Table 16). There was, however, little evidence to suggest a substantial marine dietary component. Archaeobotanical evidence indicated that wheat and oats formed the greatest fraction of the cereal component of diet. Variability in isotopic signatures at Box Lane presumably reflect a range of socioeconomic backgrounds for the individuals at the site. Less enriched $\delta^{15}N$ signatures may indicate the presence of lower status individuals heavily reliant on cereals in the form of bread, pottages and ale with meat being consumed in very small amounts. Foraging for fruit, vegetables and nuts would have been very common among low status groups. The priest and patron from St Giles had enriched $\delta^{15}N$ values, suggesting greater fish consumption among elite groups (Bownes, Clarke and Buckberry 2018). Animal bone recovered from ditches associated with the site also provide evidence of butchery and meat consumption. Cattle, horse, sheep, goat, pig, dog, fallow deer and domestic fowl were identified. Fallow deer were high status animals and may indicate the presence of higher status individuals proximate to the site (Roberts and Burgess 1999). This is consistent with historical evidence of a deer park located to the north-west of Pontefract (Roberts and Whittick 2013).

Table 16: Dietary profile of the Box Lane assemblage, Pontefract.

Site	**Box Lane**
Dietary Staples	Mainly cereals: wheat and oats.
Dietary Supplements	Vegetables (grown on plots) Foraging (fruits and nuts). Limited marine component but likely occasional freshwater fish. Animal protein (Beef, pork and mutton) depending on social status.
Milling Technology	Water mills were situated along the water course located to the north of the excavation area but grinding stone fabric is unknown (Roberts and Whittick 2013)
Social Status	Likely of variable social status representing the local parish and possibly the Cluniac Monks, however, due to a lack of evidence for different burial areas within the cemetery difficult to distinguish social groups within the cemetery.
Sex differences	No evidence in the literature.

5.1.2.1.1.3 Hereford Cathedral Close (HE93)

The skeletons examined were derived from the excavation of the area west of the Bishop’s Cloister at Hereford Cathedral conducted by the City of Hereford Archaeology Unit in 1993; the Mappa Mundi excavation (Figure 29 to Figure 31). The area is bordered on the west by a road called Palace Yard/ Gwynne Street. 1129 recognisable inhumations were found, however, the minimum number of individuals encountered was considerably greater and were represented by disarticulated remains resulting from substantial disturbance of the graves. Of the distinct burials, 119 were male, 223 were female and 707 were indeterminate.

Burials were recovered from three main areas: a large pit covering a third of the excavation area and containing an estimated 5000 individuals (many of whom were not retained for further analysis); three mass graves in the western portion of the site likely dating to the late 14th or early 15th centuries associated with the Black Death; and the main burial area of the cemetery (Figure 32). The large pit was interpreted as a gravel extraction quarry and destroyed many of the earlier late Saxon burials at the site. Several late Saxon burials were located in the south-eastern portion of the excavation area and were differentiated from the later mediaeval use of the site by greater burial depth (0.8m deeper). One of the skeletons examined (Sk3767) was buried with a 'pillow' stone and a copper alloy ring suggesting a Late Saxon burial date. These burials were orientated with their heads to the west consistent with Christian burial practice (Stone and Appleton-Fox 1996)

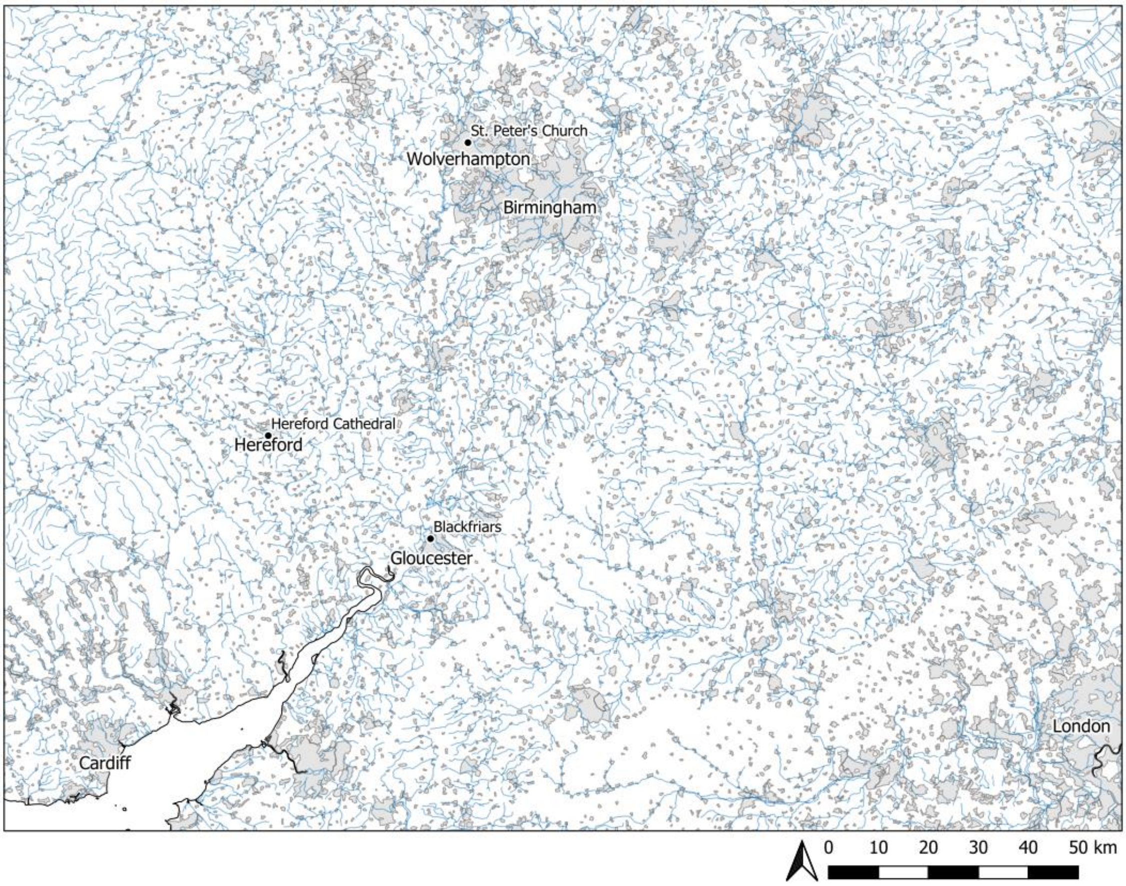


Figure 29: Map showing the location of the excavations from which the Hereford Cathedral, Blackfriars and St Peter's Church assemblages were recovered. Contains OS data © Crown copyright and database right 2021.

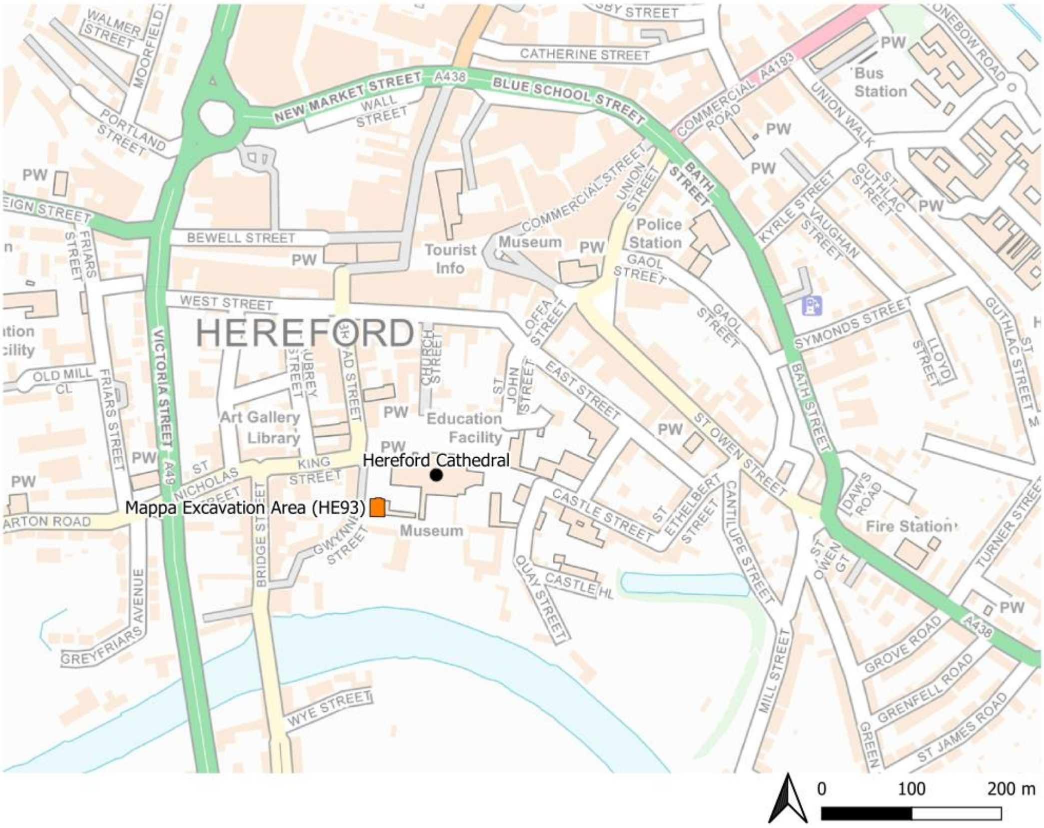


Figure 30: Map showing the location of the 1993 Mappa Mundi excavation which was situated immediately to the west of the cloister of Hereford Cathedral. Contains OS data © Crown copyright and database right 2021.

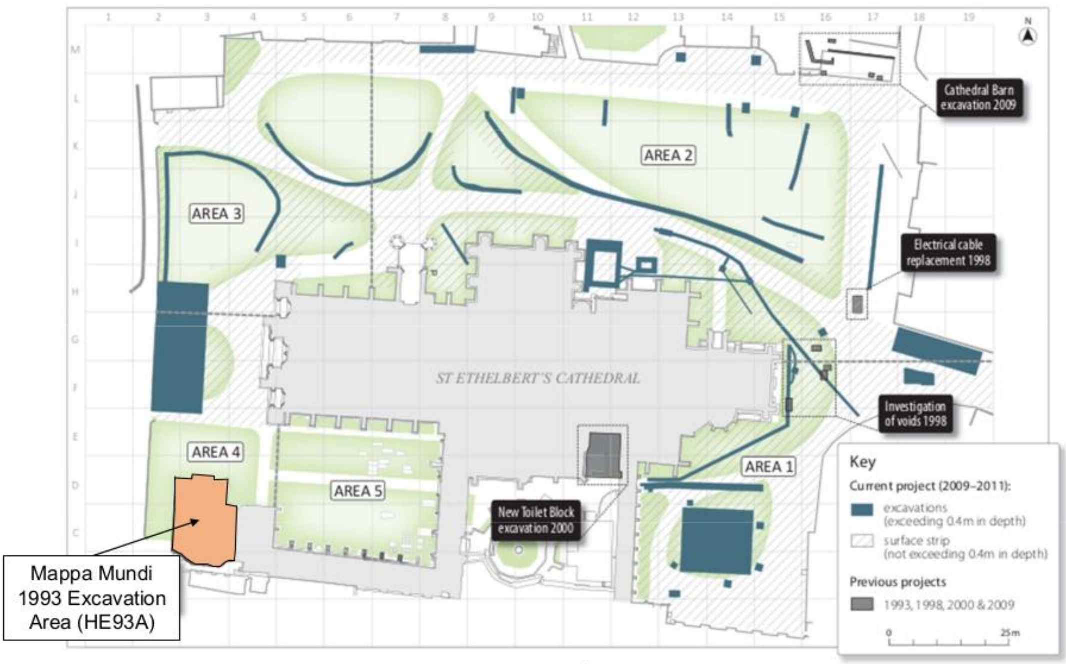


Figure 31: Map of Hereford Cathedral showing the location of the Mappa Mundi excavation area (orange) from which the Hereford assemblage was derived (Site code HE93A). The location of the later excavation areas targeted by Headland Archaeology from 2009-11 described in Boucher et al. (2015) are shown in blue. Figure modified from Craddock-Bennett (2017: illustration 10).

The mediaeval portion of the cemetery yielded the majority of burials encountered, which were probably interred from the 12th to the 16th centuries. These later interments had their arms more frequently over their chests or stomach rather than at their sides or across their pelvises, which may suggest inhumation in a coffin rather than a shroud. Social status could not be readily identified among the burials. Very high-status individuals would have been buried in the cathedral itself whilst a wide diversity of social classes would have been buried in the cemetery. Stone and Appleton-Fox (1996) hypothesised that higher status individuals would be buried closer to the altar, and therefore be more concentrated in the eastern portion of the excavated cemetery area. This is supported by the location of the 14th century mass graves in the western area of the site furthest from the altar. The cemetery area might be associated with the parish of St John. A road, known as St John’s Place, was located in the west of the excavation area and ran immediately west of the cemetery (Figure 32). This may indicate an association between the parish of St John and the cemetery area. St John’s parish lacked a parish church but included small parcels of land across the city, including the city centre. These individuals would have been served by an altar in the cathedral and so it is reasonable to suggest that they were buried within the cathedral cemetery. In this instance, the burial area would represent all social classes.

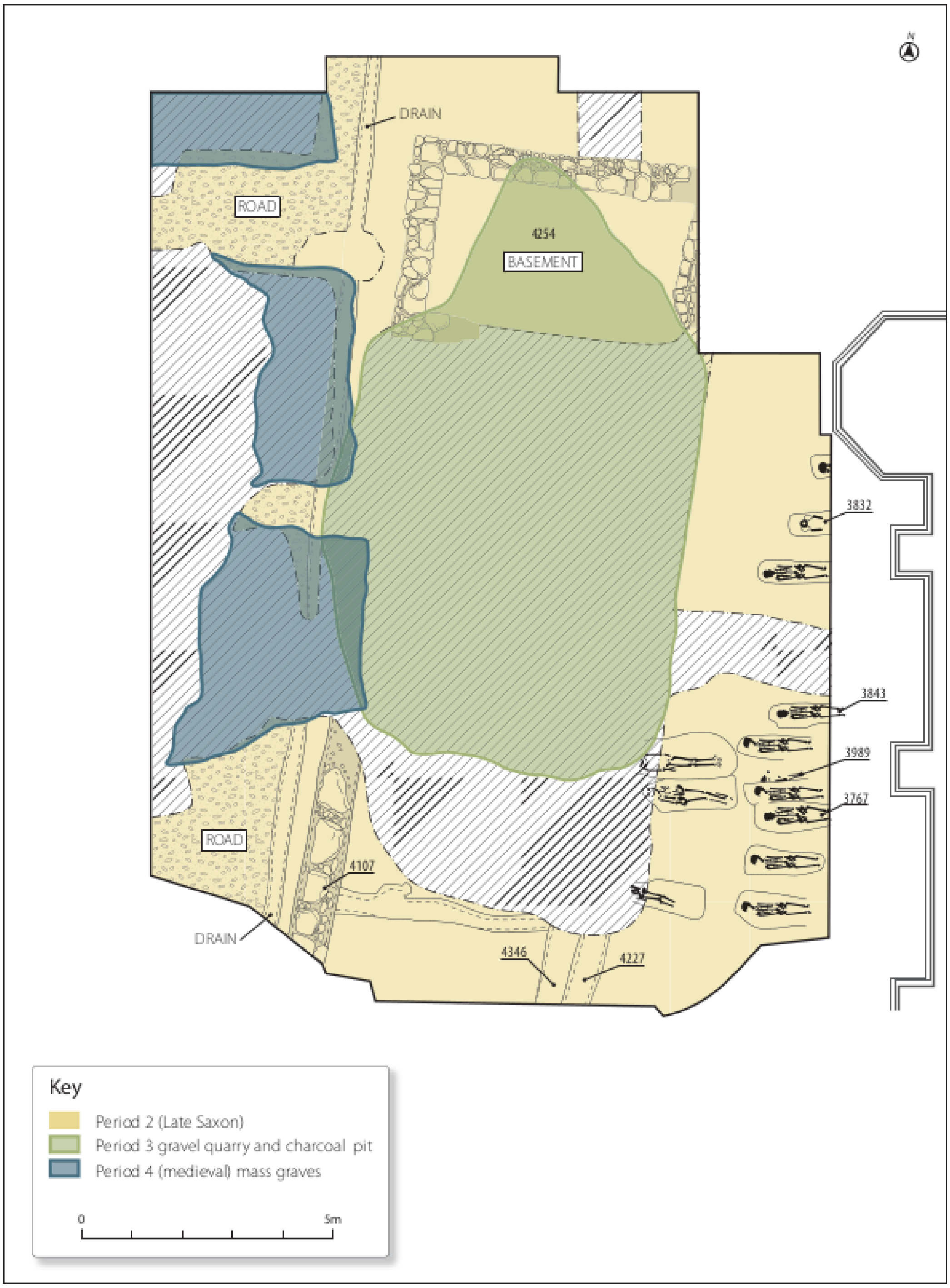


Figure 32: Key features of the 1993 Mappa Mundi excavation at Hereford Cathedral. Figure from Craddock-Bennett (2017: illustration 11) which was redrawn from Stone and Appleton (1996). The mediaeval phase of burials was present above the period 2 (Late Saxon) material.

Hereford is located on the river terraces of the River Wye in the west of England close to border with Wales (Figure 29). The City of Hereford had developed into a city with a grid of roads surrounded by formal defences by the 9th century. The first documentary evidence of a cathedral church dates to AD803-805. The settlement underwent a revival during the Norman period during which the commercial heart of Hereford shifted from near the cathedral to the area known today as High Town. A new marketplace was added in AD1067 and tax advantages offered to Norman settlers in the city likely led to a rapid growth in population during this period (Stone and Appleton-Fox 1996).

A new cathedral was started under the Normans from AD1107-15, including a cloister and chapter house for non-secular canons and a Bishop's palace (Stone and Appleton-Fox 1996). The Romanesque Norman cathedral was consecrated in AD1144. During this period, St Guthlac's Priory relocated to the site of the modern-day county hospital where it operated until AD1539. Hereford Cathedral operated a monopoly on the burial rights of individuals within the five parishes of the city and several beyond the city walls from AD1108. Fees paid for burial made an important contribution to cathedral revenues. The deanery extended between 5-10 miles beyond the boundary of the city, however, there was not a direct concordance between the parishes within the deanery and those whose burial rights were bound to the cathedral. A royal licence was given to the dean and the chapter to enclose the cemetery in AD1389 to avoid disturbance of graves by swine and other animals. This provides the first documentary evidence of the Cathedral Close. Attempts were made to weaken the burial monopoly from the late 13th century onwards, although, the chapter continued to reinforce the monopoly. On February 28th, AD1289, the rector of Hampton accepted that the men of Hampton and Tupsley were to be buried in the cathedral cemetery if their goods exceeded 6 shillings at the time of their death. The bodies of men worth less than 6 shillings, children and women, regardless of wealth, could be buried in the churchyard at Hampton without dues being paid to the chapter (Forrest 2010).

Parishes within the city were subject to a more stringent burial monopoly. Many parishes laid out during the founding of the city were not provisioned with churchyards as they lay within the area of the monopoly. Even the poorest parishioners from within the city were buried at the cathedral. It was asserted by the dean and chapter on 30th July, AD1362, that the cathedral had the right to conduct the funerals and receive the due of the entirety of Hereford (Forrest 2010). During this period, the individuals buried at Hereford cathedral would have comprised the entire socioeconomic spectrum of the inhabitants of the city, in addition to, males worth more than 6 shillings from the surrounding parishes. A higher ratio of male to female skeletons recovered during excavation of the Cathedral Close lends support to this practice (Boucher *et al.* 2015).

The burial monopoly was weakened during the 14th century when Mabel le Rous, the widow of John le Rous, the lord of the manor of Allensmore, appealed to the Court of Canterbury due to the treatment of her husband's remains. An attempt by Bishop Orleton to reconsecrate the parochial churchyard of Allensmore, southwest of Hereford, on 27th March AD1318 was denied by the dean and chapter, who asserted that only children and paupers could be buried there in order to preserve the cathedral's burial monopoly. Despite this, it had been reported in AD1346 that individuals had been buried there who were not women or paupers and, as a result, it was recommended by Bishop John Trellick that these illegally buried bodies be exhumed. This included the remains of John le Rous. Following Mabel le Rous' appeal, the Court of Canterbury decreed that burial would be permitted at Allensmore but that any mortuary fees would still be due to the cathedral. The monopoly was further relaxed during and following the Black Death due to overcrowding of the cathedral burial grounds, likely represented by the mass graves in the western portion of the Mappa Mundi excavation area (Figure 32). Local parochial burial became more common during this period. Local burial concretised the community of the living and the dead, who were bound together by the spiritual economics of purgatory. The physical remains were proximate to the prayers of, and pious donations to, the local church (Forrest 2010). All burials were suspended within the Cathedral Close from the 25th March AD1791 unless the individual died within the precinct of the cathedral, such as members of the clergy (Boucher *et al.* 2015).

Archaeological evidence suggested that industrial activity at the Cathedral Close had ended by the 12th century (Boucher *et al.* 2015). Evidence of intensive ironworking dating from the 10th-12th centuries was uncovered during excavations of the Cathedral Close in 2009-11. The Domesday Book recorded the dues paid by the smiths of Hereford and attests to the scale of the industry within the city. During the Mediaeval period, Hereford was synonymous with wool production. Several fulling mills were located along the River Wye and wool processing was also performed as a cottage industry. Wool production had declined in Hereford by the 17th century as key centres for production emerged in northern England (Boucher *et al.* 2015).

Macrobotanical remains indicate the principal cereals consumed within the city. In the 12th century, barley was the chief cereal crop consumed and was supplement by oats. Other cereals such as wheat were also grown (Table 17). Charred grains of clean barley were recovered during the Mappa Mundi 1993 excavation. Barley would have been primarily consumed in the form of gruel or soup, rather than bread, or used for brewing (Stone and Appleton-Fox 1996). A deposit of charred material from Bennington Street dating to the late 11th to 12th centuries was composed of 90% wheat with very few weed seeds or contaminants present (Williams 1985). It is possible that the millstones that were used in Hereford during the Mediaeval period were made of Welsh stone, although manorial records for this region are inadequate (Farmer 1992). At nearby Worcester, a mediaeval barrel latrine radiocarbon dated to AD1440±70 years, yielded numerous tiny bran fragments and cereal pollen attesting to the importance of cereal cultivation and consumption in the region. The beetle remains recovered indicated the presence of broad beans and potentially infested grain stores. Fruit pips attested to the consumption of fruits including strawberry, apple and grapes (Greig 1981).

Fishbones and shellfish were abundant at the Mappa Mundi 1993 excavation indicating that fish formed an important dietary component. Freshwater fish were likely caught from the River Wye and used as a substitute for meat on fast days (Stone and Appleton-Fox 1996). Eel and carp bones were recovered from the Worcester mediaeval barrel latrine and were likely caught locally in the River Severn and tributaries (Greig 1981). The majority of animal bones recovered were derived from cattle. The recovery of immature animals may indicate deliberate slaughter for meat and the low number of bone fragments recovered per individual may indicate the introduction of retail butchery, in which smaller portions of meat were being sold (Noddle 1985).

Isotopic analysis of 20 individuals from the Cathedral Close yielded $\delta^{15}N$ values lower than those of individuals from contemporary Yorkshire and Cheshire suggesting a lower consumption of foods from higher trophic levels. This is unexpected given the location of Hereford on the River Wye, which would have likely facilitated access to abundant fish. $\delta^{13}C$ values were consistent with other contemporary mediaeval sites indicating a largely terrestrial diet. An absence of an appropriate isotopic baseline for the Hereford region limits the comparisons that can be made. High levels of variability in δ15N values in the individuals sampled may indicate variability in the quantities of meat and fish consumed by individuals interred at the Close, consistent with the range of social classes buried at the cemetery (Halldórsdóttir *et al.* 2019).

Radiocarbon dating was applied to intercutting burials from the later 2009-2011 phase of excavation at Hereford Cathedral to assist with the dating of inhumations. Seven out of thirteen of the burials were dated firmly to the 13th century, however, two of the final burials dated to the15th-17th centuries. Strontium and oxygen isotope analysis of the enamel of 24 individuals from the assemblage dating from the early 12th to the mid-13th century indicated that several individuals were of non-local origin. Strontium isotope ratios suggested that four of the men came from areas characterised by granites and Palaeozoic rocks, such as northern and western Britain, whereas three other men exhibited ratios consistent with a chalk and limestone geology, such as southern and central England or Normandy (Boucher *et al.* 2015). This supports the existence of migration to Hereford although it is not possible to judge the scale of it. By AD1285, the rights and privileges of widows and eldest draughts of freemen of Hereford gave anyone marrying them the right to elect a member of parliament potentially encouraging movement to the city (Boucher *et al.* 2015).

Table 17: Dietary profile of the assemblage from Hereford Cathedral.

Site	**Hereford Cathedral**
Dietary Staples	Barley, wheat, rye, oats, broad beans and peas consumed as porridges and loaves. Potentially large amounts of bran retained in cereal foods consumed.
Dietary Supplements	Vegetables (Onions and leeks) grown on plots within city Marine and estuarine protein (Ling, herring and eel) Animal protein (Beef, pork and mutton) depending on social status. Isotopic evidence may indicate individuals from mediaeval Hereford sampled consumed smaller quantities of higher trophic level foods that those from York.
Milling Technology	Grinding performed in water and windmills using stones probably of Welsh stone.
Social Status	Civilians of variable social status drawn from within the city and surrounding local parishes. The burial monopoly of the cathedral meant that all social classes were interred at the Close who lived within the city wall during the mediaeval period. High dietary variability supported by isotopic data.
Sex differences	Isotopic values were not significantly different between males and females although males had slightly higher mean values for δ15N and δ13C.

5.1.2.1.1.4 Blackfriars, Gloucester (BF)

The assemblage from Blackfriars, Gloucester (Figure 29), was excavated from a trench, 20m by 2.5m, situated in the southern end of the Ladybellegate Street Car Park, between Southgate Street and Longsmith Street, adjacent to the standing monument of Blackfriars (Figure 33). The Dominican Friary (Blackfriars) was established in Gloucester in AD1239 at the behest of Henry III and Stephen de Herneshull (Palmer 1892). Three orders of friars had houses in Gloucester and were known for the relative poverty of their lifestyles (Holt 1985). They were especially impoverished prior to the dissolution. Alms and donations were frequently supplied to the friary to pay for food, including donations from the King (Palmer 1892). The Priory was sold to Thomas Bell for the sum of £240 5 shillings and 4 pence on July 21st AD1539 following the dissolution of the monasteries, after which the Friary burial ground would not have been used (Palmer 1892; Atkin 1992).

The land east of the Friary was utilised as the Friary burial ground with its first documented use in AD1246 when it was expanded. The cemetery was included in the excavation area. The remains of some 140 burials were recovered from the excavation trench, however, ground probing radar indicated that the overall cemetery assemblage may comprise upwards of 2000 individuals. The burials included the friars themselves, including a priest with his pewter chalice and paten, in addition to women and high numbers of infants and children. This suggests that benefactors to the Friary and their families were also interred in the burial ground. Furthermore, it is possible that the friars may have operated a hospital at least until the late 15th century and hospital patients may have been buried at the Friary. By the end of the 14th century, the graves were packed closely together and frequently disturbed earlier burials. (Atkin 1992).

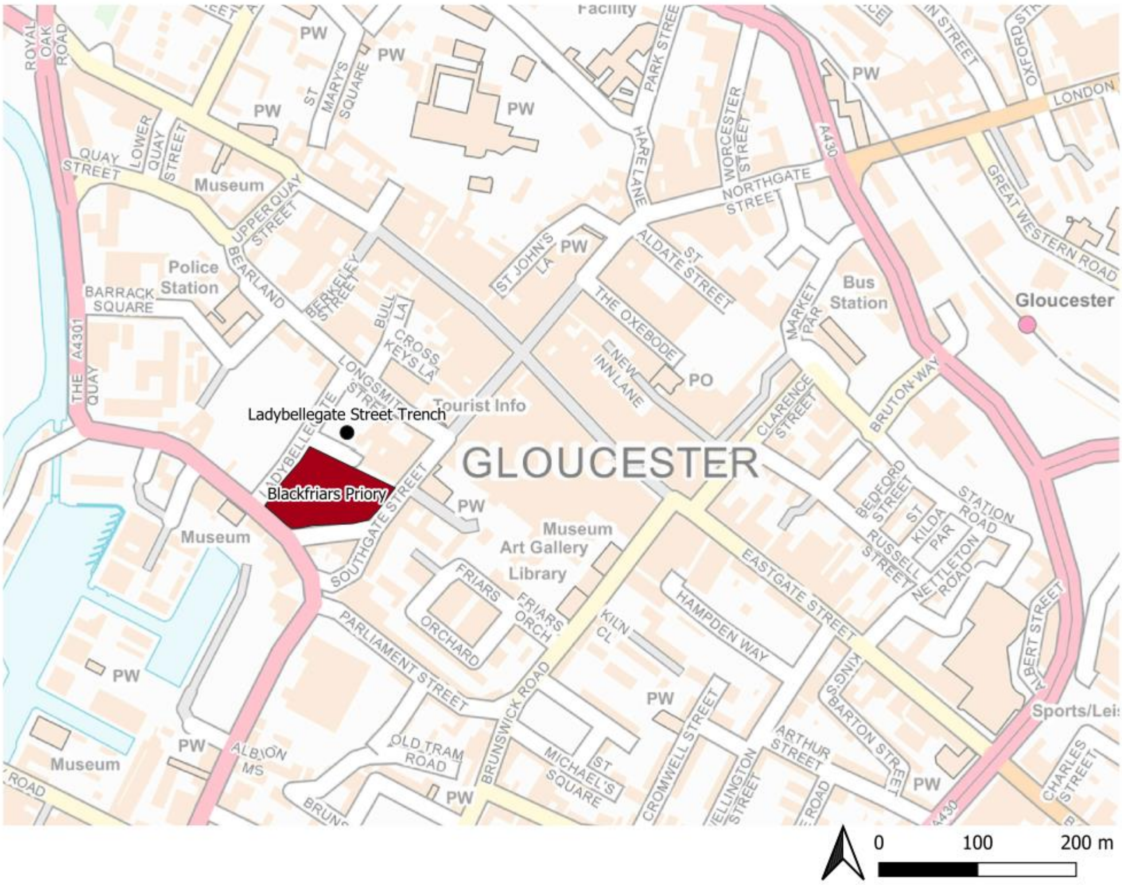


Figure 33: Map showing the location of the Ladybellegate Street Excavation trench excavated in 1991 adjacent to the Blackfriars Priory, Gloucester. Contains OS data © Crown copyright and database right 2021.

During the Mediaeval period, Gloucester was a middle-ranking town located in the west of England on the River Severn (Holt 1985). It was founded as a Roman *colonia* in AD96-98. It later developed in extent and population size from the 10th century until the 15th century following the construction of a royal palace at

Kingsholm (Atkin 1992). Poll tax records from AD1377 indicate that 2239 taxpayers were present in Gloucester compared to around 7000 in York. Gloucester functioned as an inland port on the River Severn during this period whilst Bristol dealt with seaborne trade. As the lowest bridging point on the river, Gloucester also served as an important market and distributive centre. Wool from the Cotswolds and iron from the Forest of Dean passed through Gloucester port and market. Records of credit relationships indicate that Hereford and Gloucester were closely associated as part of a distribution network across the west of England. The Severn Valley was a rich grain producing area and quantities of bread and ale were frequently brought to the town by rural merchants and villagers; grain was typically wheat and barley (Holt 1985).

Charred cereal remains recovered from features associated with a mediaeval field system in Gloucestershire, dated to the 12th century, support the local cultivation of free-threshing bread wheats, likely as the principal cereal crop, alongside supplementary barley, oats and rye. The small quantities of rye recovered suggested that this formed only a minor component of the crops cultivated (Longman 2005). Millstones recovered during the excavation of Bishop's Cleeve, Gloucestershire, were composed of Upper Old Red Sandstone quartz conglomerate. May Hill Sandstone appeared to increase in popularity during the Mediaeval period (Enright and Watts 2002).

The affluent inhabitants of Gloucester had access to sea fish as well as salmon, eels, shad and lampreys from the Severn. A Gloucester lamprey could cost as much as 10 shillings in Lent, 6 to 8 times the weekly wages of a labouring man, so such fish would have supplied noble households (Holt 1985). The friar-preachers had access to a garden for producing fruit and vegetables to supplement a diet comprised chiefly of cereals (Palmer 1892).

Strontium and oxygen isotope data obtained from dental enamel, derived from three individuals from the Blackfriars cemetery dating from the 12th to the 16th century, indicated that some of the individuals interred at the cemetery originated from different places in Britain. Two individuals appeared to come from the west of Gloucester and the third individual from the north east of Britain (Budd *et al.* 2004).

Table 18: Dietary profile of Blackfriars, Gloucester.

Site	**Blackfriars, Gloucester**
Dietary Staples	Wheats, rye, oats, broad beans, peas and barley consumed as porridges and loaves. Wheat appeared the predominant cereal crop in the region based on archaeobotanical remains.
Dietary Supplements	Fruit and vegetables grown in the friary. Marine and estuarine protein (Ling, herring and eel) Animal protein (Beef, pork and mutton) depending on social status. No dietary isotopic evidence available.
Milling Technology	Grinding performed in water and windmills using stones probably derived from Wales, such as May Hill sandstone.
Social Status	Highly variable. Friars may have practiced relatively abstemious dietary regime with little meat. Benefactors of the friary may have consumed greater quantities of fish and meat. If the friary functioned as a hospital, inmates may have been of highly variable social status.
Sex differences	Little historical or archaeological evidence.

5.1.2.1.1.5 St James and St Mary Magdalene, Chichester (CH86)

The assemblage was derived from the excavation of the cemetery associated with the mediaeval leprosarium and later post-mediaeval almshouse of St James and St Mary Magdalene, Chichester (Figure 34). The site was situated approximately 700m to the Northeast of the St Michael's Litten excavation area (ESC11) along St Pancras (Figure 35). This assemblage was selected to provide an opportunity to assess whether OFA could identify dietary differences within the context of a single cemetery assemblage. There is historical and archaeological evidence to indicate that individuals suffering from leprosy may have been prescribed a diet consistent with medieval medical theory (Rawcliffe 2006; see section 2.2.1.6). In addition, the situation of this cemetery within Chichester, alongside the temporally later St Michael's Litten assemblage, enabled a focus on diet within the town through time.

Figure 34: Map showing the locations of St Bride's Church, St Michael's Litten and St James and St Mary Magdalene assemblages in relation to London, Chichester and Portsmouth. Contains OS data © Crown copyright and database right 2021.

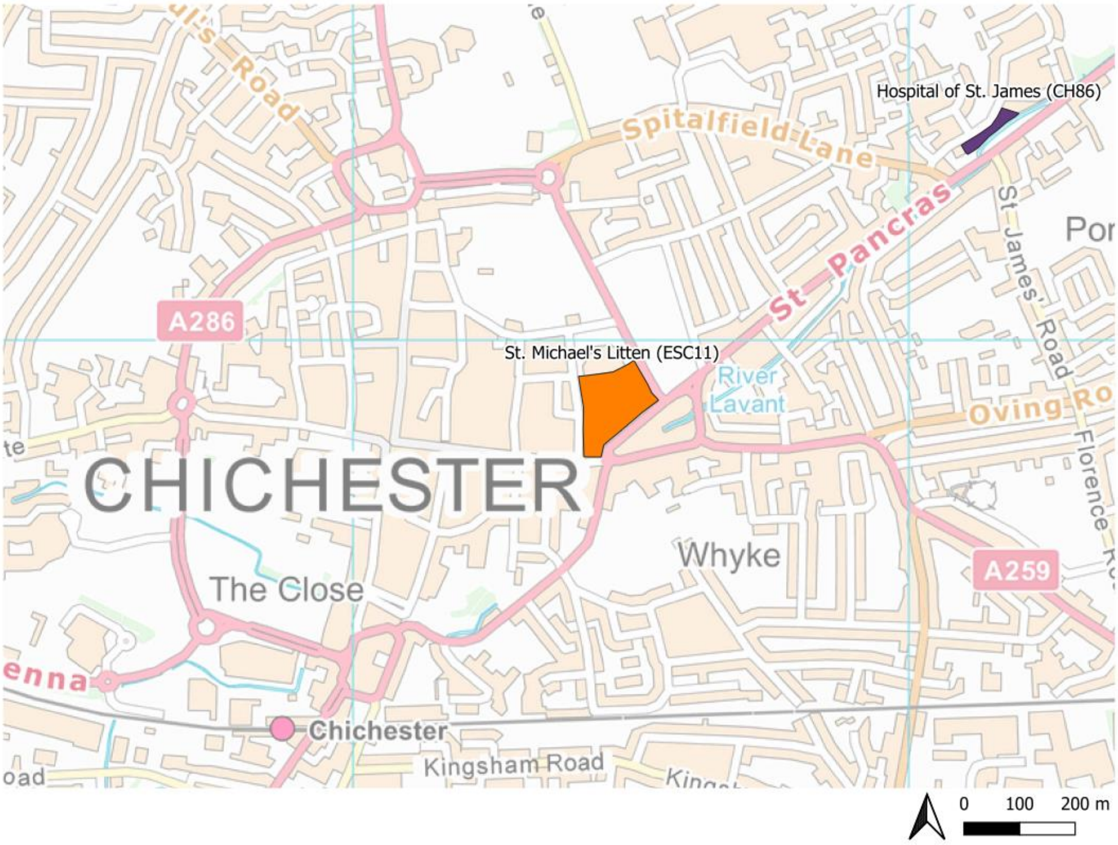


Figure 35: Map of Chichester showing the location of St Michael's Litten (ESC11) at Eastgate square (shown in orange) and the location of the Hospital of St James and St Mary Magdalene (CH86) east of the centre of Chichester along St Pancras road (shown in purple). Contains OS data © Crown copyright and database right 2021.

The assemblage comprised 285 adult individuals of whom 84 showed osseous changes consistent with lepromatous leprosy (Magilton *et al.* 2008). Individuals with leprosy and males were concentrated in the south western portion of the excavation area (Area A) whilst females, subadults and non-leprous individuals became more frequent in Area B (Figure 36 and Figure 37; Table 19). The large number of indeterminate individuals in Area B was due to the frequency of subadult individuals in that area. Individuals included in the current study were identified as having lepromatous leprosy if they presented osseous changes consistent with rhinomaxillary syndrome (Table 20). Waldron (2007) regarded rhinomaxillary syndrome as pathognomonic of lepromatous leprosy. Associated changes include:

- resorption of the alveolar process in the centre of the maxilla with eventual loss of the central incisors.
- destruction of the anterior nasal spine.

- pitting on and eventual destruction of the nasal conchae
- resorption of the nasal septum.
- pitting on the palatine process of the maxilla.
- resorption and remodelling of the margins of the nasal aperture.

Table 19: Distribution of sexes (Male (M), Female (F) or Indeterminate (?)) among the two cemetery areas of St James and St Mary Magdalene, Chichester (CH86).

	Area A			Area B		
Sex	**M**	**F**	**?**	**M**	**F**	**?**
N	102	14	10	88	67	103
Percentage of Total	26.56%	3.64	2.60	22.91	17.44	26.82

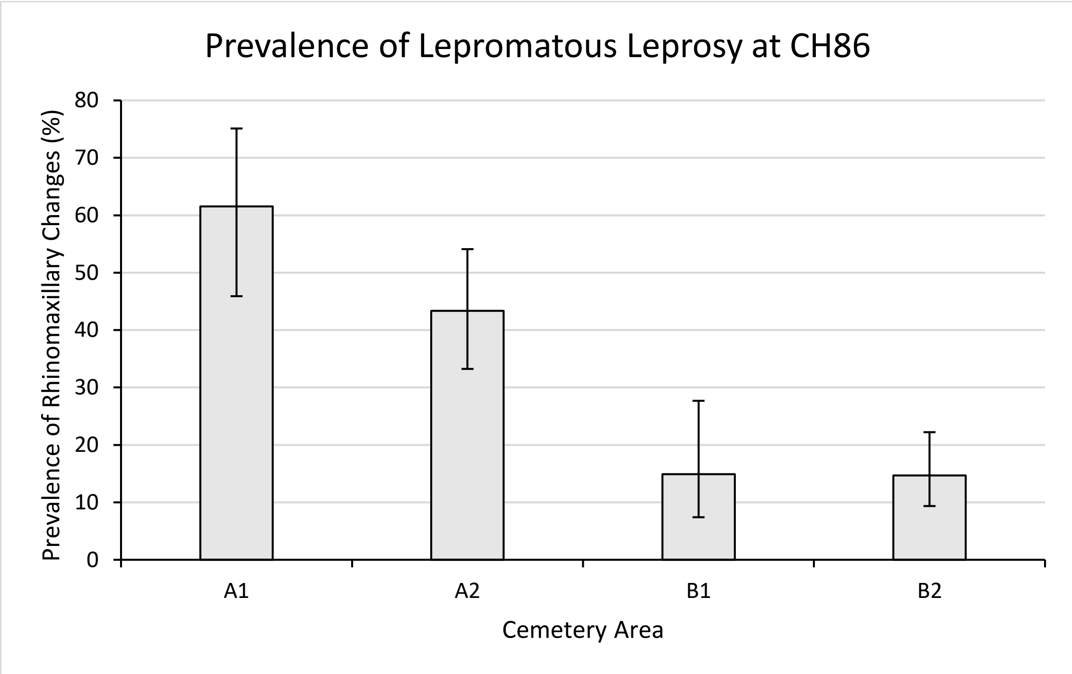


Figure 36: Bar chart showing the prevalence of skeletal changes consistent with lepromatous leprosy in each of the cemetery areas excavated associated with the leprosarium and later almshouse of St James and St Mary Magdalene, Chichester (CH86). 95% confidence intervals for the prevalence rates are shown.

Table 20: Prevalence of lepromatous leprosy among the individuals included in the current project from the St James and St Mary Magdalene assemblage. Lepromatous leprosy was identified using the operational definition of Waldron (2007). 95% confidence intervals are given for the prevalence values.

Lepromatous Leprosy	**Area A**		**Area B**	
	N	**Prevalence**	**N**	**Prevalence**
Absent	3	75%	9	25%
Present	9	43 to 95%	3	5 to 57%

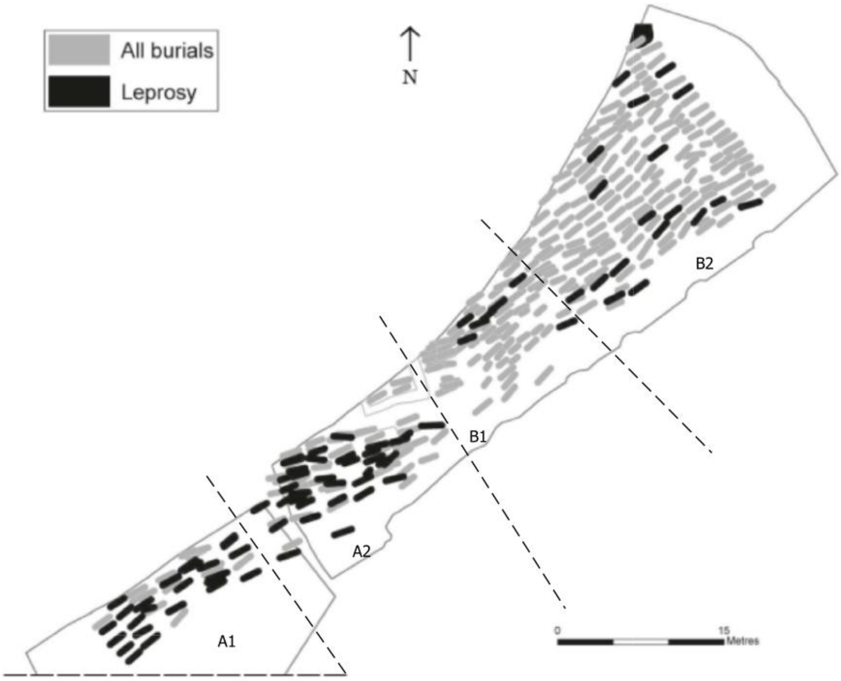


Figure 37: Map showing the distribution of burials with leprosy across the excavation area of St James and St Mary Magdalene leprosarium, Chichester. The dashed lines demarcate the divisions between the different areas of the cemetery: A1, A2, B1 and B2. Figure modified from Magilton et al. 2008 (Modified from Fig. 7.20; page 105).

The hospital was probably founded some time before AD1118 when the land on which it was constructed was administered by the cathedral and was intended to house eight leper brethren. The *leprosarium* of St James and St Mary Magdalene is referred to as the only hospital in Sussex for lepers in the AD1200 *Mappa Mundi* ascribed to Gervase of Canterbury (Magilton *et al.* 2008). During the 14th and 15th centuries, numerous historical records exist for bequests and offerings to the institution; the inhabitants of which are frequently referred to as 'the poor' of St James perhaps suggesting a shift in function to an almshouse during this period. During this period, the leprosarium was likely an all-male institution. The final documentary reference to leper inmates is the AD1418 will of William Neel of Chichester who left 6 shillings to the lepers of St James (Magilton *et al.* 2008). The exact date of admittance of the first women to the institution is uncertain, however, John Cressweller in AD1527 left 2 pence to every brother and sister of St James indicating their admittance by this date. By the end of the 17th century, the almshouse was in decline and noted for having only a single poor female inhabitant remaining (Turner 1861).

The burials, therefore, probably span the early 12th to the late 17th century. The south-western portion of the cemetery were mostly male with changes compatible with leprosy in 61.5% of individuals. The number of individuals displaying changes consistent with lepromatous leprosy was reduced to 15% in the north eastern parts of the cemetery (Area B2; Figure 37). If leprosy is taken as an indicator of the chronology of burials at the cemetery, the earliest burials were in the south western area and the most recent in the north eastern area (Magilton *et al.* 2008).

A previous study of this assemblage (Magilton *et al.* 2008) and a study of the assemblage associated with the *leprosarium* of St Mary Magdalene at Winchester (Roffey *et al.* 2017) found copious dental calculus among several individuals with lepromatous leprosy. This has been attributed to poor oral hygiene and potentially a soft and pulpy hospital diet. The isotopic values of individuals from the *leprosarium* of St Mary Magdalene, Winchester, were consistent with the monastery of Hyde Abbey, Winchester, suggesting it may have been typical for lepers at *leprosaria* to consume diets similar in composition to monastic institutions (Roffey *et al.* 2017). In the Mediaeval period, leprosy was regarded as an imbalance of bodily humours and, therefore, dietary measures were encouraged to restore humoral balance. Lepers were encouraged to eat foodstuffs that were mild and moist, such as eggs, poultry, good pork and fresh fish which could be easily digested and cool the overheated digestive system. Leprosaria often had fishing rights and reared dairy cattle, pigs and hens making it possible for the appropriate diet to be provided (Brenner 2010).

The *leprosarium* derived income and supplies from farms, such as the Broyle in AD1407 (Magilton *et al.* 2008). Treatments often prescribed the consumption of meat and milk; therefore, higher rates of meat consumption might be anticipated among the leprous portion of the cemetery. Following the decline in leprosy from the 15th century onward (Manchester and Roberts 1989) and the change in function of the institution to an almshouse, it is expected that the diets consumed by the inmates would be less rich in meat and more closely resemble the grain rich and meat poor diets of the majority of people from the late Mediaeval and early Post-Mediaeval periods (Stone 2006). The material benefits awarded to the occupants of almshouses were highly variable and largely depended upon the generosity of any stipends given to them for living expenses as the majority of almshouses did not provide full board. Meat and dairy products would have frequently been foregone in times of financial shortfall (Nicholls 2017).

In the 1250s Chichester was named as a potential source of French millstones by the bishop of Winchester, who had several demesne mills during the period. The local production of flour may have been performed using these French millstones but it is possible that Chichester was principally involved in the import of these stones rather than in their use (Farmer 1992).

Table 21: Dietary profile of the assemblage from St James and St Mary Magdalene Leprosarium and almshouse, Chichester

Site	St James and St Mary Magdalene, Chichester
Dietary Staples	Leprosarium: Potentially a soft and pulpy diet mainly of pottages and broth. Early modern almshouse: Wheats, rye, oats, broad beans, peas and barley consumed as pottage and loaves. Potentially large amounts of bran retained in cereal foods consumed.
Dietary Supplements	Leprosarium: Eggs, poultry, good pork, dairy products and fresh fish if diet corresponded to that recommended by mediaeval medical theory. Almshouse: Vegetables (Onions and leeks) grown on plots associated with the almshouse. Marine and estuarine protein (Eel, oysters and molluscs). Limited meat.
Milling Technology	Many millstones were obtained from Chichester during the mediaeval period and would have included expensive French stone (Farmer 1992). Grinding performed in water and windmills using stones probably of Welsh stone or perhaps French stone where they could be afforded.
Social Status	Lepers were of variable social status; however, the main contrast is likely between the later poor and the earlier individuals with lepromatous leprosy. Affluent members of mediaeval society would occasionally seek to be buried alongside lepers as it was believed that lepers underwent purgatory and suffering on earth easing their journey to heaven (Magilton *et al.* 2008).
Sex differences	Few females were interred during the early period of use of the cemetery; therefore, sex differences may relate to chronological changes in the diets consumed by individuals at the site (Magilton *et al.* 2008).

5.1.2.1.2 Mediaeval and Post-Mediaeval periods (AD1100-1900)

5.1.2.1.2.1 St Michael’s Litten, Chichester (ESC11)

The assemblage, largely dating to the Post-mediaeval period (16-19th centuries), was derived from an excavation of Eastgate square, Chichester (Figure 34 and Figure 35), conducted by Archaeology South East from August 2011 to January 2012. Two previous phases of archaeological evaluation had indicated the presence of a mediaeval and post-mediaeval cemetery at the site referred to as St Michael’s Litten, or The Litten. The cemetery was estimated to have been in use from AD1100–1850, however, the majority of burials excavated date from the 17th-19th centuries. A total of 1,730 skeletons were encountered, of which 420 were retained at the Institute of Archaeology, University College London (Hart 2012).

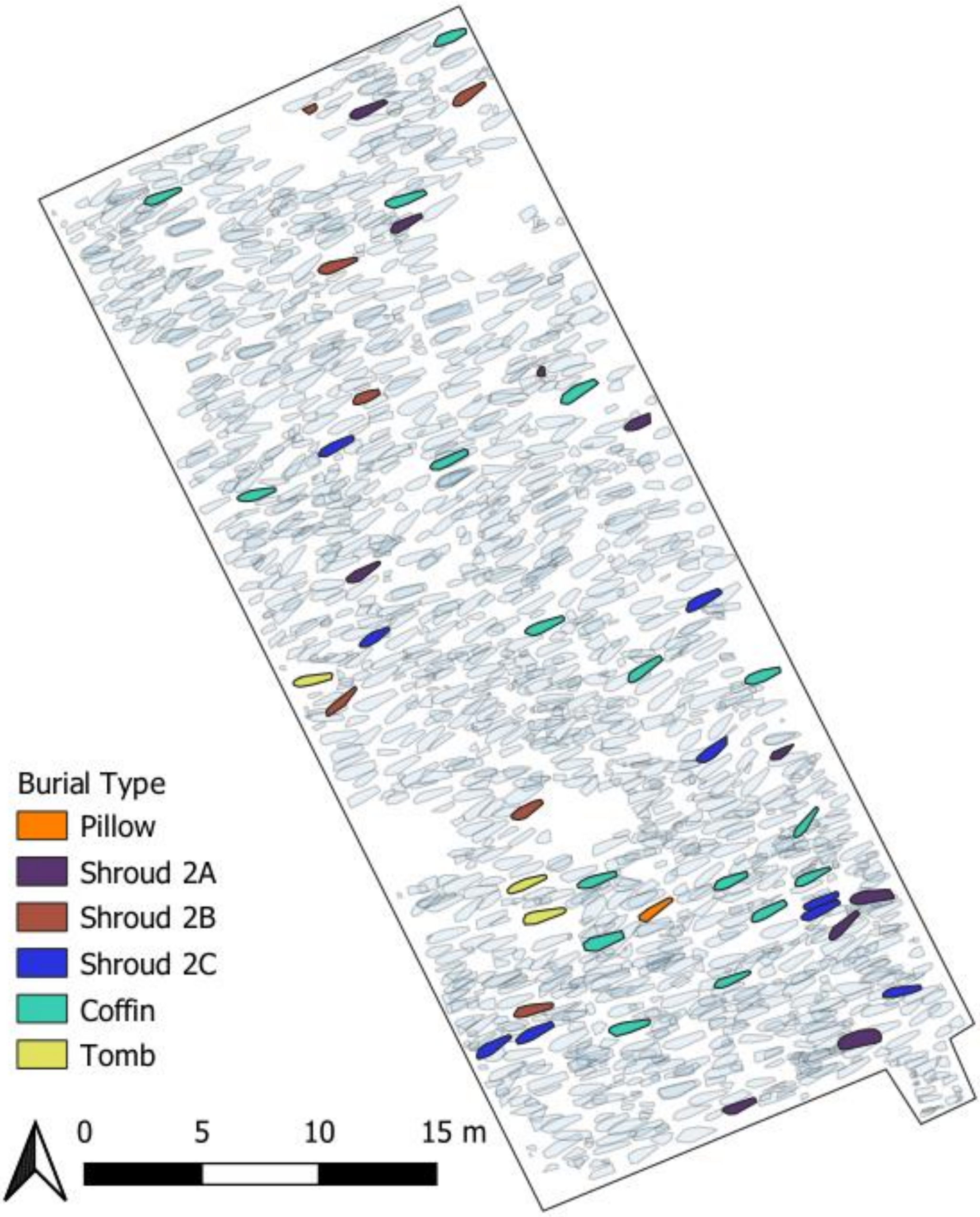


Figure 38: Locations of the skeletons examined in the current research in the St Michael's Litten cemetery excavation area, Chichester (ESC11). The legend entries for burial type are presented in chronological order. The single pillow burial dates to the Mediaeval period (10-12th century), shroud 2a and 2b to the Mediaeval and Early Post-Mediaeval periods, the majority of shroud 2c burials to the 18-19th centuries, coffined and tomb burials to 18th-19th century.

Seven burial types were identified at the cemetery and four of these were included in the current research (Figure 38; Table 22):

- Pillow burials, with an arrangement of unmodified locally available greenstone or limestone cobbles placed around the head, were associated with the Mediaeval period (dated from the 10th-12th centuries). A single individual of this burial type satisfied the inclusion criteria.

- Uncoffined simple shroud burials were the most common across the excavated area and were ubiquitous in both the Mediaeval and Post-Mediaeval periods making the chronological sequencing of these burials challenging. Three main types of shroud burial were encountered based on the positioning of the arms and hands (Table 22). Shroud 2c burials were chiefly aligned with the well-defined rows of 18th-19th century coffined burials, whereas, shroud 2a and 2b burials largely were not. In the current analysis, the shroud burials, therefore, were divided into an early and a late phase according to the positioning of the body. Shroud 2a and 2b burials were attributed to the Mediaeval and early Post-Mediaeval periods and shroud 2c burials to the Industrial era. A degree of uncertainty remains, however, without further spatial analysis being undertaken (Hart 2012).
- Coffin burials were predominately aligned on an ENE-WSW axis forming distinct rows. All the associated iron coffin furniture recovered was heavily corroded but dated the burials to the 18th-19th centuries.
- A total of 29 brick tombs were excavated across the site. These were also aligned with the rows of coffined inhumations and were dated to the 18th-19th centuries using coffin furniture. Several of the tombs included multiple stacked inhumations suggesting repeated use of the same plot likely by a single family. None of the individuals included in the current study were associated with a coffin plate so could not be named (Hart 2012). The coffined and tomb burials were included in the Industrial period assemblage in the final analysis (Table 21).

Table 22: Table showing the dates and distribution of burial types included in the current research from St Michael's Litten, Chichester.

Burial Type	Date range estimate	Total Number Excavated	Number Included in Current Project	Burial Position	Period grouped in
Pillow	900-1100	13	1	Pillow burials, where stones are placed around the head	Mediaeval and Early Post-mediaeval
Shroud 2A	1100-1700	357	9	Uncoffined; arms crossed over the abdomen	Mediaeval and Early Post-mediaeval
Shroud 2B	1100-1700	174	8	Uncoffined; hands placed over the pelvis	Mediaeval and Early Post-mediaeval
Shroud 2C	1700-1900 (Mainly)	242	9	Uncoffined; arms placed by the sides of the skeleton	Industrial
Coffin	1700-1900	288	16	Coffined interments dated using coffin furniture	Industrial
Tomb	1700-1900	55	3	Coffined interments within brick-built tombs	Industrial

Chichester shifted from an economic dependence on wool to grain, typically wheat, barley and oats, in the 16th century (Morgan 1992). In the 18th century, commerce shifted from Chichester to other ports. Industry, such as needle making, and the trade in corn declined (Ballard 1898). The population of the town doubled from 2400 to 4752 people between 1670 and 1801 (Reger 1996).

The majority of Chichester's less affluent inhabitants likely consumed a diet dominated by wheat, barley and oats, which would have been available for purchase at the weekly corn market (Table 23) (Green 2011; Stone 2006). Chichester was known for its thriving beast market as well as commercial fishing activities providing animal protein. A comparison of carbon and nitrogen stable isotopes between burial types (n=40) found significant differences between tomb and coffin burials and tomb and shroud burials. The greatest δ15N values were associated with tomb burials. This may indicate slightly higher consumption of animal protein by higher status individuals buried in tombs. The relatively higher δ15N values for shroud burials may indicate the use of freely available resources found at Chichester Harbour such as molluscs and oysters (Dhaliwal *et al.* 2020).

The isotopic results generally indicated that the people of post-mediaeval Chichester ate primarily C3 plants and terrestrial fauna that also fed on these plants. Marine protein was likely not the primary source of protein based on the carbon and nitrogen isotope data. It is possible that the observed values indicate the consumption of omnivores, such as pig, as a dominant terrestrial meat source. This is consistent with historical evidence that there was a focus on the consumption of freshwater riverine species (such as eel) as well as pigs for dietary protein in Chichester. There were no significant differences between the isotopic profiles of the sexes. The isotopic study was, however, limited by the lack of a comparative isotopic baseline for local fauna (Dhaliwal *et al.* 2020). In the nearby parish of Portsmouth, the diet of the typical labourer was primarily constituted by bread, a little cheese and tea. Milk was not available, and meat was provided once per week (Eden 1795).

Table 23: Dietary profile of St Michael's Litten assemblage, Chichester (ESC11)

Site	St Michael's Litten, Chichester
Dietary Staples	Cereals: Wheat, barley and oats
Dietary Supplements	Meat available at local beast market (particularly pigs) Freshwater riverine species (eel, molluscs and oysters)
Milling Technology	Many millstones were obtained from Chichester during the Mediaeval period and would have included expensive French stone (Farmer 1992). Grinding performed in water and windmills using stones probably of Welsh stone or perhaps French stone where they could be afforded.
Social Status	Isotopic data indicated that tomb burials had greater access to regular meat (both marine and terrestrial protein) than coffin and shroud burials indicating higher social status.
Sex differences	No isotopic evidence to support sex differences in diet consumed.

5.1.2.1.3 Industrial Period (18th-19th Century)

5.1.2.1.3.1 St Bride’s Church, Fleet Street (SB79)

St Bride’s was probably first established in the 5th century AD shortly after the Roman occupation of Britian and was later referred to in a grant from Henry II (AD1133-1189) to the Templars (Figure 34 and Figure 39). The church was destroyed in the Great Fire of London (AD1666) and then rebuilt by Christopher Wren. The building was again heavily damaged in an air raid on the 29th December 1940 and left ruined. Following the damage inflicted upon the church, the opportunity was taken to excavate the lower stratigraphic layers of the church site, which revealed a mosaic pavement and possible Roman villa. Seven sealed vaults were encountered during the excavation containing the charnel remains of thousands of individuals. In addition, 227 skeletons and coffins had to be moved to reach the Roman material. These individuals, who were accompanied by lead coffin plates giving name, age and date of death, were retained for future research. The first individual was born in AD1696 and the last in AD1852 (Harvey 1968). This assemblage of known-age and sex individuals, dating from the 18th-19th centuries, formed an important part of the Industrial-era assemblage included in the current research. Thirty-one individuals satisfied the inclusion criteria. Their average age at death was 40.74 years and ranged from 18 to 77. The average date of death was AD1818.

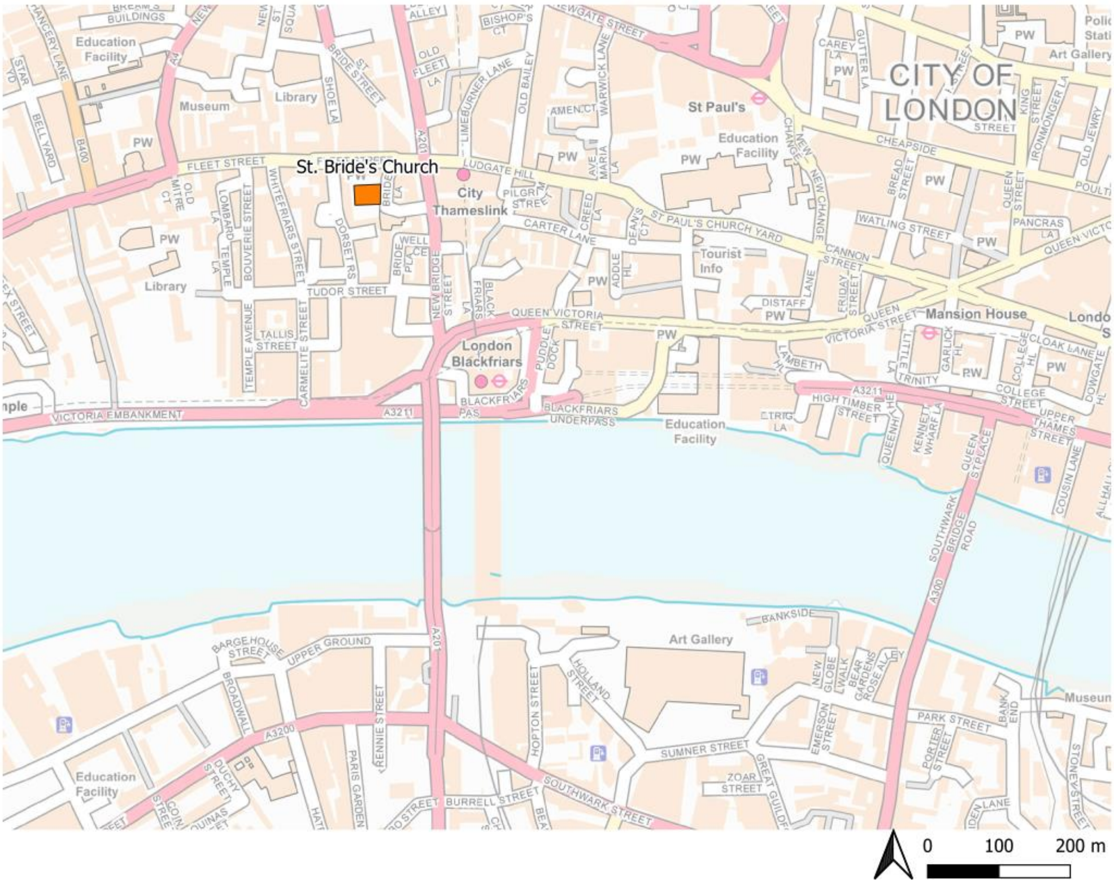


Figure 39: Map showing the location of St Bride's Church, Fleet Street, from which skeletal material from the crypt was examined dating from the 18th-19th centuries. Contains OS data © Crown copyright and database right 2021.

A large proportion of the individuals interred at St Bride's were likely workers involved in trade and crafts along the Thames but burial records indicate that the status of the individuals interred varied greatly, ranging from the lord mayor to individuals in poverty. Qualification for burial at St Bride's church may have principally depended on location rather than social status (Harvey 1968). Eight individuals were classified as of higher social status because their name was accompanied by a title such as Esquire, Sir or Right Honourable. A high level of dietary variability can, therefore, be anticipated (Table 24). The diet of the poorer individuals interred at St Bride's is indicated by that of the workhouse in the nearby parish of St Martin's in the Fields; the majority of meals comprised bread and butter, with occasional cheese, or milk-porridge (Eden 1795). In contrast, the budgets of the expanding middle classes would have allowed for daily meat consumption (Burnett 1989). The preference for white wheaten bread, containing relatively little bran, was well-established in 18th and 19th century London (Fay 1923; Collins 1975).

Table 24: Dietary profile of St Bride's church, London, assemblage.

Site	St Bride's Church, London
Dietary Staples	White wheaten bread
Dietary Supplements	Meat and fish available depending on household income Occasional butter, milk, cheese. Sugar consumed in tea or as treacle spread on bread
Milling Technology	Grinding was performed in large scale water powered and steam powered mills, such as the urban flour mill in Barking (Haslam 2011).
Social Status	High variability in the social status of individuals interred at the crypt
Sex differences	Limited historical and archaeological evidence

5.1.2.1.3.2 Coronation Street, South Shields (CS06)

The assemblage from Coronation Street, South Shields, was excavated by Oxford Archaeology North in 2006 during the construction of a supermarket. Coronation Street itself was built in the 1970s and cuts across the southern portion of a cemetery associated with the Church of St Hilda (Figure 26 and Figure 40). The excavation comprised a main trench to the south of Coronation Street and a narrow trench necessary for the redirection of the sewer main.

The main trench showed a phase of pre-burial activity, involving several dumping layers, a ditch and the accumulation of material by the Mill Dam. This was followed by three distinct phases of post-mediaeval burial activity: a phase pre-dating the raising of the burial ground in AD1816-18, an intermediate phase of burial associated with the raising of the burial ground and a later phase of burials dating from AD1818-1860. Most of the individuals included in the current study dated to the last phase of burials (n=19 of 25).

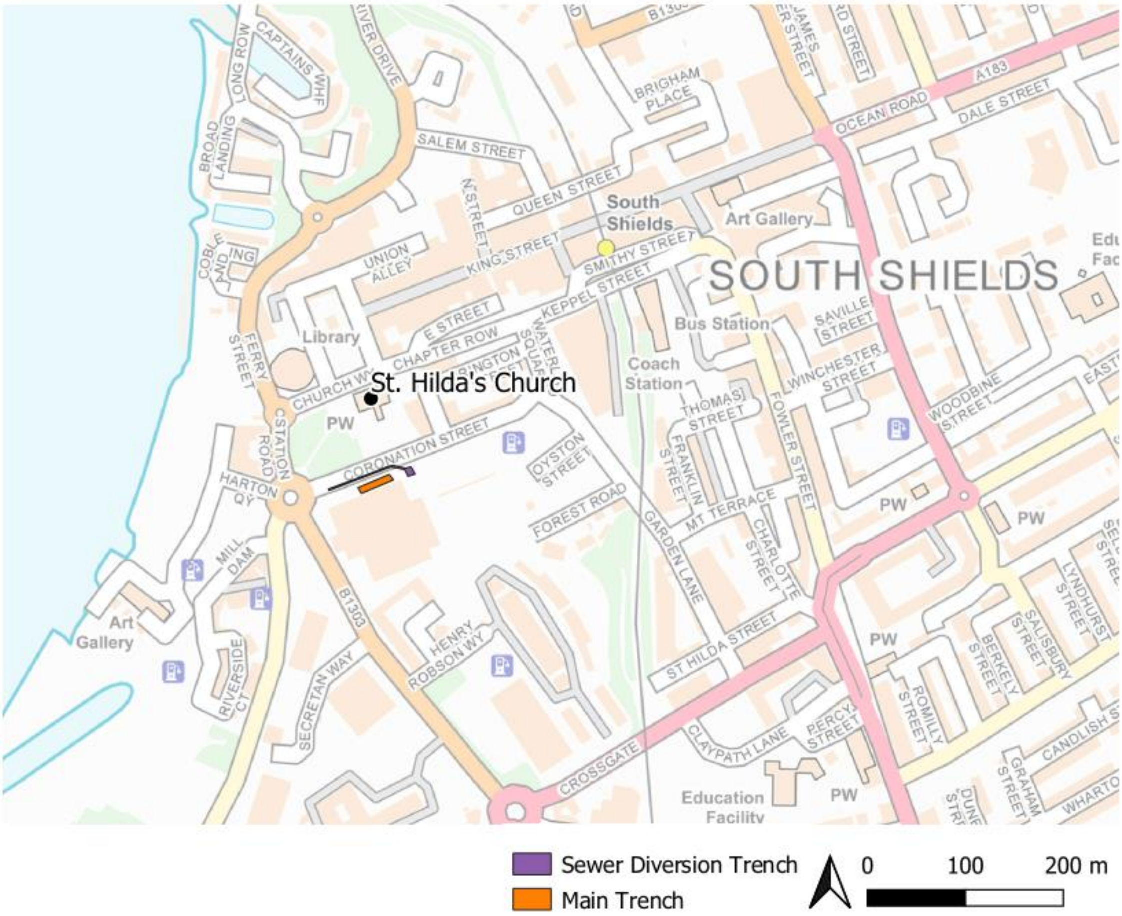


Figure 40: Map showing the location of the areas of excavation from which the skeletal material from Coronation Street were derived (purple and orange). The assemblage was associated with the church of St Hilda. Contains OS data © Crown copyright and database right 2021.

A portion of the lower horizon of burials included many pre-term and perinatal infants and may have lain outside the original cemetery boundary. 87 well-preserved subadults were excavated of whom 54 were neonate or preterm. Perhaps it was the area used for the burial of unbaptised infants outside of consecrated ground. Many of the burials provided evidence for coffins and there was limited evidence for the intercutting of graves. In the final phase of burial activity, grave cuts could not be identified as the deposits were highly disturbed and heterogenous. 126 burial events were distributed among 31 plots in the main trench whereas in the sewer trench 48 burials were found across 30 plots. The close spacing of skeletons within each plot suggested a rapid phase of successive interments with some skeletons located directly on top of each other likely due to the formation of voids as successive coffins rotted away. The presence of charnel material attested to the frequent disturbance of early grave cuts. 117 adult skeletons were excavated of which 52 were probably female, 51 were likely male and 14 remained indeterminate (Raynor *et al.* 2011).

The church may be associated with the Anglian nunnery of Abbess Hild, who was granted land in AD648 by Aidan to the south of the Tynemouth. There is, however, a paucity of documentary evidence for this early monastery. Its mediaeval successor, first mentioned in AD1402, served the small village of South Shields. The original mediaeval burial ground was likely located to the north of the excavation area proximate to the church. During the 18th century, South Shields was characterised by a period of rapid settlement expansion and industrialisation. The burial ground at the Church of St Hilda's was raised in 1816 and 1818 before being officially closed on 1st July 1855. Most of the individuals were interred in less expensive mass-produced coffins indicating that they were probably working class. Variability in coffin furniture and burial situation suggested the cemetery group occupied a relatively wide range of financial statuses. The richer burials at the site were less ornate, however, than most other contemporary middle- and upper-class crypts (Raynor *et al.* 2011). The occupations of the inhabitants of the town included sailors, ferrymen coal-heavers and miners, mechanics and tradesmen. Barley, oats, wheat and turnips were cultivated locally (Table 25). Individuals in poorhouses consumed potatoes and milk as the principal component of their meals and white bread only three times a week. Fresh milk was more widely available than in southern counties (Eden1795).

Table 25: Dietary profile of Coronation Street, South Shields.

Site	Coronation Street, South Shields
Dietary Staples	Barley, oats and wheat consumed in the form of bread and oatmeal. Potatoes. Vegetable broth.
Dietary Supplements	Occasional marine (Red Herring) and animal protein (mainly bacon) Cheese, milk and butter Sugar (often consumed in tea) or consumed as treacle
Milling Technology	Steam powered and water powered mills. Unlikely to be roller mills as most burials predate AD1850.
Social Status	Dietary meat component closely associated with household income and was likely negligible to extremely rare in poorer households.
Sex differences	Greater meat consumption associated with the head of the household who was typically male

5.1.2.1.3.3 St Peter’s, Wolverhampton, Overflow Cemetery (StP)

The assemblage was derived from the excavation of the 19th century overflow burial ground for St Peter’s Collegiate Church, Wolverhampton, carried out by Birmingham University Field Archaeology Unit from 2001 to 2002 during the extension of the Harrison Learning Centre, University of Wolverhampton (Figure 29 and Figure 41) (Adams and Colls 2007).

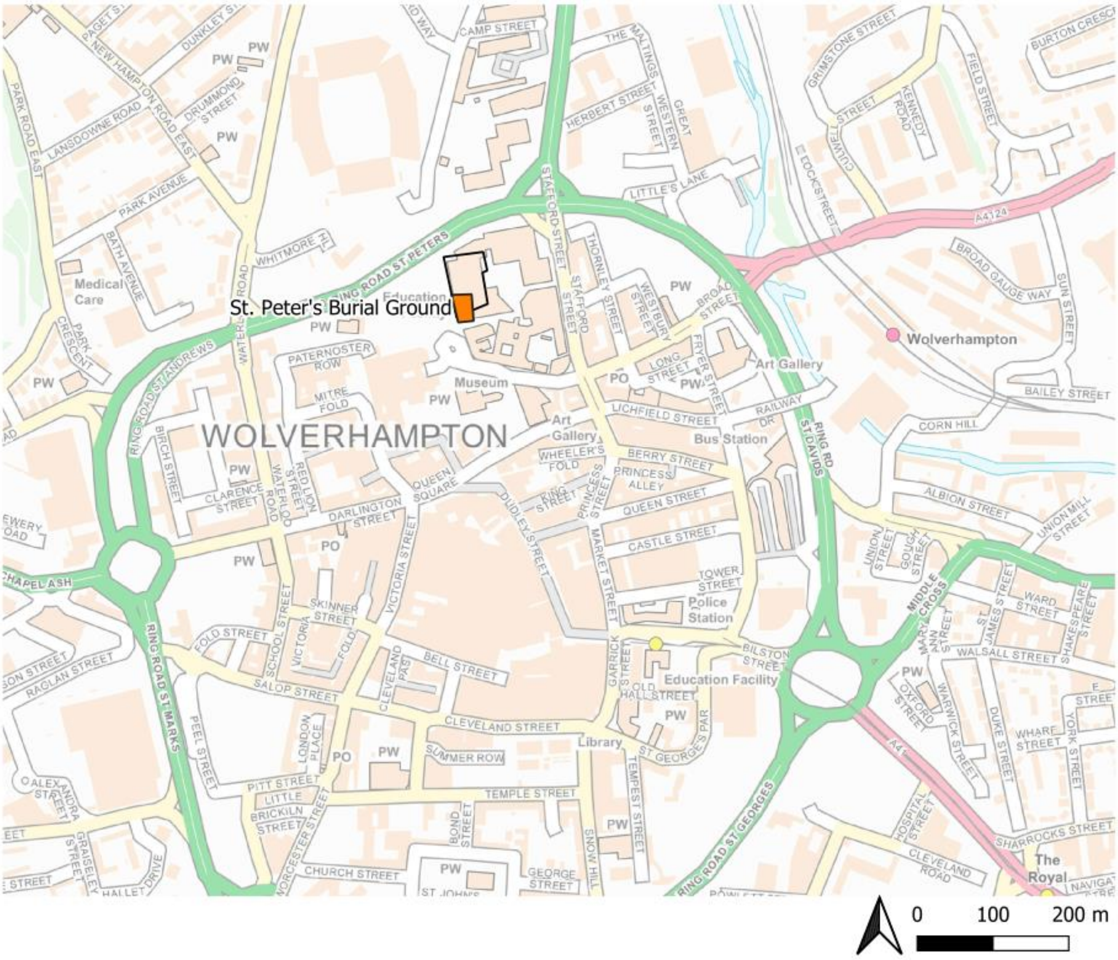


Figure 41: Map showing the location of the excavation of the overflow burial ground of St Peter’s Collegiate Church, Wolverhampton from 2001-2002 (shown in orange). The outline of the full extent of the cemetery is indicated by the area demarcated by the black line which includes the excavation area. Contains OS data © Crown copyright and database right 2021.

St Peter’s church is thought to have been founded in the 7th century AD and was likely an important early Christian centre in the area. The grounds and gardens of the Deanery of Wolverhampton occupied the excavation area until AD1819 at which point the ground was consecrated as an overflow cemetery for St Peter’s church. Seven brick-built vaults were encountered across the excavation area alongside earth cut graves (Figure 42). Six of these were located along the western boundary of the site and the seventh further to the south. The vaults were largely intact but infilled with a mixture of modern rubble and debris suggesting they had been cleared. Vault Seven was better preserved. A total of 152 burials were recorded. The vast majority of these were earth cut graves, located in the southern portion of the excavation area, and were typically aligned east-west with the skeleton in an extended supine position. Of the burials, 58 were subadults (aged under 18 years) and 92 were adults. 39 adults were identified as male and 41 as female. The remainder were of indeterminate sex. The grave cuts were frequently intercutting suggesting intensive use of the cemetery area. Coffin preservation was generally poor, however, where coffin furniture was preserved a date of AD1830-1880 was indicated by the style of the fittings (Adams and Colls 2007).

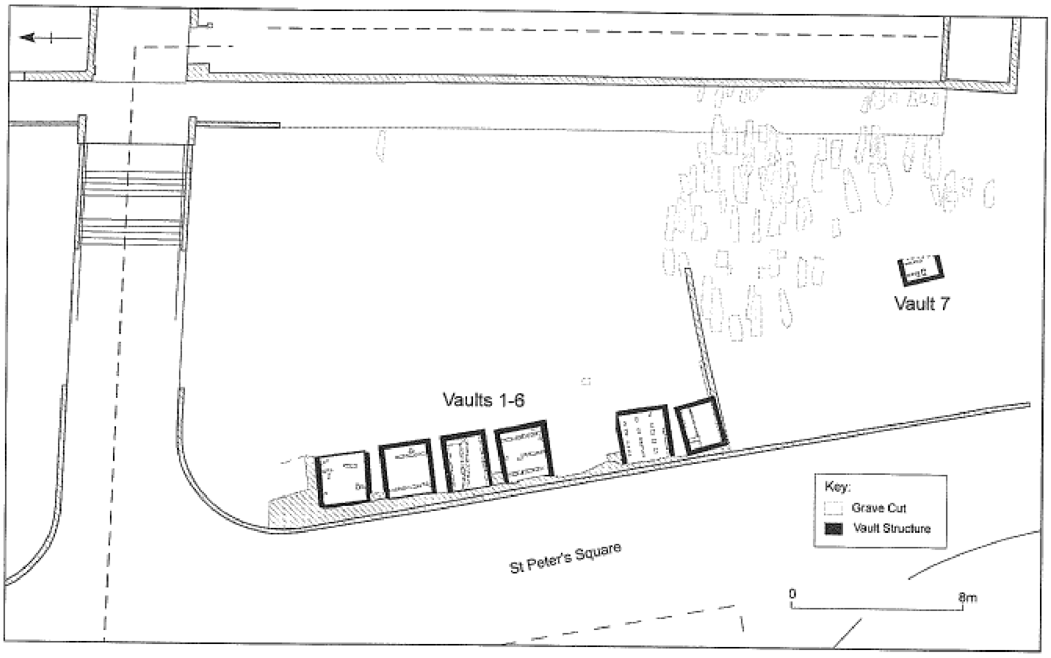


Figure 42: Map of the excavation area of St Peter's overflow cemetery. Figure reproduced from Adams and Colls 2007: figure 8 page 9).

Some 25,560 burials were recorded in the St Peter's parish register between 1800 and 1850. The population of the town rose rapidly from 18,380 in 1821 to 49,985 in 1851 as it developed as a manufacturing centre. Many people were involved in ironmaking and other workshop activities (Shaw 1977). The register did not record how many of these burials took place in the churchyard and how many in the overflow cemetery. The cemetery corresponded to this period of rapid urban growth. The growth of the town in this period was fuelled by rich coalfields, supplies of iron ore and fire clay to the east. W. A. Lewis, lecturing at

Wolverhampton in 1848, linked the high death rate in town with poor living conditions. Conditions were frequently overcrowded and were accompanied by a poor diet, particularly for children. The 1843 Children's Employment Commission stated that bad meat is continually sold at markets and that children frequently depended on red herrings, potatoes or bread with lard on it (Adams and Colls 2007). In 1849, approximately 500 people died as a result of an outbreak of cholera which could be associated with the use of the overflow cemetery (Shaw 1977).

A spectacle maker's family with four children in Wolverhampton in the late 18th century consumed around 14lb of flour, 12lb of meat, 2lb of cheese and 2lb of butter per week alongside potatoes, milk, sugar and tea. Meals alternated between bread and cheese or meat and vegetables (Table 26) (Eden 1795). In the poor house dietary content was similar but probably involved smaller amounts of meat; on meat days the poor generally saved a small amount for subsequent days, whereas bread and broth formed the bulk of the diet (Eden 1795). Following the success of the Union Mill built in Birmingham in 1796-97, a cooperative steam corn mill was constructed in Wolverhampton in 1809-12. This probably operated as a miller and baker. The Wolverhampton Society distributed around 500 bushels of flour and 770 quartern loaves per week and supplied about 50 shops in the area (Tann 1980). Much of the bread consumed would have been of a similar composition and quality for most of the individuals interred at the cemetery.

Table 26: Dietary profile of the St Peter's Overflow Cemetery, Wolverhampton, assemblage.

Site	St Peter's, Wolverhampton
Dietary Staples	Wheaten bread, broth and potatoes
Dietary Supplements	Marine protein (Red Herring) Animal protein (Mainly bacon) Cheese and butter Sugar (often consumed in tea)
Milling Technology	Steam powered cooperative mill from 1812 resulting in a more standardised and cheaper loaf for Wolverhampton inhabitants.
Social Status	Dietary meat component closely associated with household income and was likely negligible to extremely rare in poorer households.
Sex differences	Greater meat consumption associated with the head of the household who was typically male

5.1.3 Methods for establishing the biological profile of the individuals examined

Sex and age-at-death were estimated in order to test hypotheses concerned with differences in diet within time periods and cemetery groups. Sex and age-at-death estimates were made for each individual using standard osteological techniques.

Where preservation of the pubic bone was adequate, an assessment of the ventral arc, the subpubic concavity and the medial aspect of the inferior pubic ramus were performed using the nonmetric method of Phenice (1967). These traits have been reported to have a sex estimation accuracy of up to 95%, however, in the context of archaeological material the os pubis is frequently fragmented or damaged rendering the Phenice method ineffective (Kelley 1979). This was the case in most of the individuals examined. Consequently, the cranium and greater sciatic notch of the innominate bone were evaluated following Buikstra and Ubelaker (1994, p.18, 20) and formed the primary criteria in determining sex in most individuals. Correct sex assignment in three known sex collections was 80% when ordinally scoring the morphology of the greater sciatic notch (Walker 2005). Similarly, Inskip *et al.* (2019) reported an 81% accuracy when using the greater sciatic notch alone to sex mediaeval skeletons that had also been sexed using ancient DNA analysis from the medieval St John's collection Cambridge.

Femoral head diameter was measured and used to support the non-metric sex estimate for each individual that could be assessed. Preference was given to measuring the right side where present. Femoral head diameter is typically more dimorphic than dental measurements; high sex estimation accuracies have been reported based on femoral head diameter when building population specific discriminant functions (~80% correct classification) (Figure 44; İşcan and Miller-Shaivitz 1984; İşcan and Shihai 1995) when compared to dental metrics (İşcan and Kedici 2003; Zorba *et al.* 2012). Sex estimation using metric traits, such as femoral head diameter, requires the use of population specific values (İşcan and Shihai 1995). As such, individuals with sufficient preservation of the pelvis, for whom a non-metric sex estimate could be obtained, were used to obtain a set of femoral head diameter values for each assemblage. Individuals without adequate preservation of the innominate bone but with sufficient preservation of the femoral head could then be compared to these values to obtain a sex estimate. Individuals were only sexed using this method if their femoral head diameter was equal to or greater than the median value for males or less than or equal to the median value for females in that assemblage. Lower classification accuracies have been reported when using the cranium alone (Lewis and Garvin 2016), therefore, a sex estimate was only made in the absence of the pelvis if both the skull and femoral head diameter were strongly consistent with a particular sex. For example, if most cranial traits were scored as a 1 (Buikstra and Ubelaker 1994, p.20) and the femoral head diameter was less than or equal to the median value for females in the assemblage the individual would be classified as a female. Individuals with intermediate femoral head diameters, absent or intermediate cranial and pelvic non-metric traits were classified as indeterminate.

The method of sex estimation used sought to maximise the number of individuals for whom a sex estimate could be obtained given the often-fragmentary state of many of the skeletons examined. The elements targeted, the greater sciatic notch and the femoral head, were commonly well-preserved in the assemblages. A limitation of this approach is that different levels of accuracy would be expected for each individual depending on the traits that were present and assessable. Despite this, sex estimates were made using traits that have been reported to present high levels of accuracy (80% or greater) in known sex assemblages. This should reduce the error associated with the misclassification of individuals when conducting the statistical analyses necessary to assess differences in diet related to sex in each period (Sections 6.2.1.1 and 6.2.2.1). Ambiguous individuals were excluded from the analyses conducted to address research questions concerned with sex differences.

Skeletal age-at-death estimation was based on the assessment of degenerative changes in the auricular surface of the ilium. This method was selected because the pubic symphysis was commonly absent. Dental wear methods require an understanding of the rate at which dental wear accumulates over time within an assemblage, such as through examining the dentitions of juveniles at different stages of dental eruption (Miles 2001). This would have demanded the examination of individuals not otherwise suitable for inclusion in the project. Rates of dental wear likely differed markedly between the Mediaeval, early Post-mediaeval and Industrial periods. The auricular surface was selected for age-at-death estimation as it is durable and commonly preserved in fragmentary skeletal material (Osborne *et al.* 2004). The Buckberry and Chamberlain method (2002) was used rather than the Lovejoy *et al.* (1985) method as the latter assumes interdependency between the degenerative changes observed when assigning skeletal age phases. Individuals with a Buckberry-Chamberlain score of 9 or less were classified in the younger age-at-death category and those with a score of 10 or greater in the older category. This approach is supported by an earlier study of material from St Bride's Church, Fleet Street (Falys et al. 2006); it was found that the use of gross categories of age progression better reflected the actual distribution of age-at-death within the assemblage rather that attempting to convert the Buckberry-Chamberlain scores obtained into ten-year age categories The individuals from the St Bride's Church included in the project were of known age and sex.

5.1.4 Assemblage Demography

Table 27 and Table 28 detail the sex and age-at-death distributions of the assemblages examined. Several mediaeval assemblages had poor preservation of the lower portion of the body, therefore, the pelvis was frequently absent rendering a sex estimate inconclusive when based on the cranium alone. A markedly larger proportion of the Industrial individuals (38%) were categorised within the older age-at-death category compared to the Mediaeval period (4.4%) (Figure 43). This was due to more rapid rates of wear in the Mediaeval period which frequently rendered the wear stages of the lower second molars too advanced for performing wear facet analysis, particularly in older skeletal age-at-death categories.

Table 27: Sex distribution of the individuals selected from the assemblages examined and used to perform OFA.

Site	Indeterminate	Female	Male
York Barbican	17	8	7
Blackfriars, Gloucester	4	2	3
Box Lane, Pontefract	4	3	0
St James and St Mary Magdalene, Chichester	3	13	8
Hereford Cathedral	16	14	12
Mediaeval Summary	44	40	30
Coronation Street, South Shields	7	6	12
St Michael's Litten, Chichester	0	19	27
St Bride's, London	0	13	18
St Peter's, Wolverhampton	5	5	8
Industrial Summary	12	43	65

Table 28: Age-at-Death distribution using the Buckberry-Chamberlain method (2002) of the *individuals selected from the assemblages examined and used to perform OFA.*

Age Category	Unknown	Younger	Older
Buckberry-Chamberlain score	**-**	**≤9**	**≥10**
Site			
York Barbican	3	25	4
Blackfriars, Gloucester	1	8	0
Box Lane, Pontefract	2	5	0
St James, Chichester	0	24	0
Hereford Cathedral	13	28	1
Mediaeval Summary	19	90	5
Coronation Street, South Shields	3	11	11
St Michael's Litten, Chichester	1	35	10
St Bride's, London	0	15	16
St Peter's, Wolverhampton	6	7	5
Industrial Summary	10	68	42

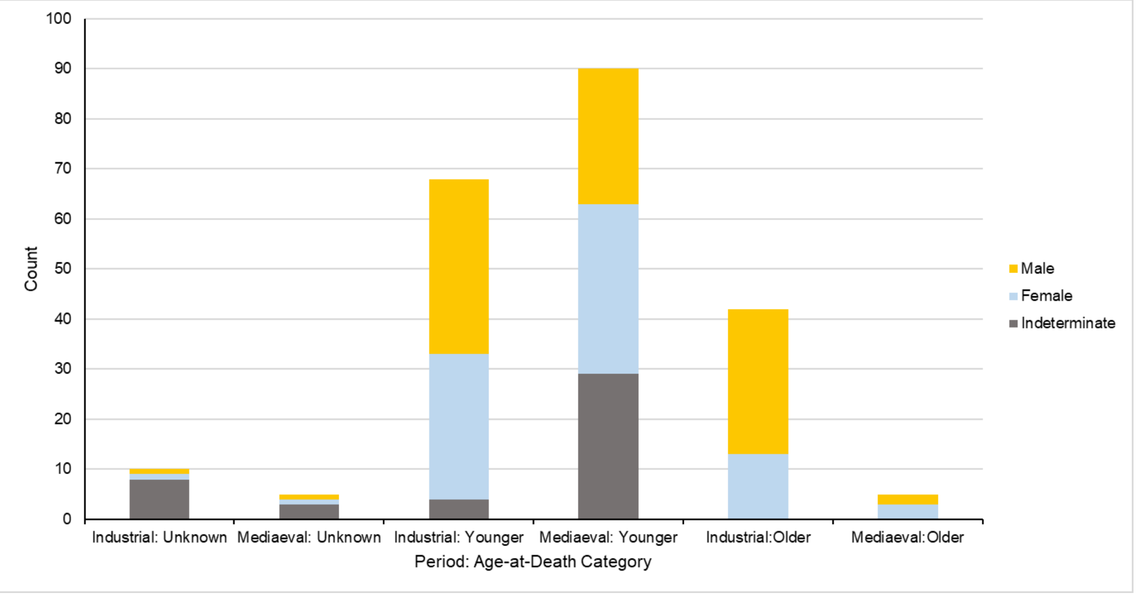


Figure 43: Stacked bar chart showing the demographic composition of the individuals that satisfied the selection criteria for the current study.

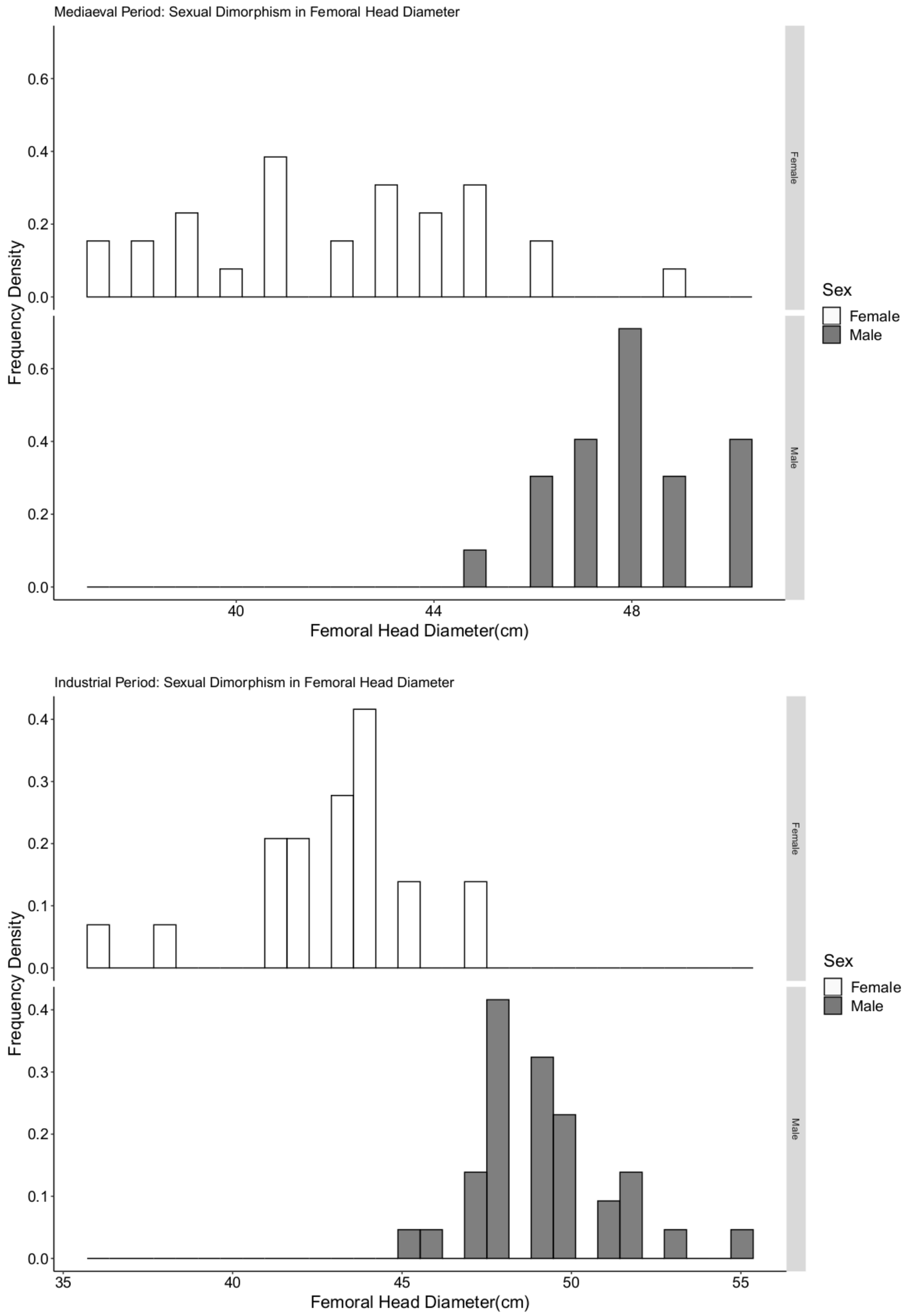


Figure 44: Histograms showing the distribution of femoral head values in the assemblages examined from the Mediaeval and Early Post-Mediaeval periods (upper) and the Industrial Period (lower). The two periods were separated as their femoral head diameter values differed significantly (Wilcoxon Rank Sum Test; W = 1813, p-value = 0.009). The data was not normally distributed in either period (Shapiro-Wilk Test; p-value<0.05), therefore, non-parametric testing was used to assess sexual dimorphism. Femoral head diameter differed significantly between the two sexes in both periods supporting their sex estimates derived using non-metric traits (Wilcoxon Rank Sum test; Mediaeval W = 23.5, p-value <0.001; median female 43cm vs. male 49cm; Industrial W=8, p-value<0.001; median female 43cm vs. male 48cm;). Sexual dimorphism for femoral head diameter was 11.94% in the Mediaeval period and 14.19% in the Industrial period (calculated

using the method of Garn et al. *1967*). *A histogram was used to present this data as a means of examining the distribution of values associated with each sex and period and to look for outliers in the data. A histogram was selected rather than a boxplot as it enables the number of individuals associated with each femoral head diameter interval to be inferred directly from the plot. The modal values for each sex and period combination could also be identified. Histograms perform well when comparing two distributions, however, box plots are more appropriate when comparing multiple distributions.*

5.2 Methods

The central hypothesis of this thesis required the formulation of theoretical chewing models for the Mediaeval and early Post-Mediaeval periods (AD1100-1700) and the Industrial period (AD1700-1900) to identify any differences in masticatory behaviour in response to dietary change. As such, a three-stage method of wear facet assessment was used to reconstruct chewing behaviours in each period:

- The first stage involved the qualitative assessment of the wear facet pattern and the recording of dental pathology, occlusal variability and Smith wear scores (1984) across the dentition present.
- In the second stage, static OFA (Kullmer *et al.* 2009), a method of digital 3D dental wear pattern analysis, was utilized to assess quantitatively the wear pattern on the lower 2nd molar of each individual examined (n=234). Masticatory behaviours can be inferred from wear facet size, inclination and orientation.
- The third stage, which was applied to a subset of the individuals examined (n=32), involved the dynamic simulation of the power stroke for individuals that displayed adequate preservation of both upper and lower molar rows using the Occlusal Fingerprint Analyser software package. This method uses dental wear facet patterns to infer the movement trajectory of the lower molars during the power stroke.

5.2.1 Background wear facet mapping and recording of dental pathology

The initial assessment was the macroscopic examination of the wear facet pattern of each individual. Each dentition was compared to an idealized diagram (Figure 45) showing all potential wear facet positions within an Angle Class I occlusion (see section 3.7.1 Static and Dynamic Occlusion). In this diagram, wear facets are numbered using the system developed for hominin molars by Maier and Schenk (1982) and used by Kullmer *et al.* (2009) (see section 3.5 Facet Labelling). A simple qualitative binary presence/absence system of recording was employed. Wear facets were identified using a strong directional light and a magnifying glass. They were only assessed on a tooth if the occlusal surface was entirely present without any destruction resulting from ante-mortem chipping, post-mortem damage or carious destruction. Wear facet counts were grouped according to tooth type and/or position. Prevalence values did not differ significantly between the time periods for the wear facet groupings considered (Appendix section 10.1).

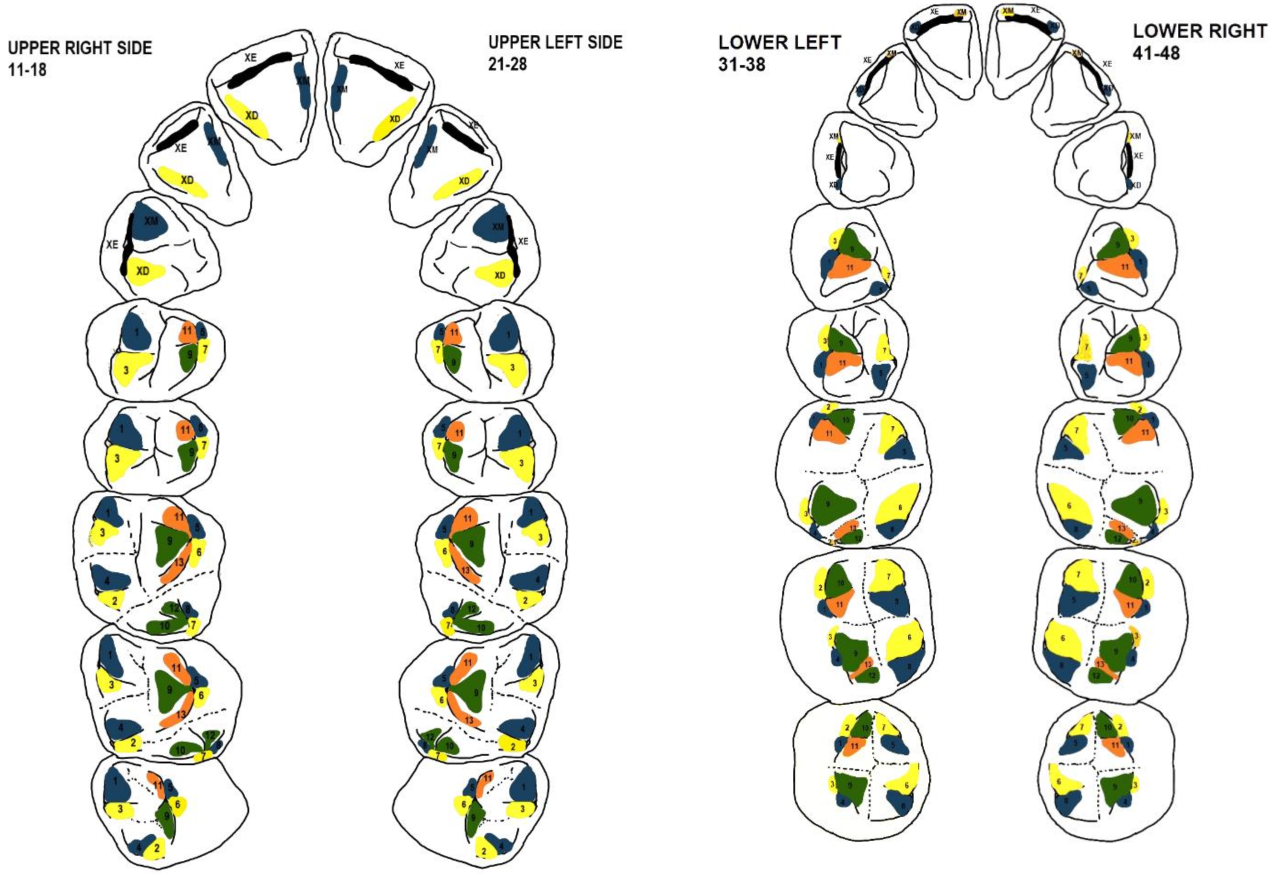


Figure 45: Upper and lower dental arcades showing the potential location of the wear facets assessed during the first stage of wear facet analysis for each individual. Teeth were numbered and recorded using the FDI tooth numbering system (Fédération Dentaire Internationale 1971). Figure created by author.

5.2.1.1 Recording within-arch dental pathology and occlusal variability

A background understanding of the states of the dentition in each assemblage examined is important in situating any differences in the dental wear patterns observed against a wider backdrop of changing patterns of occlusion, dental pathology and the retention of teeth (Kaidonis *et al.* 2016; Margvelashvili *et al.* 2016). The loss of antagonistic dental surfaces due to ante-mortem tooth loss or cavitated carious lesions may limit the development of certain wear facets. A consideration of dental pathology also provides additional evidence to confirm the differences in dietary content and composition described historically (Burnett 1989; Mennell 1996) and previously attested to archaeologically (e.g. Moore and Corbett 1975).

A full comparison of dentognathic pathology between the Mediaeval and Early Post-Mediaeval periods and the Industrial period was beyond the scope of the current project. This is chiefly due to the selection of a small subset of each assemblage characterised by well represented upper and lower dentitions, with limited loss of occlusal surfaces and teeth, for the purposes of conducting OFA. The necessity of selecting individuals from younger skeletal age-at-death categories with sufficient occlusal topography to facilitate dental wear facet analysis will also limit how representative the individuals selected are of the skeletal assemblages examined as a whole (Fiorenza *et al.* 2018). The methods outlined below attempted to provide a summary of the state of the dentition of each individual examined.

Dental caries provides an indication of the quantities of cariogenic carbohydrates in the diet but is a complex condition to record archaeologically (Hillson 2001). Ideally a scheme of recording should be utilised that assesses the presence and extent of lesion progress on each crown and root surface for every tooth present (Hillson 2001). Previous studies have focused on extensive comparisons of caries prevalence between the Mediaeval and Industrial periods; therefore, this was not the focus of the current project (Corbett and Moore 1976; Moore and Corbett 1975). Instead, recording was principally required as the destruction of the coronal surface by a carious lesion will frequently obliterate part or all of the occlusal wear pattern of a particular tooth. Furthermore, the presence of a cavitated carious lesion will prevent an impression of that tooth being taken without risking substantial damage to the specimen. As a result, only cavitated carious lesions involving the crown were recorded where present for each tooth position. The absence of the recording of non-cavitated lesions, in which only demineralisation and surface roughening have occurred, will have resulted in the underestimation of caries prevalence in the current study. Consequently, it was not possible to assess the variability in lesion expression and sites of initiation across the skeletal assemblages examined. An analysis of the distribution of cavitated coronal lesions across the different tooth classes was still possible. The overall prevalence of cavitated carious lesions in the material examined could also be compared between the pre-Industrial and Industrial groups.

The mesial migration of teeth due to ante-mortem tooth loss may alter the relationship between opposing teeth and modify the pattern of wear facets that develop (Kaifu *et al.* 2003). Furthermore, the number of teeth lost ante-mortem between the two periods gives an indication of the likely overall functional efficiency and longevity of the dentition, given that masticatory performance in modern clinical studies has been shown to be primarily dependent upon the number of functional posterior occlusal units in the dentition (Hatch *et al.* 2001; Ikebe *et al.* 2012; Löe *et al.* 1978; Neely *et al.* 2001).Consequently, ante-mortem tooth loss was recorded across each dentition examined.

Dental crowding provides an indication of any increase in the discrepancy between tooth substance and jaw size, which has been associated with a reduction in jaw size in contemporary industrialised groups (Corruccini 1999). The number of teeth that were rotated/displaced across the dentition were, therefore, also recorded.

Dental chipping provides insight into the exposure of the dentition to repeated heavy loading and may also suggest the frequent intervention of hard foreign particles, such as quartz grains and bone, between the occluding teeth. This may offer evidence of food preparation techniques, dietary content and the use of teeth as tools. A previous study has indicated a reduction in tooth chipping in Post-mediaeval assemblages relative to the Mediaeval period (Scott and Winn

2011), therefore, an assessment of dental chipping was not deemed necessary in the current study.

Periodontal disease results in a reduction in occlusal support (Margvelashvili *et al.* 2016). Clinical studies, however, have not found a significant relationship between individual periodontal status and masticatory efficiency and behaviour (Kosaka *et al.* 2014; 2018) or between periodontal status and jaw adductor muscle activity during mastication (Fernandes *et al.* 1994). Periodontal disease (Kerr 1991, 1994, 1998), therefore, was not recorded in the current project.

Periapical periodontitis occurs when pulpal inflammation spreads through the apical foramen of the tooth triggering an inflammatory response in the surrounding periodontal tissues (Hillson 1996). This can result in the resorption of the surrounding bone to accommodate expanding granulation tissues. Prior to the adoption of a diet high in sugar in the Industrial era, periapical periodontitis has been considered one of the major causes of ante-mortem tooth loss in an archaeological context (Alt *et al.* 1998). Periapical lesions can occasionally be detected following an external macroscopic examination of the jaws, such as when the walls of the lesion have been broken to reveal the underlying cavity. The presence of a sinus draining to the surface of the bone may indicate the presence of an abscess (Dias and Tayles 1997). Accurate diagnosis of the extent and location of periapical lesions, however, requires radiographic examination of the jaws (Hillson 1996). In a study of sixty mandibles from Mediaeval France, several periapical lesions could only be identified using radiographic methods (Lucas *et al.* 2010). Similarly, 74% of the periapical lesions identified radiographically in a study of 189 maxillae and 182 mandibles from the mediaeval cemetery of Stara Torina, Serbia, were not detected during external observation (Djurić and Rakočević 2007). Radiographic examination of the jaws of the individuals included in the current project was not possible, due to time, cost, and transportation constraints. Consequently, periapical lesions were not recorded in the current project due to the limitations of detecting them using external macroscopic methods alone.

Given the dietary changes in the Industrial period, characterised by the consumption of an increasingly processed and cariogenic diet, the following hypotheses were tested in the current project:

1. There was an increase in the prevalence of cavitated carious lesions in the Industrial period as sugar contributed increasingly to the overall proportion of calories consumed.
2. Industrial assemblages will be characterised by more extensive ante-mortem tooth loss due to more extensive tooth extraction and loss, due to loss of periodontal attachment or dental caries.
3. An increase in the proportion of individuals with dental crowding in the Industrial period

Ante-mortem tooth loss, post-mortem tooth loss, cavitated carious lesions and rotation, displacement (R/D), impaction, and anomalous eruption of teeth were recorded using the operation definitions given in Table 29.

Table 29: Operational definitions used to identify the dental pathological conditions recorded in the current study.

Category	Definition
Ante-mortem tooth loss	The tooth is missing, and the socket is either partially or wholly remodelled to a level contour.
Post-mortem tooth loss	The tooth was either absent or broken post-mortem, however, the socket was present.
Cavitated carious lesion crown	Only coronal carious lesions were assessed unless a gross lesion involving both the coronal and root surfaces was present. A tooth was classed as carious if a cavity was present on the crown surface of the tooth. There was no differentiation between carious lesions that penetrated just the enamel, to the dentine or to the pulp chamber.
Minor rotation/displacement (R/D)	The tooth was classed as minorly rotated/displaced if it was less than or equal to 45° from the ideal arch form and/or was displaced from its ideal arch position by ≤2mm (Harris and Corruccini 2008).
Major rotation/displacement (R/D)	The tooth was classed as majorly rotated/displaced if it was more than 45° from the ideal arch form and/or was displaced from its ideal arch position by >2mm (Harris and Corruccini 2008).
Impaction/Anomalous Eruption	The tooth has not reached its normal position in the tooth row or is impacted.

5.2.1.2 Calculating rates of presence of within-arch dental pathology and occlusal variability

A prevalence rate in the traditional sense was not calculated for the dental pathology recorded; the number of individuals affected expressed as a proportion of the total number of individuals in the population (Waldron 2007; 2008). Instead, the number of tooth sites affected by each pathological condition were calculated using the following methods along with 95% confidence intervals:

1. For ante-mortem tooth loss, rotation/displacement, and impaction the number of assessable sites affected by each condition were expressed as a proportion of the total number of sites that could be assessed for each individual (Including sites where socket and tooth were present,

socket only was present, or socket was partially or fully remodelled and tooth absent):

$$Proportion\ of\ Sites\ affected\ per\ Individual = \frac{Number\ of\ Sites\ with\ Condition\ in\ Individual}{Total\ number\ of\ Sites\ Present\ for\ Individual} \times 100$$

2. For cavitated carious lesion, the number of teeth with cavitated carious lesions was expressed as a proportion of the number of teeth assessable for each individual:

$$Proportion\ of\ Teeth\ with\ Carious\ Lesions\ per\ Individual = \frac{Number\ of\ Teeth\ with\ Cavities\ in\ the\ dentition}{Number\ of\ Teeth\ Present\ in\ the\ dentition} \times 100$$

3. The value calculated for the proportion of teeth with carious lesions per individual will be highly influenced by the variable retention of the anterior dentition, which are typically less frequently affected by carious lesions (Hillson 2001). The proportion of teeth, divided into anterior, premolar and molar classes, affected by carious lesions was, therefore, also calculated for each period.

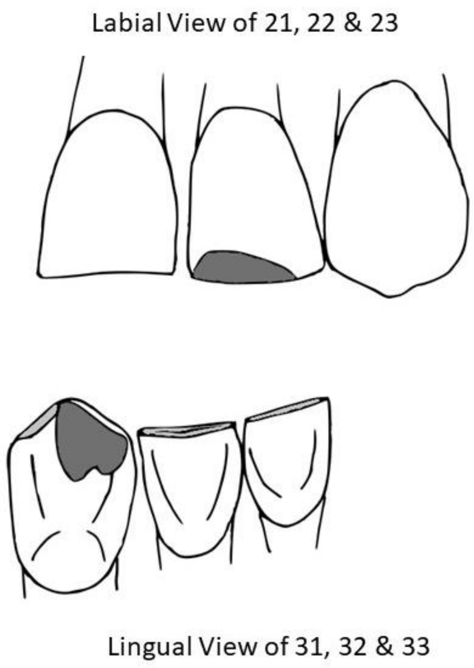
$$Proportion\ of\ Teeth\ with\ Cavitated\ Carious\ Lesions = \frac{Number\ of\ Teeth\ with\ Cavities}{Total\ Number\ of\ Teeth\ Present} \times 100$$

5.2.1.3 Recording between arch occlusal variability

The identification of many occlusal abnormalities using diagnostic criteria from dentistry requires the placement of the jaws in their correct anatomical position. Post-mortem alteration and fragmentation of the mandible and maxilla, however, can often lead to difficulties in reconstructing inter-arch relationship by simply placing the mandibular condyles within the glenoid fossa (Vodanovíc *et al.* 2012). Methods for identifying occlusal variability in skeletal material have previously attempted to match attrition facets between the upper and lower dentition in order to reconstruct occlusal relationships in archaeological specimens (Sarig *et al.* 2013). Using the information pertaining to occlusion in dental wear facets, a series of operational definitions were developed and employed to classify occlusal variability based on how dental wear facets might be expected to deviate from their anticipated position within an Angle Class I occlusion. Further work is required to evaluate whether Angle Class (Angle 1907) can be effectively determined using wear facet data as has been suggested by Fiorenza *et al.*

(2010). For that reason, it was not attempted here. The incisors were seldom sufficiently represented in individual dentitions to assess the relationship between them, such as a measurement of overbite and overjet, therefore, this was not considered in the current research.

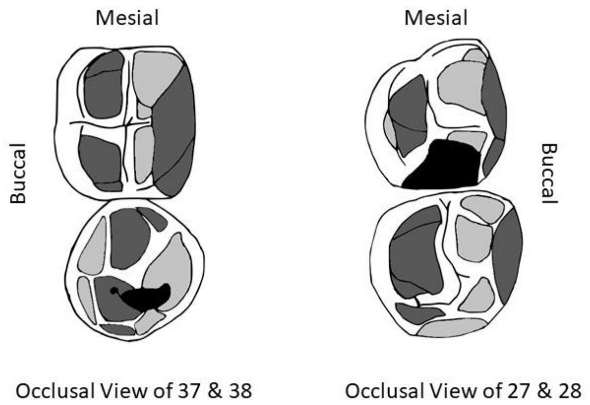
Definitions were developed for inferring the presence of crossbites in the assemblages examined (Figure 46 and Figure 47). Crossbites are defined as an abnormal labio-lingual or bucco-lingual relationship between one or more of the maxillary and mandibular teeth. In anterior crossbites, the maxillary incisors involved are positioned palatal to their mandibular antagonists in centric occlusion (Borrie and Bearn 2011). Posterior crossbites occur in the canine, premolar or molar region. In the molars, the buccal cusp of the upper molar typically occludes with the central fossae of its lower antagonist (Rilo *et al.* 2007).



Operational definition for Crossbite involving the Anterior Teeth

- Facets XM and/or XD are present on the labial surface of one or more of the upper incisors rather than the palatal surface.
- The corresponding facets XM and/or XD are situated on the lingual surface of the crown of the antagonistic tooth rather than the labial.
- If present on one side this may be termed unilateral or if present on both sides bilateral.
- **Example:** Anterior crossbite involving the lateral left incisor and lower left canine (SK1629 from site ESC11). The wear facets that satisfy the operational definition are marked in dark grey.

Figure 46: Operational definition for crossbites involving the anterior teeth. Dark grey indicates the contacts involved in the crossbite situation.



Example: Posterior crossbite on the left side (Sk1986 from assemblage ESC11). Lingually inclined facets are dark grey and buccally inclined facets are light grey. Note lingually inclined facets on metaconid and entoconid and buccally inclined facets on the paracone and metacone of the second molars.

Operational definition for Posterior Crossbite

Upper Molars

- Wear facets are located on the buccal slopes of the paracone and metacone in at least one molar.
- Lingual Phase I facets (5, 6, 7 & 8) are not well developed and may be present on the buccal slope of the paracone and metacone rather than the lingual.

Lower Molars

- Buccal Phase I facets are absent or very small in the antagonistic lower molar.
- Additional lingually inclined wear facets are present on the lingual slopes of the metaconid and entoconid.
- Dental wear is likely to be heaviest on the metaconid and entoconid rather than the protoconid and hypoconid.

Figure 47: Operational definition for crossbites involving the posterior teeth in which the upper teeth are shifted lingual to their anticipated position within an Angle Class I occlusion.

Attempts have been made to identify bruxism, parafunctional activity involving tooth grinding and jaw clenching, using dental wear (see section 3.4.1). Pathognomonic ‘bruxofacets’ have been described as flat, smooth, shiny areas with sharp edges. These correspond to similar antagonistic areas on the opposing teeth (Lindqvist 1973). Unusual patterns of dental wear have been reported clinically in bruxing individuals, often when the incisors are involved in the bruxing activity. This includes heavy shelf-like wear effecting the palatal surface of the maxillary incisors (Khan *et al.* 1998; Sameera *et al.* 2017). Clinical studies indicate, however, that bruxism cannot be definitively diagnosed solely based on dental wear patterns alone. The distribution of dental wear observed may result from other factors, such as erosive agents (Khan *et al.* 1998) or the presence of occlusal variability (Restrepo *et al.* 2006). Consequently, attempts were not made to develop an operational definition for diagnosing bruxism based on wear facet patterns.

5.2.1.4 Gradient of Dental Wear

Initial differences in wear between the 1st and 2nd molars, due to differences in eruption time, should be retained as the teeth are worn. A comparison of the degree of wear between successively erupting molars should indicate the rate of wear in each individual and also within and between assemblages (Miles 1963; Scott 1979b). Dental wear was assessed using the Smith system (1984) (Figure 48 and Table 30).

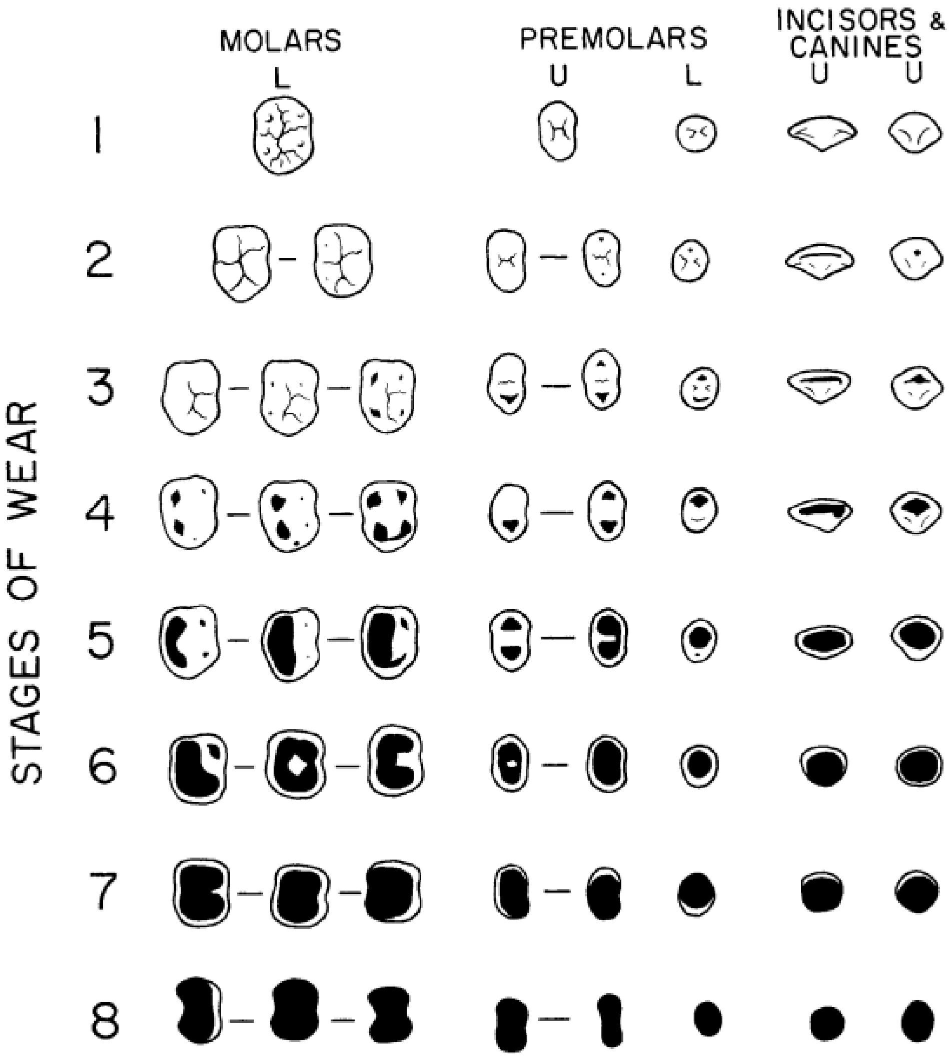


Figure 48: Smith scoring system used to assess degree of dental wear in the current research (Smith 1984; Figure 3). Individuals included in the research needed to have at least one lower second molar with a Smith wear score of 2. See Table 30 *for written descriptions of each stage.*

Table 30: Written descriptions for the scoring system used to assess extent of dental wear across the dentition in the current project. Scoring system taken from Smith (1984; Table 2).

Score	Molars	Premolars	Incisors and Canine
0	Missing or cannot be coded	Missing or cannot be coded	Missing or cannot be coded
1	Unworn to polished or small facets (no dentine exposure)	Unworn to polished or small facets (no dentine exposure)	Unworn to polished or small facets (no dentine exposure)
2	Moderate cusp removal (blunting). May show up to one or two pinpoint exposures of dentine on the cusp tips	Moderate cusp removal.	Point or hairline of dentine exposure
3	Full cusp removal with some dentine exposure (pinpoint to moderate)	Full cusp removal and/or moderate dentine exposure	Dentine line of distinct thickness
4	Several large dentine exposures; still discrete.	At least one large dentine exposure on one cusp.	Moderate dentine exposure no longer resembling a line
5	Two dentinal areas coalesced.	Two large dentine areas (which might be slightly coalesced)	Large dentine area with enamel rim complete
6	Three dentinal areas coalesced	Dentinal areas coalesced with enamel rim still complete.	Large dentine area with enamel rim lost on one side.
7	Dentine exposed on entire surface with a largely intact enamel ring.	Full dentine exposure, loss of rim on at least one side.	Enamel rim lost on two sides or small remnants of enamel remain.
8	Severe loss of crown height, breakdown of enamel ring and crown surface takes on the shape of the roots.	Severe loss of crown height; crown surface takes on shape of roots.	Complete loss of crown, no enamel remaining, crown surface takes on shape of roots.

Differences in occlusal relief and the obliqueness of dental wear facets between the Mediaeval, early Post-Mediaeval and Industrial periods may be attributable to differences in the abrasive content of the diets consumed. As such, a measure of the gradient of dental wear between successively erupting molars in each period also provides an indication of the abrasive load in the foods eaten and will assist with the interpretation of the metrics derived from OFA. The gradient of dental wear between the 1st and 2nd molars was calculated for each assemblage and period using the following formula:

$$Gradient\ of\ Dental\ Wear = \frac{Mean\ 2nd\ Molar\ Wear\ Score}{Mean\ 1st\ Molar\ Wear\ Score}$$

Due to ante-mortem and post-mortem tooth loss, sample size was increased by calculating the mean Smith wear score for the 1st and 2nd molars for each individual using both upper and lower molar wear scores.

5.2.2 Occlusal Fingerprint Analysis (OFA)

The size, inclination and orientation of dental wear facets across the occlusal surface of each tooth provide a record of the interaction between antagonistic tooth crowns during the power stroke (discussed in section 3.4.1). The close relationship between jaw movements, occlusal wear and the physical properties of the food eaten enables the reconstruction of masticatory behaviours from dental wear facet patterns (Fiorenza *et al.* 2011a; Kullmer *et al.* 2009). OFA requires high resolution virtual 3D dental models to describe and quantify occlusal wear patterns. The following section details the workflow developed to perform OFA in the current project and the problems that had to be overcome during the development of the methods used. The steps performed during the analysis of each individual were:

- The wear stages of the lower second molars present in the dentition, which were the target of OFA (as detailed in section 5.1.1.3), were assessed. The individual was included in the project if at least one of the lower second molars had a Smith Score of 2 (Table 30; 1984).
- The lustrous qualities of enamel limit the direct extraction of surface scan data from dental specimens. A dental gypsum, therefore, had to be made which could then be used for 3D model generation.
- High resolution 3D surface scan data then had to be generated of the lower second molar. An appropriate method of 3D model generation had to be identified.
- OFA is performed using 3D metrology software, therefore, a suitable solution had to be found. OFA involves the delineation of the perimeter of each wear facet on the occlusal surface of the virtual model. The area of each facet identified is calculated. The inclination and orientation of each

wear facet in three-dimensional space is defined by the dip angle and dip direction, respectively.

5.2.2.1 Dental impressions and model casting

The reflective and lustrous qualities of enamel render the reconstruction of 3D surfaces directly from the original surfaces of teeth problematic (Fiorenza *et al.* 2009; Mathys *et al.* 2019). A dental gypsum model was produced of the lower second molar of each specimen for the purposes of 3D model generation.

An impression was taken of each lower second molar. All impressions were taken using polyvinylsiloxane due to its dimensional stability and capacity to reproduce fine surface details (Varvara *et al.* 2015). Dental impressions were taken using a two-phase, two-step, putty-wash technique. Several studies have reported that this technique results in a more accurate reproduction of surface details and a reduction in the frequency of surface defects than monophasic or two-phase, one-step techniques (Caputi and Varvara 2008; Hung *et al.* 1992; Jamshidy *et al.* 2016; Millar 1998; Varvara *et al.* 2015). A rough impression of the target tooth was made using President® Putty Soft (Coltène/Whaledent Inc). Once set, the inside of the rough impression was coated with President® Light Body (Coltène/Whaledent Inc) and placed back on the target teeth and allowed to set. The light body records a high level of surface detail whilst the use of the putty increases the overall dimensional stability of the impression (Jamshidy *et al.* 2016).

The dental casts were made using non-reflective dental die stone (Suprastone® Dental Die Stone Type IV; Kerr Corporation). Dental die stone was mixed by hand following manufacturer's instructions and poured into the dental impressions using a vibrating table to minimise the quantity of air bubbles introduced into the model. In addition, an epoxy resin model was made of each tooth. The resin model was coloured with black pigment to give it an opaque finish. Wear facet boundaries are slightly more sharply defined on the resin models when compared to the dental gypsum models, therefore, they were used to assist wear facet identification when examining the virtual models. Resin models are highly reflective, however, and as a result are not suitable for 3D scanning.

5.2.2.2 3D Model Generation

Structure from motion photogrammetry (SfM) and structured light scanning (SLS) were investigated as potential methods of 3D model generation. SLS systems are capable of producing high resolution polygonal models but systems with sufficiently high resolution are expensive and thus not universally available. SfM is a passive technique of non-contact surface scanning that only requires access to a high-quality digital camera and suitable processing software. SfM is a more cost effective and increasingly widely available technique for 3D surface data acquisition (Hess *et al.* 2018). It was not possible to find an adequate SLS system within UCL, whereas cameras and software suitable for SfM were readily available. For this reason, SfM was carefully tested first, whilst also looking outside UCL for an appropriate SLS system. This was eventually found in the Department of Engineering at Cambridge University.

5.2.2.2.1 Structure from Motion (SfM) Photogrammetry

Several studies have indicated that 3D models generated using SfM frequently approach or match the resolution of models generated using conventional laser and SLS systems (Clini *et al.* 2016; Cullen *et al.* 2018; Hess *et al.* 2018; James and Robson 2012). Within a clinical context, SfM has been shown to generate 3D dental models within the <0.5mm level of clinical acceptability of original dental casts (Fu *et al.* 2017). Given this potential, experiments were conducted to examine the utility of SfM within the context of the current project.

SfM is a method of 3D data acquisition that offers a readily available and low-cost alternative to structured light, laser or CT scanning systems as image capture only requires access to a conventional camera (Micheletti *et al.* 2015). In SfM, a series of overlapping photographs is taken, to cover the target object or area. Software extracts key points from the photographs through the identification of correspondences between images. This extracted database of features is used to resolve simultaneously camera position, alignment and scene geometry. An initial 3D cloud of points on the target object is generated from the reconstruction and matching of the key points in multiple photographs. Further points can then be added to this so-called sparse point cloud and transformed into a more densely defined 3D mesh representing the topography of the target object surface (Szeliski, 2011, Westoby *at al.* 2012).

Several factors impact the quality and resolution of the final 3D models produced by SfM and require consideration when developing a strategy for image acquisition (Table 31) (James and Robson, 2014; Morgan *et al.* 2017; Mosbrucker *et al.* 2017). The resolution of the final 3D model produced is directly dependent upon the surface texture of the target object, therefore, highly textured objects with images taken at higher resolutions will result in the best models (Salvi *et al.* 2010). Surface texture refers to the pattern or structure on a surface and is dependent upon localised variability in the reflection and geometric properties of an object (Luhmann *et al.* 2013). The enamel of tooth crowns is very smooth and highly reflective, which from the start suggested that there might be difficulties with both SfM and SLS. For this reason, less reflective dental gypsum models were used as the basis of 3D model generation when performing both methods.

Table 31: Factors that influence the quality and resolution of 3D models generated using SfM.

Factor	Impact on 3D model produced
The texture of the target object	The resolution of the final 3D model produced is directly dependent upon the surface texture of the target object (Salvi *et al.* 2010). Highly textured objects with images taken at higher resolutions will result in the best models.
Number of photographs taken	Greater numbers of photographs, with maximised overlap, increase the redundancy of the key point correspondences identified between images and enhance the final resolution of the model (Westoby *et al.* 2012).
Distance to the target object	Photographs taken closer to the object of interest increase the spatial resolution of each photograph and the resolution of the final model (Westoby *et al.* 2012).
Method used to scale target object	Scale is often the greatest contributor to the error budget of SfM models. The use of physical targets with a clear centroid and high contrast, which span the full area to be reconstructed provide more accurate scaling (Mosbruker *et al.* 2017).
Angle between camera positions	Convergent images centred on the target object rather than images taken in parallel to the object will reduce the surface deformation of the final point cloud obtained (James and Robson 2014; Morgan, Brogan and Nelson 2017).
Lighting conditions	Illumination should be diffuse and, as consistent as possible, between photographs. Intense shadows must be avoided as they will obscure areas of the target object and potentially result in holes in the final point cloud (Mosbrucker *et al.* 2017).
Lens used	Lenses used for image capture should have a stable and fixed focal length (35-105mm). This will improve the camera calibration model, which describes the internal optical geometry of the camera, during the image matching process (James and Robson 2012). A Canon EF 100mm macro lens was selected over a Sigma DG 70mm macro lens as it resulted in a 22.8% increase in density of the dense point cloud.
Camera settings	To minimize image distortion, ISO should be set as low as possible (≤400), aperture to f/5.6-11.0 and images should be recorded in RAW rather than jpeg formats (Mosbrucker *et al.* 2017).

Greater numbers of photographs that are convergent upon the target object and have maximised overlap increase the redundancy of the key point correspondences identified between images and thus enhance the final resolution of the model (James and Robson 2014; Westoby *et al.* 2012). Illumination should be diffuse to avoid intense shadows that might result in holes in the final point cloud (Mosbrucker *et al.* 2017). A camera rig was constructed to standardise the sequence of image capture for each specimen (Figure 49). The rig facilitated full, and evenly distributed, photographic coverage of each dental model. It also increased the speed of image acquisition for each specimen as the position of the camera could be rapidly altered by changing the inclination of the arm upon which it was mounted (Table 33). Camera settings used for image acquisition were kept constant (Table 32). Experiments with model generation, using subsets of images of decreasing number, indicated that improvements in point cloud density were not marked when using >100 images, whereas, a steep decrease in point cloud density occurred in image sets of <70 images. Consequently, 80 images were captured of each dental model using the custom-built camera rig (Figure 50). The angle between image captures during turntable revolutions was 22.5º for each of the five camera positions used. Camera settings were kept constant to improve the camera calibration model (Table 32) and followed the recommendations of Mosbrucker *et al.* (2017). 3D model generation using SfM was a more time intensive process than when using the alternative SLS system (Table 33).

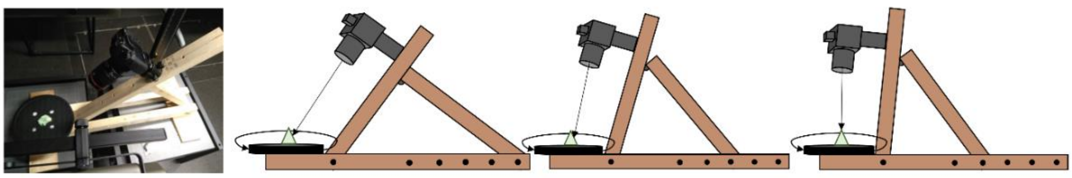


Figure 49: Camera rig constructed to facilitate consistent image acquisition for SfM model generation. The turntable was painted black to make it easier to mask the background during the model generation process in Agisoft Metashape.

Table 32: Camera settings used to generate image sets for performing structure-from-motion photogrammetry and focus-stacked structure-from-motion photogrammetry.

Setup	Normal SfM	Focus Stacked SfM
Camera	Canon EOS6D (20.2megapixels)	Canon EOS6D (20.2megapixels)
Lens	100 mm Canon EF Macro lens	65mm Canon MP-E Macro lens
Number of Images	80 16 per turntable revolution with 5 different camera positions	20-30 images per camera position were taken and imported into Helicon Focus 30 full-focus composite images produced per dental model to achieve full coverage
Aperture F-number	11	2.8
Shutter speed	1/40s	1/2000s
ISO	100	100
Lighting	Copy stand used to provide consistent non-directional ambient light	Copy stand used to provide consistent non-directional ambient light
Image Format	RAW	JPG
Scale	4 Agisoft Metashape coded markers distributed around the target object provided known distances for scaling the 3D model. The markers spanned the full area to be reconstructed in order to provide more accurate scaling.	Several coded markers (2mm in size) with a clearly defined centroid were fixed adjacent to the tooth to provide known distances for scaling the 3D model.
Number of 3D dental models produced using method	17 dental specimens from the St Michael’s Litten, Chichester (ESC11) assemblage	9 dental specimens from the St Michael’s Litten, Chichester (ESC11) assemblage (these individuals were also included in the assessment of regular SfM)

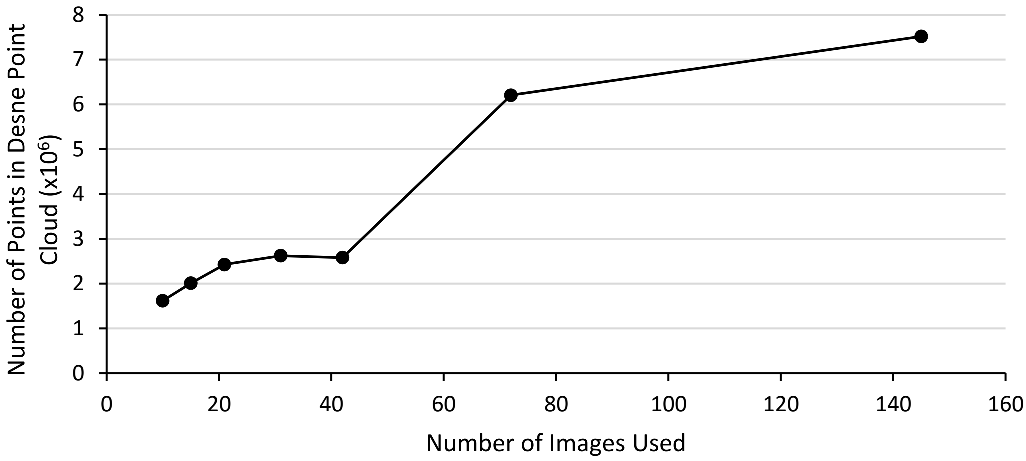


Figure 50: Association between image number and point cloud density. The model generation process for Sk 5134 (from St Michael's Litten) was repeated using subsets of differing size of the total number of images taken. Higher numbers of images were not associated with a linear increase in point cloud density. A steep decrease in point cloud density occurred in image sets of <70 images and improvements in point cloud density were not marked when using >100 images.

Photogrammetric software finds correspondences between the parts of images that are in focus, which may lead to failure in the point matching procedure when using macro lenses with a shallow depth of field (Kontogianni *et al.* 2017a). Focus stacking has been suggested as a method to circumvent this issue (Clini *et al.* 2016) but will result in substantially longer image acquisition and processing times. Focus stacking involves taking a series of macro images at different focal planes for each camera position. The focal plane is shifted by either moving a camera with a fixed focus on a macro rail system or by manually adjusting the focusing distance. All the detail in focus within each image taken at different focal planes can then be combined to produce a composite focused image (Clini *et al.* 2016; Gallo *et al.* 2014). A previous study has indicated that the use of focus stacking may enhance the quality of the reproduction of small-scale surface details (Kontogianni *et al.*, 2017b). A preliminary assessment of the application of focus stacked SfM (FS-SfM) to the generation of 3D dental models was undertaken.

Image capture for focus stacking was performed using a Canon EOS6D with a Canon MP-E 65mm lens mounted on a StackShot macro rail system (Cognisys, Inc.). Between 19 and 40 images were taken at each camera position depending on the depth of the details of interest visible. The focal plane was shifted 650µm between images using the macro rail. Each stack of images was combined using Helicon Focus Pro (v. 7.8.5) to produce a single in focus composite image for each camera position. The software provided several options but, as images were captured in a sequential order, the depth-map approach was used for composite image generation in which the regions in which the sharpest pixels exist in each source image are identified (HeliconSoft, 2019; Kontogianni *et al.*, 2017b). The composite focused images can then be imported into photogrammetric software and 3D models generated using these images. Focus Stacked SfM (FS-SfM) took substantially more time to perform 3D model generation than the other methods assessed (Table 33).

Table 33: The time taken to perform surface data acquisition and 3D model generation for each method used in the current study. Depth map and dense cloud generation was slower when performing normal SfM when compared to FS-SfM as more photos were used to produce each 3D model (80 images compared to 32 images).

Method of 3D Model Generation	Surface Data Acquisition and 3D Model Generation	Time Taken (minutes)	Total Time (minutes)
Structured Light Scanning	Scanning of dental model	10	15
	Polygonise data and export model	5	
Normal Photogrammetry	Photographic capture of dental model (80 images)	20	100
	Agisoft: Align photos	5	
	Agisoft: Depth map and dense cloud generation	70	
	Agisoft: Build mesh and export model	5	
Focus Stacked Photogrammetry	Photographic capture of dental model (30 views with stacks averaging 23 photographs)	120	180
	Focus-stacking of images in Helicon	30	
	Agisoft: Align photos	5	
	Agisoft: Depth map and dense cloud generation	10	
	Agisoft: Build mesh and export model	15	

For both SfM and FS-SfM, the image sets captured were imported into Agisoft Metashape Professional Edition (v.1.5.5) and a standard workflow was developed and followed (Figure 51). Structure-from-Motion photogrammetry has a tendency to produce an uneven distribution of points in the final point cloud and often incorporates high levels of redundancy (Hassett and Lewis-Bale, 2017). Therefore, a protocol for cleaning the sparse point cloud in Agisoft Metashape was developed to enhance the accuracy of the final reconstructed object surface and reduce reprojection error (Figure 51; Delaunoy *et al.* 2008; Gargallo *et al.* 2007). Model generation was conducted on a computer with 64GB of RAM, a 4.20GHz processor and a separate 8GB graphics card. The time taken to produce each SfM model would be greater than the time given in Table 33 if using a less powerful computer. The 3D models generated were exported in .stl format for analysis (stereolithography format, each .stl file describes the surface geometry of a 3D object).

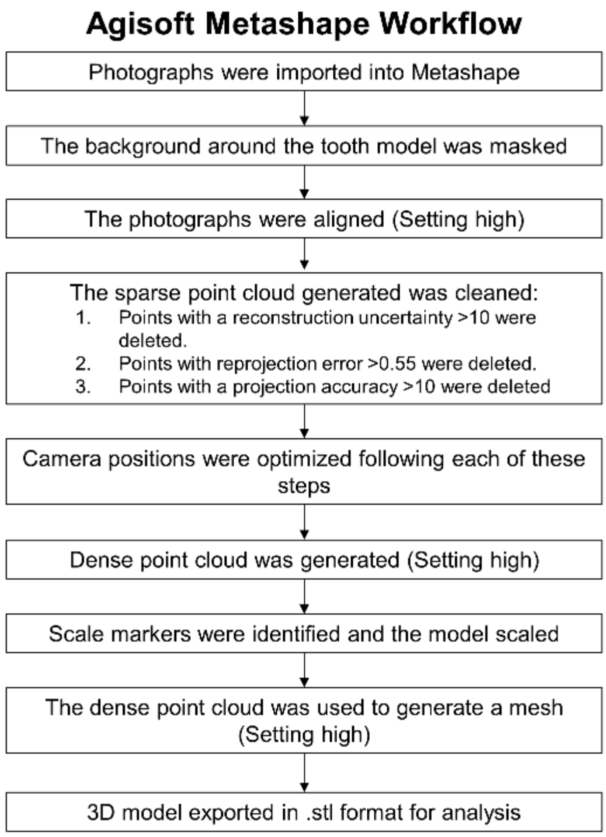


Figure 51: Agisoft Metashape Workflow used for Structure-from-Motion model generation in the current paper. All operations were performed on high settings.

5.2.2.2.2 Structured Light Scanning (SLS)

Structured light scanning systems (SLS) have been used in the majority of previous OFA studies (such as Fiorenza *et al.* 2018; Kullmer *et al.* 2009) and are therefore the benchmark for the quality of 3D model required for conducting OFA. In SLS systems, the target object is illuminated by a series of alternating patterns of light. A stereo pair of cameras records the deformation of the structured light pattern projected onto the object and estimates the underlying geometry of the object based on the distortion of the pattern (Geng 2011; Salvi *et al.*, 2010). For this project, 3D dental models were generated using a GOM ATOS 80 Scanner (GOM, Braunschweig, Germany), kindly made available by the Department of Engineering at the University of Cambridge (https://whittle.eng.cam.ac.uk/lab/facilities/gom-scanner-photogrammetry-system/). The scanning system uses a blue light projector, to filter out ambient light better. Each dental model was mounted onto the robotic arm of the scanner using a magnet and zinc-coated steel washer glued to the base of the dental model (Figure 52). The GOM scanner offers a minimum point-to-point spacing of 30µm. Data acquired were imported directly into ATOS professional (v 2018 Hotfix 3; GOM, Braunschweig, Germany), the software used to operate the 3D scanner, and then converted into a polygonal mesh, which could be exported in stereolithography (.stl) format for analysis.

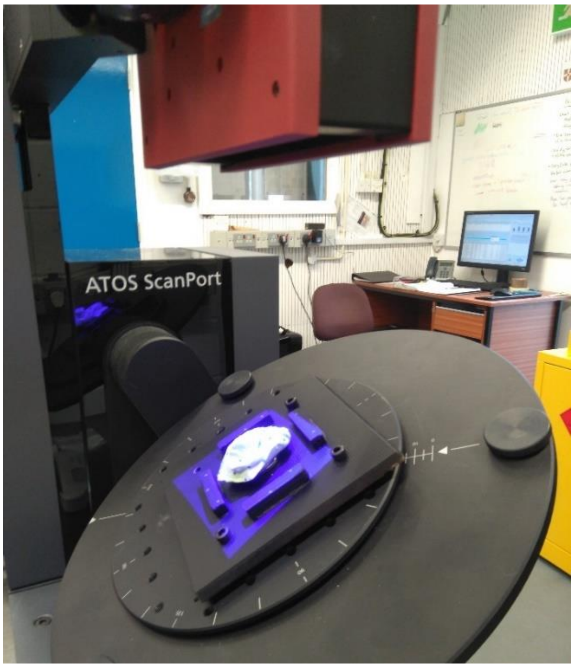


Figure 52: GOM ATOS Core 80 Scanner used for 3D model acquisition. The specimen is scanned from multiple viewpoints to generate a complete reconstruction of the object's surface. The scanner requires at least 3 markers to be visible in each scanned data cloud for automatic alignment of scans to be performed.

5.2.2.2.3 The fidelity of 3D dental models generated using Structure from Motion Photogrammetry.

To determine whether the SfM models produced were suitable for OFA, a qualitative and quantitative comparison of the fidelity of the photogrammetric dental models was undertaken using reference 3D models generated using the GOM SLS scanner. The SfM, FS-SfM and SLS virtual models used to perform this assessment were produced using dental gypsum models of lower second molars (n=17) from the St Michael's Litten (ESC11) assemblage. Only 9 3D dental models were produced using FS-SfM due to the time intensive character of 3D model generation using this method. The comparison of the quality of the 3D models produced involved:

- A qualitative examination of the surface detail of the 3D models produced.
- A repeatability study of photogrammetric model generation and a quantitative assessment of how closely the photogrammetric dental models approximated the overall size and shape of the 3D model produced using the SLS scanner.

- A comparison of the wear facet area data generated when applying OFA to SfM, FS-SfM and SLS versions of the same lower second molar.

5.2.2.2.3.1 Qualitative assessment of photogrammetric model detail and surface quality

The major features of the occlusal surface, such as the fissure system and arrangement of cusps, were readily visible on the 3D models generated using all three methods. The surfaces of the SfM models were characterised by a high level of point redundancy and noise across the occlusal surface, however, resulting in a 3D mesh in which the boundaries of dental wear facets and other topographic features were poorly defined (Figure 53). The surface details on the 3D models generated using FS-SfM were characterised by particularly high levels of surface noise and extremely high point densities. Despite this, the definition of surface features, particularly the boundaries of dental wear facets, was slightly enhanced on the FS-SfM models relative to those derived using conventional SfM (Figure 54).

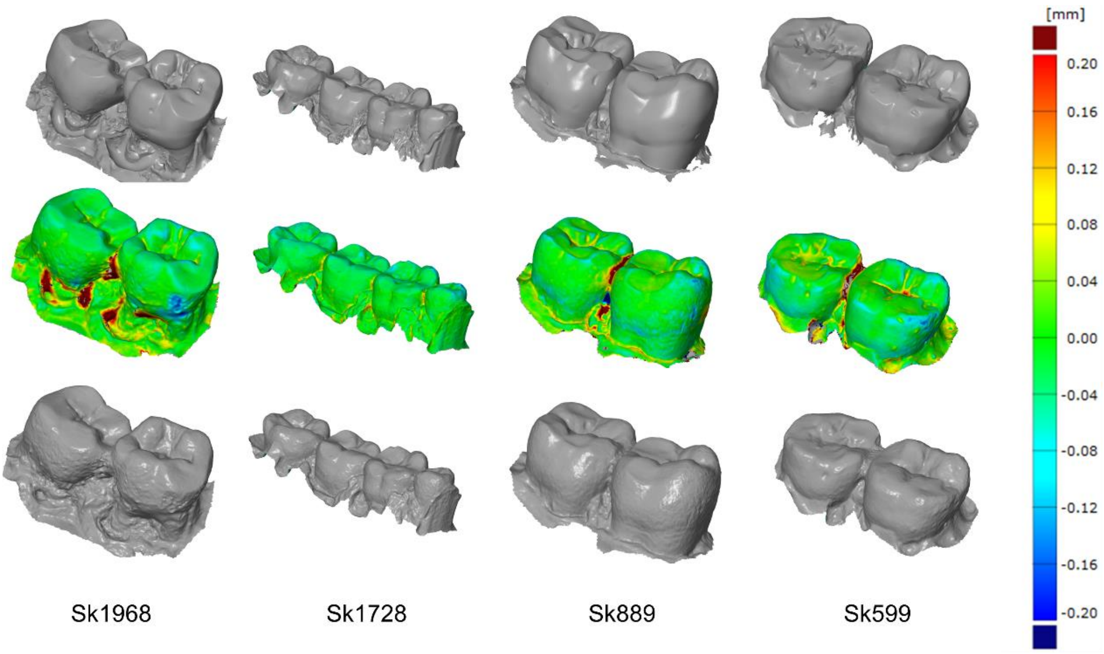


Figure 53: Examples of SfM (Lower row) and SLS versions (Upper row) of four 3D dental models. The central row presents visualisations of the deviation between the aligned meshes expressed using the colour scale on the right.

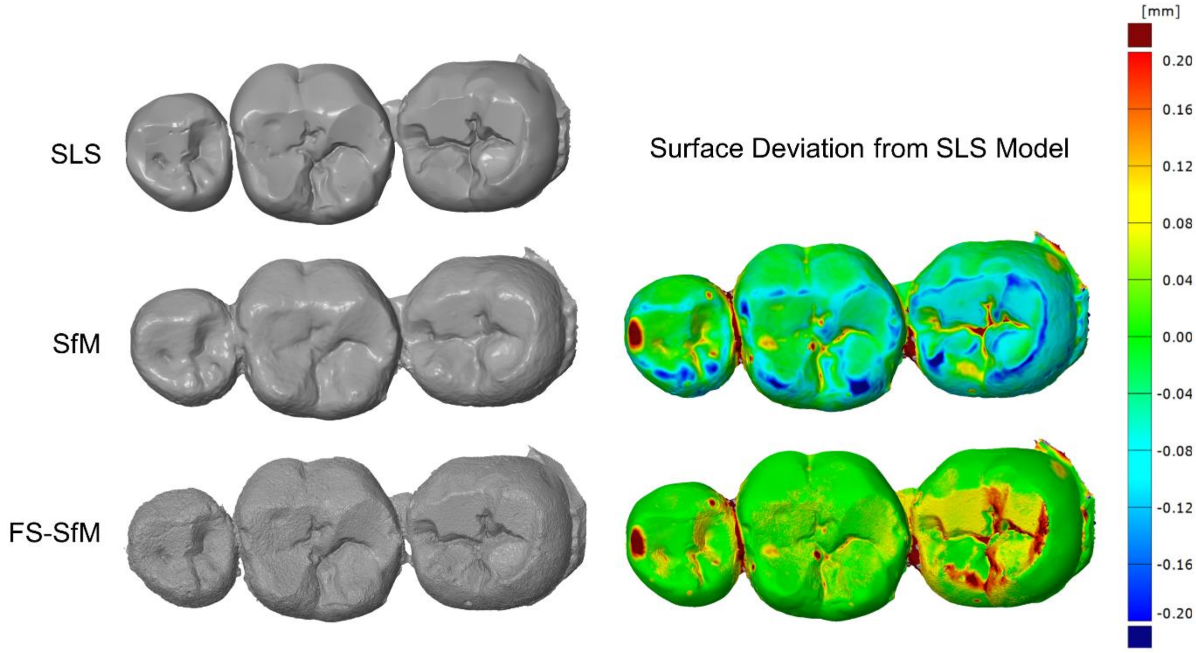


Figure 54: Occlusal view of 3D models of SK4293 generated using SLS, SfM and FS-SfM. The surface deviation between the SfM and SLS model and the FS-SfM and SLS model is visualised in the images on the right using the colour ramp.

5.2.2.2.3.2 Repeatability of photogrammetric model generation and accuracy of representation of overall tooth geometry by SfM models.

Concerns have been raised over the repeatability and accuracy of SfM (Napolitano and Glisic, 2018), therefore, prior to quantitatively comparing the SfM with the SLS models a repeatability study was conducted to investigate the consistency with which SfM can generate 3D models of the same object when the sequence of image capture is closely replicated. The process of SfM image capture and model generation was conducted twice for three dental models from the St Michael's Litten assemblage using the custom-built camera rig. Repeated image capture was performed on separate days. Following 3D model generation, the two versions of the 3D model of each specimen were aligned and the distances between the two-point clouds measured using CloudCompare software (v 2.9.1). The alignment of the two 3D models was performed using the fine registration function in the software, which uses the Iterative Closest Point algorithm. The same protocol was followed to determine how closely the SfM and FS-SfM models approximated the overall geometry of the 3D SLS reference models.

Photogrammetric model generation using the camera rig for image capture resulted in models of consistent and replicable quality. The mean difference between replicate photogrammetric models ranged from 59 to 90µm (Figure 55). The virtual 3D models generated using SfM were of relatively consistent quality and could be readily replicated due to the production of a camera rig that ensured the sequence and distribution of image capture was highly repeatable. A study of the repeatability of 3D photogrammetric model generation of a plaster model of a full dental arcade reported levels of discrepancy between replicates of up to 500µm and a mean value of 204µm; the greatest deviation was concentrated in the posterior dentition. When the assessment of model deviation involved a subset of the full arcade, as was the case in the current research, the mean value of deviation between replicates was reduced to 57µm (Stuani *et al.* 2019). This reflected the deviation found between repeated photogrammetric models in the current assessment and suggests that this magnitude of error is to be anticipated within the model generation process.

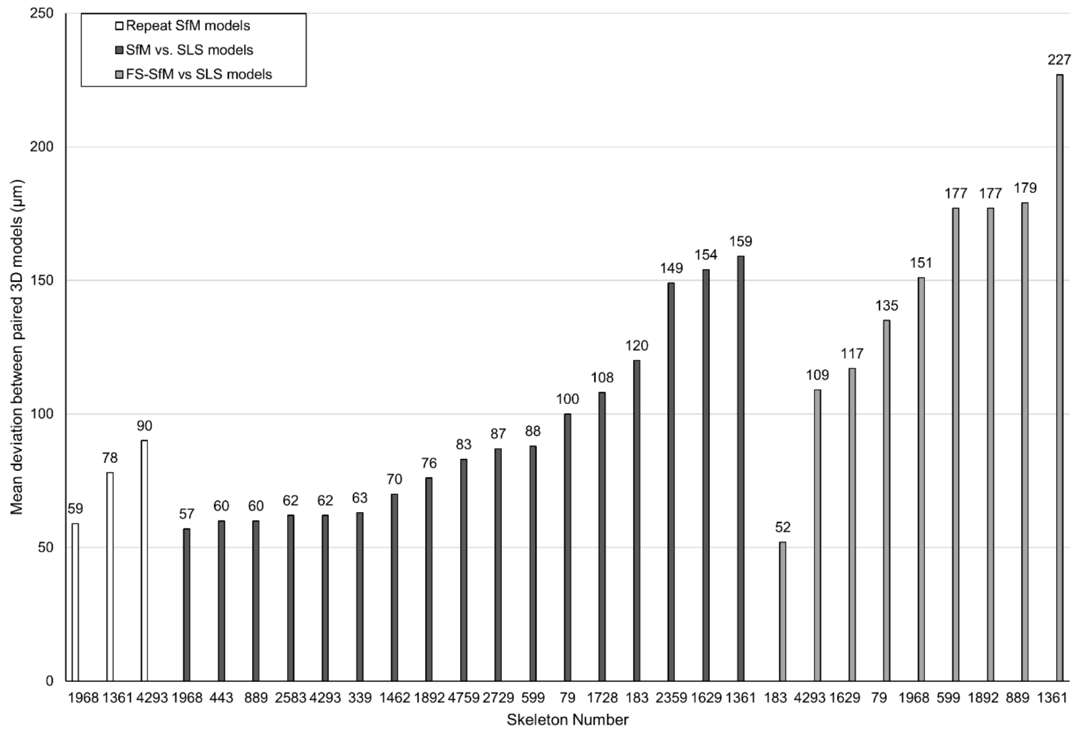


Figure 55: Bar chart showing the mean difference between aligned replicate SfM 3D models (white), the mean difference between 3D models generated using SfM and SLS (dark grey) and the mean difference between 3D models generated using FS-SfM and SLS (light grey).

The deviation between matched SLS and SfM point clouds was relatively low with mean differences between aligned point clouds ranging from 57 to 159µm (Figure 53 to Figure 55). Focus stacking did not result in 3D models that more closely approximate the overall dimensions of the SLS reference models (Figure 55). Overall tooth shape was captured effectively using SfM photogrammetry and supports previous studies that have found relatively low levels of deviation between point clouds of small objects derived from SfM and SLS systems (<100 µm) (Kontogianni *et al.* 2017a, Kontogianni *et al.* 2017b). The close approximation of the overall size and shape of the SfM virtual models is close to the 0.1mm accuracy that has been suggested as necessary for virtual models to have diagnostic value for clinical treatment (Taneva *et al.* 2015; Fu *et al.* 2017).

5.2.2.2.3.3 A quantitative assessment of whether SfM and FS-SfM models can be used to conduct OFA

In order to assess whether the photogrammetric 3D dental models produced were of sufficient quality for the requirements of the current project, the procedure for conducting OFA, described in section 5.2.2.3, was applied to SfM, FS-SfM and SLS versions of the same tooth (n=17 for the SfM models and n=9 for the FS-SfM models). The size of each wear facet identified was calculated and compared between the different digital versions of the same tooth. In addition, the crown area of each tooth at the level of the central fossa was calculated using the method described in section 5.2.2.3.8.

Measurements were compared using the Bland-Altman approach (1986). Close agreement would be indicated by a mean difference between measurements close to 0 and 95% limits of agreement that are small relative to the magnitude of the measurements being taken. Percentage error was calculated for each comparison to describe the relationship between the magnitude of the measurement and the error in the measurement. Paired sample t-tests and repeated-measures ANOVA were used to determine whether any differences in measurement were significant. Statistical analysis was conducted in R statistical software (v.3.6.1). The potential for agreement between two methods will depend on the repeatability of each measurement (Bland and Altman, 1986). Consequently, dental wear facet identification and area measurements were performed 10 times on the SfM and SLS models of a single specimen (Sk1968). Each of these measurement sets was obtained on a different day. Harris and Smith suggested that relative technical error of measurement (TEM) and ANOVA provide good indications of measurement precision (2009). The absolute and relative technical error of measurement (TEM) were calculated for the repeated SfM and SLS facet area measurements using the method outlined by Langley *et al.* (2018). A relative TEM in the assessment of metric traits of <1.5% for intra-observer error was deemed acceptable (Langley *et al.* 2018).

The mean difference between measurements of crown area between SfM and SLS models did not differ significantly (Table 34). Most values fell within the 95% limits of agreement (Figure 56). Crown area differed significantly between FS-SfM and the SLS reference models, however, the percentage error was smaller for the FS-SfM models than the SfM models (Figure 56). Wear facet area measurements were significantly larger in the SfM models than in the reference SLS models (Table 34). The percentage error was 101% (Figure 56). Wear facet area measurements also differed significantly between the FS-SfM and SLS models, however, the magnitude of this difference was smaller (Table 34; Figure 56). The percentage error figure was markedly less when comparing differences in crown area measurements relative to differences in wear facet area measurement. In addition, ten of the wear facets evident in the gypsum model and the SLS model could not be identified in the SfM model due to the poor quality of the occlusal surface detail.

Table 34: Results of paired sample t-tests comparing crown area and wear facet area measurements derived using photogrammetric dental models and the SLS reference models.

Comparison	t	df	p-value	Mean difference	95% CI lower	95% CI upper
SfM vs SLS Crown Area	-0.59	16	0.56	-0.24	-1.10	0.62
FS-SfM vs SLS Crown Area	5.15	8	<0.001	2.54	1.75	4.57
SfM vs SLS Facet Area	-6.10	143	<0.001	-0.55	-0.72	-0.37
FS-SfM vs SLS Facet Area	2.02	78	0.05	0.14	0.002	0.28

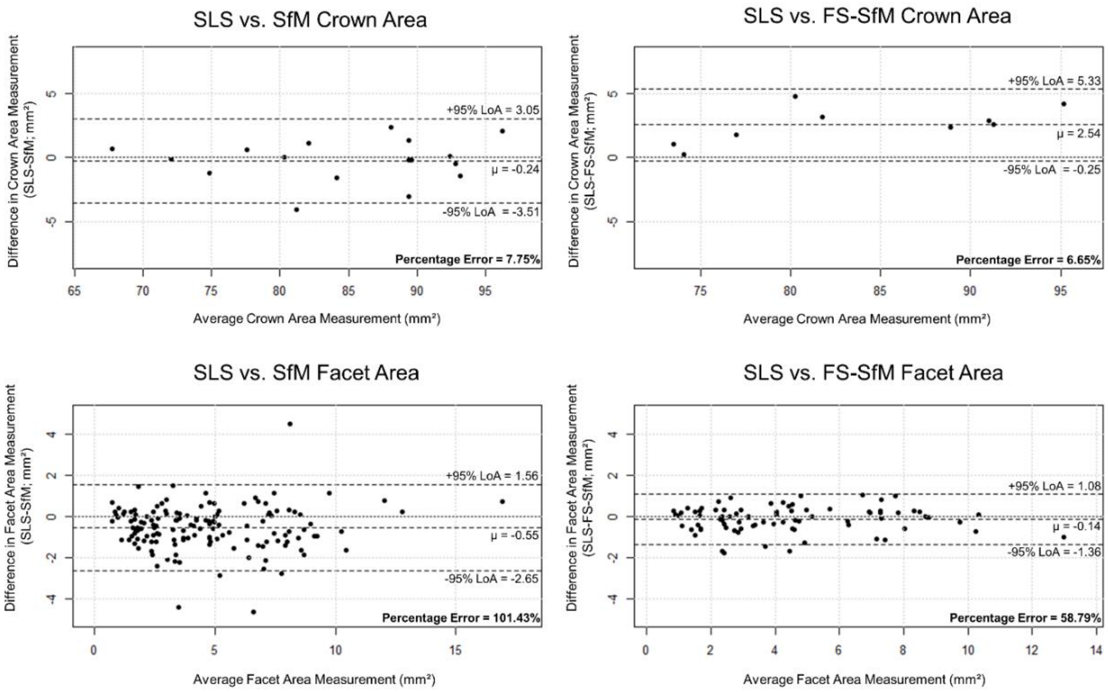


Figure 56: Bland-Altman plots illustrating the distribution of differences between crown area measurements (mm^2) of SLS and SfM models (upper left); crown area measurements (mm^2) of SLS and FS-SfM models (upper right); wear facet area measurements (mm^2) of SLS and SfM models (lower left); wear facet area measurements (mm^2) of SLS and FS-SfM models (lower right). The upper and lower 95% limits of agreement (LoA) are given.

Relative TEM was markedly larger when measuring and identifying occlusal wear facets in the SfM models when compared to the SLS models (Table 35). The large relative TEM for wear facet area measurement in the SfM models was beyond the level of acceptability for repeated measures of metrics (>1.5%) (Langley *et al.* 2018). The mean measurements for wear facet area were not significantly different between the ten repeated sets of measurements for the photogrammetric models (Repeated measures ANOVA, F (df= 4.50) = 1.89, p=0.11), however, the magnitude of difference between the means of repeated measurement sets was smaller for the SLS models (Repeated measure ANOVA, F (df= 3.65) =0.57, p=0.67).

Table 35: Table comparing absolute and relative TEM for wear facet area measurements in SfM and SLS 3D models of Sk 1968 (ESC11).

	SfM	SLS
Absolute TEM	0.38	0.06
Relative TEM (%)	8.21	1.36

5.2.2.2.4 Implications of methodological assessment of structure-from-motion photogrammetry for the current research

SfM provided a method for generating virtual dental models of consistent quality that closely approximated the size and shape of those derived using an SLS system, if not providing sufficient detail for the current project (Silvester and Hillson 2020). Previous studies have similarly highlighted the potential for photogrammetry to closely preserve object geometry and yield measurements comparable to those derived from 3D models produced using high resolution scanning techniques (Fourie *et al.* 2011; Katz and Friess, 2014). Measurements derived from photogrammetric models of larger skeletal elements, such as crania, have also been shown to be comparable to those taken using the original specimens (Morgan, Ford and Smith, 2019). Other studies have highlighted the efficacy with which 3D shape analysis and identification can be performed using photogrammetric models; for example, the variation in ear shape among Qin terracotta warriors has been quantified (Bevan *et al.* 2014) and 3D reference collections of insect specimens have been successfully generated to assist identification (Nguyen *et al.* 2014; Ströbel *et al.* 2018).

Despite the high levels of repeatability and the capacity of SfM models to approximate closely the overall size and shape of teeth, the representation of small-scale details of the occlusal topography and dental wear patterns was poor when compared to the SLS reference models. Teeth are characterised by areas lacking textural variation alongside areas with textural variation occurring at a very small-scale which may limit the potential for passive non-contact imaging techniques, such as SfM, to locate correspondences between images (Santoši *et al.* 2018). There was a tendency to overestimate wear facet size where boundaries were difficult to define due to high levels of surface noise and poor definition of surface details. This is consistent with the study by Evin *et al.* (2016) which found that the tooth rows of wolf crania were captured in more detail using an SLS system rather than photogrammetry. Similarly, a pilot study examining the utility and practicality of using photogrammetry to digitise casts of full dental arcades found that the technique was inferior in performance to high resolution dental scanners and was not of sufficient accuracy to be incorporated into treatment workflows, however, they may still have diagnostic value (Stuani *et al.*

2019). The deviation between wear facet area measurement derived from the SfM and SLS models exceeded the magnitude of variation between individuals and assemblages examined in previous OFA studies (e.g. Fiorenza *et al.* 2011a) suggesting that SfM, when conducted using the methods outlined in the current study, does not yield virtual models of adequate quality for the analysis of dental macrowear patterns. In addition, the identification of several facets, typically less than 1.5 mm^2 in area, was frequently not possible on the SfM models as they simply were not visible.

Focus stacking was associated with a slight increase in the quality of the capture of surface details when compared to conventional SfM. This slightly improved the accuracy of wear facet identification and measurement, however, high levels of surface noise meant that the deviation of these measurements from those derived from the SLS reference models was still beyond the limits of acceptability for the performance of OFA. Model quality remained inadequate to perform OFA without extensive mesh decimation and smoothing, which may have detrimental effects on topology and measurements (Veneziano *et al.* 2018). Similar improvements in the accuracy of the reconstruction of fine scale surface detail have been reported when using focus-stacking to generate 3D models of archaeological ceramics and figurines (Clini *et al.* 2016; Kontogianni *et al.* 2017b; Kontogianni *et al.* 2017b). High quality 3D models have been generated of extremely small insect specimens (1.5mm body size) using focus stacked photogrammetry, however, these results were achieved using a complex workflow and largely automated systems (Nguyen *et al.* 2014; Ströbel *et al.* 2018). The high input of time needed for capturing and processing the images required for focus stacking (Gallo *et al.* 2014) renders it impractical for the generation of large numbers of 3D dental models without access to a specially designed automated system. A SLS system provides a more rapid and detailed surface acquisition method where available.

Consequently, due to the limitations of SfM and FS-SfM discussed, the 3D models in the current project were generated using the SLS system described in section 5.2.2.2.2 to ensure higher levels of accuracy and precision when conducting OFA.

5.2.2.3 Static OFA using GOM Inspect

5.2.2.3.1 Initial Virtual Model Preparation

Previous studies (such as Fiorenza (2009)and Kullmer *et al.* (2009)) have developed a workflow for conducting OFA in the software package Polyworks (Innovmetric). This software was not available at UCL and is prohibitively expensive, therefore, GOM Inspect (GOM, Braunschweig, Germany) was identified as a free alternative to Polyworks. A workflow for conducting OFA in GOM Inspect (Version 2018 Hotfix 6) was developed for the current project.

Surface smoothing and decimation are often applied within 3D modelling to reduce topographic noise and the faceted appearance of 3D models. Surface smoothing relocates the vertices of a mesh to obtain a smoothly curved surface. Decimation reduces the overall number of triangles in the mesh whilst attempting to retain the overall shape of the object. The high quality of the SLS scan data generated meant that the meshes generated for the current project did not require any smoothing or decimation. This prevented the potential loss of topographic detail and distortion of measurements that have been associated with applying these mesh editing processes (Veneziano *et al.* 2018). In virtual models involving multiple teeth, the lower second molar was first isolated by selecting and deleting the adjacent teeth. The isolated tooth model could then be analysed separately (Figure 57).

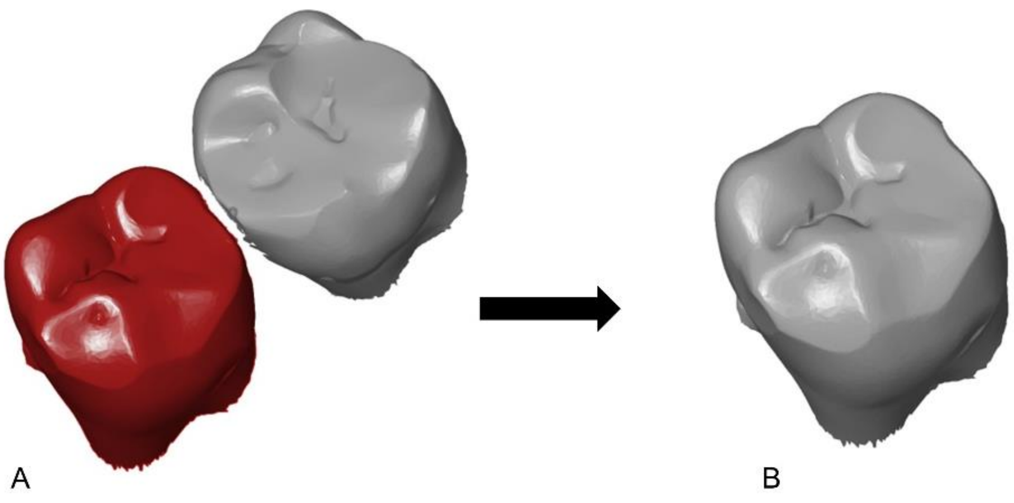


Figure 57: The virtual segmentation of the molar row: A) The lower second molar is selected from the virtual tooth row. B) The selection is inverted and the other teeth deleted isolating the lower second molar for analysis.

Occasionally very small air bubbles were present on the dental gypsum models and these defects were reproduced on the surface of the virtual dental model created by the SLS system. These areas were manually identified, outlined and removed from the virtual model and the surface reconstructed using the close hole function in GOM Inspect. Teeth cut from molar tooth rows were frequently missing mesial and distal surfaces obscured by neighbouring teeth. Following segmentation from the molar row, any missing surfaces were virtually reconstructed in GOM Inspect providing an approximation of the actual surface (Figure 58). This process utilised the existing 3D mesh to extrapolate the geometry of the missing 3D surface. This approach is most effective when applied to planar regions rather than areas of more complex topography.

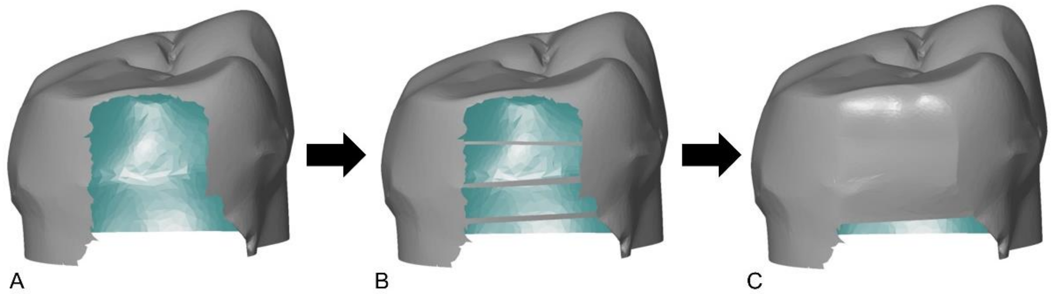


Figure 58: Reconstruction of missing tooth surfaces. A) The missing distal surface of a lower second molar extracted from a tooth row. B) Mesh bridges are constructed across the missing area. C) The interactive hole closing function is used to virtually reconstruct the missing surfaces between the mesh bridges.

5.2.2.3.2 Orientation

OFA requires each specimen to be orientated in the same way prior to wear facet analysis. This was achieved using a standard reference plane fitted to the cervical margin of the tooth. A curve was drawn around the cervix of the tooth and the area 0.5mm either side of it was selected. A gaussian best-fit plane was then fitted to the selected area. The reference plane needs to be independent of the occlusal surface as dental wear progressively modifies and obliterates landmarks on the crown (Figure 59) (Kullmer *et al.* 2009; Ulhaas *et al.* 2004). The cervical plane of each tooth model was then translated to a standardised x-y plane (Kullmer *et al.* 2009). The buccal direction was aligned with the positive y direction, the mesial axis of the tooth was aligned with the positive x direction (in left teeth) and the occlusal direction was aligned with the positive z direction.

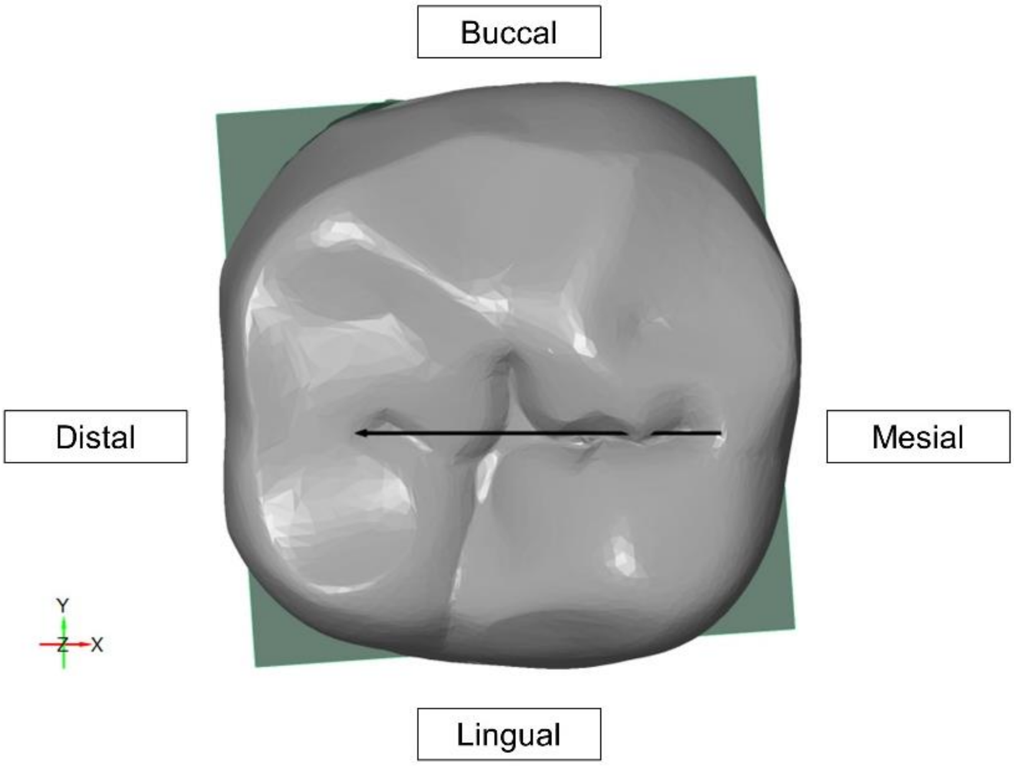


Figure 59: Each tooth was orientated using the plane-line-point function in GOM Inspect. The cervical reference plane becomes the z-plane, the mesial-distal axis of the tooth becomes the x-axis, and the deepest point of the central fossae becomes point (0, 0, 0) within the virtual model's coordinate system. The mesial-distal axis was defined by two points: the first was the most mesial aspect of the fissure system and the second was the most distal aspect of the fissure system.

5.2.2.3.3 Wear Facet Identification and Area Measurement

Once aligned, the wear facets on the occlusal surface of each specimen were delineated using a surface curve (Figure 60). The resolution of the three-dimensional virtual models was adequate for wear facet identification, but, the occlusal surface was not always reproduced exactly and occasional blurring of the boundaries of adjoining facet areas occurred due to the limitations of model construction and visualisation. An epoxy resin replica of the tooth was available to confirm wear facet boundaries and increase the accuracy of wear facet identification.

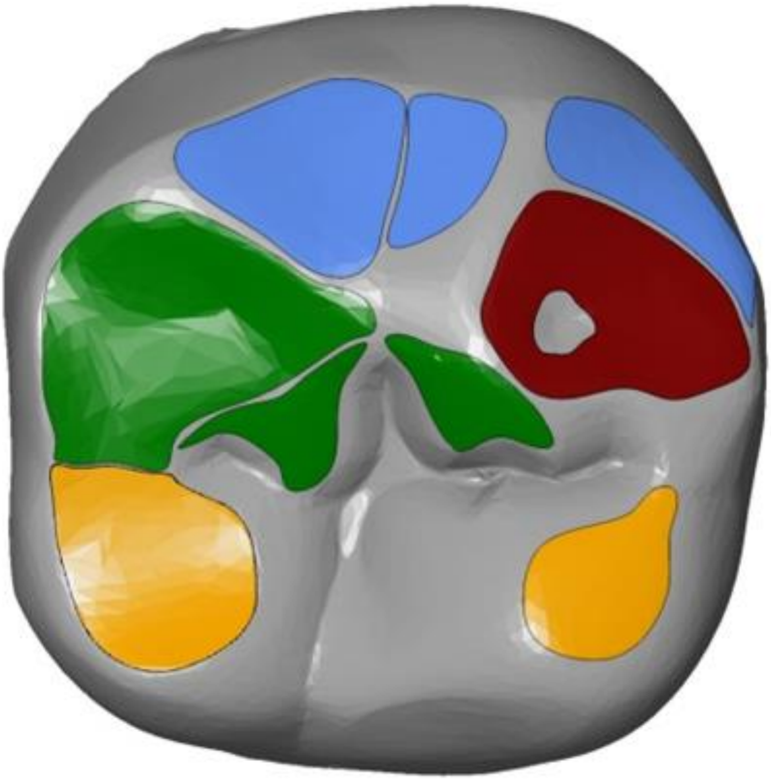


Figure 60: Wear facet identification and area measurement. Wear facets outlined on the virtual dental model. Buccal phase I wear facets are coloured light blue, lingual phase I facets are coloured orange and phase II wear facets are coloured green. The tip crushing area on the protoconid is highlighted with brown; note slight dentine exposure.

The mesh area bounded by the curve demarcating the border of each wear facet was selected in turn and measured to give the area of the wear facet in mm^2. Larger teeth will typically develop larger wear facets than their smaller counterparts when they both exhibit a similar wear stage. Consequently, the size factor had to be removed for comparisons to be made between teeth by dividing each wear facet group by the total wear facet area across the occlusal surface, excluding tip crushing areas. Individual wear facet area was scaled using total wear facet area rather than projected crown area as a measure of tooth size for two reasons. Firstly, the analysis of wear facet area composition sought to highlight differences in dental function during the power stroke. As such, the primary focus was on the ratio between the different wear facet types that comprise the total wear facet area rather than the overall quantity of wear expressed as a proportion of projected crown area. Secondly, this ensured that the wear facets formed a composition which summed to 100% enabling the data to be analysed using a compositional statistical approach (Section 5.2.2.5.1).

For each tooth, wear facets were first grouped according to their functional role during the power stroke (Section 3.4.1): buccal phase I wear (facets 1, 2, 3 and 4), lingual phase I wear (facets 5, 6, 7 and 8) and phase II wear (facets 9, 10, 11, 12 and 13). The relative proportion of the total wear facet area constituted by each wear facet group was then calculated. The formula used to calculate relative buccal phase I area is given below as an example:

$$Relative\ Buccal\ Phase\ I\ Facet\ Area = \frac{Sum\ of\ the\ areas\ of\ facets\ 1, 2, 3\ and\ 4}{Total\ wear\ facet\ area} \times 100$$

Tip crushing areas were also identified predominantly on the tips of the buccal molar cusps. These wear areas lack a clearly defined dip direction, are frequently more shallowly inclined than wear facets associated with the power stroke and have more poorly demarcated boundaries (Kullmer *et al.* 2009). They cannot be definitively attributed to the normal power stroke and may be principally active during puncture-crushing cycles so were considered separately from phase I and II wear facets (Fiorenza *et al.* 2018; Janis 1990). For each tooth with identifiable tip crushing areas, a tip crushing index (TCI) was calculated using the following formula in which the total tip crushing area is expressed as a proportion of the total two-dimensional planar area of the tooth (Figure 61). This acted to eliminate the influence of tooth size on the total tip crushing wear area dimensions obtained.

$$Tip\ Crushing\ Index\ (TCI) = \frac{Total\ Area\ of\ Tip\ Crushing\ Area}{2D\ Planar\ Tooth\ Area} \times 100$$

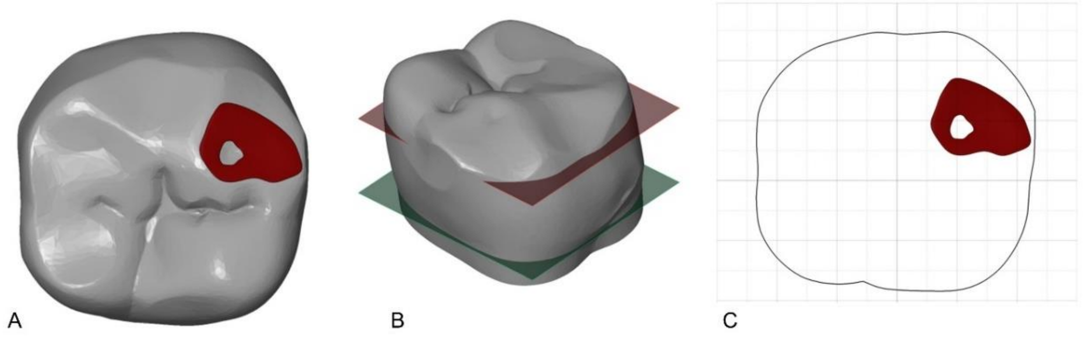


Figure 61: Procedure for obtaining the tip crushing index (TCI). A) Tip crushing areas are demarcated and their area measured. B) An occlusal plane is created by translating the cervical reference plane (green) to the level of the deepest point of the central fossa (red). The cross-sectional area of the tooth crown is calculated at the level of the occlusal plane. C) Total tip crushing area is expressed as a proportion of the two-dimensional planar area of the tooth at the level of the occlusal plane.

5.2.2.3.4 Dip angle

The orientation of each wear facet in three-dimensional space was defined by its dip angle and dip direction. The dip angle is the inclination of the wear facet in relation to the cervical reference plane (Figure 62) (Kullmer *et al.* 2009).

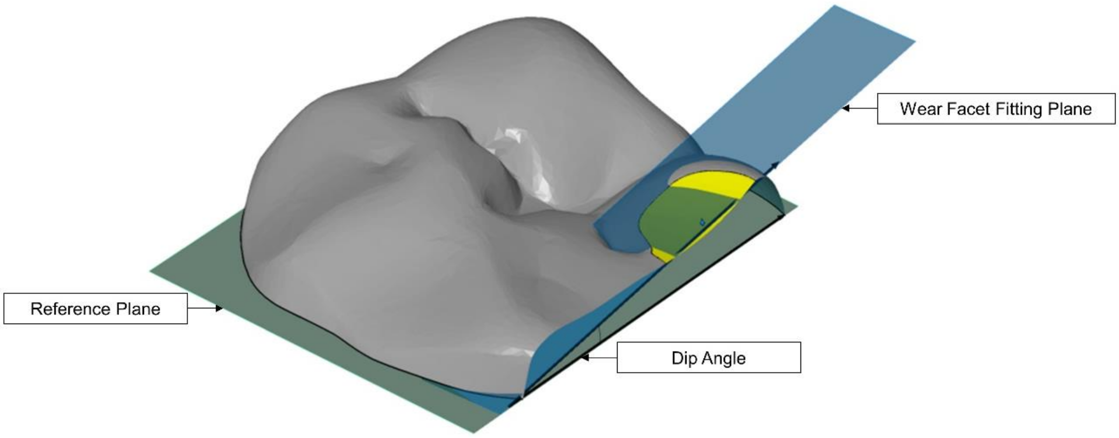


Figure 62: A Gaussian fitting plane is projected onto each identified wear facet. The dip angle is the angle between the cervical reference plane and a best-fit plane projected onto the wear facet.

5.2.2.3.5 Dip direction

Dip direction describes the direction in which the wear facet is orientated measured from 0° to 360° (Figure 63 and Figure 64) (Kullmer *et al.* 2009). This angle is perpendicular to the strike angle, which is the horizontal orientation of the plane fitted to the wear facet measured in relation to the mesio-distal axis of the tooth crown. The mesial direction of the aligned tooth model is defined as 0°. Dip direction angles for medioprotrusive and mediotrusive facets are given by GOM Inspect as positive values between 0° and 180°. These values are converted to a 0° and 360° scale by subtracting them from 360° to make them consistent with previous OFA studies (e.g. Fiorenza *et al.* 2018). Dip direction is measured clockwise from the mesial point for teeth from the right side and anti-clockwise for teeth from the left.

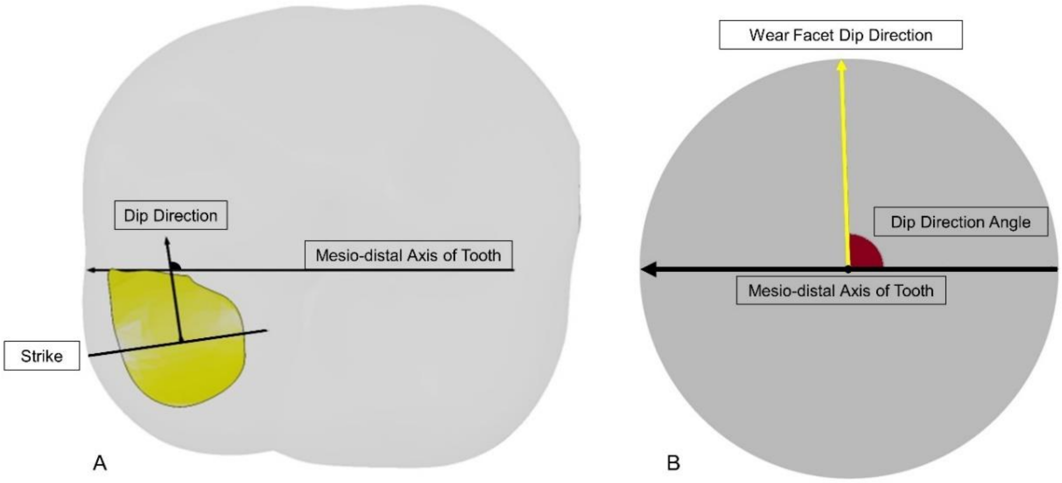


Figure 63: Wear Facet Dip Direction: A) Occlusal view of tooth showing the dip direction of the wear facet shown. This is perpendicular to the normal of the wear facet's gaussian best-fit plane created to calculate the dip angle B) When projected onto the cervical reference plane, the dip direction is the angle between the mesio-distal axis of the tooth (defined as 0°) and the vector defining the direction in which the wear facet is inclined.

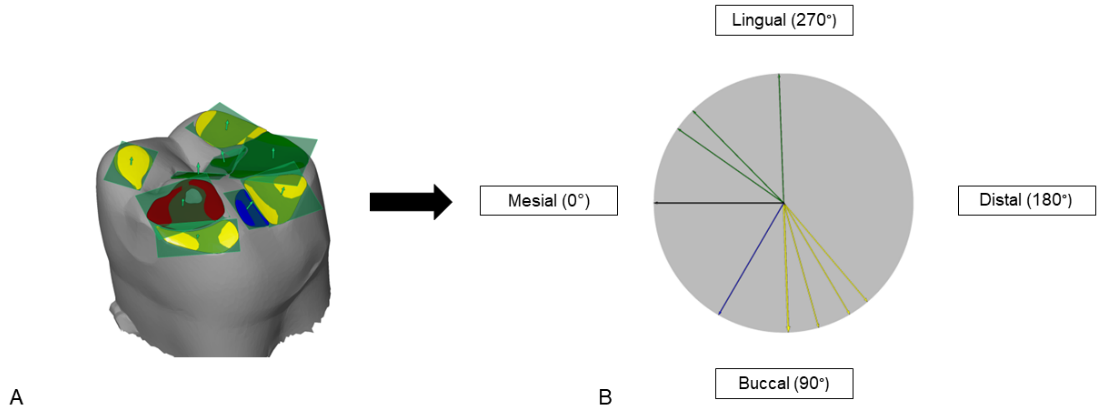


Figure 64: A) To measure the dip direction, each facet best-fit plane is projected onto the cervical reference plane to create its dip direction plane. The normal of this projected plane is defined by the cross product of the normal of the reference plane and the wear facet's best-fit plane. A dip direction reference plane is created by constructing a plane that is defined by the cross-product of the mesio-distal axis (x axis) of the aligned tooth model and the normal of the reference plane. B) Two-dimensional occlusal compass showing dip directions of the wear facets. Dip direction is the angle between the normals of these two projected planes. The black line at 0° indicates the mesial axis of the tooth against which dip direction is measured. The example represents a second molar from the left side of the dentition.

5.2.2.3.6 3D Occlusal Compass Generation

In order to produce a vector that summarises both the dip angle and dip direction, a line is created with its origin at point 0, 0, 0 within the aligned dental models coordinate system that is orthogonal to the dip direction plane for the wear facet and its best-fit plane projected onto the wear facet. This process is repeated for each wear facet to produce a compass diagram (Figure 65). The occlusal compass enables prominent jaw movement pathways to be inferred based on the orientation and inclination of each wear facet. The OFA compass of an anatomically modern human, that exhibits a typical pattern of occlusal contacts, should consist of the four major directions of jaw movement with relatively clear differentiation between the directions of movement (Fiorenza and Kullmer 2016). Wear facets 1, 4, 5, 8 are typically associated with lateroretrusion, wear facets 2, 3, 6 and 7 with lateroprotrusion, facets 9, 11 and 12 with mediotrusion and immediate side shift and facets 10 and 13 with medioprotrusion (as discussed in section 3.6). There is often overlap between medioprotrusive and mediotrusive wear facets, however. Tip crushing facets are not included in the OFA compass as they cannot solely be attributed to the power stroke and may be in function during other parts of the chewing cycle (Fiorenza *et al.* 2018).

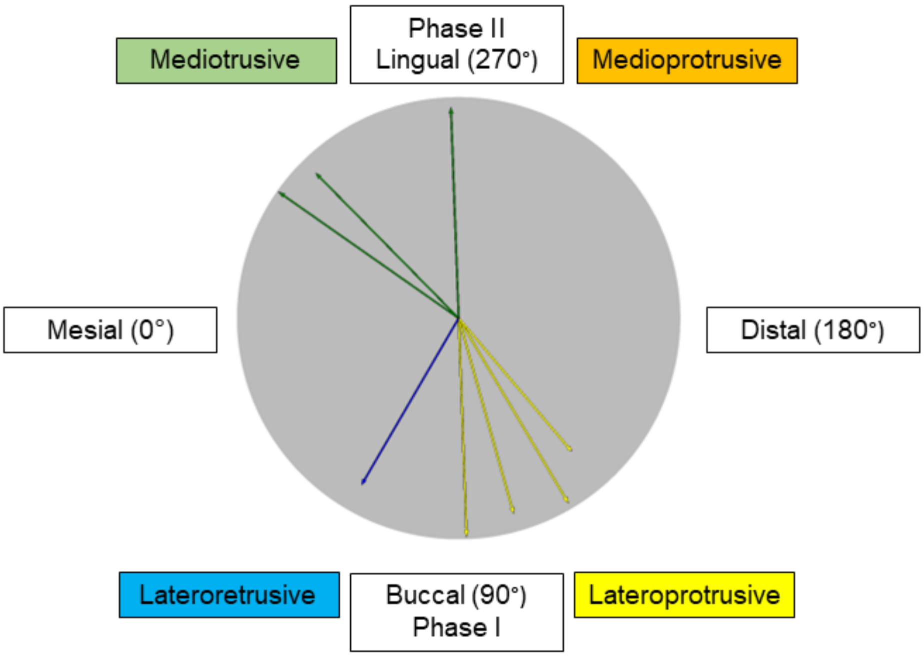


Figure 65: Illustration of the occlusal compass concept. Each wear facet is represented by a single vector. Lateroretrusive facets are typically associated with a dip direction of 0-90°, lateroprotrusive facets with 90-180°, medioprotrusive facets 180-270° and mediotrusive facets 270-360°. Medioprotrusive and mediotrusive vectors are often overlapping (Fiorenza and Kullmer 2016). The directions of jaw movement required to bring each wear facet into contact with its antagonist takes maximum intercuspation as its starting point. Phase I facets generally have dip directions between 0-180° and phase II facets between 180-360°. The proximity of the vector to the edge of the circle indicates the steepness of the inclination of the wear facet relative to the reference plane; vectors closer to the edge of the circle are less steep.

5.2.2.3.7 Mastication Compass

The mastication compass concept provides a means of visualising the direction and inclination of jaw movement during each phase of the power stroke in three-dimensions using a two-dimensional diagram (Koenigswald *et al.* 2013). This builds on the occlusal compass concept by combining the orientation and inclination of each wear facet to summarise the overall incursive and excursive movements during the power stroke (Figure 66). Facets 1, 3, 5 and 6 were used to calculate the orientation and inclination of the incursive phase I movement as the teeth move into maximum intercuspation. Facets 9 and 11 were used for the excursive phase II movement as the teeth move out of maximum intercuspation. The range and variation of lower jaw movements is highly dependent upon the degrees of freedom offered by the temporomandibular joint and the system of masticatory musculature (Vinyard *et al.* 2011). In addition, once the teeth come into occlusal contact, the morphology of the antagonistic tooth row will guide and modify the initial jaw movement pathway (Koenigswald *et al.* 2013). The mastication compass concept has principally been applied to interspecies comparisons examining the power strokes of extant and extinct mammals. The variation within a single species has not been extensively visualised using this method (Koenigswald *et al.* 2013; 2016).

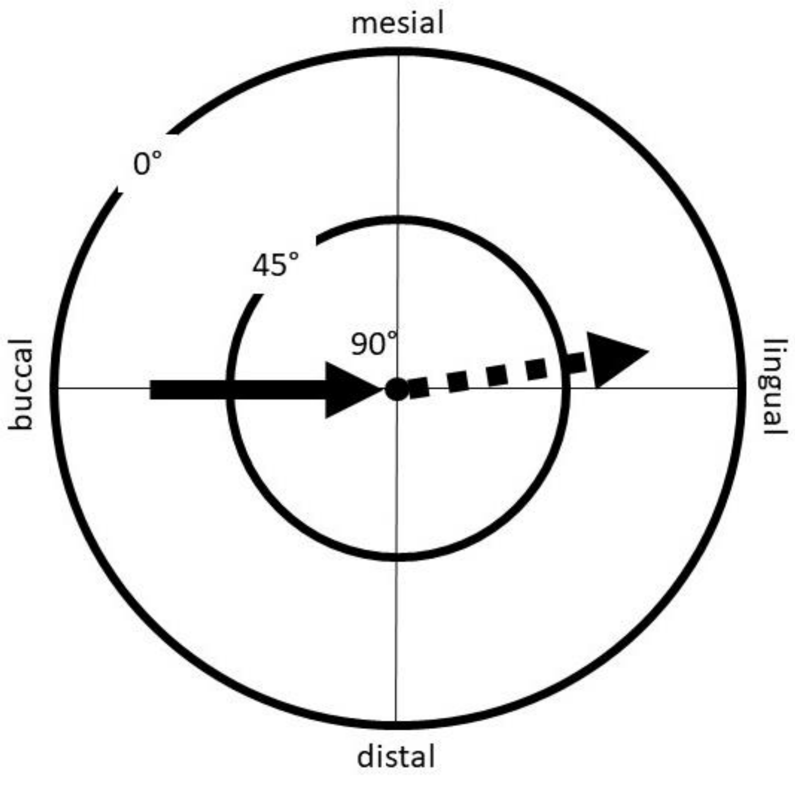


Figure 66: Mastication compass illustrating a two-phase power stroke typical of anatomically modern humans. Each compass summarises the direction of jaw movement on the left side during the power stroke. The direction of each phase of the power stroke is illustrated by an arrow within the unit circle. The origin of the circle corresponds to centric occlusion. The proximity of each arrow to the circumference of the circle indicates the inclination of each phase of the power stroke (Koenigswald et al. 2013). The example illustrates a lingually orientated upwards phase I incursive movement (represented by the black arrow) and a slightly mesio-lingually orientated excursive downwards phase II movement (represented by the dashed arrow). Phase I and phase II movements have similar inclinations in this example.

5.2.2.3.8 Occlusal Relief Index (ORI)

Occlusal relief index (ORI) provides a measure of the complexity and steepness of occlusal topography (Figure 67) (Kullmer et al. 2002; M'Kirera and Ungar 2003; Ulhaas et al. 2004). The formula for calculating ORI is:

$$Occlusal\ Relief\ Index = \frac{3D\ Tooth\ Area\ above\ level\ of\ Occlusal\ Plane}{2D\ Tooth\ Area\ at\ the\ level\ of\ Occlusal\ Plane}$$

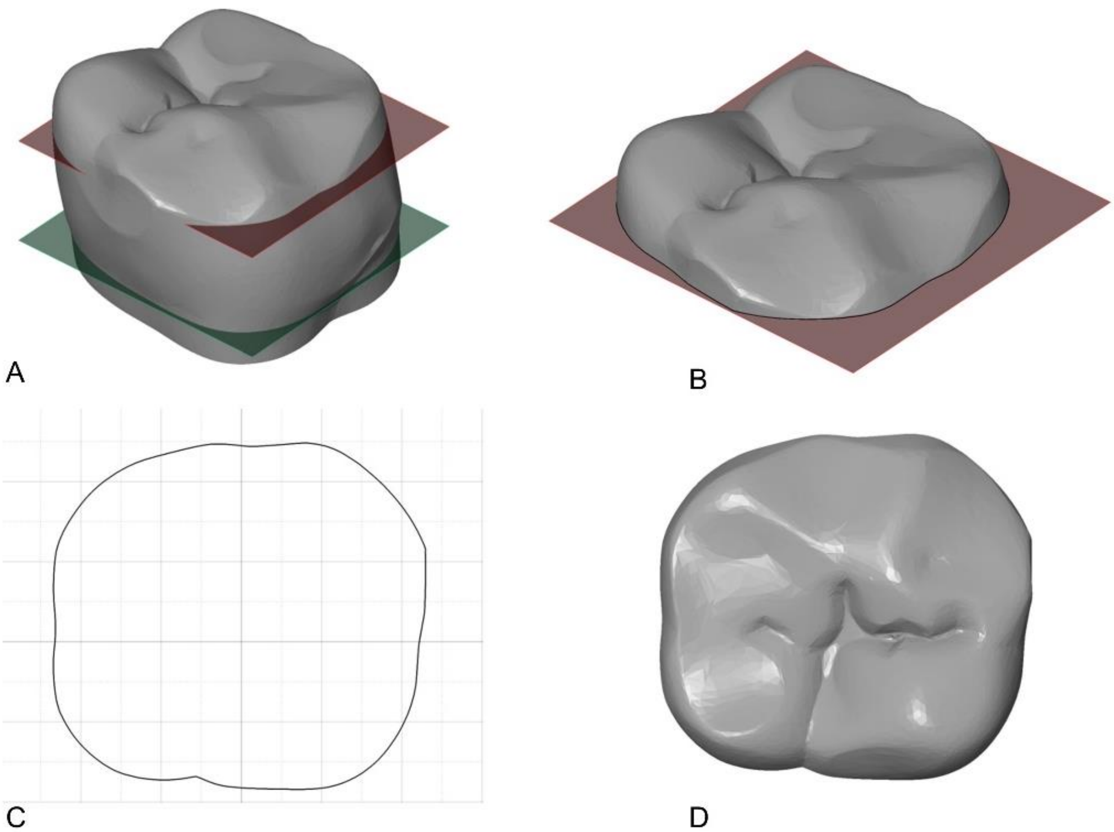


Figure 67: Process for calculating ORI using GOM Inspect. A) Firstly, the cervical reference plane (green) is translated along the z-axis to the deepest point of the occlusal surface (red). This is typically the deepest point of the central fossa. B) The polygonal model is then cut at the level of the occlusal plane. C)The 2D area of the tooth is measured at the level of the occlusal plane. D) The 3D occlusal area is measured from the level of the occlusal plane. ORI is the area of D divided by the area of C.

5.2.2.4 Dynamic OFA

The power stroke can be dynamically simulated using the Occlusal Fingerprint Analyser software package, developed by DFG Research Unit 771 (https://www.ifgeo.uni-bonn.de/en/ifg_homepage/departments/paleontology/labs/vertebraten/ehemalige-forschergruppen/for-771/ofa). This provides a complimentary approach to static OFA when reconstructing chewing patterns in skeletal material by visualising the trajectory of the lower teeth during the power stroke based on the wear facet patterns of antagonistic molars (Kullmer *et al.* 2020). This data was used, alongside the information encoded in the wear facet patterns of the lower second molars analysed, to develop the theoretical chewing models to describe and compare masticatory behaviours in the mediaeval and industrial periods in the current project (presented in section 7.1.4). A subset of the total number of individuals was selected as only a minority of the total number of individuals had adequate preservation of the upper and lower molar rows (Table 36). In addition, full dynamic OFA simulations require a high input of time, which was the major limiting factor in the number of simulations that could be performed (Table 37).

Table 36: The assemblages from which the individuals used to conduct dynamic OFA simulations were derived.

Industrial Era (1700-1900AD)		
Site	**Code**	**Number of Individuals**
St Michael's Litten, Chichester (Late)	ESC11	9
St Bride's Church, Fleet Street	SB79	5
The Church of St Hilda, Coronation Street, South Shields	CS06	4
St Peter's Wolverhampton	StP	1
	Total	19
Mediaeval and Early Post-mediaeval (1100-1700AD)		
Site	**Code**	**Number of Individuals**
St Michael's Litten, Chichester (Early)	ESC11	3
All Saint's Church, Fishergate, York	BARB	5
Hereford Cathedral	HE93	3
Box Lane	BL	0
Blackfriars	BF	0
St James and St Mary Magdalene, Chichester, West Sussex	CH86	2
	Total	13

Table 37: Details of the time taken to complete each stage of the method required to perform both static OFA and dynamic OFA for a single individual.

Stage of method	**Time input (mins)**
Initial assessment of individual dentition and biological profile.	60
Taking of dental impressions of molar rows.	20
Production of dental gypsum and resin models of upper and lower molar rows.	20
Preparation of dental gypsum model for 3D scanning and generation of 3D model using GOM SLS scanner	30
Analysis of wear facet pattern of the lower second molar in GOM Inspect	60
Alignment of upper and lower molar rows in GOM Inspect using wear facet pattern.	60
Creation of collision trajectory in Occlusal Fingerprint Analyser to simulate the power stroke.	120
Total time input per individual	370

5.2.2.4.1 Preparation and alignment of tooth rows

Dental gypsum models were produced of the upper and lower molar rows on one side of the dentition using the method described in section 5.2.2.1. 3D models of the antagonistic teeth were produced using a GOM ATOS 80 SLS system. Upper and lower models could not be scanned whilst placed in maximum intercuspation, therefore, the upper and lower molars were aligned in GOM Inspect using a best-fit alignment that matched opposing upper and lower wear facet areas (Figure 68). In the initial alignment step, the molar rows were treated as two separate virtual models and the teeth in the upper and lower molar rows were not moved independently.

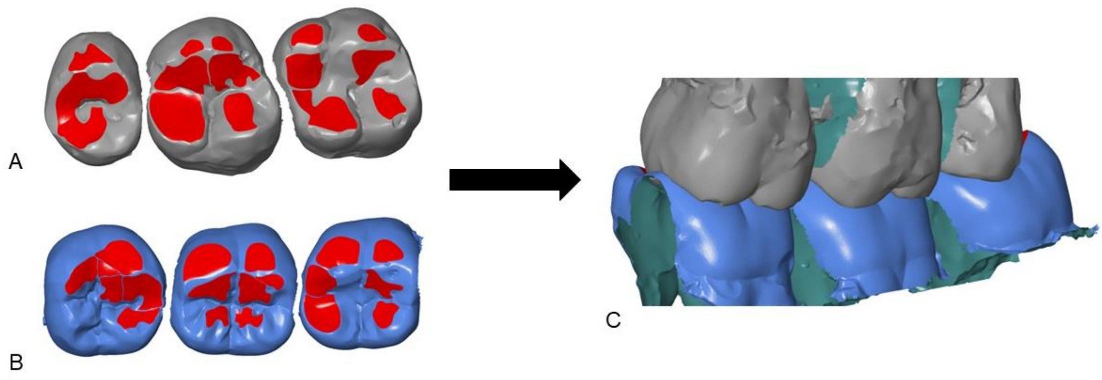


Figure 68: Process used to align upper and lower tooth rows to perform dynamic OFA. A) Upper tooth models were imported into GOM Inspect and aligned using the procedure for isolated teeth described in section 5.2.2.3.2. The upper second molar was used to create the geometry necessary to perform this alignment (The reference plane was fitted to the cervical plane of the upper second molar, the occlusal direction corresponded to the negative z direction, the mesial-distal axis of the tooth defined the x-axis and point 0, 0, 0 was defined as the tip of the protocone of the upper second molar). B) Wear facets were identified on both the upper and lower molar rows. C) The lower molars were translated and rotated into an approximation of maximum intercuspation by using a best-fit alignment procedure.

The teeth in skeletal material lack periodontal support and as a result attempts to align upper and lower molar rows in skeletal material are complicated by the slight movement of individual teeth when dental impressions are being taken. This frequently resulted in the absence of contacts at occlusal positions with well-defined wear facets after the initial alignment step. Consequently, after initial alignment, each tooth was digitally cut from the virtual molar row and aligned separately in sequence using the wear facets identified to optimise the approximation of maximum intercuspation. The second molars were aligned first as they typically retained more restrictive occlusal topography than the first molars. The first molars were then aligned followed by the third molars. Following Angle's scheme (1907), in normal occlusion each tooth, apart from the third molar, should receive the support of two antagonists. In the example given (Figure 68), occlusal support is largely limited to a single antagonist for each tooth. Teeth with clear occlusal support from two antagonists had to be aligned using the single tooth to approximate the correct distance between the two antagonists and account for the post-mortem movement of the teeth. For example, facets 7 and 10 on the lower second molar, which occlude with facets on the distally inclined slopes of the metacone and hypocone of the first molar, were frequently used to estimate the correct distance between the upper first molar and second molars.

5.2.2.4.2 Occlusal Fingerprint Analyser Simulation

Dynamic simulations of the power stroke were performed using the Occlusal Fingerprint Analyser software package (v.2.0). The lower aligned digital tooth models were translated in GOM Inspect along the z-axis so that there was a gap of 2mm between the upper and lower tooth rows. This was used as the standard distance between the tooth rows for the jaw open position during each simulation. The antagonistic molars were then imported into the Occlusal Fingerprint Analyser software in the jaw open position.

A collision trajectory was then constructed using the simple collision mode in the software by assigning a series of path points to the lower tooth model. Each path point is a target location set by the user which the lower tooth model will try to reach during the simulation. The locations of these path points are determined by attempting to optimise the wear facet area in contact during each phase of the power stroke (Figure 69). Each power stroke trajectory comprised 5 path points. Following the first collision, the area and inclination of the zones of contact are calculated and a break-free algorithm is used to deflect the colliding lower tooth model in the direction of the next path point. The lateral component of each phase of the power stroke, reflected in the position of the path points, was estimated based on the inclination and size of the wear facets associated with that phase.

Larger phase I wear facets that were shallowly inclined, for example, required a greater lateral displacement to bring the full surface of each wear facet into contact during the simulation.

The movement of the lower tooth model was broken down by the software into a series of timesteps in each simulation. The distance moved in each timestep was set at 0.05mm. The timestep value can be set lower to increase the detail of the movement trajectory between each path point. The software attempts to calculate any collisions between opposing teeth during each time step. Movement then proceeds directly in the direction of the next path point or the lower tooth row is deflected in that direction using the break free algorithm. Additional computing power and time is required for smaller timestep distances. A value of 0.05mm represented a compromise between achieving a relatively high-resolution collision trajectory and efficiency in computing resources.

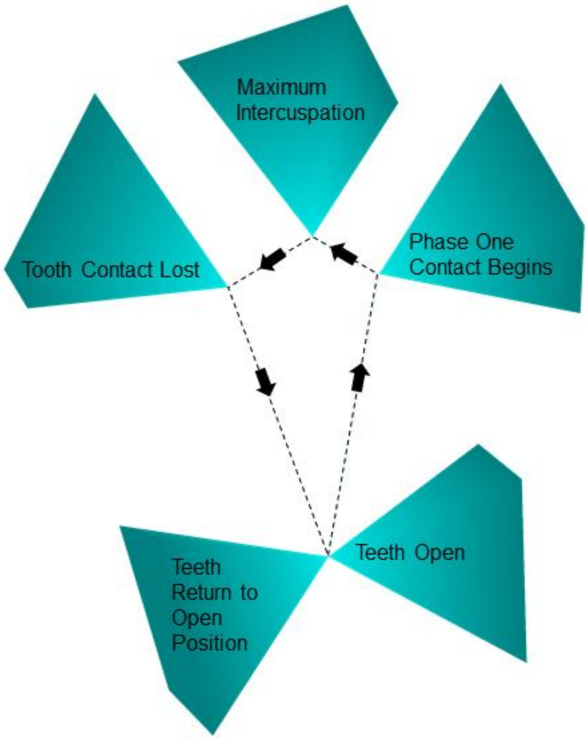


Figure 69: Example of the collision trajectory constructed in Occlusal Fingerprint Analyser software to simulate the power stroke between the aligned upper and lower tooth rows. The collision trajectory comprises five path points (the blue triangles) each of which represent a key stage during the power stroke. The position of each path point is determined by experimentally attempting to maximise the wear facet area that is in contact during the power stroke simulation. Simulations are adjusted until this is optimised. The teeth begin 2mm apart and the lower teeth follow the designated trajectory between the five path points attempting to reach each one in turn. Any time a tooth surface comes within 0.3mm of its antagonist a collision is detected. The area in contact is then calculated and the lower teeth proceed in the direction of the next path point.

The collision simulation concludes once the lower tooth model has attempted to reach all the path points in the sequence to produce a simulation of the entire power stroke and the lower teeth have returned to their starting position (Figure 69 and Figure 70). A profile of the areas in contact at each time step can then be generated for the simulation (Figure 71). The distance at which a collision would be detected was set at 0.3mm. The proper motion function was active, which enables teeth in the molar row to move away from the opposing molar group when a collision occurs. This provides an approximation of the action of the periodontal ligament during the power stroke. Diagrams and video clips can be produced using the software to describe the simulated power stroke (as presented in section 6.1.3).

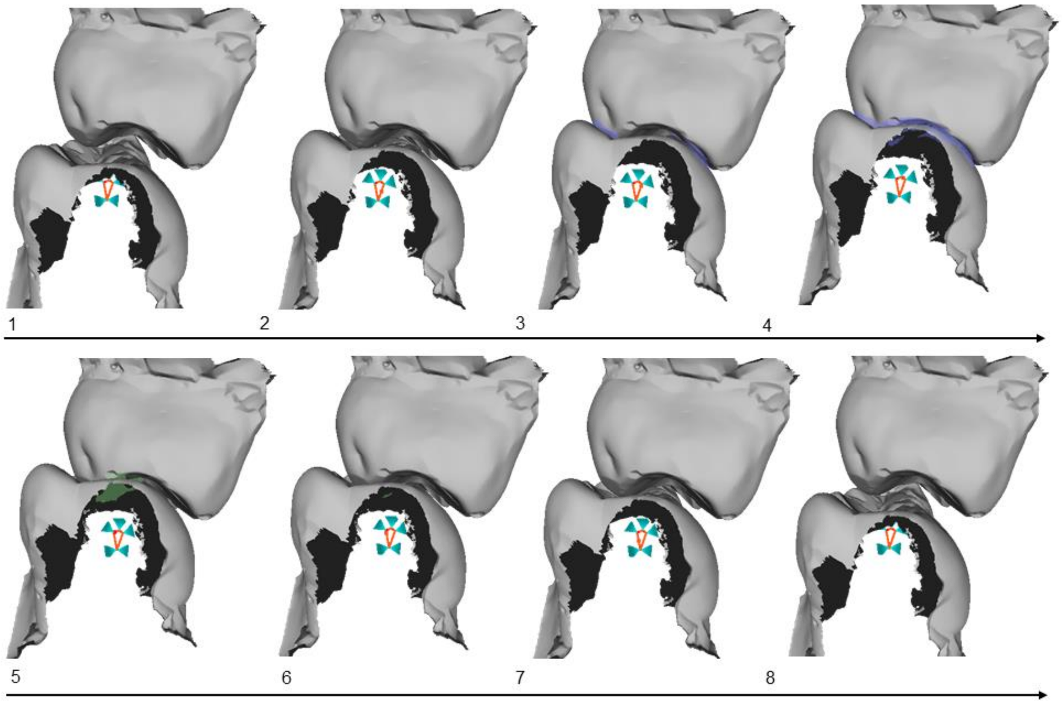


Figure 70: An example of a power stroke collision trajectory presented as 8 snapshots. The orange teardrop shape in the central image at each step illustrates the collision path. The lower molar teeth move from their open position 2mm apart in the direction of the path point that corresponds to the first phase I contacts (snapshot 1). The lower teeth move laterally and upwards until phase I of the power stroke commences (snapshot 2-3). The lower teeth then move medially during phase I of the power stroke until maximum intercuspation is reached (snapshot 4). Phase II follows maximum intercuspation as the lower teeth continue to move medially (snapshot 5). Occlusal contact is then lost (snapshot 6) and jaw opening begins. The lower teeth move laterally and downwards to return to their starting position (snapshot 7-8). This completes the power stroke simulation.

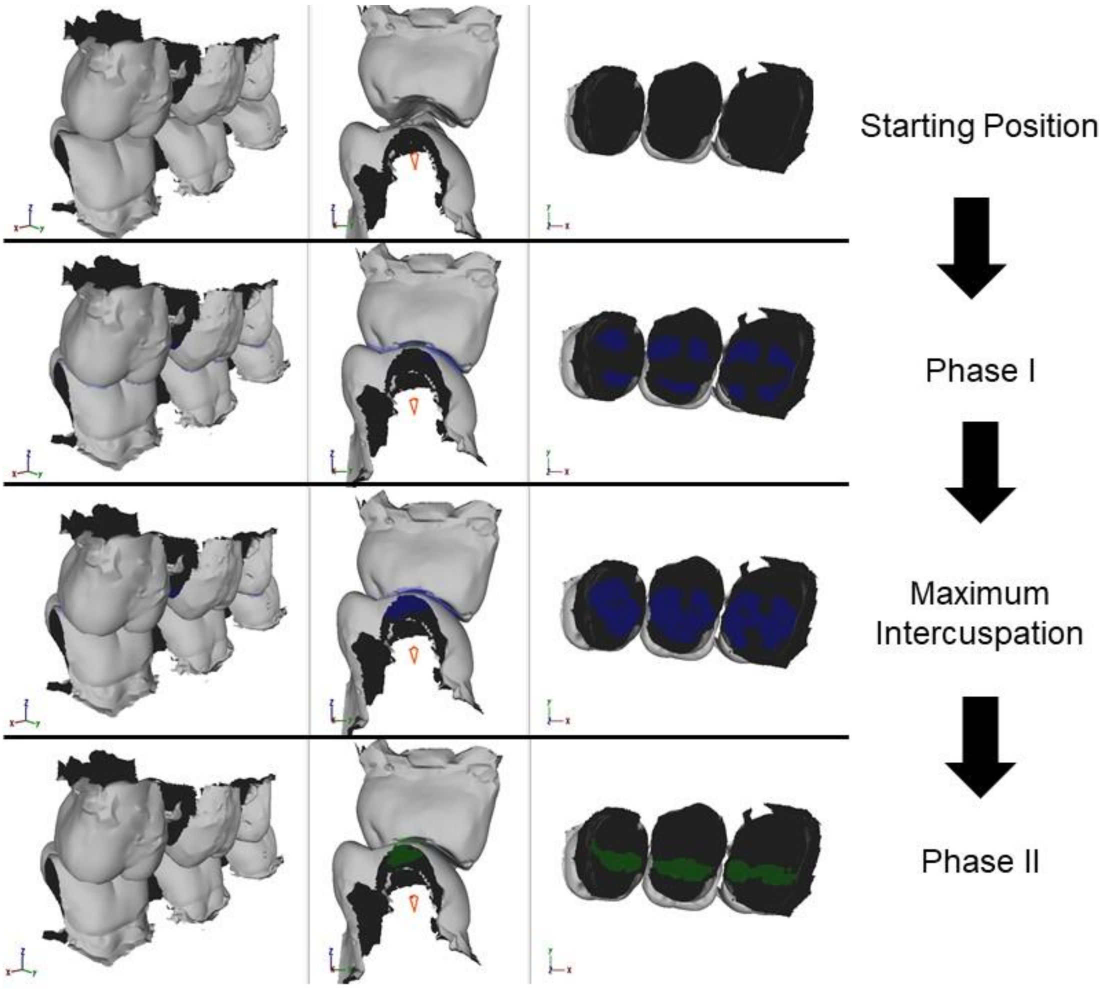


Figure 71: Dynamic simulation of power stroke conducted using Occlusal Fingerprint Analyser software. This diagram highlights the collisions that were detected at each key stage of the power stroke during this simulation. The orange teardrop shape in the central image at each step illustrates the collision path.

5.2.2.4.3 The data generated by each simulation and analysis

The timestep at which key stages of the power stroke for the lower second molar were reached were recorded for the final simulation conducted for each individual (Table 38). This highlighted any differences in the duration of the power stroke and the number of timesteps required to reach each key stage between individuals.

Table 38: Operational definitions used to identify key stages of the power stroke during dynamic OFA simulations. The timestep (TS) at which each of these stages was achieved was recorded.

Stage of the Power Stroke	Definition
First Contact	This was treated as time step 1 for the purposes of calculating the TS for the subsequent stages of the power stroke.
Full phase I contacts	This stage was reached when maximum collision areas were detected across phase I wear facet areas and phase II contacts were not yet involved.
First phase II contact	The first collision involving a phase II contact area was detected. It represents the start of the period of the power stroke during which both phase I and phase II wear facets are in contact prior to maximum intercuspation.
Maximum intercuspation	The stage at which the greatest collision area was detected on the lower second molar involving both phase I and phase II facets.
Phase II only	This stage was reached following maximum intercuspation when only phase II wear facets were in contact and a distinct phase II movement began.
Loss of contact	The time step at which collision areas were no longer detected and tooth-tooth contact was lost.

In addition, the rate of increase/decrease in contact area was calculated between each of these stages using the following formula:

$$Rate\ of\ change = \frac{Area\ at\ current\ power\ stroke\ phase - Area\ at\ previous\ power\ stroke\ phase}{Time\ step\ of\ current\ phase - Time\ step\ of\ previous\ phase}$$

Canonical variance analysis was performed in R statistical software (v3.6.1) using the Morpho package to examine the differences in simulated collision profiles between the skeletal assemblages examined. Canonical variance analysis aims to simplify the description of differences between groups and present the differences between group means. The original data are transformed into a new coordinate system defined by the canonical variates, which are linear combinations of the original variables. The within group variation is used to scale the axes of the new coordinate system produced. The first canonical variate is the axis across which the means of the groups examined are most effectively differentiated. This differs from principal components analysis which aims to summarise the differences between individuals (Zelditch *et al.* 2012). Canonical variance analysis was, therefore, deemed more appropriate to visualise differences between the collision simulations conducted for each assemblage in the current context.

5.2.2.5 Statistical Analysis and data visualisation

Different types of data are produced when performing OFA, including compositional and circular data. Conventional statistical testing cannot be directly applied to compositional or circular data and, therefore, different strategies of statistical analysis had to be formulated for each data type. Statistical analysis and graph generation was conducted using R statistical software (v3.6.1) and Microsoft Excel.

Any data that were neither compositional nor circular were analysed using traditional statistical methods. Homogeneity of variance and the normality of the data was assessed using Levene's test and the Shapiro-Wilk test, respectively. Parametric testing (independent sample t-tests and one-way ANOVA) were used if the assumptions were met and non-parametric testing (Wilcoxon rank sum tests and Kruskal Wallis H tests) if they were not. Effect sizes (Cohen's d) and statistical power were calculated where parametric testing was used.

Variables that could be assessed using parametric testing were displayed as dot plots overlain with the mean values for each group with 95% confidence intervals (Figure 72). This is because independent sample t-tests compare the means of two groups. The median provides a more appropriate measure of central tendency in skewed and non-normally distributed data (Campbell *et al.* 2007). As such, boxplots were selected to visualise the differences between the median and distribution of the groups being compared when considering non-parametric datasets. These plots were created using R statistical software packages car and ggplot2.

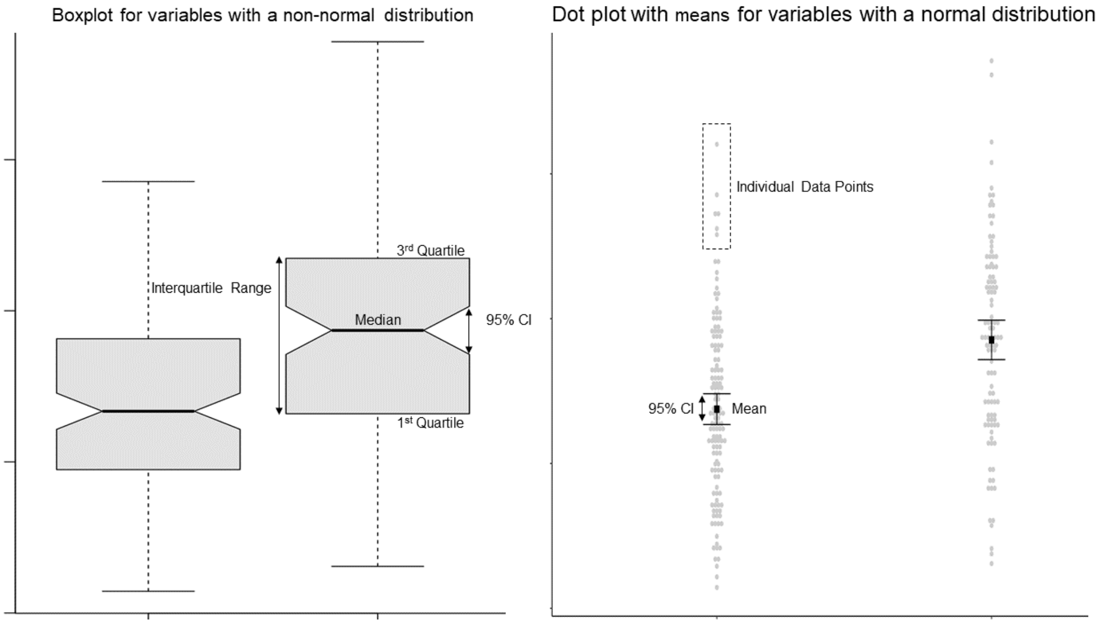


Figure 72: Explanation of plots used in the results section to visualise data that are non-normally and normally distributed.

5.2.2.5.1 Compositional data: Relative Wear Facet Areas

Dental wear facet areas across the lower second molar were classified as either buccal phase I, lingual phase I or phase II wear facets. The percentage of the total wear facet area associated with each type of wear (Buccal phase I, Lingual Phase I and Phase II) was calculated for each individual lower second molar. The formulas are given in section 5.2.2.3.3. The composition of the dental wear facets on each lower second molar sum to a constant value (100%), which was defined as the total area of the wear facets on the occlusal surface, excluding tip crushing areas. This is referred to as the constant sum constraint. This data is therefore compositional in character and requires particular statistical treatment (Aitchinson 1984; Egozcue *et al.* 2003). The value of each component comprising the total wear facet area only conveys relative information unless considered in relation to its ratio to the other components. For example, differences in the proportion of the total wear facet area constituted by buccal phase I wear between individuals can only be meaningfully discussed whilst also considering the differences in lingual phase I and phase II wear facet area proportions between individuals. Consequently, single components cannot be interpreted in isolation from the other components. This renders the data intrinsically multivariate. In addition, due to the constant sum constraint, any correlation observed between the components of the composition may be spurious and at least one correlation between elements must be negative (Aitchison 1986; Egozcue and Pawlowsky-Glahn 2011, Tolosana-Delgado and van den Boogaart 2011).

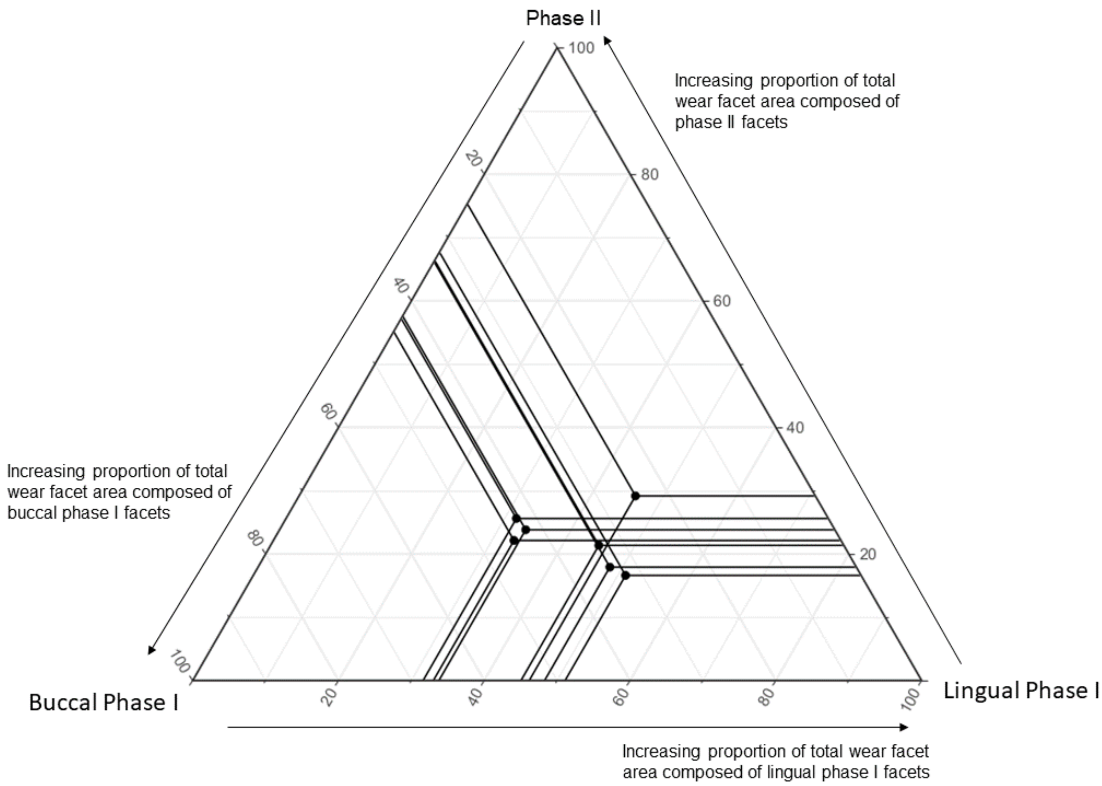


Figure 73: Example of a ternary plot. Each data point represents the composition of the total wear facet area of a lower second molar. Crosshairs are plotted for each data point in this example to indicate the proportion of the total wear facet area of each lower second molar composed of each type of wear facet. The proximity of the data point to the apex of the triangle associated with each type of wear facet indicates the ratio between the three types of wear facet. Closer proximity to the apex labelled lingual phase I, for example, would indicate a larger proportion of lingual phase I wear facets on that lower second molar in relation to buccal phase I and/or phase II wear facets.

The wear facet area data in the current research could be visualised as an equilateral triangle or a ternary plot as the composition of the total wear facet area was formed of three components (buccal phase I, lingual phase I and phase II wear). Ternary plots provide an effective visualisation of compositional data, particularly when the composition is comprised of only three variables (Figure 73). This is because the sample space of the data are a two-dimensional simplex, which forms an equilateral triangle (Pawlowsky-Glahn *et al.* 2015). A ternary plot is a diagram that displays three variables which sum to a constant. Each axis corresponds to one of the three variables that form the composition. Observation are plotted within the equilateral triangle formed by the three axes. The ratio of the three variables for a given observation are graphically displayed based on the position of the plotted point within the triangle. Ternary diagrams were produced in R using the package ggtern.

The interpretation of these plots requires an understanding of the types of dietary input and masticatory behaviours that are likely to modify the relative size of each of the types of wear facet on a given tooth. Figure 74 provides an example of the dietary profiles likely to result in the enlargement of each type of wear facet area based on the work of Janis (1990), Fiorenza *et al.* (2011a, 2011b) and Zanolli *et al.* (2019).

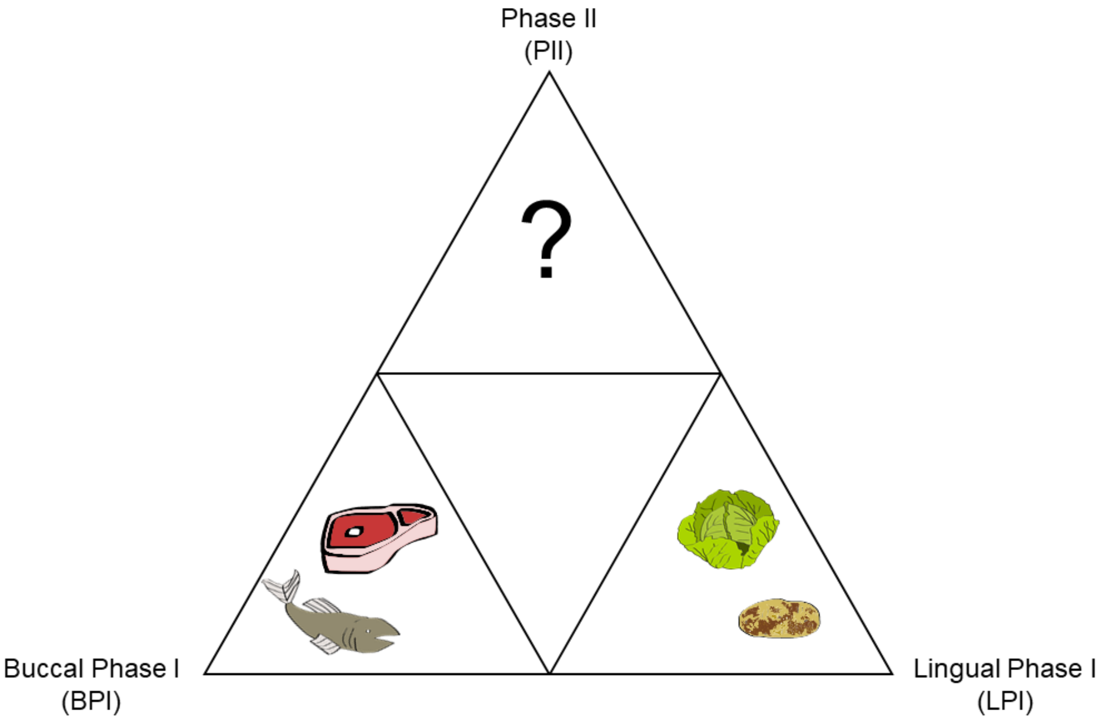


Figure 74: The types of food that have been associated with an increase in the relative size of each type of wear facet area in anatomically modern humans. The enlargement of buccal phase I wear has been associated with a dietary profile which regularly features soft, fibrous and/or tough foods, such as meat, requiring a prominent shearing action during oral process. In modern hunter-gatherers, a diet that is both harder and tougher and requires a greater transverse occlusal movement during oral processing, such as tuberous roots, seeds and plant foods, has been linked to larger lingual phase I wear facets. In herbivorous mammals, larger phase II wear facets have been reported in frugivores consuming fewer leaves, however, their functional role in anatomically modern humans remains unclear.

Many authors argue that conventional statistics cannot be applied to compositional data as it is hard to distinguish effects resulting spuriously from the constant sum constraint (Aitchison 1986). Aitchison (1982; 1984; 1986) proposed using log-ratio transformation to overcome the issues associated with compositional data. This method preserves the multivariate nature of the dataset and standard statistics can be applied to the coordinates generated. If necessary, an inverse log-ratio transformation can be used to transform the coordinates back into the components of the composition from which they were derived to assist interpretation.

Isometric log-ratio transformation involves the transformation of the compositional data into real world coordinates whilst preserving all their metric properties. This enables conventional statistics to be directly applied to the coordinates generated by enabling angles and distances in real space to be associated with the angles and distances in the simplex (Egozcue *et al.* 2003). A disadvantage of this method is that it requires the selection of an orthonormal base for the transformation, of which there are theoretically an infinite number. An appropriate orthonormal base, however, can be obtained by constructing a balance using the inherent structure of the composition being analysed (Figure 75 and Figure 76; Egozcue and Pawlowsky-Glahn 2011; Mateu-Figueras, Pawlowsky-Glahn and Egozcue 2011). The method used for performing this transformation in R using the compositions package is presented in Boogaart and Tolosana-Delgado (2013). Cluster analysis using the entire data set of lower second molar relative wear facet areas was conducted to determine the balance that would be used to perform the isometric log transformation of the data set.

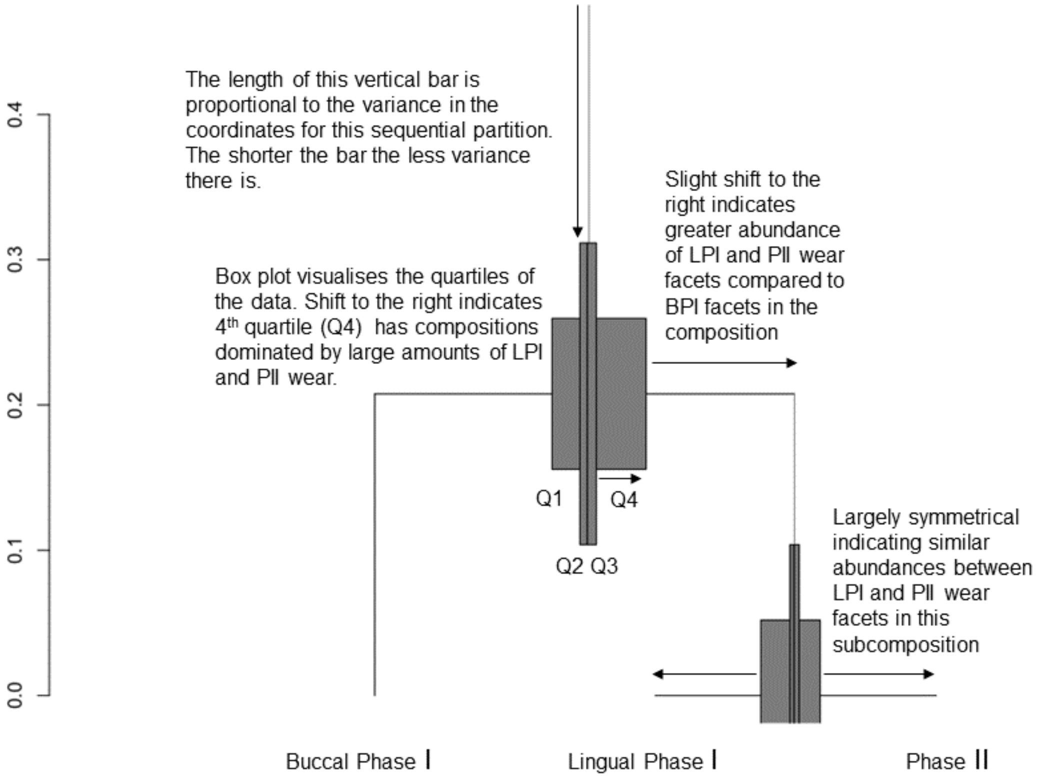


Figure 75: Balance-dendrogram showing the balance formula used to perform the isometric log transformation of the relative wear facet area data of the lower second molars in the current research. Hierarchical cluster analysis using Ward's method was applied to the data when transformed using Aitchinson's (1986) centred-log ratio transformation in order to produce this dendrogram (see Egozcue et al. 2003 for mathematical proofs). Each of the sequential binary partitions corresponds to a two-part composition; the first is between buccal phase I and the other two types of wear facet. The first sequential binary partition is shifted slightly towards the lingual phase I and phase II part of the balance indicating that these wear facet types were more abundant in the composition of the lower second molars than buccal phase I wear facets. The size of the boxes plotted on the partition indicate a larger variance in the upper quartile of the lingual phase I and phase II wear facet values. The second balance between lingual phase I and phase II wear facet types is more symmetrical. The length of the vertical rays connecting the sequential binary partitions are of a similar length indicating similar levels of variance between each wear facet type. This balance formula (expressed as ((Phase II/Lingual Phase I)/Buccal Phase I) was used to conduct all isometric log transformations in the current research (Egozcue and Pawlowsky-Glahn 2005).

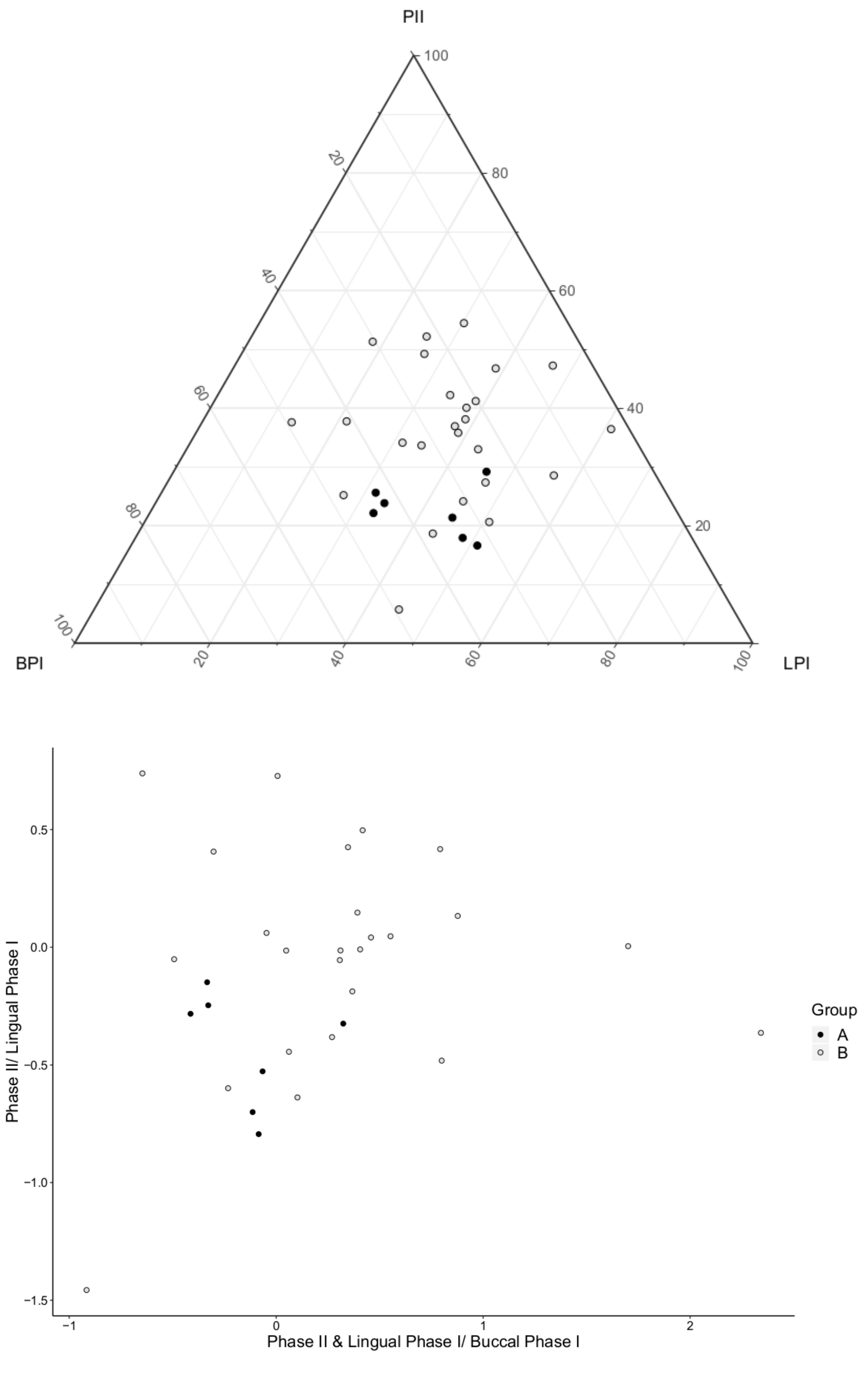


Figure 76: Example of the isometric log transformation performed in the current analysis on two groups to enable conventional statistical approaches to be applied to the data. The upper ternary plot shows the untransformed data within its original sample space, an equilateral triangle or a two-dimensional simplex. The lower scatterplot shows the isometric log transformed coordinates of the data. The balance base used for the orthonormal transformation of the data was (Phase II/Lingual Phase I)/Buccal Phase I) as indicated by Figure 75.

Baxter (1992) criticised the efficacy of compositional statistics to yield interpretable results as it often gives undue weight to minor components of the composition. This was highlighted in relation to archaeomaterials datasets in which a large disparity can exist between the size of each component and they are frequently highly multidimensional (Baxter 1992). The dimensions of the wear facet area compositions being analysed in the current study are low (only three dimensions), however, and typically occupy similar proportions of the compositional whole.

5.2.2.5.2 Permutational analysis of variance (PERMANOVA)

Linear models can be fitted directly to the isometric log-transformed data (Tolosana-Delgado and Boogaart 2011), however, many traditional multivariate statistics rely on the assumption that the data conforms to a multivariate normal distribution (Boogaart and Tolosana-Delgado 2013). This assumption is typically unrealistic for many bioarchaeological datasets as they commonly have skewed and asymmetric distributions and may contain assemblages with few observations. Permutational multivariate analysis of variance (PERMANOVA) provides a dissimilarity measure using distribution-free permutation techniques. It is semiparametric in that it retains a classical partitioning structure of main effects and interaction terms analogous to ANOVA. The F-statistic produced is a result of a comparison of within group variance with the variance among different groups (Figure 77; Anderson 2001; 2017). The larger the value of the F-statistic generated the more likely it is that the null hypothesis of no difference between group means is false. The probability value is generated by comparing the F-value generated with simulated F-values produced by randomly shuffling the data by a specified number of permutations (Figure 78; Anderson 2001). In addition, PERMANOVA can also be applied to non-Euclidean distance matrices (Anderson 2001). The utility of transforming compositional data using a log-ratio approach prior to performing PERMANOVA has been highlighted (Brückner and Heethoff 2017).

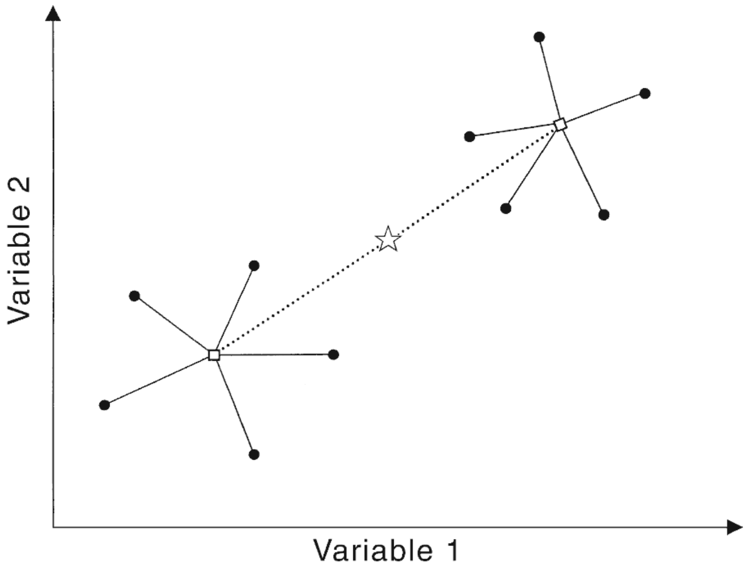


Figure 77: Representation of MANOVA for two groups that differ in location with respect to two variables. The within-group sum of squares is the sum of the squared distances from individual replicates to their group centroid (solid lines). The among-group sum of squares is the sum of the squared distances from group centroids to the overall centroid (dotted lines). Individual observations are marked as lack dots, the group centroid as white squares and the overall centroid as a star (Figure 1 from Andersen 2001).

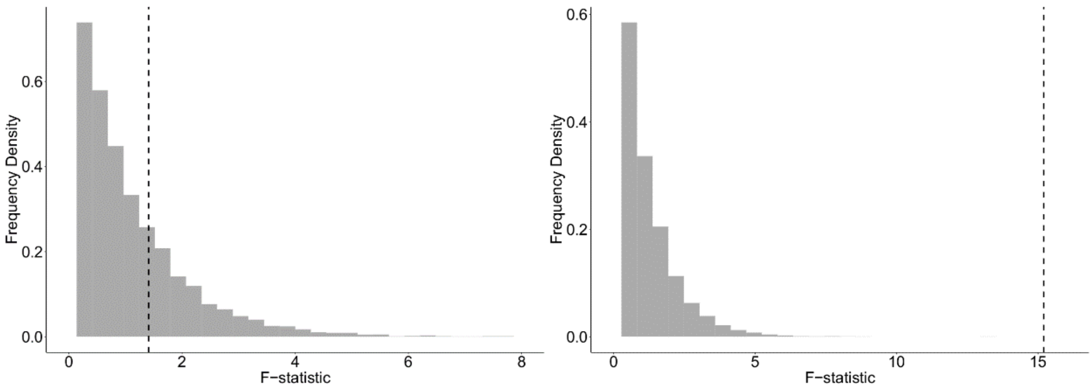


Figure 78: Histograms showing two examples of the comparison between the F-statistic generated using the actual data divided by group (dashed vertical line) and the frequency density of the F-statistic values generated using a random set of 9999 permutations of the data. In the plot on the left, the actual F-statistic value was not larger than the values generate under permutation therefore the null hypothesis would not be rejected. In the plot on the right, the actual F-statistic is much larger than the values produced under random permutation indicating that the null hypothesis of no difference between the groups could be rejected (Anderson 2001).

Two assumptions underly PERMANOVA. The first is that each observation is independent and the second that they have similar distributions. Similarity in distribution is important as the p-value is derived through permutations. Several F-statistics are obtained by randomly exchanging multivariate observations between groups. If there were no differences between the groups, the observations would be exchangeable between them. Significant results from this method may result from differences in within-group variation rather than different mean values between groups, therefore, a permutational test assessing homogeneity of multivariate dispersions (PERMDISP) should be performed alongside PERMANOVA (Figure 79). This will help establish whether significant differences among groups is due to differences in the spread of the data or differences in location or a combination of the two (Anderson 2001).

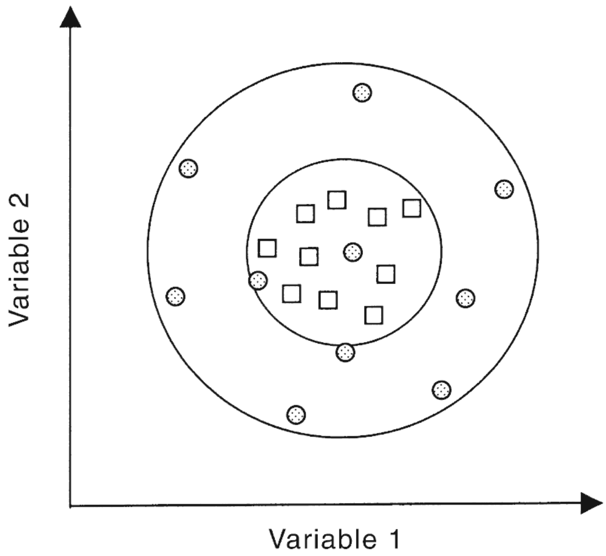


Figure 79: Examples of two groups that differ in dispersion but not in location. The dispersion of the group represented by circles was larger with respect to the two variables than the group represented by white squares (Anderson 2001: Figure 4).

A distance measure appropriate to the hypothesis being tested must be selected for performing PERMANOVA. It is compatible with any distance measure, however, it is advised that test be run using two or more distance measures to demonstrate that any significance reported is not dependent on the distance matrix selected. The Bray-Curtis measure of similarity is commonly used in ecology, but the measure is incompatible with negative integers (Anderson 2006). Negative integers are generated by the isometric log-transformation process. Euclidean distances were, therefore, calculated between multivariate observations in the current study when isometric log-transformation had been performed. PERMANOVA conducted using Euclidean distances have been shown to capture significant differences between groups as effectively as the Bray-Curtis matrix (Brückner and Heethoff 2017).

The statistical design of the current research combines a compositional isometric log-ratio transformation of the data (Tolosana-Delgado and Boogaart 2013) with PERMANOVA (Anderson 2001). A recent study which involved compositional OFA data utilised PERMANOVA applied to the Bray-Curtis similarity matrix of the raw relative wear facet area data (Zanolli *et al.* 2019). This statistical testing method was also adopted in the current research to assess whether the isometric log-transformation procedure used produced comparable results. The statistical procedure used for analysing compositional data involved:

1. The isometric log-ratio transformation was applied to the data. Isometric log-ratio transformation of the data was performed using a balance base calculated using cluster analysis as described in Figure 75.
2. A distance measure for the statistical analysis was selected. Euclidean distance was selected as negative integers can be included. The distances among centroids are equivalent to Euclidean distances among the arithmetic averages calculated separately for each variable when a Euclidean measure of distance is used (Anderson 2017).
3. PERMANOVA was applied to the distance matrix generated. The permutation parameter is set to 9999. Type I PERMANOVA was used if the effect of only one factor was being assessed and type II PERMANOVA was used if multiple factors and/or interaction effects were being assessed. Differences between groups are visualised in a ternary plot.
4. If the dependent variable being assessed had more than two factor levels post-hoc pairwise testing was carried out. The p-values obtained were corrected using the Benjamini and Hochberg (1995) method, which controls the false discovery rate. This method of correction was selected as a less conservative alternative to the Bonferroni approach (Anderson 2001).
5. The assumption of homogeneity of multivariate dispersion was assessed using a PERMDISP test for each PERMANOVA test performed. The permutation value was set to 9999. The results of the PERMDISP tests are reported in appendix section 10.2 unless significant and homogeneity of multivariate dispersion could not be assumed.
6. All the research questions considered a single independent variable in isolation, however, PERMANOVA requires the assessment of any interaction effects between each of the independent variables being considered. These are presented in appendix section 10.3. Only one significant interaction effect was found (Section 6.2.1.2.3).

7. A second PERMANOVA was performed using the raw compositional data following the method described by Zanolli *et al.* (2019). A Bray-Curtis similarity matrix was calculated using the relative wear facet area data and formed the basis of the PERMANOVA calculation. Type I or type II PERMANOVA was selected using the criteria in point 3 above.

All compositional statistical analysis was conducted using the packages RV-AideMemoire 0.9-0.66 and composition in R statistical software.

5.2.2.5.3 Circular Data: Dip Direction

The dip direction generated to describe wear facet orientation is defined on an angular scale and as such lacks a designated zero and the designation of high and low values is arbitrary unlike linear scales. Consequently, commonly used statistical techniques cannot be applied (Berens 2009). The R package circular was used to generate plots to visualise the distribution of dip direction angles for each period and to conduct statistical analysis. The differences in the mean value and distribution of the dip direction values between the periods for each wear facet position were assessed using the following tests outlined in Pewsey, Neuhäuser, and Ruxton (2013).

- Rayleigh’s test: this is a statistical test to assess the distribution of directional values. If $p<0.05$ the alternative hypothesis is accepted which states that there is a unimodal distribution around the circle of unknown mean direction unless this has been separately calculated.
- Watson’s large sample non-parametric test for a common mean dip direction: this statistical test assesses whether there are any significant differences in mean direction between groups. This test unlike many others does not assume a common dispersion or distribution for the groups being compared.
- Watson’s two-sample test for a common distribution: the statistical test assesses whether circular data could have been drawn from the same distribution. If $p<0.05$, there is evidence that the circular data was drawn from two significantly different distributions.
- Wallraff’s nonparametric test for a common concentration: a statistical test of circular homoscedasticity. If $p<0.05$, there is evidence that the variable being tested differs significantly in its variance depending on the size of the value. A measure of concentration (the mean resultant length or Rho) is given.

6 Results

A list of the abbreviations commonly used in the results section is given in Table 39.

Table 39: Abbreviations commonly used in the results chapter for site names and the reporting of statistics.

Site Names	**Abbreviation**
Mediaeval and Early Post-Mediaeval Sites	
York Barbican	BARB
Box Lane, Pontefract	BL
Blackfriars, Gloucester	BF
Hereford Cathedral	HE
St James' and St Mary Magdalene, Chichester	CH86
St Michael's Litten, Chichester (Early)	ESC11 (Early)
Industrial Sites	
St Michael's Litten, Chichester (Late)	ESC11 (Late)
Coronation Street, South Shields	CS
St Peter's, Wolverhampton	StP
St Bride's Church, London	SB79
Data Analysis	
Isometric log-ratio transformed data	ILR
Permutational multivariate analysis of variance	PERMANOVA
Permutational test of homogeneity of multivariate dispersions	PERMDISP
Probability	P-value
Null Hypothesis	H_0
Sum of Squares	Sum of Sq.
Mean of Squares	Mean of Sq.
Standard Deviation	SD
Interquartile Range	IQR
Degrees of Freedom	df
Variables	
Buccal Phase I Facets	BPI
Lingual Phase I Facets	LPI
Phase II Facets	PII
Occlusal Relief Index	ORI
Tip Crushing Index	TCI

6.1 Do dental wear facet patterns indicate that a change in masticatory behaviours occurred between the Mediaeval and Early Post-Mediaeval periods (AD1100-1700) and the Industrial era (1700-1900AD)?

6.1.1 Gradient of Dental Wear and Occlusal Relief

6.1.1.1 A reduction in the gradient of dental wear between the first and second molars should occur.

The discrepancy between the Smith wear scores (Section 5.2.1.4) of the first and second lower molars was significantly greater in the pre-Industrial assemblages (Wilcoxon Rank-sum Test W = 2329.5, p-value<0.0001; Figure 80). Dental wear gradients did not differ significantly between the mediaeval assemblages examined (Table 40). The Coronation Street assemblage had greater differences between the first and lower second molar Smith wear stages than the two later Industrial-era assemblages; St Bride's and St Peter's (Figure 80).

Table 40: Table showing the results of PERMANOVA of the Bray-Curtis dissimilarity matrix assessing the relationship between site and dental wear gradient. Homogeneity of dispersion could be assumed (Table 114*).* ***Null Hypothesis: Wear gradients between the first and second molars did not differ significantly between the assemblages examined****.*

	Sum of Sq.	Mean of Sq.	df	F-value	R^2	P-value (>F)	H_0
Site	0.94	0.10	9	9.43	0.30	0.0001	Rejected
Residuals	2.22	0.01	200		0.70		
Total	3.16		209		1.00		

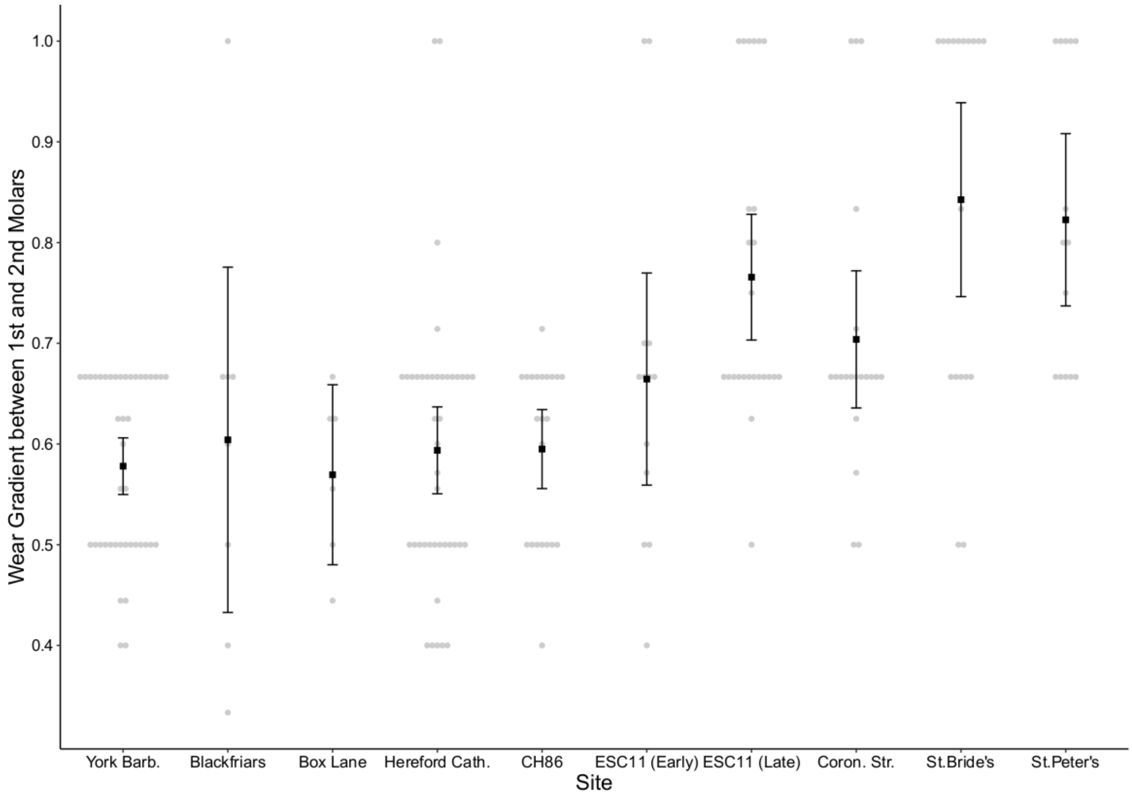


Figure 80: Plot showing the mean values for wear gradient score for each assemblage examined with 95% confidence intervals (black squares with error bars). Wear gradient was calculated by dividing the second molar wear score by the first molar wear score. Sites are arranged chronologically along the x-axis. The distribution of wear gradient scores for each site are visualised as a dot plot (grey circles).

Table 41: Table showing the results of permutational pairwise testing following the rejection of the null hypothesis that wear gradients between the first and second molars did not differ significantly between the assemblages examined. Pairwise comparisons that differed significantly are highlighted in bold. There were not significant differences between any of the Mediaeval assemblages examined, however, they differed significantly from all the Industrial-era assemblages. The early Post-Mediaeval portion of the ESC11 assemblage differed significantly from all the Industrial-era assemblages except for the Coronation Street assemblage. The Coronation Street assemblage differed significantly from the St Bride's and St Peter's assemblages.

Pairwise Comparison of Wear Gradients	BARB	BF	BL	HE	CH86	ESC11 Early	ESC11 Late	CS	StP
BF	0.66	NA	NA	NA	NA	NA	NA	NA	NA
BL	0.89	0.82	NA	NA	NA	NA	NA	NA	NA
HE	0.76	0.82	0.82	NA	NA	NA	NA	NA	NA
CH86	0.63	0.66	0.66	0.78	NA	NA	NA	NA	NA
ESC11 Early	0.09	0.56	0.38	0.24	0.30	NA	NA	NA	NA
ESC11 Late	**0.00**	**0.04**	**0.03**	**0.00**	**0.00**	**0.09**	NA	NA	NA
CS	**0.00**	0.13	0.06	**0.01**	**0.01**	0.56	0.22	NA	NA
StP	**0.00**	**0.02**	**0.00**	**0.00**	**0.00**	**0.03**	0.63	**0.05**	NA
SB79	**0.00**	**0.02**	**0.02**	**0.00**	**0.00**	**0.04**	0.56	**0.05**	0.82

Average Smith wear scores were calculated for each tooth type by combining the wear scores for all upper and lower antagonists and antimeres present for each tooth type (central incisor through to 3rd molar). Individuals were only included if at least one of every tooth type was present. Smith wear scores differed significantly between the two periods (Table 42).

Wear gradients were calculated for each tooth position by expressing the wear stage for the tooth position as a proportion of the wear stage of the second molar. The second molar was selected for the calculation of wear gradients as this tooth was present in all the dentitions examined as the lower second molar was the target of OFA. The lower second molar also exhibited a Smith wear score of 2 in all the individuals selected providing a stable reference between individuals.

Pre-Industrial individuals typically had more advanced wear stages across all tooth types when compared with the lower second molar, except for the third molar. The difference in wear gradient between the two periods was most marked in relation to the first molar. Wear was more advanced on the first molar relative to the second molar in the Mediaeval and early Post-mediaeval periods (Figure 81). The third molar was typically less worn when compared to the second molar in the pre-industrial group. Individuals examined dating to the Mediaeval period were typically of younger age-at-death categories, therefore, the third molar had only just come into wear at the time of death. In the Industrial period, the wear stages of the second and third molars were frequently consistent.

Table 42: Results of PERMANOVA comparing average Smith wear scores across all tooth positions between the two periods. Homogeneity of multivariate dispersion could be assumed (Table 115). ***Null Hypothesis: Wear gradients for each tooth position when compared with the second molar did not differ significantly between the two periods.***

	Sum of Sq.	Mean of Sq.	df	F-value	R^2	P-value (>F)	H_0
Period	0.13	0.13	1	10.67	0.08	0.0004	Rejected
Residuals	2.04	0.01	172		0.92		
Total	2.17		173		1.00		

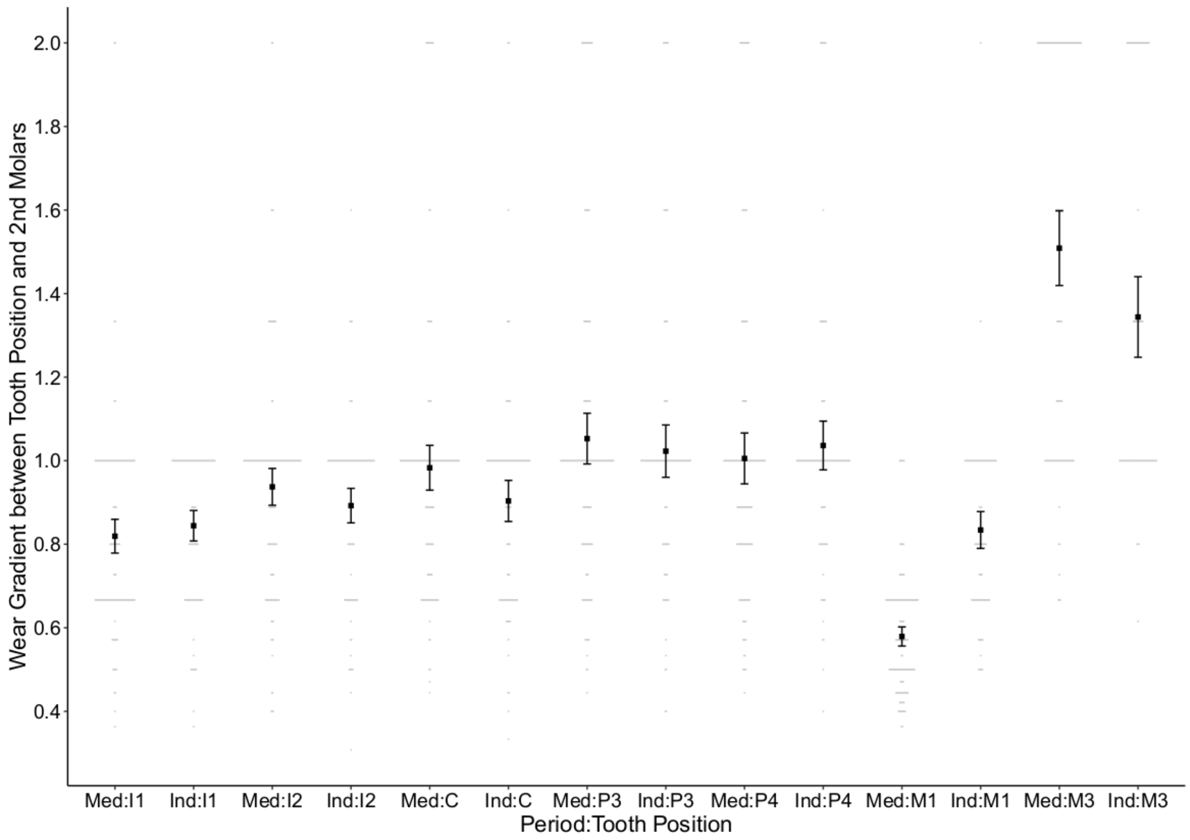


Figure 81: Plot showing the mean wear gradient between each tooth position and the lower second molar for each period (black square with 95% confidence intervals). Individual data points are visualised as grey dots for each period by tooth position combination. The most evident differences in wear gradient between tooth positions is the more advanced wear on the first molar relative to the second molar and less advance wear on the third molar in the Mediaeval and Early Post-Mediaeval periods relative to the Industrial.

6.1.1.2 The occlusal relief of the lower second molar would be expected to be less heavily reduced in the Industrial period across the entire occlusal surface.

Significantly greater ORI values were observed in the lower second molars of individuals dating to the Industrial period (Figure 82; Table 43). This indicated that higher relief and topographic complexity across the occlusal surface characterised the Industrial individuals examined. The magnitude of the effect of period on ORI was moderate (Table 43).

Table 43: Result of independent sample t-test examining the effect of period on ORI. ***Null hypothesis: ORI did not differ significantly between the two periods.***

Industrial Mean ORI	1.57
Standard Deviation	0.14
Mediaeval Mean ORI	1.48
Standard Deviation	0.12
t-value	5.48
Degrees of Freedom	206.12
p-value	<0.0001
Effect size	0.73
95% CI effect size	0.46 to 1.00
Statistical power	1.00
H_0	Rejected

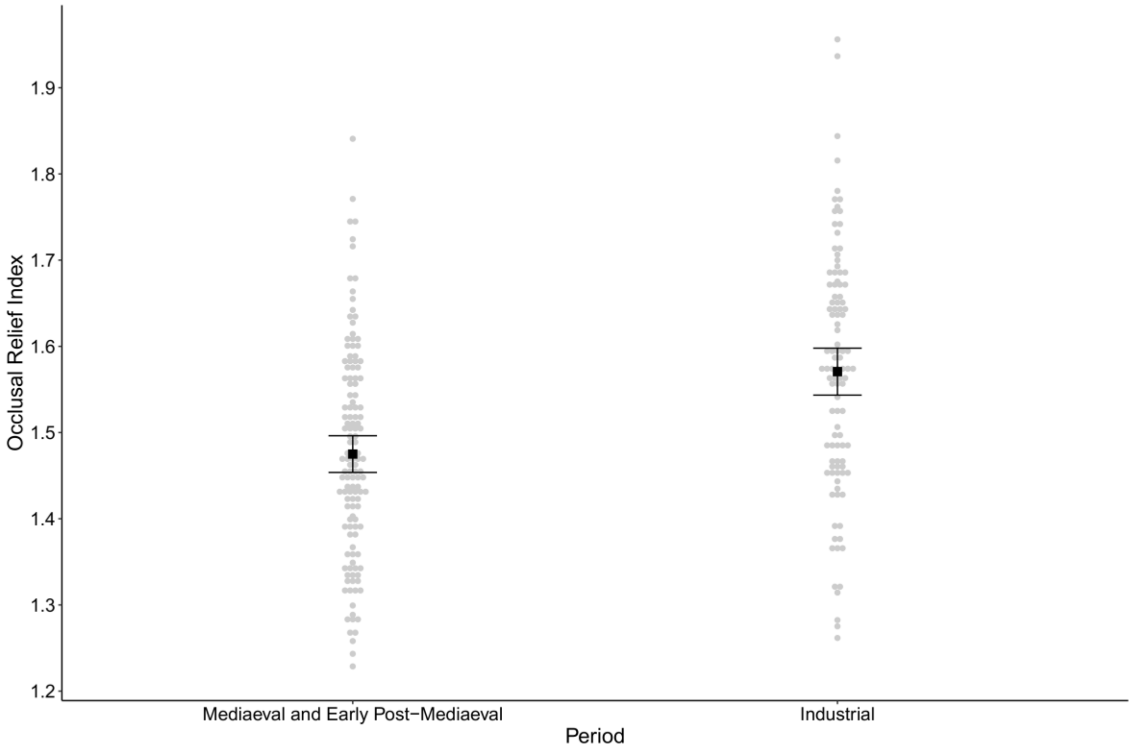


Figure 82: Plot comparing mean ORI values for the lower second molars between the two periods (black squares with 95% confidence intervals). Grey dots visualise each individual ORI value for the lower second molar targeted by OFA. The data was normally distributed (Shapiro-Wilk test W=0.99, p=0.08) and homogeneity of variance could be assumed (Levene's test F value=1.72, p=0.19).

6.1.1.3 Higher intensities of tip crushing wear would be anticipated in the pre-industrial group due to the incorporation of larger quantities of abrasive particles in the diet resulting in more extensive cusp removal.

Tip crushing wear facet area, expressed as a percentage of total 2D wear facet area, was significantly larger among the Mediaeval and early Post-Mediaeval group (Figure 83; Wilcoxon rank sum test; W = 5273, p-value = 0.004). In addition, tip crushing areas had significantly more obliquely inclined dip angles in the Industrial period (Figure 83; W = 6579, p-value = 0.02).

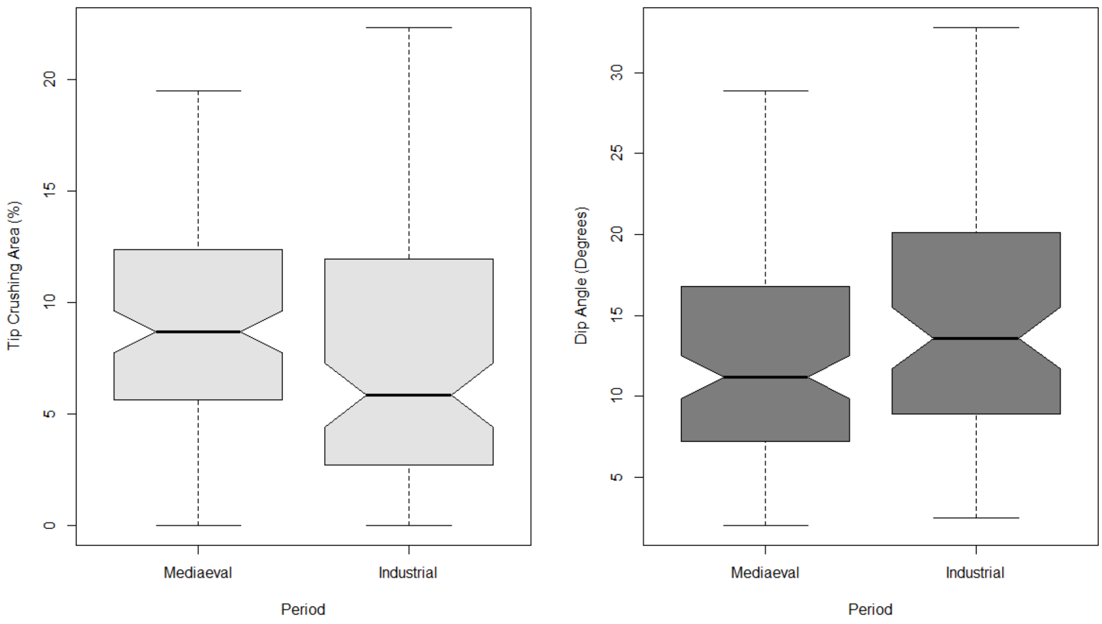


Figure 83:Left: Boxplot showing the influence of period on tip crushing area. Notch gives 95% confidence interval of the median. Tip crushing area is expressed as a percentage of the cross-sectional 2D area of the tooth crown (described in section 5.2.2.3.3). Individuals from the pre-industrial group had more strongly developed tip crushing areas. Tip crushing area values were not normally distributed so non-parametric statistical testing was used (Shapiro Wilk test W = 0.81, p-value <0.001). The null hypothesis that tip crushing values are not significantly influenced by period was rejected.

Right: Boxplot comparing the average tip crushing dip angles between periods. Pre-industrial individuals exhibit slightly less steeply inclined tip crushing areas. The null hypothesis that dip angles for tip crushing facets did not differ significantly between the two periods was rejected.

6.1.1.4 Summary of differences in overall dental wear expression across the dentition and dental wear gradient

The difference in wear score between the first and second molars in the pre-industrial group was significantly larger reflecting a higher gradient of dental wear among these assemblages and the gradient of wear between the third and second molars was slightly less. ORI values for the lower second molars were significantly greater in the Industrial period indicating the retention of greater amounts of occlusal topography. Tip crushing areas on the lower second molar were significantly larger in the Mediaeval and early Post-Mediaeval periods when expressed as a proportion of the cross-sectional crown area of the tooth. These tip crushing areas were slightly more shallowly inclined in the pre-industrial group.

6.1.2 OFA: Comparison of Wear Facet Patterns of the lower second molars between the Mediaeval and Early Post-Mediaeval periods and the Industrial era.

6.1.2.1 Background wear facet pattern

6.1.2.1.1 Sidedness: left versus right

In both periods, relative dental wear facet areas did not differ significantly depending on whether the lower second molar was selected from the left or right side (Table 44 and Table 116; Figure 84). The molars from the left and right side could, therefore, be pooled in the subsequent analysis.

Table 44: Effect of sidedness on relative dental wear facet area in the pre-Industrial and Industrial groups. ***Null hypothesis: the relative wear facet areas of the lower second molars examined did not differ significantly between teeth taken from either the left or the right side of the dentition.***

ILR data Mediaeval	df	Sum of Sq.	Mean of Sq.	F-model	R^2	p-value	H_0
Left vs Right	1	0.56	0.56	1.41	0.01	0.25	Not Rejected
Residuals	128	50.84	0.40		0.99		
Totals	129	51.39			1.00		

ILR data Industrial	df	Sum of Sq.	Mean of Sq.	F-model	R^2	p-value	H_0
Left vs Right	1	0.39	0.39	0.79	0.01	0.45	Not Rejected
Residuals	102	50.07	0.49		0.99		
Totals	103	50.46			1.00		

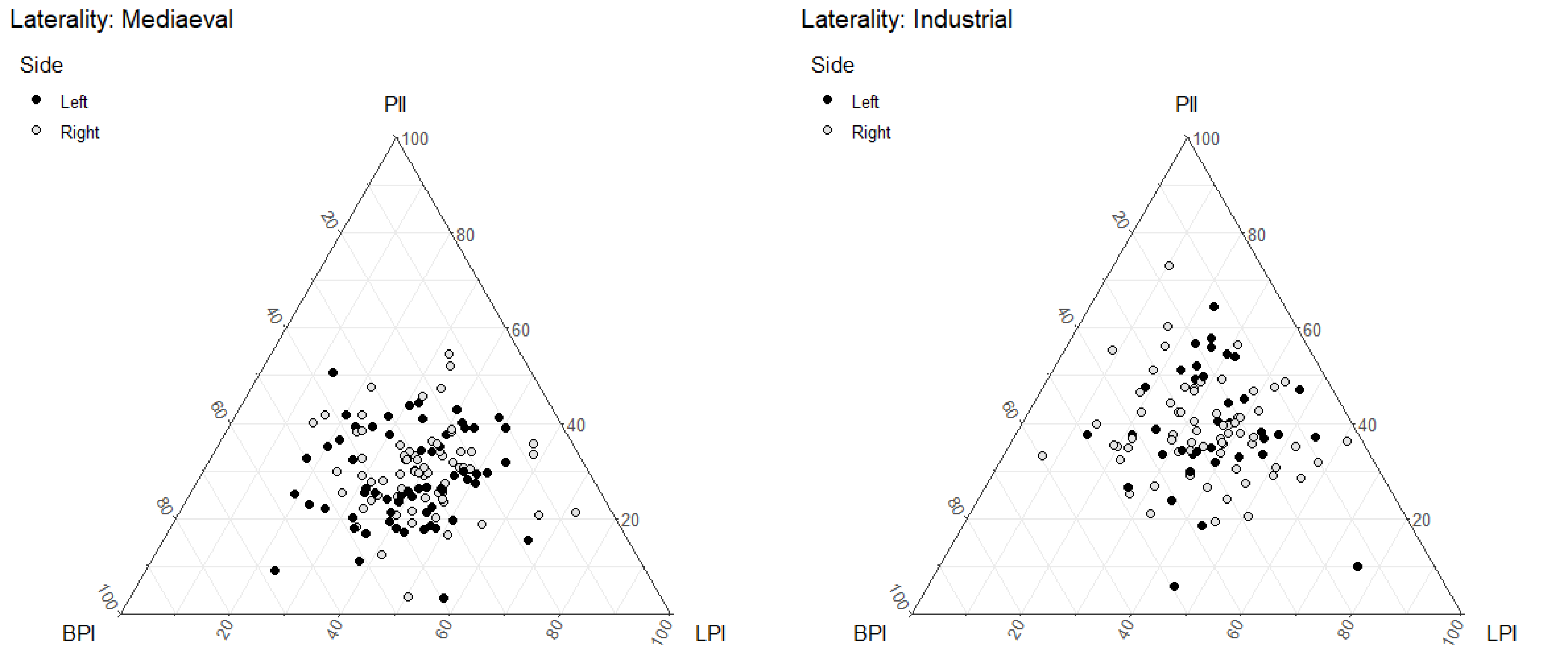


Figure 84: Ternary plots showing the absence of difference in relative wear facet area between left and right lower second molars drawn from different individuals in the pre-industrial and industrial group.

6.1.2.1.2 Background wear facet pattern of the lower second molar

In both periods, wear facets 6, 9 and 11 were the most commonly present and were developed in over 90% of the lower second molars examined (Figure 85). Facets 1 and 3 were the most frequently expressed BPI facets and had similar frequencies in both periods. On the metaconid, facet 5 was regularly present in both periods, however, facet 7 was more commonly developed in the Mediaeval and early Post-Mediaeval periods. Facet 10 was more regularly present in the Industrial period. This was likely due to the frequent incorporation of this facet within the tip crushing area on the protoconid in the pre-industrial group. Facet 12 was often poorly differentiated from facet 9 in the pre-industrial lower second molars assessed resulting in a low prevalence relative to the Industrial period. Facets 6 and 8 on the entoconid were also more commonly merged in the pre-industrial group resulting in a slightly lower frequency of facet 8 in this period. The majority of 95% confidence intervals were overlapping, however, except for facets 10, 12 and 13. This indicates a significant difference between the prevalence of these wear facets between the two periods.

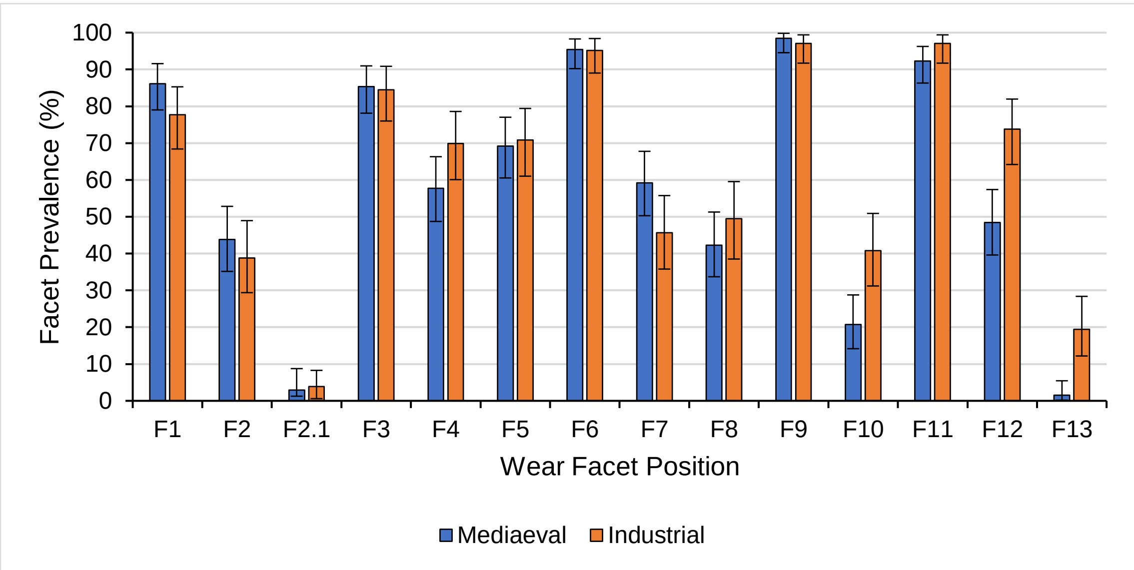


Figure 85: Bar chart showing the prevalence of each wear facet type among the assemblages examined divided by period. The 95% confidence interval for the proportion is expressed as an error bar for each wear facet position.

6.1.2.2 The composition of the wear facet area of the lower second molar should indicate a decrease in the lateral component of jaw movement during the power stroke as dietary content became more heavily processed.

In the Mediaeval and early Post-Mediaeval group, BPI and LPI wear facet areas occupied a larger proportion of the total wear facet area. The Industrial assemblages were characterised by greater proportions of phase II wear at the expense of phase I wear (Figure 86; Table 45). Wear facet composition differed significantly between the two periods (Table 46). The differences in wear facet proportions were significant regardless of whether the isometric log-ratio (ILR) transformed data or raw data was used for statistical analysis (Table 46).The data satisfied the assumption of homogeneity of multivariate dispersion (Table 117).

Table 45: Centre values for industrial and pre-industrial groups.

Period	N	BPI centre	LPI centre	PII centre	Total variance	Metric standard deviation
Mediaeval and Early Post-Mediaeval	130	30.88	39.84	29.27	0.39	0.40
Industrial	104	26.25	34.05	39.69	0.49	0.45

Table 46: Results of the permutational multivariate analysis of variance (PERMANOVA) assessment of the relationship between period and wear facet area composition. ***Null hypothesis: Relative wear facet area was not significantly influenced by time period.***

Standard data	Df	Sum of Squares	Mean of Squares	F-model	R^2	p-value	H_0
Period	1	0.48	0.48	22.77	0.09	0.0001	Rejected
Residuals	231	4.86	0.02	0.02	0.91		
	232	5.34			1.00		
ILR data	**Df**	**Sum of Squares**	**Mean of Squares**	**F-model**	**R^2**	**p-value**	**H_0**
Period	1	8.56	8.56	19.46	0.08	0.0001	Rejected
Residuals	231	101.62	0.44		0.92		
	232	110.19			1.00		

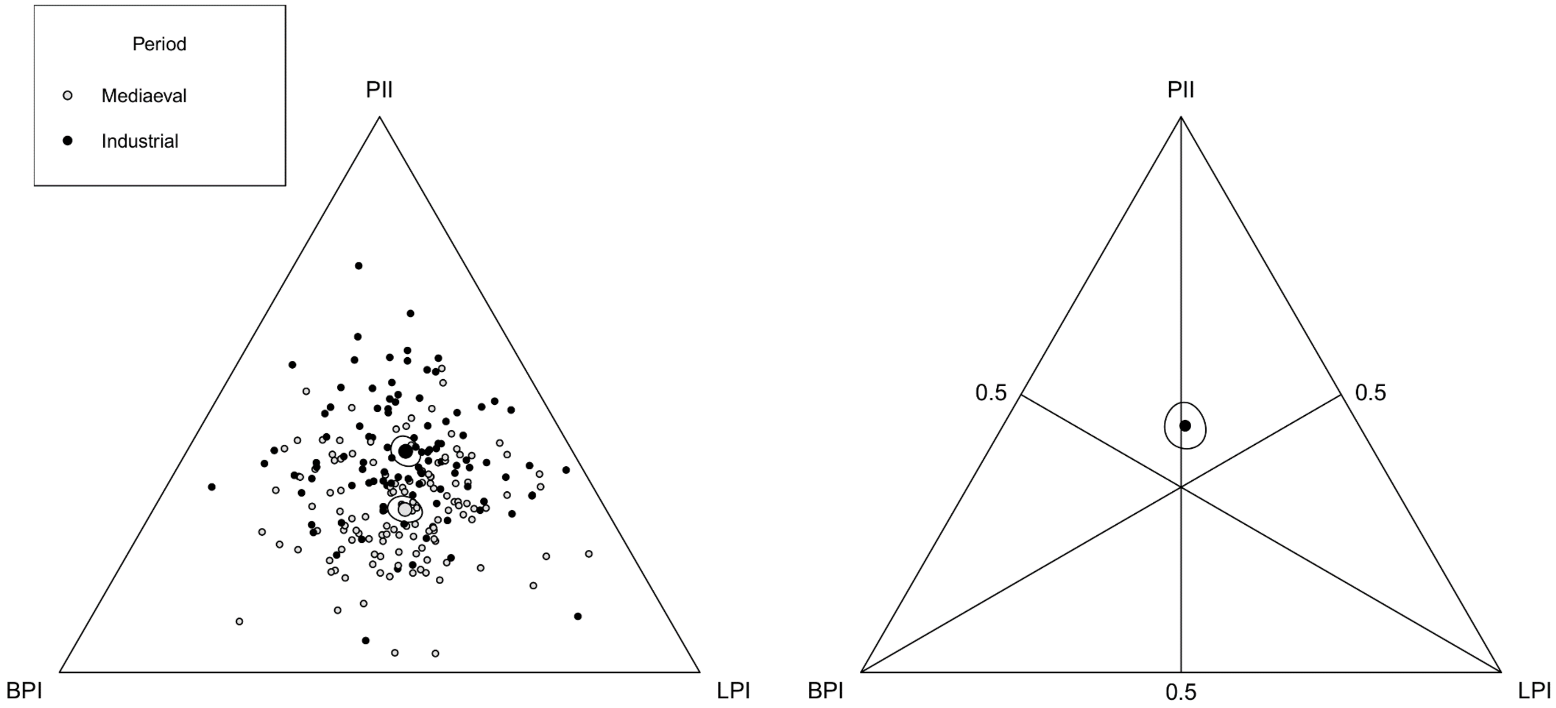


Figure 86: Left: Ternary plot showing the relationship between period and relative wear facet area (composed of BPI, LPI and PII facet areas). The Industrial group is displayed as black circles and the Mediaeval and early Post-Mediaeval group as white circles. The centre value for each period is represented as a larger filled shape surrounded by 95% confidence regions. The Industrial group is represented by a large black circle and the pre-Industrial group a large white circle.

Right: The second ternary plot shows the direction of the perturbation required to translate the mean of the Industrial group onto the mean of the pre-Industrial group, represented as the black point surrounded by its 95% confidence region. The intersection of the three black lines is equivalent to the null hypothesis that states there is no significant difference between the two periods. The location of the black point indicates that a reduction in the wear facet area composed of PII facets is the principal difference between the two periods with a slight shift towards larger LPI facet areas.

6.1.2.3 The wear facets on the lower second molar should be more obliquely inclined due to anticipated differences in the inclination of each phase of the power stroke.

The mean dip angles for each wear facet type were calculated for every individual (BPI: facets 1, 2, 3, 4; LPI: facets 5, 6, 7, 8; PII: facets 9, 10, 11, 12, 13). BPI and LPI mean dip angles were significantly steeper in the Industrial assemblages (Figure 87, Table 47). PII wear facets were typically more steeply inclined in the Industrial period; this difference approached significance (Table 47).

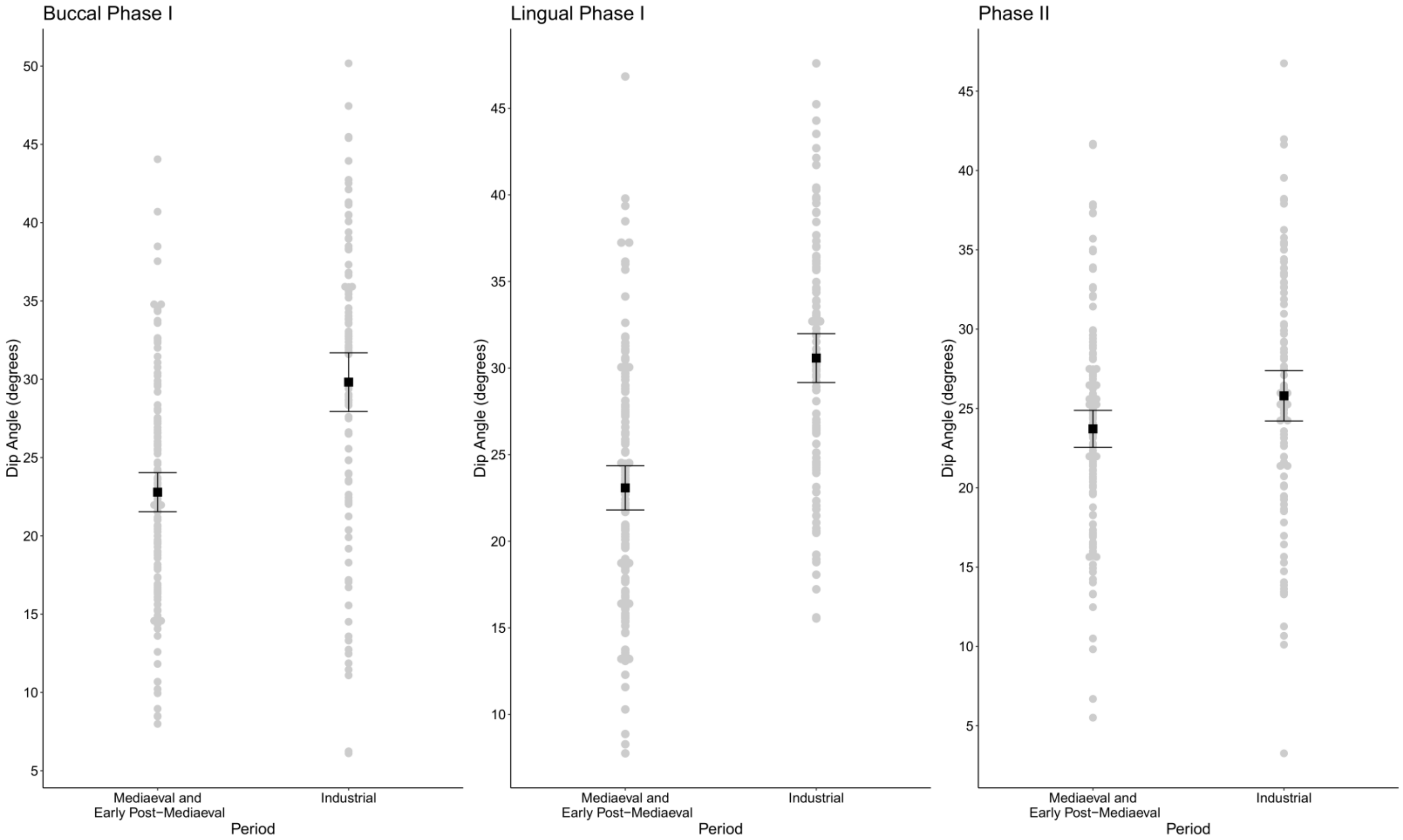


Figure 87: Dot plots with means and 95% confidence intervals plotted showing the mean dip angle of the wear facets associated with each phase of the power stroke divided by period

Table 47: Result of independent sample t-tests comparing mean dip angles between the Industrial and pre-Industrial groups. Dip angle data was normally distributed (Shapiro Wilk test BPI p-value=0.29; LPI p-value=0.15; PII p-value=0.64). ***Null hypothesis: The dip angle values for the wear facets associated with a given phase of the power stroke did not differ significantly between the two periods.*** *Bonferroni adjusted p-value for 3 tests= 0.017

Power Stroke Phase	BPI	LPI	PII
Industrial Mean Dip Angle(°)	29.81	30.58	25.79
Industrial Standard Deviation	9.59	7.22	8.08
Mediaeval Mean Dip Angle (°)	22.79	23.08	23.71
Mediaeval Standard Deviation	7.18	7.35	6.72
t-value	6.19	7.8	2.09
Degrees of Freedom	183.97	220.69	195.23
p value*	<0.001	<0.001	0.038
Effect Size	0.84	1.03	0.28
95% CI Effect Size	0.57 to 1.11	0.75 to 1.30	0.02 to 0.55
Statistical Power	1.00	1.00	0.85
H_0	**Rejected**	**Rejected**	Not Rejected

Within each period, dip angles differed significantly between BPI, LPI, PII and tip crushing wear areas (Table 48 and 49). Consequently, pairwise post-hoc comparisons were performed (Table 50). Dip angle steepness increased from tip crushing areas to phase II facets and from phase II facets to phase I facets in the Industrial period. In the Mediaeval and early Post-Mediaeval periods, dip angles did not differ significantly between phase I and phase II wear facets. Tip crushing facets remained significantly less steeply inclined, however.

Table 48: Results of Kruskal Wallis tests examining the relationship between facet type (BPI, LPI, PII and tip crushing) and dip angle. Kruskal Wallis tests were used as homogeneity of variance could not be assumed, however, normality could be assumed. ***Null Hypothesis: There was not a significant difference in the inclination of the dip angles of the wear facets associated with each aspect of the power stroke in either period.***

Kruskal Wallis test	Chi-squared	df	p-value	H_0
Industrial Period	145.79	3	<0.0001	Rejected
Mediaeval Period	161.96	3	<0.0001	Rejected

Table 49: Mean and median values for the dip angles associated with each type of wear facet divided by period.

Facet Function	Industrial				Mediaeval and Early Post-Mediaeval			
	Mean	SD	Median	IQR	Mean	SD	Median	IQR
BPI	29.81	9.59	31.75	12.54	22.79	7.18	22.58	9.69
LPI	30.58	7.22	30.79	10.97	23.08	7.35	22.98	10.97
PII	25.80	8.08	25.55	11.89	23.71	6.72	24.20	7.66
Tip Crushing	14.28	6.82	13.61	11.11	12.09	6.26	11.21	9.51

Table 50: Results of Dunn test for Kruskal-Wallis multiple comparisons examining the relationship between mean dip angle and phase of the power stroke in the Industrial period (White background) and in the pre-Industrial group (Grey background). P-values adjusted with the Benjamini-Hochberg method. ***Null hypothesis: for each pairwise comparison, there is not a significant difference between the inclination of wear facets associated with the wear facet function being compared.***

	BPI	LPI	PII	Tip Crushing
BPI	X	0.81	0.45	**0.00**
LPI	0.56	X	0.51	**0.00**
PII	**0.00**	**0.00**	X	**0.00**
Tip Crushing	**0.00**	**0.00**	**0.00**	X

6.1.2.4 There may be slight changes in wear facet orientation suggestive of differences in the directionality of the incursive and excursive components of the power stroke.

6.1.2.4.1 Dip Direction

Facets 1-13 showed a preferred orientation of dip directions rather than a uniform distribution (Rayleigh's test $p<0.001$). Rao's spacing tests indicated that all the wear facet dip directions, except for tip crushing areas, deviated significantly from an evenly spaced distribution indicating directionality (Table 51). These preferred orientations and directions conformed to the major directions of jaw movement conventionally associated with each wear facet (Kullmer *et al.* 2009). The mean dip direction was plotted for each wear facet position and period combination (Figure 88 to Figure 90). Watson's large sample non-parametric test for a common mean direction found that the mean dip direction for each wear facet position, except for facet 3, was not significantly related to period following Bonferroni correction (Table 51 and Table 52). This test does not assume any underlying distribution or common dispersion. Watson's two-sample test indicated that the dip directions for each wear facet position shared a common distribution irrespective of period. In addition, the dip directions for each wear facet position divided by period could have been drawn from a common concentration (Table 52).

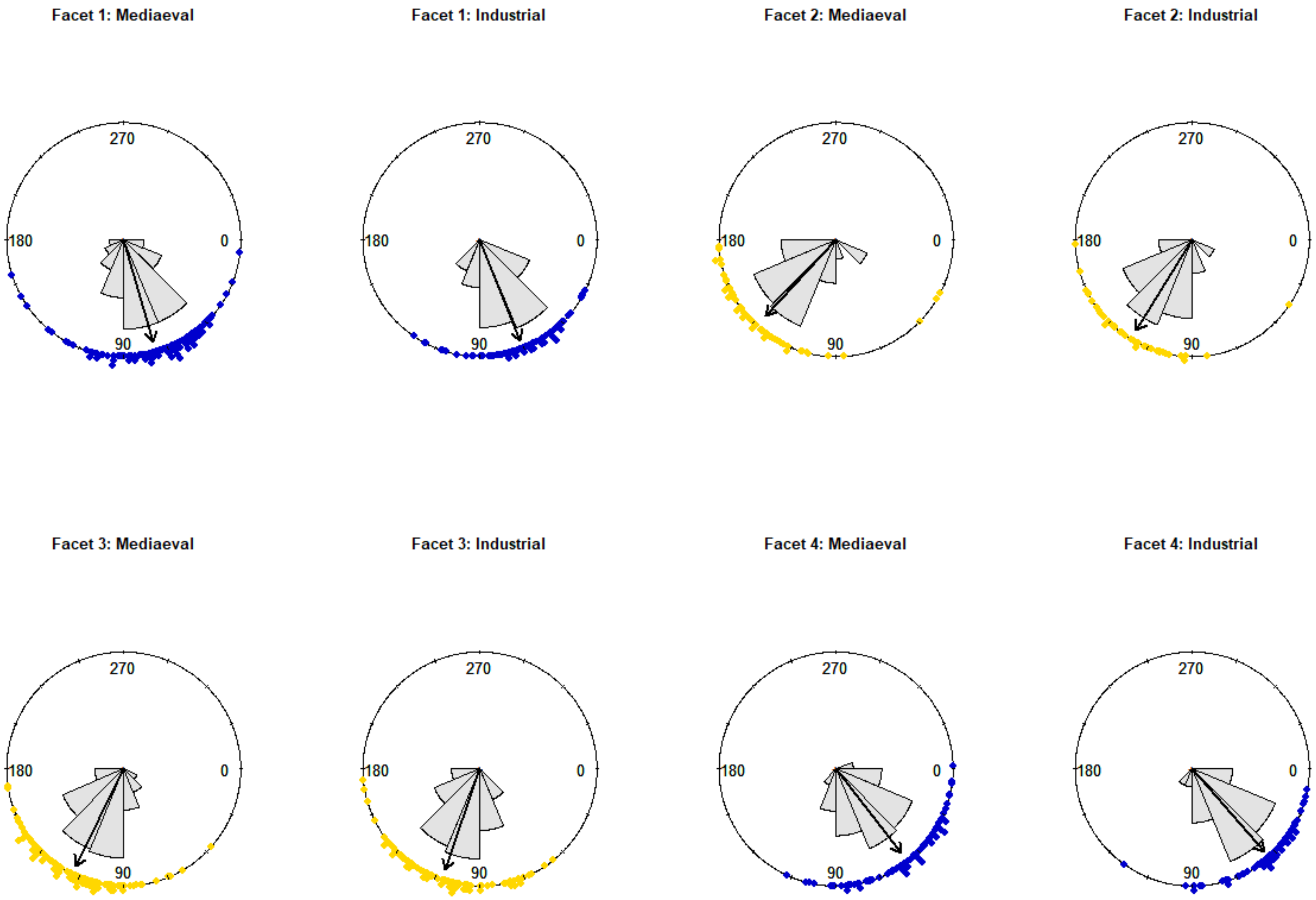


Figure 88: Dip directions for BPI facets divided by period. Blue indicates lateroretrusive facets (1 and 4) and yellow indicates mediotrusive facets (2 and 3).

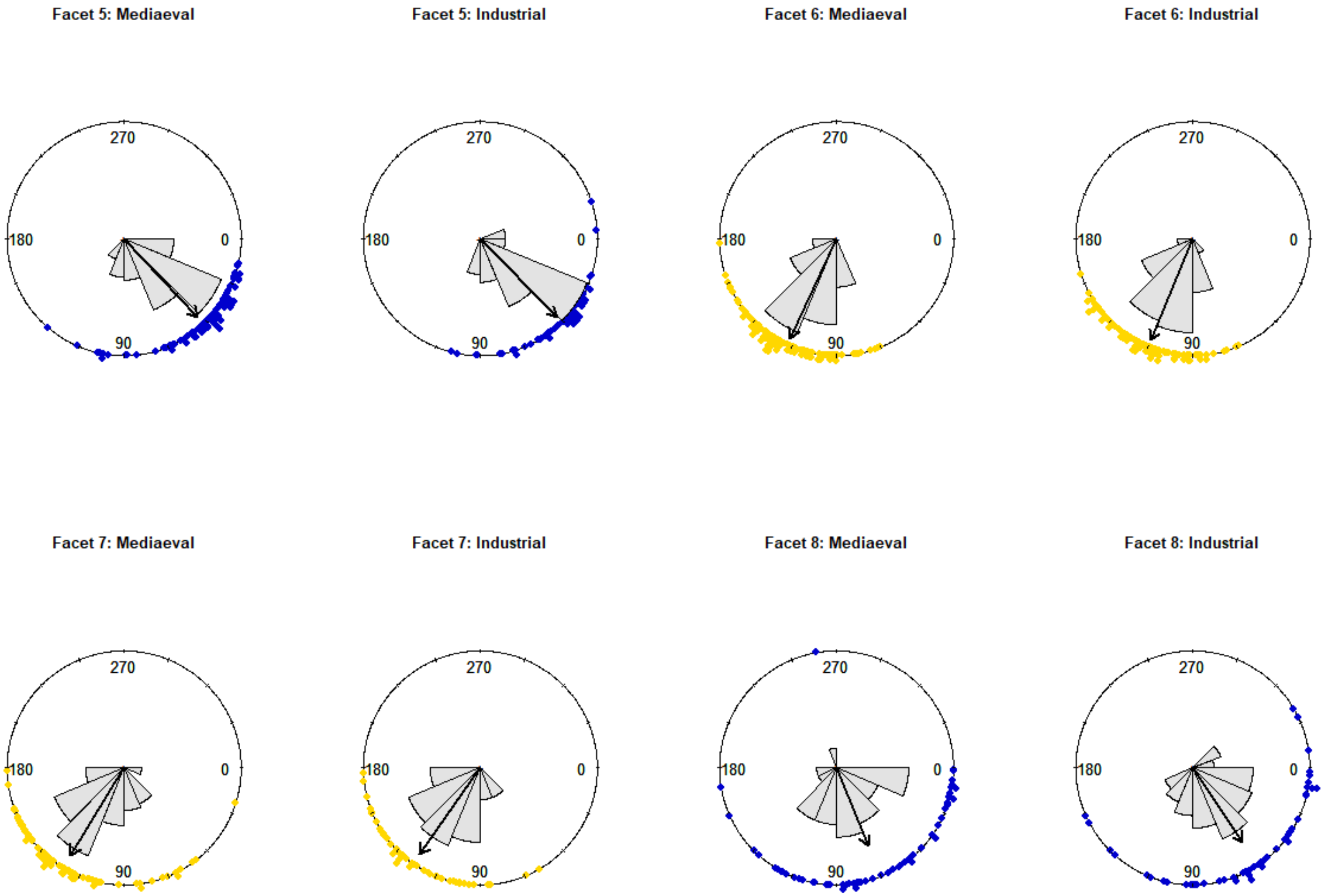


Figure 89: Dip direction for LPI facets divided by period. Blue indicates lateroretrusive facets (5 and 8) and yellow indicates mediotrusive facets (6 and 7).

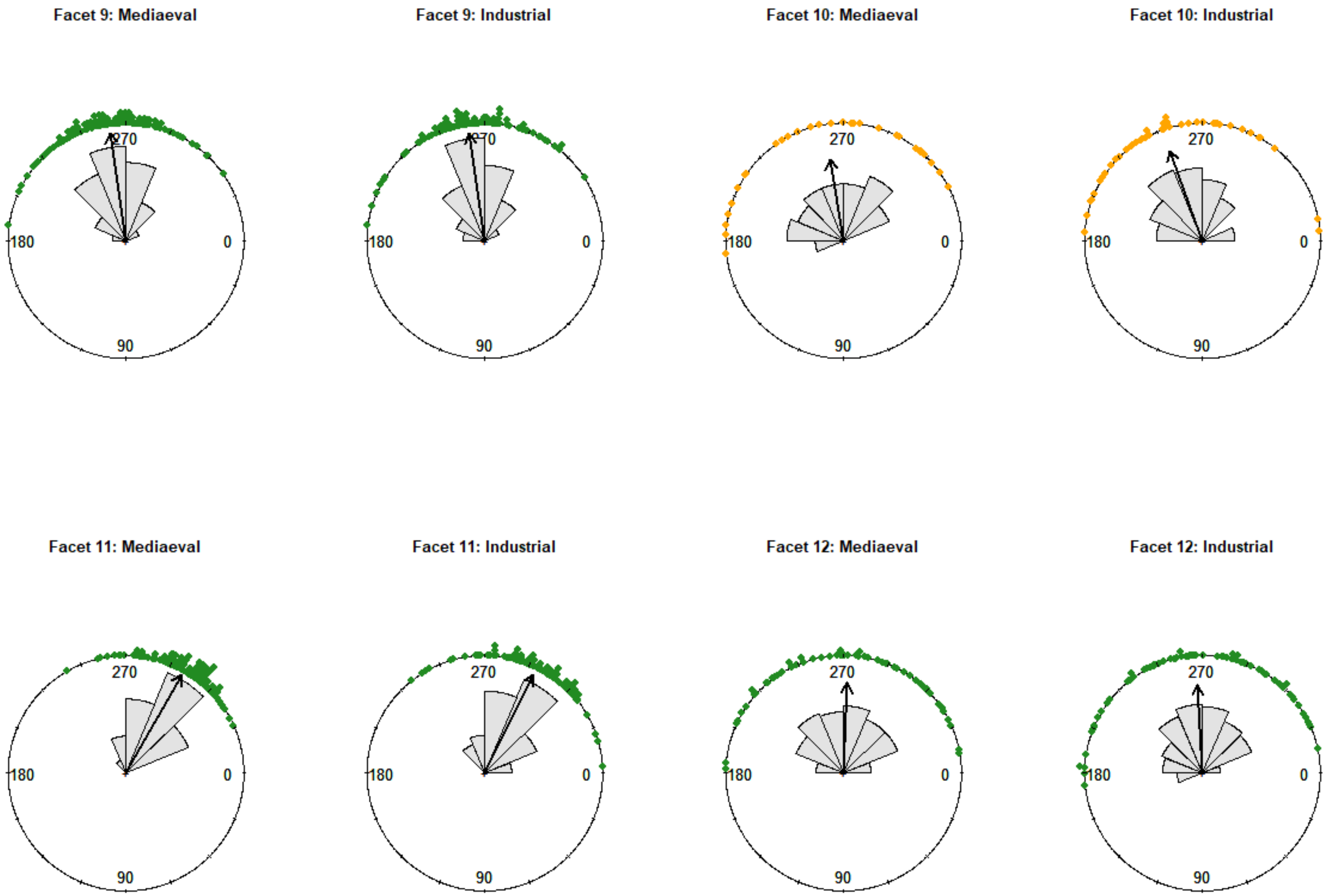


Figure 90: Dip direction for PII facets divided by period. Green indicates mediotrusive facets (9, 11 and 12) and orange indicates medioprotrusive facets (10). Facet 13 was not included as it was absent in most individuals.

Table 51: Mean dip direction values for the pre-Industrial and Industrial assemblages for each wear facet position. Rho is a measure of the concentration of the dip direction values around the mean as a proportion of 1. The closer the value is to 1 the more concentrated the observations. N refers to the number of each type of wear facet recorded in each period. Circular SD refers to the circular equivalent of standard deviation. Rayleigh's test is a statistical test used to assess unimodal deviations from a uniform distribution. The alternative hypothesis is that there is a unimodal distribution in the direction of the mean value given.

	Mediaeval and Early Post-Mediaeval					Industrial				
Facet	Mean (95% CI)	Rho	N	Circular SD	Rayleigh's test	Mean (95% CI)	Rho	N	Circular SD	Rayleigh's test
1	73.63 (69.1-78.1)	0.91	110	0.46	<0.001	67.54 (63.1-71.9)	0.93	80	0.37	<0.001
2	132.52 (126.29-138.77)	0.89	61	0.49	<0.001	121.70 (114.61-128.61)	0.91	41	0.44	<0.001
3	116.24 (111.81-120.62)	0.92	111	0.43	<0.001	108.89 (103.64-114.19)	0.91	86	0.40	<0.001
4	52.51 (47.03-58.62)	0.88	78	0.48	<0.001	49.05 (44.98-54.19)	0.94	72	0.35	<0.001
5	47.87 (43.07-53.35)	0.89	96	0.49	<0.001	48.75 (43.35-54.55)	0.89	73	0.47	<0.001
6	114.06 (110.18-117.8)	0.91	121	0.41	<0.001	111.49 (107.2-115.7)	0.93	97	0.37	<0.001
7	119.25 (112.27-125.88)	0.85	77	0.56	<0.001	123.72 (115.02-131.31)	0.88	46	0.51	<0.001
8	66.78 (56.17-80.42)	0.69	56	0.85	<0.001	55.97 (44.19-67.55)	0.76	51	0.74	<0.001

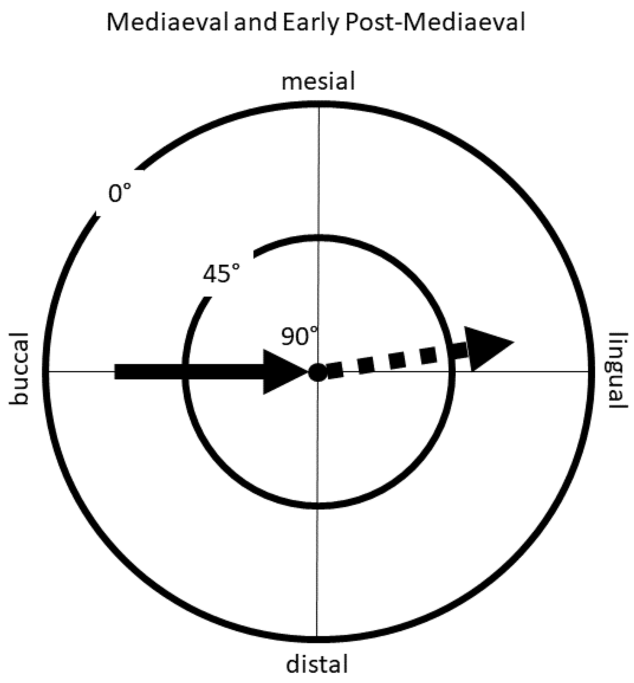
Facet	Mean (95% CI)	Rho	N	Circular SD	Rayleigh's test	Mean (95% CI)	Rho	N	Circular SD	Rayleigh's test
9	251.28 (257.06-265.21)	0.89	126	0.48	<0.001	252.33 (258.04-267.11)	0.92	98	0.41	<0.001
10	250.45 (242.33-280.01)	0.70	29	0.85	<0.001	249.93 (239.5-260.84)	0.81	44	0.64	<0.001
11	299.89 (296.77-303.19)	0.94	119	0.38	<0.001	295.94 (291.82-300.3)	0.93	96	0.33	<0.001
12	272.33 (256.13-277.84)	0.76	62	0.73	<0.001	266.66 (256.13-277.84)	0.69	74	0.85	<0.001
13	247.88 (223.17-281.99)	0.91	3	0.44	0.07	271.35 (244.26-298.22)	0.70	16	0.85	<0.001
Hypoconid tip crushing	274.69 (-289.96 to 41.07)	0.04	39	2.51	0.93	55.30 (-101.07-223.17)	0.07	35	2.28	0.83
Protoconid tip crushing	295.91 (161.99-233.51)	0.22	100	1.73	0.007	197.41 (112.86-267.02)	0.14	66	1.97	0.26

Table 52: Statistical testing comparing mean dip direction, distribution and concentration for each facet position between the two periods (Bonferroni adjusted p-value=0.003). Significant values are highlighted. Null hypothesis of Watson's large sample non-parametric test: period does not significantly influence the mean dip direction of the wear facet. Null hypothesis of Watson's two-sample test for a common distribution: the distribution of dip direction values for the wear facet do not differ significantly between the two periods. Null hypothesis for Wallraff's test for a common concentration: the concentration of the dip direction values for the facet do not deviate significantly between the two periods.

	Watson's large sample non-parametric test for a common mean dip direction		Watson's two-sample test for a common distribution		Wallraff's nonparametric test for a common concentration	
Facet	Y_g	p-value	Test statistic	p-value	Test statistic	p-value
1	<0.01	1.00	0.05	>0.10	0.55	0.46
2	5.99	0.01	0.15	> 0.10	0.15	0.70
3	11.12	**0.00**	0.08	> 0.10	0.20	0.66
4	0.03	0.87	0.16	0.05-0.10	6.80	0.01
5	1.57	0.21	0.08	> 0.10	1.90	0.17
6	1.09	0.30	0.09	> 0.10	0.06	0.81
7	1.40	0.24	0.03	> 0.10	0.04	0.84
8	0.03	0.87	0.10	> 0.10	1.66	0.19
9	0.43	0.51	0.05	> 0.10	0.00	0.99
10	2.41	0.12	0.17	0.05-0.10	0.01	0.93
11	1.46	0.22	0.01	> 0.10	0.01	0.93
12	0.58	0.46	0.03	> 0.10	0.00	0.97
13	X	X	0.10	> 0.10	0.00	0.97
pr-t	9.30	**0.00**	0.08	> 0.10	0.38	0.54
hd-t	0.17	0.68	0.03	> 0.10	0.46	0.50

6.1.2.4.2 Mastication Compasses

Differences in orientation and inclination of the power stroke between the two periods were visualised as mastication compasses (Figure 91). Phase I of the power stroke was significantly less steeply inclined in the Mediaeval period than the Industrial period (Table 53). The orientation of phase I and phase II movements did not differ significantly between the two periods (Table 54). The phase I incursive movement was lingually directed whereas the phase II excursive movement was slightly mesiolingually orientated.



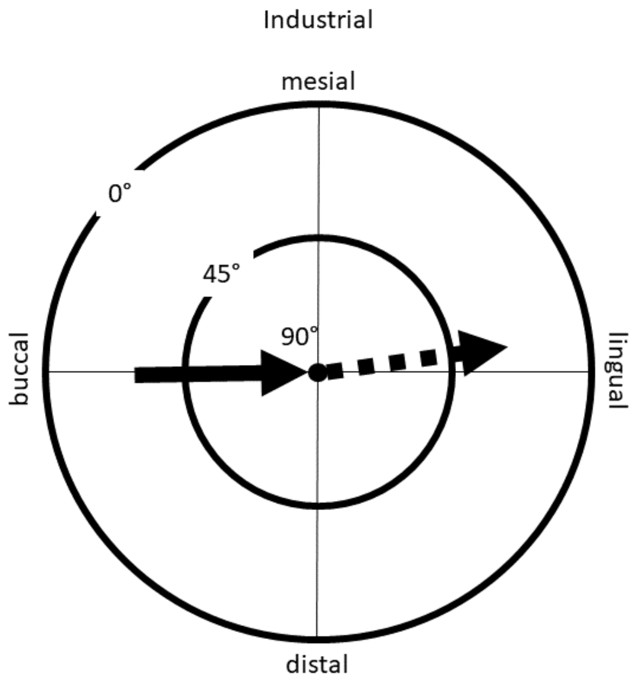


Figure 91: Visualisation of the mean inclination and orientation of phase I (bold line) and phase II (dashed line) of the power stroke for the pre-Industrial and Industrial groups. The orientation of the incursive and excursive occlusal motion is consistent between the two periods with overlapping 95% confidence intervals (pre-Industrial Phase I 90° (88° to 94°) and Phase II 279° (276°to 282°) compared to Industrial Phase I 89° (86° to 92°) and Phase II 278° (274° to 282°). The inclination of the phase I and phase II movement in the Industrial period was more steeply inclined, however.

Table 53: Independent sample t-test comparing the inclination of phase I and II movements between the Industrial era and Mediaeval and early Post-Mediaeval periods. ***Null hypothesis: the inclination of either phase I or phase II of the power stroke did not differ significantly between the two periods.***

Power Stroke Phase	Phase I Inclination	Phase II Inclination
Industrial Mean (°)	30.42	27.51
95% CI Industrial Mean	28.92 to 31.94	25.63 to 29.31
Standard Deviation	7.65	9.52
Mediaeval Mean (°)	23.33	25.02
95% CI Mediaeval mean	22.21 to 24.39	23.74 to 26.28
Standard Deviation	6.37	7.38
t-value	7.56	2.18
df	199.75	190.68
p value*	<0.001	0.03
Effect size	1.02	0.29
95% CI effect size	0.74 to 1.29	0.03 to 0.55
Statistical Power	1	0.59
H_0	**Rejected**	Not Rejected

Table 54: Results of Watson's large sample non-parametric test for a common mean dip direction comparing phase I and II movement orientation between the two periods. ***Null hypothesis: the orientation of either phase I or phase II of the power stroke did not differ significantly between the two periods.***

Power Stroke Phase	Phase I	Phase II
Industrial Mean (°)	89°	278°
95% CI	86° to 92°	274° to 282°
Circular Standard Deviation	0.34	0.34
Mediaeval Mean (°)	90°	279°
95% CI	88° to 94°	276°to 282°
Circular Standard Deviation	0.31	0.31
Yg	0.17	0.38
p-value	0.68	0.54
H_0	Not Rejected	Not Rejected

6.1.2.4.3 Summary of the differences in lower second molar wear patterns between the two periods

The dental macrowear patterns of the Industrial assemblages were characterised by a dominance of phase II facet areas over phase I. In contrast, the Mediaeval and early Post-Mediaeval group exhibited macrowear patterns with enlarged buccal and lingual phase I areas relative to phase II. Buccal and lingual phase I facets were significantly more steeply inclined in the Industrial period. Phase II wear facets were slightly less oblique in the pre-Industrial group. The inclination of the incursive phase I movement was significantly steeper in the Industrial period. Wear facet dip direction did not differ significantly between the two periods for the majority of wear facet positions neither did the orientation of the incursive phase I or excursive phase II movement.

6.1.2.5 OFA: Effect of ante-mortem tooth loss and dental caries.

6.1.2.5.1 Higher frequencies of ante-mortem tooth loss are anticipated in the Industrial period, partly due to consumption of a more cariogenic diet, higher levels of dental caries and associated tooth extraction. Clinical evidence suggests that higher levels of ante-mortem tooth loss, particularly of the posterior teeth, will impact masticatory performance.

The Industrial-era assemblages exhibited higher prevalence rates of ante-mortem tooth loss, cavitated carious lesions and minor rotation/displacement of teeth (Figure 92; Table 55). The differences in presentation of dental pathology were significant between the two periods (Table 56).

Table 55: Table giving average prevalence and standard deviation for the within arch dental pathology assessed for each assemblage. The proportion of either the total tooth sites assessed or number of teeth present with each condition was calculated for each individual examined (see section 5.2.1.2 for method). This value was then averaged to give the mean value for the group.

Dental Pathology	Cavitated Carious Lesions		Ante-mortem Tooth Loss		Minor Rotation/ Displacement		Major Rotation/ Displacement		Impaction	
Site	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
York Barbican	0.74	1.97	1.16	2.98	5.39	6.46	0.77	1.74	0.21	1.32
Blackfriars	1.87	2.92	1.04	2.21	3.02	4.31	0.44	1.33	0.00	0.00
Box Lane	2.26	3.89	1.47	2.76	3.99	4.68	2.38	6.30	1.19	3.15
Hereford Cathedral	0.91	2.10	0.77	2.01	5.83	5.88	0.78	3.79	0.00	0.00
St James and Mary Magdalene	2.41	3.95	2.89	4.49	2.65	3.82	0.39	1.32	0.50	1.34
St Michael’s Litten, Early	3.62	4.72	7.18	6.44	5.45	5.15	0.21	0.87	0.38	1.63
St Michael’s Litten, Late	1.92	3.54	6.63	12.38	5.74	6.65	0.10	0.60	0.83	2.60
Coronation Street	7.91	11.81	13.99	15.81	11.14	11.39	0.85	2.55	0.00	0.00
St Bride’s	4.88	6.14	12.09	10.57	12.56	13.53	1.54	3.99	0.39	1.27
St Peter’s	3.89	6.29	13.24	19.81	8.96	8.10	0.40	1.21	0.77	1.93

Table 56: Results of PERMANOVA assessing the relationship between period and the proportion of teeth in the dentition that exhibited each type of dental pathology recorded. ***Null hypothesis: there was not a significant difference in the mean proportion of teeth within the dentition effected by each type of dental pathology between the periods****.*

	df	Sums of Sq.	Mean of Sq.	F Model	R^2	P-value	H_0
Period	1	4.40	4.40	19.54	0.07	0.00	**Rejected**
Residuals	257	57.90	0.23		0.93		
Total	258	62.30			1.00		

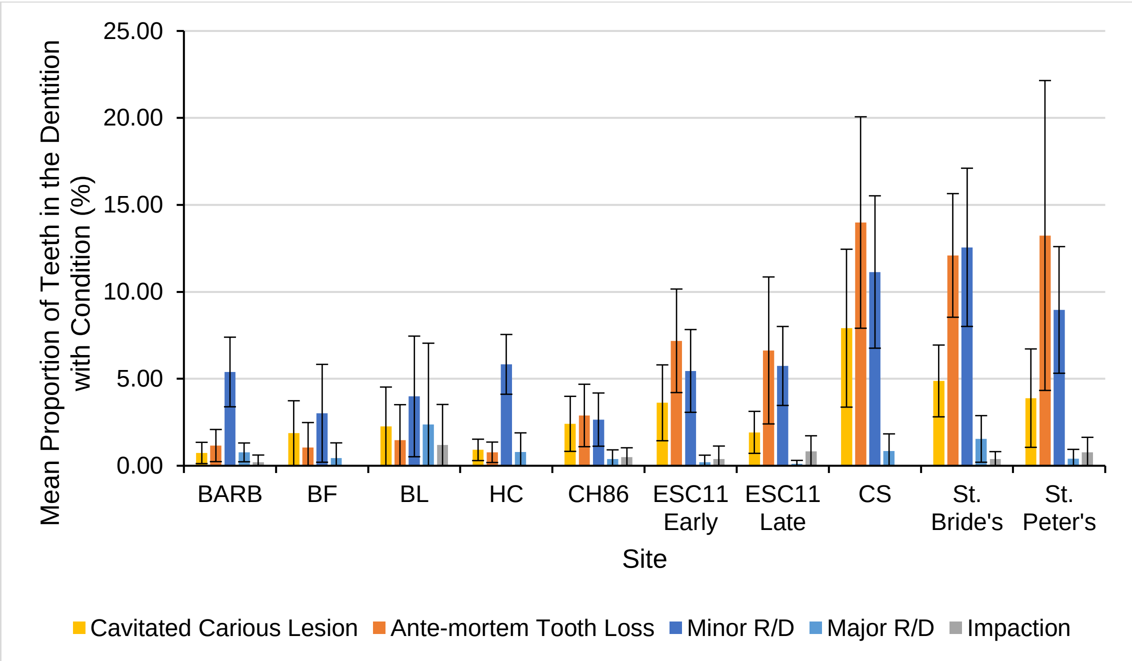


Figure 92: Bar chart showing the mean proportion of teeth within the dentition for each assemblage that exhibited each form of dental pathology recorded. For each individual, the number of teeth/tooth sites effected by the given pathology were expressed as a proportion of teeth/tooth sites that could be assessed in their dentition. 95% confidence intervals for the mean proportion of teeth in the dentition with each condition are given as error bars for each assemblage.

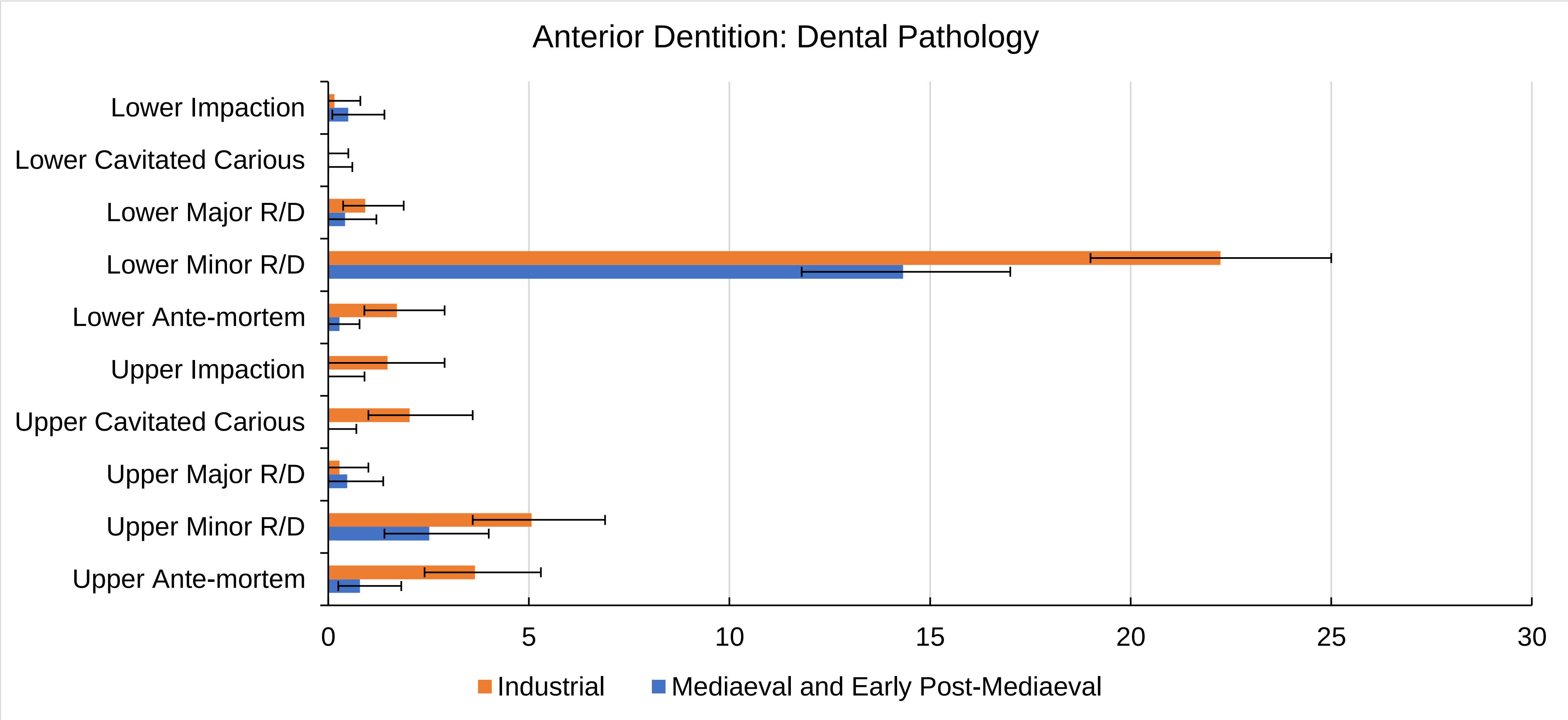
Many of the 95% confidence intervals for prevalence rates were overlapping between the Mediaeval, early Post-Mediaeval and Industrial assemblages, however, due to the small number of individuals assessed from several assemblages, particularly St Peter's, Blackfriars and Box Lane (Figure 92). Nevertheless, PERMANOVA with pairwise post-hoc testing found the differences between sites to be significant (Table 57 and Table 58). The St Peter's, St Bride's and Coronation Street assemblages differed significantly from the Hereford Cathedral Assemblage. Of the assemblages examined from Chichester, St James and St Mary Magdalene differed significantly from the late phase of St Michael's Litten, whilst the early phase of St Michael's Litten exhibited intermediate prevalence rates. St James and St Mary Magdalene, probably due to a higher prevalence of ante-mortem tooth loss, differed significantly from the other Mediaeval assemblages.

Table 57: Results of PERMANOVA assessing whether the individual prevalence rates of dental pathology differed significantly between the assemblages examined. ***Null hypothesis: the proportion of teeth within the dentition effected by the dental pathology recorded did not differ significantly between the assemblages examined.***

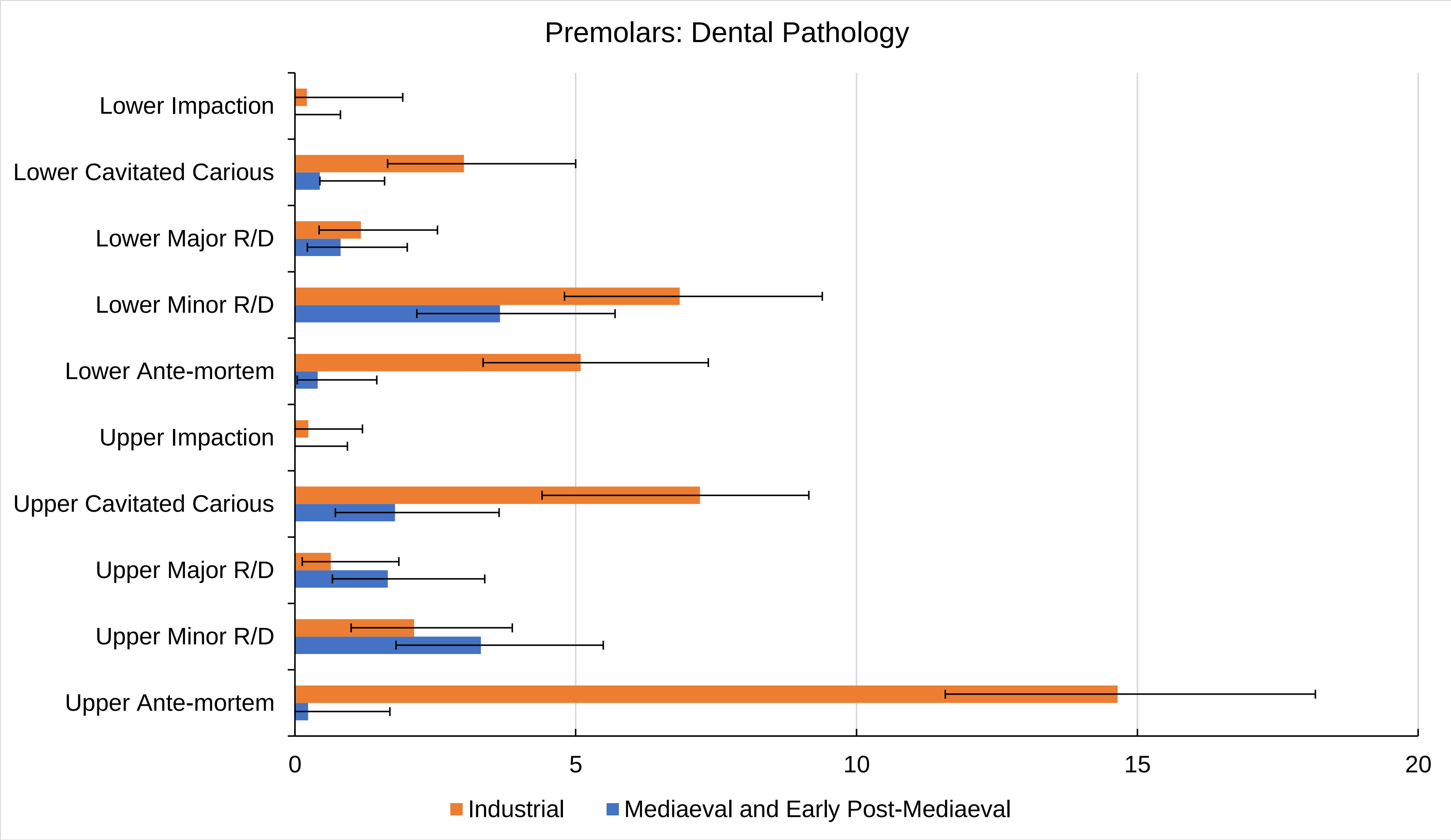
	df	Sums of Sq.	Mean of Sq.	F Model	R^2	p-value (>F)	H_0
Site	9	7.86	0.87	4.00	0.13	0.00	**Rejected**
Residual	249	54.43	0.22		0.87		
Total	258	62.30			1.00		

Table 58: Pairwise comparison of dental pathology between assemblages following significant PERMANOVA result (Table 57). Pairwise comparisons that differed significantly are highlighted in bold.

	BARB	BF	BL	HE	CH86	ESC Early	ESC Late	CS	St Peter
BF	0.69	NA	NA	NA	NA	NA	NA	NA	NA
BL	0.91	0.92	NA	NA	NA	NA	NA	NA	NA
HE	0.19	0.91	0.91	NA	NA	NA	NA	NA	NA
CH86	**0.00**	**0.00**	**0.05**	**0.00**	NA	NA	NA	NA	NA
ESC Early	**0.01**	**0.08**	0.40	**0.06**	0.37	NA	NA	NA	NA
ESC Late	0.13	0.35	0.91	0.22	**0.06**	0.50	NA	NA	NA
CS	0.87	0.50	0.87	**0.06**	**0.00**	**0.00**	**0.06**	NA	NA
St Peter	**0.00**	**0.00**	**0.02**	**0.00**	0.91	0.37	**0.02**	**0.00**	NA
SB79	**0.02**	**0.06**	0.37	**0.02**	0.61	0.54	0.61	**0.01**	**0.37**



Anterior Dentition: Dental Pathology
Lower Impaction
Lower Cavitated Carious
Lower Major R/D
Lower Minor R/D
Lower Ante-mortem
Upper Impaction
Upper Cavitated Carious
Upper Major R/D
Upper Minor R/D
Upper Ante-mortem
0
5
10
15
20
25
30
Industrial
Mediaeval and Early Post-Mediaeval



Premolars: Dental Pathology
Lower Impaction
Lower Cavitated Carious
Lower Major R/D
Lower Minor R/D
Lower Ante-mortem
Upper Impaction
Upper Cavitated Carious
Upper Major R/D
Upper Minor R/D
Upper Ante-mortem
0
5
10
15
20
Industrial
Mediaeval and Early Post-Mediaeval

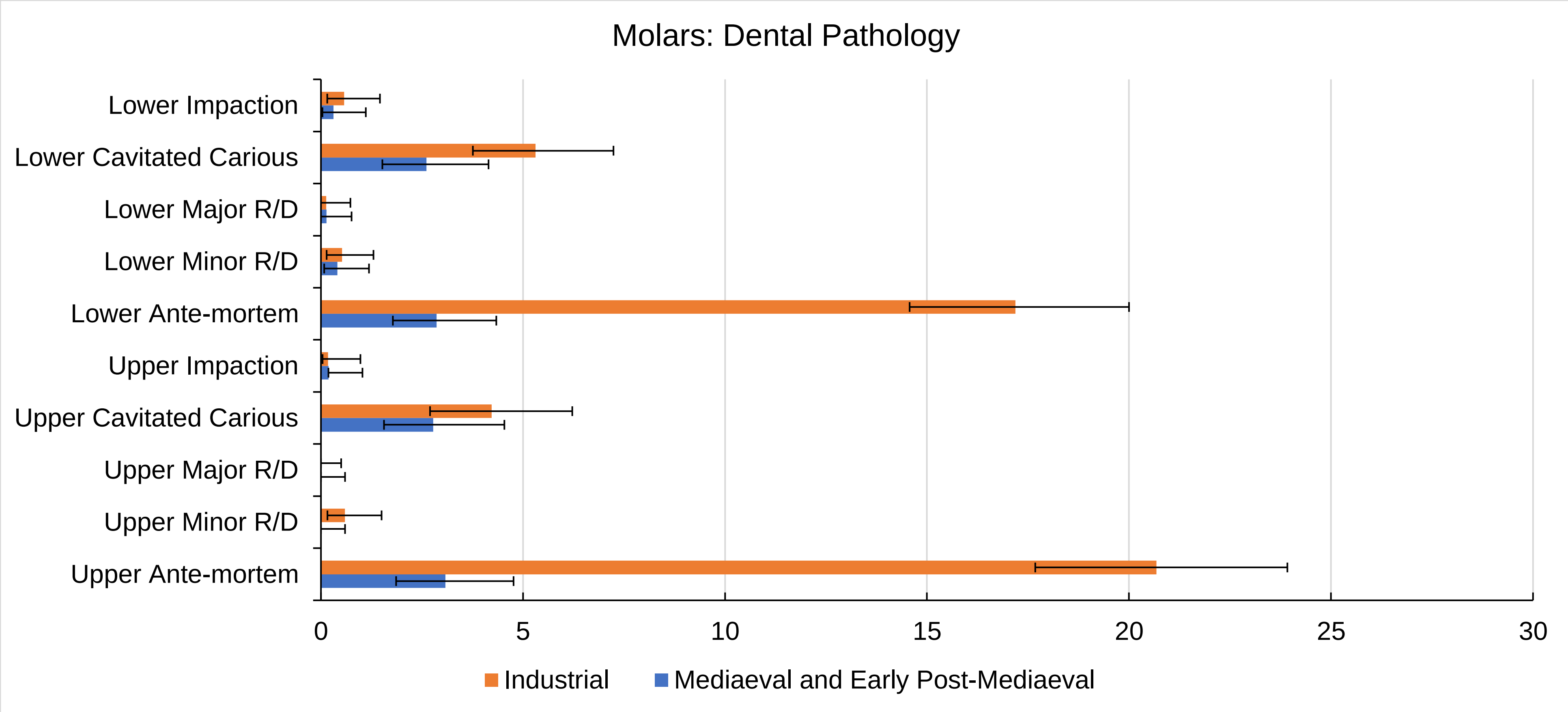


Figure 93: Upper: Bar chart showing prevalence rates for the dental pathology assessed in the anterior dentition (incisors and canines) divided by period. Prevalence rates were calculated using method in section 5.2.1.2. 95% confidence intervals are given as error bars in each bar chart. Middle: Bar chart showing prevalence rates for the dental pathology assessed in the premolars divided by period. Lower: Bar chart showing prevalence rates for the dental pathology assessed in the molars divided by period.

In the anterior dentition, the prevalence rates of minor rotation/displacement and ante-mortem tooth loss were markedly larger in the Industrial period; 95% confidence intervals were not overlapping (Figure 93). Prevalence rates of cavitated carious lesions were greatest in the premolars and molars in both periods, whereas, minor rotation/displacement of teeth was more frequent in the anterior dentition. Prevalence rates of cavitated carious lesions and ante-mortem tooth loss were higher in the premolars and molars in the Industrial period. The prevalence rates for ante-mortem tooth loss were appreciably higher in the molars in the Industrial period. Prevalence rates for major rotation/displacement and impaction did not differ dramatically between the two periods and 95% confidence intervals were substantially overlapping.

There were no significant sex-based differences in prevalence rates of carious lesions, ante-mortem tooth loss or rotation/displacement in either period (Table 59; Figure 94). The prevalence of ante-mortem tooth loss increased significantly with increasing age-at-death category in the Mediaeval and early Post-Mediaeval periods and approached significance in the Industrial period (Table 59). There was not a significant relationship between age-at-death and any of the other dental pathology recorded (Table 59).

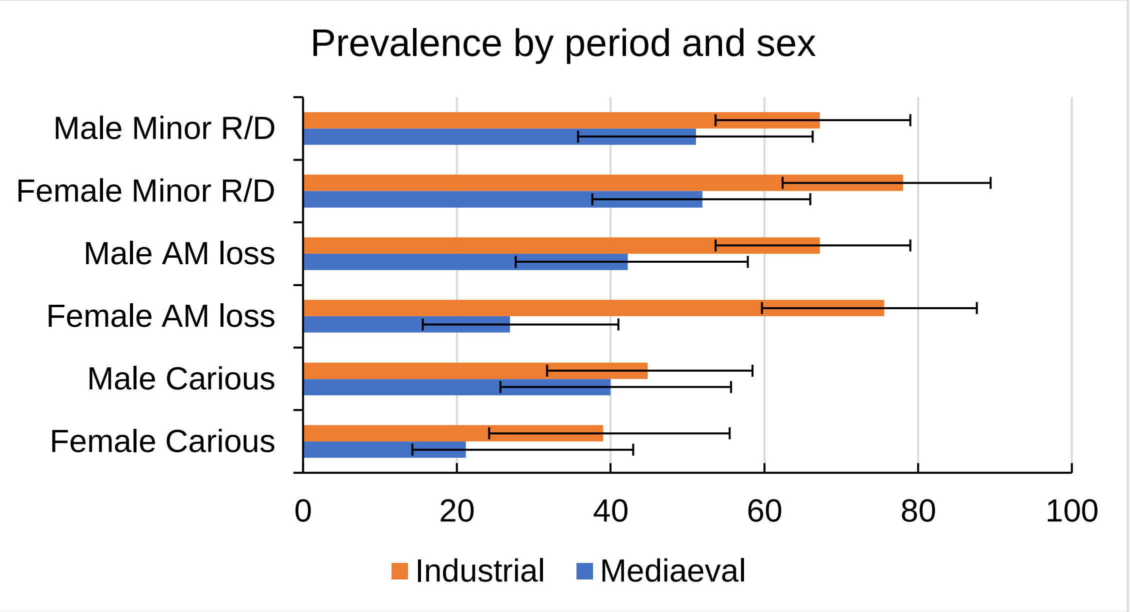


Figure 94: Bar chart showing the prevalence rate for cavitated carious lesions, ante-mortem tooth loss and minor rotation/displacement divided by sex and period.

These results confirm that there was a greater frequency of ante-mortem tooth loss, cavitated carious lesions and minor rotation/displacement in the 18th and 19th century assemblages as was anticipated based on the findings of previous bioarchaeological investigations. This can be partially attributed to the inclusion of individuals from older skeletal age-at-death categories within the Industrial material selected.

Table 59: Results of Wilcoxon Rank Sum Tests examining the relationship between sex and age-at-death and dental pathology in the pre-Industrial and Industrial groups. ***Null hypothesis: Sex and age did not significantly influence the prevalence rates of the dental pathology assessed in either period.*** *Bonferroni adjusted p-values were set at 0.003.*

Industrial Sex Differences	**W value**	**p-value**	**H_0**
Cavitated Carious Lesion	1184	0.97	Not Rejected
Ante-mortem Tooth Loss	1238.5	0.72	Not Rejected
Minor Rotation/Displacement	1454	0.06	Not Rejected
Major Rotation/Displacement	1286.5	0.19	Not Rejected
Pre-Industrial Sex Differences	**W value**	**p-value**	**H_0**
Cavitated Carious Lesion	952	0.06	Not Rejected
Ante-mortem Tooth Loss	959	0.07	Not Rejected
Minor Rotation/Displacement	1246.5	0.56	Not Rejected
Major Rotation/Displacement	1062.5	0.10	Not Rejected
Industrial Age-at-Death	**W value**	**p-value**	**H_0**
Cavitated Carious Lesion	462.5	0.89	Not Rejected
Ante-mortem Tooth Loss	285.5	0.008	**Rejected**
Minor Rotation/Displacement	511	0.58	Not Rejected
Major Rotation/Displacement	465	0.86	Not Rejected
Pre-Industrial Age-at-Death	**W value**	**p-value**	**H_0**
Cavitated Carious Lesion	580.5	0.65	Not Rejected
Ante-mortem Tooth Loss	217.5	<0.001	**Rejected**
Minor Rotation/Displacement	577	0.69	Not Rejected
Major Rotation/Displacement	625	0.96	Not Rejected

6.1.2.5.2 Mesial drift due to tooth loss and the loss of antagonistic teeth will alter occlusal relationships and may impact the dental wear patterns of the teeth involved. It is hypothesised that ante-mortem tooth loss may contribute to the overall differences observed in dental wear patterns between the two periods.

There was no clear clustering of relative wear facet area associated with generalised tooth loss on either the working and non-working sides of the dentition (Figure 95 and Figure 96). The working side was defined as the side on which the lower second molar targeted for OFA was situated. In addition, the loss of the lower first molar adjacent to the lower second molar targeted for OFA did not impact relative wear facet areas (Figure 97). A slight tendency towards a reduction in the PII proportion of the total wear face area on the lower second molar following the loss of the antagonistic upper second molar in the Industrial period was observed (Figure 98 and Table 60), however, this tendency was not found to be significant (Table 61 and Table 120). Ante-mortem tooth loss did not have a marked impact on relative wear facet area composition on the lower second molar when compared to the effects of period.

Table 60: The number of individuals with either a cavitated carious lesion or ante-mortem tooth loss of the working side lower first molar and/or working side upper second molar.

Working Side Lower First Molar Status	Mediaeval and Early Post-Mediaeval N (Prevalence)	Industrial N (Prevalence)
Cavitated Carious Lesion	8 (6.45%)	6 (6.06%)
Lost Ante-Mortem	11 (8.87%)	31 (31.31%)
Present	105 (84.68%)	62 (62.62%)
Working Side Upper Second Molar Status	**Mediaeval and Early Post-Mediaeval N (Prevalence)**	**Industrial N (Prevalence)**
Cavitated Carious Lesion	0	2 (2.38%)
Lost Ante-Mortem	4 (3.85%)	18 (21.43%)
Present	100 (96.15%)	64 (76.19%)

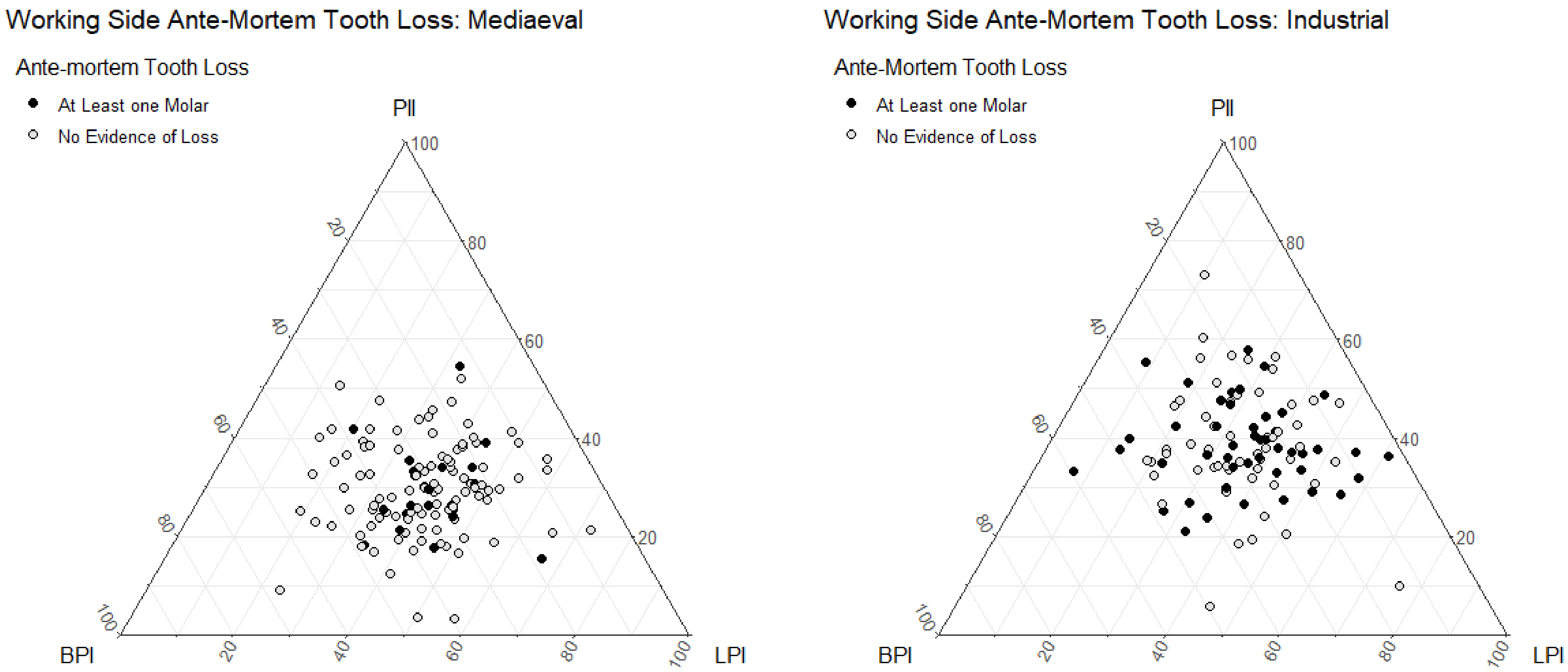


Figure 95: Ternary plots showing the lack of association between the loss of at least one molar on the working side and the relative wear facet area of the lower second molar. There is more frequent ante-mortem tooth loss on the working side in the Industrial period.

Figure 96: Ternary plots showing the lack of association between the loss of at least one molar on the non-working side and the relative wear facet area expressed on the lower second molar. There is more frequent ante-mortem tooth loss on the non-working side in the Industrial period.

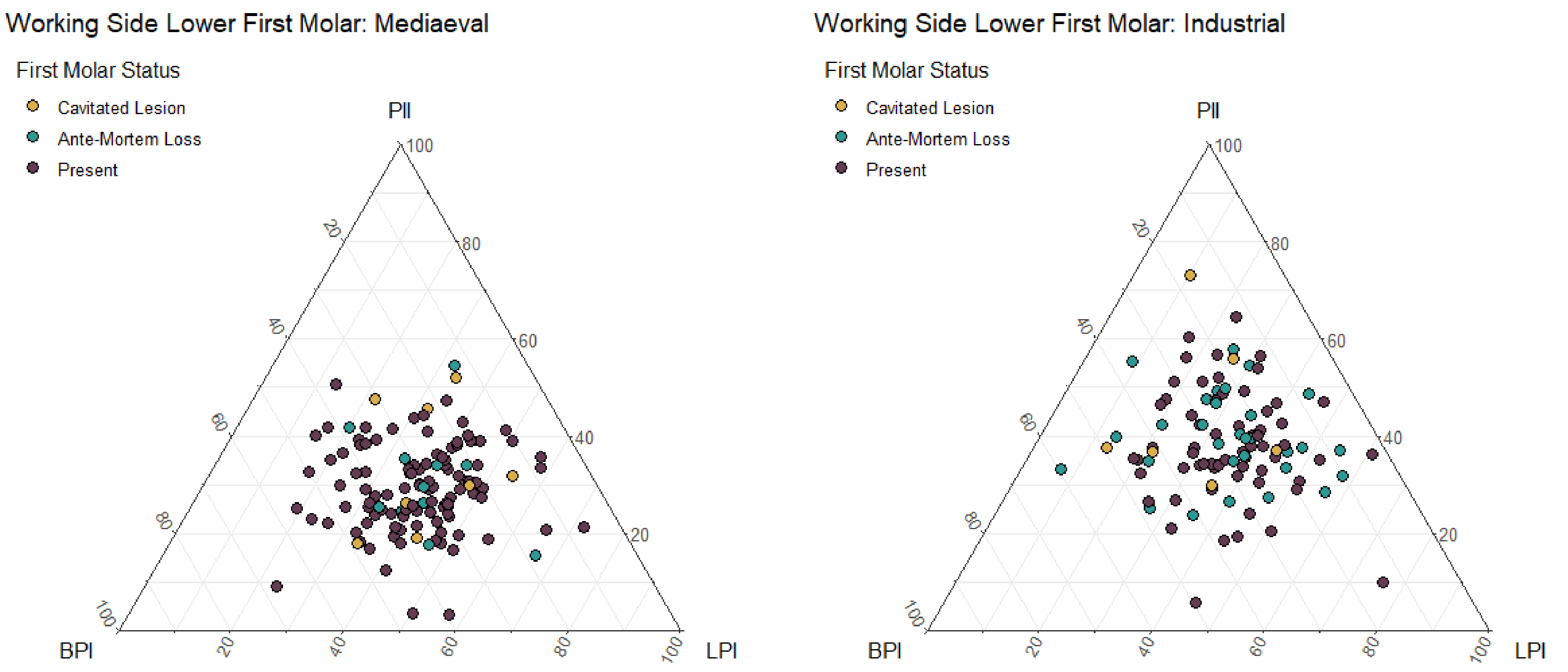


Figure 97: Ternary plots comparing relative wear facet area in the Industrial and pre-Industrial groups according to the status of the lower first molar on the working side. The distribution of points for each category were extremely overlapping, therefore, no statistical analysis was undertaken.

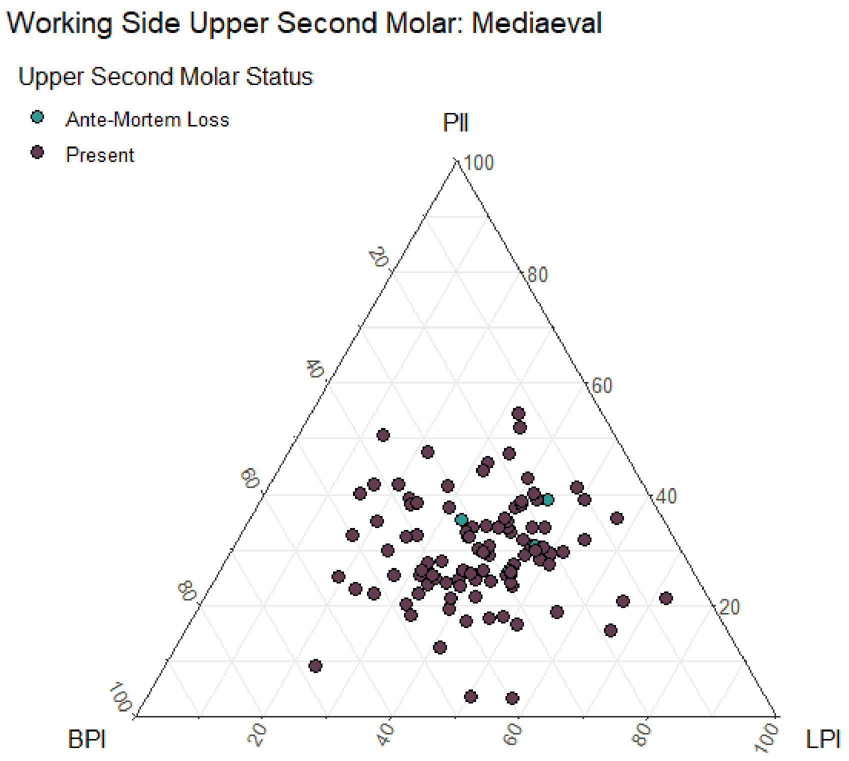


Figure 98: Ternary plots showing the relationship between the status of the upper second molar and relative wear facet area in the Industrial and pre-Industrial groups. A slight tendency towards increasing proportions of LPI wear areas at the expense of PII wear was apparent in the Industrial period with ante-mortem loss of the antagonistic upper second molar. This relationship was, therefore, assessed statistically (Table 61).

Table 61: Results of PERMANOVA examining the relationship between upper second molar status and relative wear facer area in the Industrial period. ***Null hypothesis: the loss of the occlusal support of the antagonistic upper second molar did not significantly influence the relative wear facet proportions of the lower second molar.***

ILR data	**Df**	**Sum of Sq.**	**Mean of Sq.**	**F-model**	**R^2**	**p-value**	**H_0**
Upper Second Molar Status	2	1.40	0.70	1.58	0.04	0.19	Not Rejected
Residuals	80	35.38	0.44		0.96		
Total	82	36.78			1.00		
Standard data	**Df**	**Sum of Sq.**	**Mean of Sq.**	**F-model**	**R^2**	**p-value**	**H_0**
Upper Second Molar Status	2	0.07	0.04	1.70	0.04	0.16	Not Rejected
Residuals	80	1.68	0.02		0.96		
Total	82	1.75			1.00		

6.1.3 Differences in dynamic OFA simulations between the two periods

6.1.3.1 There should be a decrease in the lateral component of the movement of the lower molars during dynamic simulations of the power stroke; a power stroke dominated by a more strongly vertically directed chopping action might be anticipated.

6.1.3.1.1 Overview of Power Stroke Simulations (Videos 1 to 8, Videos 11 to 34) The duration of the power stroke simulation following maximum intercuspation was greater in the Mediaeval and early Post-mediaeval periods reflecting an elongation of phase II of the power stroke (Figure 99). Power stroke simulations for the Industrial period, involved a more rapid increase in contact area during the terminal portion of phase I and during maximum intercuspation. In addition, the reduction in contact area was slightly more rapid following maximum intercuspation in the Industrial era (Figure 100). The differences between the profiles of the power stroke simulations between the two periods approached significance when considering the time step at which key stages of the power stroke were reached and the rate of change in contact area (Table 62).

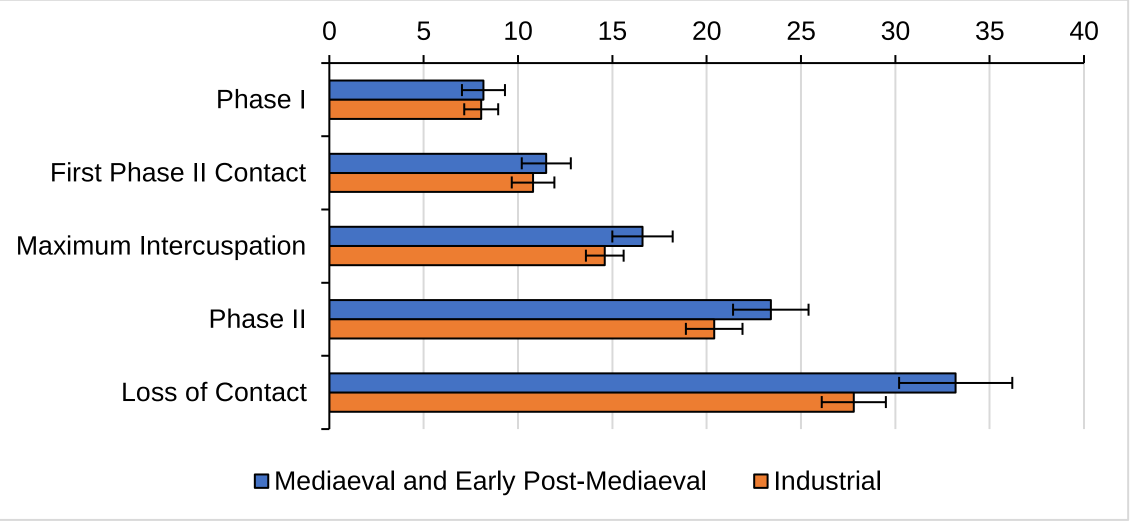


Figure 99: Average timestep at which each phase of the power stroke was reached during dynamic Occlusal Fingerprint Analyser simulations for the Mediaeval, early Post-Mediaeval and Industrial periods. 80% confidence intervals are given as error bars (Cohen 1990). The later stages of the power stroke typically occurred over a greater number of time steps in the Mediaeval and early Post-Mediaeval simulations.

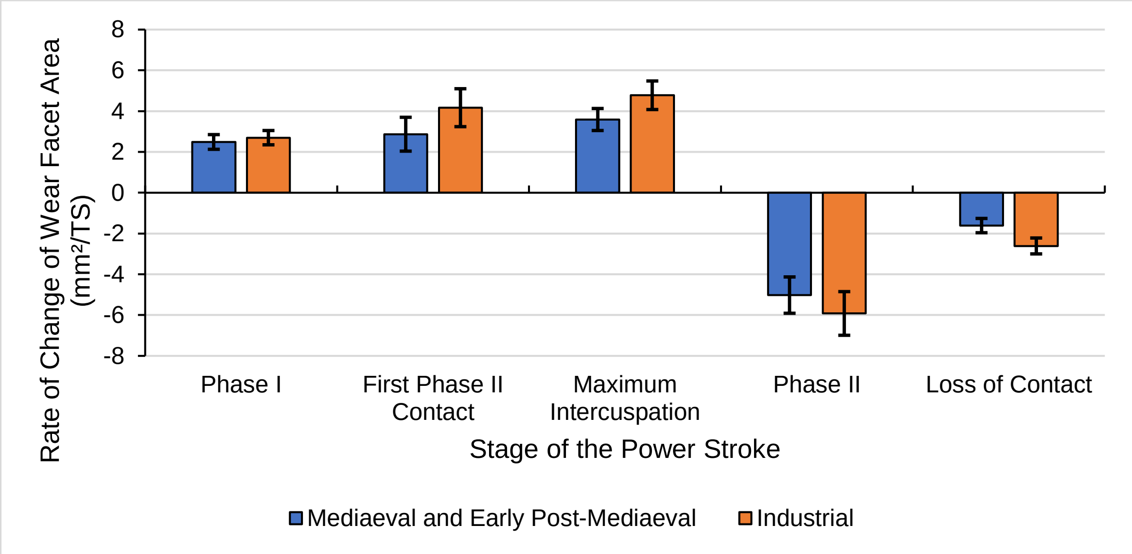


Figure 100: Bar chart comparing the average rate of change in wear facet area (mm²/Time Step) for each phase of the power stroke between the Mediaeval, early Post-Mediaeval and Industrial periods. 80% confidence intervals are given as error bars.

Table 62: Results of PERMANOVA test comparing Occlusal Fingerprint Analyser collision profiles between the pre-Industrial and Industrial groups using the Euclidean dissimilarity matrix with a permutational parameter of 9999. ***Null hypothesis: the profiles of the dynamic OFA simulations did not differ significantly between the two periods.*** *The data did not violate the homogeneity of dispersion assumption required for performing PERMANOVA (Table 121).*

PERMANOVA	**Sum Squares**	**Mean Squares**	**df**	**F**	**R^2**	**p-value (>F)**	**H_0**
Period	352.54	352.54	1	2.79	0.09	0.06	Rejected?
Residuals	3791.13	126.37	30		0.91		
Total	4143.67		31		1.00		

Canonical variance analysis (CVA) was conducted to compare the timing of each stage of the power stroke and the rate of change in collision area between the assemblages examined (Figure 101). Box Lane and Blackfriars were not included as individuals suitable for power stroke simulation were not present. The individual from St Peter's, Wolverhampton, for whom a power stroke simulation had been conducted was combined with the Coronation Street group for the analysis as this was the most temporally and geographically proximate group.

The CVA discriminated between the pre-Industrial and Industrial assemblages. The St Michael's Litten assemblage (ESC11) occupied an intermediate position

(Figure 101). The CVA model gave an overall classification accuracy of 72% and a kappa statistic of 0.64. The first canonical axis differentiated the Mediaeval from the Industrial era assemblages. This reflected the greater duration of the power stroke simulations for the pre-Industrial, particularly following maximum intercuspation. This axis also represented the more rapid increase in collision areas during the Industrial simulations; the difference between the two periods was greatest immediately prior to maximum intercuspation. Following the initial contacts of phase I, the rate of increase and decrease in collision area for each phase of the power stroke was typically greater in the Industrial assemblages.

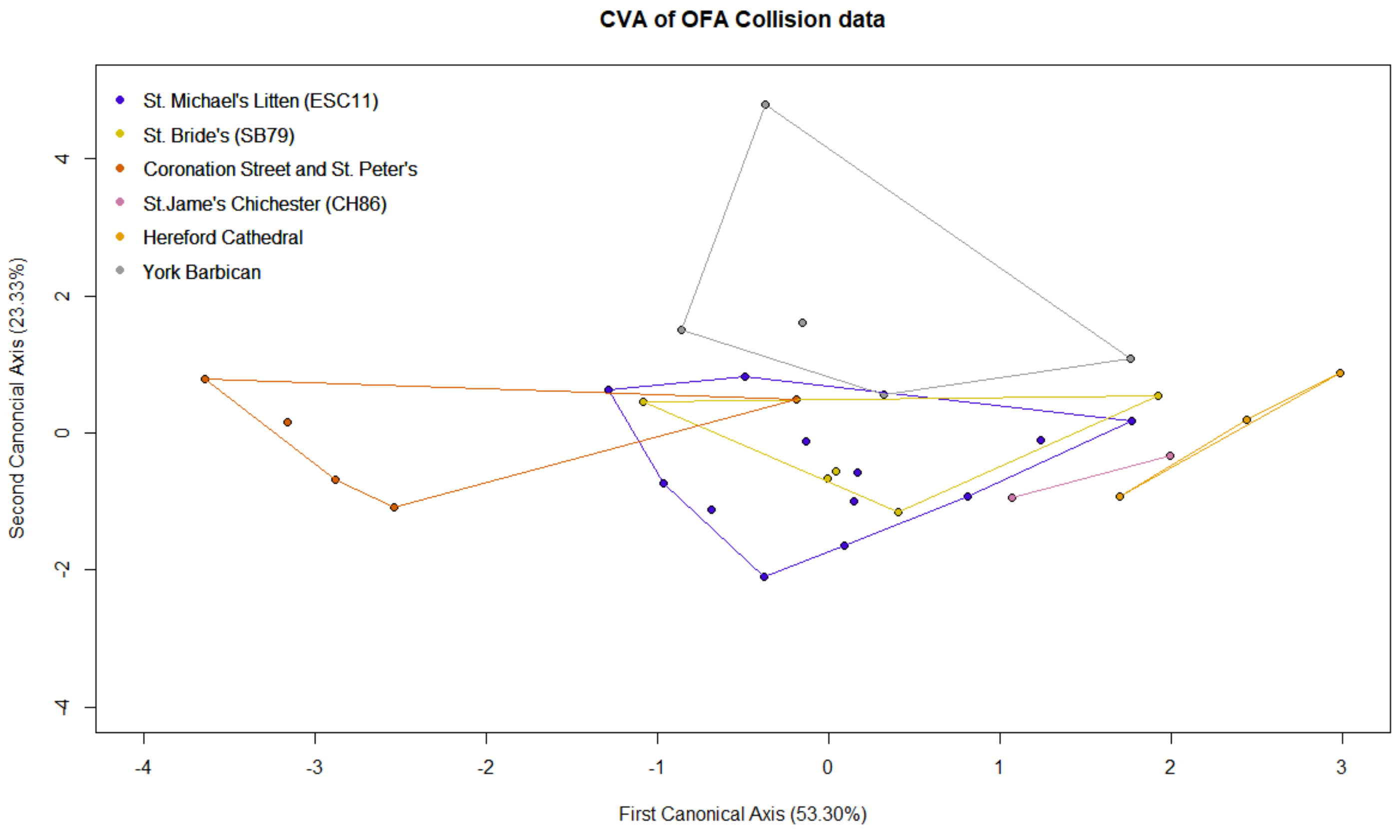


Figure 101: Scatterplot of canonical variance analysis comparing OFA collision profiles between the assemblages examined. The first canonical axis explained 53% of variation and the second canonical axis 23%. The 1st canonical axis was strongly positively correlated with the length of the power stroke in each simulation particularly the number of timesteps following maximum intercuspation and the duration of phase II of the power stroke. It was slightly negatively correlated with the rate of increase in wear facet area immediately prior to maximum intercuspation. The 2nd canonical axis was strongly positively correlated with the time step at which loss of contact occurred. It was slightly positively correlated with the rate of increase in contact area prior to maximum intercuspation.

6.1.3.1.2 Case Studies by Period and Assemblage

A dynamic OFA simulation is presented below for one individual per assemblage examined, where an appropriate individual was available. These simulations exemplify the variability in wear facet patterns and power stroke profiles within each period.

6.1.3.1.2.1 Industrial Period

6.1.3.1.2.1.1 Coronation Street: CS371 (Video 1)

CS371 was identified as a male with a Buckberry-Chamberlain score of 10 (Older age category). The individual had pipe facets unilaterally present on the left side of the dentition and moderate crowding of the anterior dentition (36% of the teeth present were minorly rotated or displaced). The individual had lost 22% of their teeth ante-mortem. This included the upper left third and fourth premolars and all the premolars and molars in the upper right quadrant apart from the third molar. A cavitated carious lesion was present on the lower right third molar.

CS371 was characterised by moderate blunting of the buccal cusps on the lower second molar, with pinpoint dentine exposure, and substantially less wear on the lingual cusps. There was a large facet 6 and 7 on the metaconid and entoconid respectively, however. The ORI of this individual (1.46) fell within the 2nd quartile range of the ORI values for the Industrial period. The occlusal relief on the lingual cusps likely played a strong guiding role during phase I of the power stroke as the teeth moved into maximum intercuspation. The wear facet pattern of the lower second molar was characterised by large phase II facets (57%) and lingual phase I facets (38%) and very small buccal phase I facets (5%) (Figure 102).

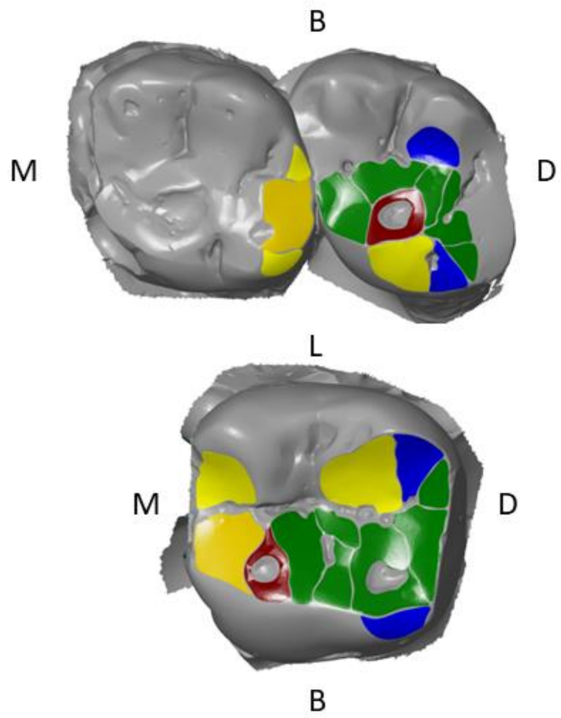


Figure 102: Wear facet maps for the upper and lower left molars of CS371. The individual is characterised by very small BPI contact areas and very large and shallowly inclined PII wear areas.

The first stage of the power stroke involving only phase I contact areas was brief in this individual and principally involved contacts on facets 4, 6 and 8. The simulated power stroke (Figure 103 and Figure 104) displayed a strong vertical component with minimal lateral deviation. This resulted in a rapid increase in contact area prior to maximum intercuspation in the later part of phase I of the power stroke. These large contact areas included both phase I and II wear facets. Phase II wear facets would have been involved in a marked shearing action during this terminal portion of phase I as trapped food particles were subjected to tensile stresses as the teeth moved into maximum intercuspation. This corresponds to the peak in EMG adductor muscle activity in many feeding studies (Wall *et al.* 2006) and represents the period in which the majority of food breakdown occurs on phase II surfaces. Following this shearing action prior to and during maximum intercuspation, contact areas are lost rapidly as the lower teeth follow a steeply vertically orientated phase II movement. Individual CS371 highlights the reduced lateral component in the power stroke of Industrial individuals concordant with the mastication of less tough and hard dietary staples. These more heavily processed foods could be primarily reduced using a strongly emphasized shearing crushing action during the terminal part of phase I of the power stroke.

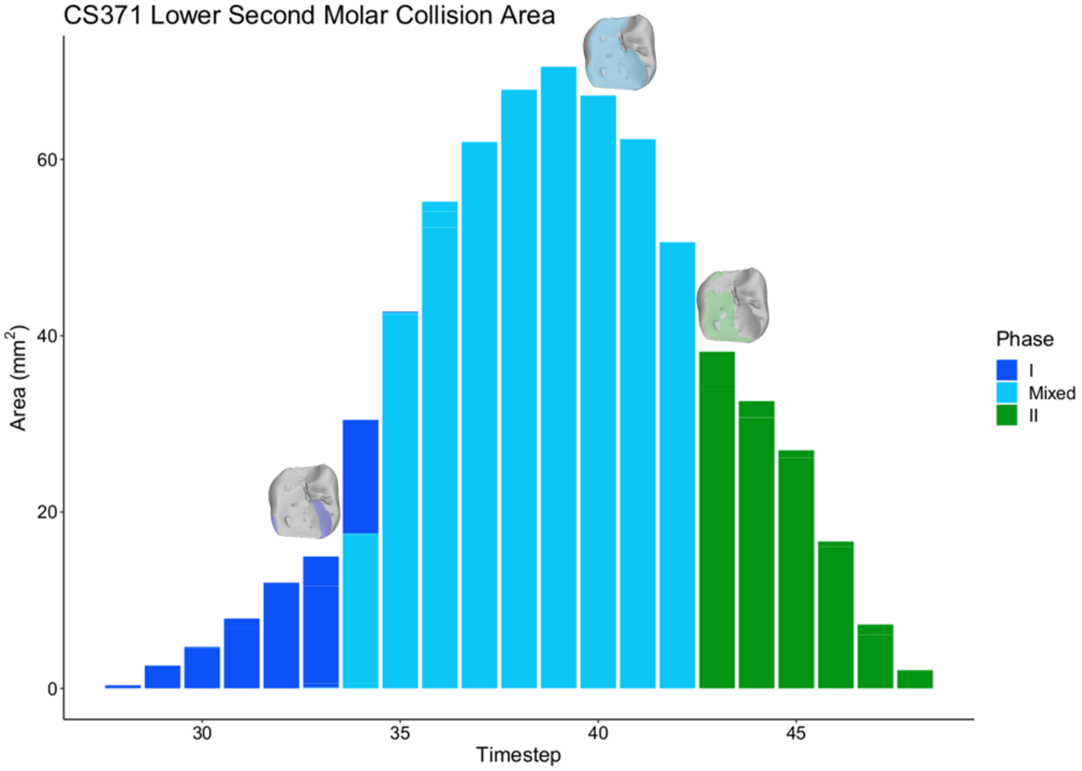


Figure 103: Stacked bar chart showing the development of contact areas during the power stroke simulation of SK371 from the Coronation Street assemblage. The period leading up to maximum intercuspation was characterised by a period of mixed contacts in which both phase I and II facet areas were involved.

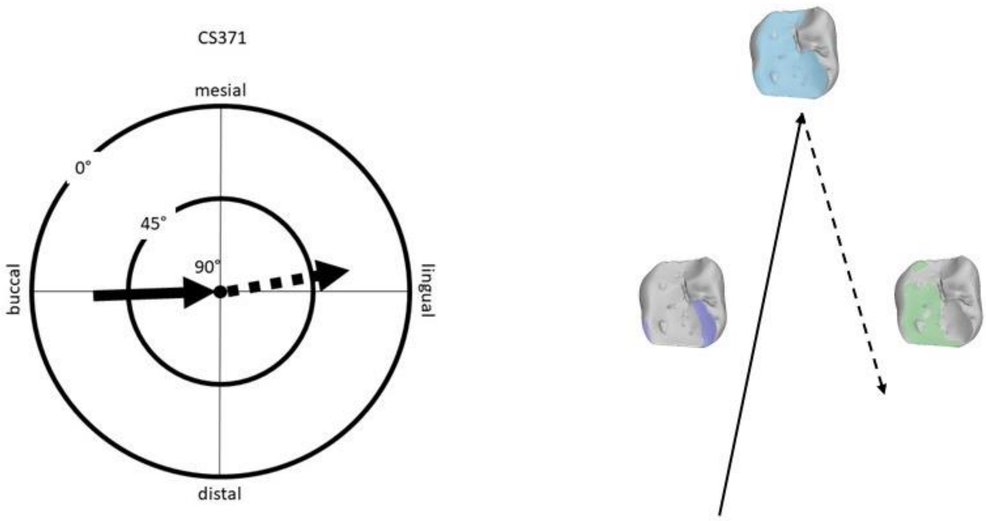


Figure 104: Visualisation of the power stroke of CS371 showing the mastication compass after Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right). The solid arrow represents the direction and inclination of phase I and the dashed arrow phase II.

6.1.3.1.2.1.2 St Peter's Wolverhampton: SK19 (Video 2)

StP19 was classified as a female with a Buckberry-Chamberlain score of 10 (Older age category). There was no evidence of pipe facets. The individual did not exhibit ante-mortem tooth loss or cavitated carious lesions across the teeth and tooth sites present. The lower anterior dentition was poorly represented. The upper left third premolar was minorly rotated.

The cusps of the lower second molar were moderately blunted and there was no dentine exposure. The high ORI value for this tooth (1.61) indicated the retention of steep and complex occlusal topography, which played a prominent guiding function during the power stroke. The total wear facet area was constituted by approximately equal quantities of BPI, LPI and PII wear (BPI 39.52%, LPI 35.34%, PII 35.14%; Figure 105). Facet 6 was very large. BPI facet areas were moderately developed. Tip crushing areas were present on the tip of the protoconid and in the distal portion of the talonid basin.

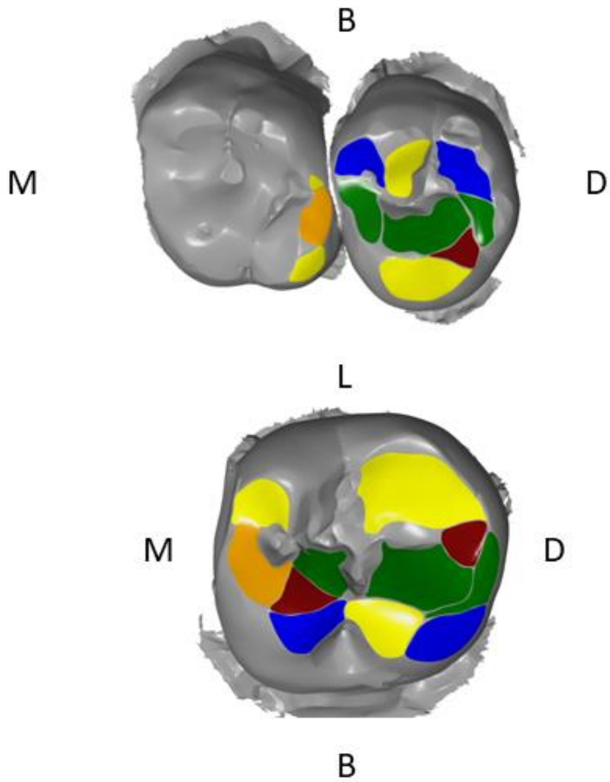


Figure 105: Wear facet maps for the upper and lower left molars of StP19. The individual is characterised by very large and shallowly inclined PII wear areas.

The initial part of the power stroke involved a moderate shearing action in which facets 1, 2, 3, 4, 6 and 7 gradually came into contact (Figure 106 and Figure 107).

This was followed by a rapid increase in contact area as facets 9 and 11 became involved prior to and during maximum intercuspation. A distinct and shallowly inclined phase II movement then occurred principally involving facets 9 and 11. The lateral component of both phases of the power stroke was moderate.

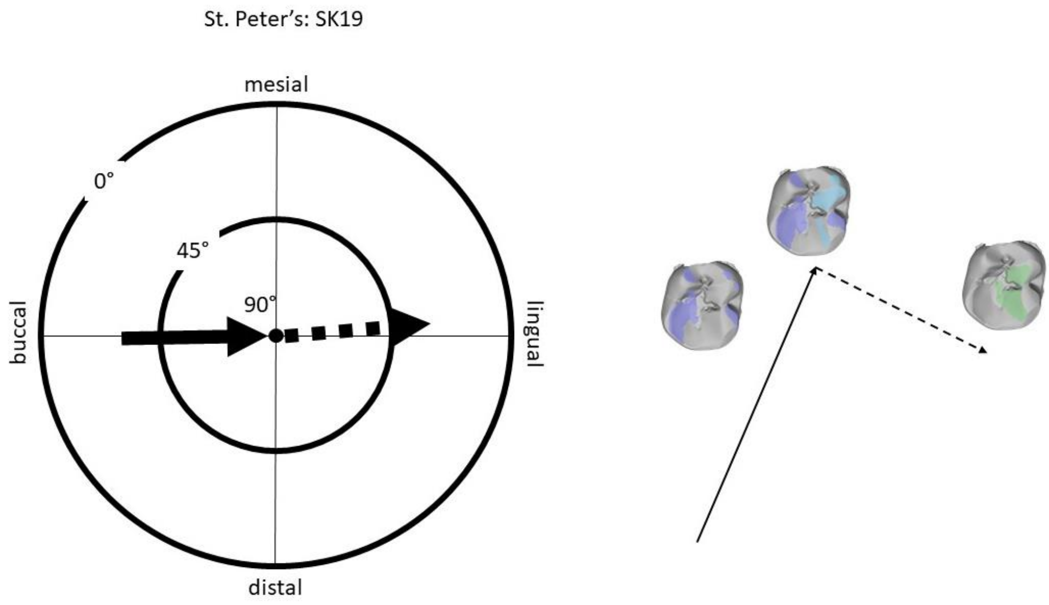


Figure 106: Visualisation of the power stroke of StP19 showing the mastication compass after Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right). The solid arrow represents the direction and inclination of phase I and the dashed arrow phase II.

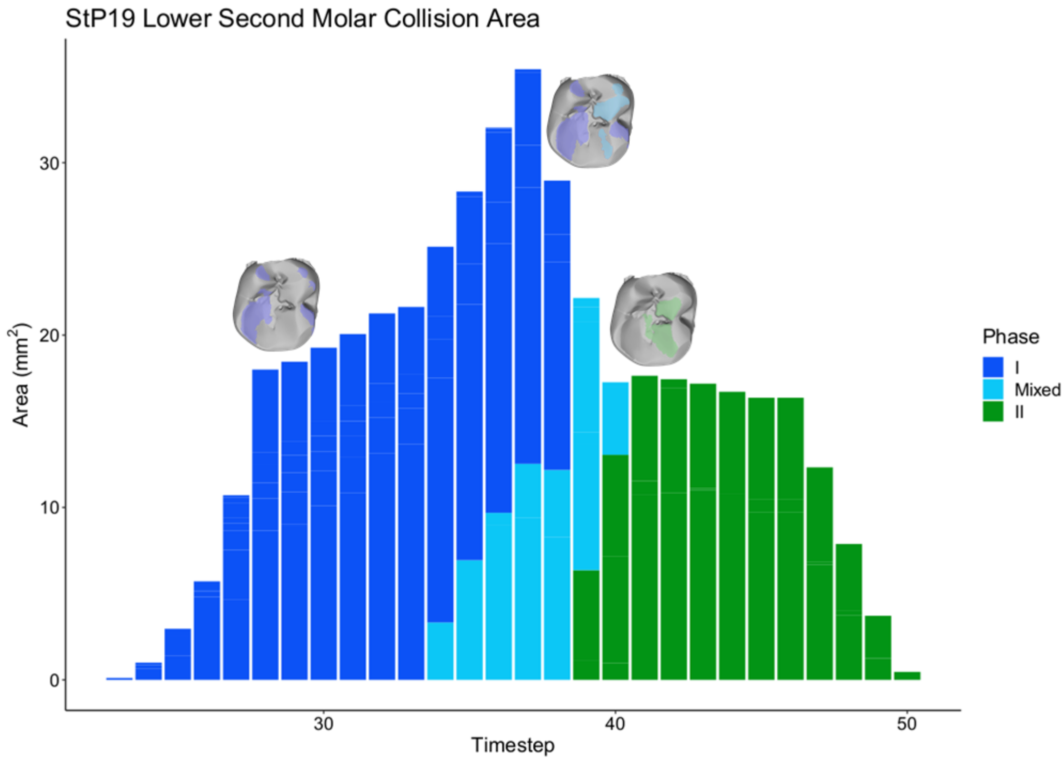


Figure 107: Stacked bar chart showing the development of contact areas during the power stroke simulation of StP19. Phase I contact areas increased rapidly from time steps 27 to 29. Contact areas increased rapidly immediately prior to maximum intercuspation involving both phase I and II facet areas. A sustained and distinct phase II movement was apparent in this individual.

6.1.3.1.2.1.3 St Bride's, London: SB221 (Video 3)

The biographical information available for SB221 described the individual as a male aged 47 (AD1783-1830). There was no evidence of interarch malocclusion or pipe facets. SB221 was characterised by moderate ante-mortem tooth loss (35.71% of tooth sites that could be assessed). A cavitated carious lesion was present on the lower right fourth premolar and the third premolar had been lost ante-mortem. The lower left first molar was lost ante-mortem and a cavitated carious lesion was present on the lower left second molar. The entire upper left molar row was lost ante-mortem. The power stroke simulation was, therefore, conducted using the right side of the dentition.

The lower right second molar had undergone moderate blunting of the cusps; however, occlusal topography remained steep and complex (Figure 108; ORI 1.59). There was an area of dentine exposure in the distal portion of the talonid basin which extended up the lingual slope of the hypoconid and the buccal slope of the entoconid. The wear facet pattern was characterised by a large proportion of LPI wear (45.61%) and PII wear (36.87%). BPI facets comprised a smaller proportion of the total wear area (17.53%).

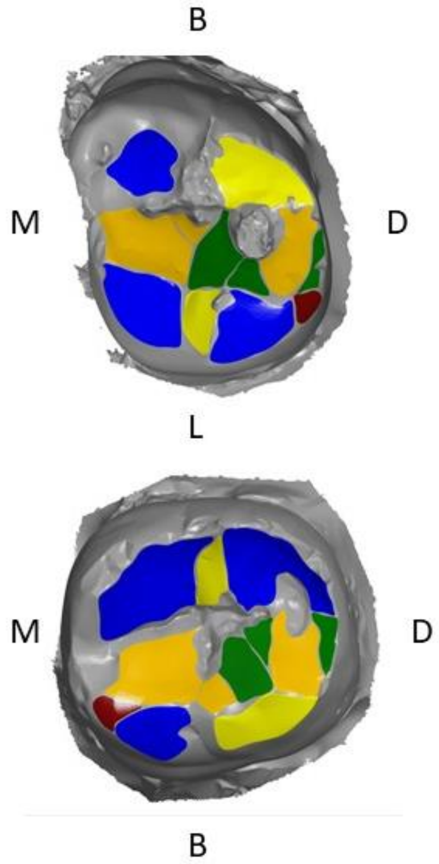


Figure 108: Wear facet pattern of SB221 lower right second molar and upper right second molar.

During phase I of the power stroke, both BPI and LPI contact areas increased quickly (Figure 109 to Figure 110). PII contact areas also became involved as the lower second molar approached maximum intercuspation resulting in a marked increase in contact area. Following maximum intercuspation, the area in contact decreased rapidly. The phase II excursive movement was very brief and had only a minor lateral component.

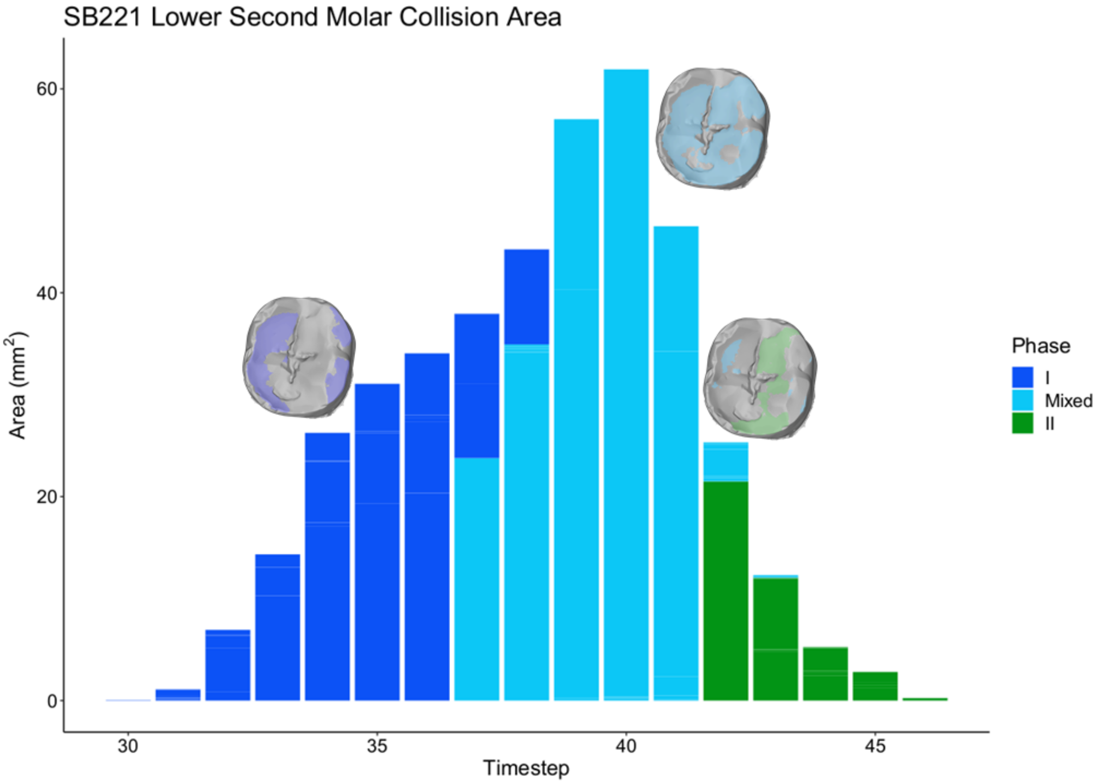


Figure 109: Stacked bar chart showing the development of contact areas during the power stroke simulation of SB221.

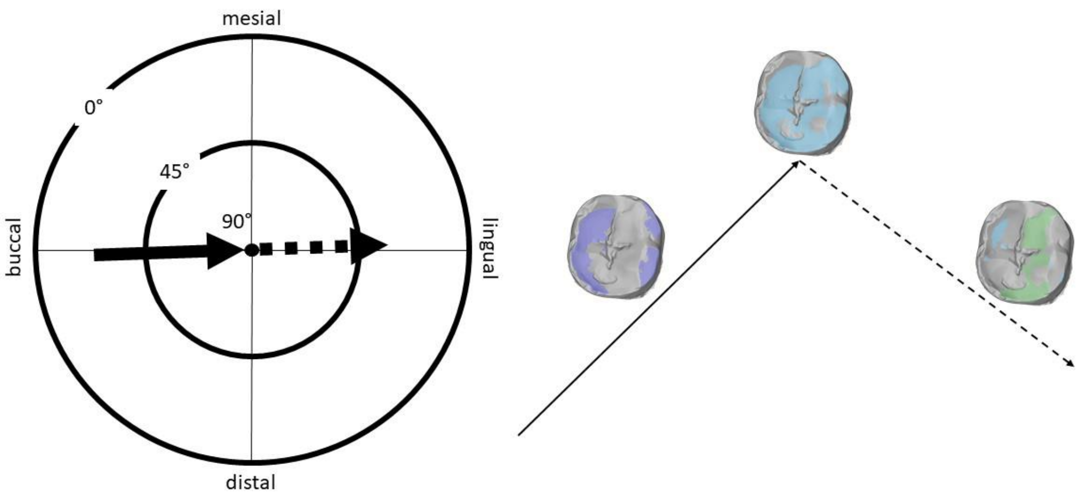


Figure 110: Visualisation of the power stroke of SB221 showing the mastication compass after Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right). The solid arrow represents the direction and inclination of phase I and the dashed arrow phase II.

6.1.3.1.2.1.4 St Michael's Litten (ESC11: Late Phase 18th-19th century): SK599 (Video 4)

Sk599 was identified as a male assigned to the younger skeletal age category (Buckberry-Chamberlain score 7). The individual was buried in a coffin and was dated to the 18th-19th centuries based on coffin furniture. There was no evidence of interarch occlusal variability or pipe facets. A small portion of the anterior teeth present were either minorly rotated or displaced. Ante-mortem tooth loss was moderate (12.5%) and included the symmetrical loss of the lower right and left fourth premolars and first molars. The ante-mortem loss of the lower right first molar had resulted in the mesial drift of the lower right second molar. Consequently, the lower second molar was principally in occlusion with the upper first rather than upper second molar (Figure 111). Cusp reduction was moderate on the protoconid and hypoconid. A large tip crushing area was present on the protoconid. Large shallowly inclined PII wear facets were developed on the lingually inclined slope of the hypoconid. These facets are likely involved in both tip crushing activity during puncture-crushing cycles as well as the power stroke sensu stricto.

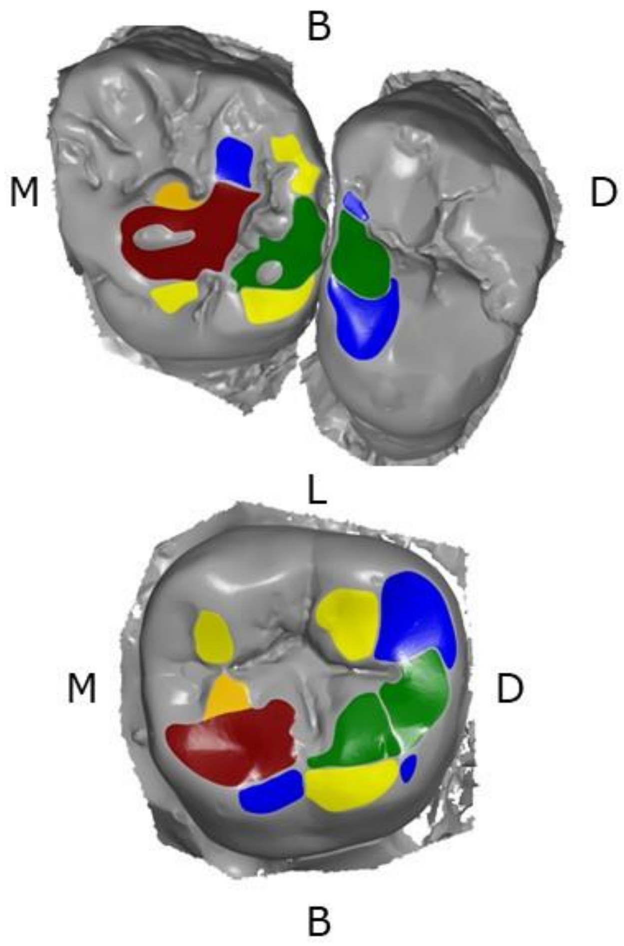


Figure 111: Wear facet maps for the upper and lower left molars of SK599 from St Michael's Litten. The individual is characterised by large tip crushing areas on the protoconid and very shallowly inclined PII facet areas.

The wear facet pattern is dominated by large PII wear areas (35.87%) and LPI areas (43.82%). BPI facets occupied a comparatively small portion of the total wear facet area (20.32%). Very large contact areas developed quickly during phase I of the power stroke; the lateral displacement that occurred during this incursive movement was small (Figure 112 and Figure 113). Prior to and during maximum intercuspation massive phase I and phase II contacts arose highlighting a prominent crushing action in this individual. Contact areas decreased markedly following maximum intercuspation. Phase II of the power stroke was short in duration and involved extremely reduced contact areas.

SK599 can be characterised as exhibiting a strongly vertically orientated crushing motion during the power stroke.

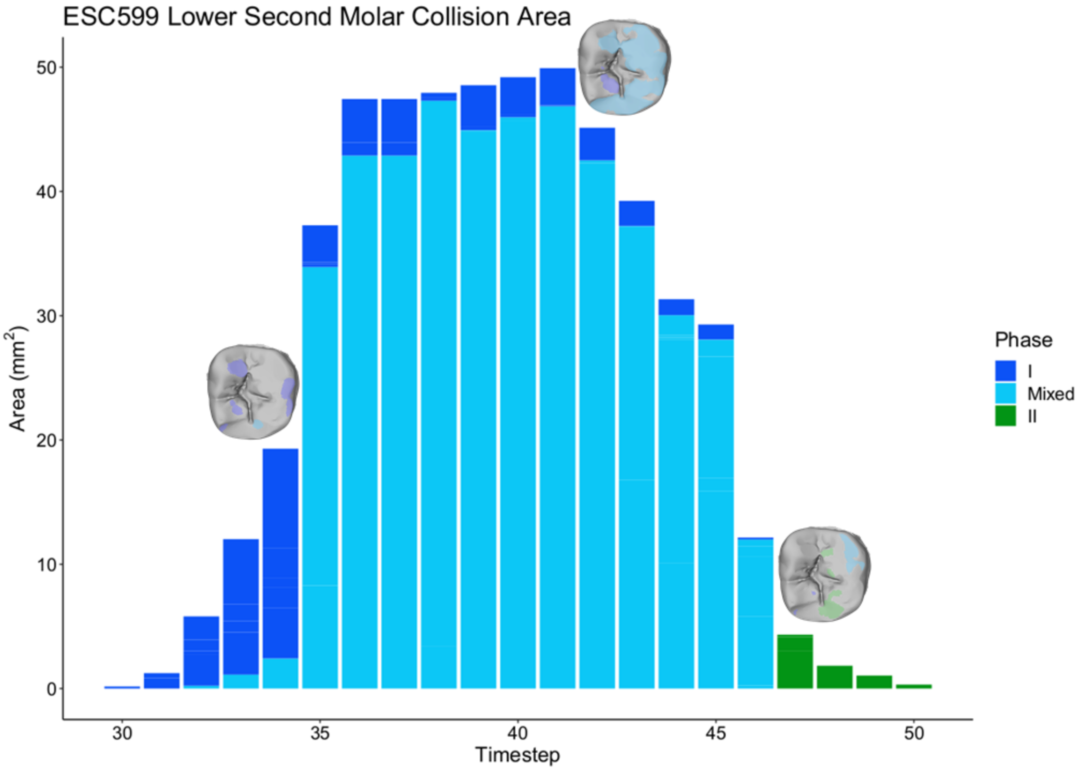


Figure 112: Stacked bar chart showing the development of contact areas during the power stroke simulation conducted for the Industrial-era individual SK599 from St Michael's Litten, Chichester (ESC11).

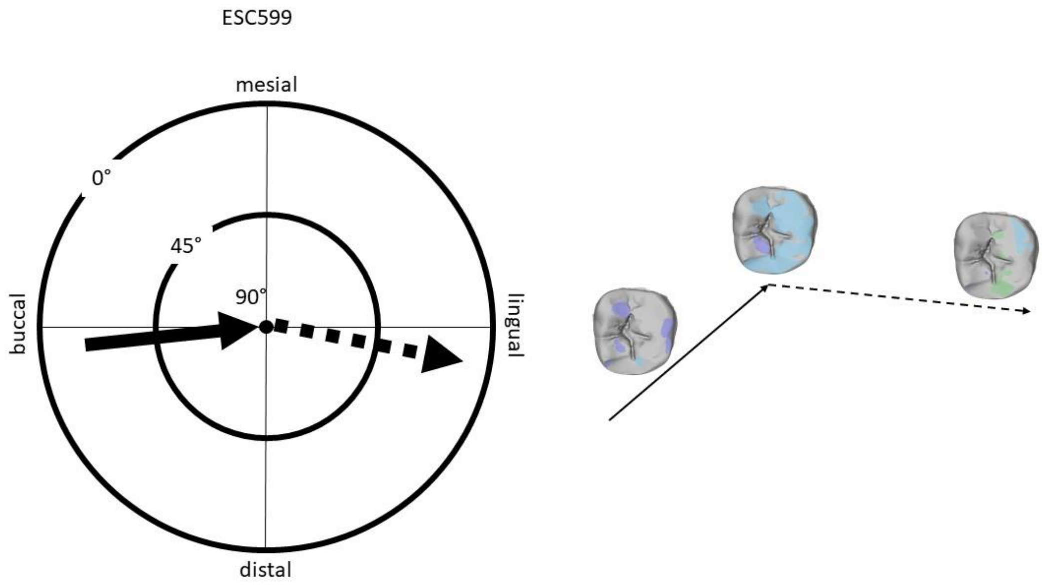


Figure 113: Mastication visualisation for SK599 dating to the Industrial era from the St Michael's Litten assemblage. Mastication compass after Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right).

6.1.3.1.2.2 Mediaeval and Early Post-Mediaeval Assemblages

6.1.3.1.2.2.1 Hereford Cathedral: HE3268 (Video 5)

The sex of HE3268 was estimated as male and the auricular surface was assigned a Buckberry-Chamberlain score of 8 (Age category: Younger). The individual did not have any ante-mortem tooth loss or cavitated carious lesions. There was some limited minor rotation/displacement of the anterior teeth (12.5% of the tooth sites assessed).

HE3268 had moderate blunting of the protoconid with less cusp height reduction on the remaining cusps, particularly the lingual cusps. The largest wear facets were facets 6 and 9. The ORI of this individual (1.43) is comparable to CS371. The occlusal relief on the lingual cusps likely played a strong guiding role during phase I of the power stroke as the teeth moved into maximum intercuspation. The wear facet pattern of the lower second molar was characterised by large LPI facets (51%). The remainder of the total wear facet area was composed of comparable quantities of BPI (22%) and PII wear (26%) (Figure 114).

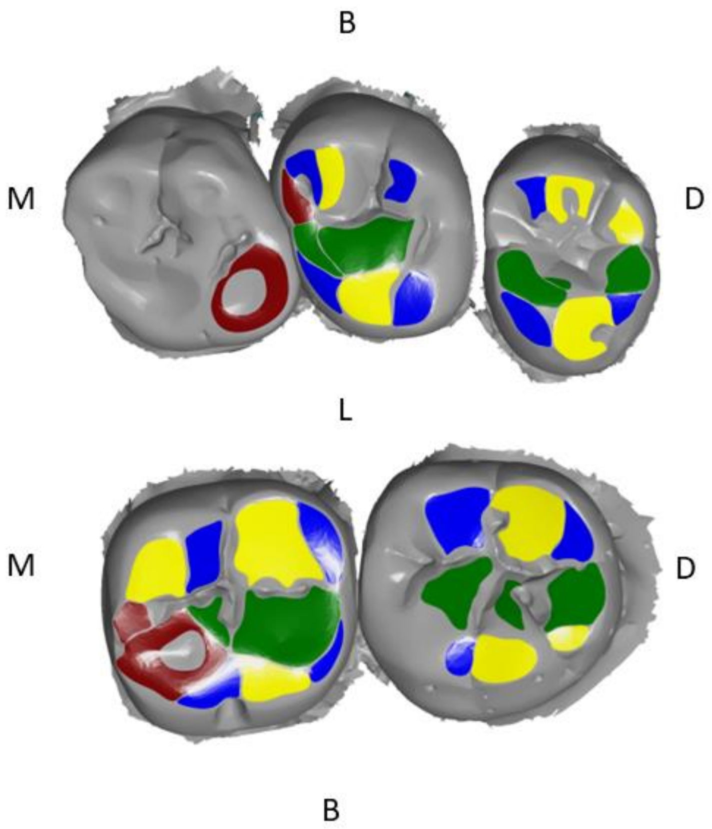


Figure 114: Wear facet maps for the upper and lower left molars of HE3268. The individual is characterised by large tip crushing areas on the protoconid and well-developed phase I contact areas.

The simulated power stroke involved a prolonged sliding contact during phase I with moderate lateral displacement of the molar row. This lateral shearing action contrasted with the highly vertically orientated power strokes exhibited by many of the Industrial individuals examined. The increase in contact areas, involving both phase I and II contact areas, occurred steadily as maximum intercuspation was approached during the terminal portion of phase I (Figure 115 and Figure 116). This was followed by a steady decrease in contact area and a distinct and elongated phase II movement. A relatively large quantity of lateral displacement of the lower molars in a medial direction occurred in contrast to the rapid loss of contact following maximum intercuspation more typical of simulations conducted for the Industrial period.

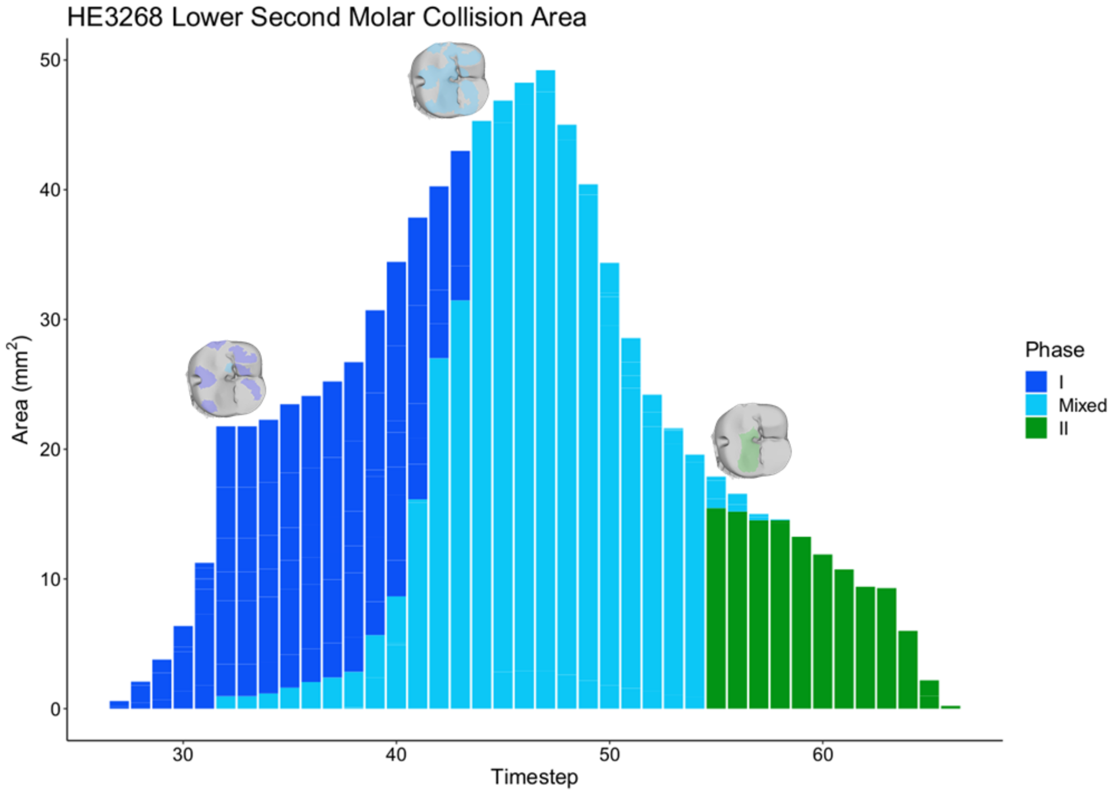


Figure 115: Stacked bar chart showing the development of contact areas during the power stroke simulation conducted for HE3268. Phase I was characterised by a prolonged shearing action due to the power stroke's relatively large lateral component. Contact areas increased rapidly immediately prior to maximum intercuspation as phase II areas were involved. An elongated phase II followed maximum intercuspation. This phase II movement involved a lateral component of similar magnitude to phase I of the power stroke.

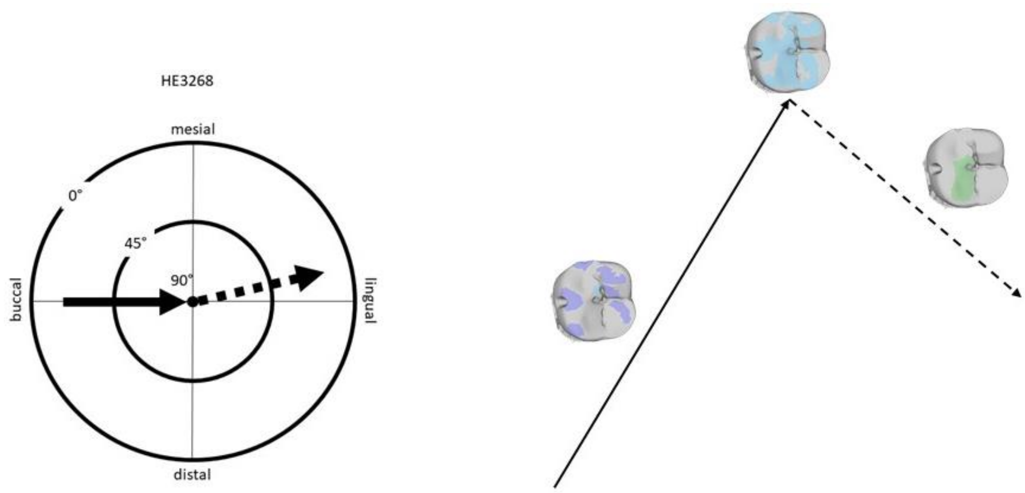


Figure 116: Mastication visualisation for HE3268. Mastication compass after Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right).

6.1.3.1.2.2.2 St James and St Mary Magdalene Leprosarium, Chichester (CH86): SK328 (Video 6)

The sex of SK328 was estimated to be male and their auricular surface score placed them within the younger age category (Buckberry-Chamberlain score 9). There was no evidence of interarch occlusal variability, however, the anterior teeth were poorly represented. There was no evidence of ante-mortem tooth loss or cavitated carious lesions. The upper left third premolar was majorly rotated/displaced and the upper left fourth premolar was minorly rotated/displaced.

There was moderate blunting of the cusps of the protoconid and hypoconid without dentine exposure. Pinpoint dentine exposure was apparent in the centre of facet 6 (Figure 117). Facet 6 remained in contact for most of the power stroke simulation suggesting that a heavy amount of food processing occurred on this surface. The wear facet pattern of the lower second molar was characterised by an almost equal quantity of BPI (39.64%) and LPI wear (36.33%). PII wear occupied 24.03% of the total wear area.

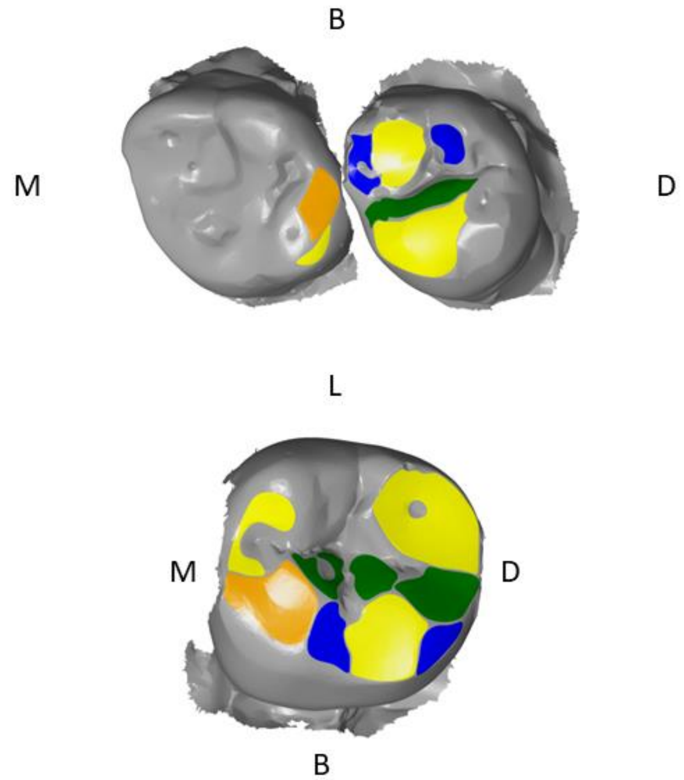


Figure 117: Wear facet map for SK328 from assemblage CH86. The individual had a large facet 6 and shallowly inclined BPI and PII wear facets.

The incursive phase I motion utilised a relatively large lateral component and was shallowly inclined (Figure 118 to Figure 119). The first involvement of phase II wear facet areas was early in the time step sequence of the power stroke simulation (TS32). A marked increase in contact area occurred prior to maximum intercuspation as phase II facet areas became increasingly involved and the entirety of the large facet 6 was in contact. The excursive phase II movement involved a steady decrease in wear facet contact area and a moderate lateral movement. The duration of the phase II movement was not as extensive as in HE3268. A small contact on facet 6 was retained until time step 47. The power stroke simulation reflected a shearing motion with a prominent lateral component rather than the more vertically orientated crushing motion more characteristic of the Industrial period.

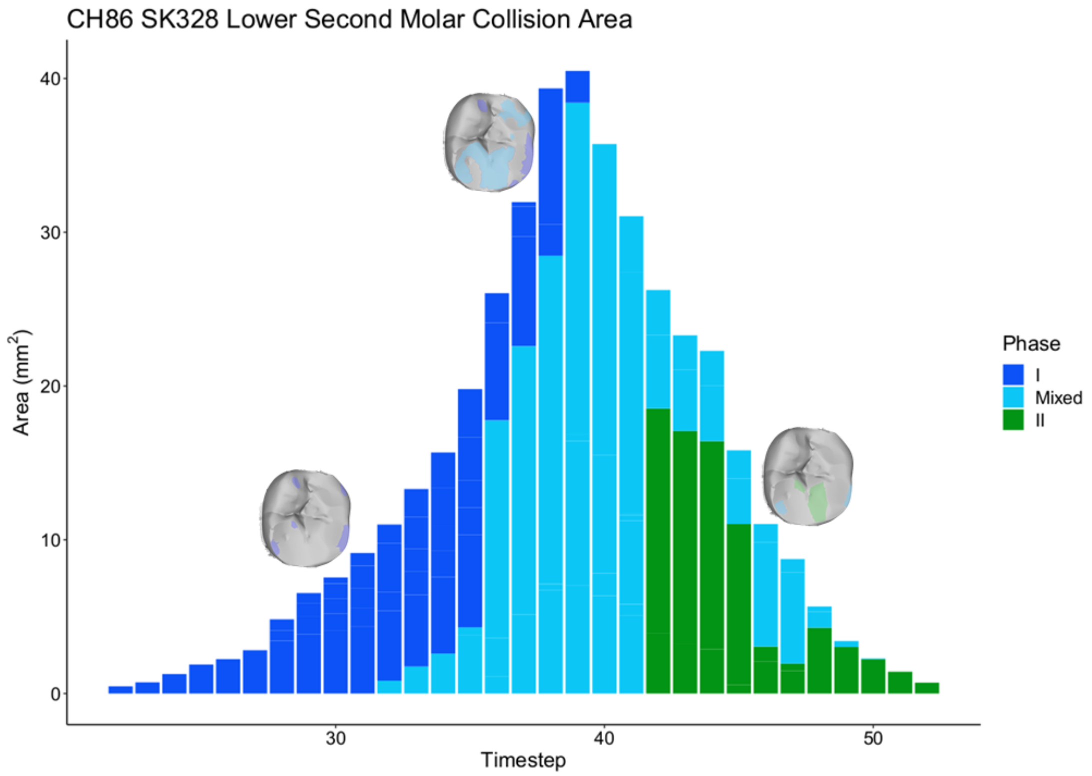


Figure 118: Stacked bar chart showing the development of contact areas during the power stroke simulation conducted for SK328 from St James' and St Mary Magdalene, Chichester (CH86).

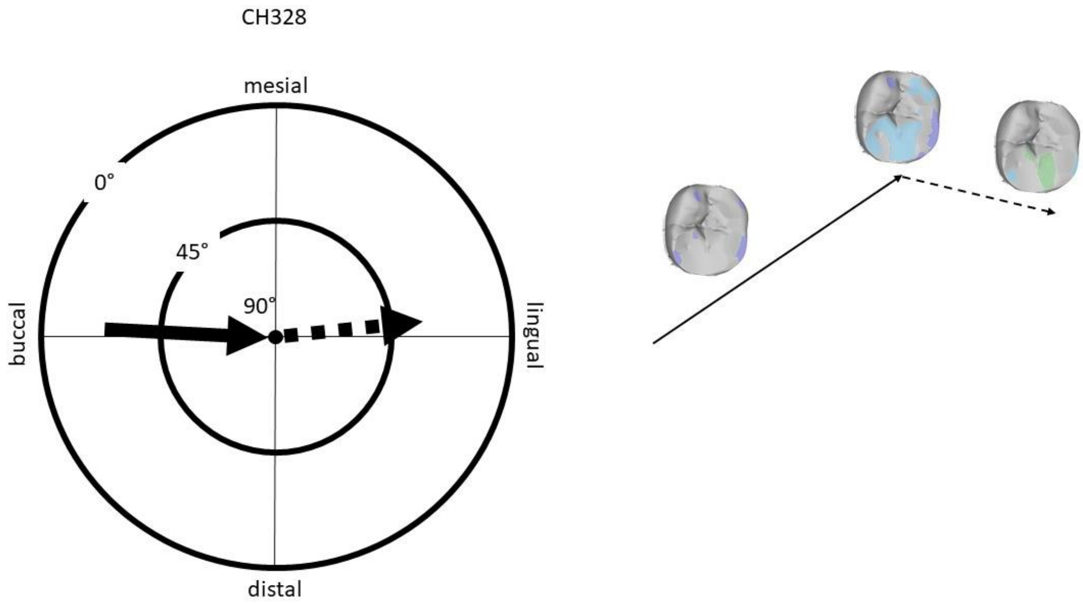


Figure 119: Mastication visualisation for SK328 from the St Jame's and St Mary Magdalene, Chichester, assemblage. Mastication compass after Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right).

6.1.3.1.2.2.3 York Barbican (BARB): SK3650 (Video 7)

The sex of SK3650 was estimated as male and they were assigned to the younger skeletal age category (Buckberry-Chamberlain score of 7). There was no evidence of interarch malocclusion or rotation/displacement. The lower right first molar was lost ante-mortem. The collision simulation was conducted using the left side of the dentition. The ORI of this individual was moderate in size (1.58) indicating only limited obliteration of occlusal topography due to wear.

There was a moderate reduction in the cusp height of the protoconid resulting in pinpoint dentine exposure. The wear facet pattern was characterised by a dominance of PII wear (39.36%) and BPI wear (34.56%). LPI wear formed a smaller proportion of the total wear facet area due to the absence of wear facet development on the metaconid (26.08%) (Figure 120).

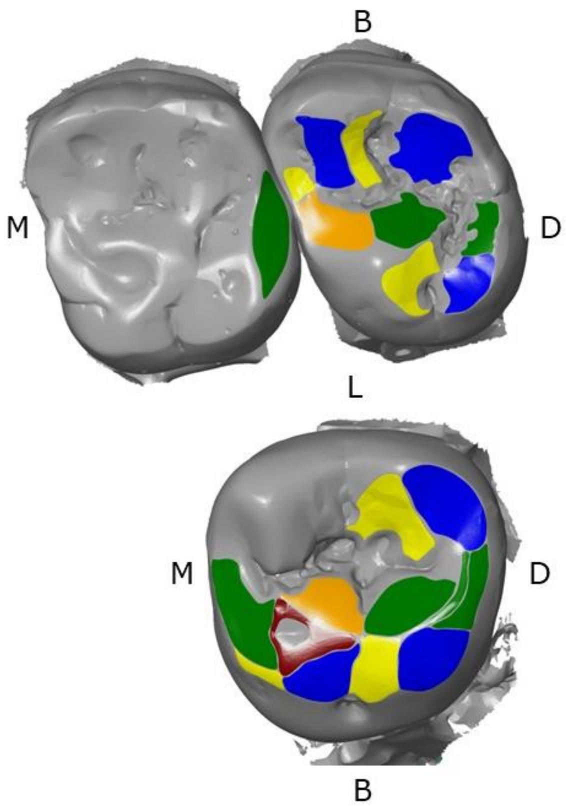


Figure 120: Wear facet map for SK3650 from the York Barbican assemblage. The individual had well developed BPI and PII wear facet areas. There was an absence of wear on the metaconid. There was a moderately developed tip crushing area on the protoconid.

The power stroke simulation was characterised by a moderate lateral component during the phase I shearing action in which contact areas increased steadily (Figure 121 to Figure 122). A sudden increase in contact area preceded maximum intercuspation as phase II facet areas came into contact. This period of extensive contact and crushing was followed by a large decrease in facet contact area and an extended phase II movement. This excursive movement involved a pronounced mesial shift.

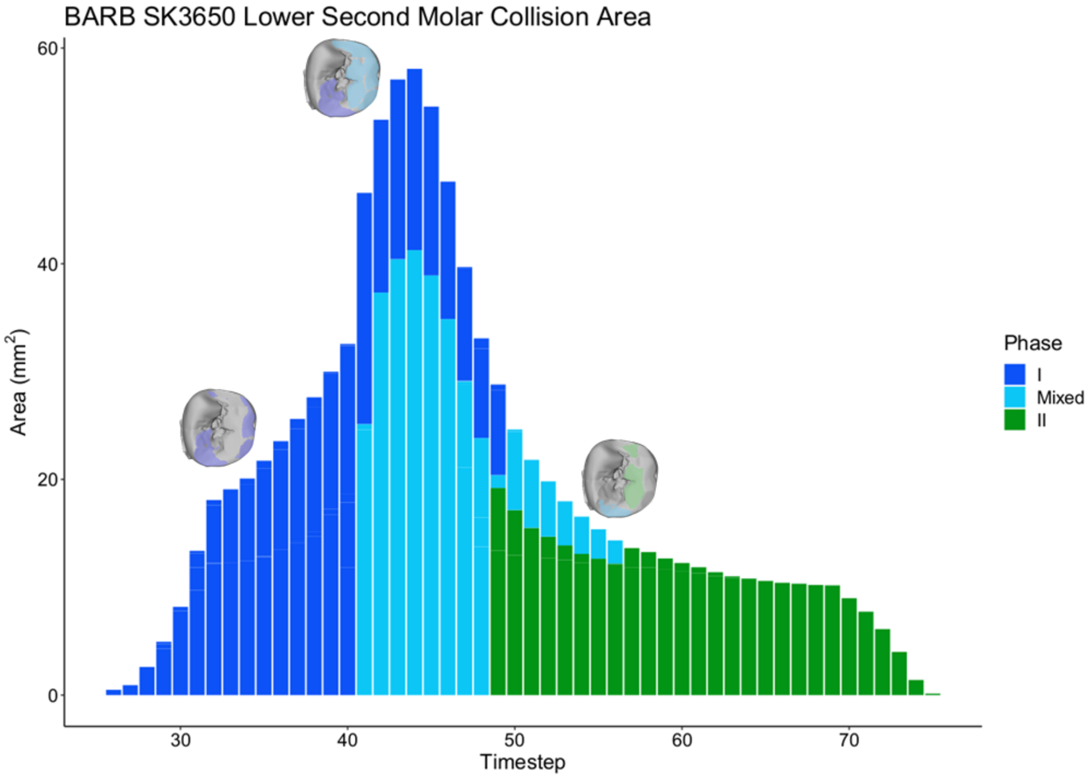


Figure 121: Stacked bar chart showing the development of contact areas during the power stroke simulation conducted for mediaeval individual SK3650 from the York Barbican assemblage. Phase I wear facet angles develop steadily during the incursive portion of the power stroke. As maximum intercuspation was reached, a large increase in contact area occurred as phase II wear facet areas became involved. Following maximum intercuspation, contacts on wear facet 6 remained distinct from the contacts involving phase II wear facets. The contact on facet 6 is visible on the stacked bar chart until time step 50.

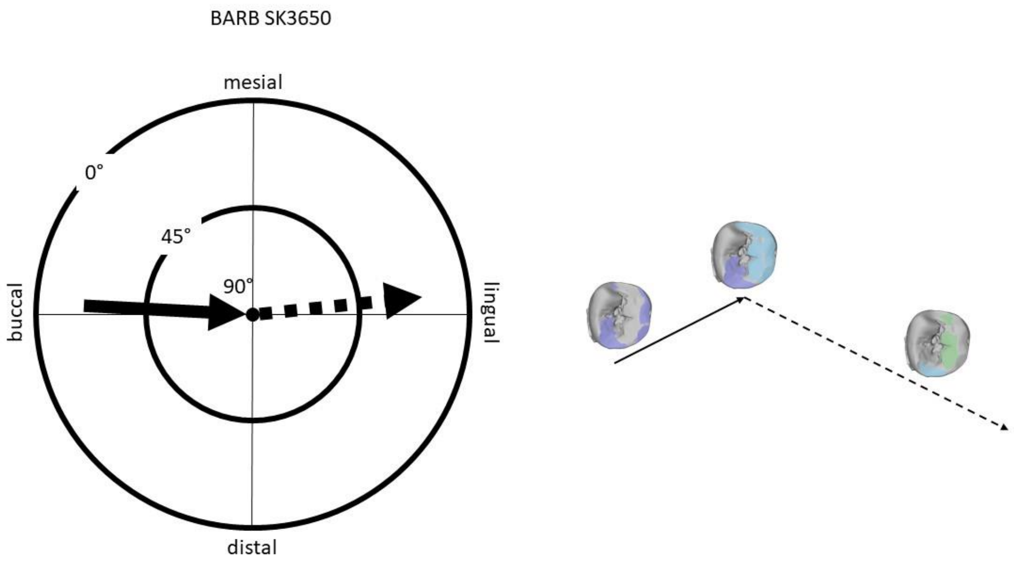


Figure 122: Mastication visualisation for SK3650 from the York Barbican assemblage. Mastication compass after von Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right).

6.1.3.1.2.2.4 St Michael's Litten (ESC11: Early Phase): SK2729 (Video 8)

SK2729 was estimated to be male and was assigned to the older skeletal age category (Buckberry-Chamberlain score 10). This individual was buried in a shroud and has an anticipated date range of AD1550-1700. There was no evidence of interarch occlusal variability. There was no evidence of minor rotation or displacement of teeth, cavitated carious lesions or ante-mortem tooth loss. Blunting of the cusps was advanced (ORI 1.30) and there was pinpoint dentine exposure on the protoconid. Most of the wear facet area on the lower second molar comprised PII wear (47.43%). BPI and LPI wear occupied similar portions of the total wear facet area (24.96 and 27.61%, respectively). Tip crushing areas on the protoconid were extensive (Figure 123).

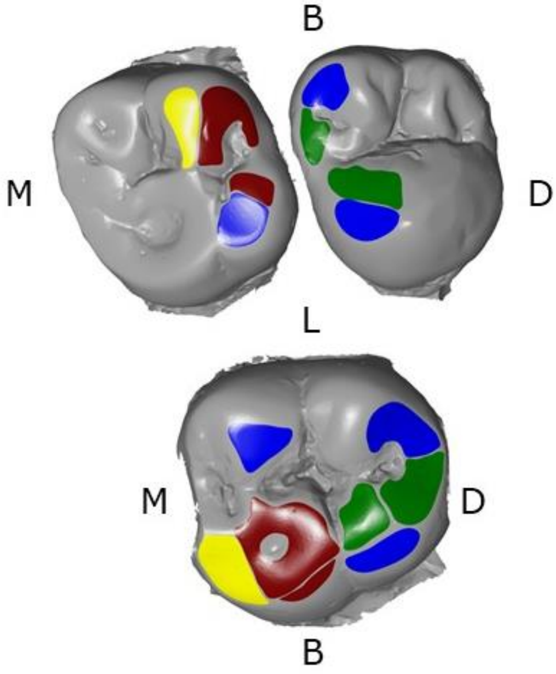


Figure 123: Wear facet map for SK2729 from the St Michael's Litten assemblage. The individual had well developed tip crushing areas on the protoconid and advanced removal of the cusp.

The incursive movement of the power stroke was shallowly inclined and involved a moderate lateral displacement (Figure 124 and Figure 125). PII wear facet areas came into contact during the terminal part of phase I of the power stroke. Following maximum intercuspation, contact areas decreased steadily and included phase I and II facet areas over the majority of timesteps. The contact on facet 5 was retained for much of the power stroke simulation. This individual can be characterised by an exaggerated vertical crushing action that also involved a lateral shift of greater magnitude relative to many of the later post-mediaeval individuals examined.

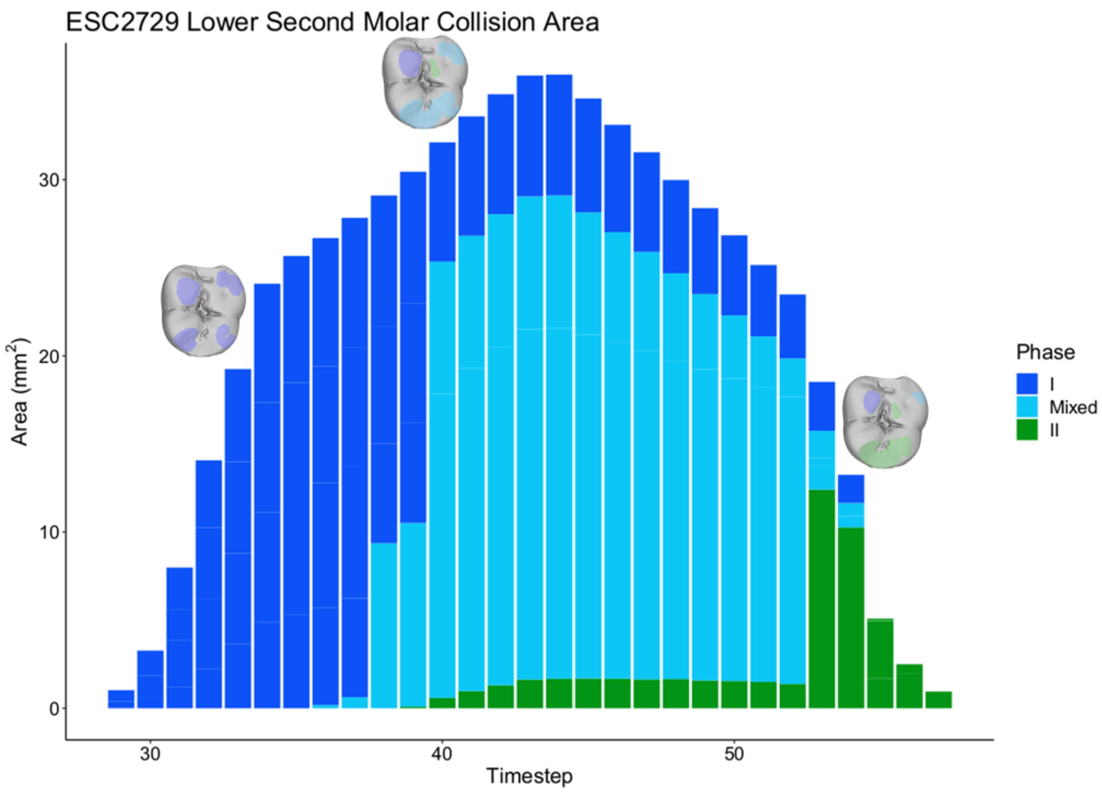


Figure 124: Stacked bar chart showing the development of contact areas during the power stroke simulation conducted for early Post-Mediaeval individual SK2729 from the St Michael's Litten assemblage (ESC11).

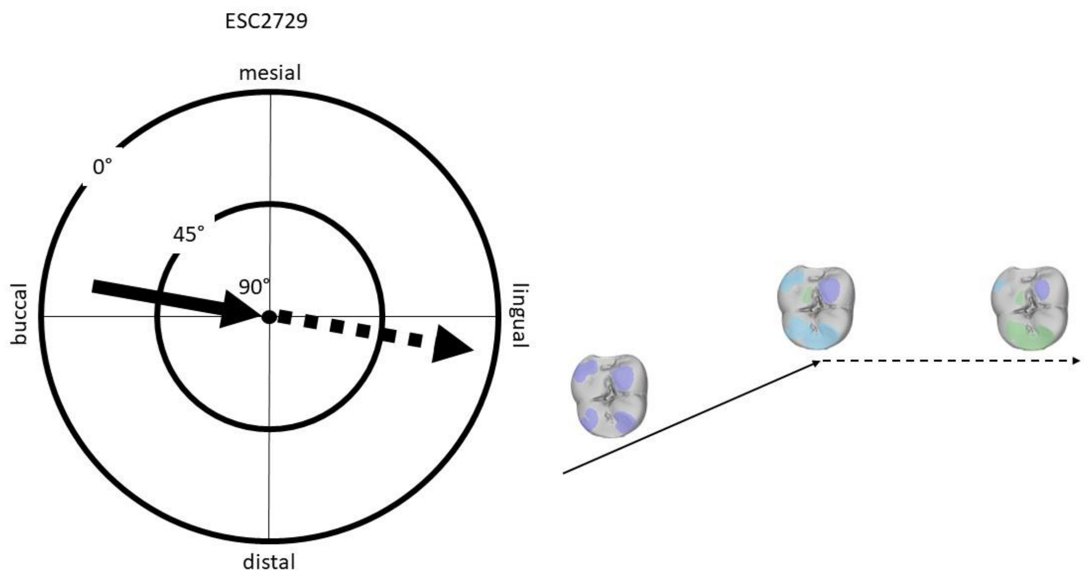


Figure 125: Mastication visualisation for SK2729 from St Michael's Litten assemblage (ESC11). Mastication compass after Koenigswald (2013) (left) and the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation (right).

6.1.3.1.3 Summary of differences in dynamic OFA simulations between the two periods

Dynamic OFA simulations conducted for individuals from both periods support the evidence for differences in masticatory behaviours indicated by OFA of the wear pattern of the lower second molars. The power stroke simulations for the Industrial period were typically characterised by a smaller lateral component of movement during both phase I and II of the power stroke. The increase in contact area was rapid immediately prior to maximum intercuspation, involving both phase I and II wear facet areas, and occlusal contacts decreased rapidly during phase II of the power stroke itself. This indicates that a more vertically directed chopping action was more characteristic of individuals dating to the Industrial-era when compared to the more laterally directed power stroke that predominated in the Mediaeval and early Post-Mediaeval periods. The dynamic OFA simulations, however, highlight the high degree of variability in power stroke profiles within each period.

6.2 Can OFA be used to identify within assemblage and period variation in dietary composition and para-masticatory behaviours that are historically and/or archaeologically described?

6.2.1 Industrial Period (AD 1700-1900)

6.2.1.1 *During the Industrial period, the largest share of any meat and cheese was typically consumed by men whilst women and children subsisted almost solely on bread, potatoes and weakened tea. A proportion of buccal phase I wear facets indicative of greater shearing activity and meat consumption would be anticipated if these dietary differences were of sufficient magnitude**.***

6.2.1.1.1 Overall

Wear facet area composition did not differ significantly between the sexes in the assemblages examined dating to the Industrial period (Table 63, Table 64 and Table 122). The relative wear facet composition of the lower second molars of males and females dating to the Industrial period overlapped extensively (Figure 126).

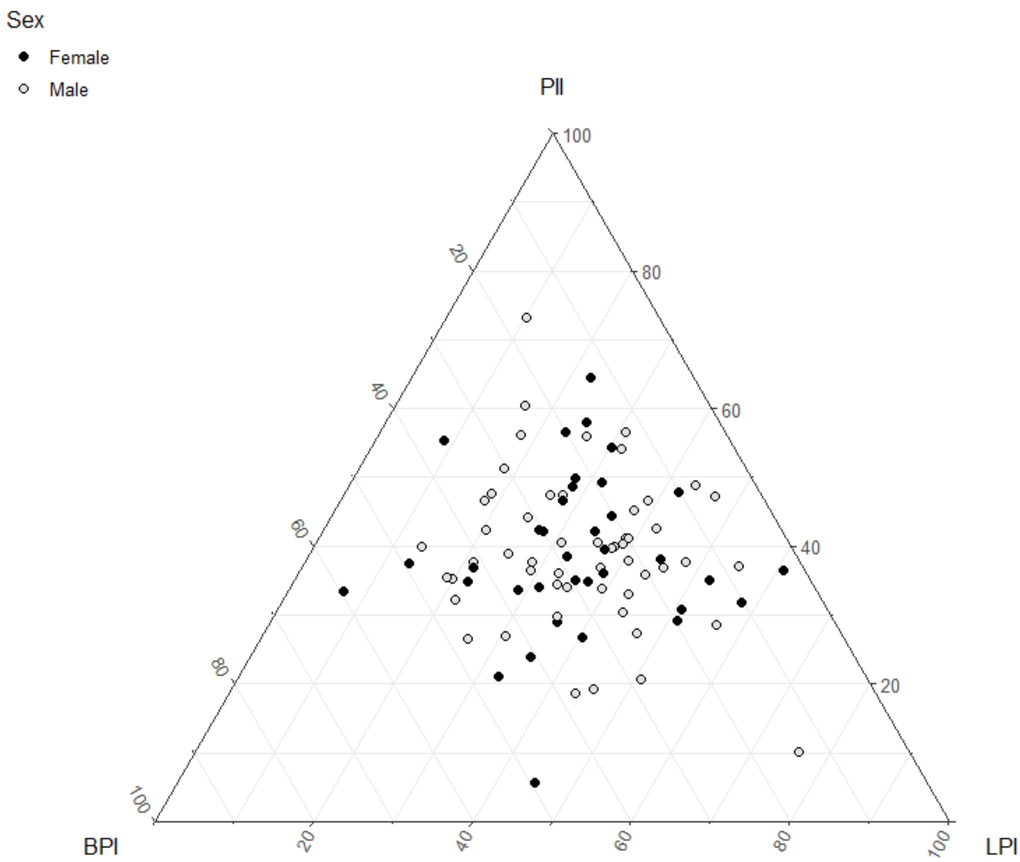


Figure 126: Ternary plot showing the relationship between sex and wear facet area composition of the lower second molar in the Industrial period.

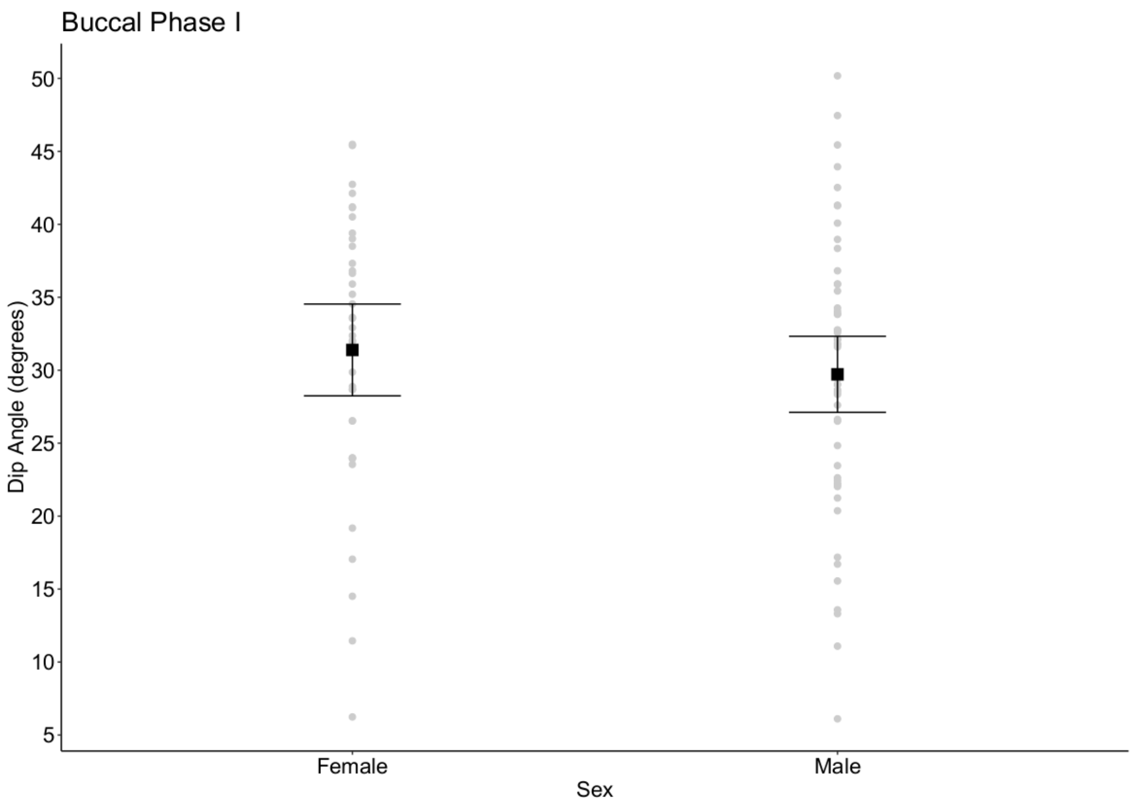
Table 63: Table showing the centre values for BPI, LPI and PII wear facet area proportions of the lower second molar in the Industrial period when divided by sex.

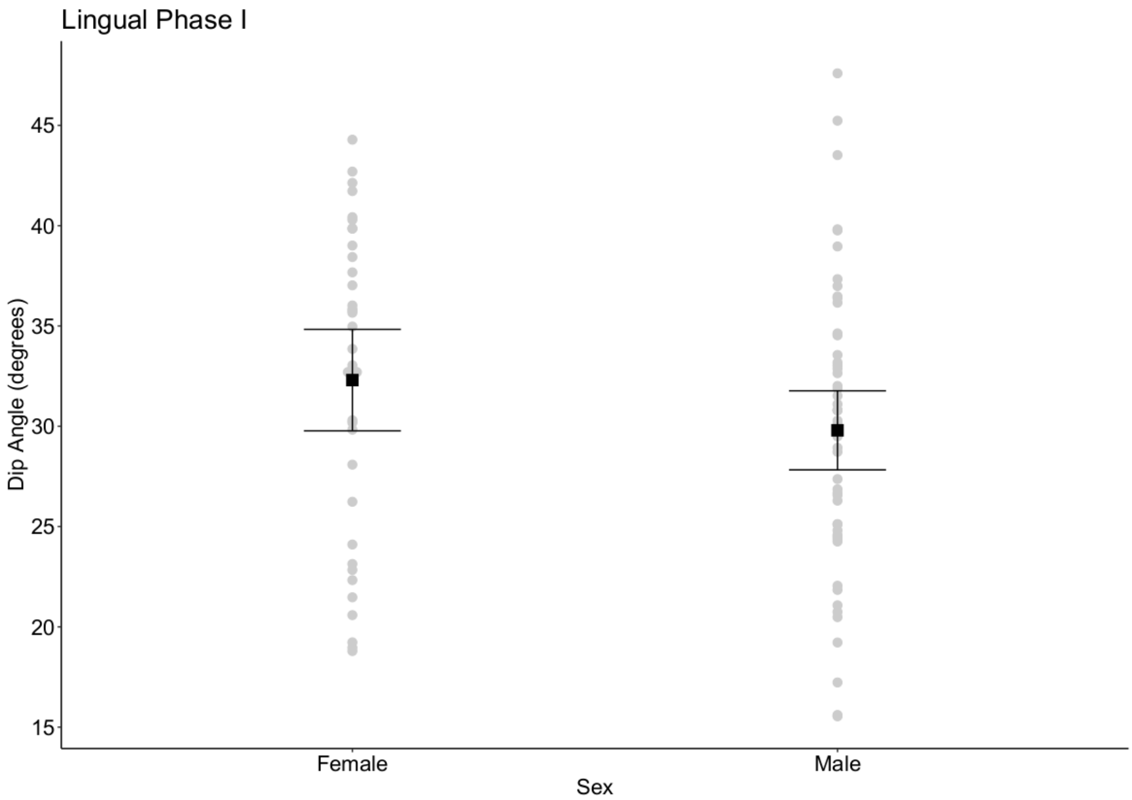
Sex	N	BPI	LPI	PII	Total variance	Metric standard deviation
Male	55	26.00	33.92	40.00	0.45	0.47
Female	37	25.78	34.19	40.03	0.67	0.58

Table 64: Results of Type I PERMANOVA used to assess the relationship between sex and wear facet area composition among the Industrial assemblages examined. ***Null hypothesis: relative wear facet area proportions did not differ significantly between the sexes during the Industrial period.*** *Homogeneity of dispersion in relative wear facet area could be assumed between the sexes in the Industrial material examined (Table 122).*

Standard data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	**R^2**	**p-value(>F)**	**H_0**
Sex	0.00	0.00	1	-0.05	0.00	0.96	Not Rejected
Residuals	2.20	0.03	88		1.00		
Total	2.20		89				
ILR data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**		**Probability (>F)**	**H_0**
Sex	0.00	0.00	1	0.00	0.00	1.00	Not Rejected
Residuals	47.59	0.54	88		1.00		
Total	47.58		89				

Dip angle did not differ significantly between the sexes for any of the wear facet types considered (Table 65). There was a very slight tendency for females to exhibit slightly steeper dip angles, however, the overlap between 95% confidence intervals around the mean was substantial in each comparison (Figure 127).


Buccal Phase I
Dip Angle (degrees)
50
45
40
35
30
25
20
15
10
5
Female
Male
Sex


Lingual Phase I
Dip Angle (degrees)
45
40
35
30
25
20
15
Female
Male
Sex

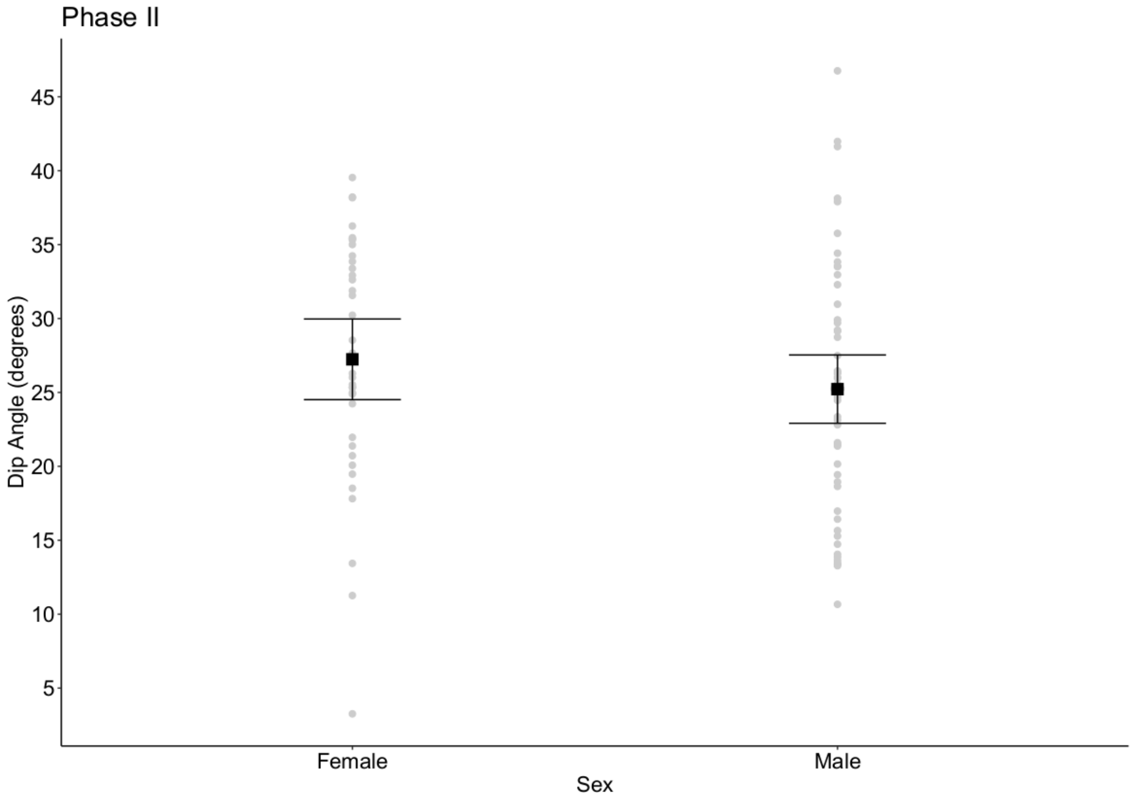


Figure 127: Dot plots with mean values and 95% confidence intervals plotted comparing dip angles for BPI, LPI and PII wear facets between the sexes in the Industrial period.

Table 65: Results of Independent sample t-tests to assess whether dip angles differed significantly between the sexes in the Industrial material examined. All data were normally distributed (Shapiro-Wilk p>0.05) and exhibited homogeneity of variance (Levene's test p>0.05). ***Null hypothesis: there were no significant differences in dip angle between the sexes for any wear facet type.*** **Bonferroni adjusted p-value=0.017.*

Wear Facet Type	BPI	LPI	PII
Female Mean (°)	31.39	32.3	27.24
Standard Deviation	9.43	7.58	8.46
Male Mean (°)	29.64	29.74	25.22
Standard Deviation	9.55	7.21	8.18
t-value	0.87	1.63	1.14
Degrees of Freedom	77.26	74.03	78.8
p value*	0.39	0.11	0.26
Effect size	0.19	0.35	0.24
95% CI Effect Size	-0.23 to 0.61	-0.08 to 0.79	-0.18 to 0.67
Statistical Power	0.14	0.37	0.20
H_0	Not Rejected	Not Rejected	Not Rejected

There was a slight tendency for ORI values to be greater among the female portion of the Industrial individuals examined, however, this relationship was not significant (Wilcoxon rank sum test; W= 492, p-value=0.10) (Figure 128). There were also no significant differences between the TCI values of male and female individuals from the Industrial period (Figure 128; Wilcoxon rank sum test; W = 950, p-value = 0.69).

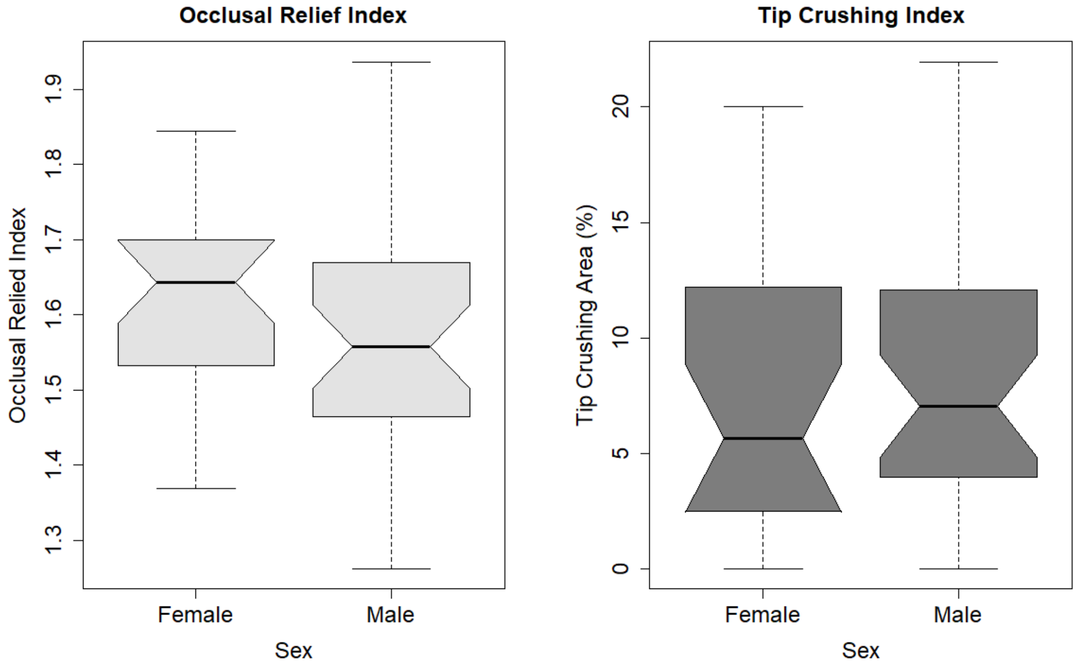


Figure 128: Boxplots showing the relationship between sex and ORI and sex and TCI in the Industrial period. ORI and Tip Crushing Area were both not normally distributed (Shapiro Wilk test p<0.05), therefore, non-parametric testing was used.

6.2.1.1.2 Within Each Assemblage

Relative wear facet areas did not differ significantly between the sexes in any of the Industrial period assemblages examined (Table 66; Figure 129). All of the assemblages examined satisfied the homogeneity of multivariate dispersion assumption indicating that variation in wear facet area composition did not differ significantly between the sexes in any of the assemblages (Table 123).

Table 66: Results of Type I PERMANOVA tests examining whether wear facet area proportions differed between the sexes in each of the Industrial assemblages examined. ***Null hypothesis for each test: wear facet area proportions did not differ significantly between the sexes in the assemblage being assessed.***

Standard data	Sum Squares	Mean Squares	df	F-value	Probability (>F)	H_0
St Michael's Litten	0.03	0.03	1	1.43	0.25	Not Rejected
St Bride's	0.00	0.00	1	0.05	0.93	Not Rejected
Coronation Street	0.01	0.01	1	0.20	0.85	Not Rejected
St Peter's	0.01	0.01	1	0.55	0.61	Not Rejected
ILR data	**Sum Squares**	**Mean Squares**	**df**	**F-value**	**Probability(>F)**	H_0
St Michael's Litten	0.78	0.78	1	1.79	0.17	Not Rejected
St Bride's	0.06	0.06	1	0.16	0.85	Not Rejected
Coronation Street	0.02	0.02	1	0.02	0.98	Not Rejected
St Peter's	0.21	0.21	1	0.38	0.69	Not Rejected

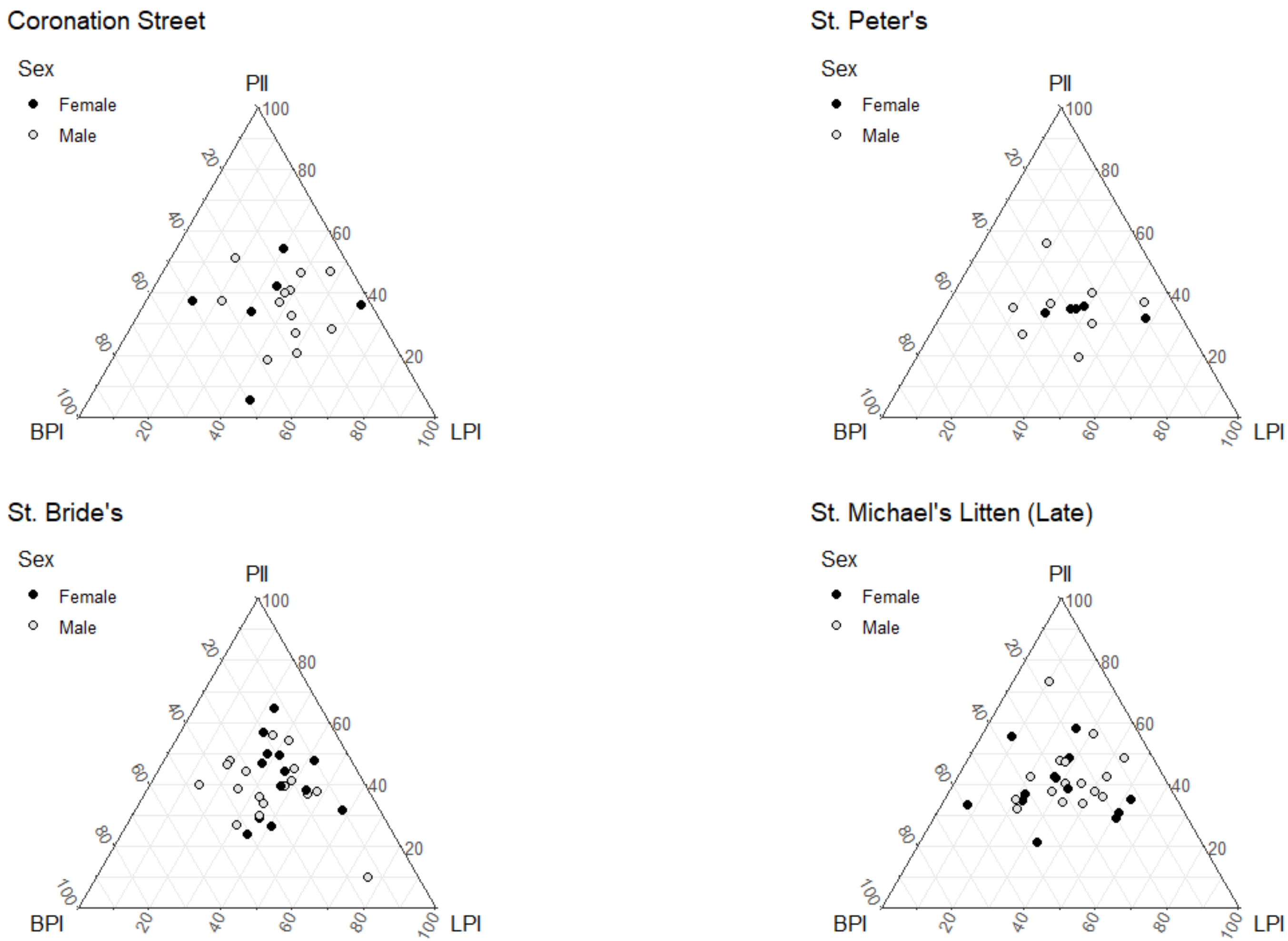
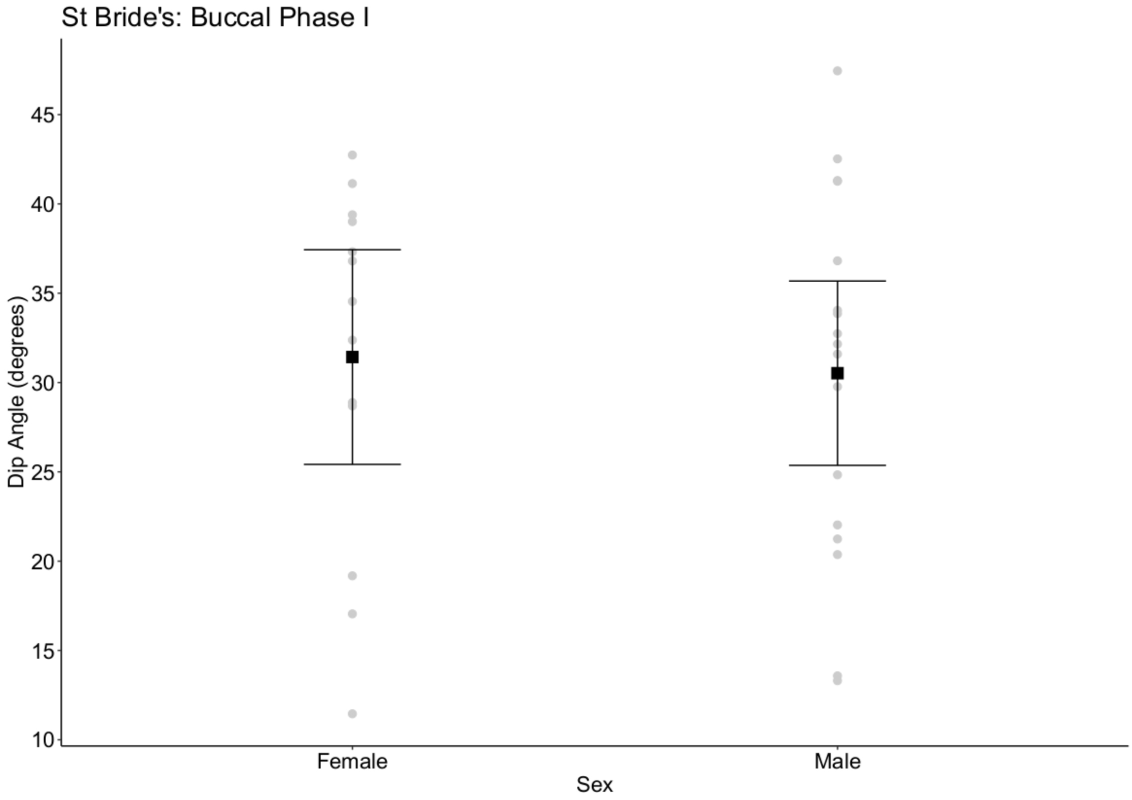
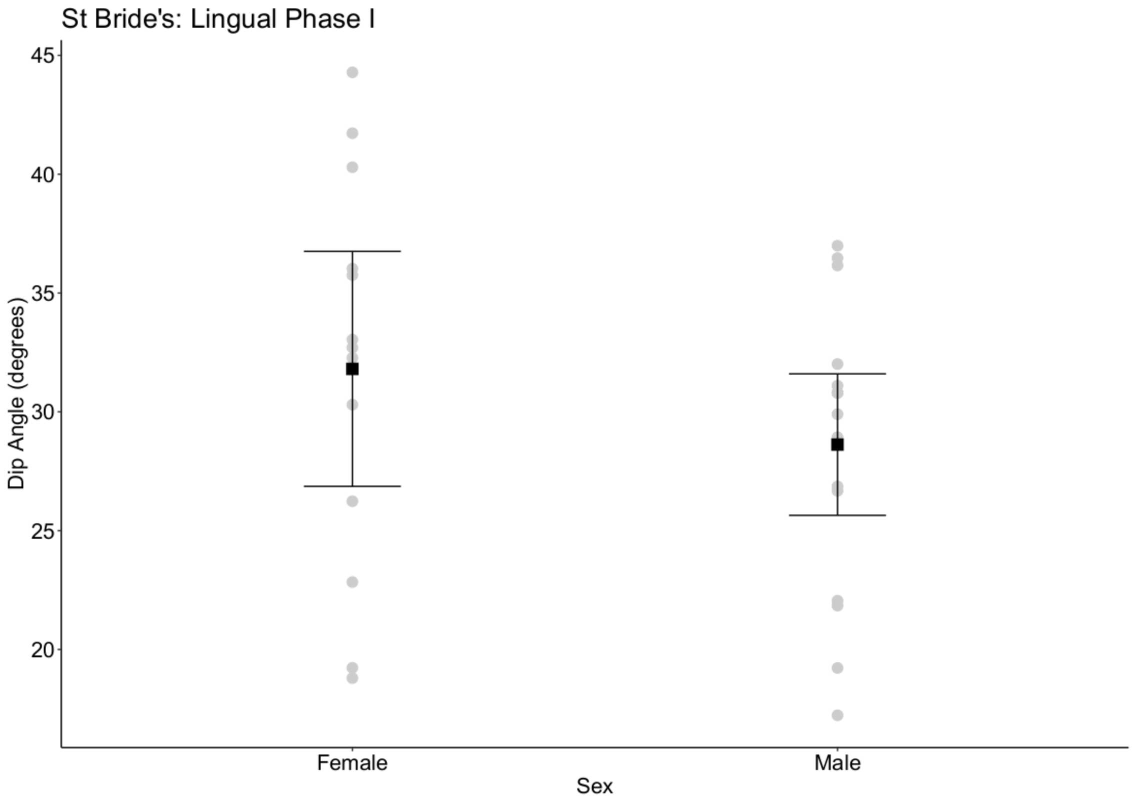


Figure 129: Ternary plots comparing relative wear facet areas between males and females in each of the Industrial assemblages examined. There was extensive overlap between males and females in each of the assemblages examined consistent with the overall comparison.

LPI dip angles were more obliquely inclined in females in the St Michael's Litten assemblage. PII dip angles were more steeply inclined in females when compared with males in the Coronation Street assemblage (Table 67 and 68; Figure 130 to Figure 133). There were no other marked sex differences in dip angle in any of the other Industrial assemblages examined. 95% confidence intervals around the mean dip angle for each wear facet type were heavily overlapping between the sexes for most of the comparisons conducted.


St Bride's: Buccal Phase I
Dip Angle (degrees)
45
40
35
30
25
20
15
10
Female
Male
Sex


St Bride's: Lingual Phase I
Dip Angle (degrees)
45
40
35
30
25
20
Female
Male
Sex

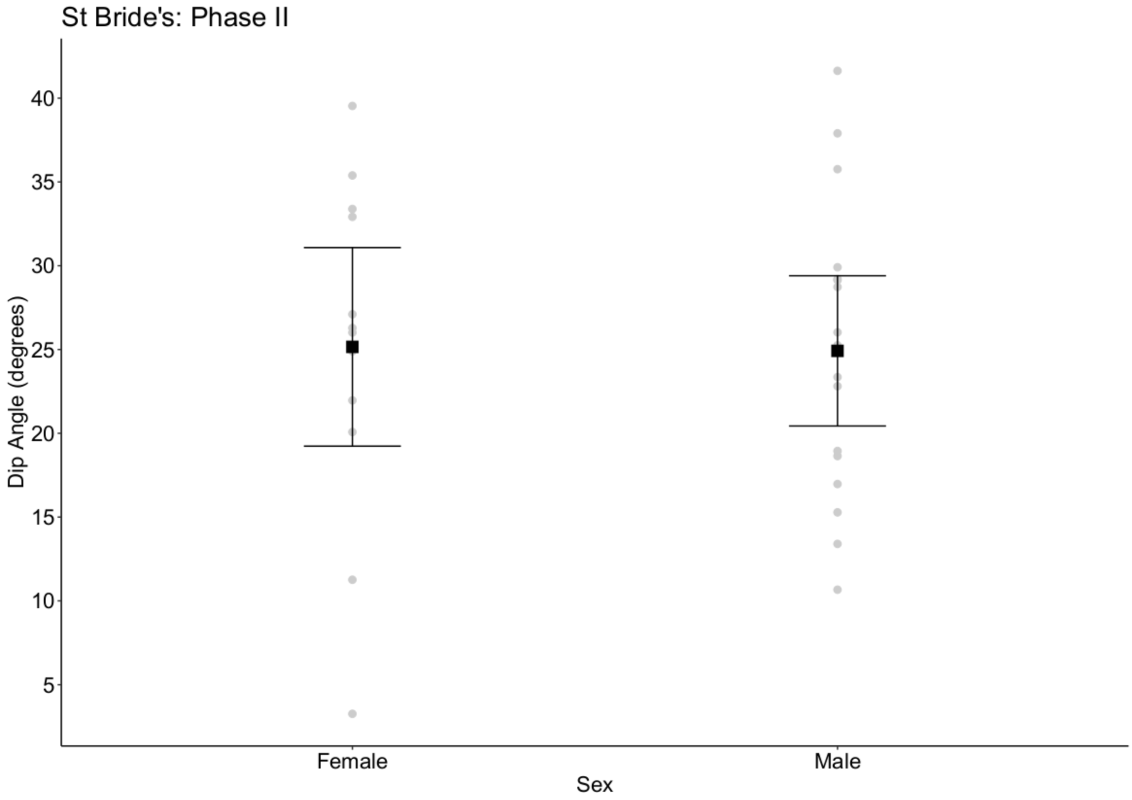
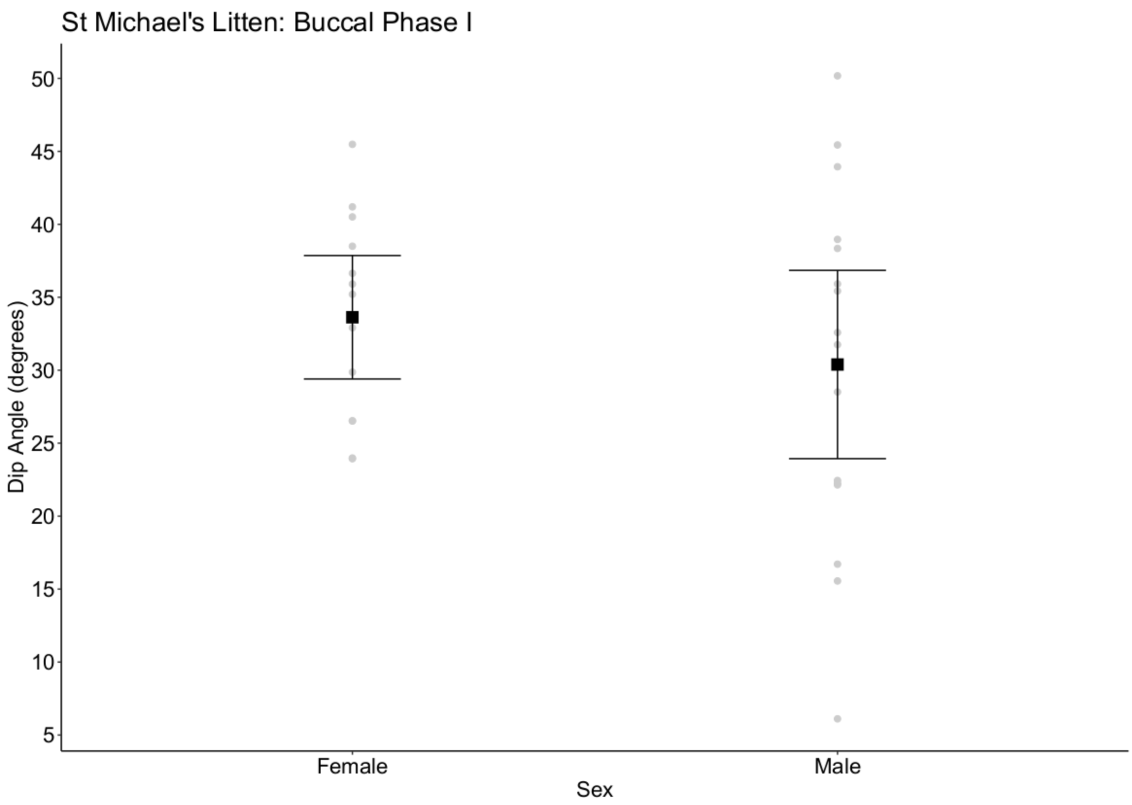
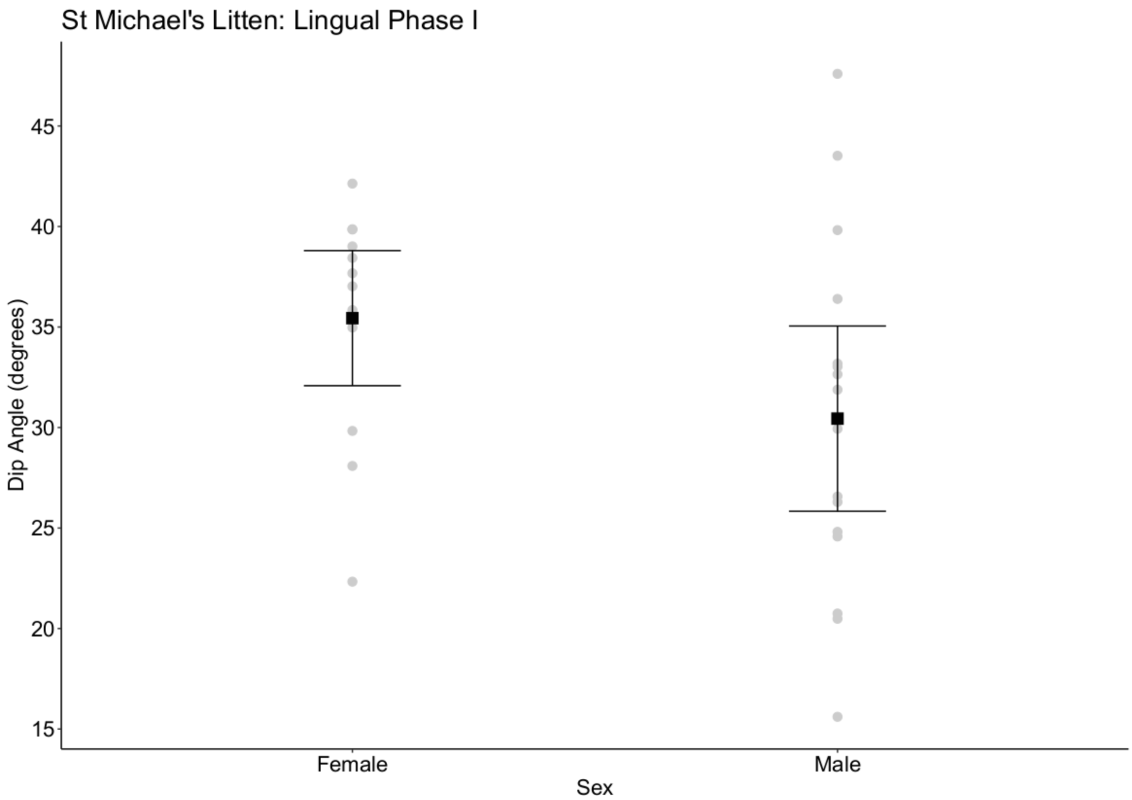


Figure 130: Dot plots with mean values and 95% confidence intervals plotted comparing the dip angle for each phase of the power stroke between the sexes in the St Bride's assemblage.


St Michael's Litten: Buccal Phase I
Dip Angle (degrees)
50
45
40
35
30
25
20
15
10
5
Female
Male
Sex


St Michael's Litten: Lingual Phase I
Dip Angle (degrees)
45
40
35
30
25
20
15
Female
Male
Sex

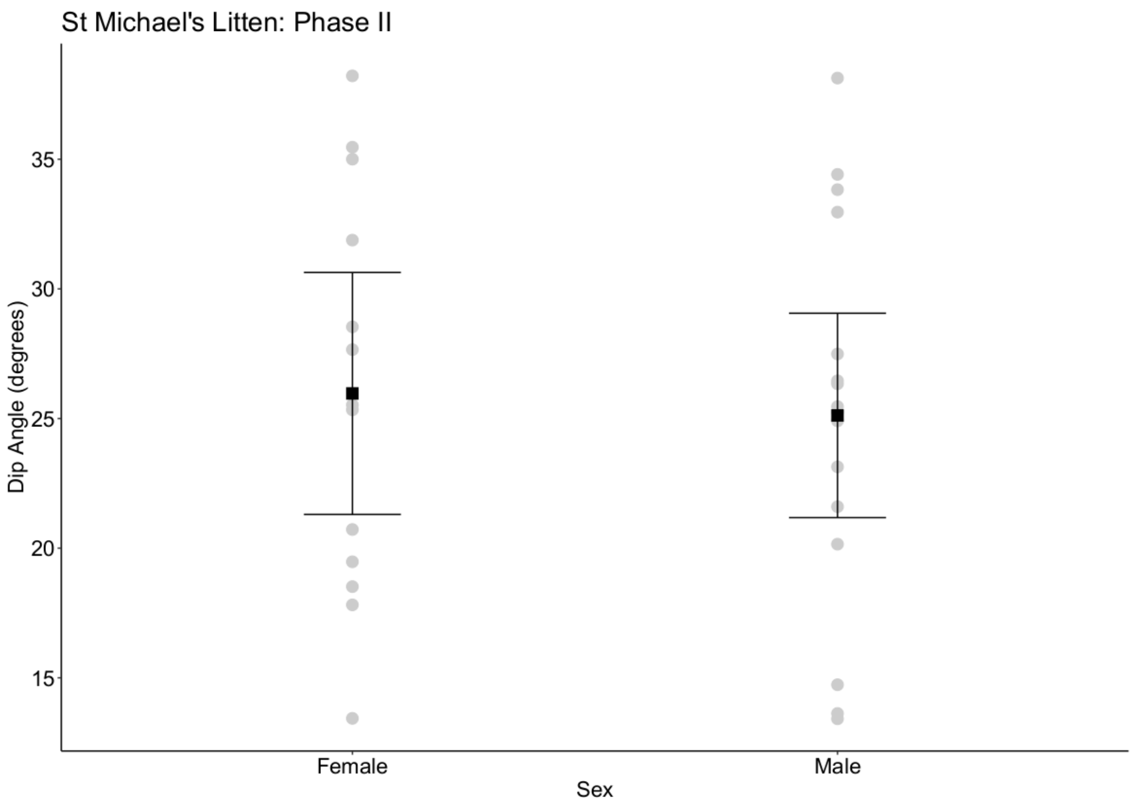
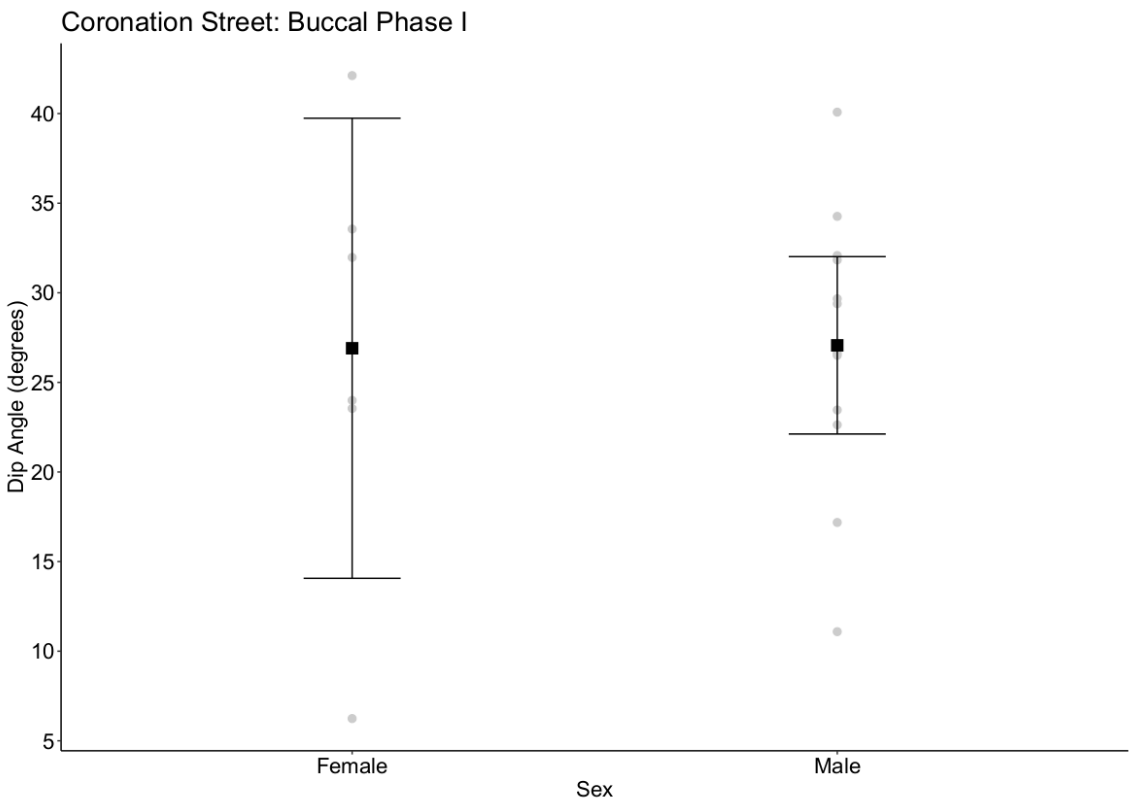
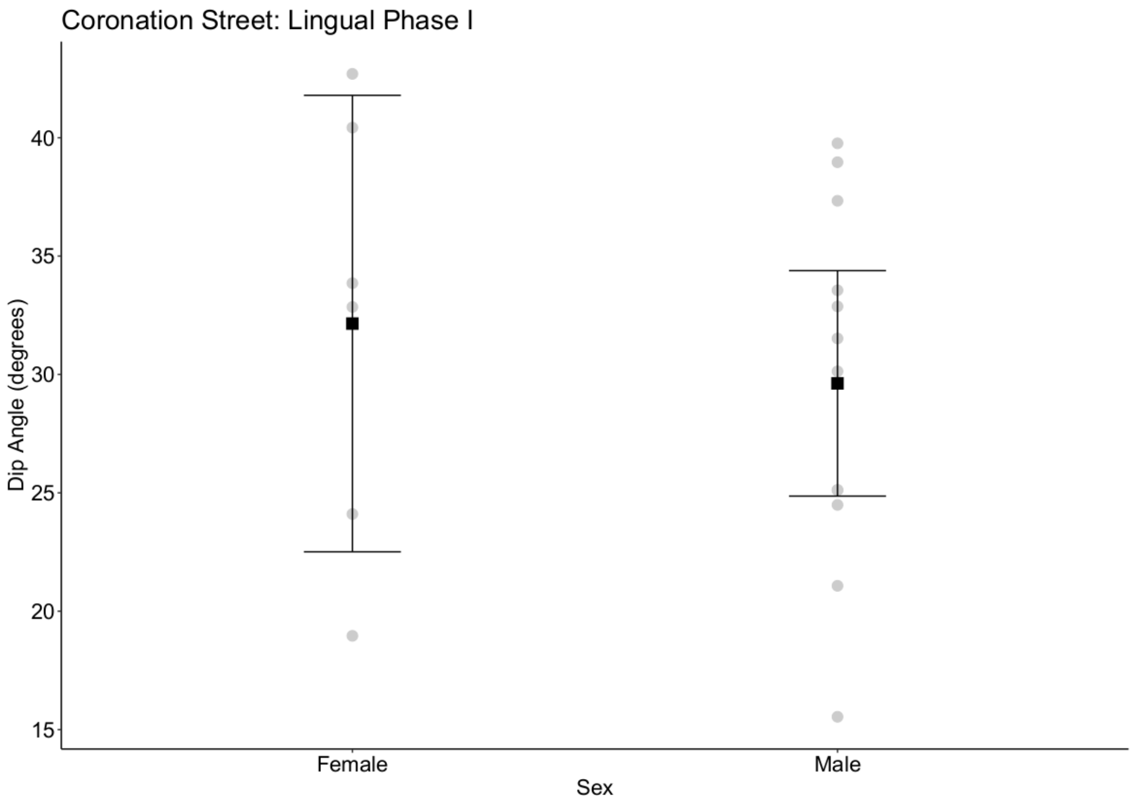


Figure 131: Dot plots with mean values and 95% confidence intervals plotted comparing the dip angle for each phase of the power stroke between the sexes in the late phase of the St Michael's Litten (ESC11) assemblage.


Coronation Street: Buccal Phase I
Dip Angle (degrees)
40
35
30
25
20
15
10
5
Female
Male
Sex


Coronation Street: Lingual Phase I
Dip Angle (degrees)
40
35
30
25
20
15
Female
Male
Sex

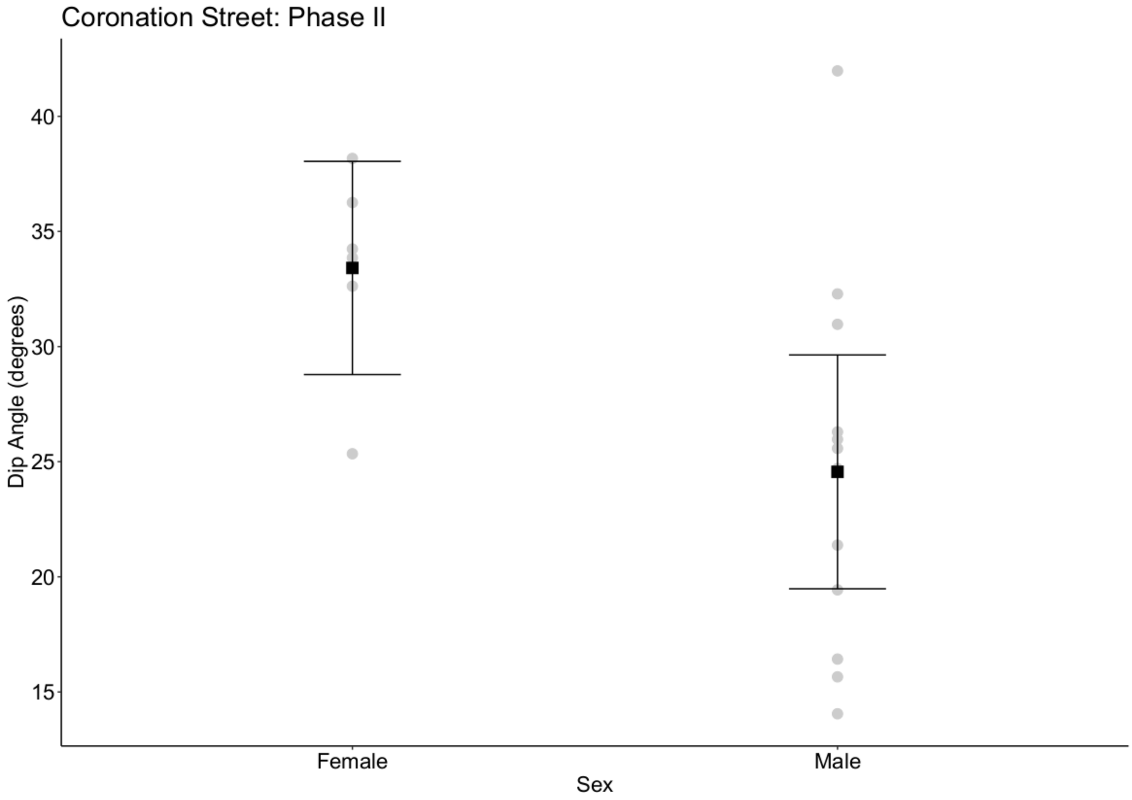


Figure 132: Dot plots with mean values and 95% confidence intervals plotted comparing the dip angle for each phase of the power stroke between the sexes in the Coronation Street assemblage. 95% confidence intervals around the mean dip angle were largely overlapping between the sexes for BPI and LPI wear facets. PII wear facets were more shallowly inclined in males than females.

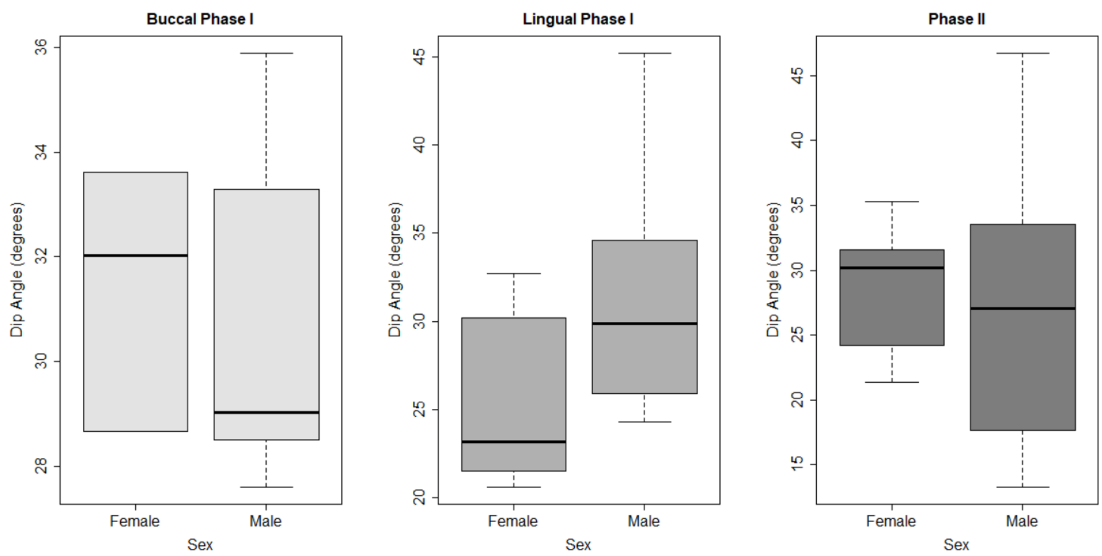


Figure 133: Boxplot showing the distribution of dip angles in the St Peter's Wolverhampton assemblage in relation to sex. The data were not normally distributed; therefore, the data were visualised using boxplots rather than dot plots.

*Table 67: Results of independent sample t-tests examining the relationship between sex and wear facet dip angle for each wear facet type for the Industrial assemblages that were normally distributed (Shapiro Wilk test; p>0.05). *Bonferroni adjusted p-value for the three tests conducted on each assemblage was 0.017.* ***Null hypothesis: dip angles did not differ significantly between males and females in the Industrial assemblage being tested.***

Wear Facet Type	BPI	LPI	PII
St Bride's			
Female Mean (º)	31.43	31.81	25.15
Standard Deviation	9.94	8.18	9.8
Male Mean (º)	30.52	28.62	24.92
Standard Deviation	10.36	5.95	9
t-value	0.25	1.19	0.07
Degrees of Freedom	26.1	20.67	24.25
p value*	0.81	0.25	0.95
Effect Size	0.1	0.47	0.03
95% CI Effect Size	-0.67 to 0.87	-0.30 to 1.25	-0.73 to 0.80
Statistical Power	0.06	0.23	0.05
H_0	Not rejected	Not rejected	Not rejected
St Michael's Litten			
Female Mean (º)	32.01	33.42	24.85
SD	7.07	6.87	6.99
Male Mean (º)	29.06	28.62	24.97
Standard Deviation	10.95	9.31	7.6
t-value	1.12	2.03	-0.05
Degrees of Freedom	43.85	43.76	40.68
p value*	0.27	0.05	0.95
Effect Size	0.31	0.58	-0.01
95% CI Effect Size	-0.29 to 0.92	-0.04 to 1.19	-0.62 to 0.59
Statistical Power	0.17	0.47	0.05
H_0	Not rejected	Not rejected	Not rejected
Coronation Street			
Female Mean (º)	26.9	32.15	33.41
Standard Deviation	7.79	7.49	7.99
Male Mean (º)	27.07	29.62	24.56
Standard Deviation	12.23	9.18	4.41
t-value	-0.03	0.58	3.03
Degrees of Freedon	7.1	8.46	15.68
p value*	0.98	0.57	0.008
Effect size	-0.02	0.31	1.25
95% CI Effect Size	-1.08 to 1.04	-0.75 to 1.38	0.10 to 2.40
Statistical Power	0.05	0.08	0.65
H_0	Not rejected	Not rejected	Not rejected

Table 68: Results of Wilcoxon rank sum tests assessing whether wear facet dip angle differed significantly between the sexes in the St Peter's Wolverhampton assemblage. Wilcoxon rank sum tests were used for this assemblage as the assumption of normality was violated (Shapiro-Wilk test p<0.05). ***Null hypothesis: there were no significant differences in the dip angles of the wear facet types between the sexes in the St Peter's, Wolverhampton, assemblage.***

Wear Facet Type	W	p-value	H_0
BPI	14	0.81	Not Rejected
LPI	9	0.28	Not Rejected
PII	20	0.57	Not Rejected

Sex differences in ORI or TCI were not consistently identified in the Industrial assemblages examined (Table 69). ORI did differ significantly between males and females in the Coronation Street assemblage, however. TCI differed significantly between males and females in the St Peter's assemblage (Figure 134).

Table 69: Results of Wilcoxon rank sum tests assessing whether ORI and/or TCI differed significantly between the sexes within each Industrial assemblage. Bonferroni adjusted p-value for each assemblage was set at 0.25. Null Hypothesis for each test: ORI and/or TCI values did not differ significantly between the sexes in the particular assemblage dating to the Industrial period being tested.

St Bride's	W	p-value	H_0
ORI	133	0.54	Not Rejected
TCI	121	0.89	Not Rejected
Coronation Street	**W**	**p-value**	**H_0**
ORI	59	0.03	Rejected?
TCI	27	0.44	Not Rejected
St Michael's Litten	**W**	**p-value**	**H_0**
ORI	273.5	0.71	Not Rejected
TCI	191	0.15	Not Rejected
St Peter's	**W**	**p-value**	**H_0**
ORI	15	0.93	Not Rejected
TCI	29	0.03	Rejected?

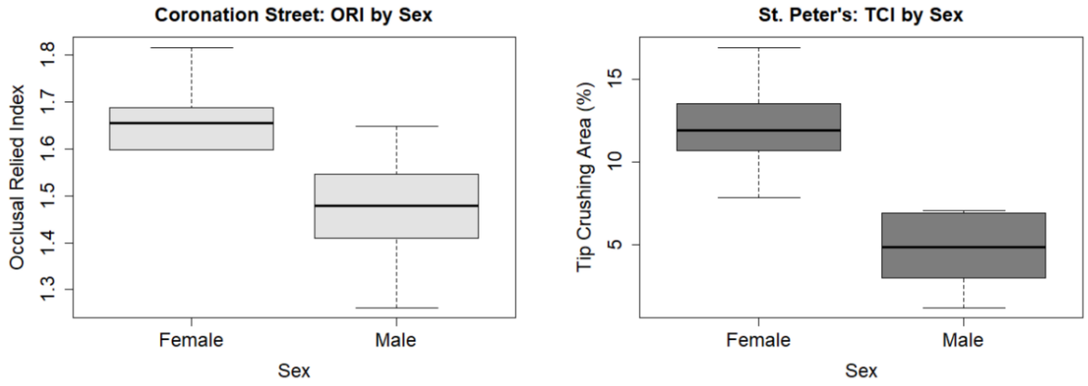


Figure 134: Left: Boxplot comparing the distribution of ORI in relation to sex in the Coronation Street assemblage. Females had significantly greater ORI values than males. Right: Boxplot comparing TCI values between the sexes in the St Peter's, Wolverhampton, assemblage. Females had significantly greater TCI values.

6.2.1.1.3 Summary

The evidence for sex differences in wear facet expression in the Industrial period was very limited. There was insufficient evidence to support the hypothesis of greater meat consumption among males in the Industrial assemblages examined, based on relative wear facet area. Small differences in wear facet dip angles were apparent, however, between males and females. In some assemblages, males exhibited slightly less obliquely inclined wear facets. Nevertheless, the small sample size for each assemblage limited the statistical power of the inferences that could be made. Larger assemblages with greater numbers of individuals appropriate for conducting OFA would be required in order to make more robust statistical inferences regarding the influence of sex on wear facet expression.

6.2.1.2 *A wider range of age groups is anticipated to be includable in OFA for the Industrial period due to an expected lower wear rate when compared to the Mediaeval and early Post-Mediaeval periods. It is anticipated that wear facet expression may change with increasing age-at-death.*

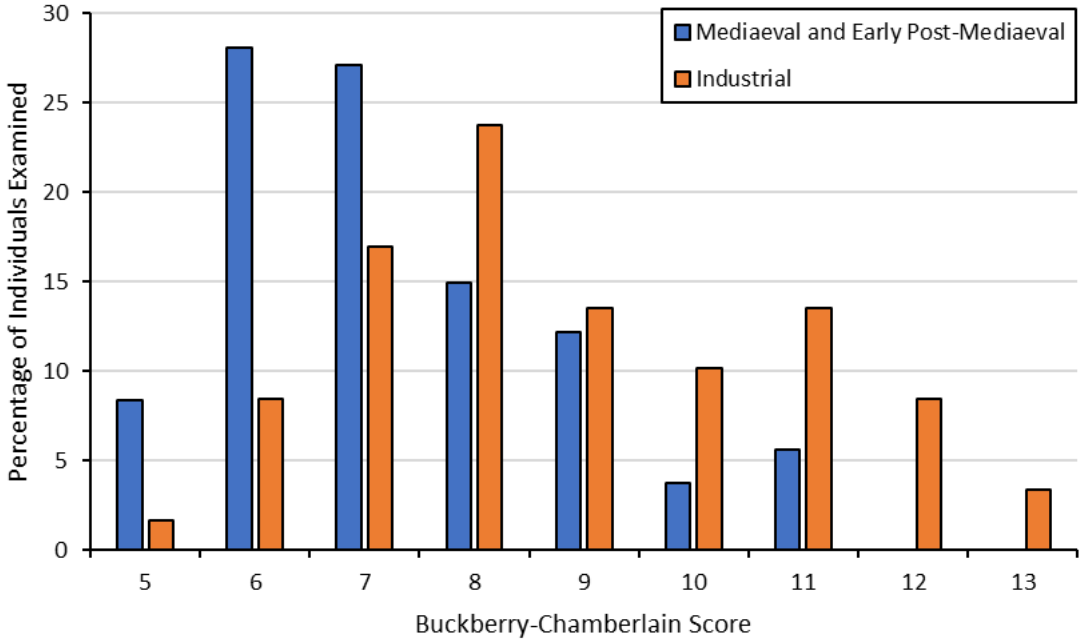


Figure 135: A higher proportion of the individuals examined in the Mediaeval period exhibited less advanced degeneration of the auricular surface (shown by lower Buckberry-Chamberlain scores) when compared to the Industrial period. The distribution of Buckberry-Chamberlain scores differed significantly between the two periods (Wilcoxon rank sum test with continuity correction; W = 4622.5, p-value <0.0001).

Older age-at-death categories were poorly represented in the pre-Industrial group (Figure 135). This was due to the selection of individuals with relatively limited dental wear on their lower second molars so that OFA could be conducted. They typically belonged to younger skeletal age-at-death categories due to the higher wear rate in this period when compared to the Industrial period. Consequently, an assessment of the influence of age-at-death on wear facet expression was limited to the Industrial period only.

6.2.1.2.1 Overall

Age-at-death category had a significant effect upon wear facet composition in the Industrial period. The associated R^2 was of a smaller magnitude than that obtained when examining the period-based influence on wear facet area composition, however (0.05 and 0.09, respectively) (Table 70 and Table 124).

The older age-at-death group had larger proportions of LPI wear facets and smaller proportions of BPI and PII wear when compared to the younger age-at-death category (Figure 136). The broader age-at-death range for the Industrial period likely contributed to the high levels of variability in relative wear facet area in the assemblages examined.

Table 70: Results of Type I PERMANOVA assessing the relationship between age-at-death category (either younger or older) and wear facet area composition. ***Null hypothesis: wear facet area composition did not differ significantly between the younger and older age-at-death categories dating to the Industrial period.***

Standard data	**Df**	**Sum of Squares**	**Mean of Squares**	**F-model**	**R^2**	**p-value**	**H_0**
Age-at-death Category	1	0.07	0.07	2.88	0.05	0.06	Rejected?
Residuals	57	1.46	0.03		0.95		
Total	58	1.54			1.00		
ILR data	**Df**	**Sum of Squares**	**Mean of Squares**	**F-model**	**R^2**	**p-value**	**H_0**
Age-at-death Category	1	2.23	2.23	3.76	0.06	0.027	**Rejected**
Residuals	57	33.80	0.59		0.94		
Total	58	36.03			1.00		

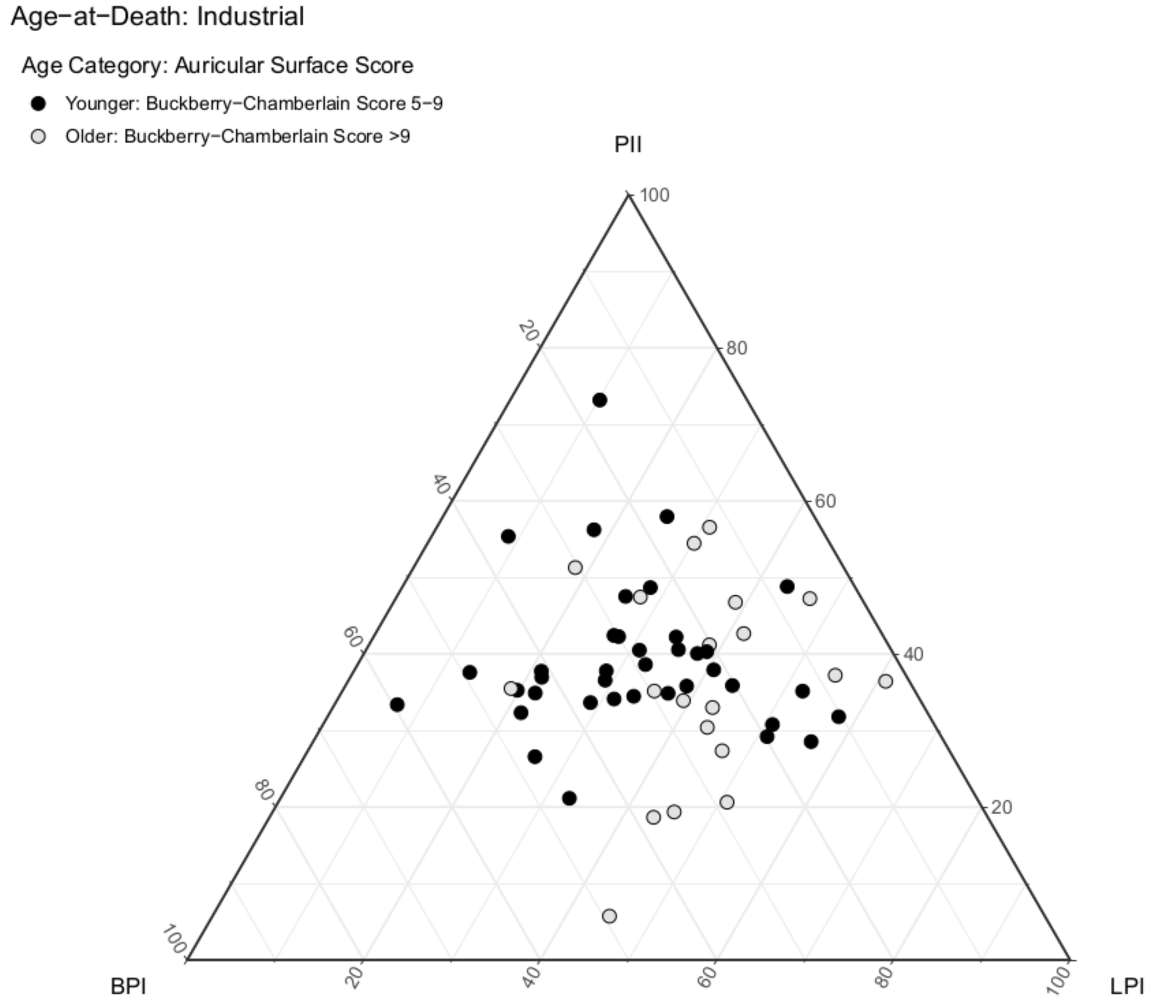
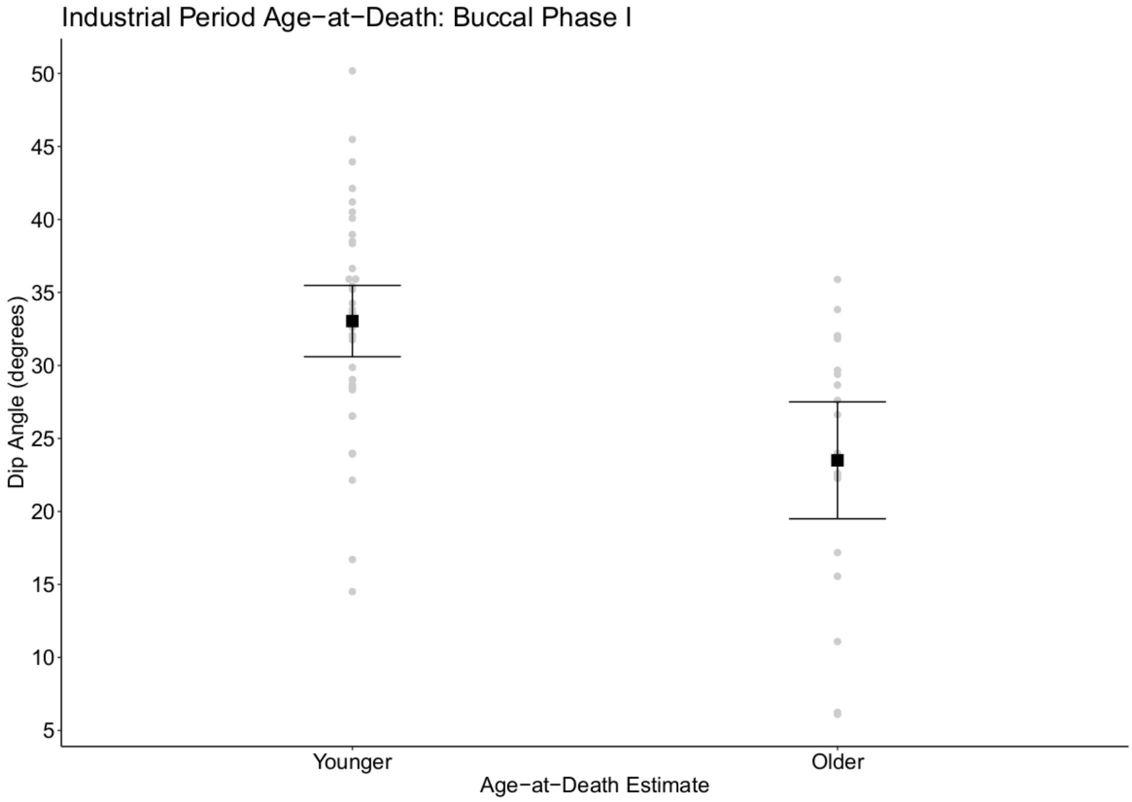
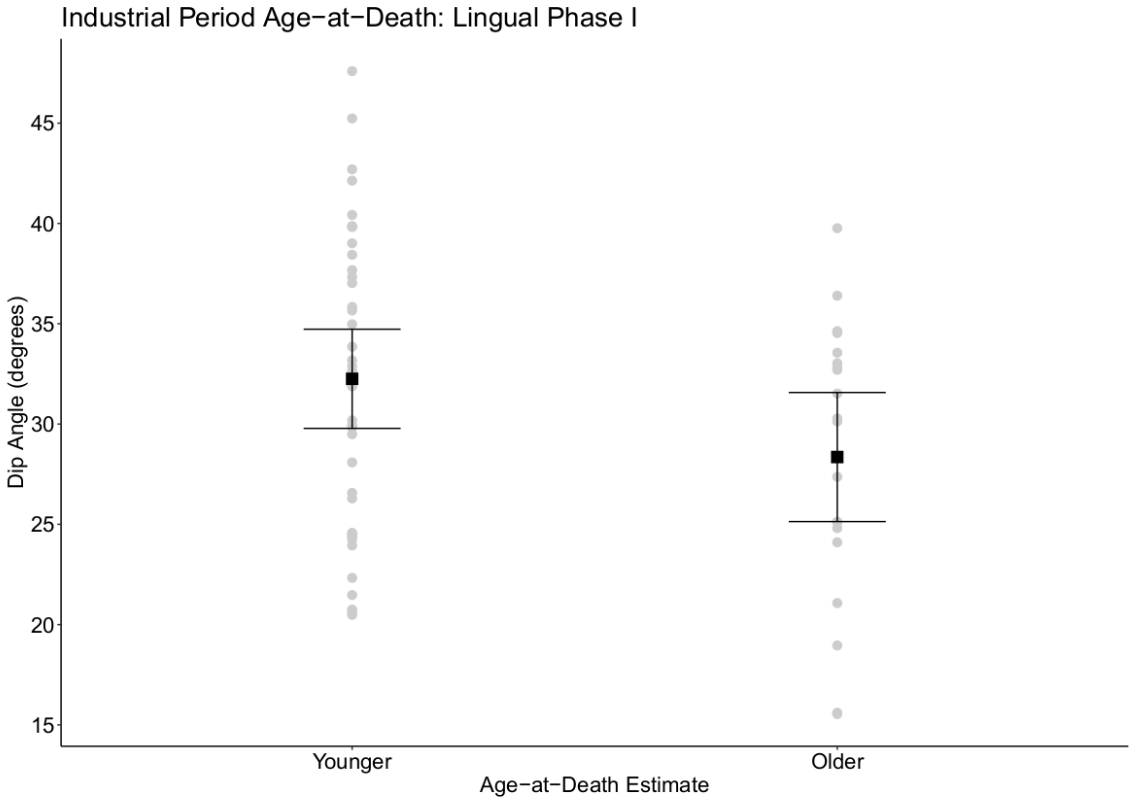


Figure 136: Ternary plot showing the relationship between auricular surface stage and wear facet area composition. Black circles correspond to younger individuals (Buckberry-Chamberlain score 5-9) and white circles to older individuals (Buckberry-Chamberlain score 10 or greater). The centre values for the younger age category were BPI 28.69%, LPI 31.13% and PII 40.17%. Centre values for the older age category were BPI 21.84%, LPI 42.21% and PII 35.95%.

BPI dip angles were significantly less steep in the older age-at-death category (Figure 137 and Table 71). LPI and PII wear facets were slightly more shallowly inclined in the older age-at-death category. The effect size of age-at-death on BPI wear facet dip angle was of a smaller magnitude than the effect size associated with period (maximum -0.50 and 0.84, respectively).





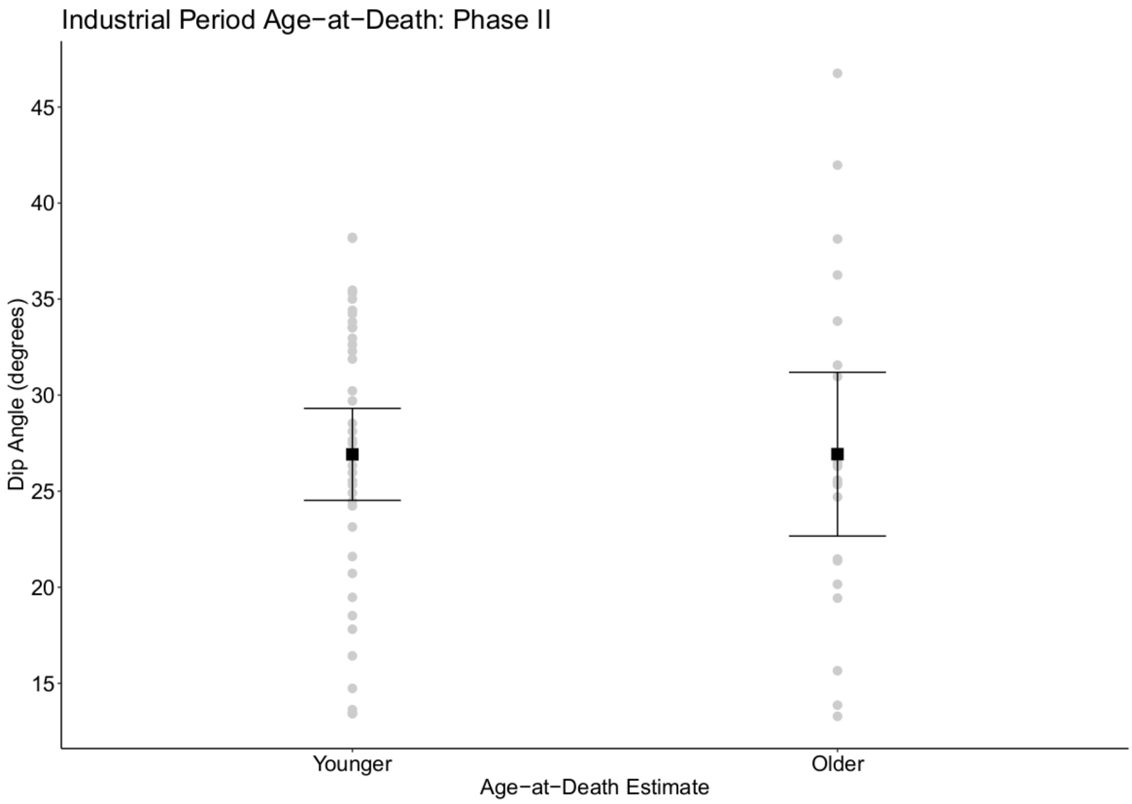


Figure 137: Dot plots comparing dip angles for BPI, LPI and PII wear facets between age-at-death categories for individuals dated to the Industrial period. Mean values with 95% confidence intervals are plotted as black squares with error bars.

*Table 71: Independent sample t-tests assessing age-related differences in dip angle during the Industrial period for BPI, LPI and PII wear facets. *Bonferroni adjusted p-value=0.017. The data for each variable was normally distributed (Shapiro-Wilk p>0.05) and exhibited homogeneity of variance (Levene's test p>0.05).* ***Null hypothesis: dip angle values did not differ significantly between younger and older age-at-death categories during the Industrial period for each of the wear facet types assessed.***

Wear Facet Function	BPI	LPI	PII
Younger Mean (º)	31.38	31.52	26.94
Standard Deviation	8.34	7.52	8.09
Older Mean (º)	26.78	28.92	24.8
Standard Deviation	9.76	6.8	8.86
t-value	-2.31	-1.75	-1.18
Degrees of Freedom	73.39	82.27	68.01
p value*	0.02	0.08	0.24
Effect Size	-0.5	-0.36	-0.26
95% CI Effect Size	-0.92 to-0.07	-0.78 to -0.6	-0.68 to 0.16
Statistical Power	0.63	0.38	0.22
H_0	Rejected?	Not Rejected	Not Rejected

ORI values were significantly less among skeletally older Industrial individuals (Table 72; Figure 138). TCI values did not differ significantly between the two age-at-death categories in the Industrial period, however, there was a slight tendency for more developed tip crushing areas among the older age-at-death category (Wilcoxon rank sum test; W = 1194, p-value = 0.28; Figure 139).

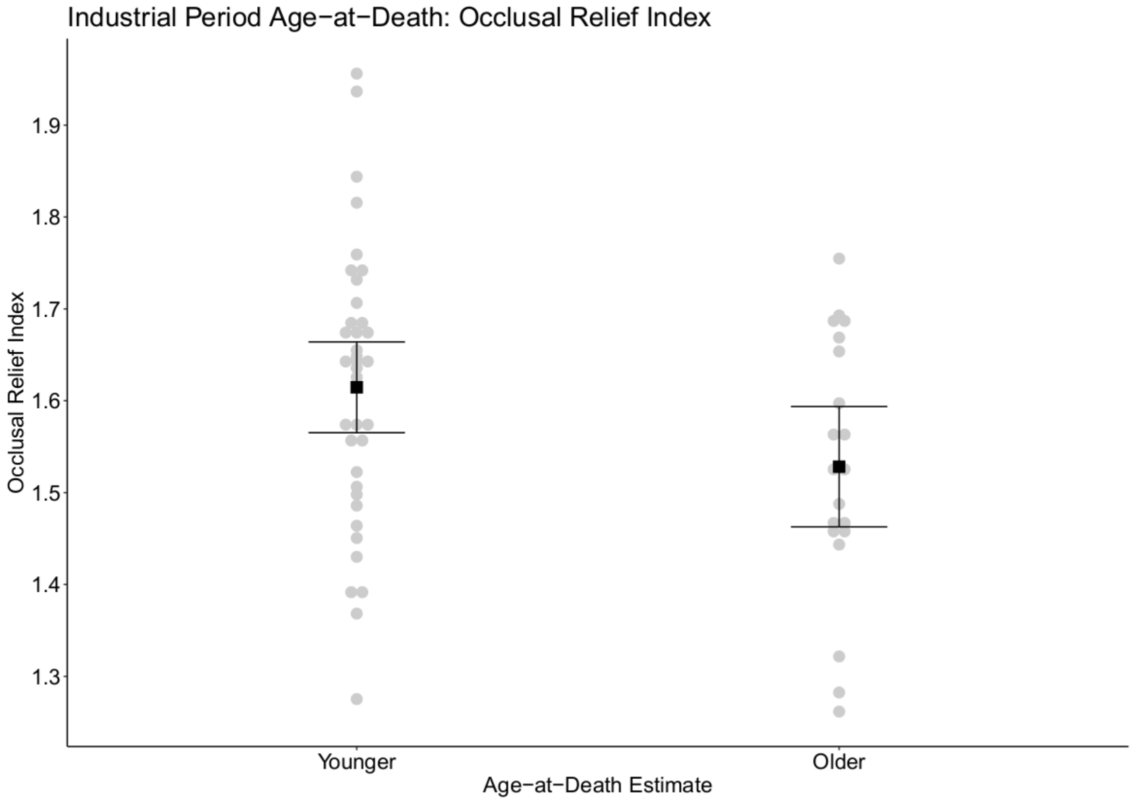


Figure 138: Dot plot comparing the ORI values between younger and older age-at-death categories among individuals dating to the Industrial period. The older age-at-death category had significantly smaller ORI values.

Table 72: Independent sample t-test assessing the relationship between age-at-death category and ORI in the Industrial period. ***Null hypothesis: ORI values did not differ significantly between older and younger age-at-death categories among assemblages dating to the Industrial period.***

Industrial Younger Category Mean ORI	1.61
Standard Deviation	0.14
Industrial Older Category Mean ORI	1.52
Standard Deviation	0.13
t-value	-3.08
Degrees of Freedom	79.14
p value	0.003
Effect size	-0.64
95% CI effect size	-1.07 or -0.21
Statistical Power	0.83
H_0	**Rejected**

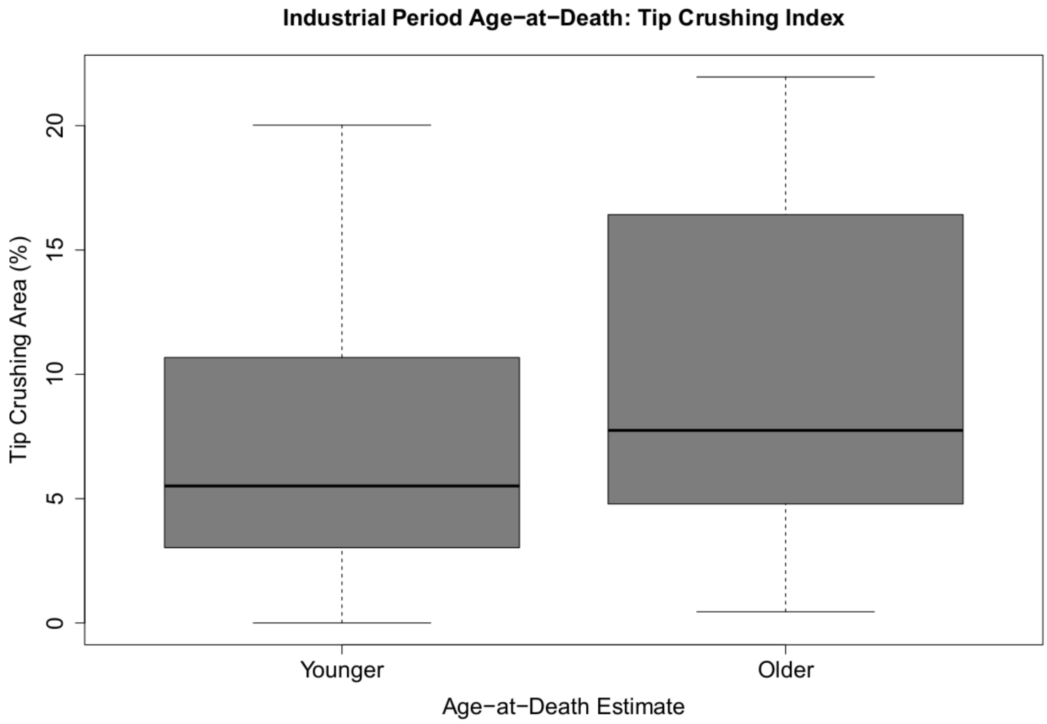


Figure 139: Boxplot comparing tip crushing area values between younger and older age-at-death categories in the Industrial period. The data were not normally distributed (Shapiro-wilk test; p<0.05).

6.2.1.2.2 St Bride's: A known age-of-death assemblage

The material from St Bride's, London, was assessed separately as a known age-at-death assemblage. In order to have large enough sample sizes for statistical testing, the St Bride's individuals were divided into 3 categories: a younger category (age-at-death 20-39 years), a middle category (age-at-death 40-49 years) and an older category (age-at-death 50+ years). Relative wear facet area did not differ significantly between the age-at-death categories into which the St Bride's assemblage was divided (Figure 140; Table 73). Older individuals had wear facet areas dominated by slightly greater proportions of PII and reduced BPI wear. This is not consistent with the trend towards larger proportions of LPI wear facet areas in the older age-at-death category in the overall Industrial group.

Table 73: Results of PERMANOVA examining the relationship between wear facet proportions and age-at-death in the St Bride's assemblage. ***Null hypothesis: wear facet area proportions did not differ significantly between age categories within the St Bride's assemblage.*** *The variable examined satisfied the homogeneity of multivariate dispersion assumption required to perform PERMANOVA (Table 125).*

Standard data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	**R^2**	**p-value(>F)**	**H_0**
Age Category	2	0.08	0.04	1.90	0.12	0.12	Not Rejected
Residuals	27	0.59	0.02		0.88		
ILR data	**Sum Squares**	**Mean Squares**	**DF**	**F**	**R^2**	**p-value(>F)**	**H_0**
Age Category	2	1.31	0.65	1.71	0.11	0.16	Not Rejected
Residuals	27	10.34	0.38		0.89		

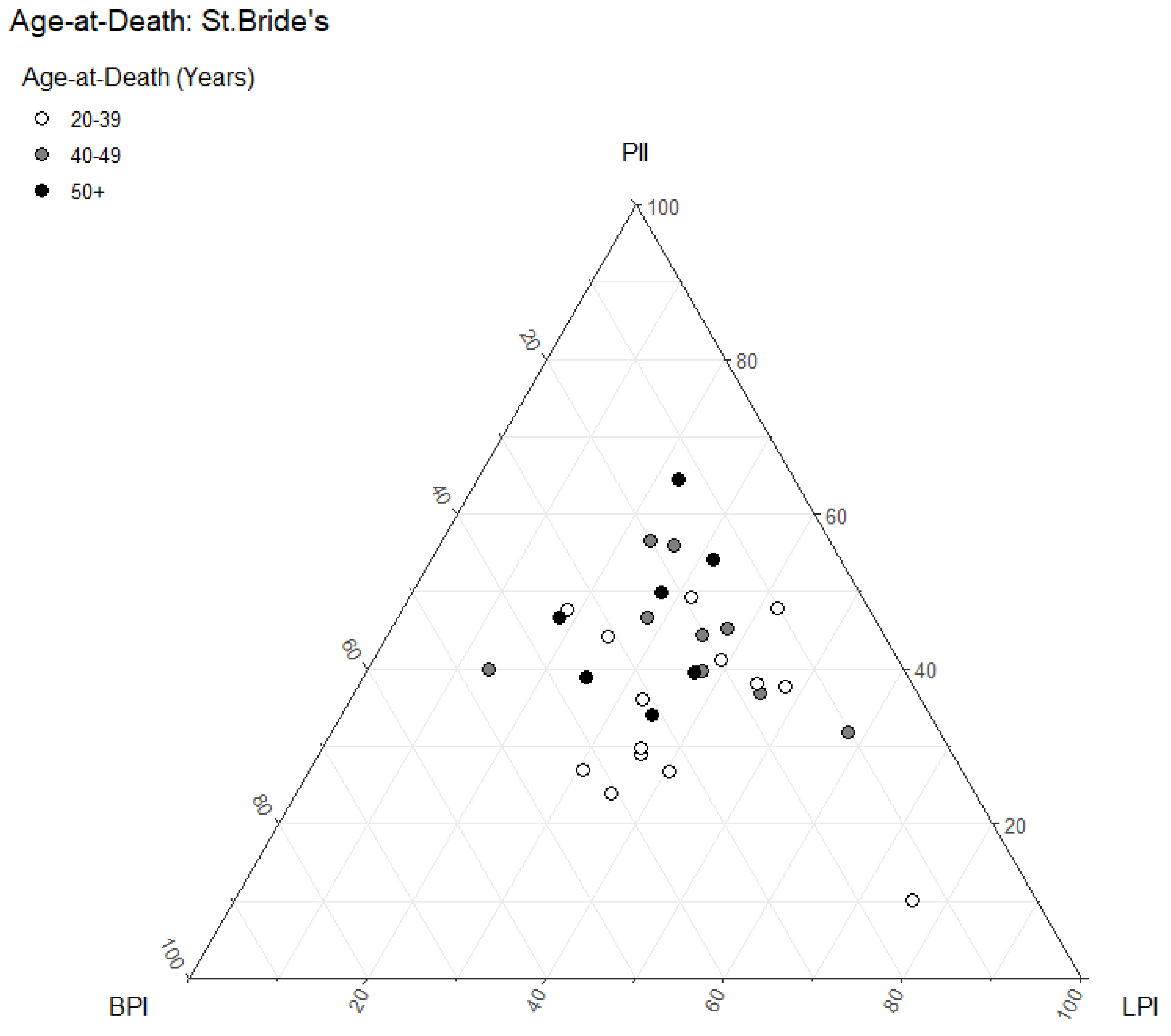


Figure 140: Ternary plot showing the relationship between age-at-death and wear facet area proportions in the St Bride's assemblage. Individuals were grouped into three age-at-death categories (younger 20-39 years, middle 40-49 years and older 50+years) in order that statistical methods remained consistent between research questions. There was not a significant relationship between age-at-death and wear facet area proportions.

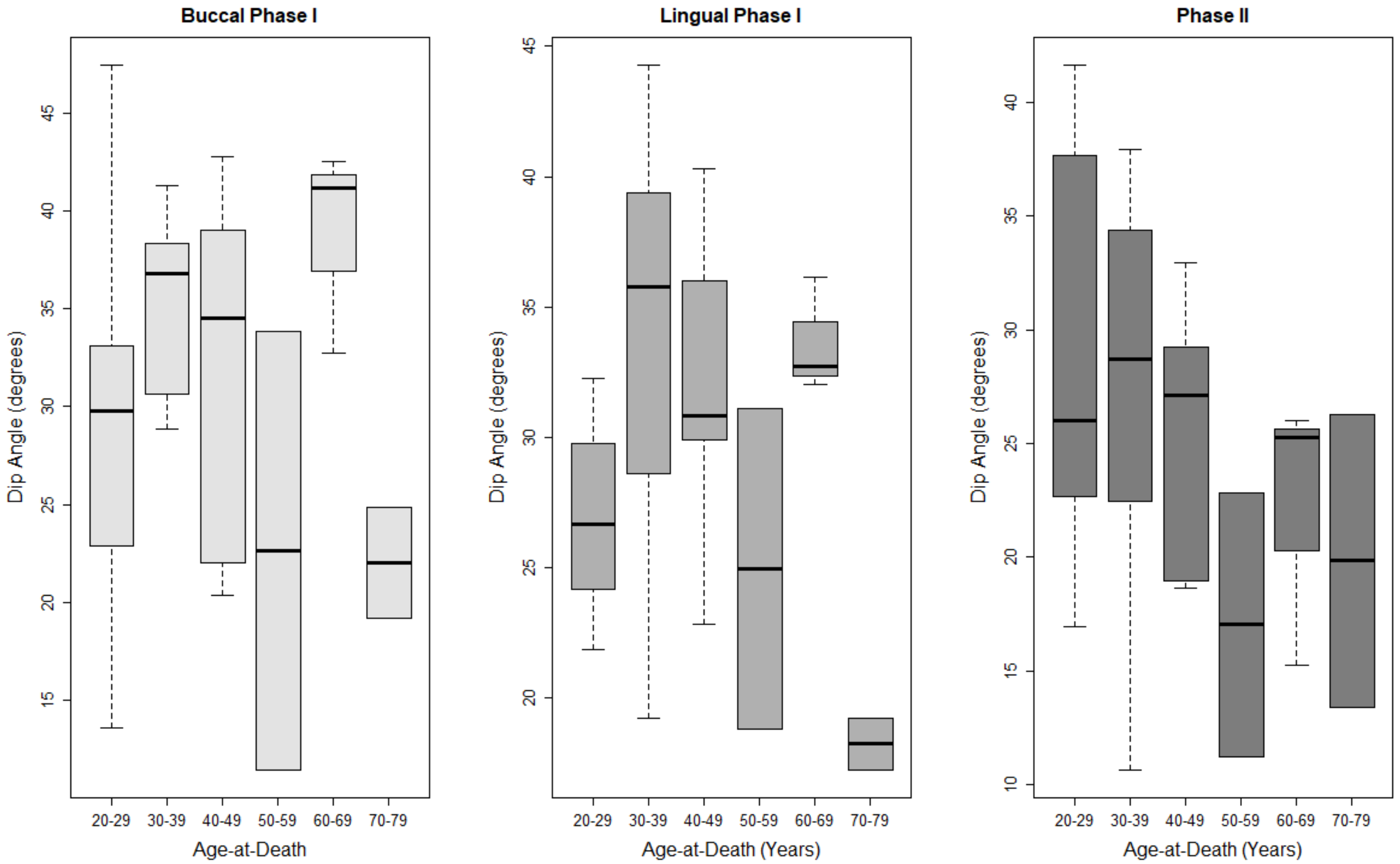


Figure 141: Boxplots showing the relationship between mean dip angle for each wear facet type and age-at-death in the St Bride's assemblage. The assemblage was of known age-at-death as coffin plates were associated with the burials. As such, the assemblage could be divided into 10-year age-at-death categories for the analysis. Dip angle values were not normally distributed therefore non-parametric testing was used to assess the relationship between dip angle and age-at-death (Shapiro-Wilk test; p<0.05).

There were not any significant differences in wear facet dip angle, however, there was a slight tendency towards less obliquely inclined dip angles in the older age-at-death categories with the exception of the individuals aged 60-69 years (Figure 141 and Table 74).

Table 74: Results of Kruskal-Wallis test assessing the relationship between age-at-death and wear facet dip angle in the St Bride's assemblage. The data were not normally distributed (Shapiro-Wilk test; p<0.05), therefore, non-parametric testing was used. ***Null hypothesis: wear facet dip angles did not differ significantly between the St Bride's age-at-death categories.***

Wear Facet Type	Kruskal-Wallis chi-squared	df	p-value	H_0
BPI	0.35	2	0.84	Not Rejected
LPI	1.45	2	0.49	Not Rejected
PII	3.72	2	0.16	Not Rejected

There were no significant differences in either ORI or TCI with increasing age-at-death, however, there was a tendency for ORI to decrease with increasing age-at-death category (Table 75; Figure 142). The largest TCI values were observed in the oldest age-at-death group (Figure 142).

Table 75: Results of Kruskal-Wallis test assessing the relationship between age-at-death and TCI and ORI in the St Bride's assemblage. The data was not normally distributed (Shapiro-Wilk test; p<0.05), therefore, non-parametric testing was used. ***Null hypothesis: ORI and TCI values did not differ significantly between the St Bride's age-at-death categories.***

Age-at-Death	Kruskal-Wallis chi-squared (df)	df	p-value	H_0
TCI	3.11	2	0.21	Not Rejected
ORI	4.65	2	0.10	Not Rejected

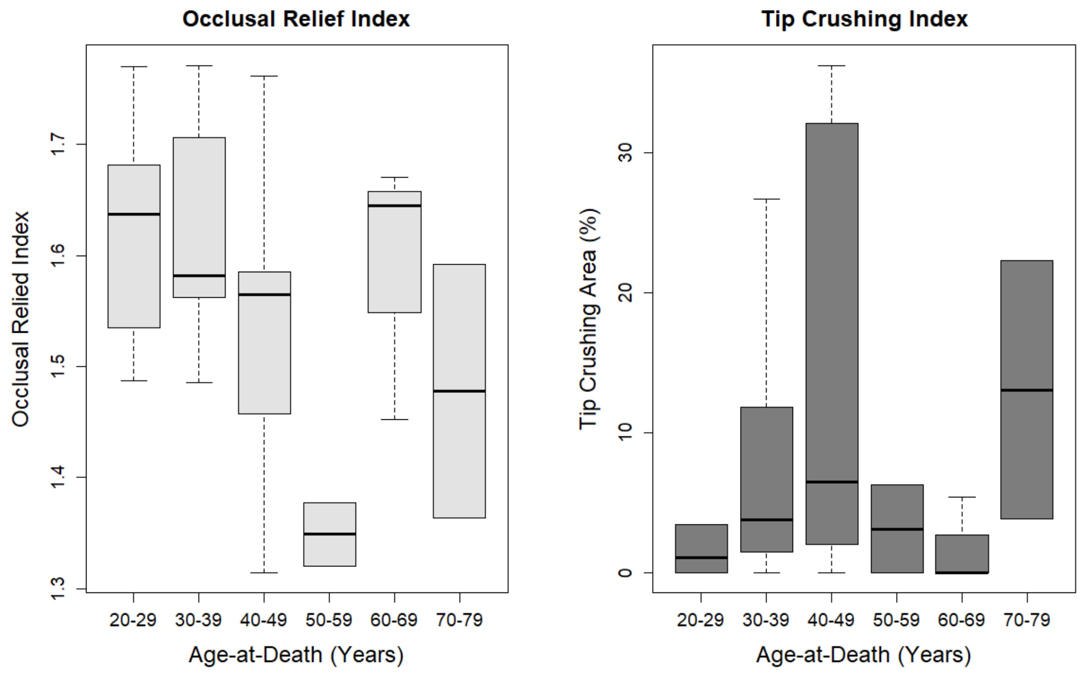


Figure 142: Boxplots showing the relationship between ORI and age-at-death and TCI and age-at-death in the St Bride's assemblage.

6.2.1.2.3 Summary

Individuals from older age-at-death categories in the Industrial period typically exhibited slightly less steeply inclined dip angles, lower ORI values and larger TCI values. The magnitude of the influence of age-at-death category on wear facet dip angle depended on the skeletal assemblage being considered (Appendix 10.3: Table 148; Figure 181 to Figure 183). Individuals from the older age-at-death category had wear facet patterns dominated by larger proportions of LPI wear and reduced proportions of BPI wear, where age-at-death was assessed using the degeneration of the auricular surface. A reduction in the proportion of the lower second molar wear facet pattern composed of BPI wear facets was also apparent in the older age-at-death categories in the St Bride's material, however, the enlargement of LPI facet areas was not apparent.

6.2.1.3 In the Industrial period, the quantities of meat consumed were highly dependent upon income and it has been asserted that differences in diet were of greater magnitude between, rather than within, social classes. Among assemblages with contextual information pertaining to social stratification, greater quantities of buccal phase I shearing wear might be anticipated among higher status individuals that habitually consumed larger amounts of meat.

6.2.1.3.1 St Bride's Church, Fleet Street (SB79)

Burial plates associated with the inhumations at St Bride's provided biological profiles for the assemblage, and in some cases biographical details. Individuals assigned to the higher social status group had a greater proportion of their total wear facet areas constituted by BPI wear facets when compared to the middle/low status group (Figure 143 and Table 76). Social status significantly influenced wear facet composition when performing PERMANOVA on the isometric log transformed data. This was not apparent when using the raw data and the Bray-Curtis similarity matrix. Individuals of higher social status showed significantly greater proportions of BPI wear relative to middle to low status individuals (Figure 143).

Table 76: Results of PERMANOVA examining the relationship between wear facet proportions and social status in the St Bride's assemblage. ***Null hypothesis: social status did not significantly influence wear facet composition in the St Bride's assemblage.*** *The variables examined satisfied the homogeneity of multivariate dispersion assumption (Table 126).*

Standard data	Sum of Squares	Mean of Squares	DF	F	R^2	p-value (>F)	H_0
Social Status	0.03	0.03	1	1.48	0.05	0.25	Not Rejected
Residuals	0.64	0.02	28		0.95		
ILR data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	R^2	**p-value (>F)**	H_0
Status	1.17	1.17	1	3.13	0.10	0.05	Rejected?
Residuals	10.48	0.37	28		0.90		

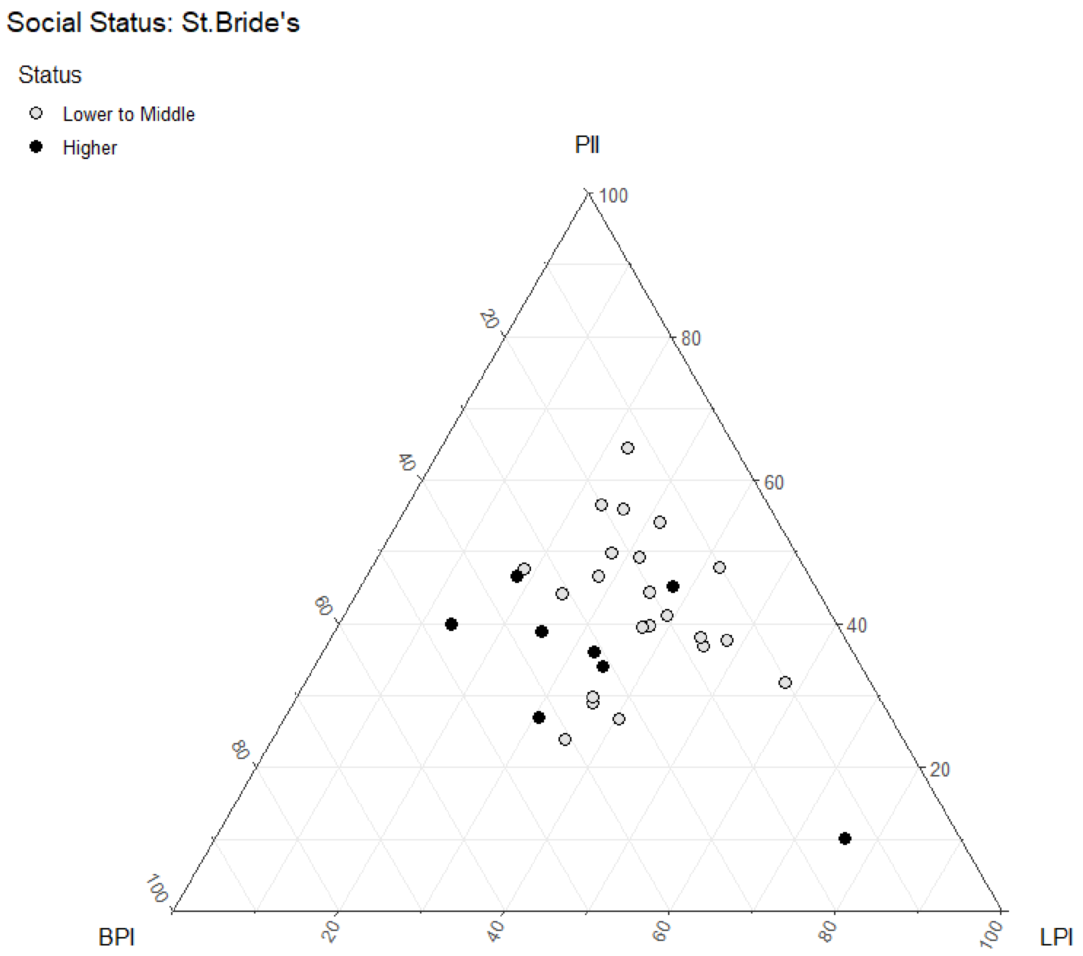
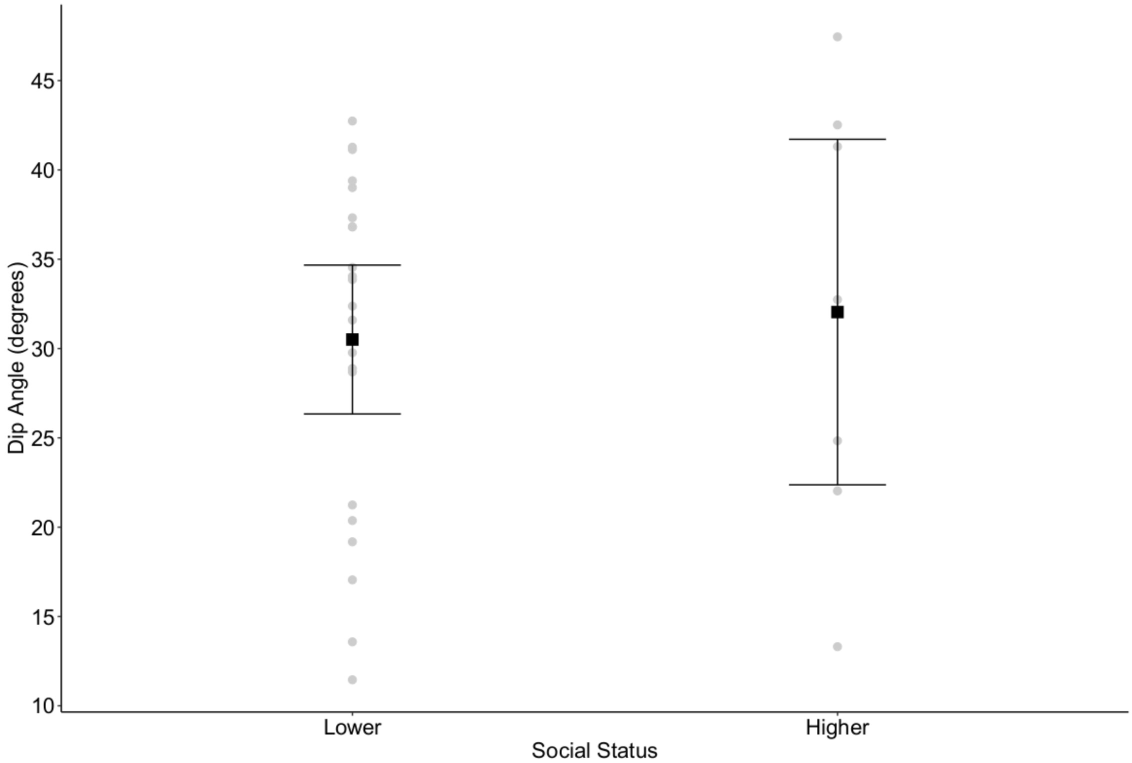


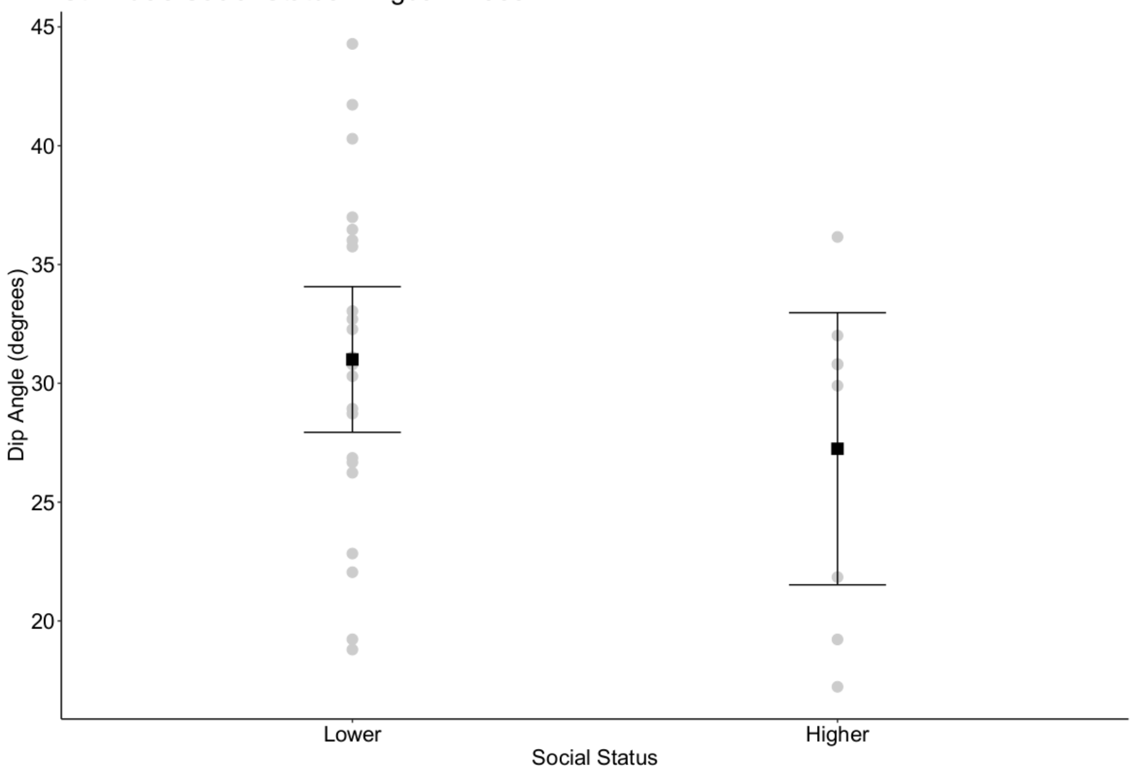
Figure 143: Ternary plot showing the relationship between social status and wear facet area composition in the St Bride's assemblage. Individuals of higher social status exhibited significantly greater proportions of BPI facets and slightly reduced proportions of PII facets. The centre value for the high-status group was BPI 32.50%, LPI 32.68% and PII 34.82%. The centre for the middle/low status group was BPI 21.83%, LPI 35.14%, PII 43.03%.

Dip angle did not differ significantly between the two social status groups in the St Bride's assemblage (Figure 144). Individuals in the higher social status category had slightly more shallowly inclined LPI and PII wear facets (Table 77 and Table 78).

St Bride's Social Status: Buccal Phase I



St Bride's Social Status: Lingual Phase I



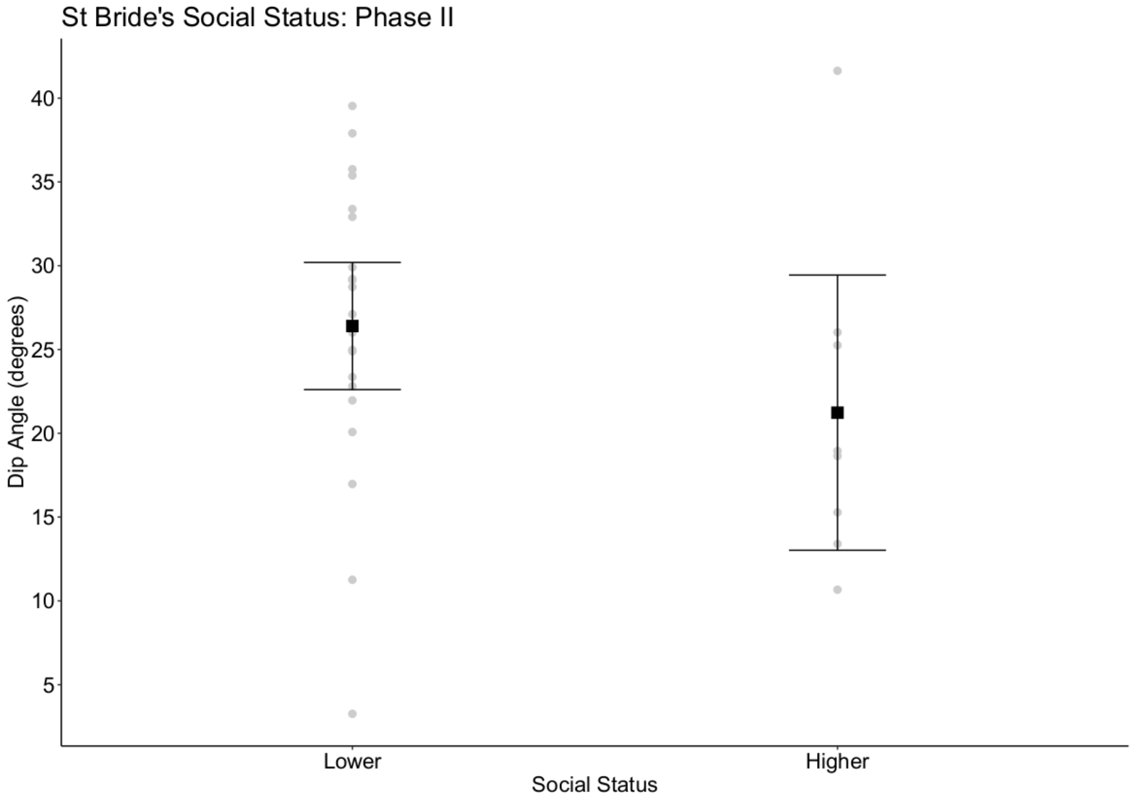


Figure 144: Dot plots with mean values plotted accompanied by 95% confidence intervals showing the relationship between social status and wear facet dip angles for BPI, LPI and PII facets in the St Bride's assemblage.

Table 77: Results of independent sample t-tests assessing the relationship between social status and dip angle in the St Bride's assemblage. Data satisfied assumptions of normality (Shapiro Wilk test p>0.05) and homogeneity of variance (Levene's test p>0.05). ***Null hypothesis: dip angle values for BPI, LPI and PII wear facets did not differ significantly between higher and lower social status groups in the St Bride's assemblage.***

Wear Facet Function	BPI	LPI	PII
Higher Status Mean Dip Angle (º)	32.04	27.25	21.23
Standard Deviation	12.5	7.23	10.4
Lower Status Mean Dip Angle (º)	30.5	31	26.4
Standard Deviation	9.4	6.91	8.56
t-value	0.34	-1.32	-1.32
Degrees of Freedom	10.56	12.57	11.11
p value*	0.74	0.21	0.21
Effect Size	0.15	-0.61	-0.65
95% CI Effect Size	-0.74 to 1.04	-1.51 to 0.29	-1.55 to 0.26
Statistical Power	0.06	0.30	0.33
H_0	Not Rejected	Not Rejected	Not Rejected

There were no significant differences between the ORI or TCI values between social status groups in the St Bride's assemblage (Table 78).

Table 78: Results of Wilcoxon Rank Sum Tests assessing whether ORI and TCI values differed significantly between social status groups in the St Bride's assemblage. Data were not normally distributed so non-parametric testing was used (Shapiro Wilk test p<0.05). ***Null hypothesis: there were no significant differences in TCI and/or ORI values between lower and higher status inhumations at St Bride's crypt, London.***

Social Status	W	p-value	H_0
TCI	90	0.71	Not Rejected
ORI	84	0.54	Not Rejected

6.2.1.3.2 St Michael's Litten Chichester (ESC11)

Social status, suggested from burial type, had a significant impact on wear facet composition in the St Michael's Litten assemblage (Table 79 and Figure 145). Individuals from coffin burials exhibited significantly higher proportions of PII wear relative to the shroud burials (Table 80). The shroud 2a burials (purportedly the earliest in date; AD 1550-1700) occupied a position on the ternary plot close to the Mediaeval distribution, which supported their inclusion in the pre-Industrial group in the overall analysis. The tomb burials closely resemble the high-status individuals from St Bride's in their wear facet composition. Shroud 2b (with uncertain dating information) are overlapping with all the other shroud burial types.

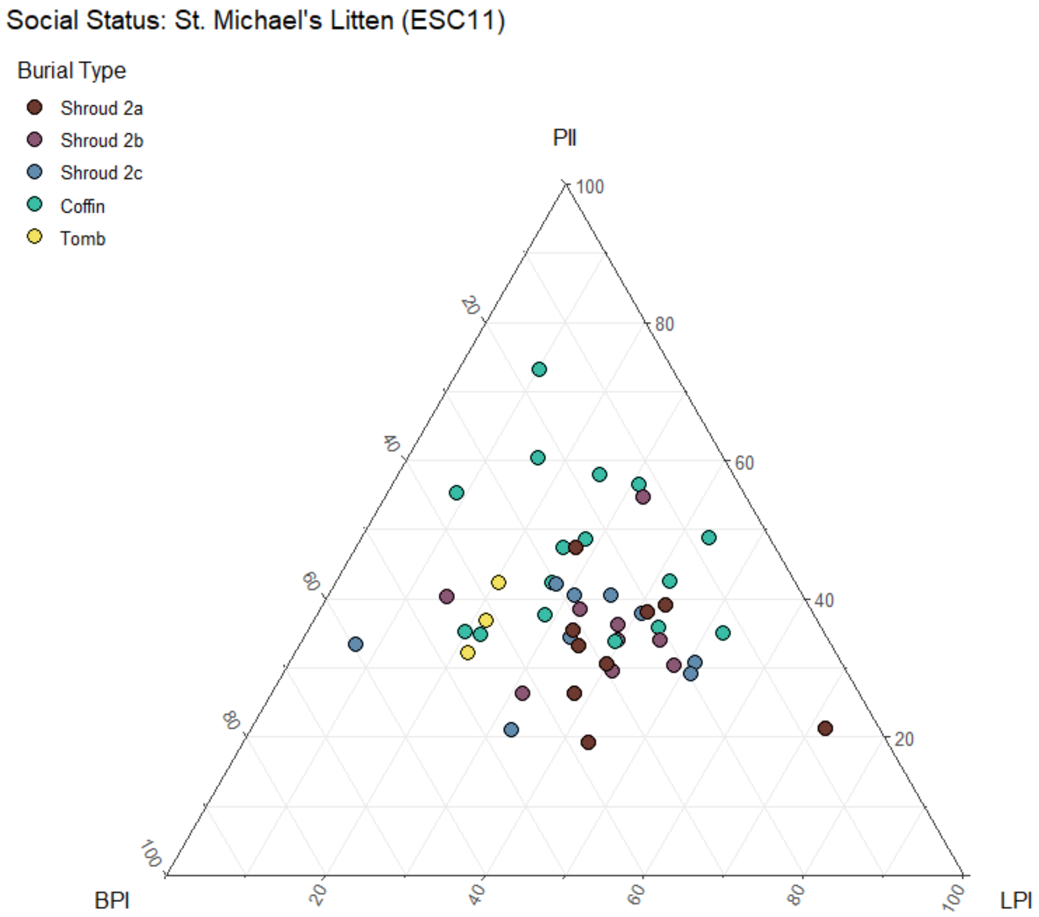


Figure 145: Ternary plot showing the relationship between burial type in the St Michael's Litten assemblage (ESC11) and wear facet area proportions of the lower second molar. Shroud 2a burials dated from approximately AD1550-1700 and shroud 2c burials from AD1700-1900. Shroud 2b burials were less precisely dated and range from AD1550-1900. These burials overlap with the other two types of shroud burial. The coffin and tomb burials date from AD1700-1900.

Table 79: Results of Type I PERMANOVA tests assessing the relationship between wear facet area proportion and burial type in the St Michael's Litten assemblage (ESC11). The variables assessed satisfied the homogeneity of multivariate dispersion assumption (Table 127). ***Null hypothesis: there was not a significant difference in the relative wear facet composition of the lower second molars of different burial types from the St Michael's Litten assemblage.***

Standard data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	**p-value (>F)**	**H_0**
Burial Type	0.21	0.05	4	2.48	0.02	Rejected
Residuals	0.82	0.02	38			
ILR data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	**p-value (>F)**	**H_0**
Burial Type	0.07	0.07	4	0.16	0.04	Rejected
Residuals	16.58	0.44	38			

Table 80: Result of pairwise post-hoc comparison of wear facet area proportions between burial types using the Bray-Curtis matrix transformed data. Only the comparison between shroud 2a and coffin burials approached significance.

	Coffin	Shroud 2a	Shroud 2b	Shroud 2c
Shroud 2a	0.06	-	-	-
Shroud 2b	0.16	0.65	-	-
Shroud 2c	0.16	0.54	0.97	-
Tomb	0.16	0.18	0.16	0.33

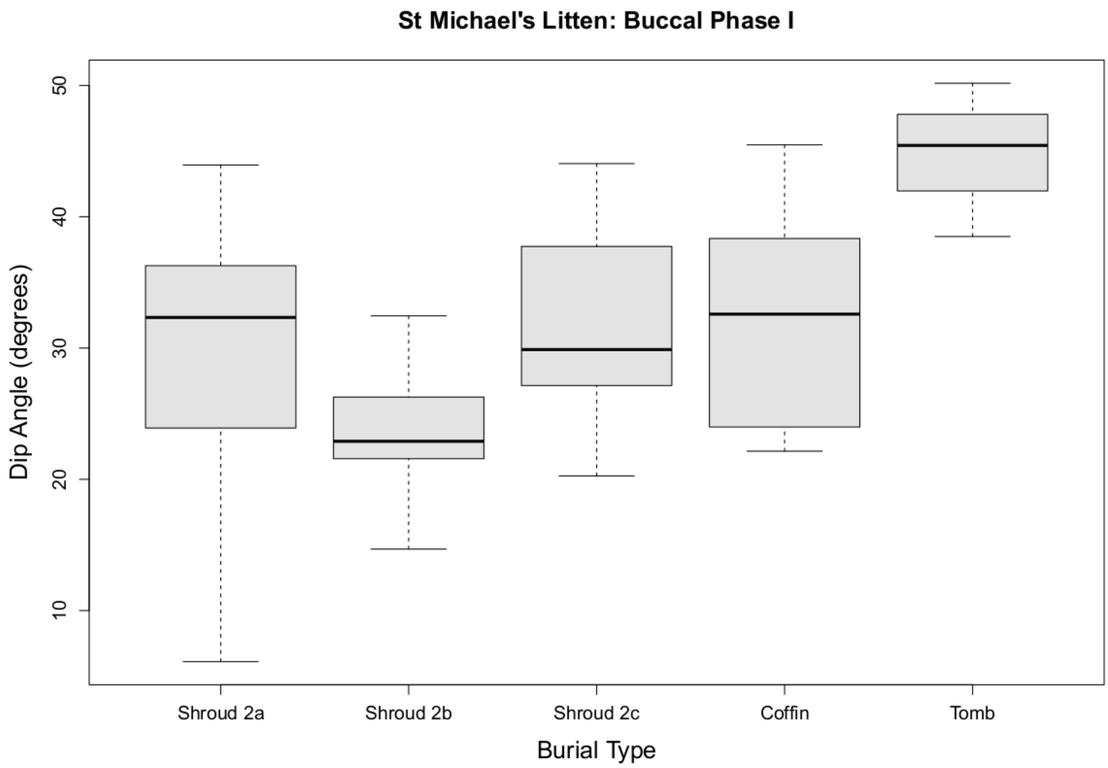
BPI and LPI dip angle differed significantly between burial types within the St Michael's Litten assemblage (Table 81). Post-hoc testing indicated that BPI and LPI dip angles were significantly steeper in the tomb burials than in the early Post-Mediaeval shroud burials (Table 82); a comparison between the earliest burials included from the assemblage (shroud 2a) and the latest (tomb). PII wear facet inclination did not differ significantly between burial types (Figure 146).

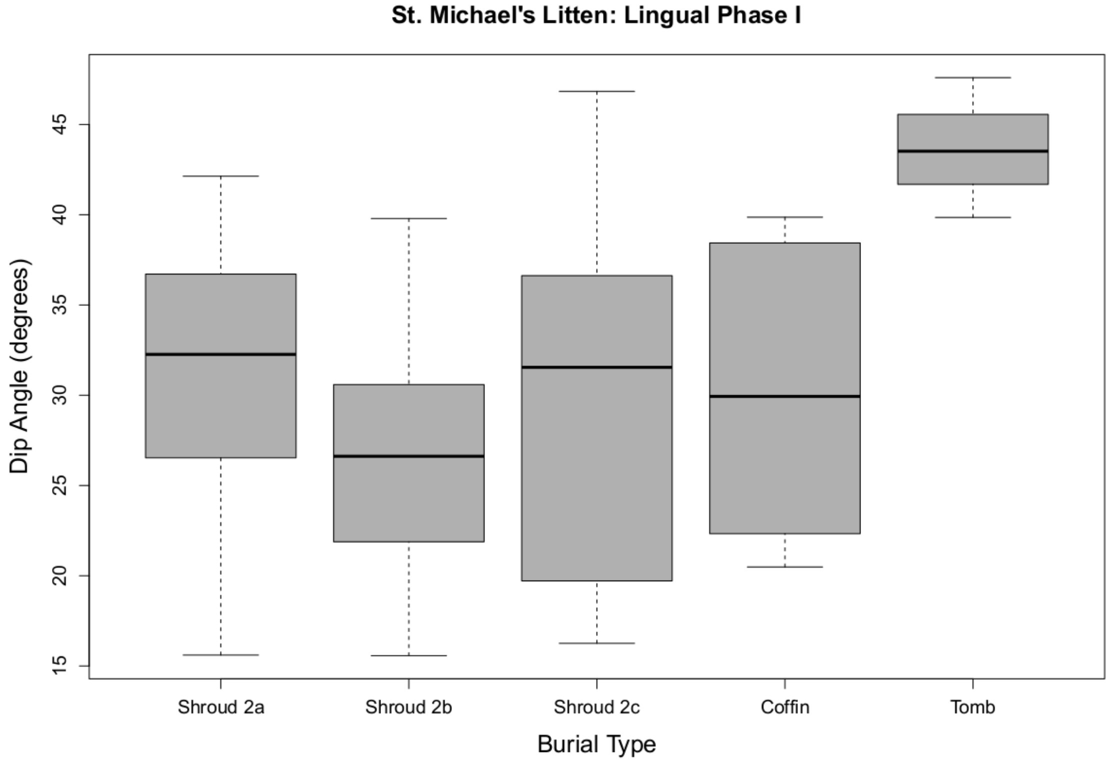
Table 81: Results of Kruskal-Wallis tests assessing the relationship between burial type and wear facet dip angle. The data were not normally distributed so non-parametric testing was used. ***Null hypothesis: dip angle values did not differ significantly between the burial types examined from the St Michael's Litten assemblage.***

ESC11 Burial Type	Kruskal-Wallis chi-squared (df)	df	p-value	H_0
Dip Angle BPI	10.96	4	0.03	**Rejected**
Dip Angle LPI	8.89	4	0.06	Rejected?
Dip Angle PII	3.30	4	0.51	Not Rejected

Table 82: Results of post-hoc Dunn pairwise comparisons found to be significant between burial types from the St Michael's Litten assemblage (p-values adjusted with the Benjamini-Hochberg method).

Dunn pairwise comparison	Z value	p-adjusted	H_0
BPI Tomb vs Shroud 2a	-3.17	0.01	**Rejected**
LPI Shroud 2a vs Tomb	-2.84	0.04	**Rejected**
LPI Shroud 2b vs Tomb	-2.63	0.04	**Rejected**





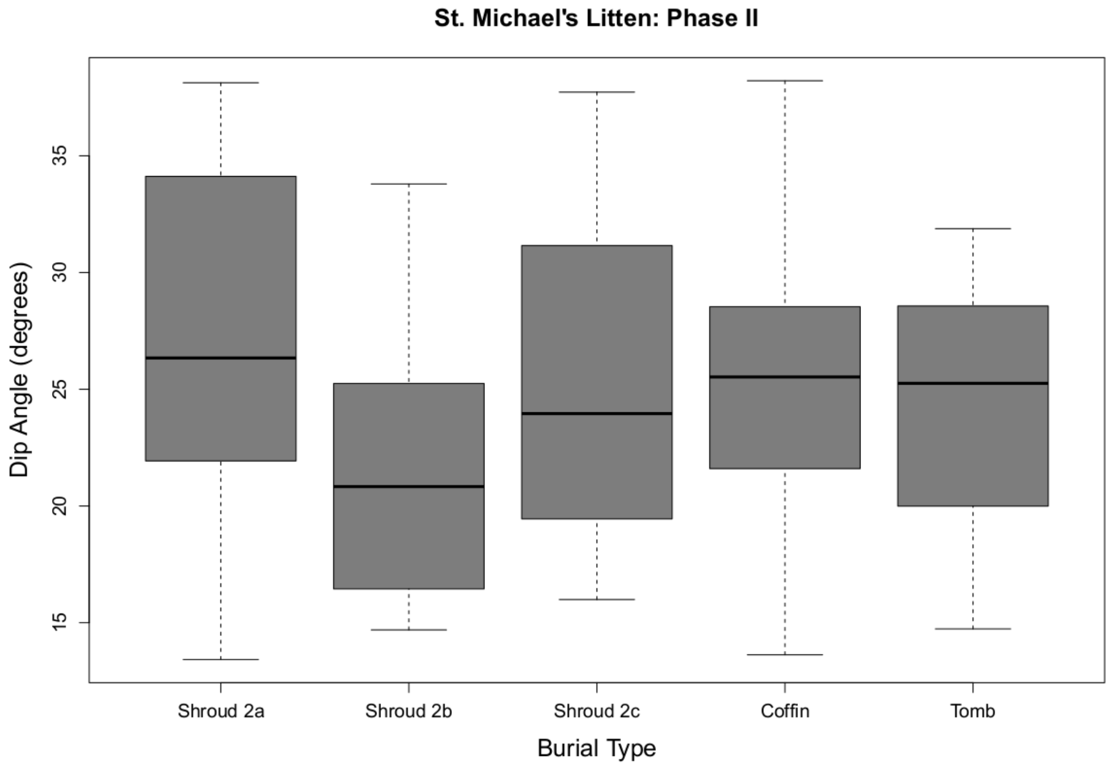


Figure 146: Box plots comparing dip angle values between burial types from the St Michael's Litten assemblage. The later burial groups exhibited steeper dip angles for BPI and LPI facets. Shroud 2a individuals had less steeply inclined PII wear facets when compared to all other burial types.

There were no significant differences in ORI or TCI in relation to burial type in the St Michael's Litten assemblage (Table 83). The lowest median ORI values and the highest TCI values were apparent in the early Post-Mediaeval shroud 2a burials, however (Figure 147). The coffin burials exhibited the lowest median TCI value.

Table 83: Results of Kruskal Wallis tests assessing the influence of burial type on ORI and TCI values in the St Michael's Litten assemblage (ESC11). ***Null hypothesis: burial type did not have a significant influence on either ORI or TCI values in the assemblage.*** *The data were not normally distributed so non-parametric testing was used.*

St Michael's Litten Burial Type	Kruskal-Wallis chi-squared (df)	DF	p-value	H_0
Occlusal Relied Index	5.82	4	0.21	Not Rejected
TCI	8.35	4	0.08	Rejected?

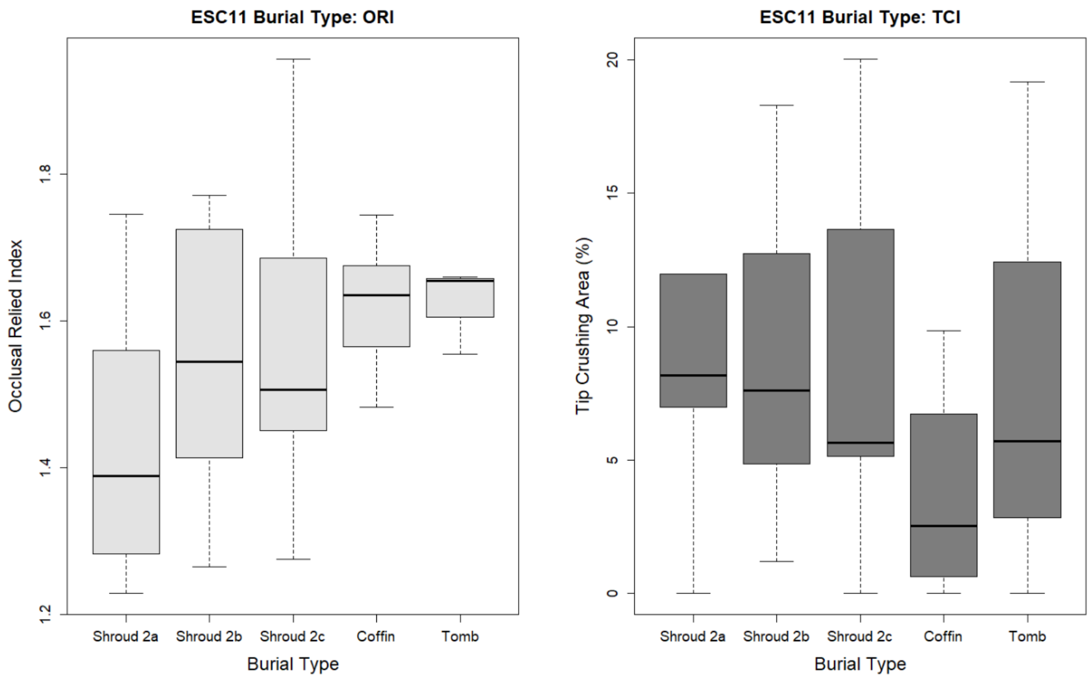


Figure 147: Boxplots showing the relationship between burial type and ORI values and burial type and TCI values in the St Michael's Litten assemblage (ESC11). Burial types are arranged chronologically along the x-axis and show a trend towards increasing ORI values and decreasing TCI value among the more recent burials.

6.2.1.3.3 Summary

In the St Michael's Litten assemblage, the coffin burials dating to the 18th-19th century differed significantly in wear facet area composition from the early Post-

Mediaeval shroud burials; coffin burials exhibited a significantly larger proportion of PII wear facet areas. The early Post-Mediaeval shroud burials had significantly more shallowly inclined BPI dip angles when compared to the 18^{th}-19^{th} century tomb burials. The shroud burials typically exhibited less steeply inclined wear facet dip angles than the later tomb and coffin burials. There was commonality in the wear facet area proportions of the high-status tomb burials at St Michael's Litten and the higher status individuals inhumed at St Bride's crypt.

At St Bride's, individuals from the higher social status group typically had greater proportions of their total wear facet area constituted by BPI facets. There were no significant differences in the obliqueness of wear facet inclination between high and low status burials.

6.2.1.4 More heavily processed white wheaten bread was taken up less rapidly in Northern England. Differences in wear facet expression would be expected if the composition of the staple food items consumed differed markedly between the north and south of England.

Wear facet area composition did not differ significantly between the Industrial sites examined and did not show a marked delineation between assemblages from different regions in England (Table 84 and 85; Figure 148). There was a slight trend towards greater proportions of PII wear in the more southerly situated assemblages, St Bride's and St Michael's Litten.

Table 84: Table showing the centre values for BPI, LPI and PII wear facet areas according to site for the Industrial period.

Site	Region	BPI	LPI	PII	Total variance	Metric standard deviation
St Peter's (StP)	Midlands	26.92	36.50	36.58	0.35	0.42
Coronation Street (CS06)	North	25.31	38.45	36.23	0.69	0.59
St Bride's (SB79)	South	24.66	34.62	40.72	0.40	0.44
St Michael's Litten, Chichester (Late) (ESC11)	South	27.57	29.02	43.41	0.48	0.49

Table 85: Results of PERMANOVA used to assess differences in wear facet area composition among the Industrial assemblages examined. ***Null hypothesis: the wear facet area composition did not differ significantly between the Industrial era assemblages examined.***

Standard data	Sum of Squares	Mean of Squares	DF	F	R^2	p-value (>F)	H_0
Site	0.19	0.03	3	1.72	0.05	0.12	Not Rejected
Residuals	2.27	0.02	99				
Total	2.39		102				
ILR data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	R^2	**p-value (>F)**	H_0
Site	2.08	0.70	3	1.43	0.04	0.20	Not Rejected
Residuals	48.28	0.49	99				
Total	50.37		102				

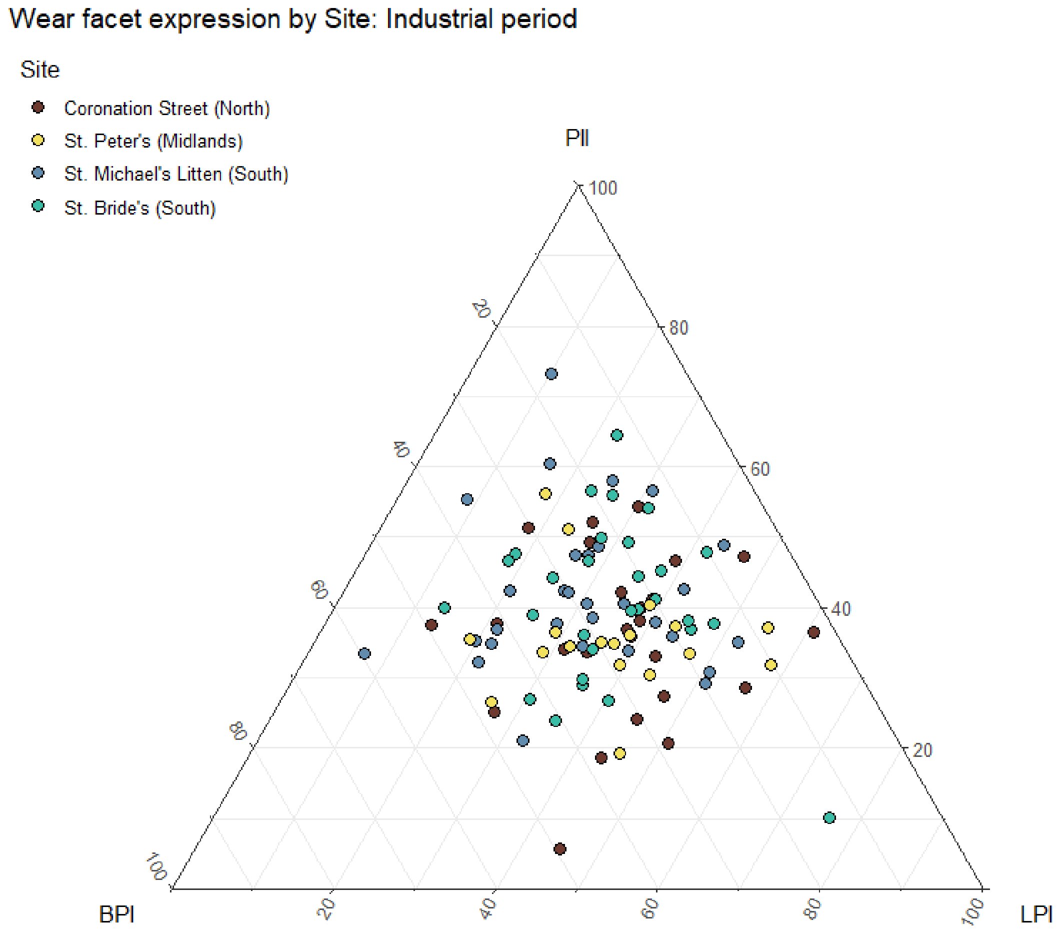


Figure 148: Ternary plot showing the variability in wear facet area proportions between the assemblages examined dating to the Industrial period. There was considerable overlap between the lower second molar wear patterns exhibited by assemblages from different regions of England.

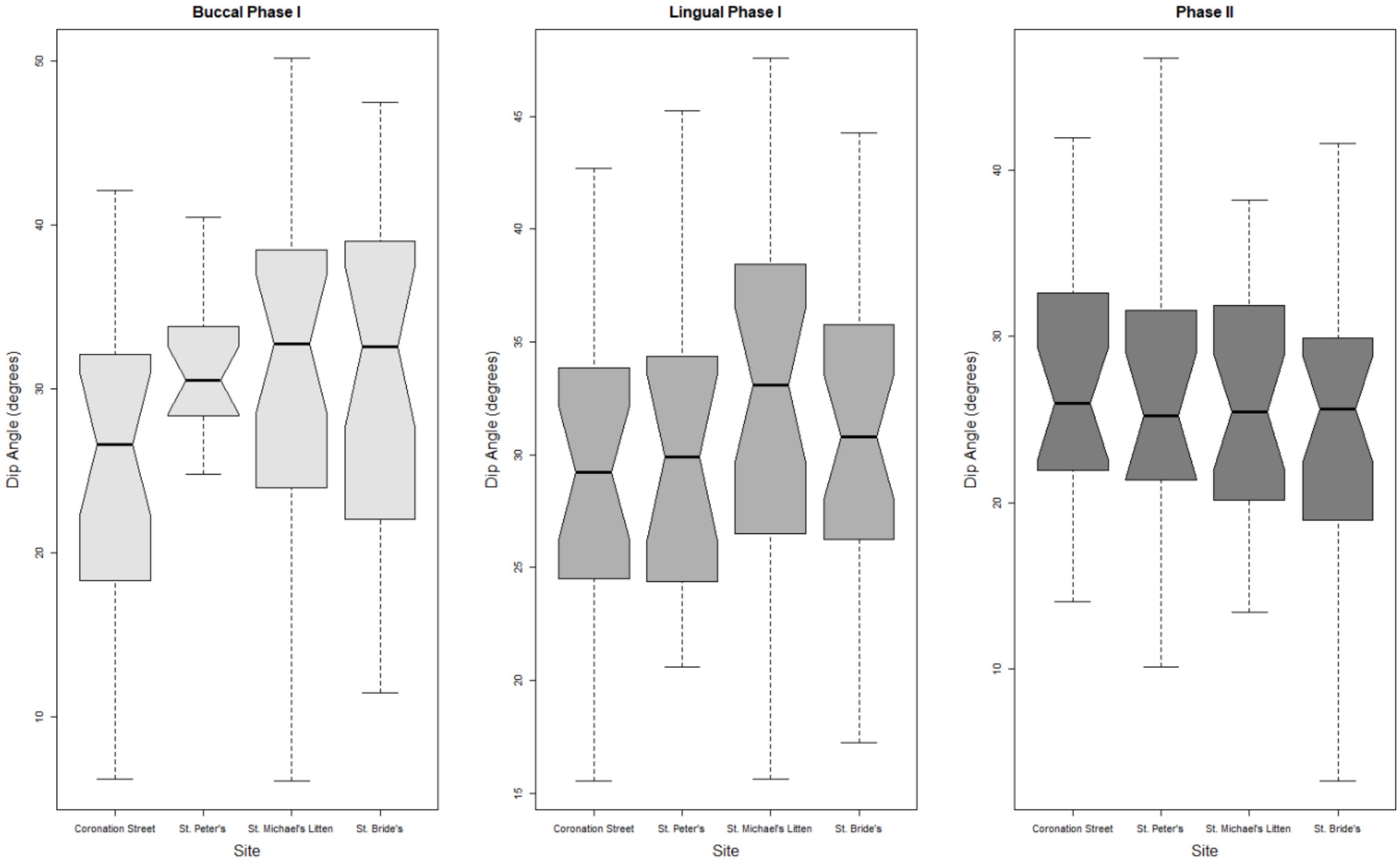


Figure 149: Boxplots comparing dip angle values for BPI, LPI and PII wear facets between the Industrial assemblages examined.

BPI, LPI and PII dip angle values did not differ significantly between the sites examined (Figure 149 and Table 86). The two southern assemblages had marginally more obliquely inclined BPI and LPI facets, however. The Coronation Street assemblage had more shallowly inclined BPI facets. The median inclination of PII wear facets did not differ markedly between the four assemblages.

Table 86: Results of Kruskal-Wallis tests assessing whether wear facet dip angles differed significantly between the assemblages. The data were not normally distributed (Shapiro Wilk test $p<0.05$). ***Null hypothesis: dip angle values did not differ significantly between the Industrial era assemblages examined.***

Wear Facet Type	Kruskal-Wallis chi-squared (df)	df	p-value	H_0
BPI	6.08	3	0.11	Not Rejected
LPI	3.17	3	0.37	Not Rejected
PII	0.54	3	0.91	Not Rejected

ORI did not differ significantly between the sites (Kruskal Wallis test chi-squared=4.88, df = 3, p-value = 0.18). The TCI differed significantly between the Industrial-era sites examined (Figure 150 and Table 87). The Coronation Street assemblage differed significantly from the St Michael's Litten assemblage and the St Bride's assemblage. Tip crushing areas equalled a larger proportion of the cross-sectional area of the tooth crown in the Coronation Street assemblage. Tip crushing proportions were slightly larger in the St Peter's assemblage than the St Michael's Litten (ESC11) and St Bride's (SB79) assemblages (Table 88).

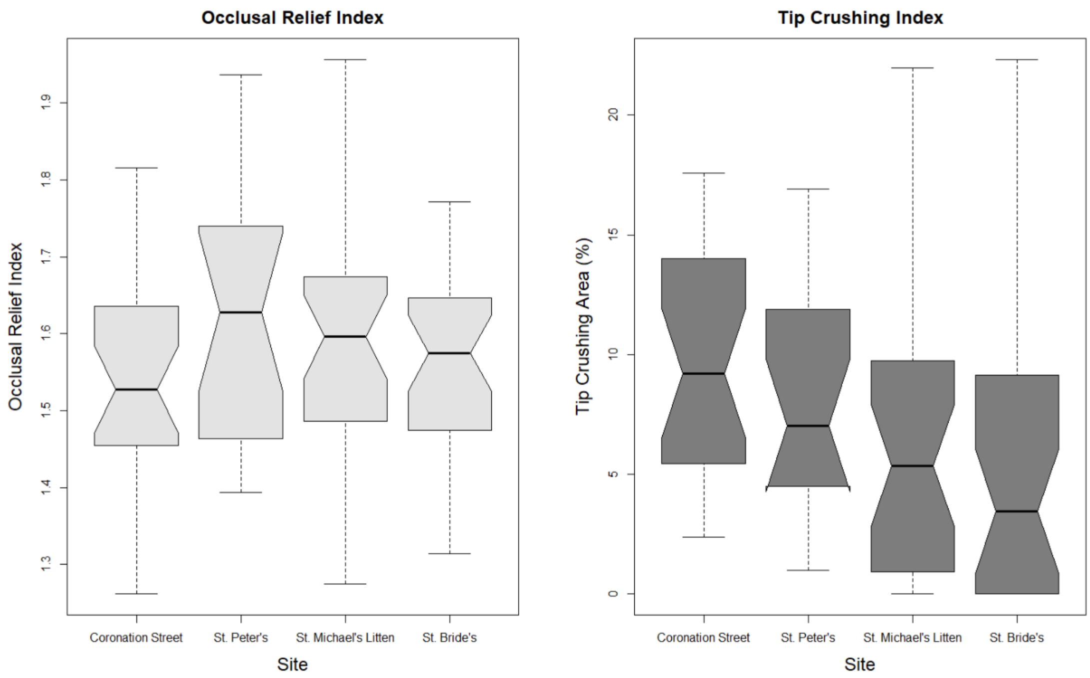


Figure 150: Boxplots comparing the occlusal relief indices (ORI) and tip crushing indices (TCI) between the Industrial assemblages examined. The data were not normally distributed (Shapiro Wilk p<0.05), therefore, non-parametric testing was used.

Table 87: Results of Kruskal-Wallis test assessing the relationship between site, ORI and TCI. ***Null hypothesis: ORI and/or TCI values did not differ significantly between the Industrial assemblages examined.***

Kruskal-Wallis Test	**Chi-squared**	**df**	**p-value**	**H_0**
ORI	4.88	3	0.18	Not Rejected
TCI	10.45	3	0.015	Rejected

Table 88: Results of pairwise comparisons using Wilcoxon rank sum tests to determine which sites differed significantly in their TCI values.

Post-hoc testing of TCI values by Site	**Coronation Street**	**St Michael's Litten**	**St Bride's**
St Michael's Litten	0.04	-	-
St Bride's	0.04	0.56	-
St Peter's	0.35	0.18	0.16

6.2.1.4.1 Summary

Wear facet area composition of the lower second molar did not differ significantly between Industrial-era assemblages from different regions of England. BPI and LPI facet dip angles were slightly more obliquely inclined in the assemblages from

Southern England. More well-developed tip crushing areas were apparent in the Coronation Street assemblage when compared to the assemblages from Southern England.

6.2.1.5 Habitual clay pipe use creates distinctive wear facets on the anterior teeth and premolars. It is expected that these will be accompanied by differences in molar wear facet expression.

Pipe facets were significantly more common in the Coronation Street assemblage than any of the other Industrial assemblages examined (Chi-Squared test; X-squared=13.78, p-value = 0.009) (Table 89). Pipe facets were commonly bilateral in the Coronation Street assemblage. The identification of facets unilaterally in several individuals from Coronation Street was likely due to the preservation of only one side of the dentition in these individuals. Pipe use was associated with significantly greater ante-mortem tooth loss (Figure 151; Wilcoxon rank sum test W=471; p=0.005).

Table 89: The distribution of pipe facets in the assemblages examined.

Site	Absent	Bilateral	Unilateral Left	Unilateral Right	Overall Prevalence (95% CI)
St Michael's Litten	48	0	1	2	5.9 2.0 to 15.9
Coronation Street	14	5	5	0	41.7 24.5 to 61.2
St Bride's	30	0	1	1	6.3 1.7 to 20.1
St Peter's	15	2	0	0	11.8 3.3 to 34.3

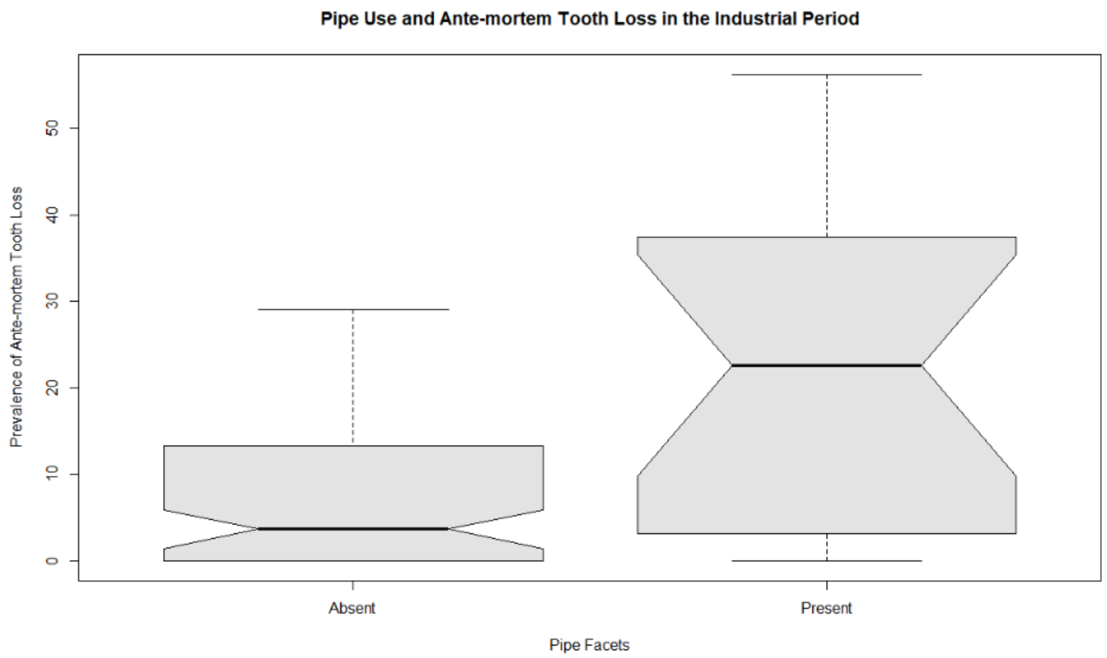


Figure 151: Boxplot showing the relationship between pipe use and the proportion of teeth lost ante-mortem in the Industrial assemblages examined. Prevalence of ante-mortem tooth loss for each individual was the number of tooth sites at which there was evidence for ante-mortem tooth loss expressed as a proportion of the total number of tooth sites that could be assessed. The data were not normally distributed (Shapiro Wilk test; $p<0.05$), therefore, non-parametric testing was used to perform the statistical comparison.

The Coronation Street assemblage provided an appropriate assemblage to compare lower second molar dental wear patterns between individuals with and without evidence of pipe use as the assemblage presented a high frequency of individuals possessing dental evidence consistent with pipe use. The presence of pipe facets in the Coronation Street assemblage was not associated with significant differences in dental wear facet proportions when compared with individuals in the assemblage without evidence of pipe use (Figure 152; Table 90 and Table 129). Despite this, there was a slight tendency for individuals with evidence of pipe use to exhibit enlarged LPI and PII wear facet areas.

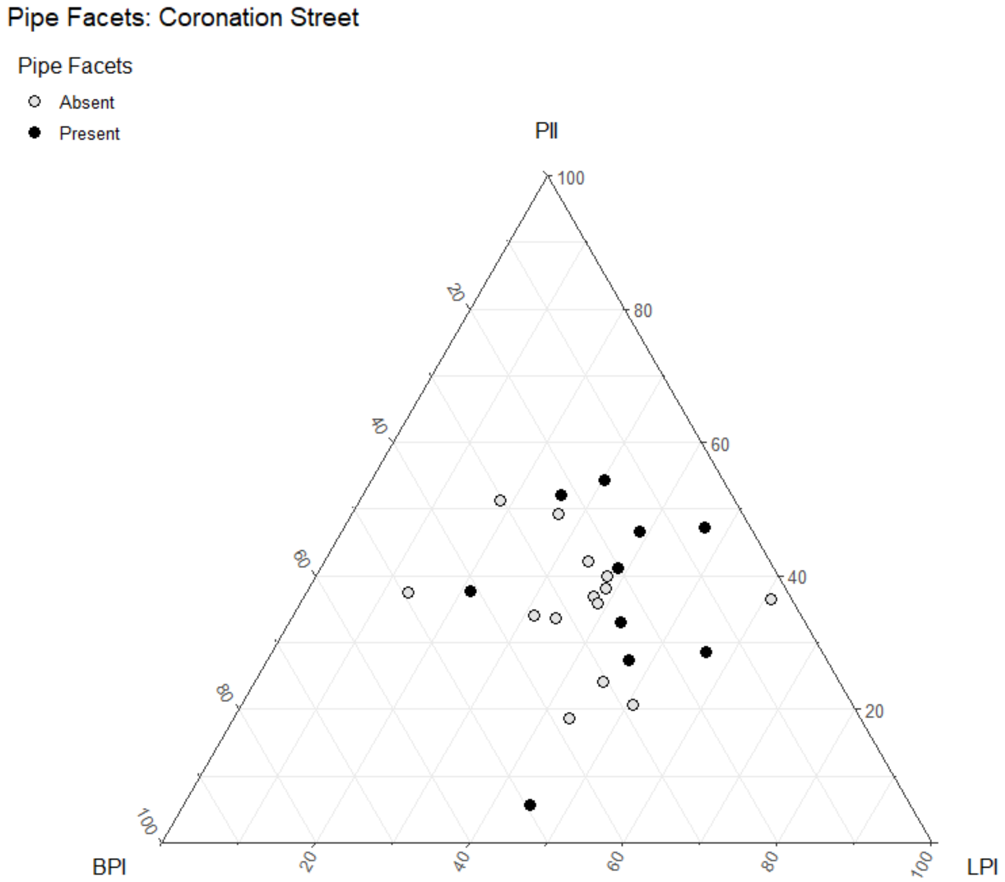
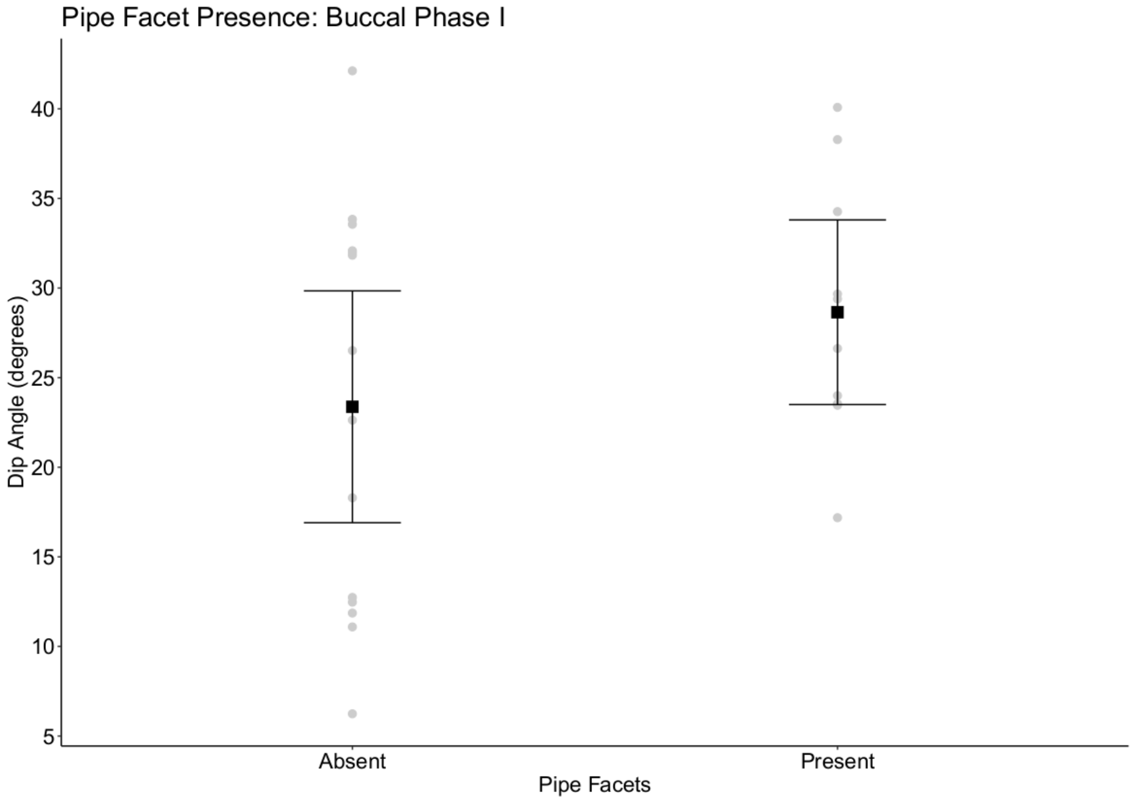


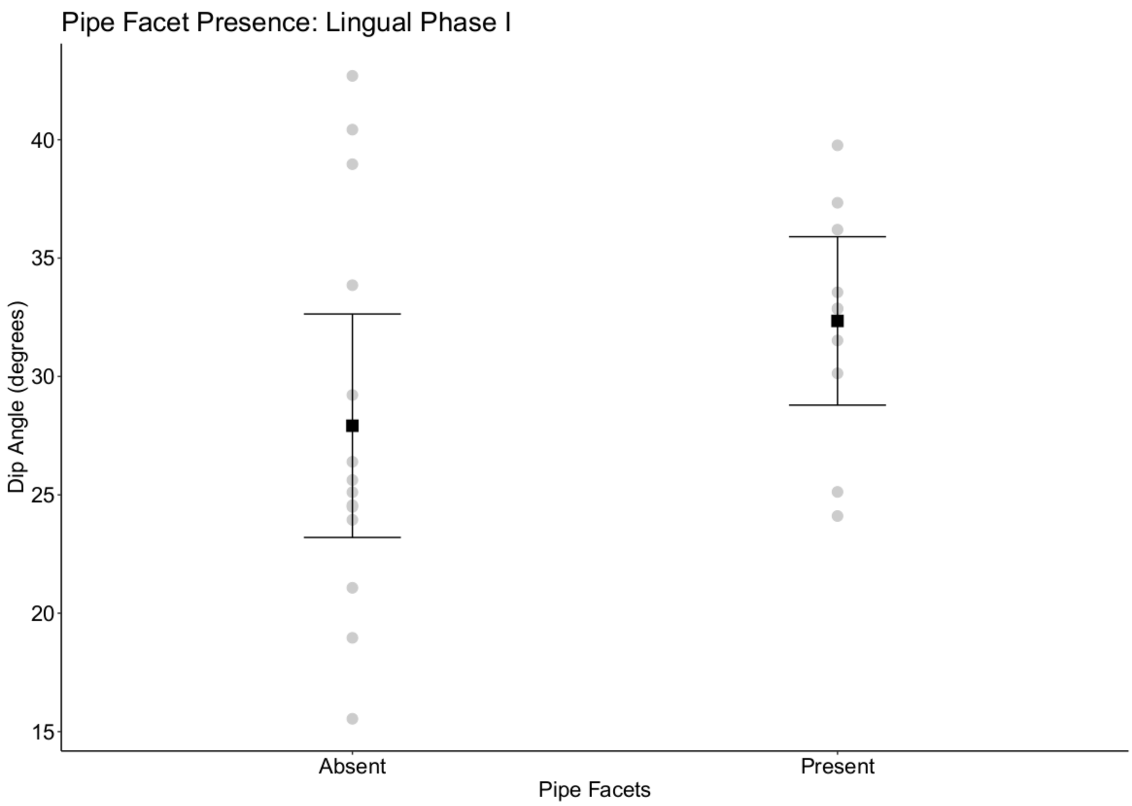
Figure 152: Ternary plot comparing relative wear facet areas of the lower second molars between individuals with and without pipe facets in the Coronation Street assemblage.

*Table 90: Results of PERMANOVA tests applied to the Coronation Street assemblage to determine whether pipe use significantly influenced wear facet area proportions. **Null hypothesis: the presence of pipe facets was not associated with significant differences in wear facet area proportions in the Coronation Street assemblage.** The homogeneity of multivariate dispersion assumption was not violated (Table 129).*

Standard data	**Sum Squares**	**Mean Squares**	**Degrees of Freedom**	**F**	**p-value (>F)**	**H₀**
Pipe Facet Presence	0.01	0.01	1	0.22	0.84	Not Rejected
Residuals	0.44	0.03	14			
ILR data	**Sum Squares**	**Mean Squares**	**Degrees of Freedom**	**F**	**p-value(>F)**	**H₀**
Pipe Facet Presence	0.03	0.03	1	0.03	0.97	Not Rejected
Residuals	13.80	0.99	14			

The presence of pipe facets was not associated with any significant differences in dip angle in the Coronation Street assemblage (Figure 153 and Table 91).





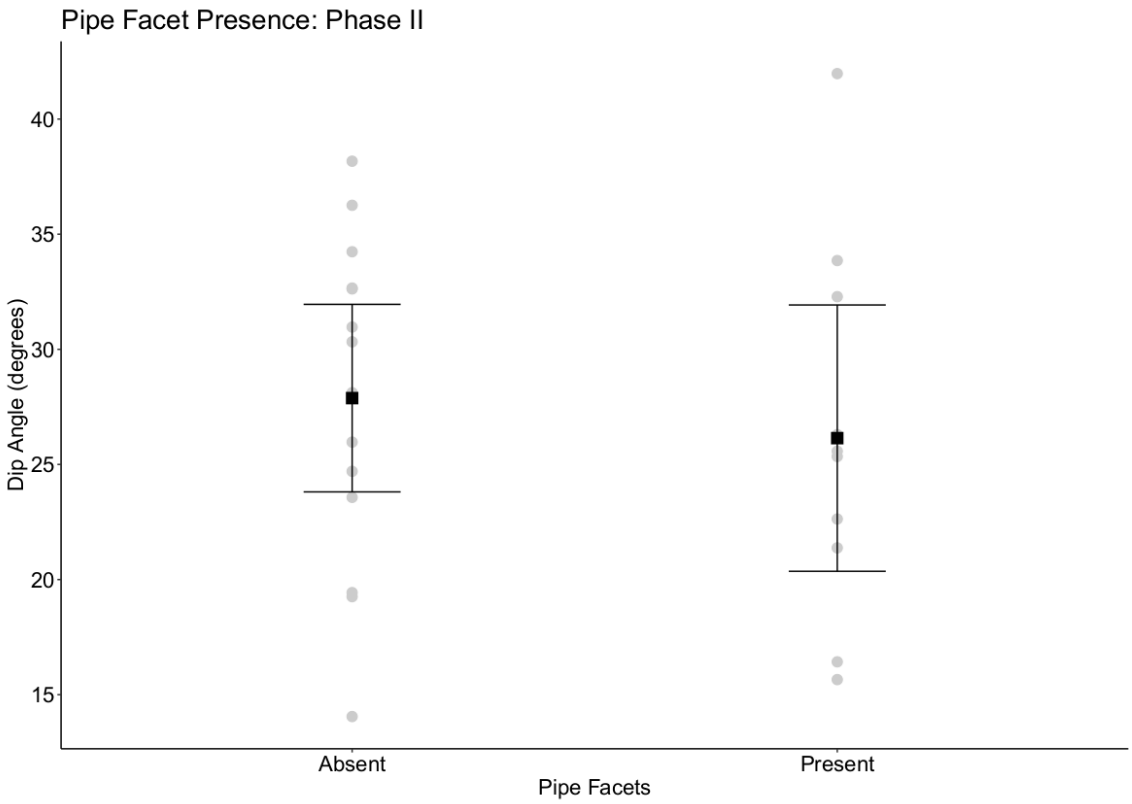


Figure 153: Dot plots comparing the distribution of dip angle values for BPI, LPI and PII wear facets for individuals with and without pipe facets from the Coronation Street assemblage. Mean values are plotted as black squares with 95% confidence intervals.

Table 91: Results of independent sample t-tests comparing the influence of pipe use on wear facet dip angles in the Coronation Street assemblage. ***Null hypothesis: pipe use did not significantly influence wear facet dip angles in the Coronation Street assemblage.***

Wear Facet Type	BPI	LPI	PII
Pipe Facet Present: Mean Dip Angle(°)	27.58	31.92	26.53
Standard Deviation	11.43	10.13	8.07
Pipe Facet Absent: Mean Dip Angle(°)	26.45	29.01	28.49
Standard Deviation	6.74	5.07	8.48
t-value	-0.26	-0.77	0.5
Degrees of Freedom	12.96	11.78	15.96
p value*	0.80	0.46	0.63
Effect size	-0.12	-0.36	0.24
95% CI Effect Size	-1.12 to 0.88	-1.36 to 0.64	-0.77 to 1.24
Statistical Power	0.06	0.11	0.08
H_0	Not Rejected	Not Rejected	Not Rejected

ORI values were slightly reduced among the individuals with pipe facets and tip crushing areas were typically marginally larger (Figure 154). ORI and TCI did not differ significantly between individuals with and without pipe facets (Table 92).

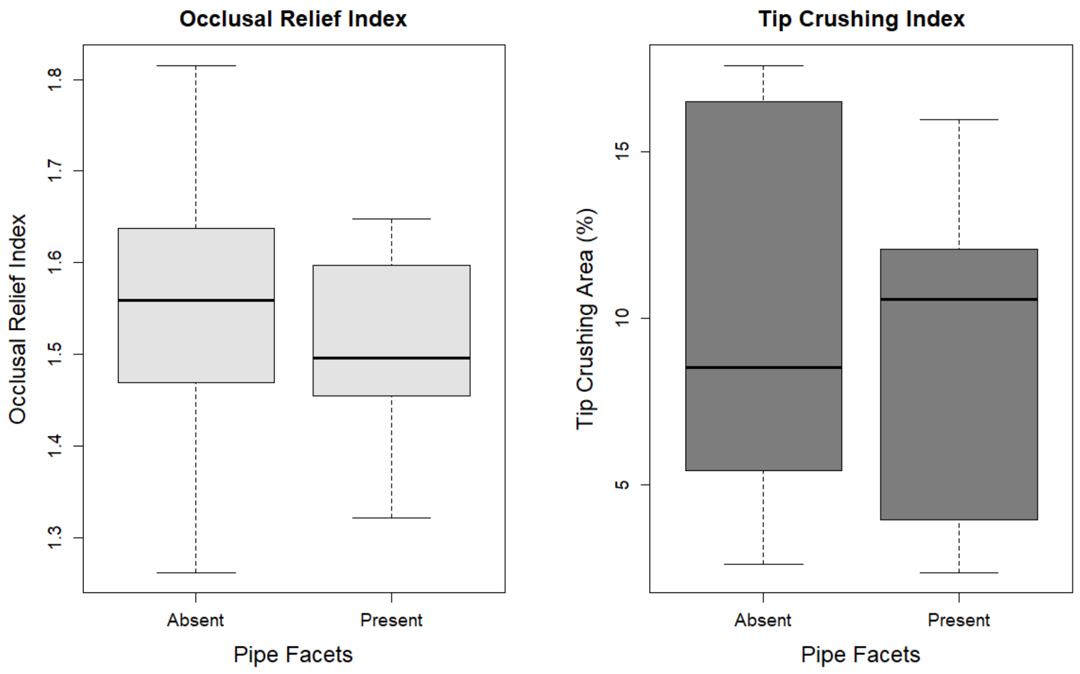


Figure 154: Boxplots comparing the distribution of ORI and TCI values between individuals with and without pipe facets in the Coronation Street assemblage.

Table 92: Results of Wilcoxon rank sum tests assessing the effect of pipe use on ORI values and TCI values. Non-parametric testing was used as the data were not normally distributed (Shapiro Wilk p<0.05). ***Null hypothesis: pipe use did not significantly influence ORI and/or TCI values in the Coronation street assemblage.***

Wear parameter	W	p-value	H_0
ORI	47	0.60	Not Rejected
TCI	52	0.34	Not Rejected

6.2.1.5.1 Summary

Pipe use did not significantly impact dental wear facet expression in the Coronation Street assemblage either in terms of relative wear facet area or inclination. ORI and TCI values also did not differ significantly between individuals with evidence for pipe use and those without. Ante-mortem tooth loss was significantly greater in individuals with pipe facets in the Industrial period.

6.2.1.6 Dental wear facets attest to the occlusal relationship between opposing molar rows. Malocclusion in the posterior dentition should be identifiable by reconstructing the relationships between antagonistic molar rows using OFA.

6.2.1.6.1 Prevalence of crossbites

The prevalence of crossbites did not differ significantly between periods using the operational definitions defined in the methods section (Table 93). A slightly higher prevalence rate of anterior crossbites was apparent in the Industrial period, however, confidence intervals for the two periods were overlapping (Figure 155).

Table 93: Results of chi-squared test assessing whether crossbite prevalence differed significantly in relation to period. P-values were obtained using Monte-Carlo simulation (replicates=10,000). ***Null hypothesis: the prevalence of crossbites did not differ significantly between the two periods.***

Type of Crossbite	X-Squared	p-value	H_0
Anterior Crossbite	2.17	0.22	Not Rejected
Canine Crossbite	0.05	1.00	Not Rejected
Posterior Crossbite	1.80	0.31	Not Rejected

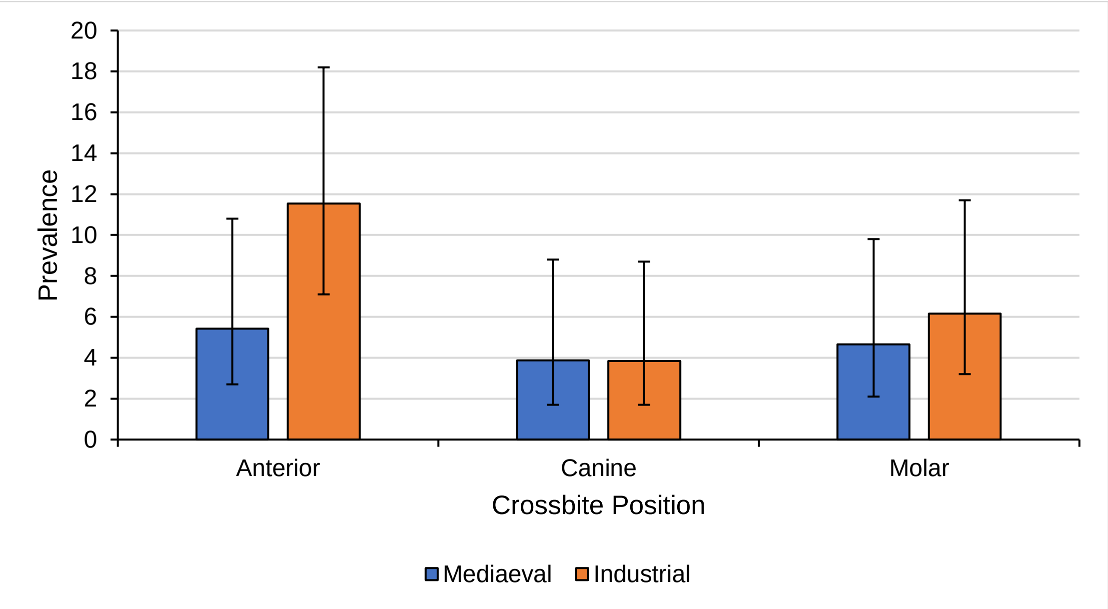


Figure 155: Bar chart showing the prevalence of crossbites in the anterior, canine and molar region for each period. 95% confidence intervals are given as error bars. All error bars were overlapping indicating a lack of marked differences in crossbite prevalence between the two periods.

6.2.1.6.2 The effect of anterior crossbites on dental wear facet expression.

Individuals with anterior crossbites did not differ significantly in lower second molar wear facet area composition from the overall assemblage in either period

(Table 130 to Table 133). As such, they were included in the main analysis of the effect of period on wear facet area (Section 6.1.2.2). Lower second molar wear facet dip angles also did not differ significantly between individuals with and without anterior crossbites in either the pre-Industrial or Industrial group (independent sample t-test $p>0.05$; Table 134 and Table 135). Consequently, these groups were not separated in the overall analysis of dip angle (Section 6.1.2.3).

6.2.1.6.3 Occlusal Variability and Power Stroke Simulations

Two individuals with interarch occlusal variability were identified who satisfied the operational definition used to identify posterior crossbites. These individuals were selected to highlight the utility of OFA in confirming the presence of occlusal variability by reconstructing occlusal relationships and an individual's power stroke.

6.2.1.6.3.1 Posterior Crossbite: St Michael's Litten (ESC11 Late phase): SK1986 (Video 9)

The sex of SK1986 was estimated as male. They were assigned to the older skeletal age category (Auricular surface score 12) and they were buried in a coffin (with a burial date of approximately 1700-1900AD). Molar wear was moderate. Cavitated carious lesions were present on the upper left second molar, the lower right fourth premolar and first molar. The left lower first molar and upper left first molar had been lost ante-mortem. There was a large cavitated carious lesion involving the upper right fourth premolar. There was some minor rotation/displacement of the anterior teeth. A power stroke simulation was performed for both the left and right sides of the dentition.

Sk1986 exhibited a unilateral posterior crossbite on the left side of the dentition in which the transverse relationship between the upper and lower second molars could be characterised as a lingual crossbite when the teeth were placed in maximum intercuspation (Figure 156 and Figure 157). The buccal slopes of the paracone and metacone of the upper second molar occluded with the lingual slopes of the protoconid and hypoconid of the lower second molar. The lingual slopes of the paracone and metacone were in contact with the buccal slopes of the metaconid and entoconid when in maximum intercuspation. Contacts were present between the lingual aspect of the metaconid and entoconid and the buccal aspect of the protocone and hypocone. The ORI of the lower second molar was 1.42. The wear facet pattern comprised 25% LPI, 46% PII and 29% facets associated with the crossbite.

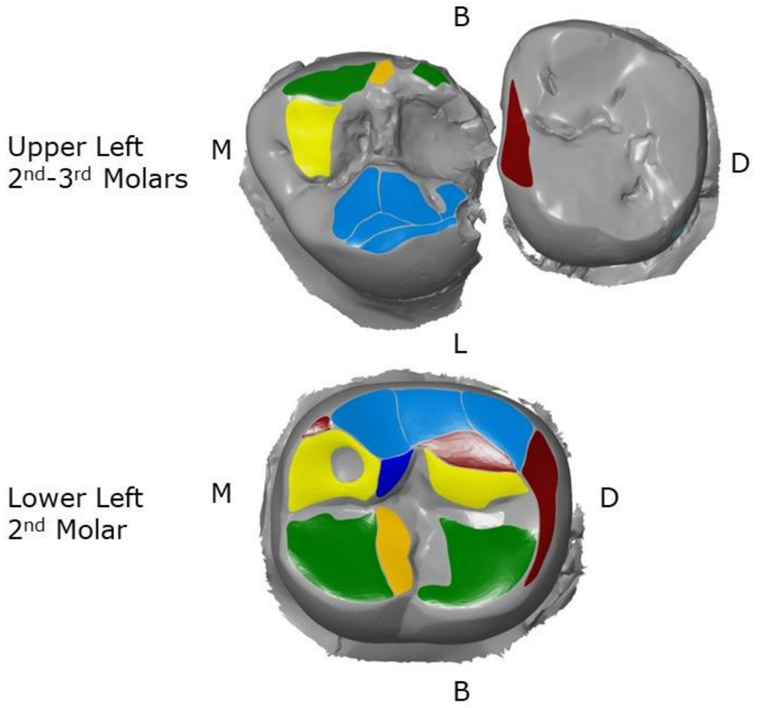


Figure 156: Wear facet map for the left molars of Sk1986. Lateroprotrusive facets are coloured yellow, lateroretrusive facets are blue, medioprotrusive facets are orange and mediotrusive facets are green. Wear facets associated with the posterior crossbite are coloured cyan and tip crushing facets are coloured brown. A large cavitated carious lesion involving the occlusal surface was present on the upper left second molar. This obscured part of the wear pattern, particularly across the distal portion of the crown.

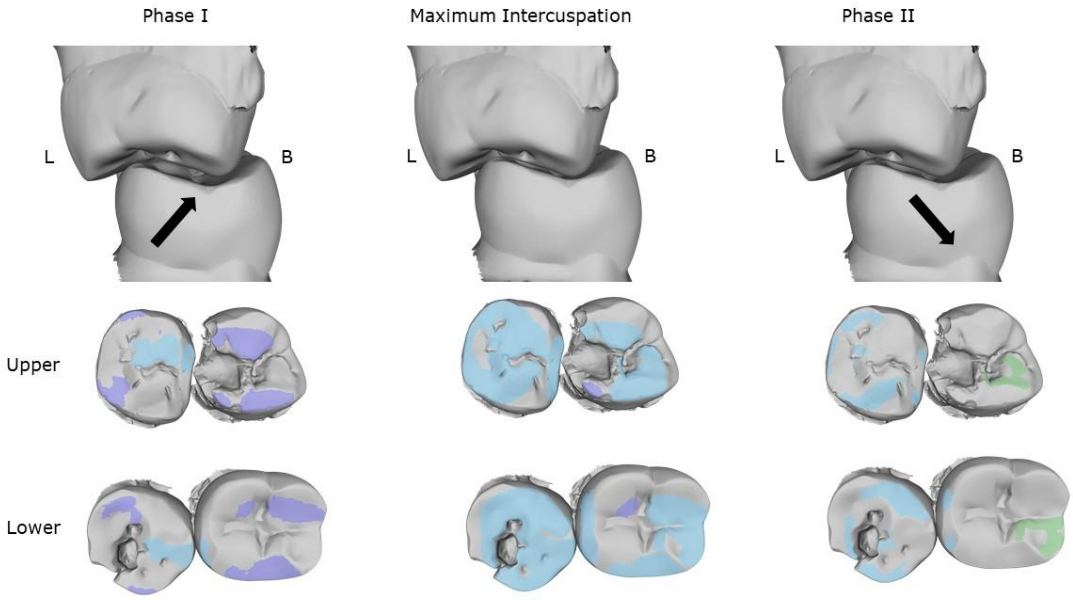


Figure 157: Mesial view of the power stroke simulation of the left molar row of SK1986. The lower molars moved from a lingual position into maximum intercuspation. A slight lateral shift brought the lower molars out of maximum intercuspation. The lingual and buccal sides of each diagram are indicated by L and B respectively. The lower diagram shows the distribution of contact areas during the power stroke simulation at each key stage of the power stroke: maximum phase I contact area, maximum intercuspation and maximum phase II contact area.

The power stroke proceeded along a lingual-buccal axis as the lower molars deviated medially during jaw closing and slightly laterally during jaw opening (Figure 157 to Figure 159). This is consistent with the reversed power stroke described in section 3.7.4. During the power stroke simulation, the crossbite facets and the phase II facets came into contact during phase I. In the reversed power stroke, they were analogous with BPI and LPI facets, respectively, in a normal power stroke. LPI facets came into contact prior to maximum intercuspation and remained in contact during an extremely brief phase II movement in which the lower molars moved laterally. There was dentine exposure in the centre of facet 7 on the lower left second molar. This facet was in contact for the majority of timesteps during the power stroke simulation.

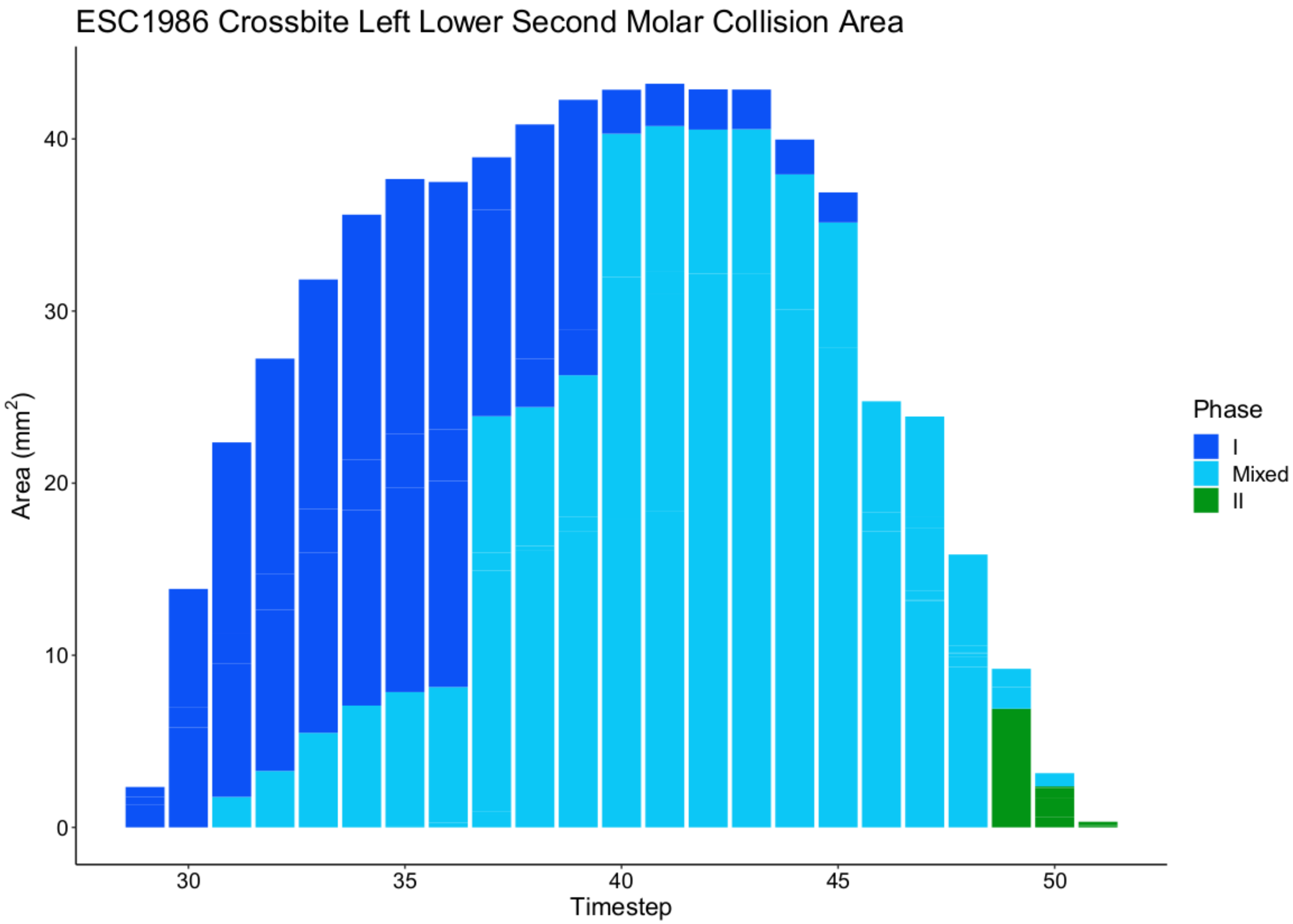


Figure 158: Stacked bar chart showing the development of collision areas during the power stroke simulation for SK1986 performed for the left side of the dentition. As the chewing cycle was reversed in this individual, phase I of the power stroke involved a rapid increase in contact areas involving phase II and crossbite facet areas (located on the lingual aspect of the metaconid and entoconid). Prior to maximum intercuspation lingual phase I facet areas also came into contact. Contact was lost rapidly following maximum intercuspation. The phase II movement was very limited as the teeth moved out of maximum intercuspation with only minor contact retained on facet 7.

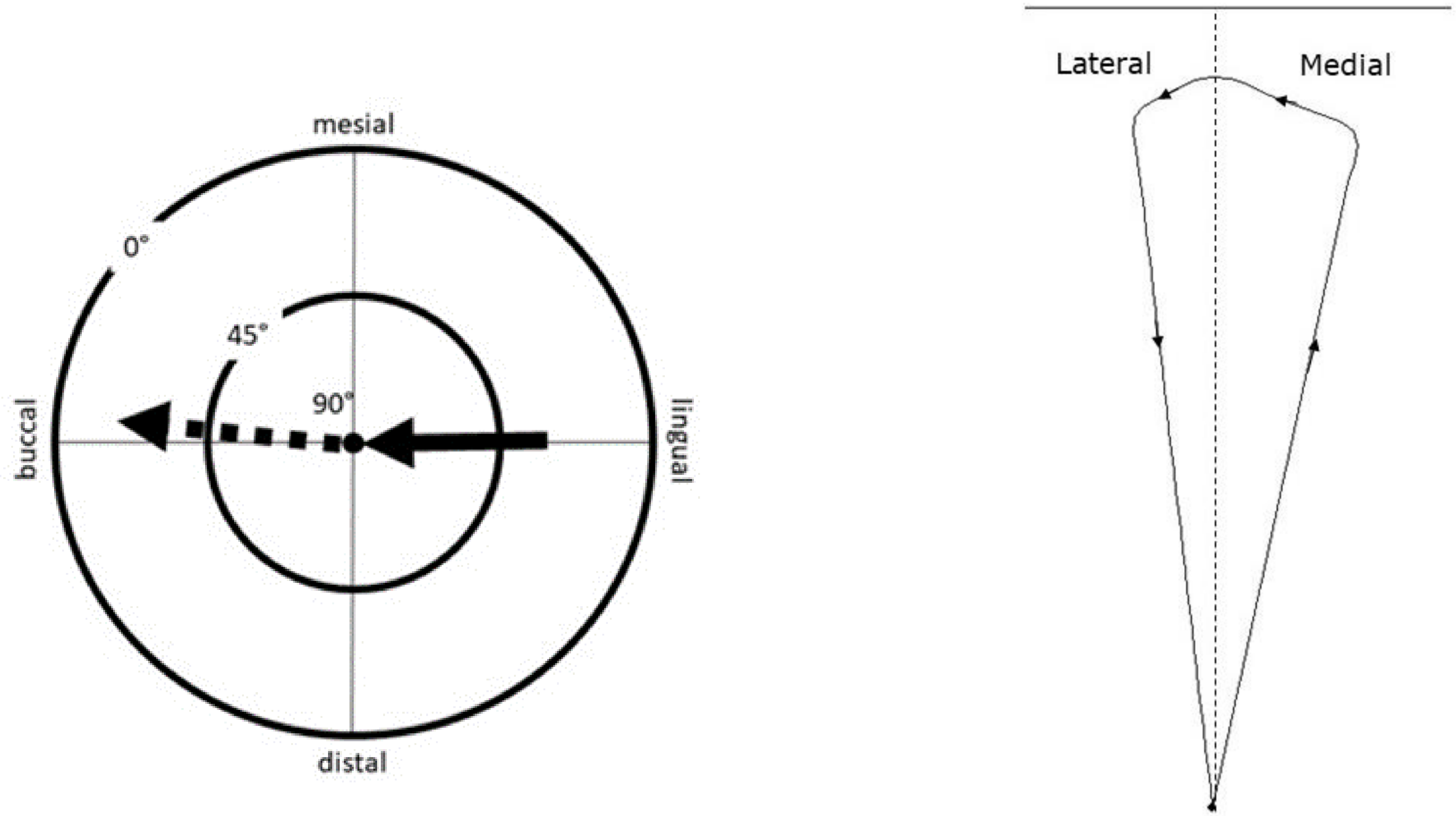


Figure 159: Visualisation of the power stroke of SK1986. Mastication compass (left) showing the orientation and inclination of phase I (bold arrow) and phase II (dashed arrow) of the power stroke. The projection of the trajectory of movement of the chewing stroke simulation onto the frontal plane conducted using the Occlusal Fingerprint Analyser package are presented on the right. The power stroke is characterised by a reverse pattern in which the lower teeth deviate medially during jaw closing and jaw opening involves a slight lateral component.

The power stroke simulation for the right side of the dentition of ESC1986 appeared to exhibit a normal chewing cycle (Video 18). The trajectory of the power stroke was bucco-lingually orientated. During jaw closing, the lower molars moved from a lateral position into maximum intercuspation. Contact on the metaconid was very limited. From maximum intercuspation, the lower teeth continued to move medially following an inclination of movement that was shallower than that observed during phase I of the power stroke (Figure 160 to Figure 162).

The transversal relationship between the right second molars in maximum intercuspation involved a very slight lingual shift of the upper molar (Figure 162). This resulted in limited development of BPI facets in this individual (15% of the total facet area) (Figure 163). LPI (44%) and PII (41%) wear facets constituted most of the total wear facet area (Figure 163). The ORI of the right side was slightly greater than the left (1.52) and likely reflects the less advanced wear on the lingual cusps when compared to the left antimere.

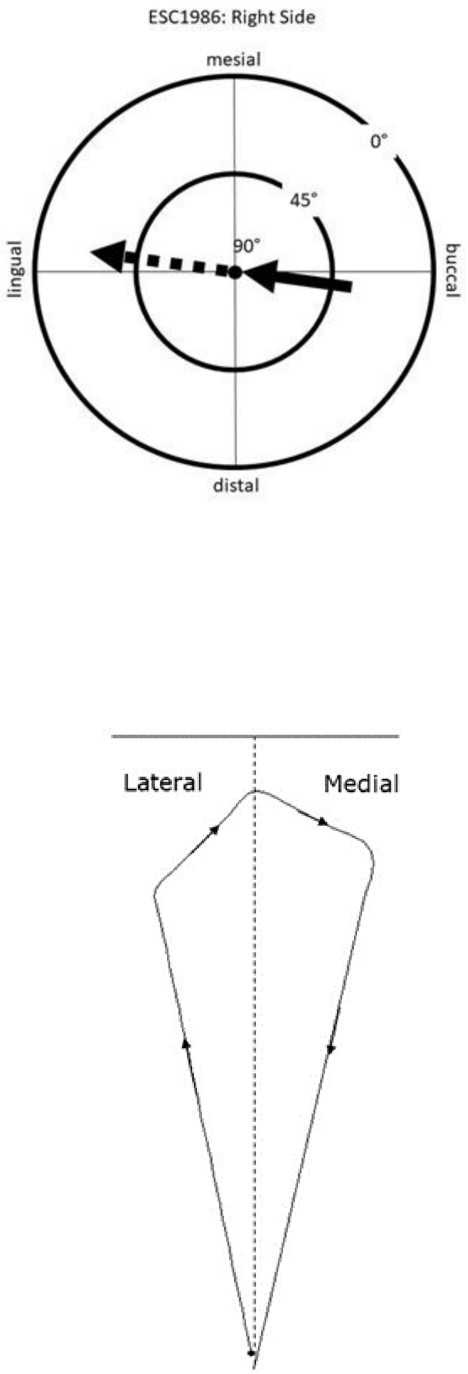


Figure 160: Visualisation of the power stroke of SK1986 on the right side. Mastication compass (above) showing the orientation and inclination of phase I (bold arrow) and phase II (dashed arrow) of the power stroke. The projection of the trajectory of movement of the chewing stroke simulation onto the frontal plane conducted using the Occlusal Fingerprint Analyser package are presented below. The power stroke is characterised by a normal pattern in which the lower teeth deviate laterally during jaw closing and jaw opening involves a slight medial component.

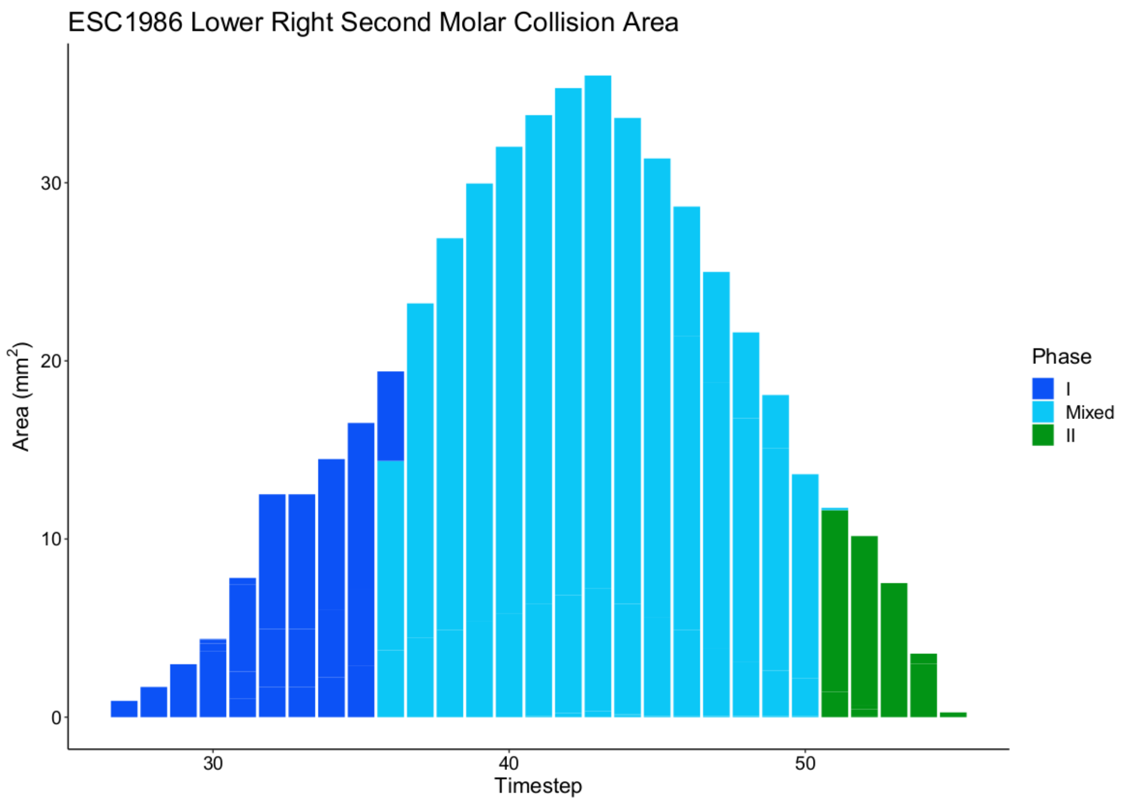


Figure 161: Stacked bar chart showing the development of collision areas on the lower second molar during the power stroke simulation on the right side of the dentition of SK1986. Contact area increased steadily during phase I of the power stroke and there was not a rapid increase in contact area prior to maximum intercuspation. Phase II involved a steady decrease in wear facet contact areas with a mix of phase I and II facet areas until the later stages of phase II.

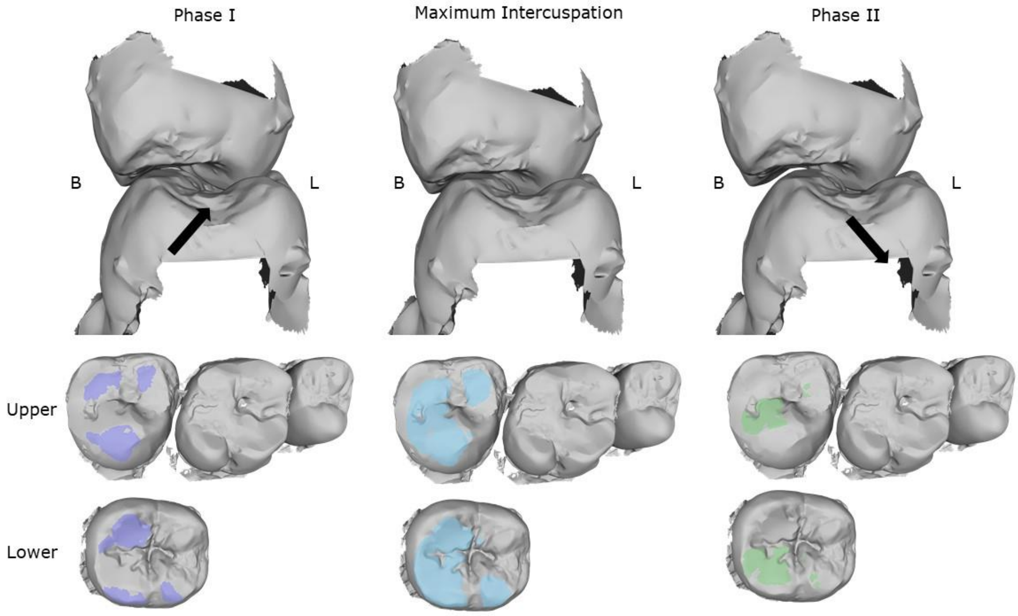


Figure 162: Mesial view of the power stroke simulation of the right molar row of SK1986 (upper). The lower molars moved from a lateral position into maximum intercuspation. A slight medial shift brought the lower molars out of maximum intercuspation. The lingual and buccal sides of each diagram are indicated by L and B respectively. The lower diagram shows the distribution of contact areas during key stages of the power stroke simulation: maximum phase I contact area, maximum intercuspation and maximum phase II contact area.

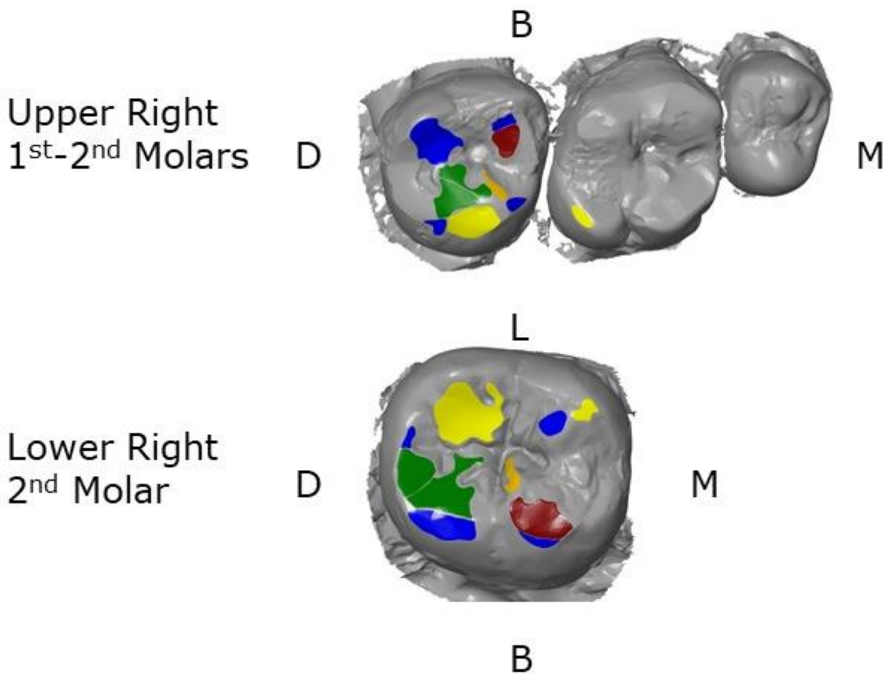


Figure 163: Wear facet map for the right molars of Sk1986. Lateroprotrusive facets are coloured yellow, lateroretrusive facets are blue, medioprotrusive facets are orange and mediotrusive facets are green. Tip crushing facets are coloured brown. A large cavitated carious lesion on the distal aspect of the lower 1st right molar had resulted in the slight mesial shift of the lower 2nd molar.

6.2.1.6.3.2 St Bride's, London: SK239. Potential Scissor Bite (Video 10)

The coffin plate associated with SK239 indicated that the individual was a male aged 35 (born 1806 and died 1841AD). They were likely of high status as they were described as a gentleman and former lieutenant in the lancers. The individual died in Fleet Street prison after serving 8 months sentence for a debt of £8000 reported to not be his own. This individual was excluded from the static OFA data analysis as their wear facets comprised only tip crushing areas. There was no evidence of pipe facets. The individual had lost the upper left first molar ante-mortem and there was some minor rotation/displacement of the lower teeth. On the right side of the dentition, the lower molar teeth were shifted lingual to their anticipated position in maximum intercuspation. This resulted in an almost cusp to cusp relationship between antagonistic molars (Figure 164 to Figure 165).

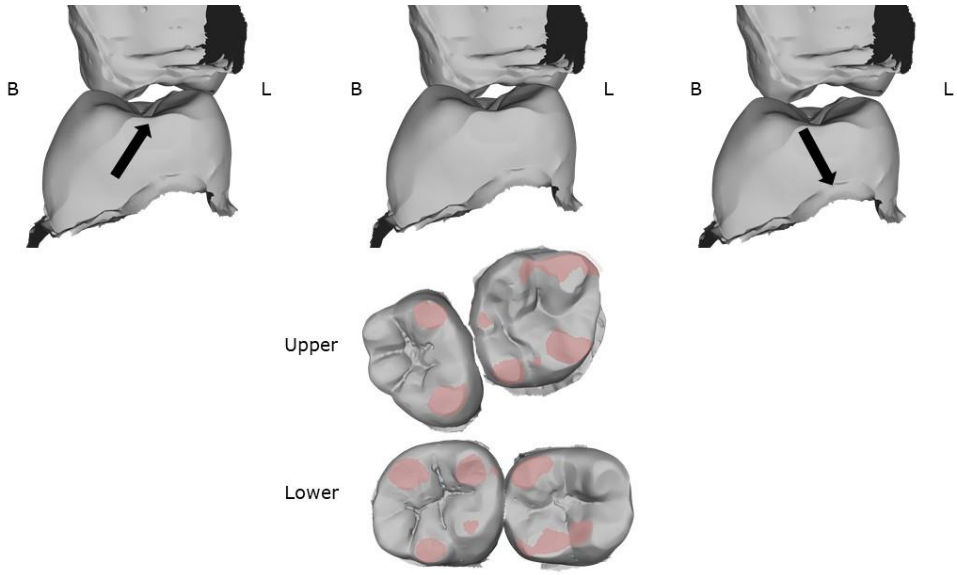


Figure 164: Mesial view of the power stroke simulation of the right molar row of SK239 (upper). The lower molars moved from a buccal position into maximum intercuspation. A slight medial shift brought the lower molars out of maximum intercuspation. The lingual and buccal sides of each diagram are indicated by L and B respectively. Lower diagram shows the distribution of contact areas during maximum intercuspation.

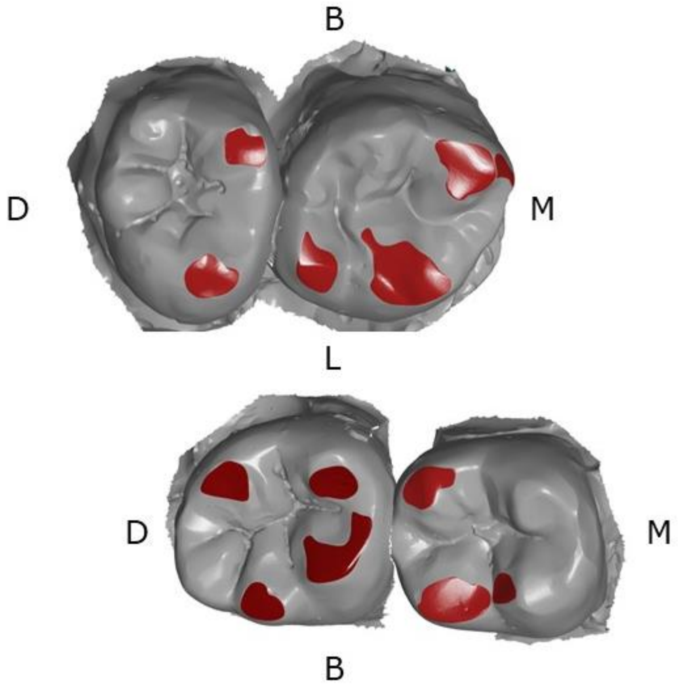


Figure 165: Wear facet map for the right upper and lower molar row of SK239 from the St Bride's assemblage. The wear facets present were classified as tip crushing areas due to their shallow inclination and positioning on or proximate to the cusp tips. The wear area on the protoconid tip of the third lower molar lacked an antagonistic wear area and occluded with the mesial portion of the trigonid basin.

The power stroke was strongly vertically orientated with only a minor lateral component (Figure 166 and Figure 167). The incursive movement involved a slight medial shift from a lateral position. Wear facets were very shallowly inclined. On the lower second molar, wear facets on the hypoconid occluded with the tip crushing area on the tip of the paracone. Tip crushing areas on the cusp tip of the entoconid occluded with the mesial slope of the protocone of the upper second molar. The individual lacked a defined phase II movement. The lower teeth moved out of maximum intercuspation following a vertical movement with an extremely limited mediotrusive component.

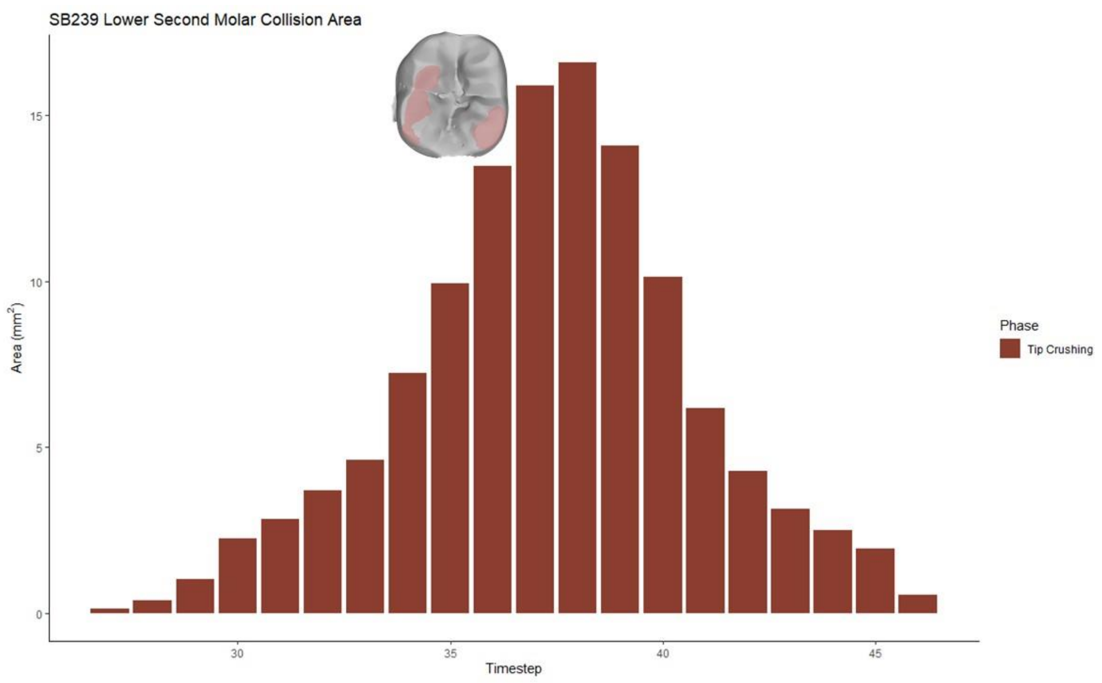


Figure 166: Stacked bar chart showing the development of collision areas on the lower second molar during the power stroke simulation on the right side of the dentition of SK239. Only tip crushing wear facets were present.

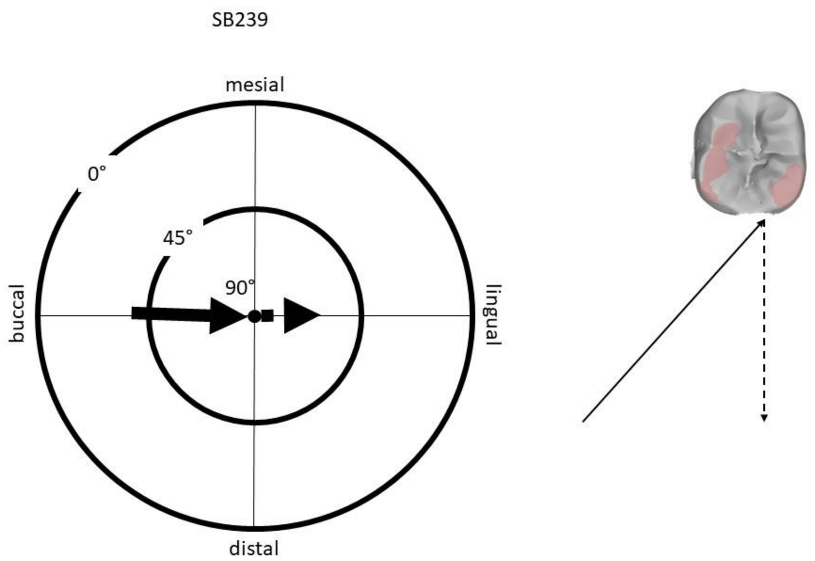


Figure 167: Left: Mastication visualisation for SK239 from the St Bride's assemblage. The compass highlights the steepness of the incursive and excursive movements of the power stroke in this individual. Right: the buccolingual profile of the power stroke derived from the Occlusal Fingerprint Analyser simulation plotted in the frontal plane. The phase I movement is steeply inclined and jaw closing involved only a very minor lateral deviation to bring all of the wear facet areas into contact. The phase II movement was almost exclusively vertical in direction.

6.2.1.6.3.3 Summary

OFA, involving both the examination of wear facet expression alongside the dynamic reconstruction of the power stroke, provides an effective tool for illustrating likely modes by which unusual wear facet patterns developed. This was demonstrated using two individuals, SK1986 from the St Michael's Litten assemblage, Chichester, and SK239 from the St Bride's crypt, London.

6.2.2 Mediaeval and Early Post-Mediaeval Period (AD1100-1700)

6.2.2.1 Historical evidence for marked sexual differences in the diets consumed in the Mediaeval and early Post-Mediaeval periods was not found. Significant differences in dental wear patterns would, therefore, not be expected.

Wear facet area proportions did not differ significantly between the sexes in the Mediaeval and early Post-Mediaeval periods (Table 94 to Table 96). Relative wear facet areas overlapped substantially (Figure 168). Variation in wear facet area composition differed significantly between the two sexes (Table 96).

Table 94: Table comparing centre values for relative wear facet proportions between the sexes in the Mediaeval and early Post-mediaeval material examined.

Sex	N	BPI	LPI	PII	Total variance	Metric standard deviation
Female	46	31.42	40.62	27.96	0.31	0.39
Male	40	33.55	37.61	28.84	0.48	0.49

Table 95: Results of Type I PERMANOVA assessing the relationship between sex and wear facet area proportions in the Mediaeval and early Post-Mediaeval periods. ***Null Hypothesis: relative wear facet areas did not differ significantly between males and females in the Mediaeval and early Post-Mediaeval groups examined.***

Standard data	**Sum of Squares**	**Mean of Squares**	**Degrees of Freedom**	**F**	**p-value (>F)**	**H_0**
Sex	0.03	0.03	1	1.89	0.15	Not Rejected
Residuals	1.17	0.02	72			
ILR data	**Sum of Squares**	**Mean of Squares**	**Degrees of Freedom**	**F**	**p-value (>F)**	**H_0**
Sex	0.46	0.46	1.00	1.27	0.28	Not Rejected
Residuals	26.80	0.36	74.00			

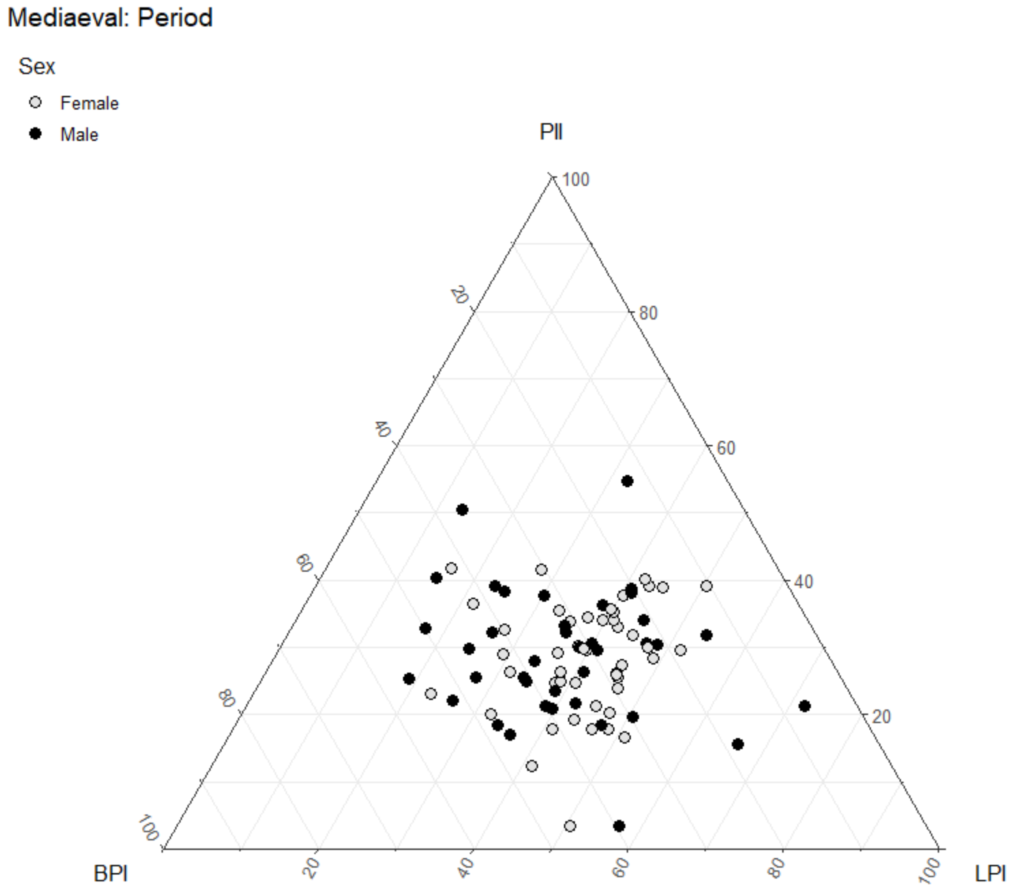


Figure 168: Ternary plot showing the relationship between sex and wear facet area composition. There was a marked overlap between the relative wear facet proportions of the lower second molar of males and females dating to the Mediaeval and early Post-Mediaeval periods.

Table 96: Results of homogeneity of multivariate dispersion test for the relationship between sex and relative wear facet area. This assumption was violated for the standard Bray-Curtis transformed data, which would suggest that if significant differences were reported this may be due to differences in variation within the group when comparing males and females rather than differences in centre values. ***Null hypothesis: within group variability in relative wear facet areas did not differ significantly between males and females in the Mediaeval and early Post-Mediaeval groups examined.***

Homogeneity of dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	Null Hypothesis
Standard	1.00	0.02	0.02	4.13	0.05	**Rejected**
	84.00	0.39	0.00			
ILR data	1.00	0.28	0.28	2.04	0.16	Not Rejected
	84.00	11.55	0.14			

The mean dip angle of each wear facet type did not differ significantly between the sexes (Table 97 and Figure 169).

Table 97: Wilcoxon Rank Sum test results for the influence of sex of wear facet dip angle in the Mediaeval and early Post-Mediaeval periods. Non-parametric testing was used as the assumption of normality was violated (Shapiro-Wilk p>0.05). ***Null hypothesis: dip angle values for the given wear facet type did not differ significantly between males and females in the pre-Industrial groups examined.***

Wear Facet Function	W	p-value	H_0
BPI	943	0.85	Not Rejected
LPI	911.5	0.95	Not Rejected
PII	756	0.16	Not Rejected

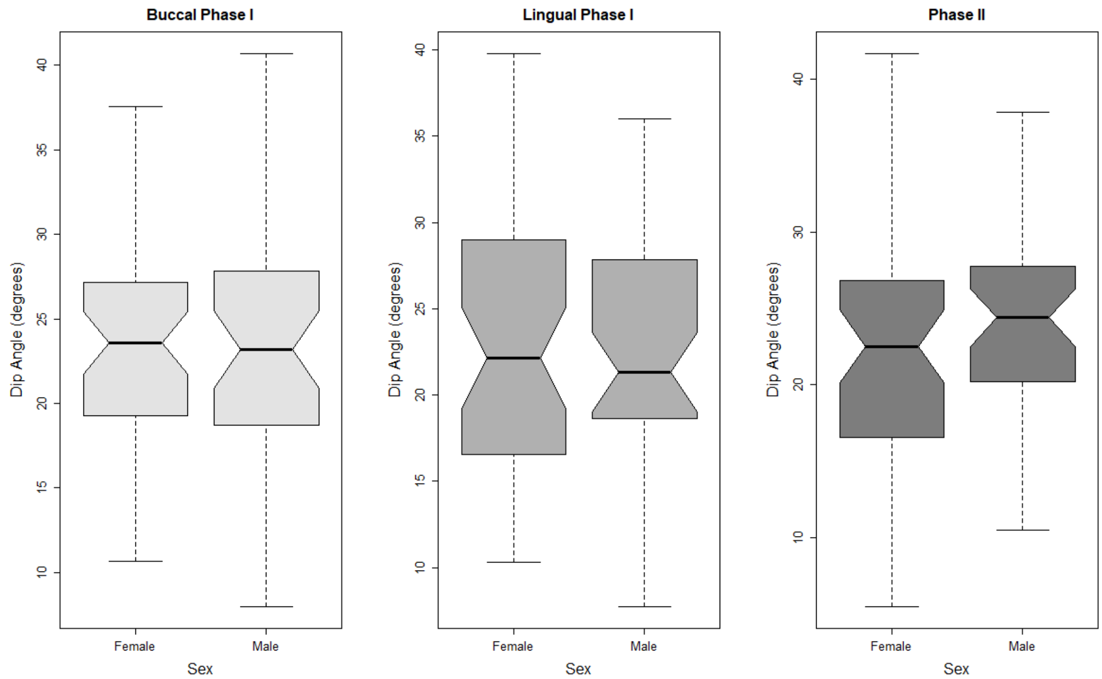


Figure 169: Boxplot showing the relationship between mean dip angle for each wear facet type and sex. The data were not normally distributed therefore non-parametric testing was used.

ORI and TCI values also did not differ significantly between the sexes in the Mediaeval and early post-Mediaeval assemblages examined (Figure 170; Table 98).

Table 98: Results of Wilcoxon rank sum tests assessing the relationship between sex and ORI and also sex and TCI in the Mediaeval and early Post-Mediaeval assemblages. Non-parametric testing was used as the data were not normally distributed (Shapiro Wilk p<0.05). ***Null Hypothesis: ORI and/or TCI values did not differ significantly between males and females in the Mediaeval assemblages examined.***

Wear Parameter	W	p-value	H_0
ORI	771	0.20	Not Rejected
TCI	1078.5	0.17	Not Rejected

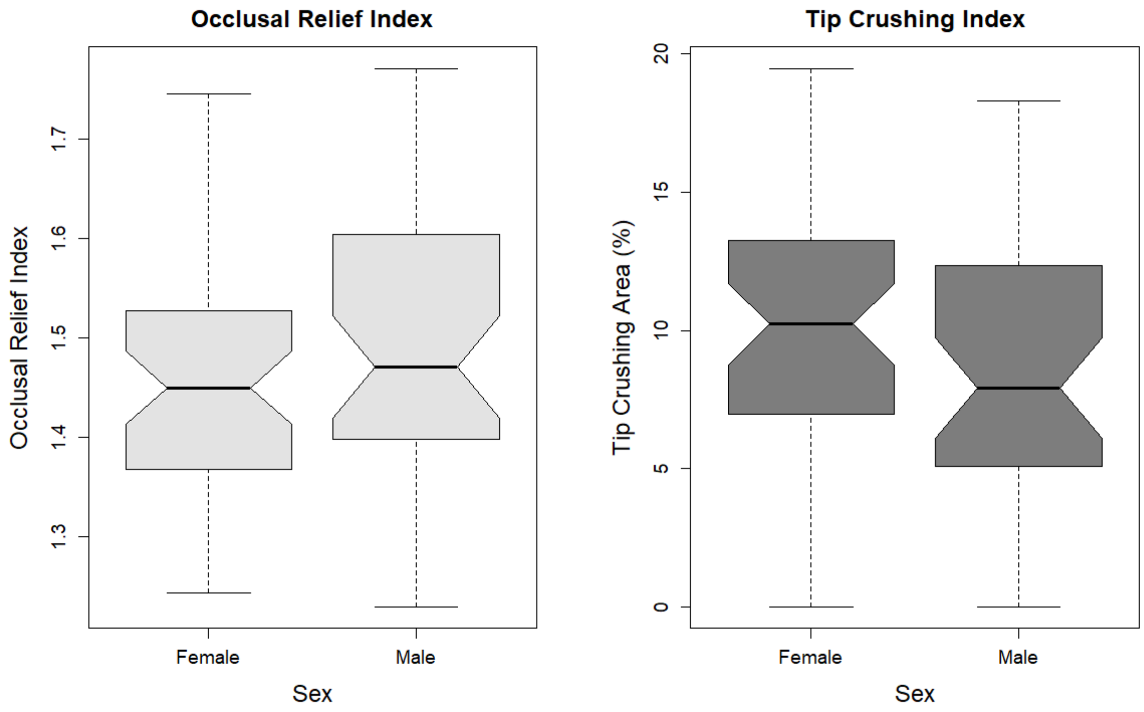


Figure 170: Boxplots comparing ORI and TCI values between the sexes in the pre-Industrial group. There was not a significant difference between the sexes.

6.2.2.1.1 Summary

There were no significant differences between males and females dating to the Mediaeval and early post-Mediaeval period in either dental wear facet patterns or the overall pattern of dental wear.

6.2.2.2 In the Mediaeval period, there is historical evidence for differences in dietary practices at institutions such as monasteries and hospitals. Contrasts in lower second molar wear patterns would be expected between the inhabitants of such institutions relative to lay cemeteries.

Several of the assemblages examined were drawn from a variety of mediaeval institutions and there were substantial differences in the temporal span across which the burials had occurred (Table 99, Figure 171). Each assemblage was grouped according to the type of cemetery from which the individuals were derived: lay, monastic or leprosarium (hospital) (Table 99). Blackfriars, Gloucester, provided the only assemblage to represent a monastic context. The St James and St Mary Magdalene assemblage was the only one associated with a hospital and later an alms house. The later period of this assemblage is largely contemporary with the early Post-Mediaeval portion of the St Michael's Litten cemetery and both of these assemblages were derived from Chichester. There were high levels of variation in the relative wear facet areas of the lower second molar in the lay group relative to the others (Figure 171 and Table 99). No significant differences were found between the assemblages examined when divided by cemetery type (Table 100).

Table 99: Table summarising centre values for the wear facet proportions for the Mediaeval and early Post-Mediaeval periods divided by site.

Site	N	Cemetery Type	Date (AD)	BPI	LPI	PII	Total variance	Metric SD
St Michael's Litten, Chichester (Early Post-mediaeval)	16	Lay Early Post Mediaeval	c.1550-1700	26.09	40.11	33.80	0.36	0.42
Blackfriars	9	Monastic	1246-1539	23.53	43.15	33.31	0.44	0.47
Box Lane	7	Lay Mediaeval	c.1100-1500	36.32	41.27	22.40	0.12	0.25
Hereford Cathedral	42	Lay Mediaeval	c.1100-1600	31.75	40.29	27.95	0.60	0.55
York Barbican	32	Lay Mediaeval	c.1100-1500	34.26	36.58	29.17	0.32	0.40
St James and St Mary Magdalene, Chichester, West Sussex	24	Hospital & Almshouse	c.1100-1600	32.47	38.33	29.20	0.16	0.29

Table 100: Results of PERMANOVA examining the relationship between cemetery type and relative wear facet area in the pre-Industrial group. ***Null hypothesis: in the Mediaeval period, relative wear facet proportions did not differ significantly between the four cemetery types examined (Lay (Mediaeval), Lay (Early Post-Mediaeval), Monastic and Leprosarium/Hospital).*** *Homogeneity of multivariate dispersion assumption was accepted (Table 136).*

Standard data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	**R^2**	**p-value (>F)**	**H_0**
Cemetery Type	3	0.08	0.03	1.50	0.03	0.18	Not Rejected
Residuals	126	2.39	0.02		0.97		
Total	129	2.47			1.00		
ILR data	**Sum of Squares**	**Mean of Squares**	**DF**	**F**	**R^2**	**p-value (>F)**	**H_0**
Cemetery Type	3	2.28	0.76	1.95	0.04	0.08	Not Rejected?
Residuals	126	49.11	0.39		0.96		
Total	129	51.39			1.00		

When the assemblages were compared individually, however, significant differences were found between the early Post-Mediaeval portion of St Michael's Litten (ESC11) and York Barbican and also between Blackfriars and York Barbican (Figure 171, Table 101 and Table 102). Box Lane was excluded from the PERMANOVA test as it violated the assumption of homogeneity of multivariate dispersion when included in the analysis (Table 137).

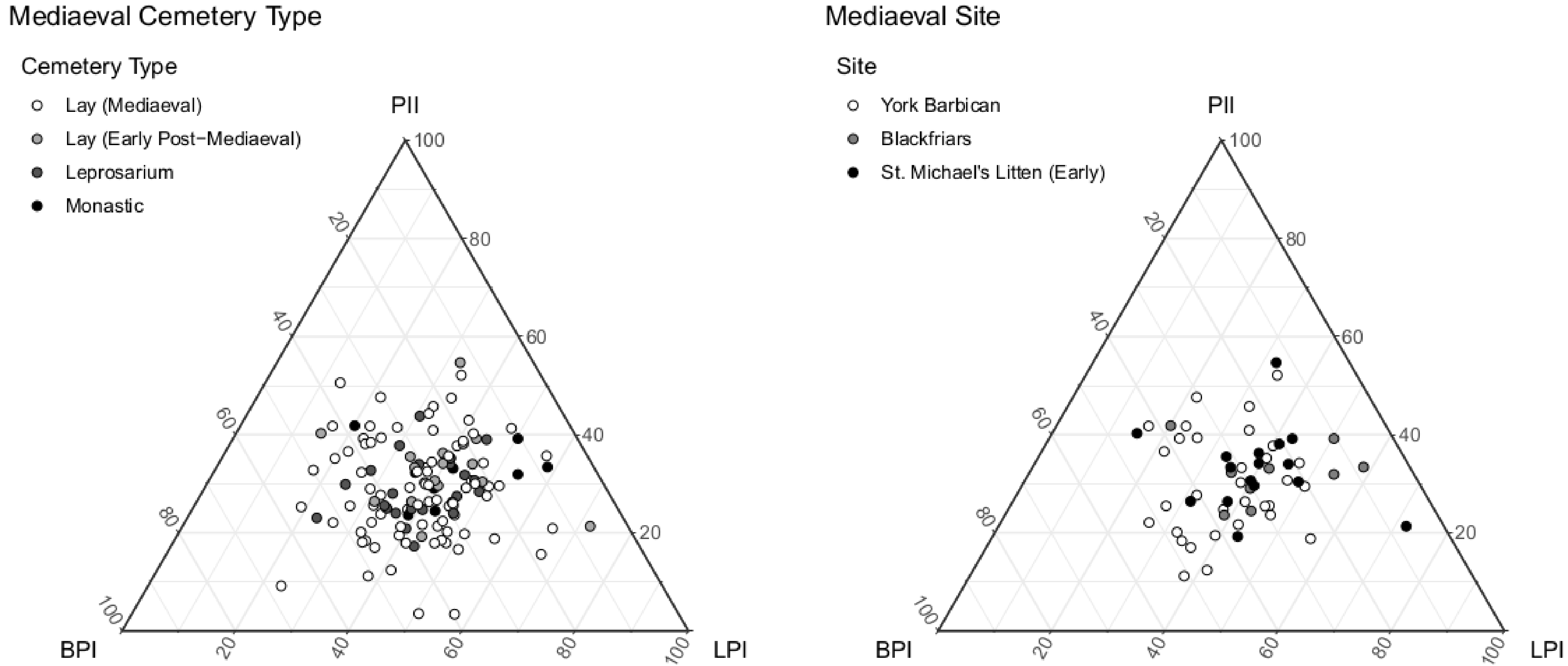


Figure 171: Ternary plots: Left: showing the relationship between cemetery type and relative wear facet areas on the lower second molars in the pre-Industrial group. Right: Pre-industrial sites that differed markedly in the relative wear facet composition of their lower second molars (Table 102). There were significant differences between the York Barbican (BARB) assemblage and both the early Post-Mediaeval portion of St Michael's Litten (ESC11) and the Blackfriars material (BF).

Table 101: Results of Type I PERMANOVA assessing the dependence of wear facet area on site during the Mediaeval and early Post-Mediaeval periods. Box Lane was excluded from this statistical analysis as when included the homogeneity of multivariate dispersion assumption was violated. In addition, the number of individuals examined from the site was comparatively low. The data satisfied the homogeneity of multivariate dispersion assumption required to perform PERMANOVA when Box Lane was excluded (Table 138). ***Null hypothesis: relative wear facet proportions did not differ significantly between the sites examined dating to the Mediaeval and early Post-Mediaeval periods.***

Standard data	Df	Sum of Squares	Mean of Squares	F-model	R^2	p-value	H_0
Site	4	0.17	0.04	2.62	0.12	0.01	**Rejected**
Residuals	74	1.21	0.02		0.88		
ILR data	**Df**	**Sum of Squares**	**Mean of Squares**	**F-model**	**R^2**	**p-value**	**H_0**
Site	5	4.54	0.91	2.52	0.14	0.01	**Rejected**
Residuals	76	27.39	0.36		0.86		

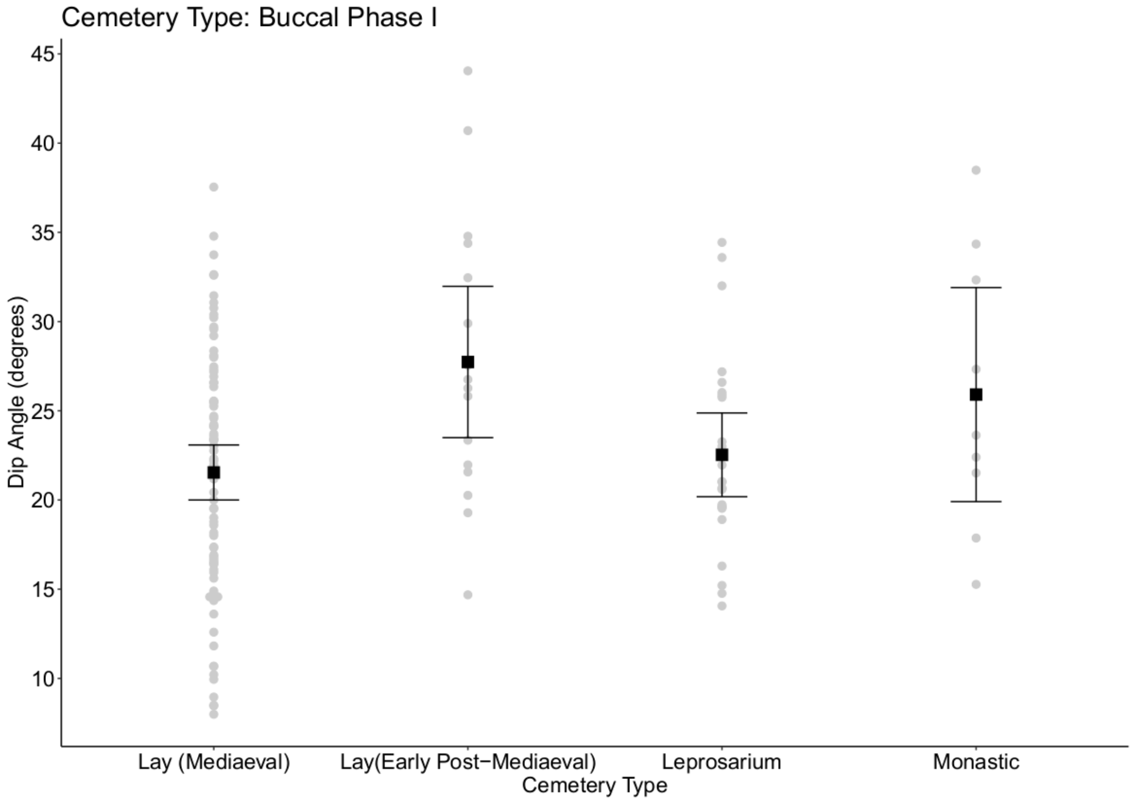
Table 102: Results of pairwise comparisons of sites using PERMANOVA on a distance matrix of the isometric log-transformed wear facet area data for the pre-Industrial group. Control of the false discovery rate was performed using Benjamini & Yekutieli (2001). The significant differences between the York Barbican, Blackfriars and early Post-mediaeval St Michael's Litten material (ESC11) reflected the slightly greater proportion of BPI wear in the York Barbican assemblage.

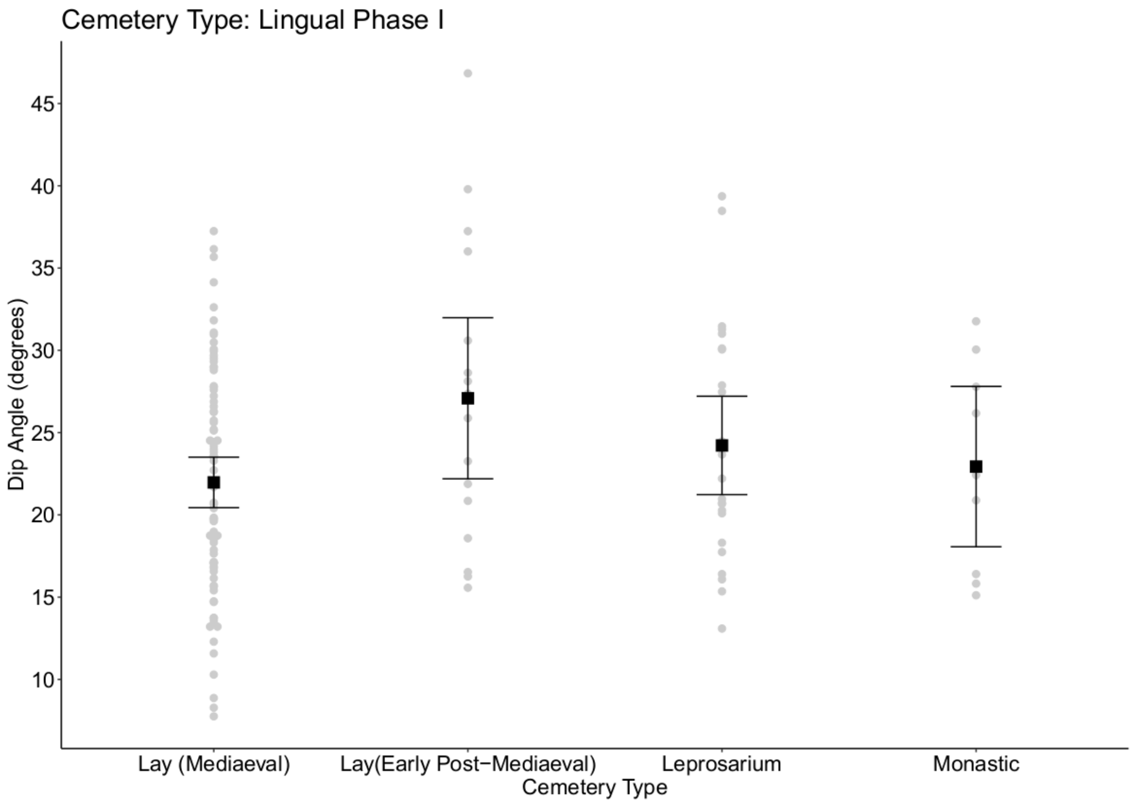
	York Barbican	Blackfriars	St James and St Mary Magdalene	St Michael's Litten
Blackfriars	0.05	-	-	-
St James and St Mary Magdalene	0.15	0.29	-	-
St Michael's Litten	0.04	1.00	0.50	
Hereford Cathedral	1.00	0.50	1.00	0.29

BPI and LPI dip angles differed significantly between the four cemetery types identified (Figure 172 and Table 103). The only pairwise difference that was significant, however, was between the Mediaeval and early Post-mediaeval components of the lay cemeteries examined when comparing BPI dip angles (Tukey multiple comparisons of means; $p<0.05$). Dip angles did not differ significantly between the assemblages examined (Table 104 and Figure 173).

Table 103: Results of one-way ANOVA examining the relationship between cemetery type and wear facet dip angles in the pre-Industrial group. Data satisfied the assumptions of normality (Shapiro Wilk p>0.05) and homogeneity of variance (Levene's Test p>0.05). ***Null hypothesis: wear facet dip angles did not differ significantly between the cemetery types examined dating to the Mediaeval and early Post-Mediaeval periods.***

ANOVA	df	Sum of Squares	Mean of Squares	F value	p-value	H_0
BPI	3	606	202.15	4.21	0.007	**Rejected**
LPI	3	387	129.13	2.47	0.065	Rejected?
PII	3	159	52.92	1.18	0.32	Not Rejected


Cemetery Type: Buccal Phase I
Dip Angle (degrees)
Lay (Mediaeval)
Lay(Early Post−Mediaeval)
Leprosarium
Monastic
Cemetery Type


Cemetery Type: Lingual Phase I
Dip Angle (degrees)
Lay (Mediaeval)
Lay(Early Post−Mediaeval)
Leprosarium
Monastic
Cemetery Type

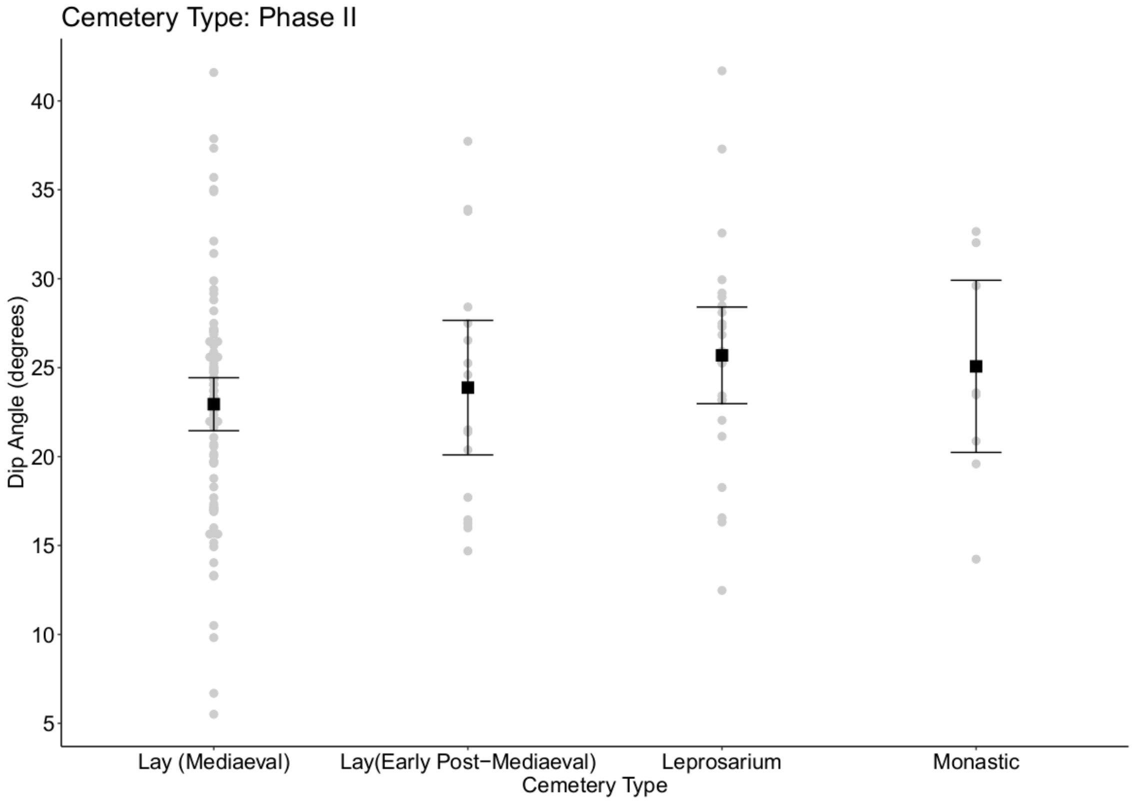


Figure 172: Dot plots with mean values plotted with 95% confidence intervals comparing BPI, LPI and PII dip angles between pre-Industrial cemetery types. 95% confidence intervals around the mean are broadly overlapping for all of the cemetery types, however, the difference in mean BPI dip angle between Mediaeval and early Post-Mediaeval lay cemeteries can be observed.

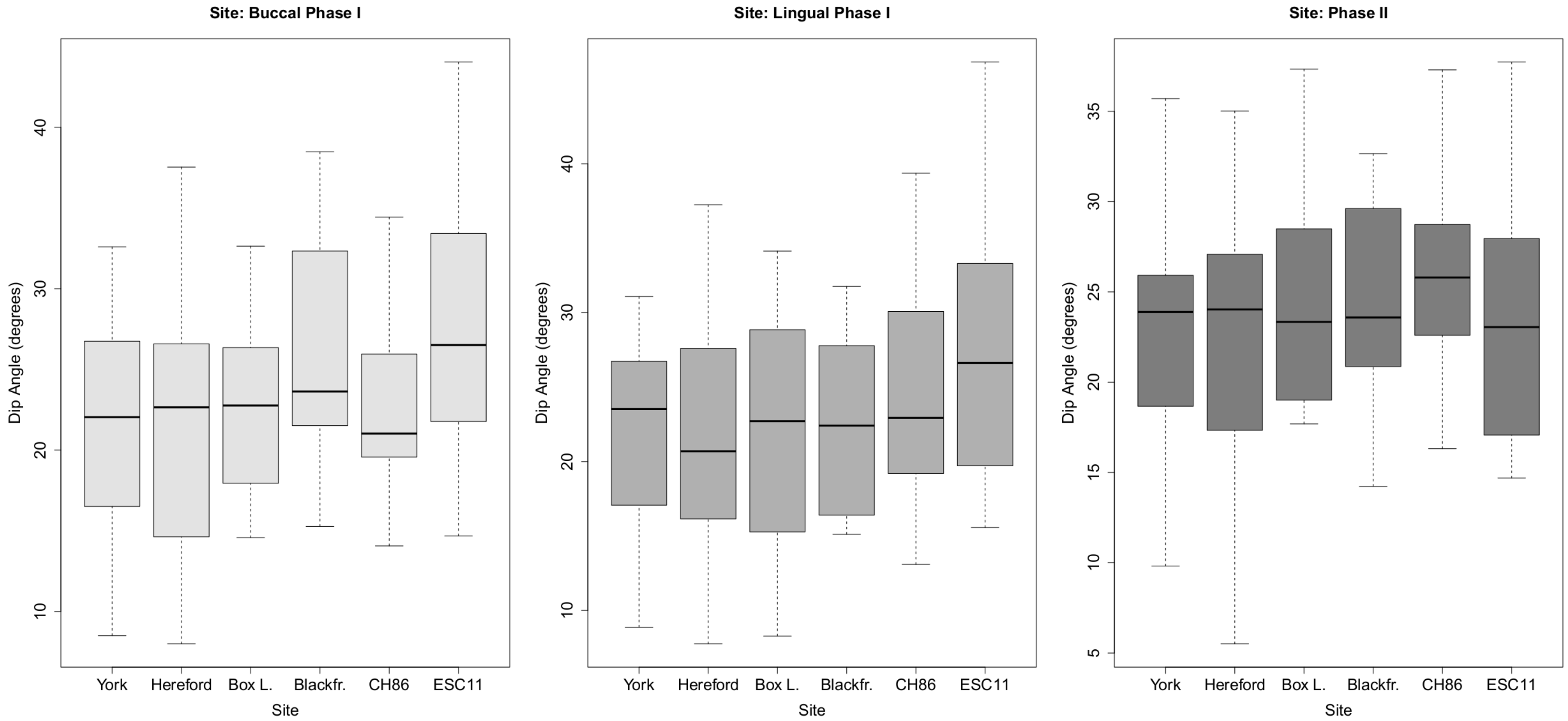


Figure 173: Boxplots comparing the distribution of dip angle values between each assemblage examined dating to the Mediaeval and early Post-Mediaeval periods. There is little differentiation between the median dip angle values of each assemblage for BPI, LPI and PII wear facets. The data were not normally distributed (Shapiro Wilk test; $p<0.05$), therefore, the data were plotted as a boxplot and non-parametric testing was used (Table 104).

Table 104: Kruskal-Wallis test results examining whether dip angles differed significantly between assemblages examined dating to the Mediaeval and early Post-Mediaeval periods. ***Null hypothesis: wear facet dip angles did not differ significantly between the assemblages examined.***

Wear Facet function	Kruskal-Wallis chi-squared	df	p-value	H_0
BPI	8.62	5	0.13	Not Rejected
LPI	4.47	5	0.48	Not Rejected
PII	4.28	5	0.51	Not Rejected

TCI values differed significantly between the pre-Industrial assemblages (Table 105 and Figure 174). Wilcoxon pairwise comparisons indicated that differences in TCI values were significant ($p<0.05$) between the York Barbican material and St James' and St Mary Magdalene, Chichester, and between York Barbican and Hereford Cathedral (Table 106). ORI values did not, however (Table 105 and Figure 174). There were not any significant differences in ORI or TCI values between Mediaeval and early Post-Mediaeval cemetery types (Table 107 and Figure 175).

Table 105: Results of Kruskal Wallis tests assessing whether ORI and/or TCI differed significantly between the Mediaeval and early Post-Mediaeval assemblages examined. Non-parametric testing was used as the assumption of normality was violated (Shapiro-Wilk p<0.05). ***Null Hypothesis: ORI and TCI values did not differ significantly between the Mediaeval assemblages examined.***

Wear Parameter	Kruskal-Wallis chi-squared	df	p-value	H_0
ORI	1.51	5	0.91	Not Rejected
TCI	15.84	5	0.007	**Rejected**

Table 106: Results of post-hoc pairwise comparisons using Wilcoxon rank sum test to identify which Mediaeval and early Post-mediaeval assemblages had TCI values that differed significantly. P-values adjusted using the Holm method.

TCI pairwise comparison	York Barbican	Blackfriars	Box Lane	St James and St Mary Magdalene	St Michael's Litten (Early)
Blackfriars	0.68	-	-	-	-
Box Lane	0.50	1.00	-	-	-
St James and St Mary Magdalene	0.007	1.00	1.00	-	-
St Michael's Litten (Early)	0.76	1.00	1.00	1.00	-
Hereford Cathedral	0.04	1.00	1.00	1.00	1.00

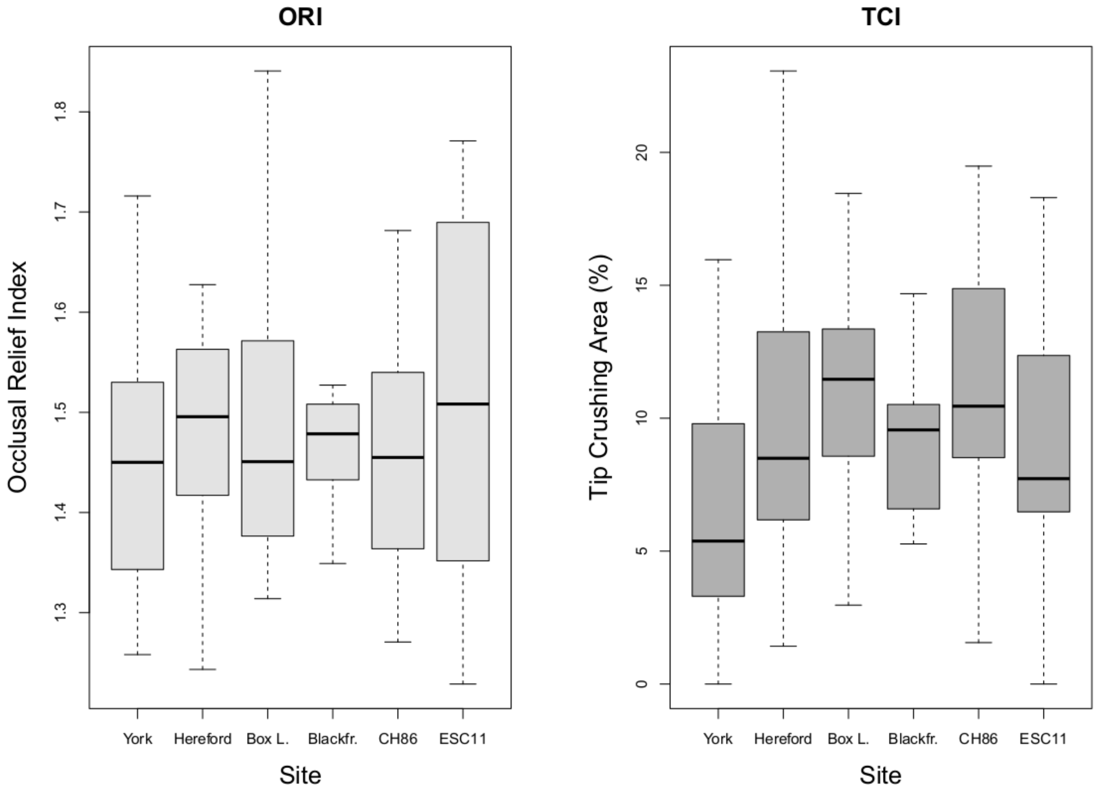


Figure 174: Boxplot showing the relationship between ORI and site and between TCI and site in the pre-Industrial group. TCI values differed significantly between St James and St Mary Magdalene leprosarium (CH86) and York Barbican and between Hereford Cathedral and York Barbican.

Table 107: Results of Kruskal Wallis tests assessing whether ORI and/or TCI values differed significantly between the pre-Industrial cemetery types examined. Non-parametric testing was used as the assumption of normality was violated (Shapiro-Wilk p<0.05). ***Null Hypothesis: ORI and TCI values did not differ significantly between the pre-Industrial cemetery types examined.***

Wear Parameter	Kruskal-Wallis chi-squared	df	p-value	H_0
ORI	0.62	3	0.89	Not Rejected
TCI	5.29	3	0.15	Not Rejected

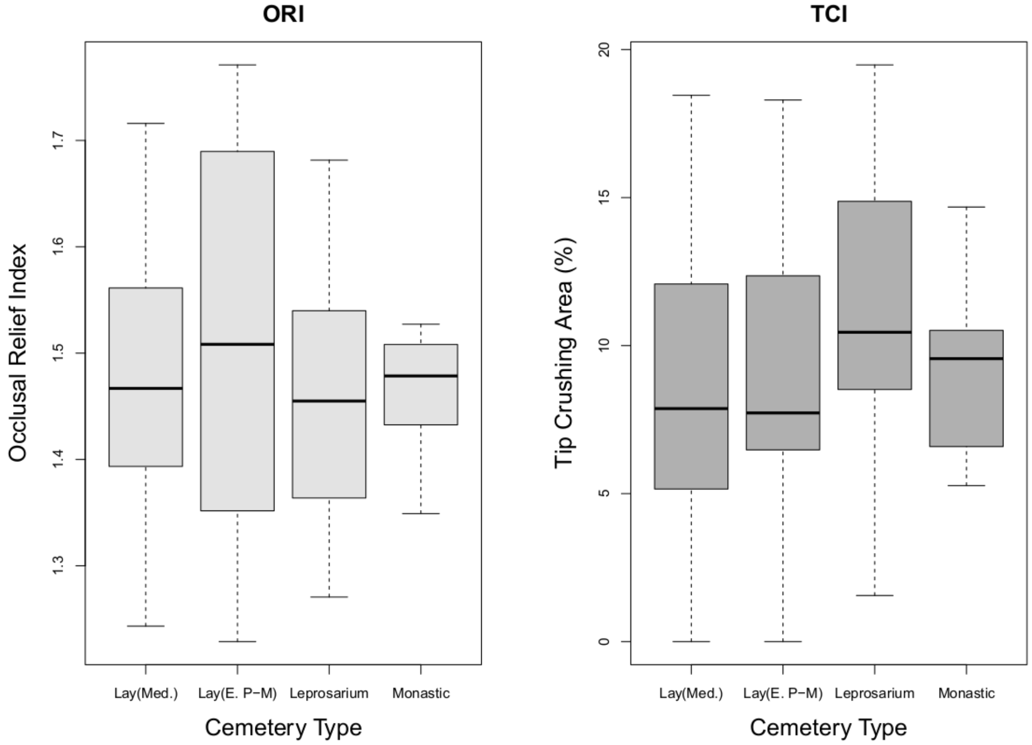


Figure 175: Boxplot comparing ORI and TCI between different cemetery types among the assemblages dated to the Mediaeval and early Post-Mediaeval periods.

6.2.2.2.1 Summary

Evidence for marked differences in wear facet expression between cemetery types dating to the Mediaeval and early post-Mediaeval period were limited. Significant differences were apparent in the mean inclination of BPI dip angles of the Mediaeval and Early Post-mediaeval portions of the lay cemeteries examined. Several of the assemblages differed significantly in several of the wear parameters examined.

6.2.2.3 Leprosy often has orofacial manifestations, which may impact masticatory behaviours. In addition, dietary measures were often utilised in the treatment of leprosy in the Mediaeval period. Individuals with lepromatous leprosy might be expected to exhibit dental wear patterns that differ from those unaffected by the pathology.

In the St James and St Mary Magdalene assemblage (CH86), a significantly greater proportion of the individuals examined with changes characteristic of lepromatous leprosy were associated with excavation area A, which is purportedly the earlier portion of the cemetery (chi-square 4.17, df = 1, p-value = 0.04). The interaction effect between cemetery area and the presence of leprosy was therefore considered to determine whether the observed differences in relative wear facet area could be attributed to the presence of leprosy, temporal differences between cemetery areas or a combination of the two. Wear facet area proportions differed significantly between individuals with leprosy and those without rather than between the two cemetery areas (Figure 176; Table 108). Individuals with skeletal changes consistent with lepromatous leprosy had greater proportions of BPI wear, at the expense of both LPI and PII wear. There were no significant interaction effects between cemetery area and the presence of rhino-maxillary syndrome in influencing relative wear facet areas.

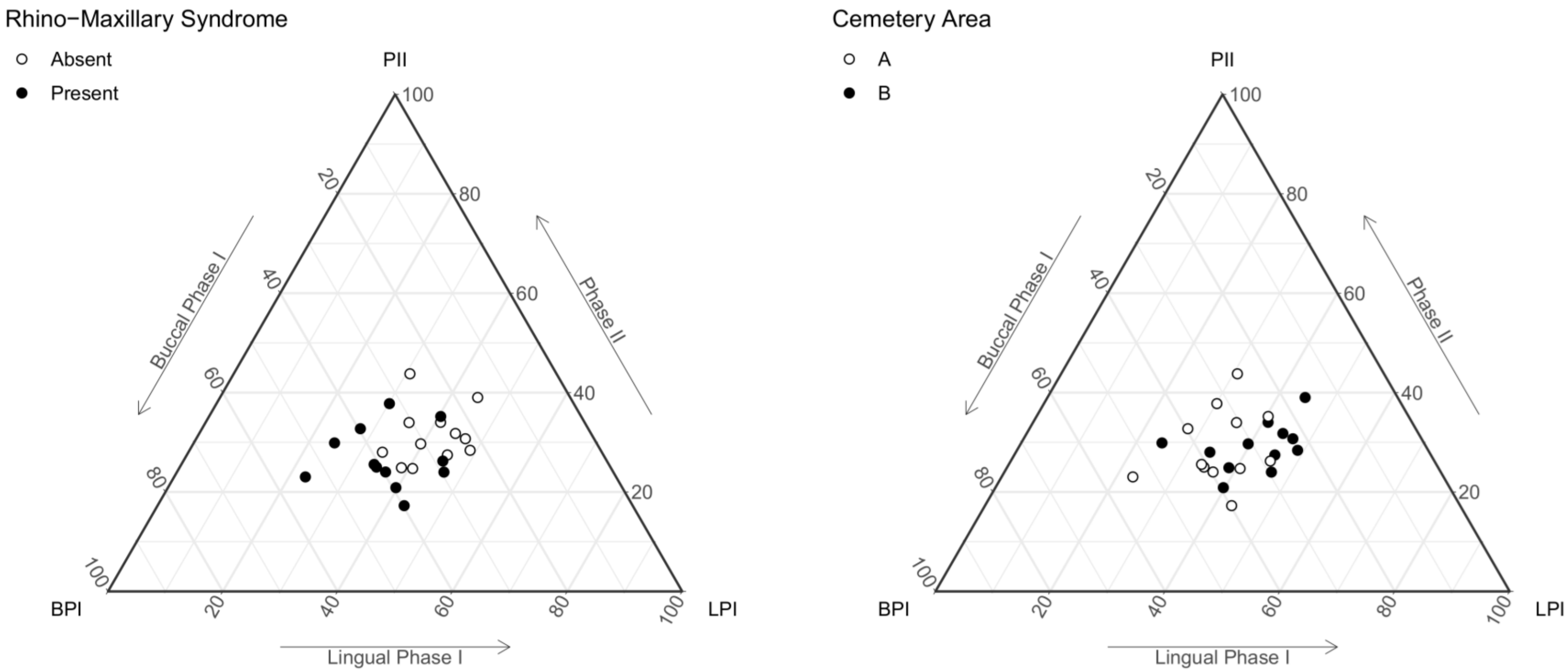


Figure 176: Left: Ternary plot showing the differences in wear facet area proportions of the lower second molars of individuals with and without osseous changes characteristic of Rhino-maxillary syndrome from the cemetery of the Hospital of St James and St Mary Magdalene, Chichester. Centre values for individuals with leprosy BPI 37.92%, LPI 35.27% and PII 26.80%. Centre values for individuals without leprosy BPI 27.45%, LPI 41.13% and PII 31.14%. Right: Distribution of relative wear facet areas according to cemetery area. Cemetery area A was the area reported to be the temporally earlier (approximately AD1100-1400) and consisted of burials with a higher prevalence of skeletal changes consistent with lepromatous leprosy. Cemetery area B likely principally included burials dated to the period during which the cemetery was used by the later alms-house and included a greater number of subadults and females (AD1400-1600).

Table 108: Results of the type II PERMANOVA assessment of the relationship between the presence of rhino-maxillary changes, cemetery area and wear facet area composition. The significance of any interaction effects between the presence of leprous changes and cemetery area on wear facet area composition was also assessed. ***Null hypothesis: significant differences in wear facet area composition in the St James and St Mary Magdalene assemblage were not associated with the presence of skeletal changes consistent with lepromatous leprosy and/or cemetery area.***

Standard data	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Leprosy	0.03	0.03	1.00	2.42	0.08	Rejected?
Area	0.01	0.01	1.00	0.95	0.45	Not Rejected
Leprosy: Area Interaction Effect	0.01	0.01	1.00	0.63	0.60	Not Rejected
Residuals	0.25	0.01	20.00			
Total	0.30		23.00			
ILR data	**Df**	**Sum of Squares**	**Mean of Squares**	**F-model**	**p-value**	H_0
Leprosy	0.61	0.61	1.00	4.54	0.02	**Rejected**
Area	0.11	0.11	1.00	0.79	0.44	Not Rejected
Leprosy: Area Interaction Effect	0.05	0.05	1.00	0.36	0.69	Not Rejected
Residuals	2.71	0.14	20.00			
Total	3.78		23.00			

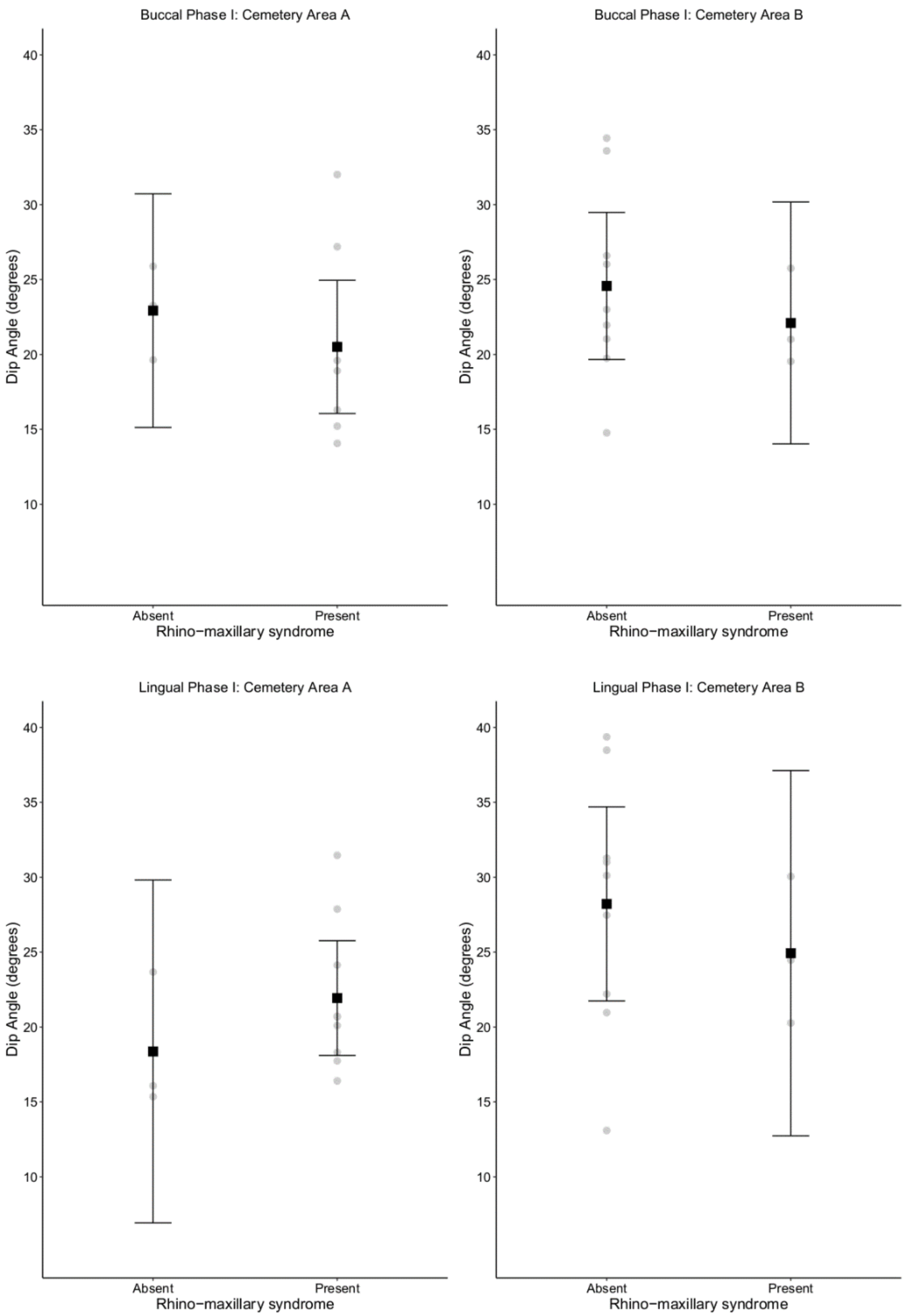
There were no significant differences in wear facet dip angle between individuals with osseous changes consistent with lepromatous leprosy and those without (Figure 177; Table 109 and Table 140). Dip angles for phase I facets were slightly less oblique in individuals with evidence of rhino-maxillary syndrome. Phase I wear facets were more obliquely inclined in area B of the cemetery when compared to area A (Table 109 to 110; Figure 177). Only the difference between LPI dip angles was significant between areas A and B of the cemetery, however (Table 110). The BPI wear facet dip angles in area B of the cemetery were less obliquely inclined irrespective of whether the individual exhibited osseous changes consistent with lepromatous leprosy. There was not a significant interaction effect between area and the presence of lepromatous leprosy and the inclination of wear facet dip angles.

Table 109: Results of PERMANOVA examining the influence of cemetery area and leprosy on wear facet dip angle. The Bray-Curtis similarity matrix was used as the transformation for performing the test. ***Null hypothesis: wear facet dip angles did not differ significantly between cemetery areas and/or individuals with and without skeletal changes consistent with lepromatous leprosy.***

Standard data	df	Sum of Sq.	Mean of Sq.	F-model	p-value	H_0
Area	0.03	0.03	1.00	2.42	0.08	Rejected?
Leprosy	0.01	0.01	1.00	0.95	0.44	Not Rejected
Area: Leprosy Interaction Effect	0.01	0.01	1.00	0.63	0.61	Not Rejected
Residuals	0.25	0.01	20.00			
Total	0.30		23.00			

*Table 110: Results of independent sample t-tests examining whether wear facet dip angles differed significantly between cemetery areas. *Bonferroni adjusted p-value=0.017.* ***Null hypothesis: Wear facet dip angles did not differ significantly between cemetery areas.***

Wear Facet Function	BPI	LPI	PII
Area A Mean (°)	21.11	21.04	24.37
Standard Deviation	5.22	4.95	6.71
Area B Dip Angle Mean (°)	23.95	27.39	27.01
Standard Deviation	5.72	7.63	6.14
t-value	-1.27	-2.42	-1.00
Degrees of Freedom	22.00	18.86	22.00
p value*	0.21	0.03	0.32
Effect Size	-0.52	-0.99	-0.41
95% CI Effect Size	-1.37 to 0.34	-1.88 to -0.09	-1.27 to 0.44
Statistical Power	0.24	0.66	0.17
H_0	Not Rejected	Rejected?	Not Rejected


Buccal Phase I: Cemetery Area A
Buccal Phase I: Cemetery Area B
Lingual Phase I: Cemetery Area A
Lingual Phase I: Cemetery Area B
Dip Angle (degrees)
10
15
20
25
30
35
40
Absent
Present
Rhino−maxillary syndrome

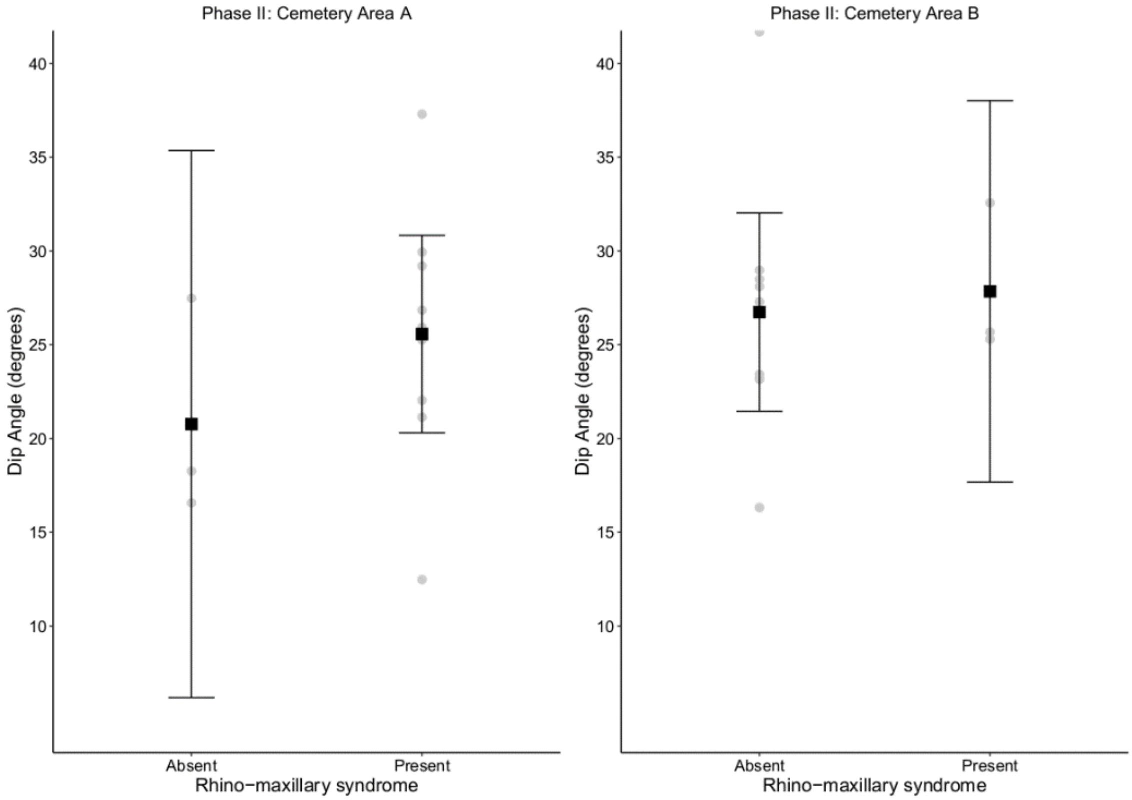


Figure 177: Dot plots with mean values plotted with 95% confidence intervals comparing mean dip angles in the lower second molars between cemetery areas (Area A and B) and individuals with and without skeletal changes consistent with leprosy from the St James and St Mary Magdalene assemblage, Chichester (CH86).

There were higher ORI values in the lepromatous leprosy group in cemetery area A (Figure 178). This effect was not apparent in cemetery group B. Tip crushing wear was less developed in the lepromatous leprosy group of cemetery area A relative to those without (Figure 178). The only difference that approached significance was between the TCI values of the two cemetery areas although the 95% confidence intervals around the mean values overlapped extensively (Table 111 and Table 112). Larger ORI values were more typical of individuals from cemetery area B rather than cemetery area A irrespective of the presence of lepromatous leprosy (Table 112). The interaction effect between leprosy and cemetery area was not significant for either ORI or TCI. The smallest p-value was associated with the interaction effect of area and leprosy on ORI, however, suggesting that ORI values were likely influenced by both the presence of leprosy and cemetery area (Table 111).

Table 111: Results of PERMANOVA of the Bray-Curtis similarity matrix examining the effect of leprosy and cemetery area on ORI and TCI in the St James and St Mary Magdalene cemetery, Chichester. The significance of the influence of any possible interaction effect between cemetery area and the presence of lepromatous leprosy was also assessed. ***Null hypothesis: ORI values and/or TCI values did not differ significantly between cemetery areas and/or individuals with and without skeletal changes consistent with lepromatous leprosy.***

ORI	Df	Sum of Sq.	Mean of Sq.	F-model	p-value	H_0
Area	0.01	0.01	1.00	0.15	0.88	Not Rejected
Leprosy	0.04	0.04	1.00	0.62	0.54	Not Rejected
Area: Leprosy Interaction Effect	0.07	0.07	1.00	1.14	0.31	Not Rejected
Residuals	1.19	0.06	20.00			
Total	1.33		23.00			
TCI	**Df**	**Sum of Sq.**	**Mean of Sq.**	**F-model**	**p-value**	**H_0**
Area	0.03	0.03	1.00	2.42	0.08	Rejected?
Leprosy	0.01	0.01	1.00	0.95	0.45	Not Rejected
Area: Leprosy Interaction Effect	0.01	0.01	1.00	0.63	0.62	Not Rejected
Residuals	0.25	0.01	20.00			
Total	0.30		23.00			

*Table 112: Results of independent sample t-tests examining the influence of cemetery burial area and leprosy on TCI and ORI. *Bonferroni adjusted p-value=0.0125. Null hypothesis: ORI values and/or TCI values did not differ significantly between cemetery areas and/or individuals with and without skeletal changes consistent with lepromatous leprosy.*

Wear Feature	ORI	TCI	Wear Feature	ORI	TCI
Area A Mean	1.42	10.59	**Leprosy Absent Mean**	1.48	12.94
Standard Deviation	0.10	4.94	**Standard Deviation**	0.12	5.86
Area B Mean	1.5	12.45	**Leprosy Present Mean**	1.44	10.11
Standard Deviation	0.10	5.85	**Standard Deviation**	0.10	4.67
t-value	-1.99	-0.84	**t-value**	1	1.31
Degrees of Freedom	22.00	21.40	**Degrees of Freedom**	22.00	20.95
p value*	0.06	0.41	**p value***	0.33	0.2
Effect size	-0.81	-0.34	**Effect size**	0.41	0.53
95% CI effect size	-1.69 to 0.07	-1.19 to 0.51	**95% CI effect size**	-0.44 to 1.26	-0.32 to 1.39
Statistical Power	0.48	0.13	**Statistical Power**	0.17	0.24
H_0	Not Rejected	Not Rejected	**H_0**	Not Rejected	Not Rejected

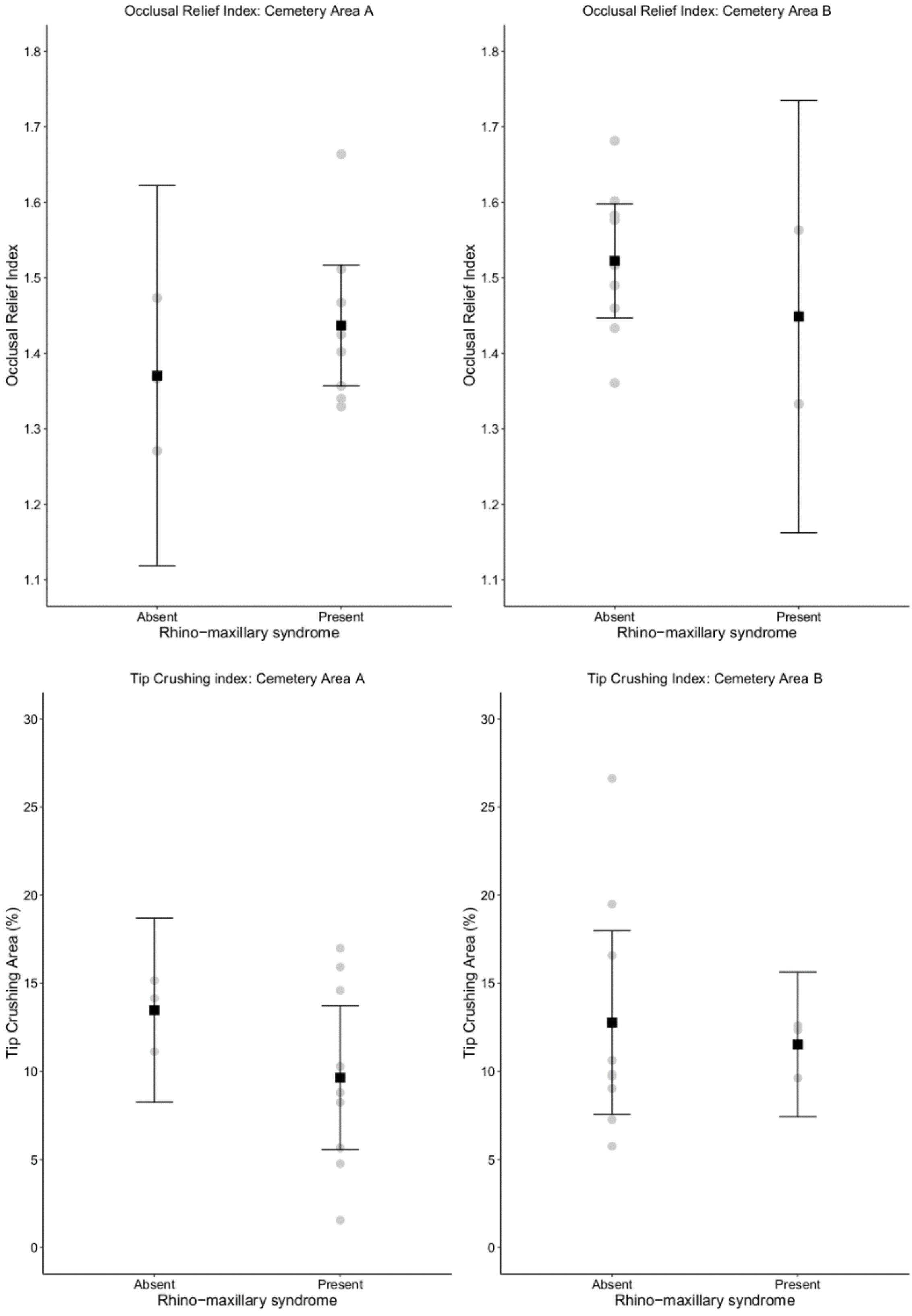


Figure 178: Dot plots with mean values plotted with 95% confidence intervals comparing mean ORI and TCI values in the lower second molars between cemetery areas (Areas A and B) and individuals with and without skeletal changes consistent with leprosy from the St James and St Mary Magdalene assemblage, Chichester (CH86).

6.2.2.3.1 Summary

Individuals with rhino-maxillary syndrome exhibited wear facet patterns on the lower second molars characterised by larger proportions of BPI wear when compared to those without osseous changes indicative of lepromatous leprosy. Cemetery area did not significantly influence relative wear facet area proportions. Dip angles did not differ significantly between individuals with and without lepromatous leprosy. A slight tendency was observed towards more obliquely inclined dip angles in area B, the temporally later portion of the cemetery. ORI and tip crushing values did not differ significantly between individuals with and without leprosy or between cemetery areas.

7 Discussion

7.1 Do dental wear facet patterns indicate that a change in masticatory behaviours occurred between the Mediaeval and Early Post-Mediaeval periods (AD1100-1700) and the Industrial era (1700-1900AD)?

7.1.1 Gradient of Dental Wear and Occlusal Relief

7.1.1.1 ***A reduction in the gradient of dental wear between the first and second molars should occur****.*

The pre-Industrial assemblages showed significantly greater gradients of dental wear between the first and second molars when compared to the Industrial material. The gradient of dental wear between the second molar and the other tooth classes in the dentition, however, were not markedly larger in the Mediaeval and early Post-Mediaeval periods. The third molar was typically less worn relative to the second molar in the pre-Industrial material. All individuals examined exhibited at least one lower second molar with a Smith wear score of 2 providing a stable reference between the wear patterns expressed. Teeth erupting in succession, such as the first and second molars with an interval of approximately six years (Hillson 1996), provide an estimation of differences in the rate at which dental wear accrues between assemblages (Miles 1963; Scott 1979; Smith 1972). The greater disparity between molar wear scores for both the first and second molars and the second and third molars, in the Mediaeval and early Post-Mediaeval periods suggested a higher abrasive load within their dietary regimes.

Wear gradients were found to be significantly smaller in the St Bride's, London, and St Peter's Wolverhampton, material than in the Coronation Street, South Shields, and early St Michael's Litten, Chichester, assemblages. The later date of the St Bride's and St Peter's assemblages (c.1800-1850) likely meant that access to more heavily processed dietary staples, such as refined white bread, was more extensive than for the individuals interred at St Michael's Litten (Collins 1975). The Coronation Street assemblage is approximately contemporary with the two lower wear gradient assemblages (cemetery closed c.1855), however, their dietary composition may have included greater quantities of less heavily processed grains, such as barley and oats (Eden 1795).

7.1.1.2 *The occlusal relief of the lower second molar would be expected to be less heavily reduced in the Industrial period across the entire occlusal surface.*

ORI values for the lower second molar were greater in the Industrial period as anticipated. Moderate cusp reduction was generally restricted to the buccal cusps of individuals from the Industrial period, whereas, the reduction of occlusal topography was typically more advanced across the entire occlusal surface in individuals from the Mediaeval and early Post-Mediaeval periods. Greater ORI values are consistent with a reduction in the abrasive content of the dietary staples consumed following shifts in milling technology in the 18th and 19th centuries (M'Kirera and Ungar 2003; Stone 2006).

Furthermore, occlusal relief guides and modifies the initial jaw movement pathway. This guidance is, however, reduced with progressive wear (Koenigswald *et al.* 2013; Maier and Schneck 1982). The retention of steeper occlusal topography in the Industrial period would result in a greater restriction of potential movement pathways during mastication. The possession of relatively unworn occlusal forms in the Industrial period reflects the shift towards the retention of a 'neotenous' pattern of occlusion later into life in industrialised 20th-21st century groups, which were previously evident only among the younger age categories of pre-industrial groups (Kaidonis *et al.* 2014).

In addition, finite element analysis simulations of power strokes involving progressively worn specimens have indicated that the unworn occlusal form concentrates tensile forces in the buccal cervical region of lower post-canine teeth rather than the forces being directed to the root apex, as is the case in more worn specimens (Benazzi *et al.* 2016). This may lead to a greater propensity towards dental failure due to the repeated concentration of forces in the cervical region of the tooth during mastication (Benazzi *et al.* 2013b).

7.1.1.3 *Higher intensities of tip crushing wear would be anticipated in the pre-industrial group due to the incorporation of larger quantities of abrasive particles in the diet resulting in more extensive cusp removal.*

Tip crushing wear was not considered alongside phase I and II wear as tip crushing wear cannot be attributed to the normal power stroke (Fiorenza *et al.*

2018). Tip crushing areas were found to have significantly less obliquely inclined dip angles than either phase I or phase II wear facets in the current research highlighting the difference in their functional role during mastication. The formation of tip crushing areas might be principally associated with puncture-crushing cycles occurring prior to the occurrence of chewing *sensu stricto* within the chewing sequence (Fiorenza *et al.* 2020; Janis 1990;). The shallower inclination of tip crushing areas observed would be consistent with the more vertically orientated direction of jaw movement that typifies puncture-crushing cycles (Hiiemae 1978; Maier 1984).

Tip crushing areas were significantly larger when expressed as a proportion of the cross-sectional area of the lower second molar in the Mediaeval and early Post-Mediaeval periods. In addition, tip crushing areas were less obliquely inclined in the Mediaeval and early Post-Mediaeval periods. The enlargement of these shallowly inclined subcircular wear areas suggested more advanced dental wear and cusp reduction during puncture-crushing cycles in the pre-industrial material. In herbivorous mammals, enlarged tip crushing areas appeared associated with the consumption of dietary items that have to be pulped or fractured, such as fruit, nuts, seeds and buds (Janis 1990), however, these items did not feature prominently in the diets of either period (Burnett 1989; Stone 2006).

7.1.1.4 Discussion of differences in dental wear gradient and occlusal relief

Several factors likely contributed to the greater gradient of dental wear and reduction in occlusal relief in the Mediaeval and early Post-Mediaeval periods. A decrease in the number of chewing cycles required to orally process less biomechanically demanding and more heavily processed dietary staples likely occurred in the Industrial period (Perren 1990; Stone 2006; Teaford and Oyen 1989). More extensive lateral movements of the jaw are used to process tougher foods which results in flatter occlusal wear planes at more rapid rates (Watson 2008). Finally, greater quantities of abrasive particles would have been retained within mediaeval flour prior to post-mediaeval shifts in milling technology (Burnett 1989; Stone 2006).

Prohibitions were placed on the use of rotary quern stones in the 12th century to protect manorial incomes shifting the focus of grain processing to manorial mills rather than domestic contexts (Ottoway and Rogers 2002). The millstones used by mediaeval mills were frequently constructed from imported basaltic lava from the Niedermendig district of Germany, such as at the mediaeval Yorkshire village of Wharram Percy (Farmer 1992), or sandstone (Millstone grit and Welsh stone) (Enright, Watts and Bircher 2002). In addition, the sieving of the meal produced was performed by hand using a wool or linen sieve resulting in the retention of many of the coarser particles within the flour in the Mediaeval period (Petersen and Jenkins 1995). Consequently, the bread consumed in the Mediaeval period would have contained higher proportions of exogenous abrasive particles, such as quartz and silica; this would include both wind-blown minerals introduced during harvesting and preparation as well as material derived from the milling process itself.

Experimental nanowear studies have indicated that quartz dust is harder than enamel and capable of immediately fracturing and removing chips from the enamel surface. Tooth tissue chips that have already been removed from the dental surface may also then be active in the process of dental wear. Siliceous phytoliths, which are softer than enamel, are capable of deforming the enamel surface. It remains debated whether phytoliths play a subordinate role to quartz grit in processes of dental wear (Kaiser *et al.* 2018; Lucas *et al.* 2013; Lucas *et al.* 2020; Ungar *et al.* 2020). In contrast, developments in milling technology and the processes used to sieve the meal in the 18th and 19th centuries would have reduced the quantities of abrasive particles in the dietary staples consumed (Burnett 1989; Perren 1990). The differences in wear gradient between the two periods was consistent with the developments in milling technology that occurred during the Industrial period. Enlarged tip crushing wear areas in the Mediaeval and early Post-Mediaeval material may also have resulted from a more rapid reduction in cusp height during puncture-crushing cycles due to repeated exposure to higher quantities of exogenous abrasive particles within the dietary staples consumed.

The dental evidence supports the historically reported contrasts in food preparation technologies between the Mediaeval and Industrial periods. A shift from the abrasion dominated model of dental wear characteristic of pre-Industrial assemblages had started to occur in the Industrial-era as the foods consumed became more heavily refined (d' Incau *et al.* 2012). The dietary changes occurring in the 18th-19th centuries were followed by the transition to a modern model of dental wear dominated by erosive wear mechanisms and the retention of a largely unworn occlusal form late into life (d'Incau *et al.* 2012; Kaidonis 2008; Kaidonis *et al.* 2014; Kaifu *et al.* 2003).

7.1.2 OFA: Comparison of Wear Facet Patterns of the lower second molars between the Mediaeval and Early Post-Mediaeval periods and the Industrial era.

There were no significant differences between the relative wear facet areas of lower second molars taken from either the left or right side. The frequency with which each wear facet position was expressed across the lower second molar did not differ markedly between the two periods. Facet 7 was slightly more commonly developed in the Mediaeval and early Post-Mediaeval periods reflecting greater involvement of the metaconid in the power stroke. Facet 10 was more common in the Industrial period as it was more frequently incorporated into the tip crushing area on the protoconid in the pre-Industrial material.

7.1.2.1 The composition of the wear facet area of the lower second molar should indicate a decrease in the lateral component of jaw movement during the power stroke as dietary content became more heavily processed.

The Mediaeval and early Post-Mediaeval lower second molar macrowear pattern was dominated by greater proportions of buccal phase I and lingual phase I wear. Greater traverse jaw movement has been associated with the enlargement of lingual phase I facet areas in modern hunter-gatherers. This included groups, such as the Khoe-San and Australian Aborigines, who were more reliant on hard and abrasive food stuffs, such as seeds and other plant materials (Fiorenza *et al.* 2011; Fiorenza *et al.* 2020). Larger buccal phase I facet areas in the pre-Industrial group are consistent with a prominent and prolonged shearing action during the incursive portion of the masticatory stroke and the consumption of tougher foods (Fiorenza *et al.* 2011a; Janis 1990).

In contrast, Industrial individuals frequently exhibited poorly developed phase I wear facets and had wear facet patterns dominated by phase II wear. This may reflect a briefer phase I shearing action with a reduced lateral component of movement. Lingual phase I wear facets in the Industrial period, particularly facets 5 and 7 located on the metaconid, were frequently small in size suggesting the consumption of less abrasive and softer food items that do not require large traverse jaw movements during oral processing (Fiorenza *et al.* 2011).

The large proportion of phase II wear (>40%) in individuals from the Industrial period is in contrast to previous studies that have examined wear facet area proportions in modern hunter-gatherers and Palaeolithic anatomically modern humans and Neanderthals (Fiorenza *et al.* 2011a; Fiorenza *et al.* 2015; Oxilia *et al.* 2020) and the majority of pre-Industrial individuals examined in the current analysis. In extant ungulates, large phase II facets have been associated with a more heavily frugivorous diet (Janis 1990), however, this relationship between increased frugivory and large phase II facets was not apparent in modern hunter-gatherers (Fiorenza *et al.* 2011a). Large phase II facets indicate extended excursive contacts during the power stroke, more consistent with the larger talonid basins present in great ape lower molars rather than anatomically modern humans (Knight-Sadler and Fiorenza 2017; Zanolli *et al.* 2019). This indicates that phase II facet areas in industrialising modern humans are likely principally performing a different role during mastication.

Some authors have associated phase II facets with a grinding function, combining a shearing and crushing action, during phase II of the power stroke (Janis 1990; Kay and Hiiemae 1974). Experimental observation of bone strain and muscle activity during the power stroke in primates and dental microwear textures, however, indicated that the forces principally responsible for phase II facet creation are likely active immediately prior to, and possibly during, maximum intercuspation (Hylander *et al.* 1987; Krueger *et al.* 2008; Wall *et al.* 2006). Similarly, the peak in contact force also occurred during maximum intercuspation during a finite element analysis simulation involving antagonist human first molars and their supporting tissues. Contact force decreased rapidly following maximum intercuspation, however, contact force was still sizeable during phase II of the power stroke (Benazzi *et al.* 2016). In addition, a similar pattern of jaw adductor muscle activity was found in a study of EMG profiles during mastication in modern humans. Peak muscle activity occurred prior to maximum intercuspation and declined rapidly during jaw opening in the early stages of the chewing cycle. The peak in muscle activity occurred at the time of or immediately after maximum intercuspation in the middle and late stages of mastication (Grigoriadis *et al.* 2014). In this model of food breakdown during the power stroke, food particles are compressed against phase II wear facets, formed within the talonid basin in the lower molars, during the terminal part of phase I of the power stroke and during maximum intercuspation, proximate to or during the peak in jaw adductor muscle force (Kruegar *et al.* 2008).

Phase II wear facets may also be active during the puncture-crushing cycles involved in the oral processing of softer and less biomechanically demanding dietary staples (Crompton and Hylander 1980; Teaford 1985; Wall *et al.* 2006). This suggests that in modern humans from the Industrial period, large phase II facets, accompanied by a reduction in the size of shearing phase I wear, most likely reflects an amplification of the crushing mechanism during the terminal part of phase I and the beginning of phase II of the power stroke rather than an exaggeration of phase II of the power stroke itself. An increase in terminal phase I/phase II wear areas might be anticipated in individuals consuming a habitually softer diet as food is crushed within molar basins during power strokes that involve a relatively small lateral component. This contrasts with coarser pre-industrial foods that required a pronounced shearing action and prolonged chewing cycles (Kaidonis 2008; Kaifu 2000; Kullmer *et al.* 2009).

7.1.2.2 The wear facets on the lower second molar should be more obliquely inclined due to anticipated differences in the inclination of each phase of the power stroke.

Buccal phase I and lingual phase I wear facets were significantly more obliquely inclined in the Industrial period. Phase II wear facets were slightly less steeply inclined in the Mediaeval and early Post-Mediaeval periods but not significantly so. The inclination of molar wear provides a reflection of food preparation and processing techniques and the quantities of abrasive material incorporated into the diet (Fiorenza *et al.* 2020; Le Luyer, Rottier and Bayle 2014; Smith 1984). The steeper inclination of dip angles in the Industrial period supports a reduction in the demands placed on the masticatory apparatus as dietary content became increasingly processed. Changes in milling technology during the 18th-19th centuries reduced the biomechanical requirements for the oral processing of bread, the principal dietary staple consumed during the period, by producing more heavily refined grades of flour with increased removal of the bran and other abrasive particles (Burnett 1989; Perren 1990). Smith argued that more oblique wear in agriculturalist groups relative to hunter-gatherers was closely associated with their consumption of more heavily processed and cooked grains (1984). Dip angles were found to differentiate proto-farmers (Natufians) from traditional hunter-gathers; proto-farmers had more obliquely inclined wear facets. Steeper wear facet inclination was also likely reflective of reduced quantities of extrinsic and intrinsic abrasives in the diets of agriculturalists relative to modern hunter-gatherers (Fiorenza *et al.* 2018). This trend towards increasingly obliquely inclined wear facets appears to have continued into the Industrial period as diets became less biomechanically demanding and incorporated fewer intrinsic and extrinsic abrasive particles.

In addition, the increasingly steep wear facets in the Industrial period may also reflect a reduction in the lateral component of the masticatory stroke (Smith 1984). This is consistent with the inferences made using the relative wear area data. Clinical feeding studies have observed differences in masticatory strokes in response to changes in the resistance and consistency of the food being processed. Tougher foods are more frequently processed with a larger lateral component of jaw movement, whereas, soft food, such as modern bread, are characterised by slim drop shaped movements often with a greater vertical amplitude (Laird 2017; Pröschel and Hofmann 1988). In Cebus, foods with a higher toughness were found to be chewed with a greater lateral and reduced vertical component when compared to lower toughness test foods (Reed and Ross 2010). This steeper angle of approach during chewing cycles and reduced lateral element during the power stroke would be concordant with the steeper wear facet dip angles observed in the Industrial period.

During the Industrial period, phase I wear facets exhibited significantly steeper dip angles than the phase II wear facets. Phase I wear facets have been associated with shearing activity during the incursive movement of the power stroke (Janis 1990; Kay and Hiiemae 1974). The steeper inclination of these wear facets would support a strongly vertically directed incursive movement with a moderate lateral deviation during the first part of phase I of the power stroke. The incursive movement in the Industrial period would have also been more closely guided by the retention of greater amounts of the occlusal topography and cusp height, as indicated by the larger ORI values that characterised the Industrial era.

The steepness of the occlusal topography would have likely amplified the strongly vertically directed shearing action occurring during phase I of the power stroke. The shallower inclination of phase II wear facets indicates their role principally in puncture-crushing activity and crushing activity prior to and during maximum intercuspation during which jaw adductor muscle force typically peaks in anatomically modern humans (Grigoriadis *et al.* 2014).

In contrast, there was a lack of significant differences between the dip angles of phase I and II wear facets in the pre-Industrial group. This is likely attributable to the inclusion of greater quantities of intrinsic and extrinsic abrasive particles within the Mediaeval diet, including coarser parts of the grain and material introduced by the milling process (Drummond and Wilbraham 1957; Stone 2006). The larger abrasive load of the Mediaeval diet was also reflected by the reduction of occlusal topography across the entirety of the tooth, reflected by smaller ORI values and larger tip crushing areas. The magnitude of the difference between pre-Industrial and Industrial phase II dip angles was markedly less that the magnitude of difference between the inclination of their phase I facets. This suggests that the principal mode of formation of phase II wear facet areas was consistent between the two periods and probably occurred prior to and during maximum intercuspation. Greater perpendicular masticatory forces during the phase I shearing action in response to the tougher foods being consumed contributed to the less obliquely inclined phase I wear facets in the Mediaeval and early Post-Mediaeval periods (Smith 1984; Fiorenza *et al.* 2018).

Furthermore, in contemporary Australian Aborigines, with advanced tooth wear and a substantial reduction in cusp height, it was observed that the masticatory stroke shifted from a tear drop shape to a broader pattern with an extended lateral shift. This shift has been compared to the wide lateral component inherent in the masticatory strokes of herbivorous species in order to achieve functional efficiency when breaking down coarser and tougher foods (Barret 1969; Kaidonis *et al.* 2014). In Aborigines, the potential for lateral displacement during mastication was enhanced by alternate intercuspation (section 3.7.4); the divergence in the pattern of arch growth resulting in a greater maxillary than mandibular arch breadth. In contrast, dental arches are more commonly parallel in modern populations (Brown, Abbot and Burgess 1987; Brown *et al.* 2011). The high rate of dental wear, the more heavily reduced and more shallowly inclined occlusal topography of the molar row and the larger quantities of phase I wear characteristic of the Mediaeval and early Post-Mediaeval periods indicate a similar process of adaptation of the masticatory cycle to the greater toughness of the pre-Industrial diet. The greater occlusal relief and steepness of wear facets during the Industrial period would have resulted in a more orthal hinge-like action during mastication, more typical of carnivorous mammals, and more appropriate for the shearing and squashing of their increasingly heavily processed food stuffs (Kaidonis *et al.* 2014).

7.1.2.3 There may be slight changes in wear facet orientation suggestive of differences in the directionality of the incursive and excursive components of the power stroke.

There was a lack of significant differences between dip direction values for all of the wear facet positions, except for facet 3. The mean values for the dip direction for facet 3 did not differ substantially between the two periods, however, and fell within the expected range for lateroprotrusive wear facets. The mean value, concentration and distribution of dip direction values conformed to the directions of jaw movement anticipated when applying OFA to anatomically modern humans (Kullmer *et al.* 2009; Kullmer *et al.* 2012). This indicated that the vast majority of the wear facets examined were produced by masticatory behaviours during the power stroke rather than non-masticatory tooth use. The deviation of wear facets from their anticipated orientation within the occlusal compass scheme has been associated with the use of teeth as tools in Neanderthals (Fiorenza 2015) and anatomically modern humans dating to the Middle Palaeolithic (Fiorenza and Kullmer 2013).

The lack of significant differences between the orientation of incursive and excursive movements between pre-Industrial and Industrial groups suggests a consistent sequence of jaw movement in anatomically modern humans (van der Bile *et al.* 2006). Collectively, the anatomical configuration of the muscles of mastication, the morphology of the temporomandibular joint (TMJ) and the topography of the antagonistic dentition are integral to the control of jaw movement. The TMJ determines the degrees of freedom of movement (Koenigswald *et al.* 2013). The basic rhythmic activity of jaw-opening and jaw-closing is likely evoked by a central pattern generator located in the brain stem and has even been shown to be present in animals lacking sensory feedback from peripheral receptors (Goodwin and Luschei 1947; Lund and Kolta 2006; Kolta *et al.* 2010; Weijs 1994). Sensory inputs, however, modify chewing cycles, particularly the relative lateral and vertical components of jaw movement, according to food properties (Peyron *et al.* 2002). Occlusal relief guides and modifies the initial jaw movement pathway, however, this guidance is reduced with progressive wear (Koenigswald *et al.* 2013; Maier and Schneck 1982).

These factors result in overarching commonalities in the direction of incursive and excursive movements within a given species. The incursive movement in anatomically modern humans proceeds along a lingually directed axis and the excursive movement proceeds in a linguo-mesiolingually orientated direction. A similar orientation of the incursive and excursive components of the power stroke in anatomically modern humans, despite a slightly greater mesiolingual component to the incursive movement, was observed during finite element analysis in a study by Benazzi *et al.* (2016).

7.1.2.4 Higher frequencies of ante-mortem tooth loss are anticipated in the Industrial period, partly due to consumption of a more cariogenic diet, higher levels of dental caries and associated tooth extraction. Clinical evidence suggests that higher levels of ante-mortem tooth loss, particularly of the posterior teeth, will impact masticatory performance.

Prevalence rates for cavitated carious lesions and ante mortem tooth loss were significantly greater among individuals from the 18th and 19th centuries than in the Mediaeval and early Post-Mediaeval periods. Higher per individual prevalence rates of ante-mortem tooth loss and cavitated carious lesions were characteristic of the St Bride’s, St Peter’s and Coronation Street material. The St Bride’s assemblage comprised many older and high-status individuals and reflected a parish embedded within the London dietary pattern, which comprised cariogenic white wheaten bread and sweetened tea (Burnett 1989; Harvey 1967). The preference for and greater availability of more heavily processed cariogenic white bread was well-established in London from the 1750s onwards prior to diffusing to the majority of England by 1800 (Collins 1975; Fay 1923). These later assemblages would have been embedded within the distinctive urban working-class dietary pattern, which was increasingly reliant on commercially made products; bread being the first and foremost ‘convenience food’ (Burnett 1989).

A similar parallel increase in the prevalence of carious lesions and ante-mortem tooth loss was reported in assemblages dating to the 18th-19th centuries in a meta-analysis of 29 cohorts from across Europe (Müller and Hussein 2017). A temporal increase in caries and ante-mortem tooth loss prevalence, with particularly marked increases in the early Modern and Industrial periods, was also found in a meta-analysis of assemblages from 103 localities across Europe dating from AD300-1900 (Witwer-Backofen and Engel 2018). An increase in the dominance of potentially cariogenic bacteria alongside a reduction in the biodiversity of Industrial-era plaques has been also reported. This was likely associated with the incorporation of refined grain and processed sugar increasingly within the diet (Adler *et al.* 2013).

The increase in the prevalence of cavitated carious lesions in the Industrial period reflected the transformation of sugar from a prestigious foodstuff consumed conspicuously by the elite in the Mediaeval period to a commonplace luxury. Sugar came to the forefront in the later part of the 17th century as it was entangled within the vast expansion of tea consumption. Tea was readily taken up by the upper classes and then later by the poor, particularly during the 19th century. Sweetened tea began to displace alcoholic beverages as the drink of preference. Sugar became inculcated within the rhythms of daily life of every strata of society. Among the poor, treacle was often spread on bread or mixed with porridge to make it more palatable. The emergent middle classes in the late 18th century consumed hot and cold puddings and pastries with increasing frequency, sometimes forming the second or third course of meals. The extraction of sugar from beets in the 19th century also increased availability (Mintz 1985). The consumption of these imperial products of empire enmeshed the consumer within a complex web of production and trade involving slavery and the acquisition and defence of territories (Bickham 2008).

The prevalence rates for dental caries were much lower in the Industrial-era assemblages examined than have been reported in other contemporary assemblages (1.92%-7.92%). In the assemblage from Ashton-under-Lyne (average date of death c.1841), prevalence rates for individuals from the age categories most comparable to the individuals in the current study were 18.00% and 31.90% (Corbett and Moore 1976). Similarly, high caries prevalence rates of 26.50% and 21.50% were reported for St Bride’s lower churchyard and Chelsea

Old Church, respectively, dating to the 18th and 19th centuries (Mant and Roberts 2014). Preferential selection of individuals with intact occlusal surfaces to enable wear facet analysis and lower second molar wear scores of 2 (Smith 1984) resulted in a study sample predominantly composed of individuals from younger skeletal age groups. In addition, teeth were only scored as carious if a cavity was present involving the crown resulting in lower prevalence rates relative to studies that score carious lesions in their early stages of formation.

Prevalence rates of cavitated carious lesions did not differ significantly between the sexes in either period. It has been theorised that females have generally higher prevalence rates of caries due to a combination of hormonal, reproductive and social factors (Lukacs 2011). A previous study found a slightly higher frequency of carious lesions in females than males in an assemblage from Mediaeval London dating from AD1120-1538 (Walter, DeWitte and Redfern 2016). A meta-analysis supported this hypothesis by finding greater prevalence rates of ante-mortem tooth loss among females partially associated with a greater caries load (Witwer-Backofen and Engel 2018). In contrast, higher caries prevalence rates in females were not found in a prior meta-analysis (Müller and Hussein 2017) and similar prevalence rates for both sexes were found in several other studies (Corbett and Moore 1976; Esclassan *et al.* 2009; Moore and Corbett 1973; Whittaker and Molleson 1996). The current research also does not support greater caries and ante-mortem tooth loss prevalence among females, largely irrespective of group. This conclusion is preliminary, however, as a thorough assessment of dental pathology was not the primary objective of the current research and the number of individuals examined was relatively small.

In the current study, the prevalence of ante-mortem tooth loss was significantly greater in the older age-at-death categories in both periods. A very slight increase in prevalence of dental caries was observed in the older age-at-death category in both periods. In the majority of populations, successive age-cohorts show an increase in the number of carious lesions per individual (Hillson 2001), however, the progression of ante-mortem tooth loss was found to be more closely associated with age-at-death in a recent meta-analysis (Witwer-Backofen and Engel 2018). This is supported by the current study.

The lower prevalence rates of dental pathology in the Mediaeval and early Post-Mediaeval periods are consistent with the consumption of a diet with a lower sugar content that contained greater quantities of abrasives (Drummond and Wilbraham 1957; Moore and Corbett 1973). There were no significant differences between the pre-Industrial assemblages examined with the exception of St James' and St Mary Magdalene, Chichester. This cemetery was associated with the only leprosarium reported in Sussex during the 12th-13th centuries and 50% of the individuals examined from the assemblage exhibited skeletal changes consistent with lepromatous leprosy (Magilton *et al.* 2008). Rhino-maxillary syndrome, identified by the reabsorption of the anterior nasal spine and the alveolar process and palatine process of the maxilla, can lead to the loss of the central and lateral upper incisors in cases of extensive resorption and greater ante-mortem tooth loss (Anderson and Manchester 1992).

In both periods, the highest prevalence rates of cavitated carious lesions and ante-mortem tooth loss were associated with the molar teeth. Prevalence rates were lowest in the anterior dentition and intermediate in the premolar region. This is consistent with previous studies that have reported higher frequencies of carious lesions in the molars in both pre-18th century and 18th-19th century assemblages (Corbett and Moore 1976; Moore and Corbett 1973; Müller and Hussein 2017). Previous studies have similarly reported the greatest frequency of carious lesions in the molar teeth due to the function of the molar teeth within the power stroke and their complex occlusal morphology, including deep fissures that are common sites of plaque accumulation (Mant and Roberts 2015; Wasterlain, Hillson and Cunha 2009).

7.1.2.5 Mesial drift due to tooth loss and the loss of antagonistic teeth will alter occlusal relationships and may impact the dental wear patterns of the teeth involved. It is hypothesised that ante-mortem tooth loss may contribute to the overall differences observed in dental wear patterns between the two periods.

Mesial drift is the process responsible for closing the interproximal spaces between teeth, which result either from interproximal attrition or ante-mortem tooth loss (Kaifu *et al.* 2003; Yilzma *et al.* 1980). It was hypothesized that the ante-mortem loss of the first molar adjacent to the lower second molar that was the subject of OFA might influence the occlusal wear pattern that developed. The process of mesial drift following the loss of the mesially situated first molar has the potential to alter the antagonistic teeth in the upper dentition with which the lower second molar interacts during the power stroke. As the gap between the lower second molar targeted by OFA and the remaining lower teeth in the quadrant decreases, it is more likely that the second molar will occlude with the upper first molar, provided that this tooth has also not been lost ante-mortem.

The loss of the adjacent lower first molar did not significantly impact the relative wear facet area of the lower second molar targeted in either period. In addition, the loss of the antagonistic upper second molar did not result in a significant difference in relative wear facet area on the lower second molar. In the Industrial period, there was a slight tendency towards more limited development of phase II wear facet areas in the lower second molar following the loss of its second molar antagonist.

In a study of 54 individuals over a two-and-a-half-year period following premolar extraction, the distance of physiological drift approximated the width of the lost premolar (Weber 1969). A clinical assessment of the rate of closure of the extraction spaces resulting from premolar removal have indicated that the speed of mesial drift decreases over time following an initial phase (lasting around six months) of more rapid movement and tipping into the available space (Teng *et al.* 2019). The tipping of the remaining molars would likely modify patterns of occlusion, however, as dental macrowear patterns reflect the accumulation of dental wear over a substantial portion of an individual's lifetime (Fortelius and Solounias 2000), it remains unclear the duration of ante-mortem tooth loss required for the presentation of occlusal wear patterns to be quantitatively altered.

7.1.3 Differences in dynamic OFA simulations between the two periods

7.1.3.1 There should be a decrease in the lateral component of the movement of the lower molars during dynamic simulations of the power stroke; a power stroke dominated by a more strongly vertically directed chopping action might be anticipated.

An extended lateral displacement and grinding action occurred during phase I of the power stroke in the majority of simulations conducted for the Mediaeval and early Post-mediaeval periods. A steady increase in wear facet contact area occurred as the lower molars moved from a lateral position into maximum intercuspation during the incursive phase I movement. In contrast, the initial part of phase I of the power stroke for the simulations conducted for Industrial individuals involved a rapid increase in contact area and very limited lateral deviation of the lower molars as they moved into maximum intercuspation. This is consistent with the more vertically orientated shearing or pulping action required to reduce more heavily processed foodstuffs indicated by the OFA study of the wear patterns on the lower second molars.

Phase II wear facets were involved immediately prior to maximum intercuspation during all the power stroke simulations conducted. As a result, a dramatic increase in wear facet contact area occurred in all the individuals examined during the terminal portion of phase I of the power stroke. This period of mixed phase I and II contact corresponded with the peak in jaw adductor muscle activity described in EMG studies of modern humans and other non-human primates (Grigoriadis *et al.* 2014; Hylander *et al.* 1987; Wall *et al.* 2006).

The simulations performed for Industrial individuals indicated that phase II contacts were rapidly lost following maximum intercuspation and that phase II of the power stroke typically constituted a small portion of the total number of time steps for each simulation. Phase II wear facets, however, frequently constituted the largest portion of the total wear facet area in individuals from the Industrial period. This further supports the association of phase II wear in the Industrial period with the terminal portion of phase I and the crushing action occurring during maximum intercuspation rather than phase II of the power stroke itself.

In contrast, a more well-defined phase II movement was apparent during many of the Mediaeval and early Post-Mediaeval power stroke simulations. This phase II movement involved relatively prolonged contacts between phase II facet areas as the lower teeth moved mediotrusively. Consequently, in the Industrial period, phase II facet areas appeared primarily involved in the crushing activity immediately prior to and during maximum intercuspation. In the pre-Industrial group, these facet areas appear to be involved in both this crushing activity and a more clearly defined phase II movement.

7.1.4 Theoretical chewing models for each period

The differences in occlusal wear pattern used to inform the reconstruction of the theoretical chewing models for each period are summarised in Table 113.

Table 113: Summary of the differences in wear facet expression between the Mediaeval and Early Post-Mediaeval periods and the Industrial period in the current research.

Wear Pattern Feature	Contrast between pre-Industrial and Industrial groups	Possible Interpretation and implications for masticatory behaviours
Wear Facet Proportions	Greater proportion of phase II wear among Industrial individuals relative to phase I.	Reduction in lateral component of the power stroke during oral processing.
Wear Facet Dip Angles	Phase I facet dip angles were significantly more steeply inclined in the Industrial period.	A more vertically orientated shearing component during phase I of the power stroke during the Industrial period.
Wear Facet Dip Direction	Very limited differences in dip direction across wear facet positions.	Orientation of the power stroke is principally medio-lateral in both periods.
Occlusal Relief Index	Higher occlusal relief and complex topography in the Industrial period.	Higher occlusal topography will be more restrictive of the range of masticatory movements.
Tip Crushing	Larger areas of tip crushing wear expressed as a proportion of 2D crown area in the pre-Industrial group.	Increase in behaviour responsible for tip crushing wear (clenching/bruxing?) or reflects greater abrasiveness of mediaeval dietary components.
Dynamic OFA simulations	Power stroke more protracted during the earlier periods with key stages occurring at later time steps. The rate of change in collision contact area was also less rapid.	Indicates a greater lateral component to the power stroke in the Mediaeval and early Post-Mediaeval periods. This may have resulted in a more pronounced shearing action relative to the rapid increase in contact area during the crushing action apparent in the Industrial period.

7.1.4.1 Mediaeval and Early Post-Mediaeval Periods

There was typically a greater lateral component during the phase I movement of the power stroke among Mediaeval and early Post-Mediaeval individuals. This was indicated by the elongation of this phase of the power stroke during the power stroke simulations relative to the Industrial period. In addition, phase I wear facets were more shallowly inclined and occupied a greater proportion of the total wear facet area among the pre-Industrial group. Well-developed lingual phase I facet areas, more characteristic of the lower second molars examined that were dated to the Mediaeval and early Post-Mediaeval periods, also indicated greater lateral displacement of the jaw during the mastication of more abrasive, tougher and harder food stuffs (Fiorenza *et al.* 2020). The increased lateral component that characterised the pre-Industrial power stroke resulted in a less rapid increase in wear facet area prior to maximum intercuspation relative to the Industrial period during the power stroke simulations.

A rapid decrease in contact area occurred immediately following maximum intercuspation among the individuals from the Mediaeval and early Post-Mediaeval periods. Following this, however, a distinct phase II movement was apparent during the majority of their power stroke simulations. This phase II movement involved relatively prolonged contacts between phase II facet areas as the lower teeth moved mediotrusively. In the pre-Industrial group, these facet areas appear to be involved in both the crushing activity during the terminal portion of phase I of the power stroke and a more clearly defined phase II movement despite forming a smaller proportion of the overall wear facet area of the lower second molar. The power stroke was largely medio-laterally orientated in both periods examined.

Smaller ORI values and larger tip crushing areas in the Mediaeval and early Post-Mediaeval individuals may likely reflect greater quantities of intrinsic and extrinsic abrasive particles within their dietary staples (Martin *et al.* 2020; Smith 1984). The biomechanical demands placed on the masticatory system would have been larger given the greater hardness and toughness of the dietary staples consumed. This is consistent with the greater mandibular robusticity and wider dental arcades typical of individuals from the Mediaeval period relative to their Industrial counterparts. This is indicative of weaker development of the main masticatory musculature as a ramification of the transition to increasingly processed dietary staples from the 18th century onwards (Kaifu 1997; Rando *et al.* 2014).

The Mediaeval and early Post-Mediaeval chewing model is more similar in character to herbivorous dentitions that require a broad tear shape with an extended lateral component to maintain functional efficacy as crown height is steadily reduced by wear (Kaidonis *et al.* 2014).

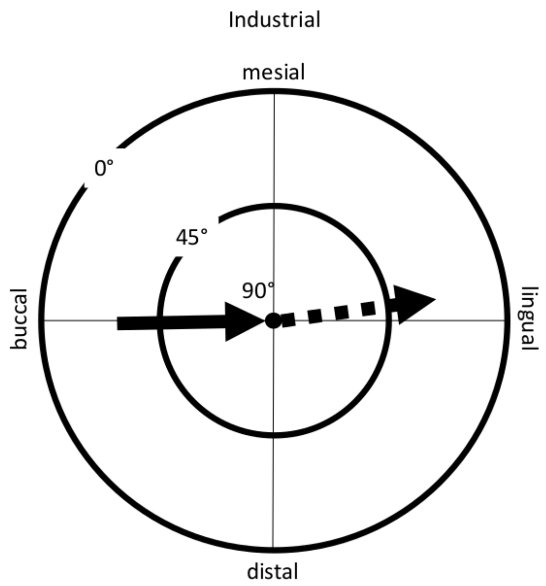
7.1.4.2 Industrial Period

A strongly vertically orientated shearing action characterised the first part of phase I of the power stroke. This was indicated by the steep dip angles of phase I facets in the Industrial period. The movement would have been more closely guided and restricted by the occlusal topography of the teeth as greater occlusal relief characterised Industrial individuals. The small size of phase I facets relative to phase II facets in the Industrial period reflects the smaller lateral component of movement during the phase I shearing action when compared to the pre-Industrial group.

The later part of phase I of the power stroke involved a rapid increase in both phase I and phase II contact areas prior to maximum intercuspation. Human and non-human feeding studies indicated that jaw adductor muscle force peaks immediately prior to maximum intercuspation (Grigoriadis *et al.* 2014; Hylander *et al.* 1987; Wall *et al.* 2006). The majority of food breakdown, therefore, likely occurred on phase II wear facet surfaces during the terminal part of phase I of the power stroke during the crushing action immediately prior to and during maximum intercuspation.

Although phase II facets occupied a greater proportion of the total wear facet area in the majority of individuals, power stroke simulations for the Industrial period indicated that contact area decreased rapidly immediately following maximum intercuspation. Phase II of the power stroke itself was typically brief and only involved small contact areas. Jaw movements are characterised by a slim drop shaped pattern when processing softer foods in modern feeding studies with a reduced grinding component (Agrawal *et al*. 2000; Bakke 1993; Pröschel and Hofmann 1988;).

The steeper occlusal topography, more vertically inclined wear facets and power stroke of individuals from the Industrial era are more analogous to the occlusal topography and power stroke of carnivores, in which the chewing stroke is strongly vertically directed and phase I shearing activity provides a prominent role in food breakdown (Kaidonis *et al.* 2014; Koenigswald *et al.* 2013). The differences in chewing model are visualised as mastication compasses for each period (Figure 179).



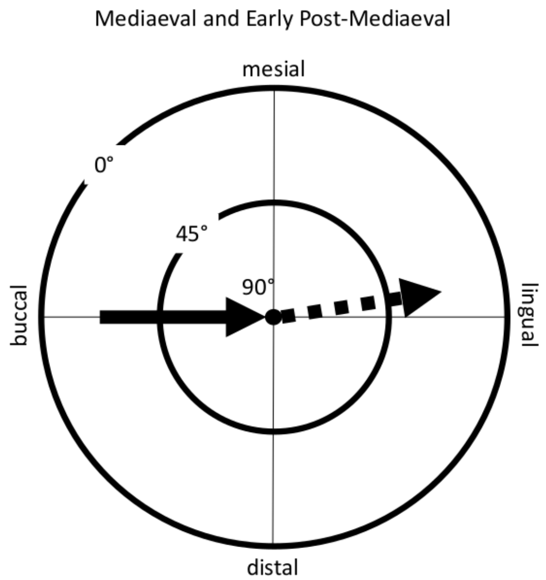


Figure 179: Mastication compasses visualising the differences in the inclination of each phase of the power stroke between the Mediaeval and Early Post-Mediaeval periods and the Industrial periods. The principal difference apparent between the two power strokes is the steeper inclination of the phase I movement in the Industrial period. The orientation of the incursive and excursive portions of the power stroke were largely consistent between the two periods.

7.2 Can OFA be used to identify the within assemblage and period variation in dietary composition and para-masticatory behaviours that are historically and/or archaeologically described?

In the current analysis, the variability within the wear facet area data was greater than that evident among the modern hunter-gatherers examined by Fiorenza *et al.* (2011a). This increased variability likely reflected the diversity of dietary items consumed in both the Mediaeval, early post-Mediaeval and Industrial periods, particularly among different social classes and geographic regions (Burnett 1989; Le Luyer *et al.* 2014; Woolgar 2016). However, as dental macrowear patterns reflect habitual diet (Fortelius and Solounias 2000), within group differences in wear facet expression would require relatively pronounced variation in the dietary staples consumed. The increase in occlusal variability and differences in the antagonistic relationships between molar rows may have also increased the variability in wear facet expression and location observed, particularly in the Industrial period. In addition, confounding factors such as habitual pipe use (Walker and Henderson 2010), clenching and other non-masticatory tooth use may increase the complexity of disentangling dietary information from other forms of tooth use in the periods examined.

7.2.1 Industrial Period (AD1700-1900)

7.2.1.1 During the Industrial period, the largest share of any meat and cheese was typically consumed by men whilst women and children subsisted almost solely on bread, potatoes and weakened tea. A proportion of buccal phase I wear facets indicative of greater shearing activity and meat consumption would be anticipated if these dietary differences were of sufficient magnitude.

No significant differences in dental wear facet expression were found between the sexes in the Industrial period. The bulk of the dietary staples consumed in the 18th-19th centuries would have been consistent between the sexes. Both sexes would have derived most of their calories from bread, potatoes, vegetables and sweetened tea. Men, within a lower-class urban setting, however, would receive the majority of meat that could be afforded. Even so, the quantity would likely be meagre and would therefore be less likely to impact habitual masticatory behaviours (Burnett 1989; Mennell 1996; Stone 2006). Isotopic studies examining the Post-Mediaeval period have not been able consistently to identify sex differences in dietary content (Dhaliwal *et al.* 2019; Nitsch *et al.* 2010). Isotopic data reflect the bulk of the diet consumed by an individual arguably with a similar resolution to dental macrowear analysis, which represents the culmination of tooth use over a substantial portion of an individual's lifetime. Commonality in the dietary staples consumed between the sexes would have masked more subtle variations in dietary content relating to supplementary dietary items.

Clinical studies have identified greater chewing force and jaw movement velocity in the masticatory cycles of men than women (Neill and Howell 1986; Youssef *et al.* 1997). The slightly less obliquely inclined wear facets in males across both phases of the power stroke, slightly smaller ORI values and slightly enlarged tip crushing areas may reflect this. Nevertheless, there were no significant differences between dip angle, ORI or TCI values between males and females in the Industrial material examined.

7.2.1.2 A wider range of age groups is anticipated to be includable in OFA in Industrial period due to an expected lower wear rate when compared to the Mediaeval and early Post-Mediaeval periods. It is anticipated that wear facet expression may change with increasing age-at-death.

In the Industrial period, individuals estimated to be older exhibited slightly greater proportions of lingual phase I wear. Age-at-death was estimated by assessing the degeneration of the auricular surface (Buckberry and Chamberlain 2002). These differences were not apparent, however, in the known-age St Bride's assemblage. The selection of lower second molars with a Smith wear stage of 2 (1984) restricted the variation in the occlusal wear facet proportions in the Industrial individuals examined. Buccal phase I dip angles were significantly less steep in the older age category. ORI values were significantly greater in the younger age category indicating the presence of greater cusp height and complex occlusal topography.

In a clinical setting, older individuals (up to 75 years of age) were still capable of adjusting their masticatory cycles to the changing physical properties of foods by modifying their vertical and lateral amplitudes. The number of chewing cycles required to produce a bolus that could be swallowed also increased with age, independent of the hardness of the food item consumed (Peyron *et al.* 2004). Consequently, largely consistent responses in masticatory parameters would be anticipated to the softer and more heavily processed foodstuffs consumed in the Industrial period irrespective of age. The older proportion of the Industrial assemblage typically exhibited greater cusp reduction and less obliquely inclined phase I wear facets. As wear advances with increasing age, further modification of the power stroke is predicted in order to maintain functional masticatory efficiency as occlusal topography provides less of a guiding function (Kaifu *et al.* 2003; Koenigswald *et al.* 2013). An increase in the lateral portion of the power stroke might be anticipated with increased age based on observations of modern hunter-gatherers with extremely advanced tooth wear (Kaidonis *et al.* 2014), however, a broader range of occlusal wear stages and skeletal age-at-death categories would be required to test this hypothesis further.

The individuals examined in the current research only represented a small cross-section of the potential age-at-death ranges within each assemblage due to the restrictive selection criteria required for the performance of wear facet analysis. OFA can only be effectively applied to lightly worn teeth (Fiorenza *et al.* 2018; Kullmer *et al.* 2009) and is largely inappropriate for the analysis of wear following the obliteration of dental wear facets after which only an assessment of the overall inclination of the wear plane of the tooth can be made. This meant that only relatively young individuals could be included from the Mediaeval and early Post-Mediaeval periods, to ensure that wear stages of the lower second molars were comparable between the two periods. For this reason, the influence of age-at-death on wear expression could not be assessed in the pre-Industrial group.

7.2.1.3 In the Industrial period, the quantities of meat consumed were highly dependent upon income and it has been asserted that differences in diet were of greater magnitude between, rather than within, social classes (Burnett 1989). Among assemblages with contextual information pertaining to social stratification, greater quantities of buccal phase I shearing wear might be anticipated among higher status individuals that habitually consumed larger amounts of meat.

Larger buccal phase I facets typified upper class individuals from St Bride's crypt. Modern hunter-gatherers consuming large quantities of meat, such as the Inuit, exhibited larger buccal phase I facets than hunter-gatherers consuming a mixed diet more reliant on tougher, harder and more abrasive plant foods (Fiorenza *et al.* 2011a). Larger buccal phase I facets may thus be reflective of the greater quantities of meat consumed by the upper classes in the Industrial material examined. Differences in diet were of greater magnitude between, rather than within, social classes (Burnett 1989). This would have entailed daily meat consumption for the more affluent. It was estimated that half a pound of meat per day would have been available to each household member for those with an income of £250 per annum (Burnett 1989). In contrast, small quantities of animal products were consumed by the working classes (Oddy 1970), which could amount to no meat at all for the poorest labourers (Engels 1844).

Socioeconomic differences in dietary content were also indicated by the analysis of the St Michael's Litten assemblage, where high status tomb burials exhibited greater buccal phase I wear facet proportions than contemporary coffin and shroud burials. This was accompanied by steeper phase I dip angles suggesting a more vertically orientated shearing component to phase I of the power stroke among high status burials. This would again be consistent with more frequent meat consumption.

Greater meat consumption by individuals interred in tombs, either from terrestrial or marine protein, was also indicated by an isotopic study comparing stable carbon and nitrogen ratios between tomb, coffin and shroud burials at St Michael's Litten. Tomb burials showed significantly enriched $\delta^{15}N$ relative to coffin and shroud burials, however, no significant differences were apparent between shroud and coffin burials (Dhaliwal *et al.* 2019). This is consistent with the wear facet data; no differences were apparent between shroud and coffin burial types and there was greater variability in the distribution of the relative wear facet areas of their lower second molars. Isotopic variably may reflect differential exploitation of potentially free resources, such as oysters and molluscs, by low-status individuals, whereas, regular access to terrestrial mammals may have been restricted to wealthier individuals resulting in them having more consistent isotopic (Dhaliwal *et al.* 2019) and dental wear signatures. The small number of tomb burials suitable for performing OFA limited the statistical power of the inferences that could be made using this data. Nevertheless, the consistency between the isotopic and dental wear data supports the interpretation.

7.2.1.4 More heavily processed white wheaten bread was taken up less rapidly in Northern England. Differences in wear facet expression would be expected if the composition of the staple food items consumed differed markedly between the north and south of England.

There were no significant differences in lower second molar dental wear patterns between the assemblages in the Industrial period from different regions of England despite historical evidence for variation in diet. The uptake of white wheaten bread was typically less rapid in the north of England (Collins 1975; Drummond and Wilbraham 1957). The northern diet typically consisted of barley bread, oatmeal, milk, butter, potatoes, and occasional meat compared to the Southern diet of wheaten bread, tea, potatoes, and cheese (Eden 1975). When compared to the assemblages from southern England, there was a slight tendency for larger proportions of lingual phase I wear in the Coronation Street assemblage, which when considered alongside slightly less steep phase I wear facet dip angles, may reflect the marginally coarser and tougher dietary profile of northern England. The small sample size for each region restricts the statistical rigour with which these relationships can be assessed.

The magnitude of any differences in wear pattern between regions would be expected to be small given that the consistency of the dietary staples consumed did not differ markedly, and a national network of goods circulation had expanded during the 19th century with the development of the railways (Burnett 1989). In any case, the quantities of meat consumed by the majority of individuals within both northern and southern assemblages would have been negligible (Mennel

1996). Marked differences in the functional demands placed on the masticatory system would therefore not be anticipated due to regional dietary differences. The greatest differences within the Industrial period were associated with the gastro-political reification of status through meat consumption and have been discussed in section 7.2.1.3 (Burnett 1989).

The only significant difference between Industrial assemblages was the greater prevalence of tip crushing wear that characterised the Coronation Street and St Peter's, Wolverhampton, assemblages. The Coronation Street assemblage likely included many sailors, ferrymen, coalheavers and miners (Raynor *et al.* 2011), whilst the St Peter's assemblage included individuals working in the iron industry and small workshops (Adams and Colls 2007). Contemporary studies of the association between bruxing activity and exertion have reported an increased prevalence of clenching behaviour and greater tooth wear among individuals that habitually engage in submaximal physical exertion during resistance training (Friedman Rubin *et al.* 2019; Huang *et al.*2014). Greater tip crushing wear might be associated with occupations that routinely required considerable physical activity and lifting which might cause tooth clenching (Restrepo *et al.* 2006). Further assessment of this hypothesis would require the examination of skeletal material for whom accurate occupational data are available. This could include the skeletons from the crypt at Christ Church Spitalfields dating to the 18th-19th centuries (Mays 2012).

7.2.1.5 Habitual clay pipe use creates distinctive wear facets on the anterior teeth and premolars. It is expected that these will be accompanied by differences in molar wear facet expression.

Several of the Industrial assemblages examined provided evidence for pipe use (up to 42% of individuals examined in the Coronation Street assemblage). Pipe use was typically male-dominated in the 18th century and the preferred 'short-clay' pipes could be clenched and held in the teeth for hours at a time (Walker and Henderson 2010). It was hypothesised that habitual pipe use may impact wear patterns on the molars given that these teeth might be involved in manipulating and stabilising the pipe within the mouth. The size of tip crushing areas of the lower second molars in the Industrial material examined, however, did not significantly depend on pipe use. Any dental modification was limited to the development of highly rounded wear areas in the incisors, canines and premolars leaving a space for pipe insertion between the upper and lower dentition (Ubelaker 1994). Tip crushing areas were slightly larger and ORI values smaller among individuals with evidence of pipe use in the Coronation Street assemblage indicative of heavier dental abrasion. High quantities of abrasive silicas were present in the clay used to produce tobacco pipes. Pipe use likely introduced higher quantities of abrasives to the oral cavity more widely, including the posterior dentition (Walker and Henderson 2010).

In addition, clinical studies have found a significant association between smoking, including pipe use, and the progress of periodontal disease (Albandar *et al.* 2000) and caries rate (Petersson and Twetman 2019; Voelker *et al.* 2013). Similarly, a study of a burial assemblage from Kilkenny City union workhouse (dating to the famine of AD1847-1851) found a significant link between periodontal disease advancement, carious lesions at and below the gum line and the presence of pipe facets (Geber and Murphy 2018). An epidemiological study of 23,376 participants drawn from across Europe examined from 1994-1998 found that smoking was associated with approximately 3 times higher risk of tooth loss (Dietrich *et al.* 2015). This supports the significant association between the number of teeth lost ante-mortem and the presence of pipe facets in the current study. Periodontal disease was not assessed in the current research so its association with pipe use could not be examined, however.

7.2.1.6 Dental wear facets attest to the occlusal relationship between opposing molar rows. Malocclusion in the posterior dentition should be identifiable by reconstructing the relationships between antagonistic molar rows using OFA. Industrial assemblages are predicted to exhibit more frequent and marked occlusal variability due to changes in the dimensions of the masticatory system as dietary content became increasingly processed.

In the current analysis, some degree of within arch occlusal variability was evident in all of the assemblages examined. A marked increase in the prevalence of malocclusion has been attributed to industrialisation and associated changes in dietary composition and content (Corruccini 1984; 1999). Previous studies, however, have argued that occlusal variability is not restricted to industrial groups. Incisor crowding was found in all individuals from the Chalcolithic site of Roaix, France (Mockers *et al.* 2004). Some degree of malocclusion and tooth misalignment was reported in 55.5% of Middle Palaeolithic anatomically modern humans from the Middle Eastern site of Qafzeh (Sarig and Tillier 2014; 2016). However, it is debated whether the observed relationship between the jaws reflected posterior crossbite situations or para-masticatory tooth use at this site (Sarig and Tillier 2016; Fiorenza and Kullmer 2013; 2015).

The prevalence of minor rotation/displacement of the anterior teeth was markedly greater in the Industrial era and approached the prevalence rates apparent in modern 20th/21st century populations. In the Industrial assemblages examined, ≈65% of individuals had some degree of rotation/displacement of the lower anterior dentition. Comparably, noticeable incisor irregularity was apparent in the examination of late 20th century US groups; only 35% of individuals examined exhibited well-aligned mandibular incisors (Proffit *et al.* 1998). Similarly, 65% of 2329 individuals (aged between 12-17 years) from contemporary Anatolia had anterior crowding (Gelgör *et al.* 2007).

The increase in the prevalence rates of rotation/displacement between the two periods in the current study is consistent with the observation of more frequent malocclusion in contemporary groups relative to their pe-Industrial counterparts. Less frequent and less severe malocclusions have been reported in mediaeval Danes and Norwegians when compared to their modern equivalents (Helm and Prydsö 1979; Evensen and Øgaard 2007). The prevalence of tooth rotation/displacement in the Mediaeval and early Post-Mediaeval periods in the current study (≈50% of individuals) was markedly greater than in Croatian material dating from the 1st to 10th centuries AD (12.9%) (Vodanović *et al.* 2012).

There was an increase in the prevalence of interarch malocclusion among individuals from the 18th and 19th centuries. The prevalence of anterior crossbites was 5% in the Mediaeval and early Post-Mediaeval assemblages and 12% in the Industrial material. Large and partly overlapping 95% confidence intervals, however, indicated that a larger sample size would be required to perform a statistically robust comparison of the two periods. There were no discernible differences in the prevalence of canine and molar crossbites in each period. The prevalence rate for anterior crossbites in the Industrial group approached the rates reported in assessments of modern industrialised 21st century groups (Gábris *et al.* 2006 (12% in 483 adolescents aged 16-18 years); Giordano *et al.* 2019 (34% of 3491 individuals aged 12 to 18 years)).

There was a paucity of individuals for whom an assessment of interarch occlusal variability could be performed. This was because the jaws of individuals needed to be sufficiently intact, and their dentitions well represented (Sarig *et al.* 2013). The operational definitions used to identify crossbites in the current study circumvented the difficulties associated with identifying occlusal variability by placing the mandibular condyles within the glenoid fossa and trying to occlude the teeth (e.g. Vodanović *et al.* 2012) by utilising dental wear facets that deviated from their anticipated position within an Angle Class I occlusion to identify occlusal variability (Maier and Scheck 1982; Sarig *et al.* 2013). The operational definitions used, however, are limited by difficulties in distinguishing dental wear facets that are formed by para-masticatory tooth use from those resulting from the malpositioning of the dental arches and individual teeth (Fiorenza and Kullmer 2013; 2016; Sarig and Tillier 2014, 2016). Exhaustive assessments of interarch occlusal variability within skeletal material require the digital or physical reconstruction of the antagonistic relationships between the teeth present within the dentition (Ponce De León and Zollikofer 1999). Dynamic simulations of the pattern of occlusal contacts can then be undertaken to assess the validity of the reconstruction (Kullmer *et al.* 2013). Consequently, the assessment of between arch occlusal variability using this method in the current study must be considered preliminary.

The presence of an anterior crossbite was not found to significantly impact lower second molar wear facet area composition or dip angle in either period. As such, no statistical evidence was present to suggest that individuals with anterior crossbites should be excluded from the overall analysis of lower second molar wear facet patterns. In a clinical setting, individuals with anterior crossbites have been found to exhibit chewing cycles with a reduced lateral component likely due to the interference of the contacts between the incisors involved in the crossbite (Nie *et al.* 2010; Piancino *et al.* 2012; Yashiro *et al.* 2004). It might be anticipated that the wear facet patterns of the lower second molars of individuals with anterior crossbites would possess more obliquely inclined wear facets as a reflection of this more vertically directed pattern of jaw movement during the power stroke. This was not apparent in the current research. The number of individuals identified as having anterior crossbites was low in both periods (Industrial group n=6 of 104 and pre-Industrial group n=2 of 130). As a result, the statistical power of the t-tests performed to assess this were low (<0.40) suggesting further analysis of a larger sample of individuals with anterior crossbites would be required to confirm these preliminary findings. This was beyond the scope of the current research as the interpretation of the effect of anterior crossbites on occlusal kinematics in skeletal individuals would require the reconstruction of full static and dynamic occlusion for each individual analysed (such as Kullmer *et al.* 2013).

Dynamic reconstructions were undertaken for SK1986 from the St Michael's Litten assemblage and SK239 from St Bride's Church, Fleet Street highlighting the utility of this approach in identifying occlusal variability in skeletal material. In SK1986, the transverse relationship between the left upper and lower molars exhibited a lingual crossbite. This was apparent when the relationship between the antagonistic molars was reconstructed digitally by matching wear facets between the upper and lower molar rows. During the simulated OFA collision (video 9), the distribution and development of wear facet contact areas supported a reversed power stroke in this individual. Phase II facets and the facets situated on the lingual aspect of the lingual cusps of the lower second molar came into contact during phase I of the power stroke. In the reversed power stroke, they were analogous with buccal phase I and lingual phase I facets in a regular power stroke. Lingual phase I facets on the lower second molar came into contact prior to maximum intercuspation and remained in contact during an extremely brief phase II movement in which the lower molars moved slightly laterally. Wear facet areas increased rapidly during phase I of the power stroke indicating a pronounced crushing action with only a short glide during tooth-tooth contact. The location of the wear facets associated with the crossbite in the lower dentition and the presence of antagonistic facets in the upper dentition suggested that the facets were likely the result of masticatory behaviours rather than para-masticatory tooth use (Fiorenza *et al.* 2019). In SK239, the lingual shift in the transverse molar relationship was not as extensive as in SK1986 resulting in an almost cusp-to-cusp relationship between the upper and lower molars when in maximum intercuspation. The simulated power stroke was strongly vertically directed for SK239 and lacked a pronounced lateral component. This was supported by the near horizontal inclination of the wear facets in this individual.

The reversed power stroke evident in the chewing simulation for SK1986 contrasts with the other power stroke simulations conducted in the current research and previous dynamic simulations of the power stroke in anatomically modern humans, in which the simulated trajectory could be verified using the dental macrowear pattern (Benazzi *et al.* 2011; 2013; 2016). Clinically, a high proportion of individuals with posterior crossbites exhibit reverse chewing cycles on the side of the dentition with the crossbite (≈59-70% of individuals) (Piancino *et al.* 2009; Piancino *et al.* 2016). The association between a posterior crossbite and a reverse chewing cycle in the current research is consistent with this observation. Reverse chewing cycles are characterised by a medial deviation of the mandible during jaw closing followed by a lateral deviation during jaw opening to ensures an overlap between opposing dental surfaces. The lateral component of reverse chewing cycles is often reduced when compared to non-reverse chewing cycles (Piancino *et al.* 2006; Piancino *et al*. 2009; Rilo *et al.* 2007). In reverse chewing cycles, the occlusal load is mainly directed buccally in the lower molars (Tomonari *et al.* 2014). The molar wear pattern on the left side of the dentition of SK1986 was characterised by large, shallowly inclined and lingually orientated wear facets on the metaconid and the entoconid consistent with the concentration of the occlusal load buccally during the period of contact during which they were involved. Their large size also suggests their involvement prior to or during maximum intercuspation when occlusal forces are at their greatest (Wall *et al.* 2006).

This represents the first identification of a reverse chewing cycle in skeletal material using OFA and highlights the utility of OFA in reconstructing occlusal relationships and identifying variability in masticatory behaviours. Future studies interested in identifying interarch occlusal variability in skeletal material would benefit from verifying any identified malocclusion by performing a comprehensive digital reconstruction of occlusal relationships and masticatory behaviours where time and resources are available. This would overcome the difficulties associated with attempting to apply criteria from dentistry (e.g. Harris and Corruccini 2008) to classify occlusal variability in often fragmented and distorted skeletal material (Kullmer *et al.* 2013; Vodanovíc *et al.* 2012).

7.2.2 Mediaeval and Early Post-Mediaeval Periods (AD1100-1700)

7.2.2.1 Historical evidence for marked sexual differences in the diets consumed in the Mediaeval and early Post-Mediaeval periods was not found. Significant differences in dental wear patterns would, therefore, not be expected.

There were no significant differences in wear facet expression on the lower second molars between the sexes in the pre-Industrial assemblages examined. Historical accounts indicate that sexual differences in the diets consumed in the Mediaeval and early Post-Mediaeval periods were typically limited to supplementary items.

Within Mediaeval thought, heavy foods, such as meat, were deemed more appropriate for males than females. Bynum argued that abstinence from food was particularly spiritually charged for women due to their association with food preparation in the Mediaeval era (Bynum 1987). In practice, however, the observance of abstinence was restricted to those affluent enough to afford the regular consumption of meat. Most individuals would have had extremely limited, and often seasonal, access to meat resulting in often closely aligned food consumption between the sexes (Woolgar 2016). Mediaeval isotopic studies provide evidence for sex-based differences in diet, such as at Newark Bay, Orkney (Richards *et al.*, 2006), however, others have not (Mays 1997). The assemblage from St Andrew's priory, also situated in Fishergate, York, immediately west of the York Barbican excavation area, indicated significant differences between the sexes. Males displayed enriched δ15N values consistent with greater access to marine protein (Müldner & Richards, 2007a). These sex differences were not apparent in the Mediaeval material included in the current study. Sex differences in dietary content were likely largely dependent upon socioeconomic factors underlying the composition of each Mediaeval cemetery site. Any dietary differences between the sexes in the Mediaeval period were probably exaggerated in the presence of marked contrast in food access, relating to societal status, religious roles and the presence of migrants.

7.2.2.2 In the Mediaeval period, there is historical evidence for differences in dietary practices at institutions such as monasteries and hospitals. Contrasts in lower second molar wear patterns would be expected between the inhabitant of such institutions relative to lay cemeteries.

The cemetery types considered did not differ significantly in the relative wear facet proportions of their lower second molars. Dental macrowear patterns, however, differed significantly between some of the pre-Industrial assemblages examined. The assemblages that differed significantly in their relative wear facet area were the early Post-Mediaeval portion of St Michael's Litten, the York Barbican assemblage and the Blackfriars, Gloucester, material.

The early Post-Mediaeval portion of the St Michael's Litten assemblage was grouped with the Mediaeval assemblages as it predated dramatic developments in milling technology that altered the consistency of dietary staples in the 18th-19th centuries (Burnett 1989; Perren 1990). The wear facet proportions of this group were intermediate between the Mediaeval and Industrial era assemblages, which was consistent with the introduction of automatic boulters within mill machinery in the 17th century. This reduced the quantities of intrinsic and extrinsic abrasive particles within the bread consumed in the early Post-Mediaeval period (Peterson and Jenkins 1995). A reduction in the shearing phase I component of the power stroke and a shift towards a power stroke more consistent with the Industrial assemblages was indicated by greater proportions of phase II wear at the expense of buccal phase I wear in the early portion of the St Michael's Litten assemblage.

The Blackfriars, Gloucester, assemblage was similarly characterised by higher proportions of lingual phase I and phase II wear and a reduction in the prominence of buccal phase I wear when compared to the other Mediaeval assemblages. The Blackfriars consumed a diet chiefly comprised of cereals and were known for the relative poverty of their lifestyles (Holt 1985; Palmer 1892) suggesting a close alignment between their dietary content and that of the majority of their contemporaries, who were also primarily dependent on cereals (Stone 2006). The differences in relative wear area proportions between the Blackfriars assemblage and several other pre-Industrial groups, therefore, is likely a product of the small number of suitable individuals from the Blackfriars site combined with the presence of several individuals with unusual wear facet area distributions. On the other hand, the poor development of buccal phase I wear facets among several of the individuals from Blackfriars would be consistent with limited access to meat and their historically documented impoverished lifestyles. The lack of significant differences between the remaining Mediaeval sites suggests that the biomechanical demands associated with the oral processing of dietary staples did not differ markedly between them.

7.2.2.3 Leprosy often has orofacial manifestations, which may impact masticatory behaviours. In addition, dietary measures were often utilised in the treatment of leprosy in the Mediaeval period. Individuals with lepromatous leprosy might be expected to exhibit dental wear patterns that differ from those unaffected by the pathology.

In the cemetery associated with the leprosy hospital of St James and St Mary Magdalene, Chichester, individuals with lepromatous leprosy were characterised by larger proportions of buccal phase I wear in the lower second molars relative to those without the condition. Several underlying factors need to be considered. It may indicate the consumption of a diet containing a larger meat component than the non-leprous individuals interred at the cemetery. The provision of meat, sometimes in the form of substandard meat donated to the *leprosarium*, formed part of the dietary prescription to rectify the humoral imbalance believed to be part of the aetiology of leprosy in Mediaeval thought (Radcliffe 2008). A focus on poultry, pork, fish and other foods perceived to be mild and moist was in contrast to the dietary regimes of the majority of Mediaeval individuals who were largely dependent on grains, particularly in the form of bread, for the bulk of their dietary calories (Stone 2006). The difference in wear pattern may reflect an increase in shearing activity necessary for the oral processing of the higher meat content of the lepers at the *leprosarium*.

Dental wear facets develop over an individual's lifetime and would require a prolonged period of consumption of a diet of contrasting composition to modify the wear facet pattern. This is because chewing behaviours would have to be consistently modified for a sustained period. The lack of skeletal changes consistent with leprosy in many of the individuals buried at the *leprosarium* of St James and St Mary Magdalene does not eliminate the possibility that they were still afflicted by the condition, exhibiting either the tuberculoid form or a less advanced form of lepromatous leprosy which may not yet have manifested osseous changes. It could be suggested that these individuals were residents at the *leprosarium* for a more limited period and therefore any contrasts between the dietary regime of the institution and that which they consumed previously would not yet have had a marked impact on their occlusal wear patterns. This would mirror the enrichment of $\delta^{13}C$ and $\delta^{15}N$ isotopic values in rib collagen relative to collagen from the femurs reported by Taylor *et al.* (2013) in their examination of three individuals from the leprosarium of St. Mary Magdalen, Winchester. The isotopic composition of rib collagen changes more rapidly than that of femurs suggesting that there was a change in their dietary composition in the final years of their life likely including greater amounts of terrestrial and/or marine protein. This may be consistent with the consumption of greater quantities of meat at the leprosarium than they had done prior to their admission (Taylor *et al.* 2013).

Another factor to consider is that clinically, orofacial lesions are commonly reported among individuals with lepromatous leprosy (Manjunath Shenoy *et al.* 2007; Rodrigues *et al.* 2017). The loss of the central maxillary incisors is a frequent consequence of resorption of the alveolar process and associated involvement of the hard palate (Waldron 2008). Chronic gingivitis may also occur. The tongue is involved in up to 25% of cases. Ulceration and repair of the perioral tissues may result in microstomia, contracture of the mouth (Naik *et al.* 2011). More uncommonly, affecting 21% of a clinical group, the maxillary and mandibular branches of the trigeminal nerve and buccal and mandibular branches of the facial nerve may be involved resulting in a sensation of anaesthesia on the affected side, which may impact masticatory behaviours and speech (Dave and Bedi 2013). The symptoms of the disease may have altered chewing behaviours and, therefore, have also modified dental wear patterns in some individuals. Many of these symptoms will not leave evidence on the bone, however, so it was not possible to account for this during our analysis.

There may also be a temporal component to the differences in wear facet area composition between the burials diagnosed with leprosy and those without in the cemetery attached to the Hospital of St James and St Mary Magdalene. The southwest portion of the cemetery is characterised by burials that were mostly male with changes compatible with leprosy in 61.5% of the group, however, this was reduced to 15% in the north eastern parts of the site. It has been suggested that leprosy may be a chronological indicator at the cemetery with the oldest burials situated in the southwest portion of the site and the most recent burials in the north-eastern portion (Magilton *et al.* 2008). An increase in prevalence of leprosy is reported in the palaeopathological literature from the 11th to the 13th centuries and there is also a peak in the foundation of leprosy hospitals during the 13th century. Following this, a decline in the prevalence of leprosy occurred from the 15th century onwards and has been associated with the cross immunity that exists between leprosy and tuberculosis (Manchester and Roberts 1989). The decline in prevalence is contemporary with the shift in function of the *leprosarium* of St James and St Mary Magdalene, Chichester, to an almshouse in AD1442 (Magilton *et al.* 2008). There was not a significant relationship, however, between cemetery area and the relative wear facet areas of the individuals examined.

Few major changes in dietary composition and food processing technologies occurred during this period. Grains were stone ground in water and windmills and then the meal was sieved by hand to separate out the flour (Drummond and Wilbraham 1957). Prior to the transition from demesne farming in the late 14th century, hospitals with estates could draw upon their tenants for fresh produce. However, in the absence of this practice, Mediaeval hospitals and almshouses were noted for their tendency to economise on the quantity and quality of the food provided in some cases (Rawcliffe 1984). It is possible that access to meat would have been greater among the lepers, given the dietary composition recommended by Mediaeval medical theory, compared to the relatively impoverished diet of the later almshouse.

8 Conclusion

Do dental wear facet patterns indicate that a change in masticatory behaviours occurred between the Mediaeval and Early Post-Mediaeval periods (AD1100-1700) and the Industrial era (1700-1900AD)?

Significant differences were found between the dental wear facet patterns of individuals dating from the Industrial era and those from the Mediaeval and early

Post-Mediaeval periods. A reduction in the size of phase I wear facets when compared to phase II wear facet areas on the lower second molar indicated a shift to a more vertically directed chewing action as the foods eaten became softer and more heavily processed during and following the Industrial Revolution. This was also confirmed by a reduction in the lateral movement of the lower teeth during the dynamic power stroke simulations performed for individuals from that period. In addition, more steeply inclined wear facets, smaller tip crushing areas and greater retention of relief across the occlusal surface highlighted the reduction in the abrasive content of the diet consumed in the Industrial era. The chewing models produced supported a reduction in the biomechanical stimulation of the masticatory system in the Industrial era, which, as a primary agent in facial growth and development, has implications for craniofacial morphology and occlusion.

The current study has illustrated the new insights that can be obtained from applying OFA to one of the most dramatic dietary transitions in the history of anatomically modern humans. This suggests that OFA could be usefully applied to other archaeologically important periods of dietary change, such as the introduction of new plant and animal resources that characterised the shift in subsistence from the Mesolithic to the Neolithic periods. In addition, the data generated by the current project provide a database of lower second molar wear patterns, comprising groups whose dietary patterns are described in detail in the archaeological and historical literature, against which groups of relatively unknown dietary composition can be compared.

Can Occlusal Fingerprint Analysis be used to identify within assemblage and period variation in dietary composition and para-masticatory behaviours that are historically and/or archaeologically described?

Previous OFA studies have focused on more pronounced dietary contrasts rather than differences within cemetery groups. The current research has given a preliminary indication that OFA can be used to identify dietary differences, provided they are relatively marked, within skeletal assemblages, for which there is historical and archaeological evidence. For example, social status was the principal axis along which dietary content varied in both periods with elite groups consuming larger amounts of meat. This was supported by the dental wear facet patterns of higher status individuals from St Michael's Litten, Chichester, and St Bride's Church, Fleet Street, which were consistent with greater meat consumption when compared with the rest of their assemblages. On the other hand, differences in the quantities of supplementary food items eaten, such as greater provisioning of meat for male members of the household in the Industrial period, were not reflected in the dental wear facet patterns analysed. Consequently, any differences in the quantities of food items that comprise only a small portion of the total foods eaten are unlikely to be detectable using OFA as the impact on chewing behaviours will probably not be substantial. Despite this, this project indicates that OFA has the potential for being used alongside other methods of reconstructing diet in the past, such as dental microwear analysis, historical accounts, stable isotope analysis, archaeobotanical and zooarchaeological evidence, in order to identify different types of eater within skeletal assemblages and to provide a more comprehensive overview of dietary composition.

Furthermore, OFA provides an insight into dental occlusion and the current research identified two individuals with posterior lingual crossbites by reconstructing the relationship between their upper and lower molars. A reverse chewing cycle was demonstrated for the first time in archaeological material by simulating the power stroke in one of the individuals with a posterior crossbite. This research supports the use of OFA to reconstruct dynamic and static dental occlusion in skeletal material, which otherwise may not be possible using methods derived from clinical dentistry given the often fragmentary state of archaeological remains. A previous study has highlighted the value of using OFA to evaluate the pattern of dental contacts and the distribution of loading stresses during chewing in a clinical setting to inform tooth restoration and prosthodontic treatment schemes (Benazzi *et al.* 2016).

Limitations of the Current Research and Future Directions

The current project focused on the occlusal wear facet pattern of the lower second molar. This decision was driven by work on primates, which has found that the lower second molar provides an effective representation of masticatory function within a species (Kay 1973; Knight-Sadler and Fiorenza 2017). In addition, the first molars were more commonly lost ante-mortem in the assemblages examined, particularly those dating to the Industrial period. The selection of the lower second molar as the target tooth for OFA expanded the number of suitable individuals for inclusion from each assemblage. Wear facet expression has been previously shown to differ significantly between the first and second molars in modern hunter-gatherers (Fiorenza 2009). This is likely due to functional differences between the molars from anterior to posterior, which relate to subtle differences in dental morphology and their position and inclination in relation to the TMJ (Spears and Macho 1998). There are also differences in the number and expression of wear facets along the tooth row relating to their position within dental occlusion; for example, facets 7 and 10 are unlikely to be present in third maxillary molars in an Angle Class I occlusion as the tooth typically only has one lower molar antagonist (Fiorenza *et al.* 2010). As such, the wear facet data derived from the current project can only be directly compared with other research examining lower second molars (e.g. Zanolli *et al.* 2019). By focusing on a single tooth position, the number of individuals that could be included and compared was maximised within the constraints of limited funding and time in order to infer differences in the power stroke between the periods.

The inclusion of an outlier group could have given greater insight into the trajectory of change in wear facet patterns, diet, and the power stroke through time in Britain. For example, differences in mandibular dimensions and robusticity have been identified between the Anglo-Saxon and Mediaeval periods in Britain and Anglo-Saxons may have proved a suitable additional comparative group (Hirst 2019). Milling technology and the physical properties of dietary staples changed incrementally across the time interval examined (Burnet 1989; Drummond and Wilbraham 1957; Stone 2006). An understanding of the power stroke and examples of wear facet patterns prior to these changes in food processing technology may have provided greater insight into the how the dietary changes that took place during the Mediaeval period effected masticatory behaviours.

The requirement that individuals exhibit a Smith wear score of 2 (1984) in order to be included in the project resulted in the Mediaeval and early Post-mediaeval group being dominated by skeletons with auricular surfaces more consistent with younger individuals. The Industrial group was characterised by a greater proportion of individuals with more advanced stages of degeneration of the auricular surface. This was primarily due to the more rapid rate of dental wear in the pre-Industrial material restricting the suitable individuals to younger age categories (as indicated in section 6.1.1). Consequently, the age-at-death distributions reflected by the auricular surface differed between the pre-Industrial and Industrial groups. Clinical research into the effect of ageing on chewing cycles have found that older individuals still retain the capacity to adapt to changing food properties, including food hardness (Karlsson and Carlsson 1990; Mioche *et al.* 2004; Peyron *et al.* 2017; Woda, Foster, *et al.* 2006). In addition, there was little historical evidence to support dramatic shifts in the physical properties of the foods eaten in advanced age in either period (Burnett 1989; Drummond and Wilbraham 1957; Griffin 2018). The effect of time period on wear pattern was greater than age-at-death. A smaller R^2 value was associated with the differences in wear facet proportions between age-at-death categories in the Industrial period when compared to the R^2 value associated with the differences in wear facet proportions between the two periods. As such, the different age distributions of the pre-Industrial and Industrial groups compared should not have markedly impacted the results of the overall analysis (section 6.1). Dental wear is an age-affected phenomenon (Hillson 1996), however, as the comparison of the lower second molars was focused on differences in the expression of wear between teeth which had a comparable quantity of wear the differences in age distribution for each period should not have been a substantial confounding factor in the analysis conducted.

The auricular surface is effective in estimating age-at-death due to its durability against taphonomic processes and the high levels of accuracy reported when applying the Buckberry-Chamberlain method to known-age assemblages (93.7% of individuals categorised within the correct ten-year interval) (Millán *et al.* 2013; Hens and Belcastro 2012). Consequently, the error introduced into the age-at-death estimates by the Buckberry-Chamberlain method would be anticipated to be low (Mulhern and Jones 2005; Osborne *et al.* 2004). The introduction of error was further mitigated by converting the raw Buckberry-Chamberlain score into two gross age categories (younger and older) rather than attempting to convert these into ten-year chronological age-at-death intervals (Falys *et al.* 2006).

Additional confounding factors may have influenced wear facet expression in the current analysis which could not be fully considered as they were beyond the scope of the project. The presence of occlusal variability can modify masticatory patterns and even restrict the pathways of movement of the mandible that are possible during chewing (Fiorenza and Kullmer 2016). The inclination of the molar teeth in the jaws may also influence the size and inclination of the wear facets that develop due to differences in how the teeth occlude during the power stroke (Oxilia *et al.* 2018). Bruxism involving the repetitive grinding and clenching of the teeth can also modify dental wear facet patterns (Restrepo *et al.* 2006). Tooth wear alone cannot be used to diagnose bruxism within a bioarchaeological context and an appropriate methodology to do so requires further development (Foley 2020). Clinical dental research links bruxism with psychosocial stress (Manfredini and Lobbezzo 2009). Dramatic changes did occur in the social environment during the Industrial era (Burnett 1989), but it is difficult to quantify whether levels of psychosocial stress increased relative to the Mediaeval period (Temple and Goodman 2014).

Ante-mortem tooth loss was significantly greater in the Industrial period, particularly in the molar and pre-molar regions. This was consistent with the heightened sugar consumption of the Industrial-era and increased prevalence of dental caries evident when compared to the Mediaeval period (Corbett and Moore1976; Mintz 1985). Mesial drift may modify the relationship between antagonistic teeth as teeth shift mesially to fill the gaps created by ante-mortem tooth loss (Kaifu *et al.* 2003). It was anticipated that this process might influence the wear facet pattern of the involved teeth, however, evidence was not found to support this in section 6.1.2.5. This analysis did not consider the degree of mesial movement of the involved teeth. A future study could quantify the change in relationship between the teeth when ante-mortem tooth loss occurs in order to determine whether the magnitude of mesial drift determines the extent to which the dental wear facet pattern is altered by ante-mortem tooth loss.

An exhaustive consideration of these factors would require the extensive reconstruction of static occlusion and occlusal kinematics in all of the individuals examined (e.g. Benazzi *et al.* 13a, Kullmer *et al.* 2013). Occlusal variability and unusual occlusal pathways, potentially associated with bruxism or para-masticatory activity, could then be identified with greater diagnostic clarity. This could not be accommodated within project due to the constraints of time, funding and skeletal preservation. It would have resulted in a dramatic reduction in the number of individuals that could have been compared.

Fundamental questions are still outstanding regarding the timeframe within which changes in diet would be observable in dental macrowear patterns using OFA. Longitudinal studies of dental wear development in humans would be required to accomplish this alongside known changes in the physical properties of the foods eaten over the duration of the study. This may not be practicable and there would be scope for this to be explored experimentally, such as by using a chewing simulation instrument (e.g. Hua *et al.* 2015)). The association between specific directions of jaw movement and the development of certain wear facets has already been established (Kullmer *et al.* 2012).

The impact of underlying dental morphology on the development of dental wear facet patterns also requires further assessment. Fiorenza *et al.* (2011b) found a weak relationship between cusp size, cusp height and wear facet development suggesting diet, food processing technologies and para-masticatory activity may be more important factors in shaping wear facet expression. On the other hand, the extent of the reduction of the hypocone in the second and third maxillary molars may strongly influence the pattern of contacts that develop during occlusion (Fiorenza *et al.* 2011b). The method employed by Fiorenza *et al.* (2011b) coarsely quantified the underlying size of the molar cusps in planimetric terms. A future study which utilised the enamel-dentine junction as an indicator of underlying tooth morphology would provide an opportunity to examine whether more subtle differences in morphology have a marked influence on the pattern of dental wear that develops. The enamel-dentine junction would be an ideal target for this analysis as it is largely unmodified by dental wear in the early stages of wear examined using OFA; it is also the primary contributor to the unworn surface morphology of the enamel (Skinner *et al.* 2008). Dental morphology does reflect underlying population structure as many dental traits evolve neutrally (Monson *et al.* 2020). It remains to be assessed whether a marked change in the underlying dental morphology occurred between the Mediaeval and Industrial periods. As this cannot be address by the current research, differences in dental morphology may have been an additional confounding factor in the comparison of wear facet patterns performed in the current project.

A Dental Revolution?

A dental revolution, a radical shift in masticatory behaviours and the functional demands placed upon the dentition, has occurred over the past three centuries. The current research has provided critical evidence to support this conclusion by illustrating how chewing behaviours have been transformed during and following the Industrial Revolution. Through this, it has addressed one of the key mechanisms underlying the changes in jaw morphology and occlusion that accompanied this dietary transition and provided an insight into the aetiology of what are often regarded as modern-day dental problems, such as malocclusion.

The research confirms that food properties are foundational to masticatory function and craniofacial development and highlights the role of the soft, processed and sweet modern diet in shaping contemporary dentitions. This may inform orthodontic and oral rehabilitation treatment schemes, which should be aware of the impact dietary composition will have on the morphology of the jaws, the occlusal relationships that develop and potentially the long-term stability of any treatments undertaken to improve occlusion. It raises the question of whether occlusion could be improved by increasing the biomechanical demands placed upon the masticatory system during childhood and adolescence. In addition, this project suggests that future changes in food processing technologies have the potential to alter masticatory behaviours and, as a consequence, the morphology and function of the masticatory system.

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10 Appendix

10.1 Prevalence of Wear Facets by Tooth Position and Type

The proportion of dental wear facets present did not differ significantly between the two groups when divided into the tooth position and type categories listed in Figure 180 (Chi-squared = 0.042, df = 12, p-value = 1). The 95% confidence intervals around the proportion of facets present were overlapping for most of the tooth positions compared. Differences were apparent, however, in the prevalence of phase II and buccal phase I wear facets on the first molars. In the Mediaeval and early Post-Mediaeval periods, first molars typically exhibited more advanced wear stages, therefore, these wear facets were more commonly obliterated or merged resulting in lower frequencies. The merging and obliteration of wear facets by generalised dental abrasion was also more common in the premolars of individuals from the Mediaeval and early Post-Mediaeval periods.

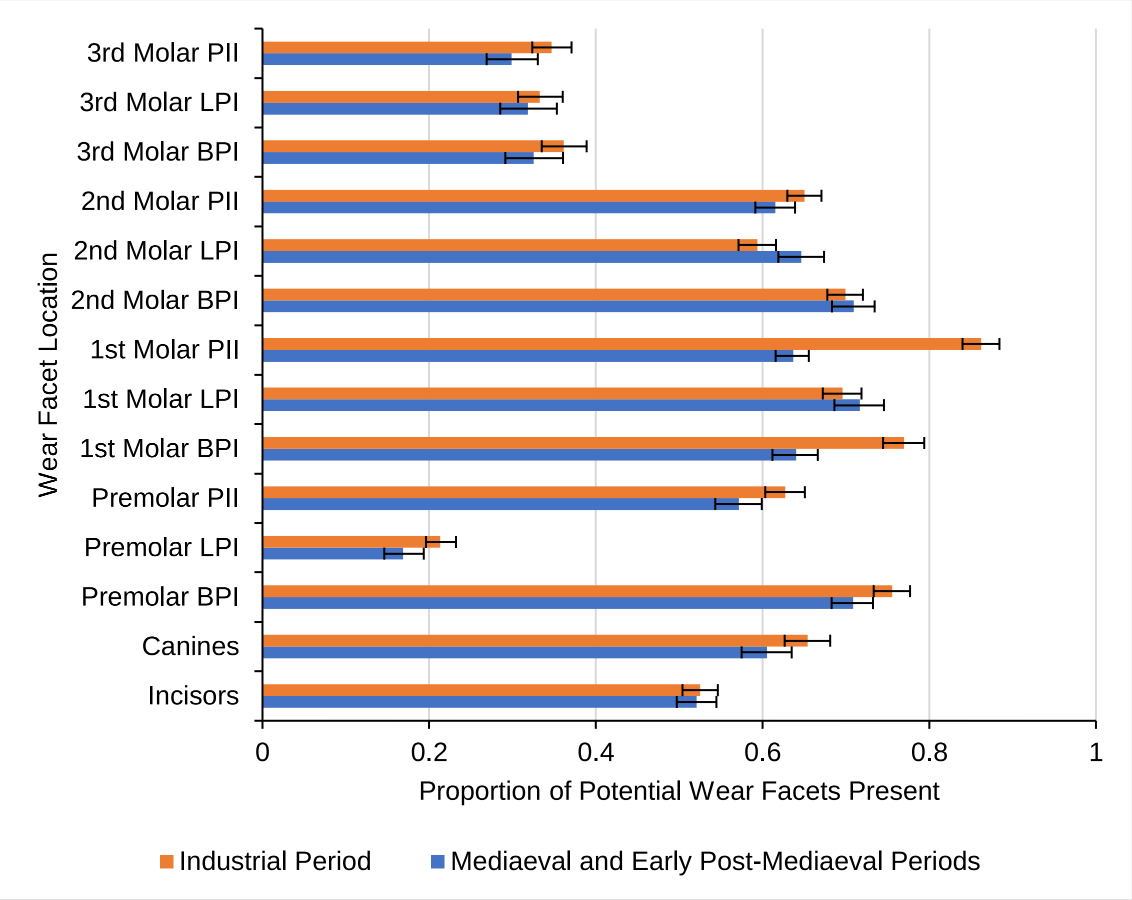

Figure 180: Bar chart comparing the proportion of the potential wear facets present (Figure 45) for each tooth type between the Mediaeval and Early Post-Mediaeval periods and the Industrial period. 95% confidence intervals for each proportion are presented as error bars.

10.2 Permutational test assessing homogeneity of multivariate dispersions for the PERMANOVA tests performed and other supplementary results.

Section 6.1.1 Differences in wear gradient between sites and time periods examined.

Table 114: PERMDISP test of wear gradient data according to site. ***Null hypothesis: within group variation in wear-gradient values did not differ significantly between the assemblages examined.***

	Sum of Squares	Mean of Squares	df	F-value	P-value (>F)	H_0
Site	9	0.06	0.01	0.85	0.57	Not Rejected
Residuals	144	1.06	0.01			

Table 115: PERMDISP test of wear gradient data across all tooth types when divided by period. ***Null hypothesis: within group variation in wear-gradient values did not differ significantly between the periods examined.***

	df	Sum of Squares	Mean of Squares	F-value	P-value (>F)	H_0
Groups	1	0.00	0.00	0.46	0.51	Not Rejected
Residuals	172	0.50	0.00			

Section 6.1.2.1.1: Differences in wear facet area composition between left and right molars.

Table 116: Assessment of homogeneity of dispersion for the effect of sidedness on relative dental wear facet area in the pre-Industrial and Industrial groups. ***Null Hypothesis: The distribution of relative wear facet area values did not differ significantly between the left and right sides of the dentition.***

Homogeneity of Dispersion	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
ILR Data Mediaeval	1	0.22	0.22	1.67	0.21	Not Rejected
Residuals	128	17.02	0.13			
ILR data Industrial	1	0.08	0.08	0.48	0.50	Not Rejected
Residuals	102	16.27	0.16			

Section 6.1.2.2: Wear facet area composition and period.

Table 117: Results of PERMDISP tests for comparison of wear facet area composition between time periods. ***Null hypothesis: within group variation did not differ significantly between the two periods.*** *The null hypothesis of homogeneity of dispersion is supported by p>0.05.*

	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard data	1	0.01	0.01	1.96	0.17	Not Rejected
	231	1.27	0.01			
ILR data	1	0.23	0.23	1.63	0.21	Not
	231	33.24	0.14			Rejected

Section 6.1.2.5.1 Within arch dental pathology by site and period.

Table 118: Results of PERMDISP test for prevalence of within arch dental pathology when divided by period. ***Null hypothesis: within group variation in within arch dental pathology did not differ significantly between the two periods.***

Homogeneity of Dispersion	df	Sum of squares	Mean of squares	F model	Pr(>F)	H_0
Groups	1	0.03	0.03	1.70	0.19	Not Rejected
Residuals	257	4.68	0.02			

Table 119: Results of PERMDISP test for prevalence of interarch dental pathology divided by site. Homogeneity of dispersion could be assumed for all comparisons. ***Null hypothesis: variation in the distribution of within arch dental pathology did not differ significantly between the assemblages****.*

Site	Df	Sum of Squares	Mean of Squares	F	p-value (>F)
Groups	9.00	0.25	0.03	1.26	0.26
Residuals	249.00	5.57	0.02		

Section 6.1.2.5.2 Mesial drift, ante-mortem tooth loss and wear facet area composition.

Table 120: PERMDISP tests for upper second molar status and relative wear facet area in the Industrial period. ***Null hypothesis: within group variation did not differ significantly between individuals with their upper second molar present and those without.***

Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
ILR Data Industrial Period	2	0.03	0.01	0.10	0.91	Not rejected
	80	11.21	0.14			
Standard data Industrial Period	2	0.01	0.01	1.00	0.35	Not rejected
	80	0.42	0.01			

Section 6.1.3 Dynamic OFA simulations compared between time periods.

Table 121: Results of PERMDISP test assessing the variation in Occlusal Fingerprint collision profiles between the two periods. ***Null hypothesis: within group variation did not differ significantly between the two periods.***

Homogeneity of Dispersion	Df	Sum of Squares	Mean of Squares	F	p-value (>F)	H_0
Groups	1	2.11	2.11	0.09	0.77	Not Rejected
Residuals	30	675.74	22.52			

Section 6.2.1.1 Industrial Period: Wear facet area composition compared between the sexes.

Table 122: PERMDISP tests assessing whether within group variation in relative wear facet area differed significantly between the sexes in the Industrial period. ***Null hypothesis: within group variation in relative wear facet area did not differ significantly between the sexes in the Industrial material examined.***

Sex Difference	df	Sum of Sq.	Mean of Sq.	F-model	Permutation	p-value	H_0
Standard	1	0.00	0.00	0.43	9999	0.52	Not
	88	0.56	0.01				Rejected
ILR data	1	0.12	0.12	0.72	9999	0.40	Not
	88	15.14	0.17				Rejected

Table 123: PERMDISP tests for comparisons of sex differences in relative wear facet area for each assemblage dating to the Industrial Period. ***Null hypothesis for each comparison: within group variation in relative wear facet area did not differ significantly between the sexes in the assemblage being assessed.***

	df	Sum of Sq.	Mean of Sq.	F-model	Perm.	p-value	H_0
Coron. Street	1	0.02	0.02	1.99	9999	0.18	Not Rejected
Standard	16	0.13	0.01				Not Rejected
Coron. Street	1	0.98	0.98	2.92	9999	0.11	Not Rejected
ILR data	16	5.37	0.34				Not Rejected
St Peter's	1	0.01	0.01	1.71	9999	0.21	Not Rejected
Standard	10	0.06	0.01				Not Rejected
St Peter's	1	0.17	0.17	1.01	9999	0.34	Not Rejected
ILR data	10	1.72	0.17				Not Rejected
St Michael's	1	0.00	0.00	0.18	9999	0.67	Not Rejected
Litten Standard data	43	0.31	0.01				Not Rejected
St Michael's	1	0.03	0.03	0.23	9999	0.63	Not Rejected
Litten ILR data	43	6.51	0.15				Not Rejected
St Bride's	1	0.00	0.00	0.20	9999	0.68	Not Rejected
Standard	28	0.19	0.01				Not Rejected
St Bride's	1	0.05	0.05	0.48	9999	0.50	Not Rejected
ILR data	28	2.91	0.10				Not Rejected

Section 6.2.1.2 Industrial Period: Wear facet area composition compared between age-at-death categories.

Table 124: Results of PERMDISP tests for the relationship between age-at-death and wear facet area proportion in the Industrial period. ***Null hypothesis: within group variation in wear facet area composition did not differ significantly between the two age-at-death categories in the Industrial period.***

Age-at-death Category	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	1	0.00	0.00	0.56	0.46	Not rejected
	57	0.39	0.01			
ILR data	1	0.45	0.45	2.30	0.14	Not rejected
	57	11.09	0.19			

Table 125: Results of PERMDISP tests for wear facet area compositions and age-at-death category among the St Bride's assemblage. ***Null hypothesis: within group variation did not differ significantly between age-at-death categories in the St Bride's assemblage.***

Age Category Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	2	0.00	0.00	0.36	0.73	Not Rejected
	27	0.17	0.01			
ILR data	2	0.10	0.05	0.45	0.64	Not Rejected
	27	3.14	0.12			

Section 6.2.1.3 Industrial Period: wear facet composition and social status

Table 126: Results of PERMDISP tests to assess within group variation in the St Bride's assemblage when divided by social status. ***Null hypothesis: variability in wear facet area proportions did not differ significantly between higher and lower/middle status groups in the St Bride's assemblage.***

Occupation Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	1	0.00	0.00	0.54	0.47	Not Rejected
	28	0.21	0.01			
ILR data	1	0.08	0.08	0.72	0.41	Not Rejected
	28	3.15	0.11			

Table 127: Results of PERMDISP tests for St Michael's Litten (ESC11) wear facet area proportions compared between burial types. ***Null hypothesis: within group variation did not differ significantly between the burial types examined from St Michael's Litten****.*

Burial Type Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	4	0.03	0.01	1.06	0.39	Not
	40	0.27	0.01			Rejected
ILR data	4	0.66	0.17	1.08	0.37	Not
	40	6.14	0.15			rejected

Section 6.2.1.4 Industrial Period: Wear facet area composition compared between the skeletal assemblages examined.

Table 128: Results of PERMDISP test assessing whether variability in wear facet area composition differed significantly between the Industrial site examined. ***Null hypothesis: the variability in wear facet area composition did not differ significantly between the Industrial sites examined.***

By Site Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	3	0.01	0.00	0.44	0.72	Not
	99	0.64	0.01			Rejected
ILR data	3	0.27	0.09	0.54	0.66	Not
	99	16.28	0.16			Rejected

Section 6.2.1.5 Industrial Period: Pipe facets and wear facet area composition.

Table 129: PERMDISP tests for the relationship between pipe facets and relative wear facet area in the Industrial Period. ***Null hypothesis: there were not any significant differences in the variation in wear facet proportions when comparing individuals with and without evidence of pipe use.***

Pipe Facet Presence Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	1	0.00	0.00	0.02	0.90	Not Rejected
	16	0.13	0.01			
ILR data	1	0.00	0.00	0.00	0.98	Not Rejected
	16	6.15	0.38			

Section 6.2.1.6 Industrial Period: Crossbites

Table 130: Results of PERMANOVA examining the relationship between wear facet proportions and anterior crossbites in the Industrial assemblages. ***Null hypothesis: wear facet area proportions did not differ significantly between individuals with and without anterior crossbites in the Industrial-era assemblage.*** *The variable examined satisfied the homogeneity of multivariate dispersion assumption required to perform PERMANOVA (Table 130).*

Standard data	Sum of Squares	Mean of Squares	DF	F	R^2	p-value(>F)	H_0
Anterior Crossbite	0.04	0.04	1	1.86	0.02	0.16	Not Rejected
Residuals	0.02	2.22	94		0.98		
ILR data	**Sum Squares**	**Mean Squares**	**DF**	**F**	R^2	**p-value(>F)**	H_0
Anterior Crossbite	0.47	0.47	1	0.92	0.01	0.37	Not Rejected
Residuals	0.51	47.51	94		0.99		

Table 131: Results of PERMDISP test for the relationship between anterior crossbite and relative wear facet area in the Industrial assemblages. ***Null Hypothesis: within group variation in relative wear facet area proportions were consistent irrespective of the presence of an anterior crossbite in the Industrial period.***

Anterior Crossbite Presence Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	1.00	0.00	0.00	0.62	0.43	Not Rejected
	94.00	0.59	0.01			
ILR data	1.00	0.09	0.09	0.54	0.46	Not Rejected
	94.00	15.71	0.17			

Table 132: Results of PERMANOVA examining the relationship between wear facet proportions and anterior crossbites in the pre-Industrial assemblages. Null hypothesis: wear facet area proportions did not differ significantly between individuals with and without anterior crossbites in the pre-Industrial assemblages. The variable examined satisfied the homogeneity of multivariate dispersion assumption required to perform PERMANOVA (Table 132).

Standard data	Sum of Squares	Mean of Squares	DF	F	R^2	p-value(>F)	H_0
Anterior Crossbite	0.02	0.02	1	1.25	0.01	0.28	Not Rejected
Residuals	2.31	0.02	123		0.99		
ILR data	**Sum Squares**	**Mean Squares**	**DF**	**F**	R^2	**p-value(>F)**	H_0
Anterior Crossbite	0.42	0.42	1	1.06	0.01	0.29	Not Rejected
Residuals	48.87	0.40	123		0.99		

Table 133: Results of PERMDISP test for the relationship between anterior crossbite and relative wear facet area in the pre-Industrial assemblages. ***Null Hypothesis: within group variation in relative wear facet area proportions were consistent irrespective of the presence of an anterior crossbite in the pre-Industrial group.***

Anterior Crossbite Presence Dispersion	Df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	1	0.01	0.01	1.46	0.28	Not Rejected
	123	0.61	0.00			
ILR data	1	0.13	0.13	0.99	0.28	Not Rejected
	123	16.28	0.13			

Table 134: Result of independent sample t-tests comparing mean dip angles between individuals with and without anterior crossbites in the Industrial period. Dip angle data were normally distributed (Shapiro Wilk test BPI p-value=0.13; LPI p-value=0.61; PII p-value=0.90). ***Null hypothesis: The dip angle values for the wear facets associated with a given phase of the power stroke did not differ significantly between individuals with and without anterior crossbites in the Industrial period.*** **Bonferroni adjusted p-value for 3 tests= 0.017.*

Wear Facet Function	BPI	LPI	PII
Anterior Crossbite present-Mean Dip Angle (°): Industrial period	34.26	35.18	21.96
Standard Deviation	9.61	9.08	8.29
Anterior Crossbite absent-Mean Dip Angle (°): Industrial period	29.56	30.31	25.98
Standard Deviation	9.75	7.02	8.21
t-value	-1.16	-1.29	1.14
Degrees of Freedom	5.70	5.40	5.68
p value*	0.29	0.25	0.30
Effect Size	0.15	-0.68	0.60
95% CI Effect Size	-0.68 to 0.99	-1.52 to 0.16	-0.24 to 1.44
Statistical Power	0.06	0.35	0.29
H_0	Not Rejected	Not Rejected	Not Rejected

Table 135: Result of independent sample t-tests comparing mean dip angles between individuals with and without anterior crossbites in the Mediaeval and early Post-Mediaeval groups. Dip angle data was normally distributed (Shapiro Wilk test BPI p-value=0.60; LPI p-value=0.12; PII p-value=0.41). ***Null hypothesis: The dip angle values for the wear facets associated with a given phase of the power stroke did not differ significantly between individuals with and without anterior crossbites in the pre-Industrial group.*** **Bonferroni adjusted p-value for 3 tests= 0.017.*

Wear Facet Function	BPI	LPI	PII
Anterior Crossbite present- Mean Dip Angle (º): pre-Industrial period	29.00	23.00	23.90
Standard Deviation	4.88	2.99	2.31
Anterior Crossbite absent- Mean Dip Angle (º): pre-Industrial period	22.87	19.76	23.61
Standard Deviation	7.24	7.44	6.72
t-value	-1.75	1.46	0.17
Degrees of Freedom	1.07	1.21	1.29
p value*	0.32	0.35	0.89
Effect Size	-0.42	1.10	-0.73
95% CI Effect Size	-1.83 to 0.99	-0.31 to 2.52	-2.14 to 0.68
Statistical Power	0.09	0.33	0.17
H_0	Not Rejected	Not Rejected	Not Rejected

Section 6.2.2.2 Mediaeval and Early Post-mediaeval periods: skeletal assemblage, cemetery type and wear facet area composition

Table 136: Results of PERMDISP test for the relationship between cemetery type and relative wear facet area in the pre-Industrial assemblages. ***Null Hypothesis: within group variation in relative wear facet area proportions were consistent between the cemetery types examined dating to the Mediaeval and early Post-Mediaeval periods.***

Homogeneity of dispersion	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	3.00	0.03	0.01	2.27	0.08	Not Rejected
	126.00	0.60	0.00			
ILR data	3.00	0.82	0.27	2.26	0.08	Not Rejected
	126.00	15.27	0.12			

Table 137: Results of PERMDISP test for the relationship between skeletal assemblage and relative wear facet area in the Mediaeval and early Post-Mediaeval periods. The null hypothesis was rejected and through step-wise removal of each assemblage it was determined that Box Lane was the assemblage responsible for the rejection of the null hypothesis. Box Lane was removed from further analysis in this section due to its small sample size. ***Null hypothesis: within group variation in relative wear facet area proportions were consistent between the skeletal assemblages examined dating to the Mediaeval period.***

Site Dispersion	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	4	0.02	0.01	1.46	0.22	Not Rejected
	74	0.30	0.00			
ILR data	5	1.42	0.28	2.37	0.05	Not Rejected
	76	9.11	0.12			

Table 138: Results of PERMDISP test for the relationship between site and relative wear facet area in the pre-Industrial group following the exclusion of Box Lane. ***Null Hypothesis: within group variation in relative wear facet area proportions were consistent between the sites examined in the Mediaeval period.***

Homogeneity of dispersion	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Standard	4	0.02	0.01	1.46	0.22	Not Rejected
	74	0.30	0.00			
ILR data	4	1.00	0.25	2.03	0.09	Not Rejected
	74	9.10	0.12			

Section 6.2.2.3 Mediaeval and Early Post-Mediaeval Periods: leprosy and wear facet expression among the St James and St Mary Magdalene Chichester assemblage.

Table 139: Results of statistical tests used to assess homogeneity of multivariate dispersion for the relationship between cemetery area, skeletal changes consistent with lepromatous leprosy and wear facet area composition. ***Null hypothesis: within group variation in wear facet area composition did not differ significantly between individual with and without leprosy and between cemetery areas.***

Dispersion	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Leprosy Standard data	1	0.00	0.00	0.41	0.52	Not Rejected
	22	0.05	0.00			
Leprosy ILR data	1	0.01	0.01	0.51	0.48	Not Rejected
	22	0.64	0.03			
Area Standard data	1	0.00	0.00	0.28	0.60	Not Rejected
	22	0.05	0.00			
Area ILR data	1	0.00	0.00	0.10	0.75	Not Rejected
	22	0.78	0.03			

Table 140: Results of homogeneity of dispersion tests assessing whether within group variation in dip angles was significant between cemetery areas or individuals with and without lepromatous leprosy. ***Null hypothesis: within group variation did not differ significantly between individuals with and without leprosy or between cemetery area groups****.*

Dispersion	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Area	1	0.00	0.00	0.13	0.72	Not Rejected
	22	0.04	0.00			
Leprosy	1	0.00	0.00	1.17	0.29	Not Rejected
	22	0.05	0.00			

Table 141: Results of permutational homogeneity of dispersion tests for the relationship between cemetery area, leprosy, ORI and TCI. ***Null hypothesis: within group variation did not differ significantly between individuals with and without leprosy and between cemetery areas.***

Dispersion: TCI	df	Sum of Squares	Mean of Squares	F-model	p-value	H_0
Leprosy	1	0.00	0.00	1.17	0.29	Not Rejected
	22	0.05	0.00			
Cemetery Area	1	0.00	0.00	0.13	0.72	Not Rejected
	22	0.04	0.00			
Dispersion: ORI	**df**	**Sum of Squares**	**Mean of Squares**	**F-model**	**p-value**	**H_0**
Leprosy	1	0.00	0.00	0.25	0.62	Not Rejected
	22	0.01	0.00			
Cemetery Area	1.00	0.00	0.00	0.02	0.90	Not Rejected
	22.00	0.01	0.00			

10.3 An assessment of interaction effects potentially influencing lower second molar wear facet area composition and dip angle: skeletal assemblage, age-at-death and sex.

A series of type II PERMANOVA tests were performed to assess whether any interaction effects were present that may influence the interpretation of the statistical testing conducted for the main analysis. This was to ascertain whether variation in dental wear facet expression on the lower second molar was dependent on a combination of variables, such as age-at-death category, sex and site. The data were divided into each period. There were no significant interaction effects influencing relative wear facet proportions or wear facet dip angle in the Mediaeval and early Post-Mediaeval periods (Table 142, Table 143 and Table 146). In the Industrial period, there were no significant interaction effects influencing relative wear facet area proportions (Table 144 and Table 145). There was, however, a significant interaction effect influencing wear facet dip angle between age-at-death category and the skeletal assemblage being assessed (Table 147). Although the relationship between age-at-death category and wear facet dip angle approached significance in the overall assessment of all the Industrial period assemblages examined (Table 147), the impact of age-at-death category on wear facet dip angle depended significantly on the assemblages being considered and compared (Table 148; Figure 181 to Figure 183). This effect was apparent in the Coronation Street and St Michael's Litten assemblages when comparing BPI and LPI dip angles.

Table 142: Results of type II PERMANOVA using the Bray-Curtis dissimilarity matrix examining whether any significant interaction effects between sex, age category and site influenced the relative wear facet area of the lower second molar in the Mediaeval and early Post-Mediaeval periods. Relative wear facet area differed significantly between several of the assemblages examined and these results are presented in section 6.2.2.

Explanatory variable	Sum of Sq.	Mean of Sq.	df	F	Probability (>F)	H_0	PERMDISP p-value
Sex	0.03	0.03	1	1.95	0.14	Not Rejected	0.14
Age	0.01	0.01	1	0.36	0.70	Not Rejected	0.48
Site	0.21	0.04	5	2.63	**0.01**	Rejected	**0.06**
Sex-Age	0.02	0.02	1	1.39	0.25	Not Rejected	0.23
Sex-Site	0.09	0.02	4	1.37	0.21	Not Rejected	0.20
Site-Age	0.03	0.01	2	0.91	0.46	Not Rejected	0.21
Sex-Age-Site	0.01	0.01	1	0.35	0.71	Not Rejected	0.22
Residuals	1.06	0.02	67				
Total	1.42		81				

Table 143: Results of type II PERMANOVA using the Euclidean distance matrix of the isometric log-transformed data examining whether any significant interaction effects between sex, age category and site influenced the relative wear facet area of the lower second molar in the Mediaeval and early Post-Mediaeval periods. Differences between several of the assemblages examined were significant and these are presented in section 6.2.2.

Explanatory variable	Sum of Sq.	Mean of Sq.	df	F	Probability (>F)	H_0	PERMDISP p-value
Sex	0.46	0.46	1	1.26	0.30	Not Rejected	0.33
Age	0.15	0.15	1	0.42	0.65	Not Rejected	0.49
Site	4.54	0.91	5	2.49	**0.01**	Rejected	**0.05**
Sex-Age	0.37	0.37	1	1.01	0.36	Not Rejected	0.43
Sex- Site	1.85	0.46	4	1.27	0.26	Not Rejected	0.21
Site-Age	0.46	0.23	2	0.63	0.60	Not Rejected	0.14
Sex-Age-Site	0.12	0.12	1	0.32	0.73	Not Rejected	0.29
Residuals	24.45	0.36	67				
Total	31.92		81				

Table 144: Results of type II PERMANOVA using the Bray-Curtis dissimilarity matrix examining whether any significant interaction effects between sex, age category and site influenced the relative wear facet area of the lower second molar in the Industrial period. None of these differences were significant when all explanatory variables were considered together.

Explanatory variable	Sum of Sq.	Mean of Sq.	df	F	Probability (>F)	H_0	PERMDISP p-value
Sex	-0.01	-0.01	1	-0.22	0.99	Not Rejected	0.41
Age	0.03	0.03	1	1.03	0.37	Not Rejected	0.80
Site	0.10	0.03	3	1.28	0.27	Not Rejected	0.92
Sex-Age	0.00	0.00	1	0.18	0.84	Not Rejected	0.94
Sex-Site	0.03	0.01	3	0.41	0.87	Not Rejected	0.59
Site-Age	0.11	0.04	3	1.42	0.21	Not Rejected	0.88
Sex-Age-Site	0.04	0.02	2	0.74	0.56	Not Rejected	0.69
Residuals	1.90	0.03	75				
Total	2.18		87				

Table 145: Results of type II PERMANOVA using the Euclidean distance matrix on the isometric log-ratio data examining whether any significant interaction effects between sex, age category and site influenced the relative wear facet area of the lower second molar in the Industrial period. None of these differences were significant when all explanatory variables were considered together. The homogeneity of multivariate dispersion assumption was not violated for any of the explanatory factors.

Explanatory variable	Sum of Sq.	Mean of Sq.	df	F	Probability (>F)	H_0	PERMDISP p-value
Sex	0.03	0.03	1	0.05	0.95	Not Rejected	0.32
Age	1.12	1.12	1	2.04	0.13	Not Rejected	0.47
Site	1.39	0.46	3	0.84	0.54	Not Rejected	0.52
Sex-Age	0.19	0.19	1	0.35	0.70	Not Rejected	0.74
Sex-Site	0.49	0.16	3	0.29	0.93	Not Rejected	0.22
Site-Age	2.04	0.68	3	1.24	0.29	Not Rejected	0.44
Sex-Age-Site	1.06	0.53	2	0.97	0.41	Not Rejected	0.26
Residuals	41.18	0.55	75				
Total	47.17		87				

Table 146: Results of type II PERMANOVA using the Bray-Curtis dissimilarity matrix examining whether any significant interaction effects between sex, age category and site influenced the dip angles of the BPI, LPI and PII wear facets of the lower second molars examined dating to the Mediaeval and Early Post-Mediaeval periods.

Explanatory variable	Sum of Sq.	Mean of Sq.	df	F	Probability (>F)	H_0	PERMDISP p-value
Sex	0.02	0.02	1.00	1.14	0.34	Not Rejected	0.11
Age	0.01	0.01	1.00	0.50	0.66	Not Rejected	0.91
Site	0.11	0.02	5.00	1.20	0.29	Not Rejected	0.29
Sex-Age	0.00	0.00	1.00	0.03	0.93	Not Rejected	0.53
Sex-Site	0.08	0.02	4.00	1.10	0.37	Not Rejected	0.21
Site-Age	0.01	0.01	2.00	0.31	0.90	Not Rejected	0.31
Sex-Age-Site	0.00	0.00	1.00	-0.12	0.98	Not Rejected	0.36
Residuals	1.25	0.02	66.00				
Total	1.48		81.00				

Table 147: Results of type II PERMANOVA using the Bray-Curtis dissimilarity matrix examining whether any significant interaction effects between sex, age category and site influenced the dip angles of the BPI, LPI and PII wear facets of the lower second molar dating to the Industrial period. An interaction effect between site and age category had a significant impact on wear facet dip angles.

Explanatory variable	Sum of Sq.	Mean of Sq.	df	F	Probability (>F)	H_0	PERMDISP p-value
Sex	0.02	0.02	1.00	1.33	0.28	Not Rejected	0.74
Age	0.05	0.05	1.00	2.69	**0.06**	Rejected?	0.19
Site	0.03	0.01	3.00	0.66	0.70	Not Rejected	0.66
Sex-Age	0.02	0.02	1.00	1.25	0.30	Not Rejected	0.26
Sex-Site	0.04	0.01	3.00	0.85	0.55	Not Rejected	0.72
Site-Age	0.15	0.05	3.00	3.03	**0.01**	Rejected	0.77
Sex-Age-Site	0.00	0.00	2.00	0.09	0.97	Not Rejected	0.65
Residuals	1.23	0.02	73.00				
Total	1.60		87.00				

Table 148: Post-hoc permutational pairwise comparison showing the influence of the interaction effect between site and age-at-death on wear facet dip angles of the lower second molar in the Industrial period.

	Older Coron. Street	Older St Michael's	Older St Bride's	Older St Peter's	Younger Coron. Street	Younger St Michael's	Younger St Bride's
Older St Michael's	0.85	NA	NA	NA	NA	NA	NA
Older St Bride's	0.15	0.15	NA	NA	NA	NA	NA
Older St Peter's	0.15	0.15	0.64	NA	NA	NA	NA
Younger Coronation Street	**0.06**	**0.07**	0.26	0.64	NA	NA	NA
Younger St Michael's	**0.03**	**0.05**	0.41	0.64	0.75	NA	NA
Younger St Bride's	0.34	0.26	0.47	0.62	0.47	0.44	NA
Younger St Peter's	0.57	0.26	0.26	0.15	0.07	0.10	0.71

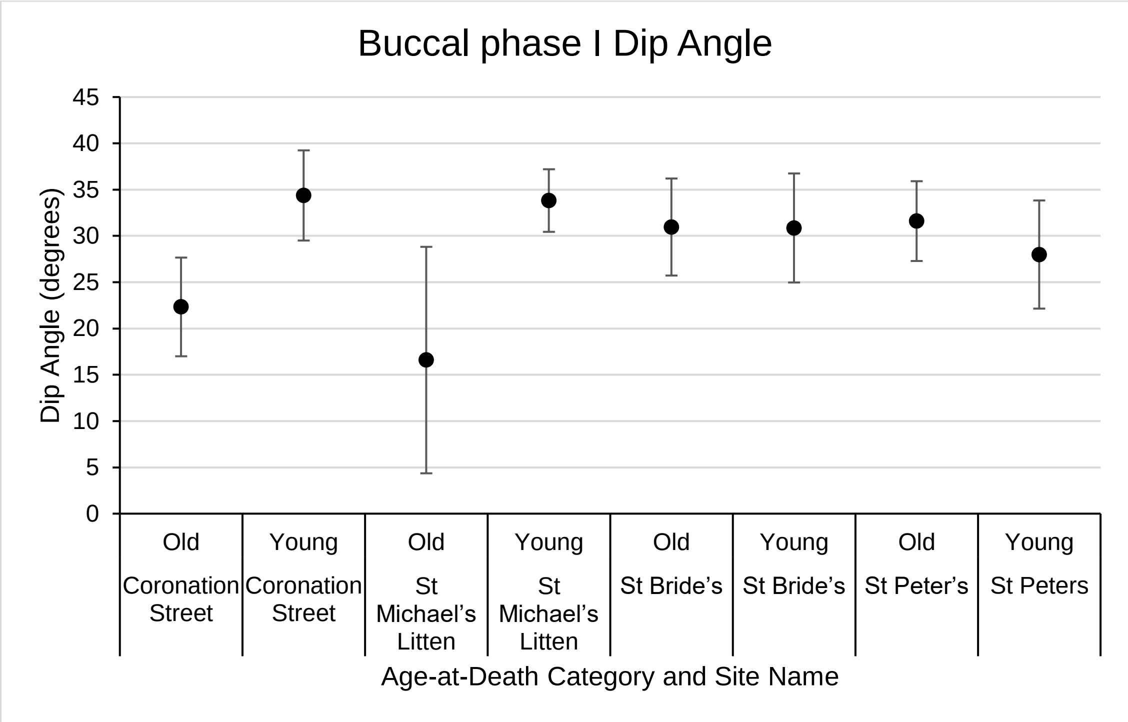

Figure 181: Plot showing the interaction effect between age-at-death category and skeletal assemblage on buccal phase I dip angles in the Industrial Period.

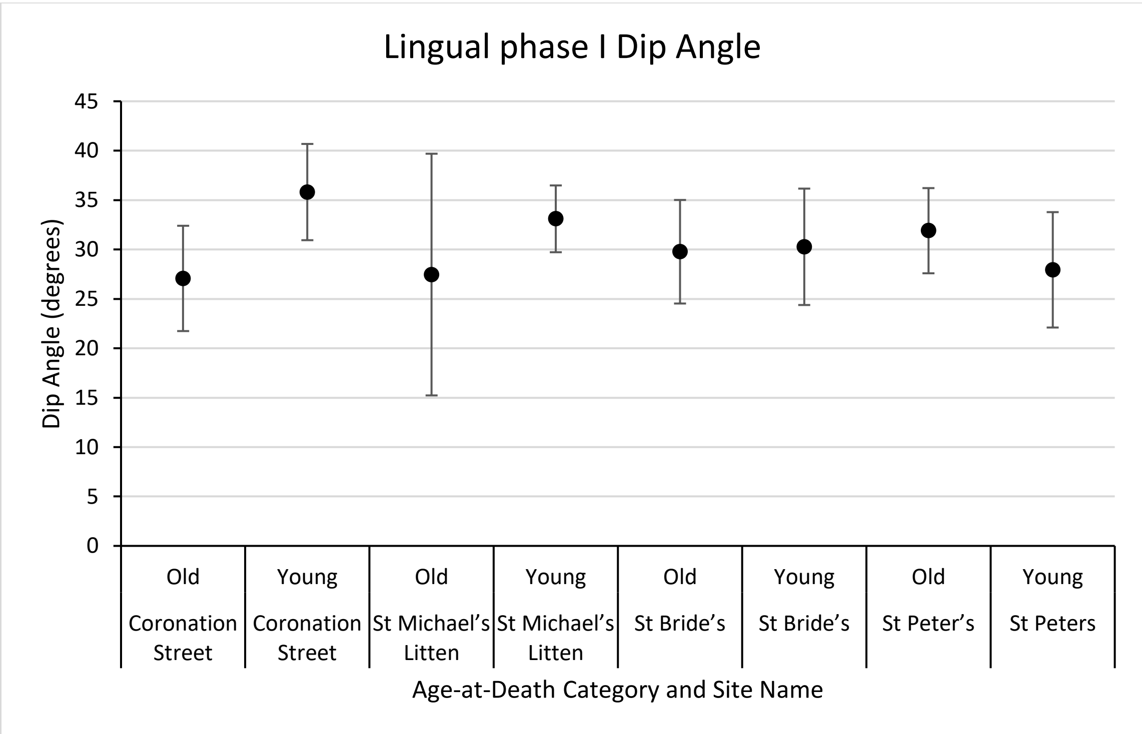

Figure 182: Plot showing the interaction effect between age-at-death category and skeletal assemblage on lingual phase I dip angles in the Industrial Period.

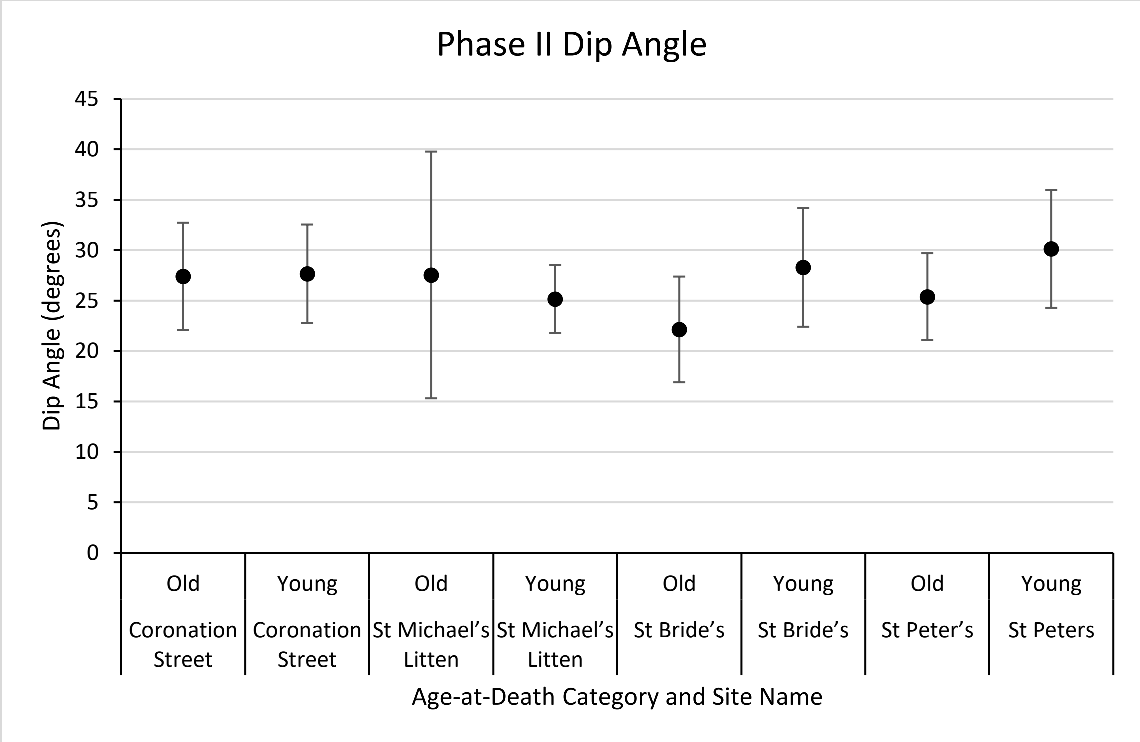

Figure 183: Plot showing the interaction effect between age-at-death category and skeletal assemblage on phase II dip angles in the Industrial Period.

10.4 List of OFA Simulation Videos

Section 6.1.3

Video 1: Coronation Street, South Shields, SK371.

Video 2: St Peter’s, Wolverhampton, SK19.

Video 3: St Bride’s Church, London, SK221.

Video 4: St Michael’s Litten Late Post-Mediaeval phase, SK599.

Video 5: Hereford Cathedral, SK3268.

Video 6: St James and St Mary Magdalene, Chichester, SK328.

Video 7: York Barbican, SK3650.

Video 8: St Michael’s Litten Early Post-Mediaeval phase, SK2729.

Section 6.2.1.6

Video 9: St Michael’s Litten Crossbite, SK1986, Left Side.

Video 10: St Bride’s Church, London, SK239.

Additional Videos used in analysis presented in section 6.1.3.1.

Industrial Period

Video 11: Coronation Street, SK243.

Video 12: Coronation Street, SK430.

Video 13: Coronation Street, SK1010.

Video 14: St Michael’s Litten, SK316.

Video 15: St Michael’s Litten, SK443.

Video 16: St Michael’s Litten, SK721.

Video 17: St Michael’s Litten, SK1629.

Video 18: St Michael’s Litten, SK1986, Right Side.

Video 19: St Michael’s Litten, SK2359.

Video 20: St Michael’s Litten, SK2584.

Video 21: St Michael's Litten, SK3639.

Video 22: St Michael's Litten, SK5180.

Video 23: St Bride's Church, SK73.

Video 24: St Bride's Church, SK152.

Video 25: St Bride's Church, SK225.

Mediaeval and early Post-Mediaeval Periods

Video 26: York Barbican, SK2033.

Video 27: York Barbican, SK2708.

Video 28: York Barbican, SK2714.

Video 29: York Barbican, SK4027.

Video 30: St James and St Mary Magdalene, SK64.

Video 31: St Michael's Litten, SK183.

Video 32: St Michael's Litten, SK465.

Video 33: Hereford Cathedral, SK787.

Video 34: Hereford Cathedral, SK3449.