University of Southampton

FACULTY OF HUMANITIES

Archaeology

Re-evaluating the use of dental wear as a tool for estimating age at death in British archaeological skeletal remains

by

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Thesis for the degree of Doctor of Philosophy

September 2019

University of Southampton

Abstract

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Dental wear is frequently used to estimate age at death in archaeological remains. However, the most widely cited dental wear ageing methods rely on underlying principles which have not been examined. Furthermore, the most widely cited method for estimating age concluded that a single dental wear chart could be applied to multiple British archaeological periods. This statement has never been validated. Thus, this thesis presents a re-evaluation of dental wear as a method for estimating age at death of archaeological remains.

Three key underlying principles were identified and tested for three dental wear ageing techniques. Dental wear was measured using an ordinal scale and continuous measurements, and dental wear rates calculated for well-documented samples dating from the British Neolithic to Post-Medieval periods. Dental wear was measured on the permanent molars of 861 individuals, aged from 6 years old to adults displaying high degrees of dental wear and ante-mortem tooth loss.

A review of dental wear rates revealed molars of the same type wear at a similar rate. The third molar showed a relatively slower wear rate compared to the first and second molars, although this difference was not great. This difference in wear rate between molar types remained constant throughout the life of the dentition, validating one of the key assumptions of dental wear ageing methods. These findings support the use of a single dental wear rate for all molars in methods of estimating age using dental wear.

The relationship between dental wear and age was confirmed across all temporal samples, supporting the continued use of dental wear as an ageing method for archaeological remains. A comparison of dental wear rates across temporal samples indicate a single wear rate may be used to estimate age in multiple archaeological populations. However, this thesis strongly recommends the development and use of population-specific wear rates to obtain the most reliable estimates of age.

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Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

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6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

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Acknowledgements

I am greatly indebted to so many people for their practical support, advice, encouragement and patience, without which the completion of this thesis would not have been possible. I am extremely grateful to the AHRC for launching the Collaborative Doctoral Partnership scheme and for funding this research, providing me with the opportunity to conduct my own research and meet some incredible individuals.

I would thank my supervisory committee, Sonia Zakrzewski, and Simon Mays for their support and guidance. Their insightful feedback and critiques have been beyond helpful, and I could not be more appreciative.

I am greatly indebted to all of the many the institutions and their staff who provided me with information regarding their collections. It is not possible to name every individual by name, but I wish to give particular thanks to those institutions listed in the Appendix A, who granted me access to their collections. I wish to thank all who gave me their time and advice when locating material for this thesis, without whom this research would not have been possible and I am eternally grateful.

I would also like to thank a number of individuals who have provided me with support and guidance throughout the PhD process. I would like to thank David Wheatley of the University of Southampton for providing guidance in photography and statistical analysis. I also thank Philip Pollard of Historic England for his enthusiasm and support during this Collaborative Doctoral Partnership. I would also like to thank Joanna Sofaer and Alistair Pike for their supportive feedback and guidance during my upgrade exam, which helped direct the next stage of my PhD.

I wish to thank those who have helped me along the way, both academically and personally. In particular my fellow osteologists at the University of Southampton. Sarah Stark, Sarah Schwarz and Steph Wright thank you for your never-ending support, encouragement and friendship during my time at Southampton. I would also like to thank the post-graduate community at the University of Southampton and my fellow CDP students, creating a space of understanding and support for this very unique journey

Chapter 1 Introduction

Estimating age at death of human remains is fundamental to the fields of archaeology and forensic anthropology, contributing to the reconstruction of life histories, building demographic profiles and identifying victims. However, estimating age at death of adult remains is fraught with issues. Many of the most widely cited methods for estimating age do not address these matters, casting doubt on the reliability of the age estimates they produce. More recently, researchers have started questioning and testing age estimation techniques leading to advances in the field. This thesis aims to continue this work by re-evaluating one of the most frequently used methods for estimating age at death: dental wear. A key interest of this research is the development of skeletal ageing methods that are reliable but also practical. This is of most use to commercial archaeologists, who are often limited both by time and in their access to resources. The choices made throughout this thesis are therefore governed by this approach.

Methods for estimating age at death in adult skeletal remains attempt to correlate chronological age with physical variations in the skeleton. Commonly used ageing techniques include scoring the degenerative changes of the auricular surface and the pubic symphysis, cranial suture fusion and dental wear. However, skeletal age indicators in adult remains are only imperfectly correlated with chronological age (Mays 2015a). Skeletal age indicators are dependent on genetic and environmental factors, such as health, activity and diet, which influence the rate of ageing of skeletal tissues. These factors vary between individuals, and between populations, producing variation in the relationship between the skeletal indicator and age.

Most ageing techniques assume the relationship between an age indicator and actual age is similar in both the reference population used to develop an ageing standard and the population under study. Past studies demonstrate the age structure of a reference sample will be reflected in the age distribution of an sample of unknown age (Bocquet-Appel and Masset 1982; Usher 2002). Many of the common ageing standards applied to archaeological populations are produced using modern reference samples. The likely difference in age-at-death structure between the target and reference sample produces inaccuracies and bias in the age estimates produced. Variation in the morphology of an age indicator and the use of inappropriate reference samples are just two areas of concern when re-evaluating methods for estimating age at death in skeletal remains. However, the use of dental wear to estimate age, especially in high attrition populations, is less sensitive to these issues compared to bony age estimates.

Dental wear is the progressive loss of the tooth tissues by various mechanisms (Chapter 4). Dental tissues do not remodel and are subject to constant wear throughout an individual's life. As a result, loss of dental tissue occurs in a predictable pattern that is associated with age (Miles 1962; Lovejoy et al. 1985a). The rate of dental tissue loss is dependent on environmental factors, such as diet, meaning dental wear rates vary between populations. However, dental wear rates may be calibrated for a target population, omitting the application of an ageing standard developed from a reference sample. Dental tissues also survive well in the archaeological environment, compared to bony elements, making the ability to estimate age from the dentition particularly useful for researchers studying past populations.

Miles (1962) and Brothwell (1963, 1972a, 1981) produced the most widely cited ageing methods using dental wear. Using an Anglo-Saxon population, Miles (1962) examined wear on the molar teeth to estimate age by progressively extrapolating wear rates from younger individuals to older individuals. The Miles dental ageing chart, which accompanied his publication, and the approach used to produce the chart is frequently used to estimate age. Reliability tests suggest that the Miles approach performs as well or better than other methods of age estimation (Nowell 1978; Kieser et al. 1983; Lovejoy et al. 1985a; Santini et al. 1990; Santini et al. 2017). However, the Miles Method requires approximately 30 juvenile individuals within a population to make reliable wear rate estimates (Nowell 1978), which is rare in excavated archaeological samples. The Modified Miles Method attempts to overcome this issue by employing the wear gradient between adult molars to estimate the rate of wear of a population (Gilmore and Grote 2012). This estimated rate of wear is then used to estimate age. Comprehensive tests of reliability have yet to be performed on the Modified Miles Method, but it presents a viable option for estimating age in skeletal samples lacking juvenile remains. Brothwell (1963) produced the most widely cited method for estimating age using dental wear, a single chart depicting stages of wear organised into age groups by molar type. Brothwell stated his chart could be applied to individuals dating from the British Neolithic to the Medieval period. However, the samples and methods employed to produce Brothwell's chart are poorly defined making it difficult to perform tests of reliability.

Although the Miles (1962) and Brothwell (1963) techniques are commonly used for estimating age their underlying principles have not been thoroughly investigated. For example, a key assumption of the Miles Method is that the wear gradient between two molars remains constant throughout the life of the dentition. Previous tests of reliability do not examine this assumption. The Brothwell chart concludes all British individuals dating from the Neolithic to Medieval period had a similar rate of dental wear. No comparative study of dental wear rates has been performed using well-documented samples to confirm this finding. This thesis aims to address such issues to ensure that the use of dental wear is a reliable method for estimating age at death in archaeological remains.

This thesis employs both ordinal and ratio measurements to evaluate the methods of Miles (1962), Brothwell (1963) and Gilmore and Grote (2012). Traditionally, dental wear is recorded using ordinal scales, which divide the continuous process of dental wear into discrete stages (Chapter 4). Ordinal scales produce imprecise measurements of wear that do not necessarily represent similar amounts of tissue loss (Molleson and Cohen 1990). More recently, measurements of crown height have been employed to measure dental wear and investigate the relationship between dental wear and age at death (Mays et al. 1995; Mays 2002; Mays and Pett 2014). Measuring dental wear on a continuous scale has the potential for a more in-depth and precise evaluation of existing dental wear methods than an ordinal scale permits. Furthermore, continuous measurements remove the subjective assessment of dental wear stages, permitting cross comparison studies.

1.1 Research Aims

The principal aim of this thesis is to evaluate the use of dental wear as a tool for estimating age at death in British archaeological remains. Four research questions are proposed to examine the validity of the underlying principles of three techniques for estimating age using dental wear: the Miles Method (Miles 1962), the Brothwell chart (Brothwell 1963) and the Modified Miles Method (Gilmore and Grote 2012). Dental wear is measured using both an ordinal scale and continuous measurements of crown height and dental wear rates calculated for well documented samples dating from the British Neolithic to Medieval period. A Post-Medieval sample is included for further comparison. This research, thus, provides a methodological contribution to the field of bioarchaeology.

Research Question 1. Do molars of the same type wear at a similar rate?

Neither Brothwell (1963) or Miles (1962) explicitly state if their dental charts represent only the lower molars, or if they represent both maxillary and mandibular molars. Furthermore, there is no indication whether the molars are from the left or right side of the mouth. Brothwell (1963) notes there may be minor differences between sets of molars, but does not provide further information. In contrast, Gilmore and Grote (2012) average the wear scores of maxillary and mandibular molars, with scores recorded for the left side unless lost. All techniques therefore assume there is a similar rate of wear across all sets of molars. This thesis calculates and compares wear rates for molars of the same type (e.g. the first molars) to test this assumption.

Investigation of the similarity of wear rates across molars of the same type is vital as archaeological remains can be fragmentary, meaning excavated individuals may not have a complete set of dentition. Results supporting a similar wear rate across molars of the same type will support the substitution of one molar for another, for example the left first molar for the right first molar, where preservation is poor. If molars of the same type wear at a different rate errors will be introduced and age estimates will be inaccurate.

Research Question 2. Do all molar types have a similar rate of wear?

The second research question investigates whether different molar types wear at a similar rate. While some studies have noted a difference in wear rates between molar types (Miles 1962; Kieser et al. 1983; Santini et al. 1990), others have not (Nowell 1978; Dreier 1994; Mays et al. 1995). This research question examines whether a single rate of wear can be applied to all molar types or if molar-specific wear rates are required.

The second part of this question examines whether wear rates between different molar types remain constant. The Miles Method identified a slight difference in wear rate between molar types but assumed the gradient of wear remained constant throughout the dental wear process (Chapter 3). The Modified Miles Method assumes a similar wear rate across all molar types, and that this remained constant. This assumption has not been previously tested. If wear rates do not remain constant across molar types, age estimates will be unreliable, especially for older individuals.

Research Question 3: how strongly is dental wear associated with age?

Clearly, there is a relationship between age and dental wear (Miles 1962; Nowell 1978; Brothwell 1989; Mays et al. 1995; Mays 2002; Santini et al. 2017). Teeth do not remodel, i.e. once the dental tissue is lost or removed it is not replaced. This relationship must be confirmed for the samples used in the current study.

This thesis calculates and examines the strength of the relationship between juvenile age and dental wear. Miles (1962) employs the rate of wear observed in the juvenile individuals of a population to estimate the functional age of adult molars. This thesis examines the relationship between juvenile age and dental wear to assess the validity of the Miles Method. A lack of relationship between dental wear and juvenile age would suggest that producing adult wear rates, and therefore age estimates, based on the juvenile sample alone is unreliable.

The relationship between dental wear and bony age estimates is also examined to ensure dental wear increases with age. This analysis aims to confirm that dental wear is progressive with age, and examines the degree of variation in dental wear measurements associated with the increase of age.

Research Question 4: Do populations dating to the British Neolithic to Medieval periods have a similar rate of wear?

Brothwell (1963, 1972a, 1981), states his dental wear chart for estimating age can be applied to individuals dating from the Neolithic to the Medieval period. Brothwell's chart implies that individuals within these periods have a similar wear pattern and wear rate (Chapter 3). Brothwell's conclusion has never been validated, therefore a comparison of period-specific dental wear rates is vital for testing the validity of Brothwell's chart. A similarity between wear rates supports the use of a single dental wear chart for estimating age in individuals dating to multiple periods. A difference, however, would support the production of population-specific dental wear charts. A Post-Medieval sample is included for further comparison.

1.2 Thesis structure

Chapter 2 reviews the most commonly employed methods for estimating age at death in skeletal remains, identifying the shortcomings and restrictions associated with each method. The use of dental wear as an age estimation technique is discussed in light of the most common issues surrounding ageing methods.

Chapter 3 examines three key methods for estimating age at death using dental wear; the Miles Method (Miles 1962), the chart of Brothwell (1963), and the Modified Miles Method (Gilmore and Grote 2012). Each method is reviewed and evaluated in light of its strengths and weaknesses for estimating age at death in archaeological skeletal remains.

Chapter 4 discusses the causes of dental wear, and the factors affecting the dental wear process. Finally, the methods used to record dental wear are reviewed.

Information about the skeletal samples is detailed in **Chapter 5**. This will provide an overview of the diet consumed, land and technology use, and a review of the burial practices observed during the British Neolithic to Post-Medieval periods. Location and sample size of each specific site included in each temporal sample is also provided.

Chapter 6 outlines the methodology developed for the present study. This includes the methods chosen for the osteological analysis of the human remains, the methods for recording dental wear, and the analysis employed to investigate the proposed research questions. Reliability tests for recording dental wear were performed prior to any statistical analysis.

Chapter 7 will present the results, structured to match the hypotheses defined in Chapter 6. **Chapter 8** will consist of a discussion of these results, providing a comprehensive review of the most widely cited methods for estimating age at death in archaeological remains. This chapter reviews the use of dental wear as a tool for estimating age.

A final summary and conclusions will be drawn together in **Chapter 9** along with a note on the limitations of this research and recommendations for further research.

The appendices supporting this work are found at the end of this document. **Appendix A** comprises of a list of the institutions visited, and where data collection was carried out. **Appendix B** presents the formula and outputs testing the reliability of the ordinal scale used in this thesis. **Appendix C** provides the output controlling for multiple comparisons using the Benjamini-Hochberg procedure. **Appendix D** comprises of the skeletal specimens used in this thesis.

Chapter 2 Estimating age at death in skeletal remains

This section reviews the bony indicators most widely used for estimating age at death and their associated weaknesses. Section 2.2 further discusses these issues and their implications for estimating age at death, considering how using dental wear as a tool for estimating age may overcome them.

Age estimation techniques can be broken into two major categories. The first examines developmental changes that occur during the growth and development of the human skeleton. Techniques using development and maturation of the skeleton apply to non-adult individuals, under 18 years of age. Once the skeleton has ceased growth, age estimation techniques rely on degenerative changes to estimate the age of individuals over 18 years. This thesis evaluates the use of dental wear to estimate age, a method for estimating the age of adult skeletal remains. Therefore, this section only reviews the methods employed to estimate age in adult individuals.

2.1 Bony methods for estimating age at death

Since the 19th century specific areas of the skeleton have been examined for age-related changes. Dwight (1881, 1890) examined the timing of cranial suture fusion and the fusion of the sternum body while later work by Todd (1920) discussed changes to the pubic bone. Since then, many methods for estimating age have been produced.

Cranial sutures, the pubic symphysis, the auricular surface and sternal rib ends are the most commonly cited macroscopic techniques for estimating age in skeletal remains along with dental wear. These methods were found to be the most frequently used in a review of three leading journals, *American Journal of Physical Anthropology*, *International Journal of Osteoarchaeology* and *Journal of Archaeological Science*, for the period May 2004 to June 2009 (Falys and Lewis 2011). Furthermore, O'Connell (2017) includes these skeletal ageing techniques in the 'Updated guidelines to the standards for recording human remains,' further highlighting their popularity. Although microscopic age estimation techniques exist, such as counting dental cementum annulations or histomorphometric analysis of cortical bone, macroscopic examination of the skeleton is less time or resource expensive. Thus, this thesis only considers macroscopic methods for estimating age.

2.1.1 Cranial Sutures

Cranial suture closure has been used as a method for estimating age since the 1920s. Multiple ageing methods exist based on ectocranial (relating to the exterior of the skull) and endocranial (relating to the interior of the skull) closure, using different sutures and different scoring systems. Even in early studies the relationship between cranial suture closure and age has been questioned for its reliability. In 1924, Todd and Lyon published a study of endocranial suture closure in Euro-American males, followed by a study on ectocranial suture closure in 1925 (Todd and Lyon Jr 1924, 1925). Todd and Lyon Jr (1924) suggested there was a definite pattern in suture closure when observing the average progress of a large number of crania, but concluded cranial suture closure was not a reliable method for estimating age due to individual variation. McKern and Stewart (1957 p.37) found similar results when studying skeletal age changes in young American males, stating the "process of closure has only a very general relationship with age…Thus, as a guide for age determination, such a trend is of little use."

In 1985, Meindl and Lovejoy published a new method for estimating age from cranial sutures. This approach used a four-point system based on the extent of closure at ten specific sites (Figure 2.1.1). Meindl and Lovejoy (1985) produced composite scores, mean age and standard deviations for observed age ranges. However, these standard deviations and observed ranges were large, indicating variability between individuals, leading Meindl and Lovejoy (1985 p.62) to conclude "the relationship between degree of closure and age is therefore only general." More recently,

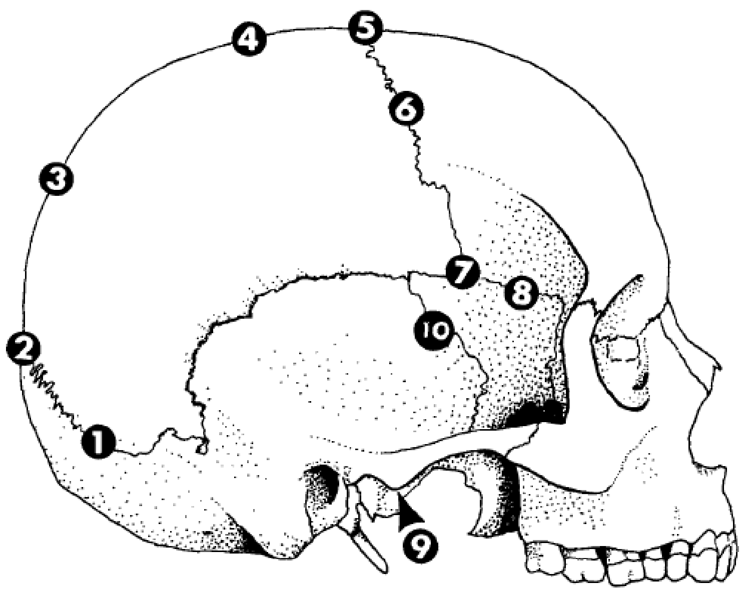

Figure 2.1.1 Ten sites at which cranial suture closure is observed following Meindl and Lovejoy (1985). Each site is assigned one of four degrees of closure. Image taken from Meindl and Lovejoy (1985 p.60).

Kroman and Thompson (2009) suggested cranial suture closure may be closely correlated to severe changes to the skeleton, such as sacroiliac fusion, ankylosing spondylitis or severe scoliosis, rather than simply advancing age. Their study identified a stronger correlation between skeletal dysfunction and cranial suture obliteration than between age-at-death and fusion rates when using the William M. Bass skeletal collection. The Bass Collection, curated at the University of Tennessee, is a collection of approximately 1000 skeletons with a date of death after the year 2000 where age, sex and ancestry are known for all individuals. Both the studies by Meindl and Lovejoy (1985) and Kroman and Thompson (2009) further suggest the technique for estimating age using cranial sutures is unreliable.

Despite evidence suggesting cranial suture closure is not a reliable technique for estimating age at death in skeletal remains, it is frequently used. Falys and Lewis (2011) found 66 out of 200 (33%) articles recorded the use of cranial sutures as a method for estimating age. The high frequency of use may be due to the ease of scoring cranial sutures. It is also a method that can be applied to samples where post-cranial elements are under-represented. Whatever the reason, researchers suggest that it is inadvisable to rely on cranial sutures as an age estimation technique, due to its inaccuracy and unreliability (Falys and Lewis 2011; O'Connell 2017).

2.1.2 Pubic symphysis

A second ageing technique uses the pubic symphysis and relies on the examination of morphological changes of the pubic bone, which begins during puberty. Pubic symphysis ageing methods divide this process into morphological stages with associated age ranges, although the number of stages varies between methods. General trait progression begins with billowing of the pubic symphysis in young adults. With advancing age, these billows fill, and the dorsal and ventral margins become better defined, forming a rim around the symphysis in middle-aged adults. Finally, degenerative features appear, such as lipping, erosion and breakdown of the symphyseal surface (Figure 2.1.2).

During the 1920s, Todd and colleagues were some of the first to document age-related changes to the pubic bone, describing ten morphological phrases with associated age ranges (Todd 1920; Todd 1921). In a study of 349 males who died during the Korean conflict, McKern and Stewart (1957) found that many of the pubic faces were not directly equitable with the ten phases defined by Todd. As a result, McKern and Stewart (1957) developed a three-component numerical scoring method. A review by Katz and Suchey (1986), using a large sample of male pubic bones, identified

Figure 2.1.2. Age related changes to the pubic symphysis. Age progression of the pubic symphysis from young to old (left to right). Image taken from Garvin et al. (2012 p.205)

issues with both techniques. Todd's system was found to overestimate age, and neither system accounted for the variability observed in the older individuals. As a result, Katz and Suchey (1986) proposed a modified Todd six-phase method. In 1990, Brooks and Suchey added 273 female pubic bones to the work of Katz and Suchey (1986), refining the morphological descriptions and presenting sex-specific age ranges. The Suchey-Brooks system is now the most widely used technique for estimating age at death using the pubic symphysis (Falys and Lewis 2011). More recently, Hartnett (2010a) revised the Suchey-Brooks system, producing new descriptions and age ranges, and a seventh phase for individuals over 70 years of age.

The reliability of using the pubic symphysis to estimate age is open to question. One reason for this is the reference samples used to produce the scoring systems. Both Todd (1920; 1921) and McKern and Stewart (1957) relied on samples made up of male individuals. Furthermore, all the above techniques rely on samples consisting of modern individuals. Brooks and Suchey (1990) argued their method was appropriate for use in a variety of contexts as their sample was derived from individuals born throughout North America, Europe, South America, and Asia, and included diverse socioeconomic backgrounds. As discussed below, the use of modern individuals may adversely affect the reliability of the age estimates when applied to archaeological individuals (Section 2.2.4).

2.1.3 Auricular surface

Lovejoy and colleagues were the first to propose the auricular surface of the ilium as a marker of age (Lovejoy et al. 1985b). Based on observations using an archaeological Libben population, and the known-age Todd collection, Lovejoy et al. (1985b) noted a strong correlation between skeletal age indicators and morphological changes of the auricular surface. These changes included surface granulation, macroporosity, billowing, striations and transverse organisation (Figure 2.1.3). Lovejoy et al. (1985b) provided descriptions of the morphological features and grouped them into eight age phases. The first seven ranges are narrow, spanning five years, the sixth phase spans ten, and the final stage is left open to include all individuals over 60 years of age. However, a test of the Lovejoy et al. (1985b) method found many of the age estimates did not fall into the correct stages (Saunders et al. 1993). Using a sample of known age individuals from a 19th century Canadian pioneer cemetery, Saunders et al. (1993) argued Lovejoy's system appeared to perform well for young adults but decreased in accuracy and reliability for individuals past 35 years old.

Figure 2.1.3. Modal changes in the auricular surface with age. Image taken from Lovejoy et al. (1985b p.24)

In 2002, Buckberry and Chamberlain proposed a revised auricular surface method for estimating age at death. The authors argued that the separate features of the auricular surface described by Lovejoy et al. (1985b) developed independently of each other. Buckberry and Chamberlain (2002) applied a quantitative scoring system, examining the different features of the auricular surface independently of one another. A blind test of the new scoring system using a known-age sample from Christ Church, Spitalfields, London showed a large dispersion of age estimates for any given morphological stage (Buckberry and Chamberlain 2002). However, the authors argued this revised method was easier to apply and may be more reliable than that of Lovejoy et al. (1985b).

A later study tested the method of Buckberry and Chamberlain (2002) using the known age at death St. Bride's, London collection, spanning the late 17th to early 19th centuries (Falys et al. 2006). The authors found that while the method was easy to apply, the revised auricular stages were too precise to compensate for the overlap caused by inter-individual variability. Falys et al. (2006) recommend reducing the number of stages and employ broader age ranges to better reflect variation in actual age. These studies suggest that the auricular surface may only be able to produce broad estimates for age at death, rather than narrower, precise age bands.

2.1.4 Sternal rib ends

Işcan and colleagues produced the earliest schemes for estimating age at death from the sternal rib end (Işcan et al. 1984a, b, 1985; Işcan and Loth 1986). Using a sample of individuals autopsied at a medical examiner's office, they observed age-related changes to the fourth rib, including pit depth, pit shape, changes in the rim wall and overall bone density and texture. From these observations, a series of phases were produced, starting with flat or billowy ends with rounded edges in young individuals. With increasing age, the rim thins, becomes irregular, and increases in surface porosity. A later study by Işcan et al. (1987) found significant differences in the timing of morphological changes between populations, suggesting the need for population-specific modification for the method.

The original studies observing age-related changes in the rib used small sample sizes, the largest consisting of 118 individuals (Işcan et al. 1984a). Hartnett (2010b) tested the accuracy of estimating age at death from the sternal end of the fourth rib using a larger sample (N = 630, 419 males, 211 females) of mixed ancestry individuals from the Maricopa County Forensic Science Centre, Arizona, and Barrow Neurological Institute, Arizona. Hartnett (2010b) suggests while there was a correlation between the Işcan and Loth systems and age at death there was room for improvement, suggesting bone weight and bone quality play a more significant role in phase assignment. As a result, Hartnett (2010b) proposed revisions to the age phases to reflect this.

Merritt (2014) compared the relative accuracy and reliability of the original Işcan methods to the revised method of Hartnett (2010b) using the William M. Bass Skeletal Collection. Merritt's results found Hartnett's revised method did not score as many individuals into the correct age category compared with the Işcan method but did perform better for overall bias scores. Both the sample used to develop Hartnett's revised method and the sample used in Merritt's test of reliability consisted of modern individuals. It is unclear how well Hartnett's sternal rib method would perform for an archaeological sample.

The fourth rib does not survive well in archaeological contexts, reducing the effectiveness of the method. Loth et al. (1994) evaluated whether the standards for the fourth rib could be applied to the ribs three and five. Ribs 3, 4 and 5 from modern autopsies of known age, sex and race were collected and an age phase assigned. Loth et al. (1994) found little difference in using ribs three or five, compared with than the fourth. In 79% of cases, all three ribs fell into the same age range, and differences were within one age phase for 98% of the sample (Loth et al. 1994). Loth et al. (1994) concluded that the standards for the fourth rib could be applied to the adjacent ribs to assess age, thus improving the chances of obtaining an age estimate for poorly preserved individuals.

2.1.5 Multi-factorial Methods

As the above demonstrates, bioarchaeologists have a range of ageing techniques at their disposal and will frequently employ multiple approaches to reach an estimate of age. However, there is no standard of to combine information produce from multiple methods. In a study of 145 members of the Physical Anthropology section of the American Association of Forensic Sciences, all but one respondent reported using multiple indicators to estimate age but there was little consistency in the way methods were combined (Garvin and Passalacqua 2012). Approaches include: taking the range of mean ages, providing a narrow and broad range, using the range from the method the user feels is most reliable, and the ages where the age ranges of various methods overlap. The most frequently approach was to produce an age range based on experience. In reality, none of these approaches are statistically robust given that different methods are developed on different samples. Multi-factorial methods have been developed in an attempt to overcome this.

In 1970, Ascádi and Nemeskéri produced the Complex Method using a sample of 105 individuals of known sex and age. No description occurs in their 1970 publication of sample size, sex, socio-economic status or class, only that their sample consisted of autopsied individuals (Brooks and Suchey 1990). The Complex Method produces an age estimate by integrating four age indicators in the humerus, pubis, femur and cranial sutures. Endocranial suture closure and changes to the pubic symphysis are assessed on a five-point scale, and the structure of the spongy bone in the proximal epiphysis of the humerus and femur are assessed on a six-phase scale. Tables were produced to take into account possible combinations of age indicator phases and age estimates produced. Acsádi and Nemeskéri (1970) claimed this approach produced accurate age estimates in 80-85% of individuals, with a margin of error of two to five years. A test of the method by Molleson and Cox (1993), using the Spitalfields Collection, revealed a systematic error when comparing the age determined by the Complex Method with actual age. Individuals under 40 years were over-aged, while those over 70 years old were under-aged. Less than 30% of the Spitalfields sample was correctly aged (within five years of real age), but 50% were estimated to be within ten years of actual age (Molleson and Cox 1993). About three-quarters of the sample was assessed to be within 15 years of real age. Molleson and Cox (1993) concluded the Complex Method was most accurate for estimating age in individuals aged between 50 and 70 years.

Lovejoy et al. (1985a) developed an alternative multi-factorial technique for estimating age. This approach can incorporate as many age indicators that are available, as long as the sample can be seriated according to each method (Bedford et al. 1993). The original study employed five indicators: the auricular surface, pubic symphysis, dental wear, ectocranial sutures and radiographic changes to the proximal femur. All age indicators were independently applied to a population and used to create an intercorrelation matrix, and subjected to principal component analysis. The final age of any individual is a weighted average of all included indicators, producing a 'summary age' (Lovejoy et al. 1985a).

Tests of the Lovejoy et al. (1985a) method suggest no single indicator age consistently performs better than the summary age (Lovejoy et al. 1985a; Bedford et al. 1993; Saunders et al. 1993). However, Saunders et al. (1993) found no significant improvement in accuracy or bias for the summary age estimates over those obtained by simply averaging age estimates from individual indicators. Furthermore, simple averages do not necessarily improve on single age estimates. For example, using a known age sample of 55 individuals interred at the St. Thomas Anglican Church in Belleville, Onatario between 1821 and 1874, Saunders et al. (1993) found summary age produced an inaccuracy and bias of 6.1 years. A simple average of all age indicators employed produced an inaccuracy and bias of 6.9 years, while the auricular surface gave an inaccuracy of 3.9 years and a bias of 3.4 years. For the purposes of age estimation, inaccuracy is the average absolute error of the age estimation, whereas bias is the mean over- or under-prediction of the individual's age (Meindl and Lovejoy 1985). These results show little improvement in accuracy and bias when using summary age, and that a simple average of multiple methods does not necessarily improve on the age estimate produced from a single method. Saunders et al. (1993)

therefore suggest age assessment should be based on individual age indicators, and then the suite of age estimates should be evaluated in turn rather than statistically.

This conclusion highlights the significance of 'experience' when producing age estimates from skeletal remains. Using a large sample of 252 known-age modern American males and females from the Bass Donated Collection and Mercyhurst forensic cases, Milner and Boldsen (2012) found experienced-based assessments of age showed considerable improvement over results for Transition Analysis (see below). These experience-based assessments utilised some of the most common methods for estimating age, including the pubic symphysis, auricular surface, cranial sutures (Milner and Boldsen 2012). While the importance of experience should not be underestimated, it is best used by those confident in the assessment of age. For those lacking this, such as students or curators, the standards applied and how information is combined to produce an age estimate are likely to vary.

In 2002, Boldsen and colleagues published a new Bayesian approach to age estimation. This was given the name 'transition analysis,' so called because the analysis relies upon the estimated age of transition between adjacent stages of an age phase or trait. Boldsen et al. (2002) scored cranial sutures, the pubic symphysis and auricular surface for age-related changes. Using a reference sample of 186 individuals from the Terry Collection, five cranial sutures were scored, as were five characteristics of the pubic symphysis and nine for the auricular surface. Traits were scored independently of one another, meaning entire structures were not forced into a single, discrete category. Boldsen et al. (2002) provide brief descriptions of age-related changes, which have been simplified from earlier work, including McKern and Stewart (1957) and Lovejoy et al. (1985b). A later validation study using 252 individuals from the Bass donated skeletal collection, and forensic cases from Mercyhurst University, showed the pubic symphysis performed the best on its own but improves when all skeletal information is combined (Milner and Boldsen 2012).

Boldsen et al. (2002) developed the ADBOU computer program, allowing users to input scores of skeletal traits and then uses transitional analysis to estimate age at death. The output includes two maximum likelihood estimates, one calculated with a uniform prior and the other calculated with an informed prior. Transition Analysis uses Bayesian analysis, whereby assumptions about the outcome are explicitly stated and incorporated into the analysis of the data (Gowland 2007). The prior, or prior probability distribution, provides the relative likelihood of different values of a parameter in the absence of any data. Therefore, the selection of the prior is important and has a significant effect on the results. If the user indicates the remains are 'archaeological' an age-at-death distribution from a 17th century Danish cemetery is used as the informed prior. If the remains are ‘forensic’ the informed prior uses 1996 USA homicide data (Boldsen et al. 2002). However, adopting an informed prior has the potential to incorporate bias discussed in section 2.2.4 relating to the use of reference samples in age estimation. Overall, Transition Analysis provides anthropologists with a relatively straightforward standardised method for estimating age at death from multiple skeletal indicators.

2.2 Dental Wear and Overcoming Issues

A review of the most commonly applied bony methods for estimating age at death identified three recurring issues with estimating age of archaeological remains. These include skeletal preservation, the variability of traits and the effect on produced age ranges, and the reliance on inappproproate reference samples. The section below discusses these issues in relation to dental wear ageing methods. First, a brief description of using dental wear to estimate age is provided. Chapter 3 provides a more detailed critique of the use of dental wear as a tool for estimating age.

2.2.1 Age estimation using dental wear

Dental wear is the process by which the hard, outer dental tissue of the enamel is progressively removed, and the underlying tissue, dentine, is exposed (Chapter 4). The amount of tooth wear experienced by an individual is strongly correlated with age, i.e. older individuals will show a higher degree of exposed dentine compared to younger individuals. Therefore, age estimation techniques using dental wear rely on the rate of wear within a population to estimate age at death.

Ever since Broca (1879) recorded stages of changing wear pattern with age in human dentition, dental wear has played a part in recording age categories. Many other studies have built on Broca’s work, detailing the pattern of wear and producing charts showing wear stages with age. Brothwell (1963) produced the most widely cited chart illustrating stages of wear with age (Figure 2.2.1). Although Brothwell’s chart is intended for estimating age in skeletal remains dating from the British Neolithic to the Medieval period, it has been applied to non-UK populations (Falys and Lewis 2011). Wear rates vary between populations and if applied to a group whose teeth wear at a slower rate, the ages of the group will be underestimated. Similarity, if a group’s teeth wear at a higher rate of wear, many individuals will be assigned an older age than their actual age. Therefore, the wear rates produced for the Brothwell chart may not be suitable for non-UK populations, or those dating to outside the Brothwell’s defined periods.

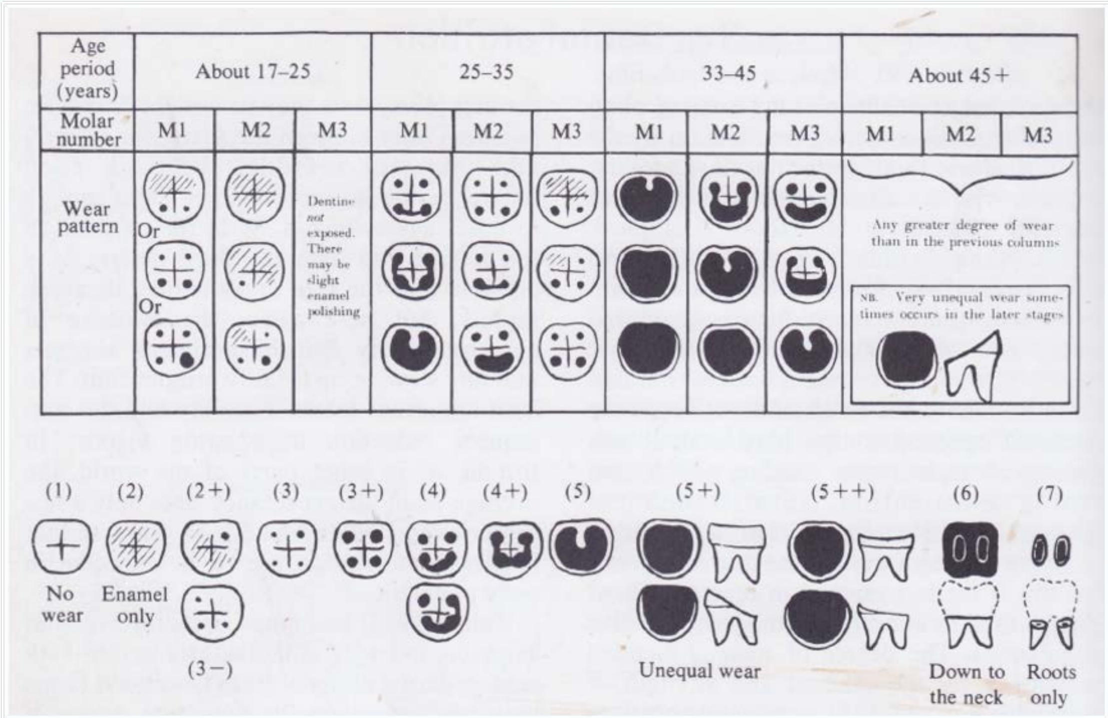

Figure 2.2.1.Brothwell's chart for estimating age at death in individuals dating to the British Neolithic to Medieval period, taken from Brothwell (1963 p. 69).

The second most widely cited method for estimating age at death using dental wear is Miles (1962). The Miles Method uses molar wear to estimate age by progressively extrapolating wear rates from juvenile individuals, whose age can be estimated with relative accuracy using dental development, to older individuals belonging to the same population (Figure 2.2.2). Tests of the Miles Method suggest that it performs well or better than other methods of skeletal age estimation (Nowell 1978; Kieser et al. 1983; Lovejoy 1985; Santini et al. 2017). This method requires approximately 20 juvenile individuals to observe a reliable wear rate (Nowell 1978). Due to their comparatively fragile nature, juvenile remains are often less well persevered in archaeological assemblages. To overcome this, Gilmore and Grote (2012) proposed the Modified Miles Method, estimating a rate of wear based on wear gradients in adult individuals. A test of the Modified Miles Method performed well compared to skeletal age estimates for a heterogeneous sample of hunter-gathers (Gilmore and Grote 2012). Both the Miles and the Modified Miles methods have two issues. The first is that the degree of error associated with age estimates increases with age, meaning the technique becomes less reliable for estimating age in older individuals. Both methods also assume the rate of wear remains constant throughout life, meaning that if the rate of wear decreases with age, both the Miles and the Modified Miles Method will underestimate age in older individuals.

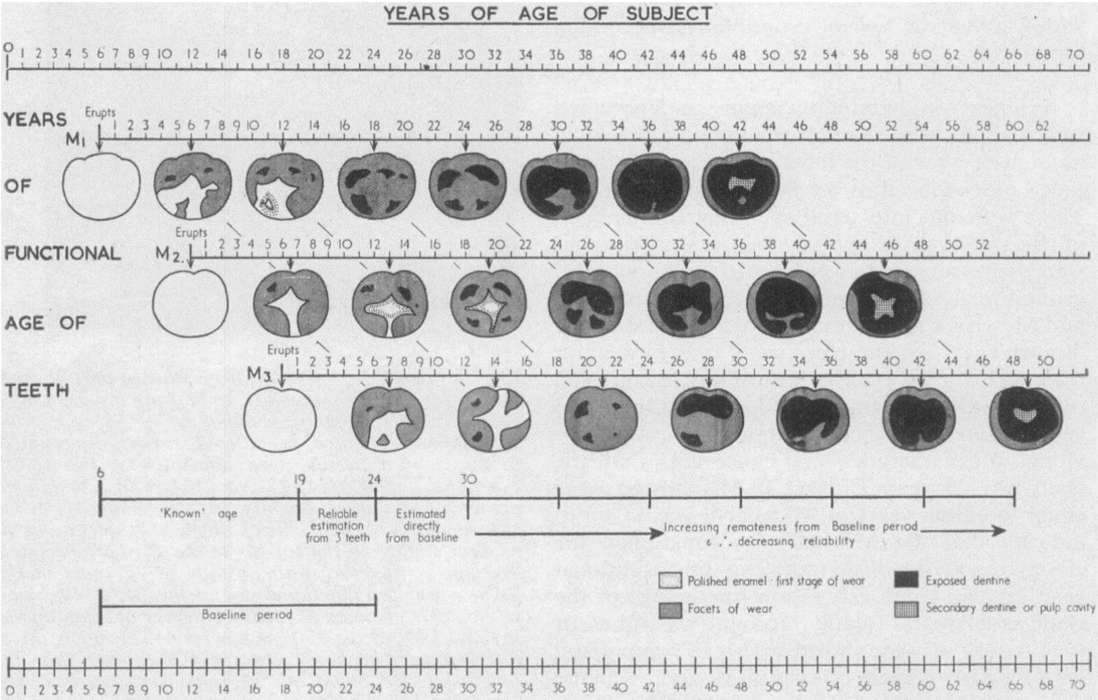

Figure 2.2.2. The Miles system for estimating age from dental wear, taken from Miles (1962 p.20).

More recently, sophisticated statistical methods have been applied to the estimation of age from dental wear. Millard and Gowland (2002) applied a Bayesian approach to estimate age from dental development and dental wear. Molar wear was scored for approximately 500 individuals from 10 Roman and Anglo-Saxon cemeteries and a Bayesian approach applied using a uniform prior. Millard and Gowland (2002) produced age estimates comparable to those given by the Miles Method in addition to producing confidence limits.

2.2.2 Preservation

The degree of preservation is one issue facing bioarchaeologists wanting to estimate age of archaeological remains. Soil acidity, soil-dwelling micro-organisms, the availability of water and soil temperature can all affect the preservation of skeletal remains (Mays 2010). Poor preservation may result in poor survivability of bony age markers, and therefore affect the ability to estimate age.

The tissues of the teeth are tough, particularly the hard outer tissue of enamel. In contrast to bone, teeth interact directly with the environment having to survive powerful mechanisms in the living mouth (see Chapter 4). Given this, it is not surprising that teeth survive well in the archaeological environment. Bone, in contrast, is comparatively fragile and can rapidly disintegrate in the ground and this is particularly true of some of the skeletal elements used in age estimation. For example, the poor survivability of the pubic symphysis hampers its ability to indicate age. Wittwer-Backofen et al. (2008) found only 17% of all pubic symphyses were available for observation in their sample (n=121) of early medieval skeletons from Lauchleim, Germany. In the known-age collection from Christ Church, Spitalfields, London, the pubic symphysis was only present for 58.9% of the sample (Buckberry and Chamberlain 2002). The comparatively good survival of the dentition in archaeological contexts means dental wear ageing methods are particularly to bioarchaeologists.

In addition to the survivability of skeletal elements, there is a historic preference of anthropologists to collect skulls over post-cranial elements (Walker, Dean and Shapiro, 1991). As a result, many museum collections contain a disproportionate number of skulls, meaning age can only be estimated through cranial suture closure or the extent of dental wear. As Section 2.1.1 discussed, cranial suture closure does not have a strong relationship with age. Therefore, dental wear is the only remaining tool for reliably estimating age at death in these remains.

2.2.3 Variation and Age Range

A range of factors affect how fast or slow bodies age, such as activity, diet and body size. As a result, much of the variation in age indicators is not associated with age (Mays 2015a). This creates a degree of noise in the relationship between skeletal age indicators and actual age, and means "skeletal age indicators in the adult are only imperfectly correlated with chronological age," (Mays 2015a p.332). For example, Merritt (2015, 2017) assigned age estimates to a large sample (n=746) of known-aged individuals from the Hamann-Todd and William Bass collections based on the characteristic of the ribs and pelvis. It was found that the commonly used methods for estimating age consistently under-aged underweight, short individuals and over-aged, heavy, tall individuals. Merritt (2015) argued rates of bone remodelling might explain the differences in skeletal age markers, with lower bone turnover rates observed in underweight individuals and heavier individuals displaying increased rates of bone remodelling. A differential rate in bone remodelling potentially affects the timing of the appearance of skeletal age markers, providing a potential explanation for the errors observed in age estimates.

With regards to bony age indicators, there are many factors other than age that have the potential to introduce variation and errors into an age estimate. Bone is a living tissue, removing and laying down new bone throughout an individual's life and is affected by genetic, hormonal and biomechanical changes. Dental tissues do not remodel, meaning that once a tooth is fully developed, it can only be altered through external, environmental factors. These factors include diet, the use of teeth as tools and food preparation methods (Chapter 4). These factors are better understood compared to those affecting bony age indicators. For example, coarse diets are largely responsible for the dental wear observed in archaeological populations, and the pattern of wear stages is a result of tooth morphology. Chapter 4 discusses these factors in more detail and how they contribute to wear.

Mays (2015a) reviewed the coefficients of determination (r^2) in 51 studies to determine how much variation in skeletal age indicators is due to factors other than age. The coefficient of determination measures the strength of a monotonic relationship between two variables. Mays (2015a) found dental wear was more correlated with age compared with bony markers when reviewing coefficients of determination in 41 studies using bony age indicators and 10 studies of dental wear reporting r^2 values. For dental wear, median r^2 was 0.52, including populations with low wear rates, whereas bony age indicators had a median r^2 of 0.38 (Mays 2015a). It should be noted the coefficients of determination taken from the original studies were based on both Pearson's correlation coefficients and Spearman's rank correlation coefficients. Furthermore, some correlations were between estimated and true age, while others were between true age and indicator stage. Nevertheless, Mays (2015a) results cautiously suggests age estimation techniques using dental wear are less affected by factors other than age, and may, therefore, be more reliable when estimating age at death of skeletal remains.

It is clear that variation exists in the relationship between any skeletal age indicator and actual age. Due to this variation, methods for estimating age are unable to produce precise and accurate age estimates. Many methods employ age ranges to account for this variation (Table 2.2.1). Some ageing techniques, including those developed by Todd (1920) or Lovejoy et al. (1985b), provide a narrow range for any given stage. While this provides fairly precise age estimates, it increases the likelihood that an individual will fall outside the given range. In contrast, large, overlapping age ranges, such as those given by Brooks and Suchey (1990), means individuals can fall into a number of different phases. Age estimation techniques employing dental wear do not use age ranges; the only one to do so is Brothwell (1963). Brothwell's stated age ranges are approximately ten years in length, with an open-ended stage for individuals aged 45 years or older (Table 2.2.1). While this is larger compared to some bony age ranges, Brothwell's ranges are not so large that they are not informative. For example, although it may be accurate to provide an age estimate to an individual ranging from 27 to 66 years, following Brooks and Suchey (1990), such an age range is not particularly informative. In contrast, Brothwell's stages indicates whether an individual is a 'young,' 'prime' or 'older' adult. However, the use of age categories by Brothwell (1963) indicates a change in wear stage almost overnight. Miles (1962) overcomes this to a degree by placing wear stages on an age scale, resulting in no clear age boundaries. Dental wear as an ageing method may never be precise, due to a degree of variation caused by extrinsic factors, but may produce more useful and consistent age ranges compared with bony age indicators.

Table 2.2.1. Age ranges reported for stages of age estimation. Age ranges taken from Todd (1920), Brothwell (1963), Lovejoy et al. (1985b), and, Brooks and Suchey (1990).

Category	Todd pubic symphysis	Brothwell dental wear.	Lovejoy et al. auricular surface	Suchey-Brooks pubic symphysis (males)
1	18-19	17-25	20-24	15-23
2	20-21	25-35	25-29	19-34
3	22-24	35-45	30-34	21-46
4	25-26	45+	35-39	34-57
5	27-30		40-44	27-66
6	30-35		45-49	34-86
7	35-39		50-59	
8	40-45		60+	
9	45-49			
10	50+			

2.2.4 The Reference Sample

One source of error in skeletal age estimation arises from problems with the reference collection on which a method is based. A reference collection consists of a number of individuals whose sex and age are known. Many of the methods for estimating age at death are created by correlating skeletal morphology to chronological age through a reference collection and using the morphology to estimate age (Hoppa and Vaupel 2002).

Osteologists have made intensive use of four major skeletal collections. The first is the Hamann-Todd collection, assembled between 1912 and 1938 by the Western Reserve University Department of Anatomy. During this time 3592 remains belonging to individuals of a low socio-economic status were collected from hospitals. A review of this collection by Lovejoy et al. (1985b) found that many of the 'known' ages ascribed to the Hamann-Todd individuals were unreliable, with discrepancies between 'stated' and 'observed' of 15 to 20 years. A second collection involves the remains of American military personnel killed in the Korean War. McKern and Stewart (1957) used this collection to produce methods for estimating age, including the pubic symphysis. This sample consists of predominately young white males and therefore does not reflect the demography of most archaeological samples. A third commonly used reference sample is the Terry Collection, consisting of 1700 skeletal remains from Washington University School of Medicine in St. Louis, later transferred to the Smithsonian Institution in Washington, DC. As with the Hamann-Todd collection, the Terry Collection is composed of individuals from low socio-economic groups (Galera et al. 1998). Finally, there is the collection employed to develop the Suchey-Brooks method for estimating age from the pubic symphysis (Suchey et al. 1986; Brooks and Suchey 1990). During 1977 and 1979 Suchey collected 1225 pubic bones from a well-documented sample of modern individuals autopsied in Los Angeles County to represent the general population regarding socio-economic status. These collections have been key for the development of many of the age estimation methods discussed in Section 2.1.

These four collections consist of individuals belonging to modern populations. More recently, the known age skeletal population of Christ Church, Spitalfields, London has been employed to assess how skeletal features relate to chronological age. For example, Buckberry and Chamberlain (2002) tested the reliability of their revised method for estimating age from the auricular surface using the Spitalfields collection. Approximately one thousand skeletons were excavated from the crypt of Spitalfields, including nearly 400 with coffin plate information providing names, age and date of death. Dates of birth ranged from 1646 to 1852, and dates of death from 1729 to 1852 (Molleson and Cox 1993). Spitalfields may be considered to be an archaeological reference sample, although the lifestyle of Post-Medieval Londoners is likely to be very different from those dating to early British periods, such as the Neolithic or Iron Age.

Bocquet-Appel and Masset (1982) were the first to emphasise the importance of the reference collection when attempting to estimate age at death of skeletal remains. They stated that each stage of an age indicator corresponds to a mean age in the reference population, which depends to a large extent on the age structure of the reference population. This means that the age structure of a reference sample will be reflected in the age distribution of the unknown aged sample, creating a bias (Usher 2002). For example, if older individuals are well represented in a reference sample, the mean age for each stage will be older than if a younger reference sample was used (Bocquet-Appel and Masset 1982).

In an attempt to find a solution to this bias, Usher (2002) suggested the use of a reference collection with a uniform distribution of ages or to apply statistical methods to avoid the effect of the age structure of the reference population. In either approach, the aim is to employ an ‘ideal’ reference collection that sufficiently represents all ages for the features being used in the ageing technique (Usher 2002), therefore minimising the amount of bias. Usher (2002) describes an ‘ideal’ reference sample as being of known-age, which has been verified by records, and where there is a good representation of any variation present in the population of interest, for example, different socio-economic statuses, races or health, inclusion of both males and females, individual of all ages, and that the reference sample is easily accessible. However, ideal reference samples are difficult to come by, and the widely used references samples described above fail to reach these requirements. For example, the collection employed by McKern and Stewart (1957) oversamples young men, and consequently has a tendency to under-age older individuals (Garvin et al. 2012). Even the Spitalfield collections, which may be considered an 'ideal' , only appears to contain individuals who may be described as middle or, at most, upper class (Molleson and Cox 1993). This means the Spitalfields collection is unable to provide an adequate representation of the working or lower classes for this period.

It is highly unlikely for a reference collection to be 'ideal', and therefore assumptions have to be made to combat this. The first is that the recorded ages of a collection are biologically correct (Usher 2002). As already discussed, Lovejoy et al. (1985a) identified discrepancies between 'stated' and 'observed' ages of 15 to 20 years in the Hamann-Todd collection, resulting in some known ages to be unreliable. If recorded known ages are unreliable, then the methods produced using this data will also be unreliable. The second assumption of a reference collection is that the ageing process of skeletal features is uniform and that the demographic processes observed in the present are assumed to be the same as in the past (Howell 1976b in Usher 2002). This implies that a skeletal feature that has been associated with age in one individual should be a marker of the same age in a different person, regardless of sex, origin, health or status. Furthermore, individuals vary, and so individuals of the same chronological age may vary in size, maturity or skeletal degeneration. This variation means that an age estimation method developed from one reference sample may produce unreliable age estimates when applied to a target population with a different demographic structure.

Section 2.1 showed the many age estimation techniques utilising bony skeletal indicators rely on modern reference samples. This approach runs the risk of incorrectly estimating the age of a population as they are not flexible enough to identify subtle differences between populations. In contrast, dental wear ageing techniques can produce population-specific profiles and do not require a reference sample. For example, the Miles Method can be applied to any population so long as there is a sufficient number of juvenile individuals in the sample (Miles 1962). Thus, techniques for estimating age using dental wear remove the need for a reference sample and as a result a large source of potential error.

2.3 Concluding remarks

Many methods exist for estimating age at death of adult skeletal remains. However, age estimation techniques using bony skeletal markers frequently rely on reference samples consisting of modern population, which are highly variable and are sometimes associated with large, overlapping age ranges. Additionally, bony elements of the skeleton do not always survive well in archaeological contexts. The use of dental wear as a tool for estimating age avoids these issues as it is possible to produce population-specific dental wear rates that are comparatively less affected by factors other than age, and survive well in the archaeological environment. For these reasons, dental wear may be at least, if not more so, reliable for estimaing age at death in archaeological remains, compared to bony methods for estimating age at death.

Chapter 3 Reviewing the key methods for estimating age at death using dental wear

Chapter 2 outlined the use of dental wear to estimate age at death in skeletal remains. This chapter examines three of denatl wear ageing methods in greater detail: the Miles Method (Miles 1962), Brothwell's chart (1963, 1972a, 1981), and the Modified Miles Method (Gilmore and Grote 2012).

The Miles Method uses molar wear to estimate age at death by extrapolating wear rates from younger individuals to older individuals within a population (Miles 1962). This method is widely used to estimate age at death in archaeological remains (Kieser et al. 1983; Cole and Waldron 2011; Lunt 2013; Armit et al. 2015).

The second method to be reviewed is Brothwell's chart. Brothwell (1963) organised stages of dental wear into age groups by molar type. This chart was the most widely cited method for estimating age using dental wear in a review of 200 articles published in three leading bioarchaeology journals (Falys and Lewis 2011).

The Modified Method of Gilmore and Grote (2012) estimates rate of wear for a given population using the wear difference between molars in adult individuals. These wear rates are then used to produce estimates of age. This technique is not widely cited but offers a potential methods for producing population-specific dental wear rates and age estimates using only adult remains.

Although alternative methods for estimating age at death using dental wear exist, such as tooth-root translucency or tooth cementum annulations, the three chosen techniques for study are well suited for archaeological samples. The methods of Miles, Brothwell and Gilmore and Grote utilise dental wear on molars, which survive well in the archaeological environment, and are non-destructive, providing age estimates for fragile remains.

3.1 The Miles Method

As described in section 2.2.1, the Miles Method systematically applies the rate of dental wear observed in a juvenile sample of a population to produce age estimates for adults of the same sample. Juvenile wear rates are calculated using the timing of molar eruption events as an indicator of how long a molar has been in functional occlusion. This means that when the second molar erupts, the first molar has been in occlusion, and in use, for about six years, thereby showing six years of wear. When the third molar erupts, around 18 years of age, the first molar will have approximately twelve years of wear and the second molar will have six years of wear. Miles arranged the adults of the same population into a series of increasing dental wear and projected the wear rates observed in the juvenile sample to estimate the functional age of young adults.

Using the functional age estimates of young adults, Miles was able to identify wear stages in functionally older individuals. This functional age plus the age of eruption produces an age estimate for an individual. By repeating this process, it is possible to estimate age for individuals with highly worn molars. Miles (1962) applied his technique to an Anglo-Saxon collection from Breedon-on-the-Hill, Leicestershire, producing a 'dental profile' (Figure 2.2.2). This dental profile depicts stages of wear at six-year intervals against time scales for the age of the subject and functional age of the three molars.

Tests of the Miles Method consistently show that it performs well and produces reliable age estimates. Nowell (1978) applied the Miles Method to a dental sample from the archaeological site of Tepe-Hissar, Iran. Age estimates produced following Miles (1962) compared well with those obtained from the pubic symphysis, aged according to the standards of McKern and Stewart (1957). Pearson correlation coefficients between estimated age from the dental wear and the pubic symphysis for the same person were significant ($r=0.82$, $p<0.005$), and there was no significant difference for mean estimated ages of the pubic bones and dentition ($p>0.005$). These results suggest the Miles Method is a reliable technique for estimating age when compared to bony age estimates. The later work of Lovejoy (1985) further supports this, where correlations between dental wear and four bony age indicators were consistently high for an adult sample ($n=202$) from the Libben site, a North American prehistoric cemetery in Ohio.

A study by Kieser et al. (1983) tested the reliability of the Miles Method using a sample of 202 living Lengua Indians of Paraguay. Actual age was determined from records of the The South American Mission Society and dental casts made of the permanent dentition. This sample was chosen for their high rate of dental attrition, and a low caries rate, which are usually associated with archaeological populations. Upper and lower molars were disarticulated to produce separate age estimates. The reliability of the age estimates was first tested using a Spearman's rank correlation coefficient between actual age and the Miles age for a random sample. The association between actual age and Miles ages was significant for both mandibular molars ($r_s=0.95$, $p<0.05$) and maxillary molars ($r_s=0.58$, $p<0.05$). A comparison of mean real ages and mean Miles ages for eight age groups using t-test was also performed. This test of paired comparisons found while there was no statistically significant difference between mean ages in any of the subgroups, the Miles Method became increasingly unreliable with increasing age (Kieser et al. 1983). While no p-values are provided the increase in difference in age estimates supports a decrease in accuray with age (Table 3.1.1). These results suggest the Miles Method is a reliable technique for estimating age, for populations with high rates of dental attrition.

Table 3.1.1.Comparison of real mean ages and mean Miles ages assigned to each of the Miles Subgroups for a sample of living Lengua Indians, Paraguay. Modified from Kieser et al. (1983 p.11)

Miles Group	Mean Actual Age	Mean Miles Age	Difference in age estimates	n
Baseline A (20-22 years)	20.38	20.55	-0.17	18
Baseline B (23-24 years)	23.50	23.70	-0.20	9
Direct estimation A (25-26 years)	25.10	24.89	0.21	19
Direct estimation B (27-30 years)	28.72	29.00	-0.28	11
Extension baseline (31-36 years)	33.60	33.50	0.10	24
Increasing remoteness A (37-46 years)	40.78	41.56	-0.78	23
Increasing remoteness B (47-56 years)	50.82	53.17	-2.35	23

More recently, Santini et al. (2017) conducted a validation study of the Miles Chart on a known-age sample using fifty skulls, recorded as being Hokkien–Hylam Chinese, excavated from a single site dating to the late 19th and early 20th Century. Individuals were assigned an age estimate based on wear on the first and second mandibular molars using the Miles Chart. There was good agreement between estimated age using the Miles chart and actual age. Approximately 86% of the estimated ages fell ±5 years of the actual age, although accuracy decreased for individuals aged over 40 years old (Santini et al. 2017). These results indicate the Miles Chart could be applied to this sample of Chinese skulls with reasonable accuracy.

The results of the Santini et al. (2017) study are interesting, due to the agreement between age estimates for a modern Chinese sample, and the Miles Chart, which was developed using an Anglo-Saxon sample. It is well understood that populations will have a different rate and pattern of wear as a result of cultural and dietary differences (Hojo 1954; Murphy 1959a; Lovejoy 1985). Santini et al. (2017) provide no details of the diet consumed but the agreement between the Chinese known ages and the Miles chart indicates a non-refined diet similar to the Anglo-Saxon sample. A poor agreement between the actual age and Miles age for the Chinese sample would not necessarily mean the Miles Method is unreliable, only that the Miles Chart cannot be accurately applied to all populations. The full Miles Method could not be performed on the Chinese sample due to the lack of juveniles. This reliability study by Santini et al. (2017) therefore only tests the ability of the Miles Chart to estimate age on a specific sample.

Reliability tests of the Miles Method and the Miles Chart suggest the method is a reliable technique for producing age at death estimates in populations with high dental wear rates. There are, however, limitations of the Miles Method, including the need for a large sample of juveniles, an assumption that the wear gradient between molars remains constant and that it is a system of diminishing accuracy with increasing age.

3.1.1 The Miles Method: the need for juveniles

A key requirement of the Miles Method is the need for a large sample of juvenile individuals aged between 6 and 18 years of age. There are two issues associated with this. The first is the need to accurately estimate age in juvenile individuals to ensure the observed wear rate is reliable.

Miles (1962) estimated age of immature skeletons following the Schour and Massler (1941) chart, consisting of 21 drawings depicting the chronology and development of the deciduous and permanent dentition. An accuracy test by Miles (1958) found the Schour and Massler (1941) chart performed well against radiographs of British known-age, modern children up to the age of 12 years old. Over the age of 12 years, however, accuracy decreases and suggests some variation in the timing of tooth eruption in older children. A recent review of three dental development charts supported this finding using a remains of individuals from known-age collections and archived dental radiographs of living patients (AlQahtani et al. 2014).

Dental development is stable in appearance and formation times due to a significant genetic component (Liversidge et al. 1998; White et al. 2011), resulting in dental growth events occurring at similar ages of children from different populations. This finding has been supported by studies observing the timing of growth events of the dentition between both modern and archaeological populations (Liversidge and Molleson 2004), and different ethnic groups (Liversidge 2011). Even though the timing of dental development varies in older children, it is the most reliable indicator of juvenile chronological age (Scheuer et al. 2000).

The second issue is the existence of large samples of juvenile remains. Miles (1962 p.882) used a sample of 32 juvenile individuals to produce his dental wear profile. Nowell (1978 p.272) states "The Miles method can only be employed on a dental population which includes dentitions of at least 20 immature individuals ageable to between 6 and 19 years on the basis of dental development alone." Large samples of juvenile remains belonging to single populations are rare for reasons including poor preservation of juvenile remains in the archaeological environment, poor recovery of remains during excavation, and differential burial practices of past population for juvenile remains (Mays 2010). As a result, juvenile remains are underrepresented in archaeological assemblages. Thismeans the Miles Method frequently cannot be used to estimate age at death for the associated adults and an alternative ageing method must be employed.

3.1.2 The Miles Ratio

Miles (1962) observed a differential rate of wear between the molars during his investigation, which he expressed as 6 : 6.5 : 7. This ratio indicates it takes the first molar six years to reach a particular state of wear, but it takes the second molar six and a half years to reach the same stage of wear as the first molar. It then takes the third molar seven years to reach the same stage. While others have also noted a difference in wear rates between molar regions (Akpata 1975; Kieser et al. 1983 in Miles 2001; Santini et al. 1990), others have not (Nowell 1978; Dreier 1994; Mays et al. 1995). It must therefore be established whether a single rate of wear can be applied to all molars in dental wear ageing methods.

Using a sample of living Nigerian dental patients, Akpata (1975) found the first molar was about two 'stages' ahead of that on the second and third molars, when scored according to Murphy's (1959a) classification. There are some issues in the remaining studies reporting a difference in wear rates across molars. Miles (2001) cites Kieser et al. (1983) as reporting a difference in wear rate between the molars. However, Kieser et al. (1983) do not explicitly state a difference in wear rates between molars, nor do they provide a dental wear profile for their population understudy. It is therefore unclear why Kieser et al. (1983) is cited in the Miles (2001) publication. Using a sample of known-age Chinese skulls, Santini et al. (1990) found a slower rate of wear in the second mandibular compared to the first mandibular molar. However, Santini et al. (1990)

employed linear regression analysis to evaluate the relationship between wear stage and functional age, which is not suitable for ordinal variables. Furthermore, few individuals within the sample exhibited a high wear score, especially for the second mandibular molar. These issues suggest the results of Santini et al. (1990) should be viewed with caution.

Ultimately, Miles (2001) argued the ratio 6:6.5:7 was not a mathematically precise ratio and would not make a large difference if omitted. A simple example shows that excluding the wear ratio, and assuming a similar rate of wear for all molars, does not make a large difference to age estimates:

> An individual has a second molar that shows a similar degree of wear as a first molar that has an estimated functional age of 30 years old. Using the Miles ratio, the estimated functional age of the individual can be calculated as:
>
> $$\frac{30 \text{ years}}{6} \quad \times \quad 6.5$$
>
> This calculation produces a functional estimated age of 32.5 years. The addition of the eruption age of the second molar (12 years) produces an age estimate of 44.5 years old.
>
> Omitting the ratio, and assuming a similar degree of wear across all molars, produces an age estimate of 42 years.

The above example shows that a small difference in wear rates between two molar regions is unlikely to produce large differences in age estimates. However, a large difference in wear rates between two molar regions is likely to produce inaccurate estimations of age.

The Miles Method further requires the assumption that the wear ratio remains constant throughout the life of the dentition. Reliability tests of the Miles Method do not explore this assumption. If the wear gradient between molars observed in the juvenile sample varies in older individuals, inaccurate age estimates will be produced and the Miles Method is not reliable.

3.1.3 The Miles Method: A population-specific method

A strength of the Miles Method is the ability to produce population-specific dental wear profiles and ages estimates. This means the Miles Method does not rely on a reference sample to produce age estimates. As discussed in Section 2.2.4, the use of a reference sample to produce standards for estimating age causes age mimicry, resulting in inaccurate and biased age estimates.

Nowell (1978), Kieser et al. (1983) and Lovejoy (1985) demonstrate how the Miles Method can be applied to different populations. The ability to produce population-specific dental wear profiles ensures that any dietary or behavioural traits of a population, which may affect the wear pattern (see Chapter 4), are considered. This population-specific approach produces more reliable age estimates, compared with ageing methods developed from reference collections.

3.2 Brothwell's chart

The second dental wear ageing method to be re-evaluated in this thesis is Brothwell's chart. The chart of Brothwell first appears in the first edition of '*Digging Up Bones*,' published in 1963. The chart organises stages of wear into age groups by molar type, allowing estimates of age to be produced quickly and easily. For this reason, and the assertion that the chart can be applied to archaeological remains dating from the British Neolithic to the Medieval period, Brothwell's chart is the commonly used and cited (Falys and Lewis 2011).

Brothwell published two further editions of his textbook, which included his dental wear chart (1972a, 1981). These later editions had almost no changes to Chapter 2.8 concerning Dental Attrition, although the third edition saw a slight adjustment to one of the age categories. The third age group in the earlier two editions is defined as 35-45 years, changing to 33-45 years in the third edition (Brothwell 1981). The reason for this change is unclear. The chart does not have any other age category that overlaps with another by more than one year so the 33-45 age group could be considered a mistake. Its appearance in the final edition of '*Digging Up Bones*,' with no reprint, however, may support a genuine change to the age group. In reality, choice of the edition makes a minimal difference when assigning an age to an individual, but does support the need for a review of Brothwell's chart.

The methodology and archaeological samples used to produce Brothwell's chart are unclear. It is possible Brothwell followed the Miles Method. Santini et al. (1990 p.176) suggest "Brothwell published a chart based on Miles' work," although there is no reference or evidence provided to support this. Brothwell was certainly aware of Miles, as well as studies by Zuhrt (1955) who examined and extrapolated juvenile wear rates and to adults. The closest indication of Brothwell's methodology is given in his 1989 paper where he states "comparing the degrees of wear in children of different periods suggests to me that until post-medieval times wear on earlier British groups was quite severe, relative to age, and comparable from period to period. In view of this, I constructed a table of wear against age which seemed to work for early British groups," (Brothwell 1989 p.305). Brothwell goes on to say that bony age estimates, such as the pubic symphysis, were used to confirm the adult dental wear age estimates. Brothwell does not provide any further information detailing the precise process for producing his chart, including the use of the Miles Method. The lack of clarity around Brothwell's methodology forces re-evaluation of his conclusion: that all individuals dating from the British Neolithic to the Medieval period have a similar rate of wear, rather than the methodology.

Brothwell (1963 p.68) states "that the rates of wear in earlier British populations do not appear to have changed much from the Neolithic to mediaeval times." The similarity of wear rates across periods is attributed to a homogeneity in diets (Brothwell 1989 p.304). Chapter 5 shows domesticated plants and animals formed the main components of the British Neolithic to Medieval period diet. However, the introduction of new foods and food processing technologies from the Romano-British period onwards (Moore and Corbett 1973; Cool 2006; Redfern et al. 2010) has the potential to alter dental wear rates. No study has compared these dental wear rates, leaving Brothwell's claim untested and unsupported. A comparison of period-specific dental wear rates is vital for testing the validity of Brothwell's chart.

Brothwell's chart is not recommended for use as an ageing standard for individuals belonging to the Post-Medieval period. The Post-Medieval period is associated with a change in diet compared with the earlier periods, with the introduction of new foods, including potato, sugar and tea (Mant and Roberts 2015). The 19th Century also saw the production of purer and more refined flour due to improved milling techniques, increasing the popularity of white bread compared to the darker rye and barley breads consumed in the earlier periods (Mant and Roberts 2015). White bread contains refined carbohydrates that are more cariogenic, i.e. they cause more tooth decay (Corbett and Moore 1976), adding to the oral pathology created by the higher consumption of sugars. This change in diet and increased pathology has the potential to decrease dental wear rates (Hillson 1996).

This change in diet observed during the Post-Medieval period may not have been universal across Britain. For example, Barton-Upon-Humber, Lincolnshire was considered a rural community during the medieval period, and did not experience significant urbanization until the late 17th Century (Clapson 2005). Post-Medieval individuals at Barton may have been less likely to have the food imports associated with larger towns and cities, resulting in a diet, and rate of dental wear, similar to that consumed during medieval times. No studies have compared Post-Medieval wear rates to those of earlier temporal periods. This thesis aims to review the dental wear rate of a Post-Medieval sample, and consider the wider application of Brothwell's chart.

Although Brothwell (1963) concludes there is a similar rate of wear across multiple temporal periods, there is little information regarding the samples employed to make this conclusion. Only the sample of the Iron Age site of Maiden Castle, Dorset is specifically mentioned (Brothwell 1963 p.70). Clearly Brothwell examined additional collections, but sample sizes and demography are unknown. The lack of clarity around both the methodology and material highlights the need for a comprehensive review of Brothwell's chart using well-documented samples.

Upon review, it is clear that a re-evaluation of Brothwell's chart is required. The chart of Brothwell (1963) is widely used and is heavily relied upon during skeletal assessments due to its simplicity (e.g. Rogers 1997; Mays et al. 2001; Margerison and Knüsel 2002; McKinley 2007; Clough 2010; Lunt 2013). It is also included in the 'Guidelines to the Standards for Recording Human Remains,' produced by the British Association of Biological Anthropology and Osteoarchaeology (O'Connell 2004, 2017) However, no comprehensive review of the charts conclusions exists. As Brothwell's chart is widely used by archaeologists, it must be evaluated for its robustness and reliability, particularly the application to multiple periods.

3.3 The Modified Miles Method

The final dental wear ageing method to be reviewed within this thesis is the Modified Miles Method, published in 2012 by Gilmore and Grote. This approach calculates the rate of wear for a population using the average wear difference between molars in adult individuals. An estimate of age is produced by dividing the degree of wear on a molar by the wear rate and adding the age of eruption for that molar (Gilmore and Grote 2012).

To test the Modified Miles Method, Gilmore and Grote (2012) scored occlusal wear of 311 individuals from hunter-gather and pastoralist populations from a variety of latitudes, with diverse population histories and diets. Occlusal wear was scored following the Scott (1979) method where dental wear is scored on a 1-10 scale for each quadrant of the molar. Age estimates from bony skeletal elements, primarily the pubic symphysis and auricular surface, for a sub-sample (n=22) were used to review the accuracy of Modified Miles Method. Roughly half of the age estimates produced using the Modified Miles Method fell within the age category based on bony age estimates. In all but one case the Modified Miles Method age estimate ±1 standard deviation range overlapped with the age category given by bony age indicators (Figure 3.3.1).

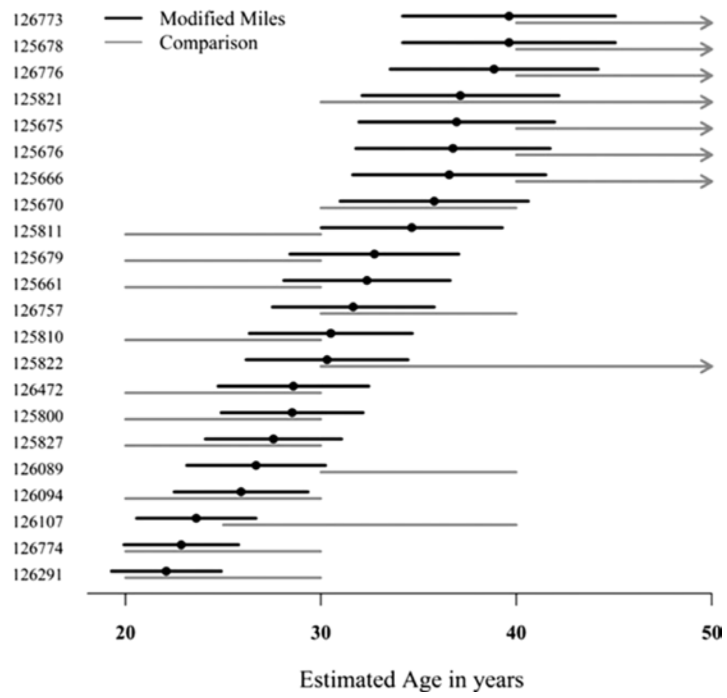

Figure 3.3.1. Comparison of age estimates produced following Modified Miles Method ± one standard deviation (black) and the age categories from pelvic age indicators (grey) for a sample (n=22) of individuals from the Phoebe A. Hearst Museum of Anthropology (University of California, Berkeley). Arrows indicate unbounded age categories. Image taken from Gilmore and Grote (2012 p.186).

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This small reliability test suggests age estimates produced using Modified Miles Method compare fairly well to those of other skeletal elements.

In contrast to the Miles Method, Gilmore and Grote (2012) calculated wear rates based on the wear difference in adult molars, overcoming a weakness in the Milles. The use of a wear gradient calculated from an adult sample potentially allows the production of population-specific wear rates and estimates of age. Thus, the Modified Miles Method provides a technique for estimating age in skeletal remains that does not rely on a standard developed from an inappropriate reference sample and a method that can be applied to samples where juvenile and post-cranial remains are under-represented. This means the Modified Miles Method has the ability to produce age estimates for a larger variety of archaeological assemblages than the Miles Method.

The Modified Miles Method requires two assumptions as a result of using an adult sample. The first assumption is that all molars within the same individual wear at the same rate, i.e. they have a wear ratio of 1:1:1, which remains constant throughout the life of the dentition (Gilmore and Grote 2012). Section 3.1.2 discussed the implications for reliably estimating age when using this assumption, and the need for its review.

The second assumption required by the Modified Miles Method is that molar wear is linear with age, i.e. dental tissue is lost at a consistent rate during an individual's life. The Miles Method does not require this assumption as molar specific wear rates are updated in a stepwise manner. It is unclear whether dental wear rates remain constant with age. Ordinal stages of wear do not necessarily represent equal amounts of tissue lost through wear, and it is unclear whether stages are passed through in regular intervals. Using mechanically ground molars, Molleson and Cohen (1990) demonstrated the ordinal stages of Brothwell (1963) did not represent equal amounts of crown height loss, and suggested this loss was not linear with age. The Modified Miles Method recorded occlusal wear following Scott (1979). Following Scott's system, molar teeth are divided into quadrants and each scored on a 1-10 scale, and the score for the whole tooth is the sum of the quadrant scores and ranges from 4-40 (Scott 1979). While this system produces a near normal distribution, which is better suited for linear models (Benfer and Edwards 1991), it may not be suitable for damaged molars. Gilmore and Grote (2012) acknowledge the need for further exploration of the relationship between Scott's wear scoring system and age to confirm the assumption that wear is linear with age. Unfortunately, this thesis was unable to assess this assumption due to the use of adult remains of unknown age at death.

A strength of the Modified Miles Method is that it has the potential to utilise quantitative measurements of dental wear. Section 4.3 describes various methods for recording dental wear, including the use of ordinal scales (Murphy 1959a; Scott 1979; Smith 1984; Dreier 1994), the measurement of crown height (Molnar *et al*., 1983; Benfer and Edwards, 1991; Mays, de la Rua and Molleson, 1995; Mays and Pett, 2014), and measuring the proportion of exposed dentine on the occlusal surface (Clement 2007). To date, the Modified Miles Method has not been adapted for quantifiable measurements of dental wear. The use of quantifiable measurements have the potential to overcome issues with ordinal scales (see Section 4.3), and therefore the ability to produce more reliable age estimates.

The Modified Miles Method may not overcome all of the issues observed in the Miles Method, but it is an under-used method for producing wear rates from wear gradients in adult individuals. Due to its recent development, there has been no comprehensive review of the Modified Miles Method. This thesis aims to evaluate the Modified Miles Method in light of its underlying assumptions and to aid in the evaluation of Brothwell's chart.

3.4 Concluding remarks

All methods for estimating age using dental wear have their strengths and weaknesses, but their simplicity means that they are the most widely cited method for estimating age in skeletal remains (Falys and Lewis 2011). Tests of reliability show the Miles Method performs well, however, the requirement of a large juvenile sample hampers its ability to estimate age for many archaeological assemblages. The underlying assumptions of the Miles Method are also in need of review. The Brothwell chart is widely cited and easily applied to archaeological remains, but the similarity of wear rates across temporal periods needs validating. Finally, the Modified Miles Method is an under-used method for estimating age using dental wear but has yet to be evaluated for its ability to estimate age. This thesis therefore aims to review these three key methods for estimating age using dental wear in light of their underlying assumptions and conclusions using well-documented samples and robust statistical procedures.

Chapter 4 Dental Wear

“Dental wear may be broadly defined as the progressive loss of the constituent tissues of teeth,” Burnett (2015p.415). Dental wear first affects the enamel, a hard, strong tissue that is resistant to wear. Removing the enamel reveals the underlying dentine in a gradual but predictable pattern. It is this pattern that has been correlated with age and forms the basis for dental wear ageing methods.

This chapter first reviews the mechanisms causing dental wear. Factors other than age that can affect the relationship between dental wear and age are then explored. Section 4.3 reviews a range of techniques used to record dental wear, and considers their strengths and weaknesses in relation to estimating age at death.

4.1 Types of dental wear

The most common types of tooth wear are attrition, abrasion, and erosion (Kaidonis 2008; Burnett 2015).

Attrition results from tooth-on-tooth contact, occurring when no food is present. Small areas of wear, called facets, are produced at the contact points between neighbouring and opposing teeth (Kaidonis 2008). These facets have microscopic parallel striations on their borders, and the dentine of the tooth remains flat. As a result, a tooth experiencing attrition has a flat and glossy surface.

Abrasion is caused by external material moving across a tooth surface. Food is the most common material, but grit, often a by-product of stone tools used for food processing, also causes abrasion. An area of wear, rather than a facet, is produced on a tooth’s surface, which is dull and irregular in appearance (Lucas 2004). Abrasion produces small features, such as pitting, gouge marks, and microscopic scratches, which can reflect the diet consumed by an individual (Kaidonis 2008; Burnett 2015). For example, scratches are produced when consuming an abrasive diet (Teaford and Lytle 1996), while harder diets create pits (Teaford and Walker 1984; Schmidt 2010).

Erosion can be defined as the “chemical dissolution of tooth substance without the presence of plaque,” and occurs when the oral environment increases in acidity (Kaidonis 2008 p.S23). For example, consuming fruit or sugary drinks, and regurgitated stomach acid leads to an increase in acidity (Burnett 2015). Erosion causes a tooth's surface to become rounded, producing a smooth, shiny surface (Bartlett 2005). At the microscopic level this appears as a "honey-comb like lattice of dissolved enamel prisms," (Bartlett 2005 p.419).

Dental wear is a result of a combination of the above wear mechanisms (Kaidonis 2008; Burnett 2015). During mastication food is compressed, flowing into the grooves and fissures of the dental crowns, causing abrasion to the occlusal surface (Benazzi et al. 2011). Teeth then grind across one another, producing wear facets due to attractional contact between the occlusal surfaces (Smith 1984). Any increase in acidity of the oral environment will then cause erosion of the teeth.

Attrition and abrasion are the most common dental wear mechanisms in archaeological populations. Archaeological populations experience high levels of abrasion, due to the consumption of highly fibrous foods and the introduction of grit from food processing techniques (Mahoney 2006; Kaidonis 2008). In contrast, erosion is the dominant wear mechanism in modern, western populations. Refined food-processing techniques result in a softer diet and an absence of grit, and means that the underlying dentine is rarely observed in modern populations (Sengupta et al. 1999; Benazzi et al. 2013; Mays 2015b). Although erosion is considered a modern disease, Kaidonis (2008) suggests that early hunter-gatherer populations were exposed to acids through their diet (e.g. acidic fruits, such as berries). These exposures were seasonal and therefore temporary with erosion having little or no effect. Erosion may have occasionally affected the occlusal surfaces of archaeological populations, but the higher rates of abrasion in these groups would result in the removal of any effects of erosion.

Attrition, erosion and abrasion each produce distinct patterns of wear, but, as shown, a tooth is rarely subject to a single type of wear. This thesis aims to review the importance of the combined effects of dental wear as a tool for estimating age at death. Henceforth, the term 'dental wear' is used to denote dental wear caused by attrition, erosion and abrasion.

Dental wear occurs at the macro- and microscopic level. Scanning electron microscopy (SEM) is frequently employed in studies of dental micro-wear to gain insights into diets consumed by individuals. For example, Mahoney (2006) compared the microwear patterns of Natufian hunter-gathers (12,500-10,250 bp) and early Neolithic farmers (10,250-7,500 bp) from northern Israel using SEM and digitised micrographs. The Natufians exploited a diverse range of animal and plant foods, involving some food preparation, while the Neolithic farmers consumed animals and cultivated plants using large grinding tools for food processing. The observed microwear patterns showed Neolithic farmers having larger dental pits and wider scratches, compared to the hunter-gathers (Mahoney 2006). These results supported a shift to a harder diet, and a change in food processing techniques, during the Natufian to Neolithic period.

While micro-wear patterns can provide information regarding the diet consumed, they have a short temporal life. Teaford and Tylenda (1991) demonstrated changes in microscopic wear patterns can occur in a matter of days or weeks using a living, modern population. While this approach is suitable for examining the link between diet toughness and dental wear, it is less suitable for estimating age at death in archaeological populations. Furthermore, the most widely cited methods using dental wear to estimate age at death only record changes in wear patterns at the macro level. For these reasons this thesis only considers dental wear at the macro-level.

All exposed surfaces of a tooth experience dental wear, with wear primarily occurring on the occlusal (biting) surface (Lucas 2004). Wear between neighbouring teeth (interproximal or interstitial wear) occurs as a result of small movements between teeth during activities including chewing and clenching of the jaw (Hinton 1982; Rose and Ungar 1998; Kaidonis et al. 2014). Figure 4.1.1 illustrates interproximal wear on a first maxillary molar, producing a concaved area (Kaidonis et al. 2014 p.167).

Figure 4.1.1. Example of interproximal wear on the first maxillary molar causing a concaved area. Image taken from Kaidonis et al. (2014 p.167).

Multiple studies have recorded interproximal wear when examining the dental wear pattern of past populations (Hinton 1982; Kieser et al. 1985; Kaifu 1999), although how it is measured is less clear. Hinton (1982 p.106) illustrates his measurements of interproximal wear facets between the second premolar and first molar, and between the first and second molars. Neither Kieser et al. (1985) or Kaifu (1999) provide such descriptions. It is difficult to standardise measurement of interproximal wear facets due to the lack of clear dental landmarks, making the measurement difficult to standardise. Methods for estimating age at death using dental wear do not record interproximal wear. A recent study by Sarig et al. (2015) suggested the presence of a relationship between the development of interproximal wear and age using a sample from the Hamann-Todd collection, consisting of modern, known-age individuals. However, no studies have evaluated the relationship between interproximal wear and age in archaeological populations. Furthermore, the most widely used dental wear ageing methods do not record interproximal wear, thus, this thesis only considers dental wear to the occlusal surface.

4.2 Factors affecting dental wear

A number of factors influence the rate and pattern of dental wear, including the size and shape of individual teeth, tooth loss, the use of teeth as tools, and the abrasiveness of food or non-dietary material. Each factor has the potential to produce unique patterns of wear and alter the rate of dental wear, creating differences between populations. These factors may affect the relationship between dental wear and age, thus impacting the ability to use dental wear as a method for estimating age at death.

4.2.1 Tooth morphology

All teeth experience dental wear including the incisors, canines, and molars, as well as both the deciduous and the permanent teeth. Many studies have recorded the dental wear pattern of different tooth types (see Hojo 1954; Murphy 1959a; Lovejoy 1985; Dawson and Robson-Brown 2013). However, the most widely used methods for estimating age using dental wear in archaeological skeletal remains examine wear on the permanent molars (Miles 1962; Brothwell 1963). This thesis therefore only considers dental wear of the occlusal surface of permanent molars.

Each tooth crown has a distinctive shape that facilitates the effective processing of food (Lucas, 2004). For example, permanent molars have multiple cusps arranged in a regular pattern that facilitates the cutting, grinding or crushing of food (Figure 4.2.1). Upper permanent molars have four main cusps, three of which form a raised triangle with a central depression or fossa (Hillson, 1996). In upper molars, the buccal (cheek side) cusps are higher relative to the lingual (tongue side), and the distolingual cusp varies in size, becoming smaller and more variable from the first, to the third molar. Lower permanent molars also have four main cusps, arranged into a rectangle,

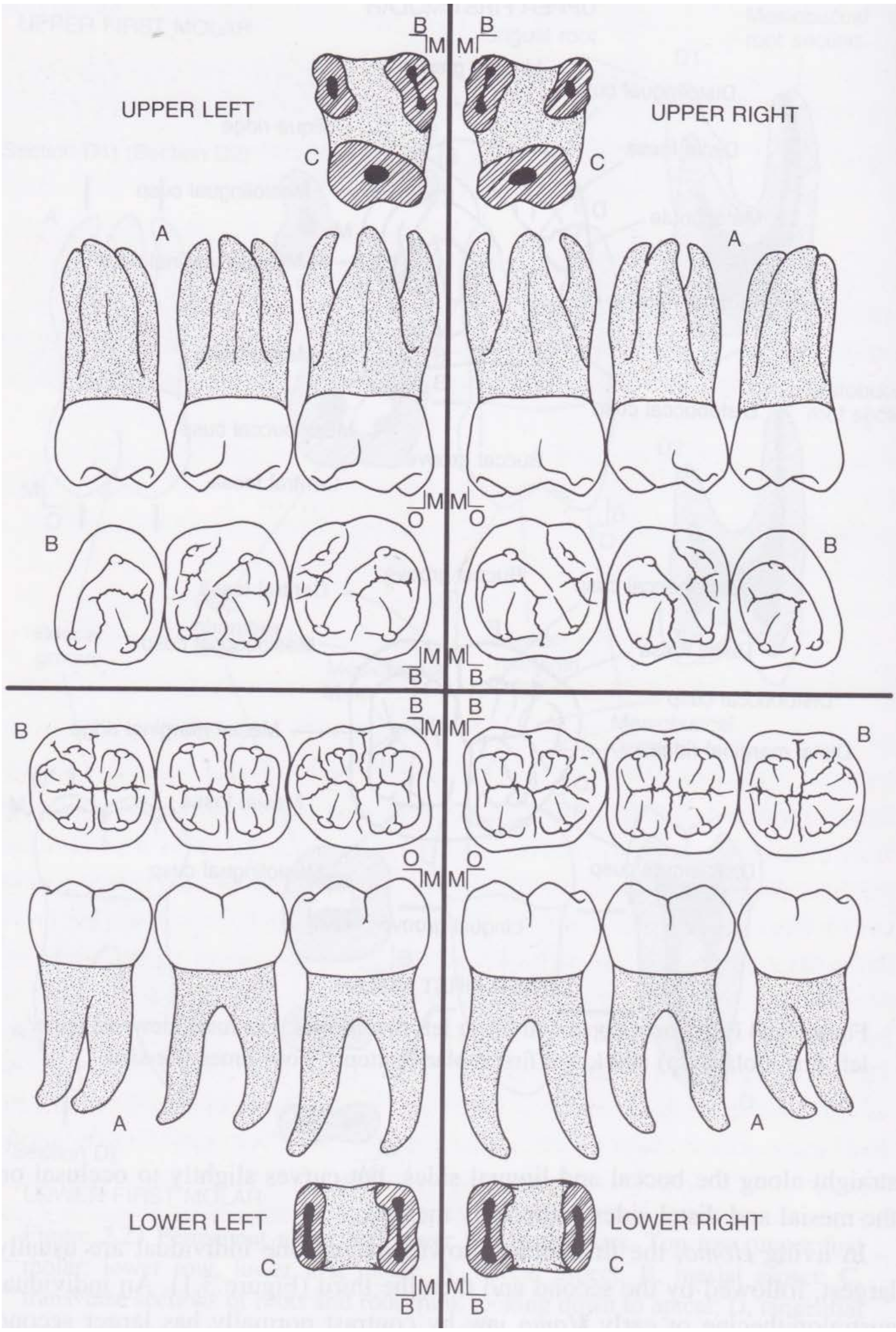


Figure 4.2.1. Permanent upper and lower molars. A, lingual aspect with first molars closed to the midline and third molars furthest from the midline. B, occlusal aspect of each molar. C, transverse root section of the first molars. Image from Hillson (1996 p.48).

of similar height (Hillson, 1996). An exception to this is the permanent first mandibular molar, which typically has five cusps.

Although the upper and lower molars differ slightly in their cusp arrangement, they have a similar pattern of wear. Dentine is first exposed on a single cusp, typically the mesio-lingual cusp on the maxillary molars and the mesio-buccal cusp of mandibular molars (Murphy 1959a; Hillson 1996). Dental wear begins on these cusps as they usually experience the highest biting force (Mays et al. 1995). Dental wear continues on the remaining cusps producing four discrete areas of exposed dentine. With progressive wear, these areas join until only an enamel rim remains. The enamel rim is eventually breached and wear continues down the root of the tooth (Brothwell 1963; Hillson 1996). Figure 4.2.2 shows the dental wear pattern for the first mandibular molar, taken from Murphy (1959a). Many authors have recorded this pattern of wear in multiple populations (Hojo 1954; Murphy 1959a; Smith 1984; Lovejoy 1985; Hillson 1996), suggesting the pattern of wear in permanent molars is regular and consistent across groups. Any variation in this sequence is therefore likely to be a result of factors other than normal tooth morphology.

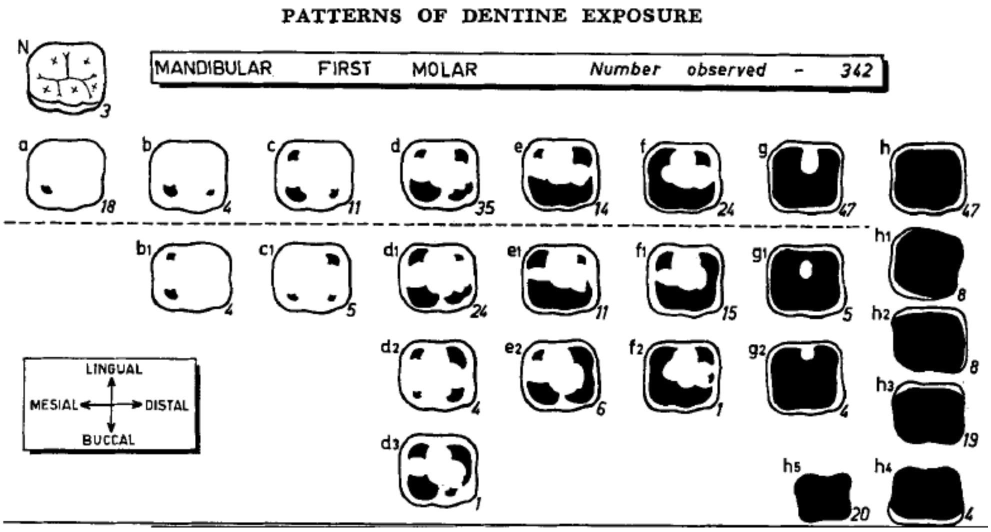


Figure 4.2.2. Pattern of dentine exposure for the first mandibular molar by Murphy (1959a p.175).

Although upper and lower permanent molars show a similar pattern of wear, they do not necessarily wear at a similar rate. Some studies identified a similar wear rate between occlusal partners (Dreier 1994; Mays et al. 1995; Esclassan et al. 2009), while others found a difference (Murphy 1959a; Molnar 1971b; Lunt 1978b; Molnar et al. 1983b; Lovejoy 1985; Gilmore and Grote 2012). The reason for these differences is unclear. Buccolingual dimensions are larger in maxillary molars (Kieser 1990b; Grine 2002; Smith et al. 2006), while mandibular molars have larger mesiodistal lengths (Kieser 1990b). A significant difference was also observed in enamel thickness and dentine area between upper and lower molars, with the maxillary molars consistently showing greater values compared to their occlusal partner (Smith et al. 2006). A difference in tooth morphology therefore has the potential to produce different dental wear rates in upper and lower molars.

Each type of molar also differs in morphology. For example, third maxillary molars may only have three cusps, while the first and second maxillary molars have four cusps (Figure 4.2.1). Likewise, first mandibular molars typically have five cusps, while the second and third mandibular molars have four cusps. All molar types, however, a similar pattern of wear (Murphy 1959a; Hillson 1996). For example, even though the third maxillary molar has three cusps, the pattern of dentine exposure is similar to that of the first and second mandibular molars (Figure 4.2.3). Using a sample of modern molars, Smith et al. (2006) observed differences in tissues proportions of different molar types. Both upper and lower molars showed a decreasing trend in dentine area and an increasing trend in enamel cap area along the molar row (Smith et al. 2006). This difference in dental tissue proportions has the potential to alter wear rates across molar types. As discussed in section 3.1.2, some studies have identified a difference in wear rate between molar regions (Kieser et al. 1985; Santini et al. 1990), while others have not (Nowell 1978; Dreier 1994; Mays et al. 1995).

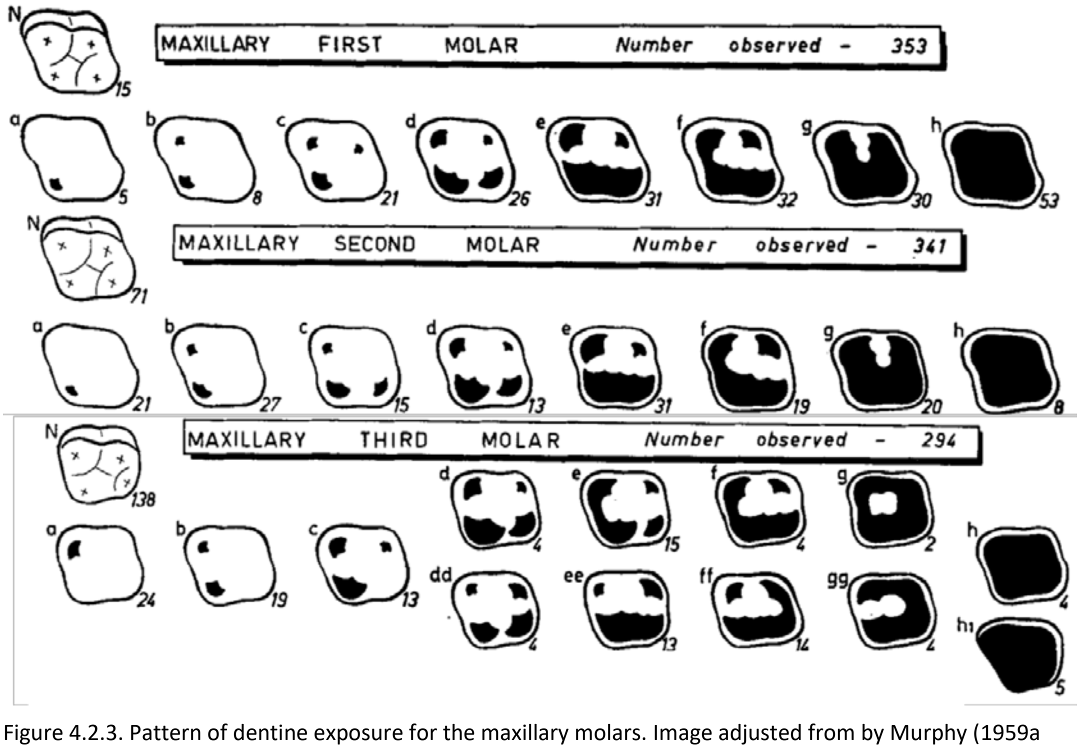


Figure 4.2.3. Pattern of dentine exposure for the maxillary molars. Image adjusted from by Murphy (1959a p.171)

Many studies record dental wear from one set of molars, selecting one side and substituting one molar for its antimere when missing (e.g. Hinton 1982; Mays et al. 1995; Benazzi et al. 2008; Gilmore and Grote 2012). This is based on the assumption that molars within a left-right pair have a similar morphology, and therefore a similar rate of wear. While multiple studies support this (Hojo 1954; Murphy 1959a; Lovejoy 1985; Santini et al. 1990; Deter 2009; Esclassan et al. 2009), comparison tests are not necessarily robust. For example, many studies state a similarity between antimere pairs based on observations, such as Hojo (1954) and Murphy (1959a), with no statistical testing. The similarity in wear rate in left-right molar pairs must also be validated to ensure the use of antimeres is appropriate for studies of dental wear, and therefore estimating age at death.

Implications for estimating age at death

Archaeological remains can be fragmentary, meaning only part of an individual's dentition may survive. Due to the difference in morphology between upper and lower molar, and between molars along the tooth rows, it is vital to establish whether a single rate of wear can be applied to all molars, or whether molar-specific wear rates are required. Unless the rate of wear has been found to be similar for all molars, the wear rate for one molar should not be applied to another as it has the potential to produce inaccurate age estimates.

4.2.2 Diet

Diet is one of the greatest factors contributing to dental wear and therefore has a large effect on the rate of wear experienced by an individual. Tougher foods require a longer 'puncture-crushing' cycle (where food is repeatedly chopped over the tooth surface), compared to softer foods (Smith 1984). This means hard and abrasive food require a higher degree of processing compared to softer foods, increasing the rate of dental wear. Populations consuming highly fibrous diets therefore have higher dental wear rates. It is well understood that British archaeological populations consumed a coarser and more abrasive diet compared to modern populations (Mays 2002; Rando et al. 2014), resulting in higher dental wear rates.

A degree of food processing may also occur prior to food entering the oral cavity. Food preparation techniques, such as the use of grinding stones, decrease the role required by teeth to effectively break down food. Although these food preparation techniques decrease food toughness, they introduce additional particles into the mastication process. This introduction of external material, such as grit from stone tools, alters the microwear pattern. For example, Mahoney (2006) found larger pits in the molars of Neolithic farmers from Israel who used food processing tools, compared with those of Natufian hunter-gathers. Furthermore, Smith (1984) noted that these hard particles introduced into the diet during the Neolithic increased the amount of wear and changed the angle in which a tooth was worn. As a result, food preparation techniques, in addition to food toughness, may alter dental wear rates.

Implications for estimating age

Dental wear rates vary between populations depending on the diet consumed, and means a wear rate produced from one population may not be accurate when applied to another. For example, a wear rate calculated for a population consuming a hard diet is likely to produce unreliable age estimates for a population consuming a comparatively softer diet.

Mays examined the relationship between molar crown height (Section 4.3.2) and age in the Romano-British population of Poundbury (Mays et al. 1995) and a known-age 19th century population excavated from Zwolle, the Netherlands (Mays 2002). A comparison of the two populations reveals a slower rate of wear in the Zwolle material, compared with the Poundbury sample. Therefore, a wear rate produced using the Zwolle sample would greatly under-estimate age for the Poundbury sample. In populations with a very soft diet, such as the modern Western populations, dental wear is unlikely to be a viable method for estimating at age death.

4.2.3 Ante-mortem tooth loss (AMTL)

Ante-mortem tooth loss (AMTL) is defined as the loss of a tooth that occurs before death and may result from tooth removal through injury or surgery, the loss of the supporting bone, or dental pathology and periodontal disease (Hillson 2001; Ortner 2003; Lukacs 2007; Roberts and Manchester 2007). Teeth that have lost their occlusal partner ante-mortem may be expected to show a reduced rate of wear (Mays 2002), as wear to their occlusal surface ceases. Wear on the remaining teeth, however, may increase as wear forces are re-distributed across the remaining dentition (Miles 1962). Using multiple regression analysis and entering tooth-loss as a dummy variable, Mays (2002) failed to reveal any effects of ante-mortem loss of occlusal partners on the relationship between crown height and age in a low wear rate sample. However, clinical studies indicate AMTL has the potential to change dental wear distributions on the remaining teeth. For example, some studies found an increase in mastication predominance (chewing predominately on one side of the mouth) in individuals with unilateral posterior missing teeth, compared to individuals with a healthy dentition (Iwashita et al. 2014; Yamasaki et al. 2016). This preference for chewing on one side due to AMTL may result in a change in wear pattern and wear rate on the remaining teeth, leading to inaccurate age estimates.

AMTL is frequently observed in past populations where dental wear is extensive, or where there is a high frequency of dental pathologies (Moore and Corbett 1971; Lukacs 2007; Mays 2013). Figure 4.2.4 demonstrates AMTL was present in British archaeological remains, with a low during the Bronze Age, and a peak in the Roman period (Brothwell 1959). This figure does not depict molar-specific AMTL, but demonstrates it is a condition of past populations. Although AMTL is not a simple continuation of the wear process, i.e. it can occur before all enamel is removed from a tooth, its presence in populations with high rates of dental wear means it should be considered when using dental wear to estimate age at death.

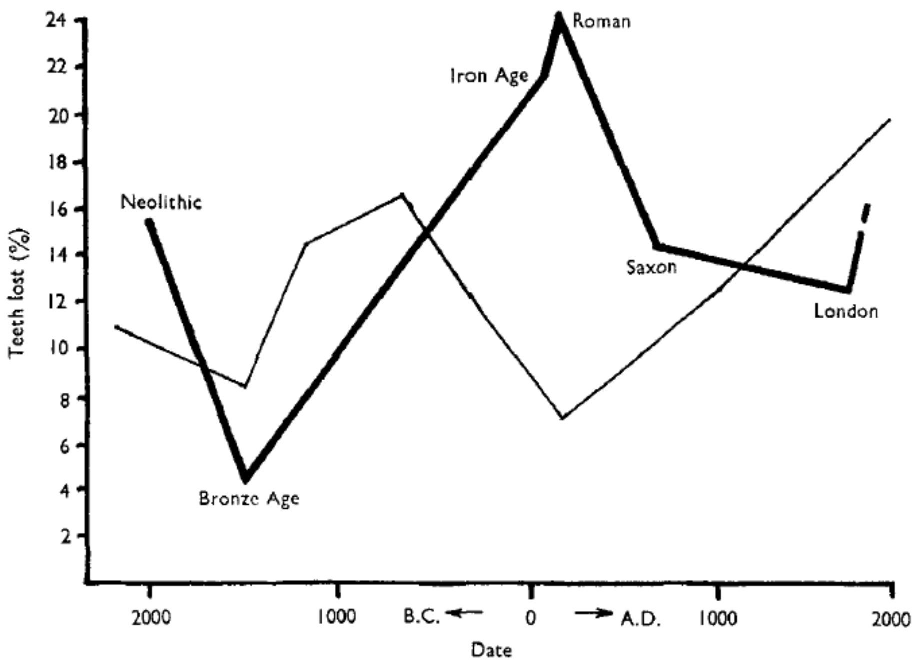


Figure 4.2.4. Graph depicting the percentage of ante-mortem tooth loss through archaeological periods. The thick, black line represents tooth loss in British populations. The thin line represents tooth loss in Greek populations. Image taken from Brothwell (1959 p.62).

Implications for estimating age

Ante-mortem tooth loss (AMTL) is associated with age, where AMTL becomes more frequent with increasing age (Durić et al. 2004; Esclassan et al. 2009; Lucas et al. 2010). One issue with using dental wear to estimate age of is that by the time individuals have passed their middle years they may have lost some, or all, of their molars. At Poundbury, few individuals had a first or second molar beyond the wear stage where only an enamel rim remains, whereas 13% had lost most, or all of their teeth ante-mortem (Molleson and Cox 1993; Mays et al. 1995). This means teeth may be shed before the later wear stages of ordinal wear scales are reached, and cannot be used in estimates of age for older individuals. Despite this, potentially older individuals with AMTL should be included in any analysis of dental wear so as not to truncate demographic profiles, giving the false impression that few survived into an advanced age in archaeological populations. However, few studies investigate the effect of AMTL on dental wear rates, which is vital in assessing the reliability of employing dental wear rates to estimate age of older individuals.

4.2.4 Culturally Induced Dental Attrition

Teeth are not just for processing food. Many individuals use their teeth as tools, holding or chewing objects, which can affect the pattern and rate of dental wear. Multiple studies have demonstrated how cultural behaviour may impact dental wear (Molnar 1971a; Hinton 1981; Clement and Hillson 2012). Clement and Hillson (2012) found high degrees of anterior tooth wear relative to their posterior teeth in a modern population of Canadian Inuit from Igloolik. The anterior dentition acted as a 'third hand' used to help with tasks, including gripping objects and chewing tough hides (Mayhall 1971). The appearance of circular notches on teeth as a result of habitual smoking of clay pipes, as identified in post-medieval Scandinavian individuals (Kvaal and Derry 1996) and post-medieval London skulls (Hillson 1996), is another way in which non-dietary uses of teeth can dental alter wear patterns.

Implications for estimating age

The use of teeth as tools has the potential to affect the dental wear pattern, particularly of the anterior teeth (i.e., the incisors and canines). Although methods for estimating age at death typically examine the permanent molars, any unusual wear pattern of the anterior teeth may affect the wear on the posterior teeth due to introduction of variation in wear distribution. Furthermore, the use of teeth as tools may produce wear patterns on individual teeth that do not conform to the typical stages used to record dental wear. As a result, the calculation of wear rates becomes difficult and may produce inaccurate estimates of age. The ability to estimate age using dental wear is therefore likely be less reliable in populations using teeth as tools. As this thesis aims to review standard methods for estimating age at death using dental wear, the skeletal samples employed in the current thesis do not include individuals or populations with evidence of using teeth as tools.

4.3 Methods for recording dental wear

The study and recording of dental wear has a long history, with the very earliest study being conducted by Broca (1879). Broca (1879) recorded wear using a five-point scale, and since then multiple studies have described and tested methods for recording dental wear (e.g. Molnar 1971a; Scott 1979; Santini et al. 1990; Fares et al. 2009; Gilmore and Grote 2012). Methods for recording dental wear typically measure the degree of exposed dentine on the occlusal surface, and the remaining enamel on a tooth. The degree of exposed dentine may be measured using ordinal stages, as a proportion of the total occlusal area, or in relation to crown height.

Both ordinal and ratio scales are used to record dental wear. Ordinal scales rank subjects based on a variable, where the differences between ranks do not need to be equal (Vogt 2011). Ordinal scales therefore divides the dental wear process into discrete stages, ordered by increasing degrees of exposed dentine. The majority of methods for recording dental wear use an ordinal scale. Ratio scales describe variables in a way that the difference between any two adjacent units of measurement is the same, and there is a true zero point (Vogt 2011). For example, molar crown height measured in millimetres is measured on a ratio scale. Both ordinal and ratio scales are discussed below in light of their strengths and weaknesses, and their implications for estimating age at death.

4.3.1 Ordinal scales

Ordinal scales have been used to record dental wear to study population-specific dental wear patterns (Hojo 1954; Kieser et al. 1985; Lovejoy 1985; Kaifu 1999; Kieser et al. 2001), and to estimate age at death in archaeological populations (Miles 1962; Brothwell 1963; Gilmore and Grote 2012). These scales vary in the method used to describe each wear stage, the terminology used and in the number of stages within a scale.

Ordinal scales either use figures or written descriptions, or a combination of both, to describe individual wear stages. For example, Brothwell (1963) uses illustrations to represent stages of wear, whereas Smith (1984) uses written descriptions. In contrast, Murphy (1959a) and Scott (1979) provide both written descriptions and schematic representations for each stage of wear. The inclusion of illustrations alongside written descriptions potentially makes recording dental wear easier. Illustrations provide an example of the typical appearance of a tooth at a particular wear stage, while written descriptions can provide more detailed information.

The terminology used to describe wear stages varies between scales. Smith and Knight (1984 p.437) use quantities of a worn tooth, such as “less than one third,” while Murphy (1959a) describes dental wear in terms of exposed dentine on molar cusps. The chosen terminology is particularly important when scales are not accompanied by illustrations, and if too complex may be problematic for inexperienced users. For example, Seligman et al. (1988 p.1323) defined enamel wear in terms of a change in tooth shape, using terms such as “flattening of cusps or grooves,” and “total loss of contour.” While these terms are descriptive, they may be better suited to an assessor who is experienced in dental anthropology.

Ordinal scales vary in the number of wear stages used to record dental wear. Some scales have as few as five stages (Broca 1879; Smith and Knight 1984; Santini et al. 1990), while others include multiples stages with common variants of pattern and degree of wear (Murphy 1959a; Molnar 1971a; Smith 1984). Scales with many stages of wear potentially decrease the amount of information that is lost as a result of dividing a continuous into discrete stages, but wear stage identification may become difficult if the difference between wear stages is too small.

Ordinal scales may or may not include common variants of wear pattern within a wear stage. The inclusion or exclusion of the fifth mandibular cusp is one such example. The fifth mandibular molar cusp is not present in all ordinal scales (e.g. Molnar 1971a; Brothwell 1972a; Scott 1979) but included in others (e.g. Hojo 1954; Murphy 1959a; Smith 1984). Scales excluding the fifth molar cusp typically have wear stages that can be applied to multiple molar types. In contrast, scales with the fifth molar cusp provide molar specific wear patterns. A preliminary review by Murphy (1959b) found that the fifth cusp was not always present and that the dentine exposure on this cusp was in close accordance with the disto-lingual cusp. Furthermore, the fifth cusp typically coalesced early on in the dental wear process (Miles 1962; Smith 1984). Excluding the fifth mandibular cusp produces simple stages of wear that can be applied to all molar types, although some information is lost with its exclusion.

A final variant in dental wear scales is the number of stages describing wear on the enamel before any dentine is exposed. Wear on the enamel can be confined to a single stage (e.g. Broca 1879; Brothwell 1963; Molnar 1971a), or can be broken into multiple stages (see Scott 1979; Smith 1984; Fares et al. 2009; Bartlett et al. 2011; Dawson and Robson-Brown 2013). Few studies, however, provide diagrams depicting the pattern of wear confined to the enamel. One study, by Dawson and Robson-Brown (2013) illustrated stages of enamel wear on the deciduous molars. These stages were based on those produced by Skinner (1997), whose wear scale could record wear on all tooth types, and for both permanent and deciduous teeth. The inclusion of enamel wear stages may be more difficult to identify for those with less experience in dental anthropology, but they provide additional information concerning the wear process. Furthermore, enamel wear stages may be particularly useful when examining the dental wear pattern of young individuals.

Implications for estimating age

The above discussion demonstrates the variation between methods for recording dental wear using ordinal scales and illustrates they are subjective. This variation inevitably results in the assessor having to decide which scale is most appropriate for their research, making cross-study comparisons difficult. The use of different scales means it would be difficult to reliably compare dental wear rates across studies.

The subjective nature of wear scales affects the ability to accurately assign wear stages to a particular tooth. As discussed, ordinal scales divide a continuous process into discrete stages and, as a result, a tooth's pattern of wear may fall between two stages. It is then at the discretion of the observer to assign an appropriate wear stage. Clear instructions on how to deal with such a specimen minimise this subjective judgement. For example, Bartlett et al. (2011 p.183) suggests "when difficulty arises in scoring a tooth surface the lower score should be applied; underestimating rather than overestimating the severity of wear." However, this has the potential to systematically under-age specimens if multiple individuals within a population consistently fall between stages of wear.

Stages within ordinal scales do not necessarily represent an equal degree of dental tissue loss. Molleson and Cohen (1990) mechanically ground twelve permanent molars, using two approaches. Series A was ground down using a drill and kept at a level plane across the occlusal surface. Crown height at each cusp was measured when wear stages following Brothwell (1963) were obtained. Series B was ground down in 0.5 mm increments and the wear pattern recorded. Molleson and Cohen (1990) found Brothwell's wear stages did not represent equal amounts of dental tissue loss. For example, the difference in crown height between Brothwell stages 1 and 2 was 0.96mm in the first mandibular molar, but only 0.31mm between Brothwell stages 3+ and 4. This suggests some stages of wear will be passed through more quickly than others, violating the assumption that dental wear is linear with age, and would result in the under-ageing of older individuals.

Molleson and Cohen (1990) also found Brothwell's wear stage 5++ persisted for multiple crown heights. This wear stage has a single, large area of exposed dentine surrounded by an enamel rim. Mays et al. (1995) proposed distinguishing stage 5++ from stage 5+, which also represents a single area of dentine with an enamel rim, with the appearance of secondary dentine as the onset of stage 5++. As Figure 4.3.1 shows, wear stage 5++ can occur at multiple crown heights, even with the onset of secondary dentine. This gives the impression that an individual stays in a single stage of wear, even though the tooth is still experiencing wear. Futhermore, this suggests a calibration based on molar wear observed at a given age and determined from the dental development of young individual, may not be accurate when extended to older individuals.

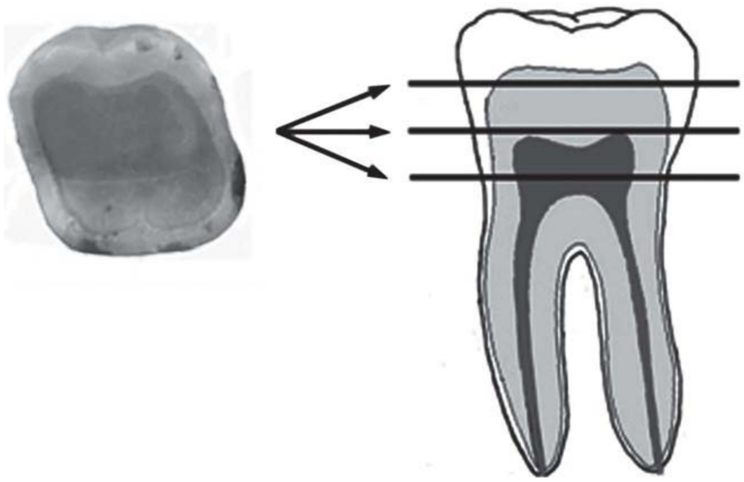


Figure 4.3.1. Depicting the different crown heights that a large area of exposed dentine surround by an enamel rim may be observed in a molar. Image taken from Nikita and Chovalopoulou (2016 p. 163).

Finally, ordinal methods have a statistical disadvantage compared to ratio data. Ordinal scales produce discrete, noncontinuous data. While this data may be useful for gross comparisons of dental wear patterns, it is unable to provide detailed information. In contrast, a recording system based on a ratio scale more accurately reflects the nature of both the wear and ageing process and allows for robust statistical testing, such as regression analysis. Ordinal scales are therefore quick and easy to apply but are limited in detailing precise information about the wear process.

4.3.2 Measurements of crown height

Measuring crown height on a ratio scale is a second approach for recording dental wear (Tomenchuk and Mayhall, 1979; Molnar *et al.*, 1983; Benfer and Edwards, 1991; Walker, Dean and Shapiro, 1991; Mays, de la Rua and Molleson, 1995; Mays and Pett, 2014). Crown height has been measured using three different approaches.

Crown height may be measured as cusp height relative to the central fossa (Tomenchuk and Mayhall 1979; Molnar et al. 1983a). Using this approach, crown height is defined as the distance from a plane tangent to the occlusal surface of the cusps to the deepest depression in the occlusal surface. To account for the variability in cusp height relative to overall tooth size, Tomenchuk and Mayhall (1979) devised a normalising index of tooth wear. Absolute cusp height (measured in millimetres) was multiplied by a constant of 100mm and divided by the product of the molar length and molar width. Tomenchuk and Mayhall (1979) produced a tooth wear index for 85 maxillary casts made from known-aged individuals from Igloolik, Canada and identified a correlation between age and the level of molar wear. Molnar et al. (1983a) measured cusp height on a sample of casts for upper and lower first molars of 64 Australian Aboriginals using a similar approach. Both simple cusp height and a normalising index was produced, and all measurements of cusp height were found to correlate with age.

While measurements of cusp height have been found to correlate with age, it is not suitable for populations experiencing high levels of wear. Figure 4.3.1 shows that with increasing wear, enamel on the occlusal is removed to leave a single area of exposed dentine. At this point, the central fossa is removed, and cusp height can no longer be measured and therefore may not be suitable for archaeological populations.

Crown height can also be defined as the distance between the cement-enamel junction (CEJ), the boundary between the enamel and cement on a tooth, and the cusp tip. Crown height for each tooth can be represented by single or multiple measurements between the CEJ and cusp tip

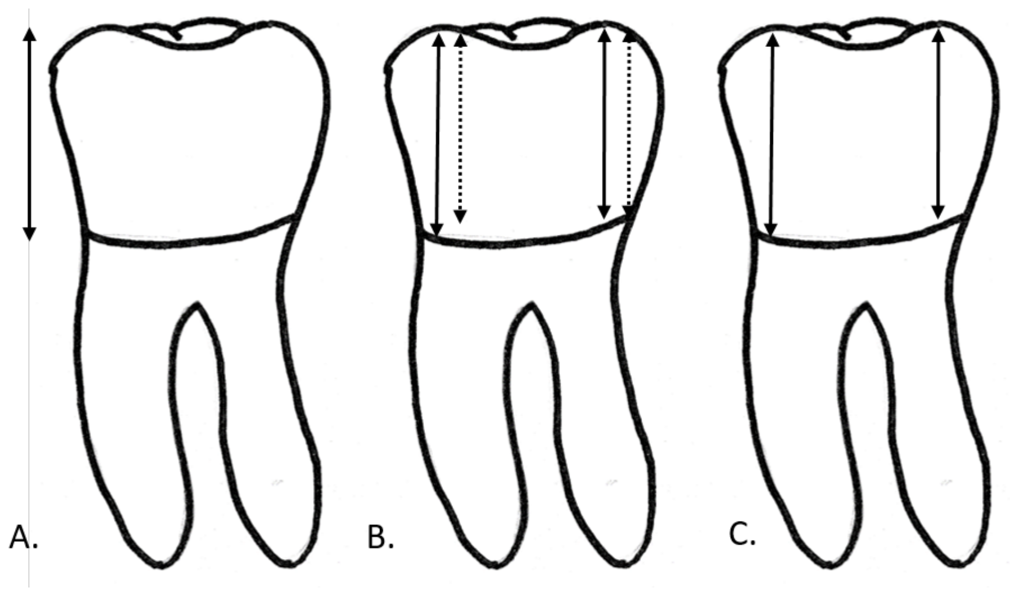


Figure 4.3.2. Measurements taken to represent crown height of a molar following A. Benfer and Edwards (1991) B. Walker et al. (1991) C. Mays et al. (1995).

(Figure 4.3.2). For example, Benfer and Edwards (1991) recorded a single measurement from the CEJ to the highest part of the crown. In contrast, Walker et al. (1991) took measurements from each of the four quadrants of the tooth. Crown height may also be recorded as the average of two measurements of crown height, with one taken at the distal and another at the mesial corners of the molar (Mays et al. 1995; Mays 2002).

Mays (2002) argued a single measurement to record crown height may be inadequate due to the irregular nature of the occlusal surface, either worn or unworn. Four measurements of crown height from a single tooth consider how wear affects the entire occlusal surface but increases the time required to measure crown height, a restricting factor for many bioarchaeologists. Mays (2002) argues two measurements, from the CEJ to the wear facets of the mesial and distal corners of the tooth, allows examination of the tooth areas that are most heavily affected by dental wear.

More recently, crown height has been measured as a crown index (CI), where average crown height (as defined by Mays et al. 1995) is divided by the medial-distal crown length (Figure 4.3.3). Mays and Pett (2014) proposed this measurement to overcome the difficulties of measuring crown height in deciduous molars, where the molar landmarks can be difficult to identify. In contrast to other crown height measurements, CI uses digital photographs to record crown index. Crown index is a measure of crown height normalised for mesio-distal tooth length at the CEJ, negating the need for a measurement scale. This means a CI around 100 indicates a crown height similar to tooth width, while a CI towards zero indicates a crown height that is considerably smaller than tooth width.

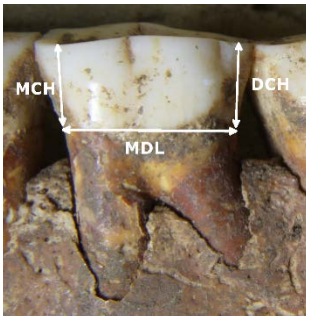


Figure 4.3.3. Crown Index measurements following Mays and Pett (2014). Image author's own.

As with the crown height measurement employed by Mays et al. (1995), crown index records the areas of a molar that are most affected by wear. The use of photographs allows a digital record of the tooth to be preserved. This is a particular benefit for remains that may undergo destructive analysis and allows future researchers to re-examine crown height even if a tooth is lost. A disadvantage of the method is the use of camera equipment, an additional expense for researchers. This method also requires a precise set-up, ensuring the tooth crown is parallel to the camera lens, to produce accurate and reliable measurements.

Implications for estimating age

The most appropriate measurement of crown height should be selected when using dental wear to estimate age in archaeological remains. As mentioned, recording cusp height is only appropriate for individuals retaining their central fossa. Although Tomenchuk and Mayhall (1979) and Molnar et al. (1983a) identified a relationship between cusp height relative to the central fossa and recorded chronological age in various living populations, these studies included few individuals over the age of 30 years old. Therefore, a wear rate calculated from molar cusp height may only provide age estimates for individuals up to middle age.

Taking four measurements of crown height from a single tooth may not be appropriate for archaeological remains. Archaeological remains can be damaged ante- or post-mortem and means four measurements for all molars may not be possible. This potentially reduces the sample size, and the ability to produce dental wear rates for a population. In contrast, the crown height measurement employed by Mays et al. (1995) provides a middle-ground, maximising the sample size while recording the dental areas most heavily affected by wear.

Recording crown height between the CEJ and the cusp tip allows the degree of wear to be recorded throughout the dental wear process. Crown height measured in this way can record dental wear starting on the enamel, before dentine has been exposed, until a tooth is lost. This approach has the potential to evaluate dental wear rates of both juveniles and adults. While ordinal scale methods may record this relationship, the continuous measurement of crown height allows for an accurate and detailed examination of the relationship between dental wear and age. Ratio scale methods for recording dental wear therefore have the potential to examine and compare wear rates of juvenile and adults individuals belonging to the same population.

4.3.3 Measuring the proportion of exposed dentine

A third approach for recording dental wear is to measure the proportion of exposed dentine on the occlusal surface. Ordinal scales can provide an idea of the amount of exposed dentine, it is not, however, a precise measurement. In contrast, measuring exposed dentine as a proportion of the entire surface overcomes this limitation, providing a value for the proportion of exposed dentine. Clement (2008) proposed such a method by employing digital photographs. The margin of the occlusal surface is identified and the area calculated as the number of pixels within the

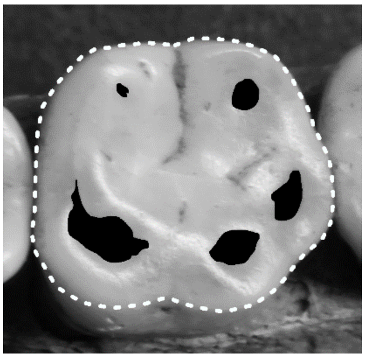


Figure 4.3.4. Image of the occlusal surface of a first mandibular molar where the occlusal surface has been outlined and the exposed dentine highlighted following Clement (2008). Image author's own.

margin. Areas of exposed dentine are measured following the same approach (Figure 4.3.4). Multiple areas of exposed dentine are measured individually and summed to give a total area of exposed dentine. The summed area of dentine is then divided by the area of the occlusal surface to provide a dentine proportion for each tooth (Clement 2008).

Recording the proportion of exposed dentine is a simple but comparatively more time-consuming method compared to crown height measurements. This is due to the processing time needed, as photographs must be taken and imported for computational analysis before any measurements can be recorded. The measurements also take more time due to the careful selection of the dental areas. In contrast, measurements using callipers or an ordinal scale are fairly instantaneous. An advantage of the exposed dentine proportion method, however, is the ability to quickly take photographs of the remains, with the additional processing and measurements undertaken off-site. This may be beneficial for those who need to access large collections as the initial recording can, in principle, be performed quickly on-site.

Implications for estimating age

One weakness of recording exposed dentine is the inability to take any measurements when there is no dentine exposure on a tooth. Mays and Pett (2014) found around a quarter of mandibular deciduous molars were excluded from their sample when using a typical early British archaeological population, an issue that also applies to permanent molars. Both the scales of Miles (1962) and Brothwell (1963) show minimal dentine exposure on the permanent molars in juvenile and young adult individuals, even in samples with high dental wear rates. Therefore, it may not be possible to calculate rates of wear of exposed dentine for juvenile individuals, a key step in the Miles Method for estimating age at death.

Molar crowns are not a perfect cuboid shape and are wider at the top with a narrower base at the cement-enamel junction (see Figure 4.2.1 and Figure 4.3.1). As a result, the occlusal surface does not remain as a constant but increases and decreases throughout the crown. This has the potential to introduce variation into dental wear rates, decreasing its ability to reliably estimate age at death. However, recording exposed dentine in this manner may be more precise and informative compared with ordinal scale data.

No study has used the proportion of exposed dentine to calculate rates of wear. This thesis explores the possibility of using such an approach and its potential application for estimating age at death.

4.4 Concluding remarks

Dental wear is a complex process that can be affected by multiple factors. The dominant causes of dental wear in archaeological remains include tooth on tooth contact and the introduction of abrasive particles, such as food and grit, into the mouth. Erosion also causes dental wear but has a minimal effect in archaeological remains. The rate and pattern of dental wear are also affected by diet, the use of teeth as tools and ante-mortem tooth loss, all of which occur in archaeological assemblages. When recording the dental wear of a population, it is vital that these factors are well understood and considered when calculating any rates of wear. Failing to do so will result in inaccurate and unreliable estimates of age.

To calculate dental wear rates, dental wear must first be recorded and measured. A suite of techniques exist to do this, varying in their ease of use and detail that they capture. While ordinal scales are the most frequently applied, due to their ease of use, they provide limited information regarding the wear process. More recent quantitative measurements of dental wear have the potential to overcome the subjective and imprecise nature of ordinal scales, and potentially provide a robust approach to examining dental wear. However, few studies have applied quantitative dental wear measurements to methods for estimating age at death. This thesis aims to rectify this by using both qualitative (ordinal) and quantitative (ratio) methods for recording dental wear, and assessing their use for the calculation of dental wear rates and age estimates.

Chapter 5 Materials

5.1 The Skeletal Material

This thesis employs well-documented archaeological sites to answer the research questions set out in Chapter 1. These sites date from the British Neolithic to Post-Medieval period and consist of juvenile and adult human remains representing the general population. For example, sites containing the remains of men, women and children were chosen over those with a particular bias, such as monastic cemeteries, which are predominantly male.

Individuals chosen for study were selected based on the following criteria: identifiable as adult or juvenile, dated to a period appropriate to the current study and having at least one measurable permanent maxillary or mandibular molar. Each temporal sample consisted of at least 30 juveniles and a minimum of 70 adult individuals. Previous studies have used a juvenile sample size between 20 and 30 individuals to produce dental wear rates that can be successfully extrapolated to produce reliable age at death estimates for adults of the same popualtion (Miles 1962; Nowell 1978). Juveniles were classified as an individual with developing dentition and had at least one erupted permanent, maxillary or mandibular, molar present for recording. An individual was considered an adult if any third molar was in full occlusion, and the fusion of long bone epiphyses was complete. The adult sample included individuals displaying all degrees of wear, from those with minimal wear on the third molar to those with extensive wear across the molars to individuals with ante-mortem tooth loss (AMTL). This ensured the entire dental wear process was observed and recorded.

The ideal reference sample would consist of individuals with a complete set of permanent molars, a pelvis and a skull. This was not possible due to the preservation of archaeological remains so a hierarchical selection process had to be applied. For each temporal sample, individuals were first selected on the presence of a complete set of molars, and who had an associated pelvis and skull. Individuals were then selected on the presence of a complete set of molars but only had a skull or pelvis present. The same approach was then applied to individuals with an incomplete set of molars with both a pelvis and a skull, and then to those with only a pelvis or a skull. The selection process then identified individuals with no associated pelvis or skull, first selecting those with a complete set of permanent molars and finally individuals with an incomplete set of molars.

The selection process included individuals with loose teeth, so long as the molar type and molar position could be identified. Single loose molars from an individual were included if they could be assigned an age group based on those defined in Brothwell's chart (1963) (Table 5.1.1), but were excluded from any analysis relating to the first two Research Questions: *do molars of the same type wear at a similar rate* and *do all molar types have a similar rate of wear*. Individuals lacking a pelvis and skull were determined to be a 'juvenile' or 'adult' based on the degree of molar development. Juvenile individuals were included in all elements of analysis, while adult individuals that were not assigned an age group were excluded from analysis relating to Research Question: *how strongly is dental wear associated with age*.

Table 5.1.1. Age groups and associated age range

Age Range (years)	Classification
6-18	Juvenile
18-25	Young Adult
25-35	Prime Adult
35-45	Middle Adult
45+	Older Adult

Table 5.1.2 provides the age at death distributions from each of the temporal samples used in the current research. Sample size within each age category was comparable across each temporal sample, although the Neolithic and Bronze Age samples showed a relatively lower frequency of individuals assigned to any age category. The low number of Neolithic individuals that could be assigned to an age group reflects the burial practices of this time period (see Section 5.2.1). These figures do not mean few Neolithic individuals lived past the age of 25 years old, but that few bony elements could be assigned to an individual to make an age assessment. The sample size for the Bronze Age sample reflects past collection practices, with a preference to collect skulls. As with the Neolithic sample, it is worth stressing that these numbers do not indicate that few Bronze Age individuals survived into old age, only that the specimens in the current research did not necessarily have their bony elements.

It is worth noting that the skeletal material was selected to illustrate the range of dental wear present within a population, rather than represent the age at death distribution of any temporal sample. A focus on capturing the entire wear process within each temporal sample intends to produce comparable data sets, and provide a reliable comparison of dental wear rates across archaeological periods. However, such an approach provides a false indication that all samples have a similar age at death distribution.

Table 5.1.2 Age at death distributions by temporal sample

Temporal Sample	Juvenile (>18 years)	Young Adult (18-25 years)	Prime Adult (25-35 years)	Mature Adult (35-45 years)	Older Adult (45+ years)	Adult (undefined age)	Total
Neolithic	40	7	0	4	0	101	152
Bronze Age	34	14	6	3	3	58	118
Iron Age	40	29	8	9	16	20	122
Romano-British	44	26	21	9	14	24	138
Anglo-Saxon	34	39	21	9	15	4	122
Medieval	32	17	14	5	16	22	106
Post-Medieval	26	20	13	8	12	23	102

5.2 The Dental Sample

Each permanent molar was recorded following Brickley and McKinley (2004). Molars were recorded as present or absent. Present molars were recorded as maxillary (Max) or mandibular (Man), first (M1), second (M2) or third (M3), left (L) or right (R). Molars were recorded as present and erupted (p), absent (\), erupting (not yet in occlusion) (PE) or unerupted (UE). Absent molars were recorded as lost post-mortem (\) or ante-mortem (X). A tooth was considered to be lost ante-mortem if the molar socket was either obliterated by remodelling or if a shallow socket remained but had been widened by remodelling (Mays 2014). If a socket retained its characteristic shape, it was considered to be lost post-mortem (Mays 2014). Other indicators for scoring molars included caries (c), damage to a tooth (d) and congenitally absent molars (CA). Following Turner et al. (1991), a tooth was considered congenitally absent, if an individual was over 17-20 years old and there were no interproximal wear facets on the distal surface of the second molars. Site-specific sample sizes are provided below, while Table 5.2.1. summarizes the dental sample employed for analysis by period and molar type.

Table 5.2.1. Summarized dental sample employed for analysis by period and molar type. Site-specific sample sizes are provided below

	Neolithic	Bronze Age	Iron Age	Romano - British	Anglo-Saxon	Medieval	Post-Medieval	Total
LMaxM1	59	93	99	111	102	71	74	609
LMaxM2	44	75	87	94	90	64	60	515
LMaxM3	25	59	49	56	45	27	36	297
RMaxM1	53	98	98	105	103	75	71	603
RMaxM2	49	78	84	89	90	61	65	516
RMaxM3	20	58	41	51	48	28	37	283
LManM1	59	94	113	123	116	98	90	695
LManM2	53	79	93	105	103	87	77	597
LManM3	34	63	50	66	67	54	54	388
RManM1	69	101	110	117	117	93	95	703
RManM2	61	84	95	106	106	78	84	614
RManM3	41	59	50	71	72	54	53	400
n teeth examined by period	567	941	969	1094	1059	790	796	**6220**
n individuals	156	118	122	138	122	106	102	**861**

L, left. R, right
Max, maxillary molar. Man, mandibular molar
M1, first molar. M2, second molar. M3, third molar

5.2.1 Neolithic

The British Neolithic, 4000 BC–2500 BC (Whittle 1999; Roberts and Cox 2003), is distinguished from the preceding Mesolithic period by a comparatively sedentary lifestyle, new material culture and the introduction of agriculture. There is little evidence for large-scale settlements or substantial housing during the Neolithic, although they are consisted to be comparatively more settled and organised that the people of the preceding Mesolithic (Pollard 1997; Whittle 1999). In addition to a change in lifestyle, the Neolithic is associated with new types of pottery and stone tool forms, not previously seen in the Mesolithic (Pollard 1997; Richards and Hedges 1999).

The Neolithic landscape was mostly wooded with evidence of localised woodland clearance allowing crop cultivation (Pollard 1997). This cultivation of crops, and the domestication of animals including cattle, sheep, goats and pigs, was a new subsistence strategy, contrasting with the hunter-gather lifestyle of the Mesolithic (Richards and Hedges 1999). This change in subsistence strategy is evidenced by the presence of animal remains and in the form of carbonised plant remains and plant impressions in pottery (Pollard 1997; Whittle 1999; McLaren 2000). Individuals relied on a terrestrial diet, which varied across Neolithic sites (Richards and Hedges 1999; Milner et al. 2004; Stevens and Fuller 2012). For example, isotope studies indicate individuals at Parc le Breos, Wales consumed a diet high in animal protein, while plant protein was a major part of the diet at Hazleton North, Gloucestershire (Richards 2000). The presence of stone querns, or hand mills, are often associated with British Neolithic sites, providing evidence of the processing of grains (Curwen 1937).

In addition to the technological advancements and shift in subsistence, the Neolithic also saw the construction of monuments. This included monuments for the dead in the form of tombs and barrows. These constructions were used for varying periods of time and ranged in size (Thomas 1988; Pollard 1997). For example, Quanterness, Orkney was used for over 500 years (c. 3000-2400 BC), with a minimum of 157 interred individuals (Pollard 1997). In contrast, Hazelton North, Gloucestershire was only in use for around 50 years, with around 41 individuals interred (Pollard 1997).

Neolithic inhumations are frequently disarticulated, with remains being separated, dispersed and co-mingled within tombs after the initial burial (Ashbee 1966; Thomas 2002; Smith and Brickley 2009). Hazelton North, Gloucestershire provides evidence of the deliberate rearrangement of burials, where Saville (1984) noted the deliberate placement of skulls and pairs of long bones. Saville (1984 p.22) suggested that the “absence of intact inhumations in passages and chambers…would suggest that bodies were left to decompose in the entrance and subsequently were taken through as bones to the interior.”

Multiple Neolithic sites were pooled for analysis to obtain the minimum number of individuals required to produce the desired sample size. Although the minimum number of individuals (MNI) within a Neolithic site may be large, for example, Quanterness has an MNI of 157, the commingling and disarticulation of the remains means many molars are lost post-mortem. This commingling also means that many of the bio-archaeological standards, including age and sex, are difficult to apply. As a result, the Neolithic sample could not be included in all aspects of analysis of this thesis. Figure 5.2.1 and Table 5.2.2 provides for the list of Neolithic sites included in the analysis with associated sample size.

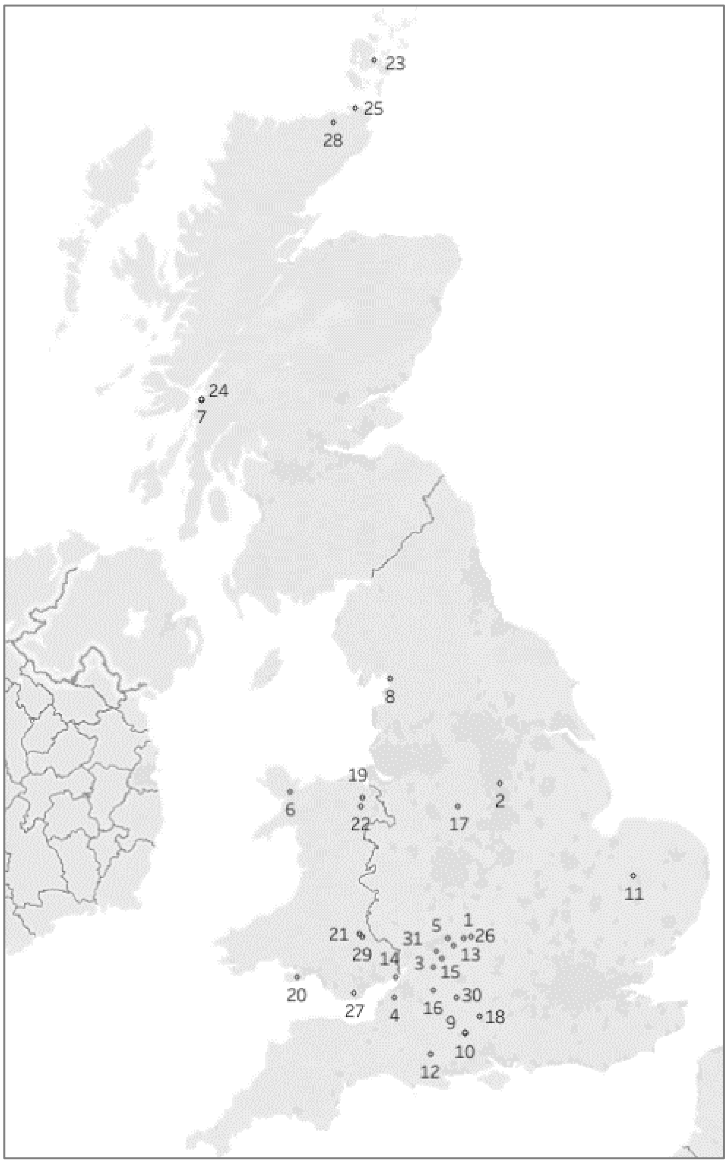


Figure 5.2.1. Map of Neolithic sites included in analysis

Table 5.2.2. Neolithic sites included in analysis. Radiocarbon dates are given where known.

Site	Primary Reference	Date	n molars	n individuals
1. Adlestrop, Gloucestershire	Donovan (1938)	3910–3700 BC. Dated by Martin Smith (A. Clark, personal communication, 17th October 2016)	6	4
2. Ash Tree Cave, Whitwell Barrow	Armstrong (1956)	-	5	1
3. Avening, Gloucestershire	O'Neil and Grinsell (1960)	-	10	4
4. Backwell Cave, Somerset	Tratman (1938)	2560 BC (4510±40 BP Ambers and Bowman 2003)	10	5
5. Belas Knap, Gloucestershire	Winterbotham (1866)		5	1
6. Bryn Yr hen Bold, Anglesey, Wales	Hemp (1936)	-	8	4
7. Distillery Cave, Oban, Scotland	Pollard (1990); Saville and Hallén (1994); Hedges et al. (1995)	-	16	7
8. Dog Holes, Lancashire	Jackson (1909, 1914)	-	29	13
9. Figsbury Rings, Wiltshire	Guido and Smith (1982)	-	10	2
10. Fussell's Lodge, Wiltshire	Ashbee (1966)	3630 BC (Wysocki et al. 2007)	3	2
11. Grimes Graves, Norfolk	Clarke (1915)	2700-2300 BC (Ambers 1997)	4	1
12. Hambledon, Dorset	Mercer and Healy (2008a)	Activity begins 3690-3640 BC and ends 3340-3300 BC (Mercer and Healy 2008b)	95	24
13. Hazleton North, Gloucestershire	Saville (1990)	3800-3500 BC (Saville 1990; Meadows et al. 2007)	77	16
14. Heston Brake, Monmouthshire Wales	Oakley (1888)	-	3	1

Table 5.1.4 continued. Neolithic sites included in analysis. Radiocarbon dates are given where known.				
Site	**Primary Reference**	**Date**	**n molars**	**n individuals**
15. Jackbarrow Longbarrow, Duntisbourne Abbots, Gloucestershire	O'Neil and Grinsell (1960)	-	14	3
16. Lanhill, Wiltshire	Keiller et al. (1938)	-	3	1
17. Long Low, Staffordshire	Barnatt (1996)	-	10	1
18. Nutbane, Hampshire	Mallet Morgan (1959)	2721 BC (Mallet Vatcher 1959; Barker and Mackey 1960)	17	2
19. Ogof Colomendy, Flintshire, Wales	Carr (1975)	2900-3100 BC (4408±33 BP Hankinson 2016)	8	3
20. Parc le Breos, Swansea, Wales	Whittle et al. (1998)	4000-3000 BC (Whittle et al. 1998)	7	3
21. Penywyrold, Powys, Wales	Savory (1984)	3960-3640 BC (Britnell and Savory 1984)	11	4
22.Perthi Chwarew cave, Denbighshire, Wales	Fisher (1926)	-	2	1
23. Quanterness, Orkney	Renfrew (1979); Davidson and Henshall (1989)	Activity begins 3510-3220 BC and ends 2850-2790 BC (Schulting et al. 2010)	1	1
24. Rachoille Cave, Oban, Scotland	Connock (1985)	3300-2900 BC (Bownes 2018)	1	1
25. Ratter East, Caithness	Sheridan (2006)	2470 BC (4427±35 BP, Sheridan 2006)	3	1
26. Swell, Gloucestershire	Rolleston (1876); Schuster (1905)	-	7	2
27. Tinkinswood, Vale of Glamorgan, Wales	Ward (1916)	-	28	10
28. Tulloch of Assery, Caithness	Corcoran (1966); Davidson and Henshall (1991)	3950-3300 BC (Sharples 1986)	18	3
29. Ty-Isaf, Powys, Wales	Briggs (1997)	3600-3300 BC (Neil et al. 2017)	12	5

Table 5.1.4 continued. Neolithic sites included in analysis. Radiocarbon dates are given where known.				
Site	**Primary Reference**	**Date**	**n molars**	**n individuals**
30. West Kennet, Wiltshire	Piggott (1958, 1962)	3600-3400 BC (Bayliss et al. 2007)	95	11
31. West Trump, Gloucestershire	Smith and Brickley (2006)	3630–3370 BC (Smith and Brickley 2006)	14	7
		Total	**519**	**156**

5.2.2 Bronze Age

The Bronze Age, 2600 BC-800 BC (Champion 1999; Roberts and Cox 2003), has evidence of permanent human settlement and agriculture (Champion 1999; Jones 2008a). Bronze Age settlements included houses in the form of round structures clustered in groups forming small, rural farms (Parker Pearson 1993). The presence of storage pits at many sites further support the practice of permanent settlement in contrast to the semi-permanent settlement of the Neolithic (Woodward 2000).

The Bronze Age is characterised by the first use of copper and bronze, with the earliest artefacts dating to 2700-2000 BC (Parker Pearson 1993). Many of the artefacts, including daggers, axes and awls, were not sharpened, while others were too large for practical use. Some have suggested these artefacts were symbols of status rather than functional tools (Parker Pearson 1993). New, finely made and elaborately decorated beakers also appeared during this period (Parker Pearson 1993). Bronze Age burials can be associated with beakers, along with other grave goods including arrowheads and daggers (Parker Pearson 1993).

The Bronze Age saw an "active manipulation of the environment by people," (Roberts and Cox 2003 p. 74), including the use of the land for agriculture. During this time crops of spelt, pea and bean were cultivated, and intensive farming practised (Stevens and Fuller 2012). The presence of saddle-querns in Bronze Age settlements further supports the use and processing of cereal grains. (Curwen 1937; Fasham 1982; Brück 1999). Excavations have revealed the remains of domesticated animals including cattle, sheep and pigs (Britton et al. 2008), and evidence of dairying supports an agricultural subsistence strategy during the Bronze Age (Copley et al. 2005). Isotope studies support this, indicating a mixed omnivorous diet, with little to no marine content, across British Bronze Age sites (Parker Pearson et al. 2016).

Burial practices during the Bronze Age varied and included both inhumations and cremations, (Parker Pearson 1993; Brück 1995; Woodward 2000; Jones 2008b). Remains were interred in barrows, either as single or multiple inhumations. Barrows were typically round, often surrounded by a ditch, and may have been in use for an extended period of time (Ashbee 1960; Woodward 2000). Therefore, Bronze Age interments varied in size, context and funery practice. For example, Easton Down, Hampshire (a ring-ditch) was used over a period of time, extending from the Neolithic into the early Iron Age, included both cremations and inhumations (Fasham 1982). Some of these burials were accompanied by grave goods (Ashbee 1960). In contrast, Helperthorpe, Yorkshire consisted of two barrows. The first had a single interment with a barbed arrow-point and two sherds of pottery (Greenwell and Rolleston 1877). The second Helperthorpe barrow had three inhumations, and parts of the pelvic bones and femur of a child. Finally, the parish of Weaverthorpe, Yorkshire, consisted of multiple barrows many with multiple burials interred over a period of time (Greenwell and Rolleston 1877). A further barrow with no interment was also present at Weaverthorpe, including the remains of an adult ox and grave goods. Cremations, the dominant burial practice, were interred alongside inhumations or formed cremation cemeteries clustering around and between existing mounds (Brück 1995; Woodward 2000; Jones 2008b).

Multiple Bronze Age sites were included in this thesis in order to produce the minimum number of individuals for the required sample size. Cremated Bronze Age individuals were not included in the sample due to the poor preservation of intact molars. Many sites were beaker burials, dating to the early Bronze Age lacking radiocarbon dates. As a result, many of the burials are identified as belonging to the Bronze Age period due to the presence of a beaker, and thus any conclusions from this thesis can only be applied to Early Bronze Age populations.

Figure 5.2.2 and Table 5.1.3 provide a complete list of Bronze Age sites included in the analysis.

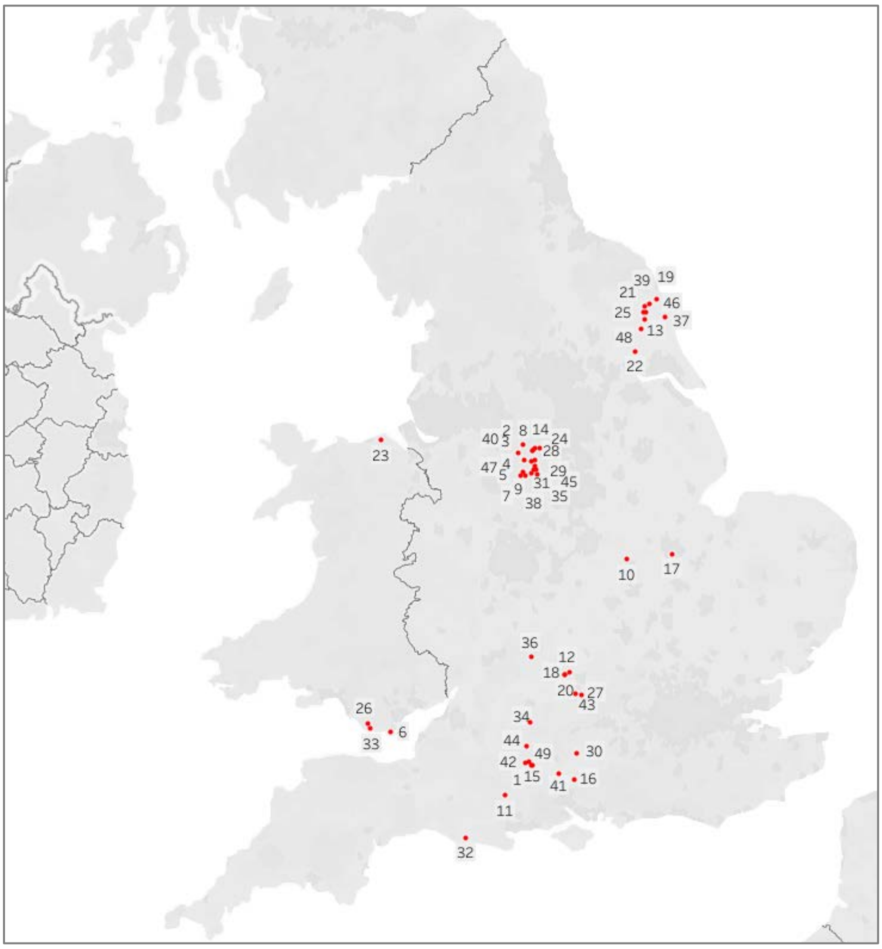


Figure 5.2.2. Map of Bronze Age sites included in analysis

Table 5.2.3. List of Bronze Age sites included in analysis. Radiocarbon dates are given where known.

Site	Primary Reference	Date	n molars	n individuals
1.Amesbury, Wiltshire	Christie et al. (1968)	-	12	1
2.Ballidon, Derbyshire	Bateman (1848, 1861)	-	11	1
3.Barrow near Arbor Low, Derbyshire	Bateman (1848, 1861)	-	5	1
4.Barrow near Castern, Derbyshire	Bateman (1848, 1861)	-	10	1
5.Barrow near Monsal Dale, Derbyshire	Bateman (1848, 1861)	-	3	1
6.Barrow near Staker Hill, Derbyshire	Bateman (1848, 1861)	-	8	1
7.Barry Island, Vale of Glamorgan, Wales	Allen (1873)	-	10	1
8.Bee Low, Derbyshire	Bateman (1848, 1861)	-	13	2
9.Blake Low, Derbyshire	Bateman (1848, 1861)	-	9	2
10.Bole, Derbyshire	Bateman (1848, 1861)	-	11	1
11.Bostorn, Derbyshire	Bateman (1848, 1861)	-	12	1
12.Caldecott, Oxfordshire	Leeds (1934)	-	11	1
13.Canada Farm, Dorset	Bailey et al. (2013)	2500-1700 BC until 1500-1150 BC (Green 2013)	29	3
14.Cassington, Oxfordshire	Leeds (1934)	-	40	5
15.Cowlam, Yorkshire	Greenwell and Rolleston (1877), Schuster (1905)	-	38	4

Table 5.1.5 continued. List of Bronze Age sites included in analysis. Radiocarbon dates are given where known				
Site	**Primary Reference**	**Date**	**n molars**	**n individuals**
16.Cross Low, Derbyshire	Bateman (1848, 1861)	-	12	1
17.Earl's Farm Down, Wiltshire	Christie (1964); Christie et al. (1968)	2010-2790 BC (4740±90, 3960±110 Callow et al. 1965)	32	4
18.Easton Down, Hampshire	Fasham (1982)	-	31	3
19.Eyebury, Northamptonshire,	Leeds (1915)	-	11	1
20.Flixton, Folkton, Yorkshire	Greenwell and Rolleston (1877)	-	23	2
21.Foxley Farm, Oxfordshire	Leeds (1938)	-	9	1
22.Ganton, Yorkshire	Greenwell and Rolleston (1877)	-	12	1
23.Goodmanham, Yorkshire	Greenwell and Rolleston (1877), Schuster (1905)	-	50	6
24.Gop Cave, Flintshire, Wales	Davies (1949)	-	16	4
25.Gotham, Nottinghamshire	Bateman (1848, 1861)	-	9	1
26.Helperthorpe, Yorkshire	Greenwell and Rolleston (1877)	-	10	1
27.Llandow, Vale of Glamorgan, Wales	Fox (1943)	-	11	1
28.Long Wittenham, Oxfordshire	Leeds (1929)	-	16	2
29.Monsal Dale, Derbyshire	Bateman (1848, 1861)	-	6	1
30.Mouse Low, Staffordshire	Carrington in Bateman (1848, 1861)	-	11	1

Table 5.1.5 continued. List of Bronze Age sites included in analysis. Radiocarbon dates are given where known				
Site	**Primary Reference**	**Date**	**n molars**	**n individuals**
31.Overton, Hampshire	Cunnington (1930)	-	14	2
32.Raystone Grange, Derbyshire	Marsden (1977)	-	3	2
33.Ridgeway Hill, Dorset	Grinsell (1959)	-	16	5
34.Riley's tumulus, Vale of Glamorgan, Wales	Ward (1919)	-	11	1
35.Rockley Barrow, Wiltshire	Cunnington (1987)	-	11	1
36.Rolley Low, Derbyshire	Bateman (1848, 1861)	-	10	1
37.Roman Road, Gloucestershire	Brett and Hart (2017)	1485-1065 BC (Brett and Hart 2017)	15	2
38.Rudstone, Yorkshire	Schuster (1905)	-	12	1
39.Shaws land near Monsal Dale, Derbyshire	Bateman (1848, 1861)	-	11	1
40.Sherburn Wold, Yorkshire	Schuster (1905)	-	30	3
41.Smerril Moor, Derbyshire	Bateman (1848, 1861)	-	10	1
42.Stockbridge Down, Hampshire	Stone and Hill (1940)	-	9	1
43.Stonehenge, Wiltshire	Evans (1984)	2400–2140 BC (Cleal et al. 1995)	4	1
44.Sutton Courtenay, Oxfordshire	Leeds (1923)	-	8	1
45.Waggon Low, Derbyshire	Bateman (1848, 1861)	-	9	1
46.Weaverthrope, Yorkshire	Greenwell and Rolleston (1877)	-	20	4

Table 5.1.5 continued. List of Bronze Age sites included in analysis. Radiocarbon dates are given where known				
Site	**Primary Reference**	**Date**	**n molars**	**n individuals**
47.Wetton Hill, Staffordshire	Bateman (1848, 1861)	-	5	1
48.Wetwang Slack, Yorkshire	Dent (1983)	1740 BC (3690±80 BP Harwell et al. 1992)	164	19
49.Woodhenge, Wiltshire	Cunnington (1929)	-	11	1
		Total	**941**	**118**

5.2.3 Iron Age

The Iron Age, late 9th Century BC - 1st C. AD (Haselgrove 2002), sees an increase in the number of settlement sites and the development of hillforts with complex earthworks and defensive capabilities. Danebury, Hampshire is one such example, where three sets of earthworks surround the site (Cunliffe 1993). The presence of storage pits and post-holes within these sites also support the use of permanent settlements during the Iron Age (Dent 1984; Cunliffe 1993; Jones 1996). Aerial photographs show further evidence of landscape modification, providing evidence for isolated farmsteads and field systems (Wainwright 1979; Cunliffe 2005).

The Iron Age has the first appearance of onsite rotary querns, an advancement on the earlier saddle quern, and indicates the processing of grains (Curwen 1937; Dent 1984; Cunliffe 1993). The Iron Age also sees a significant change in pottery production. Pottery manufacture shifted from local production during the Early Iron Age to one of regional production during the Middle Iron Age with an increase in number of distinctive pottery types (Morris 1996; Cunliffe 2005). Metal working is also evident during this period, further supporting the use of permanent settlements and technological advances. For example, Gussage All Saints, Dorset had large quantities of material associated with metal working, such as iron-working slag, fragments of crucibles and fired clay moulds (Wainwright 1979; Cunliffe 2005).

As in the Bronze Age period, Iron Age subsistence was dominated by agriculture and the use of domesticated animals. Domesticated animals, including sheep, cattle and pigs, were consumed, with little evidence of marine foods being eaten (Maltby 1996; Jay and Richards 2006; Jay and Richards 2007; Redfern et al. 2010; Stevens et al. 2010a). A range of crops were also cultivated including spelt wheat, emmer wheat, barley and oats (Jones 1996; Van der Veen and Jones 2006). This terrestrial diet was found to be similar across ten British Middle Iron Age sites (Jay and Richards 2007).

Burial practices varied during the Iron Age, with both inhumations and cremation burial rites being practised (Philpott 1991; Taylor 2001; Worley 2010). Cremation burials were the most dominant funerary practice, continuing from the Bronze Age. Inhumations dating from the Early to the Middle Iron Age are typically excavated from settlement sites and consist of disarticulated bones. In contrast, inhumations dating to the Late Iron Age are articulated and recovered from settlement sites and cemeteries (Wait G. 1985 in Redfern 2008). Iron Age inhumations can be associated with pits used for storage, or in in ditches surrounding Iron Age sites (Wait 1985). For example, Danebury, Hampshire, had approximately 300 depositions (Cunliffe 1993), many of which were disarticulated remains within pits (Stevens et al. 2010b).

As with the preceding period, multiple Iron Age sites were pooled to obtain the necessary sample size for the current study (Figure 5.2.3, Table 5.2.4). This thesis examined molars from inhumations, even though cremation was the dominant burial rite during the Iron Age. Two sites included in analysis were Iron Age cemeteries (Suddern Farm, Hampshire and Wetwang Slack, Yorkshire), which Whimster (1979) argues were uncommon and potentially introducing bias into this study. All Iron Age sites included in analysis date to the Early-Mid Iron Age (-800 to -100 BC). Therefore, any conclusions made for the Iron Age sample should only be applied to the Early-Mid Iron Age inhumations.

Figure 5.2.3. Map of Iron Age sites included in analysis

Table 5.2.4. Iron Age sites included in analysis. Radiocarbon dates are given where known.

Site	Primary Reference	Date	n molars	n individuals
Castle Ditches, Vale of Glamorgan, Wales	Hogg (1976)	-	10	1
Danebury, Hampshire	Cunliffe (1984)	550-50 BC (Cunliffe 1984)	213	36
Greystones Farm, Gloucestershire	Busby (2015)	-	16	2
Gussage All Saints, Dorset	Wainwright (1979)	790 BC – 150 AD (Wainwright 1979)	32	3
Suddern Farm, Hampshire	Cunliffe et al. (2000)	-	107	12
Wetwang, Yorkshire	Dent (1983)	190 BC - 160 AD (Dent 1984; Walker et al. 1988)	591	68
		Total	**969**	**122**

5.2.4 Romano-British

The Romano-British period spanned from 43 AD – 410 AD (Cleary 2002) and, as with the previous periods, a terrestrial diet was consumed consisting of cereal grains, meat and dairy products (Moore and Corbett 1973; Cool 2006; Redfern et al. 2010). The meat component of the diet consisted of the typical domesticated species (cattle, sheep and pig), as well as domesticated birds including ducks, chickens and geese (Cool 2006). Wild game and fish were also consumed (Redfern et al. 2010). Spelt and emmer grains continued to be consumed from the Iron Age, with the addition of barley and bread wheat (Cool 2006; Redfern et al. 2010). This variety of foods means the Romano-British exploited a wider range of food resources compared with earlier periods. This variation was further increased due to imports from Europe, including grapes, cherries and honey (Moore and Corbett 1973; Redfern et al. 2010). Food processing technologies intensified during the Romano-British period, increasing food production. For example, the introduction of animal and water-powered mills allowed larger quantities of grain to be processed into flour than in previous periods (Cool 2006).

A significant number of people lived in towns during the Romano-British period (Glasswell 2002). Major towns were laid out in a regular street-grid and included townhouses and public buildings such as the forum, public baths and sometimes an amphitheatre (Millett 1990; Cleary 2002). Small towns, in contrast, had an informal layout with few public buildings (Millett 1990; Bonsall 2013). Romano-British urban sites were associated with cemeteries, while rural settlements had fewer associated burials (Taylor 2001). Inhumation burials became popular from the mid-2nd century, with cremations occurring during the early Romano-British period (Philpott 1991; O'Brien 1999; Taylor 2001). Burials had grave goods, most commonly coins, food vessels and brooches, although the practice of giving grave goods declined towards the end of the Romano-British period.

Romano-British individuals included in this study came from late Romano-British cemeteries associated with urban settlements (Figure 5.2.4, Table 5.2.5). This means the rural and early Romano-British populations were not observed, and any conclusions drawn from the Romano-British sample should only be applied to urban, rather than rural, populations dating to the late Romano-British period.

Figure 5.2.4. Map of Romano-British sites included in analysis

Table 5.2.5. Romano-British sites included in analysis. Radiocarbon dates are given where known.

Site	Primary Reference	Date	n molars	n individuals
Ancaster, Lincolnshire	Cox (1989)	-	391	53
Alington Avenue, Dorset	Davies et al. (2002)	-	62	8
Bath Gate, Gloucestershire	McWhirr et al. (1982)	-	63	10
Lankhills, Hampshire	Booth et al. (2010)	300 - 400 AD (Booth et al. 2010)	578	67
		Total	**1094**	**138**

5.2.5 Anglo-Saxon

During the late fourth and early fifth centuries, Roman central imperial authourity broke down, leading to troops being withdrawn from Britain and a decrease in trade in markets and towns (Hinton 2006). This lead to a decrease in wealth during the Anglo-Saxon period, 410 AD – c. 1050 AD (Hills 2002), with Anglo-Saxons residing in dispersed groups of farmsteads and villages rather than towns as seen during the Romano-British period (Welch 1992; Reynolds 1999; Hills 2002). However, technological refinements still occurred. The development of the mould plough, a tool for turning over the earth rather than just cutting through it, provided a less labour intensive method for cultivating fields. In addition, oxen, and possibly water, were being used to power mills by the end of the Anglo-Saxon period (Banham 2004; Hagen 2006), allowing greater food production.

Cereal grains were the main staple food during the Anglo-Saxon period, with 'corn' being a generic term for grain (Hagen 2006). These grains included wheat, barley, and to a lesser extent, oats and rye (Banham 2004), while meat, fish, dairy, fruit and vegetables were consumed seasonably (Moore and Corbett 1971; Glasswell 2002). Individuals of high status may have consumed more meat compared with poor people (Banham 2004), although an isotopic study analysising the bone collegen of 76 adults from 18 different cemeteries suggests the Anglo-Saxon diet varied little in terms of protein sources across the country (Mays and Beavan 2012). However, individuals living in coastal areas may have consumed more marine resources compared with those living inland (Mays and Beavan 2012).

The majority of Anglo-Saxon burials were interred in cemeteries where both cremation and inhumation rites were practised (Welch 1992; Taylor 2001). Some Anglo-Saxon burials had associated grave goods, including pins, brooches, combs and beads. However, during the 7th Century there was a decline in the number of grave goods, linked with the spread of Christianity during this time (Härke 2016). The predominate Anglo-Saxon burial position was supine, placing the body on its back, in graves cut into the ground (Lucy 2000; Reynolds 2009) There is also evidence of 'deviant' burials, those that do not follow the typical burial position of Anglo-Saxon interments, during this period. These deviant burials were sometimes present in normal cemeteries, but also formed deviant cemeteries, such as execution cemeteries (Lucy 2000; Buckberry 2010).

This thesis includes two Anglo-Saxon sites, the cemetery located north west of the Roman town of Great Chesterford, Essex , and Butler's Field at Lechlade, Gloucestershire. The Great Chesterford cemetery dates to the first half of the Anglo-Saxon period (Inskip 2008), while Butler's Field had two phases of burial. The first phase lasted from around 450 AD to 600 AD, the second dates to the 7th and 8th centuries (Boyle 1998). Both cemeteries are located in the south of the UK, consisting of both inhumation and cremation burials (Evison and Annable 1994; Boyle 1998; Inskip 2008). Only the inhumation burials were included in analysis (Figure 5.2.5, Table 5.2.6).

Figure 5.2.5. Map of Anglo-Saxon sites included in analysis

Table 5.2.6. Anglo-Saxon sites included in analysis. Radiocarbon dates are given where known.

Site	Primary Reference	Date	n molars	n individuals
Butler's Field, Gloucestershire	Boyle (1998)	-	620	68
Great Chesterford, Essex	Evison and Annable (1994); Inskip (2008)	415–545 AD (Inskip et al. 2015)	439	54
		Total	**1059**	**122**

5.2.6 Medieval

Both rural and urban settlements existed in Medieval England, c. 1050 to c. 1550 AD (Schofield 2002). The majority of Medieval individuals lived in rural settlements, consisting of farmsteads, hamlets and villages, which were associated with agricultural and industrial activities (Gies and Gies 1990; White 2012). In contrast, urban settlements were involved with trade and administration (White 2012). These urban inhabitants mostly relied on foods brought into weekly markets from the surrounding countryside, as little food was grown inside the town walls.

As with the preceding periods, meat and cereal grains formed the main components of the medieval diet. Individuals of high status consumed a variety of meat, including game, fish and wild birds, and had access to finer wheat flour and imported preserved fruits (Moore and Corbett 1973; Serjeantson 2006; Stone 2006; Thomas 2007). The poor, by contrast, ate more preserved meat and would have used more inferior grains for bread making (Albarella 2006; Stone 2006). On the whole, domestic animals (cattle, sheep and pigs) provided the majority of the meat component of the medieval diet (Sykes 2006; Thomas 2007), with grains providing the "bulk of calorific intake," (Stone 2006 p. 11). Crops consisting of wheat, rye, barley, oats and mixed crops were cultivated (Stone 2006), and consumed as bread, ale or pottage (Moore and Corbett 1973).

In addition to meat, fish was consumed from the mid-Saxon period, increasing during the late 10th Century and becoming widespread by the end of the 12th Century (Serjeantson and Woolgar 2006). The increase in fish consumption during the Medieval period may be a result of fasting, set down by Christianity, which has been documented in written texts (Roberts and Cox 2003; Serjeantson and Woolgar 2006). The church dictated fasting, the abstinence from meat, for nearly half the days of the year. This included Wednesdays, Fridays and Saturdays, as well as Lent and other religious days (Buxton 1998).

The church played a significant role in the Medieval community, forming the focal point for both ritual and social gatherings, and acting as places of worship (Gilchrist 2002). During this period, there was also a movement to rebuild churches from timber structures to more substantial buildings (Gilchrist 2002; Platt 2003). St. Peter's church, Lincolnshire is an example of this. A rectangular nave replaced the original Anglo-Saxon church, which was extended in c. 1200 AD. The 14th and 15th centuries saw further work and additions to St. Peter's, including rebuilding of the north aisle and chancel (Rodwell and Rodwell 1982). Gilchrist (2002) argued these developments reflect the change in use of churches as well as providing space for a growing population across Britain.

Prior to the 12^{th} Century, only church founders or priests were permitted to be buried inside the church (Gilchrist 2002). After the 12^{th} Century, wealthy and important patrons were allowed to be interred within the church. Therefore, the majority of the Medieval population was buried in cemeteries attached to the church. Individuals were often buried in a coffin, evidence of which can both be seen at St. Helen-on-the-Walls, Yorkshire (Dawes and Magilton 1980) and St. Peter's (Waldron 2007). Grave goods in Medieval burials are rare, as Christians were not expected to be buried with objects (Daniell 1997)

Two Medieval sites were included in the analysis: St. Peter's and St. Helen-on-the-Walls (Figure 5.2.6, and Table 5.2.7). St. Helen's represents an urban Medieval settlement while St. Peter's reflects a small, rural town. Both churches underwent various phases of development, as did many churches during the Medieval period. The earliest parts of St. Helen's church date to the 10th century, being rebuilt and additions made into the 15th century. St. Helen's remained in use until 1550, with parts still standing in 1580 (Dawes and Magilton 1980). The date of the cemetery at St. Helen's falls within the development phases of the church, with no burials (other than a single sealed Roman example) known to pre-date the first building. Documentary evidence suggests that is unlikely that any burials took place within the churchyard after 1550 (Dawes and Magilton 1980). St. Peter's church dates from Anglo-Saxon to Victorian times, resulting in many phases of burial extending from c. 950 to c.1855. During excavation and analysis of St. Peter's it was decided to subdivide the history of the cemetery into five basic chronological phases, each comprising of approximately two centuries (Rodwell 2007).

This thesis uses burials from Phase C (c. 1300-1500) and Phase D (c. 1150-1300) to represent the Medieval sample. The cemeteries of St. Helen-on-the-walls and St. Peter's represent burials for the 'normal' Medieval population. Cemeteries with an obvious sex bias (such as monastic cemeteries) were deliberately excluded from analysis, allowing an examination of the dental wear for a general British Medieval population.

Figure 5.2.6. Map of Medieval sites included in analysis

Table 5.2.7. Medieval sites included in analysis. Radiocarbon dates are given where known.

Site	Primary Reference	Date	n molars	n individuals
St. Helen-on-the-Walls, Yorkshire	Dawes and Magilton (1980)	1140±80 AD and 1170±80 AD (Dawes and Magilton 1980)	372	56
St. Peters church, Lincolnshire	Waldron (2007)	1150 – 1500 AD (Bayliss and Atkins 2011)	418	50
		Total	**790**	**106**

5.2.7 Post-Medieval

In 1550 British towns were small, still suffering from a population decline during the Medieval period due to famine, caused by crop failures and cattle disease, and the Black Death (Schofield 2002). The Post-Medieval period, c. 1550 AD – c. 1850 (Whyte 2002), saw an increase in population size, producing systems of farming that would increase crop yields. One example of this system is the clearing of trees to create more land for agriculture (Crossley 1990). There were also many technological developments and innovations during the Post-Medieval period. These included brick replacing other materials in houses, the commercialisation of agriculture, the development of transport and road systems, an increase in pottery vessel types and the production of clay pipes (Crossley 1990; Whyte 2002).

The 16th century saw a massive phase of urbanisation, transforming the landscape of Britain. In 1550, the vast majority of the population lived in small towns and villages. Over the later centuries, the number of people living in large towns of over 10,000 inhabitants increased, with population growth also occurring in medium-sized towns and smaller market villages (Whyte 2002). In urban environments, suburbs expanded and construction intensified, leading to areas of tightly packed housing.

The Post-Medieval period saw the import of new foods into Britain, including potato, sugar and tea (Roberts and Cox 2003; Mant and Roberts 2015). Intensification of agriculture, resulting from technological advancements, allowed crop rotation and the introduction of fodder crops, producing animal products that were consumed all year-round (Clark 1999; Roberts and Cox 2007). These advancements, and importation of goods, resulted in a varied but highly cariogenic diet towards the end of the Post-Medieval period.

As with the Medieval period, inhumation was the dominant burial practice during the Post-Medieval period. Bodies were wrapped in shrouds, although by the 18th Century individuals were typically buried in coffins (Mihailovic 2011). Gravestones and stone monuments were a feature of the Post-Medieval graveyard and become widespread by the end of the 18th Century (Tarlow 1998; Renshaw and Powers 2016). Most individuals were interred in the churchyard, and Waldron (2007 p.32) notes “by the 18th century, the popularity of indoor burial had increased so much that space commanded a significant cash premium.” Therefore, overcrowding was not just observed in towns for the living, but also in burial grounds for the dead.

St Peter’s church was chosen for the Post-Medieval site for study (Figure 5.2.7, Table 5.2.7). This site was well excavated and documented, with clear stratigraphy to aid in the identification of

Post-Medieval inhumations from the Medieval inhumations. St. Peter's church experienced multiple phases of burial. For this thesis, burials from Phase A (c. 1700-1855) and Phase B (c. 1500-1700) were selected for the Post-Medieval sample. St. Peter's served a rural community. Therefore, any conclusions made concerning dental wear using this sample may not apply to urban Post-Medieval sites, such as Spitalfields, London. Furthermore, the St. Peter's sample spans the early post-medieval period, and may not be directly comparable to sites later post-medieval samples.

Figure 5.2.7. Map of Post-Medieval sites included in analysis

Table 5.2.8. Post-Medieval sites included in analysis. Radiocarbon dates are given where known.

Site	Primary Reference	Date	n molars	n individuals
St. Peters church, Lincolnshire	Waldron (2007)	500-1855 AD (Bayliss and Atkins 2011)	796	102

5.3 Concluding remarks

The above section provides a rationale for the sites, skeletal and dental selection process. This rationale included the use of well-documented sites, skeletal remains that could be identified as either adult or juvenile, and the presence of at least one permanent molar. This approach aims to produce an overall picture of dental wear patterns and rates for multiple temporal period samples.

This chapter also details the lifestyle, subsistence strategies and burial practices of the British Neolithic to Post-Medieval periods, and demonstrates the subtle differences between each period. For instance, Neolithic individuals consumed a relatively small range of foods and buried their dead in monuments, which were deliberately places and rearranged over time. Medieval individuals however, consumed a higher proportion of fish and buried their dead in single graves in cemeteries. The context of each temporal period will aid in the interpretation of the results in Chapter 7, and how dental wear rates may be influenced by diet and time period.

Chapter 6 Methods

This chapter details the methods used for analysis of the skeletal remains, the methods used to record dental wear and statistics employed. Each section outlines why certain methods were chosen over alternative techniques. Section 6.3 describes the four chosen methods for recording dental wear, including average crown height, crown index, percent of exposed dentine and an ordinal scale. Each technique is reviewed and reliability tests performed to ensure the chosen methods were appropriate for the current study. Section 6.4 outlines the research questions to be addressed using the data collected, and includes a discussion of the statistical methods used.

6.1 Age estimation

Juvenile age estimates from dental development were obtained using *The London Atlas* (AlQahtani et al. 2010). Dental development is stable in appearance and formation times due to a significant genetic component (Liversidge et al. 1998; White et al. 2011), resulting in dental growth events occurring at similar ages of children from different populations. Studies observing the timing of growth events of the dentition between both modern and archaeological populations, and different ethnic groups support this (Liversidge and Molleson 2004; Liversidge 2011). Using a sample of skeletal remains of individuals from collections with known age at death and archived dental radiographs of living patients, AlQahtani et al. (2014) showed *The London Atlas* produced a lower mean difference between dental and chronological age than the charts of Schour and Massler (1941) and Ubelaker (1978). Therefore, *The London Atlas* estimated age more accurately and with greater precision than the other two methods (AlQahtani et al. 2014). For this reason, *The London Atlas* was chosen to estimate age at death in juvenile individuals (Figure 6.1.1).

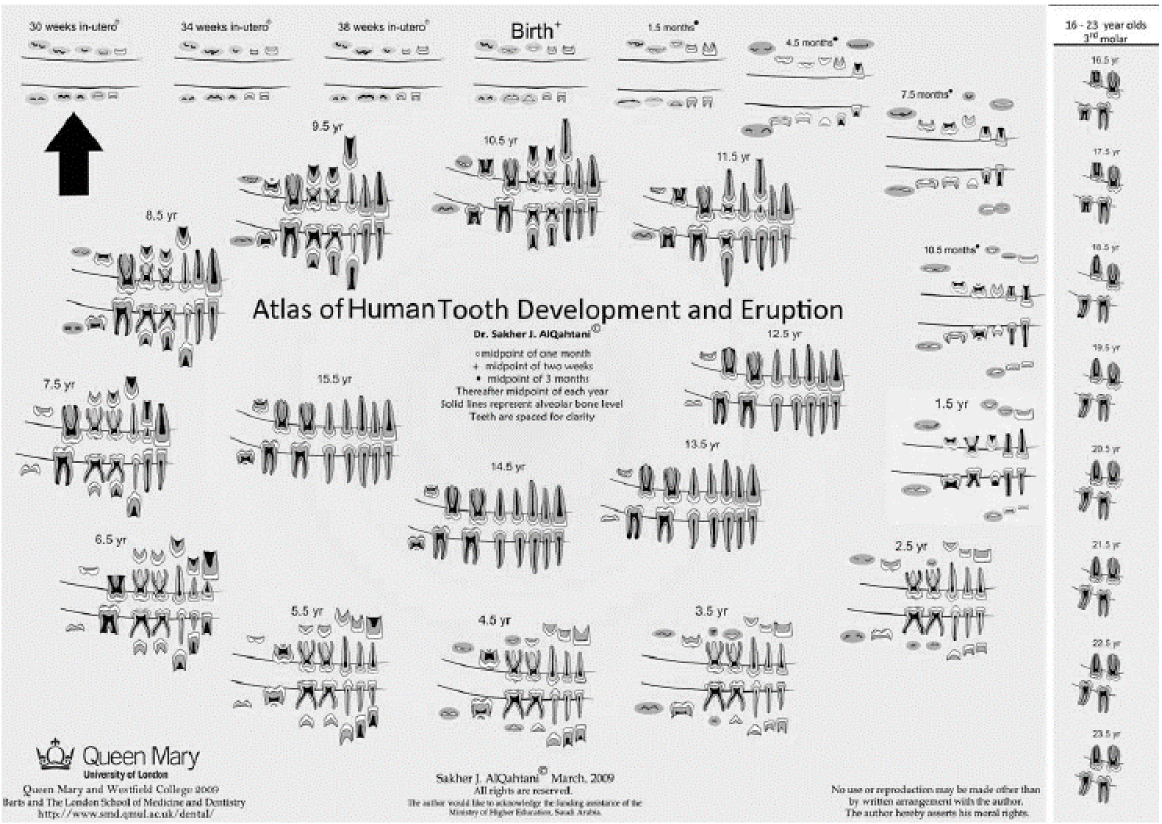


Figure 6.1.1. The London Atlas of tooth development and eruption. Image taken from AlQahtani et al. (2010 p.485).

Epiphyseal fusion was employed to confirm whether an individual was an old juvenile (under 18 years of age) or young adult (over 18 years of age). When long-bones cease growing the growth cartilage between secondary ossification centres (epiphyses) and the diaphysis (shaft) ossifies, fusing the epiphysis with the diaphysis. Epiphyseal fusion proceeds in an orderly manner, occurring throughout adolescence and early adulthood. Multiple studies have examined epiphyseal fusion events through the observation and examination of skeletal remains. For example, McKern and Stewart (1957) investigated a range of fusion sites using the skeletal remains of Korean war dead, while Schulze et al. (2006) examined the relationship between age and the ossification of the medial epiphysis of the clavicle using computed tomography. Since no single study is truly comprehensive, including all epiphysis and both sexes, many archaeological textbooks provide diagrams compiling data from multiple sources. This has the disadvantage of combining data from studies using different methodologies and sample sizes. However, epiphyseal fusion can be useful for estimating age at death in adolescents or young adults when dental development is complete, or for those with incomplete dentition.

This thesis employs the method of epiphyseal fusion according to the comprehensive figure provided by Mays (2010 p. 48). Figure 6.1.2 presents age estimates for epiphyseal fusion produced from the work of Flecker (1942) and Webb and Suchey (1985). The lower ends of the age ranges are ages at which fusion was first noted; the upper ends are those at which completely unfused epiphysis were last noted (Mays 2010).

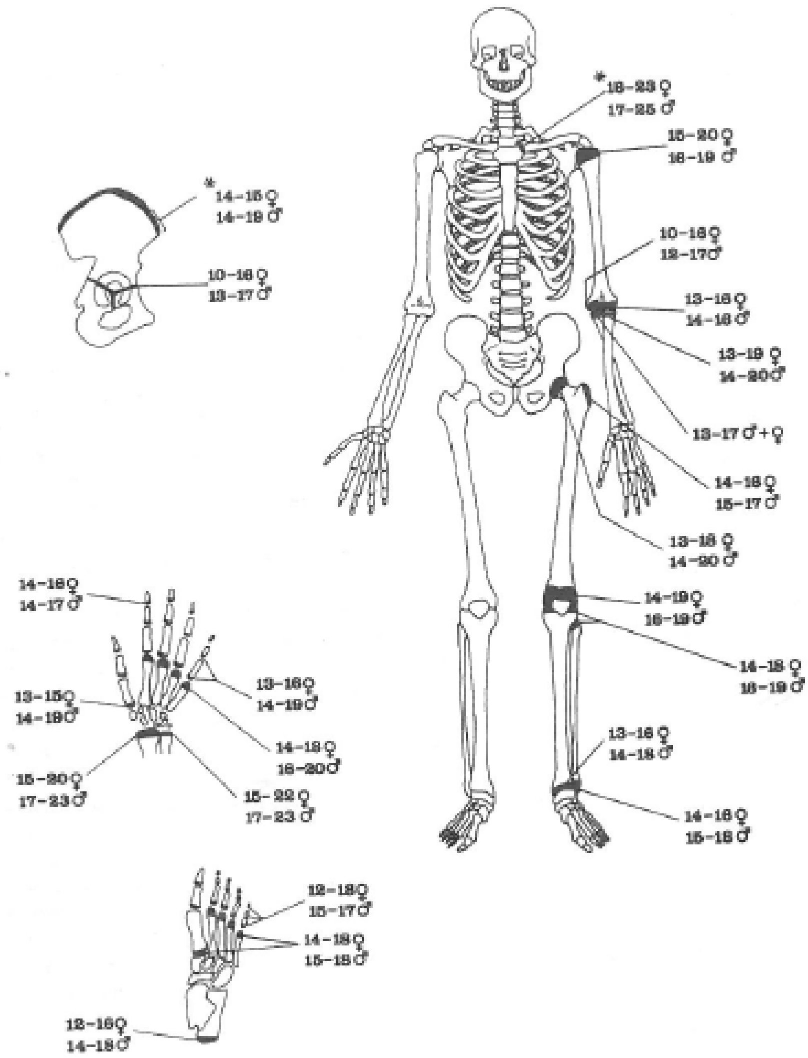


Figure 6.1.2. Diagram of estimating juvenile age from epiphyseal fusion taken from Mays (2010 p.48)

Adult age estimates were obtained using Transition Analysis (Boldsen et al. 2002). Transition Analysis scores age-related changes in the pubic symphysis, auricular surface and cranial sutures by breaking down “complex biological structures,” (Boldsen et al. 2002 p.79). Transition Analysis therefore scores traits individually, an alternative to examining the pubic symphysis, auricular surface and cranial sutures in their entirety. Scores were in accordance with written descriptions provided by Boldsen et al. (2002) and inputted into ADBOU software (Ousley 2002). Maximum likelihoods for estimated age were produced using ADBOU, allowing individuals to be assigned an age group based on those used in Brothwell's chart (1963) (Table 5.1.1). The scoring manual for Transition Analysis, example illustrations, scoring form and the ADBOU software were downloaded from http://math.mercyhurst.edu/~sousley/Software/ (Ousley 2002).

6.2 Sex Estimation

Previous studies of dental wear present varied findings with regard to sex differences in attrition rates in populations with various subsistence strategies. Some studies found no significant difference in dental wear patterns or dental wear rates between males and females (Lunt 1978b; Lovejoy 1985; Mays 2002; Benazzi et al. 2008), while others do. For example, Tomenchuk and Mayhall (1979) reported greater attrition rates in male molars compared for a modern sample of Iglookik Inuits of Canada. In contrast, Berbesque et al. (2012) identified higher wear rates in females in a living Hadza population in northern Tanzania. It is worth noting that the studies demonstrating a difference in wear rates examine populations following a hunter-gather subsistence strategy. In contrast, the populations examined in the work of Lunt (1978b), Mays (2002), and Benazzi et al. (2008) follow an agricultural lifestyle. This difference in subsistence strategy may provide an explanation for the difference in wear rates between males and females. In a study of dental wear of North American Indians from three areas, Molnar (1971) identified a difference in wear pattern and wear rate between males and females in the Californian group, following a hunter-gather lifestyle, but not in the groups from the Southwest and the Valley of Mexico, who are agriculturalists. Molnar (1971) argued there is a contrast between male and female activities in hunting and gathering cultures which does not exist at the agricultural levels, such as those represented in his study.

Prior to examination of dental wear rates, this thesis will examine the potential difference in wear rates between male and female individuals. Therefore, where possible a sex was assigned to individuals. Estimations of sex were made using features of the cranium and pelvis following the standards produced in Buikstra and Ubelaker (1994).

6.3 Methods for recording dental wear

Dental wear was recorded for each available permanent maxillary and mandibular molar using four methods: average crown height (CH), crown index (CI), the percentage of exposed dentine (%DE), and wear stage (WS). Each method was refined and tested for its reliability.

6.3.1 Average crown height (CH)

Average crown height (CH) was measured using digital callipers following Mays et al. (1995). Mesial crown height (MCH) and distal crown height (DCH) were measured as the height from the cement-enamel (CEJ) to the tip of the wear facet at the mesial and distal corners of each tooth (Figure 6.3.1). The mean of these measurements was used to express crown height.

Figure 6.3.1. Average crown height (CH) measurements. See text for full description.

CH was measured on the buccal side (tooth surface nearest the cheek) of mandibular molars and from the lingual side (tooth surface nearest the tongue) of maxillary molars. These areas experience the largest biting forces and show the largest amount of dental wear (Mays et al. 1995; Le Luyer et al. 2014).

6.3.1.1 Methods test: average crown height (CH)

In order to test the repeatability of average crown height (CH), the molars of 48 individuals were selected at random and re-measured by the same observer. Intra-observer error for average crown height (CH) was tested using a sample of Anglo-Saxon individuals from Great Chesterford (n=48). The repeatability of measuring CH was assessed using the method error statistic (Dahlberg 1940; Knapp 1992), otherwise known as the technical error of measurement (TEM). TEM is the typical degree of measurement error expected to incur when taking a measurement (Knapp 1992) and is essentially the standard deviation between the repeated measurements, quantifying the amount of variance between two measurements of the same sample (Perini et al. 2005). TEM was calculated for each molar type, and for each quadrant of the mouth.

TEM was computed as the square root of the squared differences between corresponding measurements divided by twice the sample size, following the equation:

$$Sm = \sqrt{\frac{\sum d^2}{2n}}$$

Where *d* is the difference between the repeated measurements and *n* is the number of repeated measurements. Sample standard deviation (S) was calculated to give the sample variance, i.e. the relative technical error measurement, where:

$$R = \frac{Sm^2}{S^2}$$

The relative technical error measurement (R) was converted into a percentage for simple interpretation.

Table 6.3.1 provides the TEM results for the reliability of measuring CH between two recording attempts made by the same author.

Table 6.3.1 Repeatability results for crown height for individual maxillary and mandibular molars

Tooth	Sm	S	R	%
LMaxM1	0.268	1.485	0.033	3.3
LMaxM2	0.347	1.456	0.057	5.7
LMaxM3	0.341	0.837	0.166	16.6
RMaxM1	0.207	1.028	0.040	4.1
RMaxM2	0.274	1.116	0.060	6.0
RMaxM3	0.255	1.231	0.043	4.3
LManM1	0.179	1.009	0.032	3.2
LManM2	0.241	1.347	0.032	3.2
LManM3	0.230	1.344	0.029	2.9
RManM1	0.202	1.202	0.028	2.8
RManM2	0.159	1.455	0.012	1.2
RManM3	0.273	1.187	0.053	5.3

Sm, method error statistic
S, Sample standard deviation
R, sample variance
%, sample variance expressed as a percentage of total variance
L, left. R, right
Max, maxillary molar. Man, mandibular molar
M1, first molar. M2, second molar. M3, third molar

Between 1-6% of the sample variance was likely to be made up of measurement error, excluding the left maxillary third molar (LMaxM3), which had a measurement error of 17%. The TEM value for the third molar is likely to be a result of the relatively high variation formation time and morphology compared to the first and second molars (Garn et al. 1962; Mincer et al. 1993; Solari and Abramovitch 2002). The calculated TEM values are similar to Mays et al. (1995), indicating CH is a reliable method for recording dental wear.

6.3.2 Crown index (CI)

Crown index (CI) was recorded from digital photographs following Mays and Pett (2014). CI is a measure of crown height normalised for the medial distal length (MDL) at the CEJ (Figure 6.3.2). The length of a straight line between the mesial and distal extremities of the CEJ gave the MDL. The length of a straight line measured at a right angle to the MDL from the mesial and distal extremities to the top of the molar crown gave the mesial crown height (MCH) and distal crown height (DCH). CI was measured on the buccal side of each permanent mandibular molar and lingual side of each permanent maxillary molars following the equation:

$$\mathrm{CI} = \frac{(\mathrm{MCH} + \mathrm{DCH})/2}{\mathrm{MDL}} \times 100$$

CI measurements were taken from the digital photographs, measured in pixels, using ImageJ (Ferreira and Rasband 2012). No photographic scale was required as the index depicts crown height in relation to tooth width. In order to produce accurate measurements using a photographic scale it must be be placed at the same level as the tooth surface. Placing a scale would have been difficult due to the small and undulating surfaces of permanent molars, and may have introduced additional errors into the CI measurement.

6.3.2.1 Camera set-up: Crown index (CI)

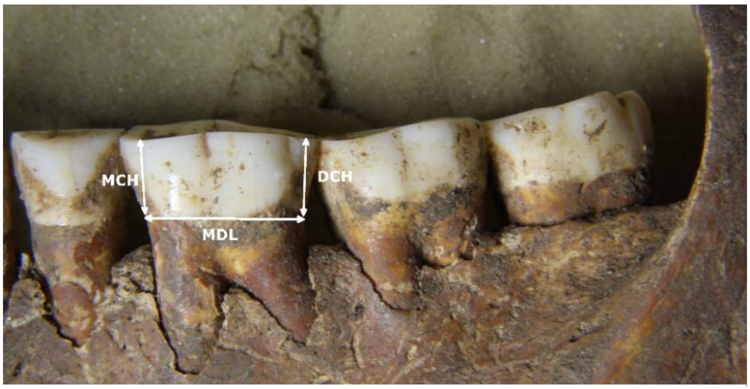


Figure 6.3.2. Crown index (CI) measurements. See text for full description.

Digital photographs were taken using a Canon 1200D camera, equipped with two macro diopters (filters) of 4x and 10x magnification. The camera was set with autofocus, a metering mode with aperture priority, an aperture of f22, and a sensor sensitivity set to 100, following Ahmad (2009a-f). This set-up produced high quality, close-up photographs of molars allowing measurements to be taken easily.

A single photograph was taken for each set of molars. Additional photographs were taken if a tooth was rotated in its socket and a complete view of the surface was not visible within the single photo. Molars were photographed in their sockets unless there was damage to the jaw and molars could not be placed in their socket. Loose molars were placed in anatomical position in a sand bath. The lingual surface of the maxillary molars and the buccal surface of the mandibular molars were orientated perpendicular to the camera lens, with the occlusal surface sitting horizontally (Figure 6.3.3).

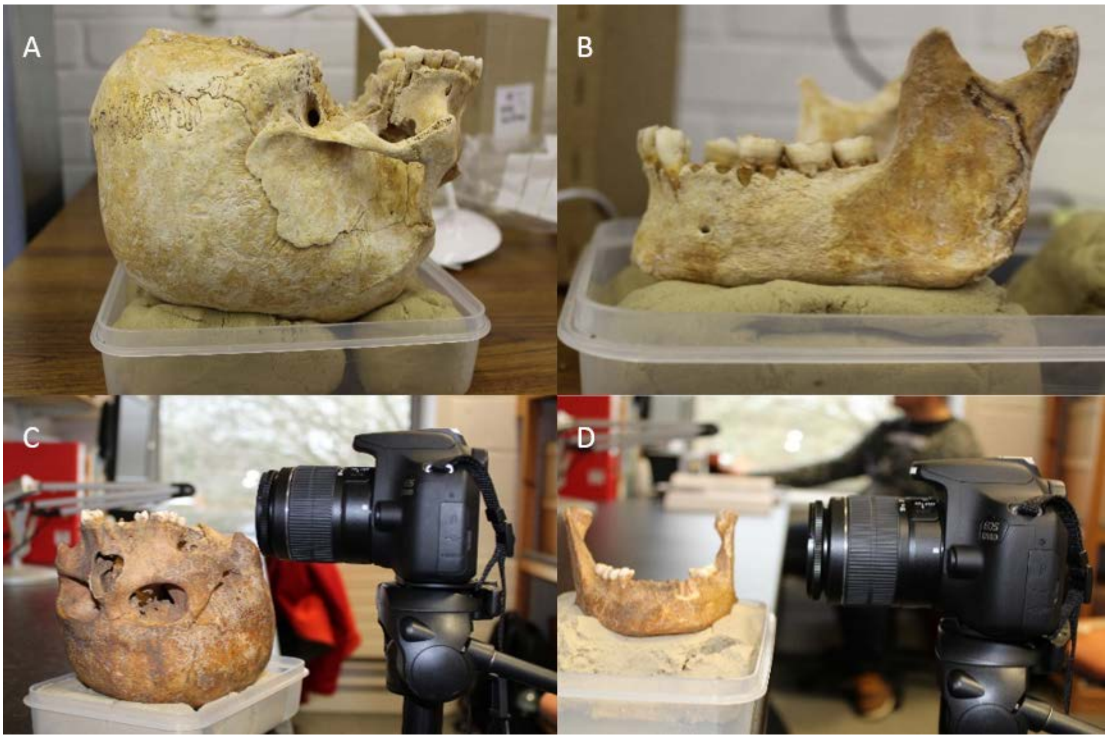


Figure 6.3.3. Camera set up for measuring crown index (CI). Ideal positioning of A. skull (A.) and B. mandible, and camera position relative to C. skull and D. mandible for measuring CI.

6.3.2.2 Methods test: Crown Index (CI)

A sample of Anglo-Saxon individuals from the site of Great Chesterford (n=20) was used to test the reliability of CI.

The first test of reliability calculated the measurement error when taking two independent measurements made by the same observer from one set of photographs. This tested the intra-observer reliability for recording CI. The two independent measurements produced a sample variance of 3-8% (Table 6.3.2), indicating that CI was able to produce reliable measurements.

Table 6.3.2. Repeatability results for measuring CI from the same set of photographs.

CI	Sm	S	R	%
LMaxM1	3.676	14.045	0.069	6.9
LMaxM2	4.778	16.984	0.069	6.9
LMaxM3	4.066	14.542	0.078	7.8
RMaxM1	3.859	19.599	0.039	3.9
RMaxM2	2.374	10.435	0.052	5.2
RMaxM3	3.804	13.772	0.076	7.6
LManM1	2.494	9.489	0.069	6.9
LManM2	1.895	11.852	0.026	2.6
LManM3	5.105	21.624	0.056	5.6
RManM1	1.690	7.202	0.055	5.5
RManM2	2.527	9.856	0.066	6.6
RManM3	3.393	12.787	0.070	7.0

Sm, method error statistic
S, Sample standard deviation
R, sample variance
%, sample variance expressed as a percentage of total variance
L, left. R, right
Max, maxillary molar. Man, mandibular molar
M1, first molar. M2, second molar. M3, third molar

A second test of reliability calculated the measurement error when the dentition for the same sample was repositioned and re-photographed to test the reliability of the camera set up. This included an additional step to test the effect of the camera angle for the maxillary molars. The lingual surface of the maxillary molars can be difficult to photograph in individuals with complete crania as the opposing tooth row can obscure the surface. The camera may be angled slightly to get a complete view of the lingual surface to overcome this issue. Therefore, a reliability test was required to examine the effect of a change in camera angle from the ‘ideal’ population, i.e. perpendicular to the camera lens.

A sample of complete crania (n= 20) was placed in the 'ideal' position, with the occlusal surface facing up and the crania made level across both sets of molars (Figure 6.3.3). The camera was placed in the 'ideal' position to the lingual surface of the maxillary molars. A digital spirit level (Aleksei 2016) was placed on the camera lens to ensure it was level, producing an angle of 0˚. The camera lens was then adjusted by five degrees in a downwards direction, producing an angle of -5^{o} between the tooth surface and camera lens. At -15^{o} the camera was not perpendicular to the tooth surface, therefore not achieving an 'ideal position'.

Table 6.3.3 shows an increase in measurement error with an increase in angle, indicating a larger measurement error occurs when the camera is not in the 'idea' position for measuring CI in the maxillary molars. These results suggest the camera should only be adjusted when necessary, e.g. when the maxillary molar lingual surface is completely obscured, keeping the angle as small as possible. It was not necessary to perform a camera angle test for the mandibular molars. Producing the 'ideal' position for measuring CI in mandibular molars was simple, as the opposing tooth row does not obscure the buccal surface.

Table 6.3.3. TEM results to show the degree of measurement error between an ideally positioned and angled camera lens.

Camera Angle	N	Sm	S	R	%
LMax 0° vs -5°	49	3.902	17.355	0.051	5.05
RMax 0° vs -5°	45	3.753	13.492	0.077	7.74
LMax 0° vs -10°	49	4.876	15.228	0.103	10.25
RMax 0° vs -10°	45	4.137	13.492	0.094	9.40
LMax 0° vs -15°	49	5.555	15.228	0.133	13.31
RMax 0° vs -15°	45	4.952	13.492	0.135	13.47

Sm, method error statistic
S, Sample standard deviation
R, sample variance
%, sample variance expressed as a percentage of total variance
L, left. R, right
Max, maxillary molar. Man, mandibular molar

The reliability of taking two independent measurements from two sets of photographs was examined to assess the reliability of measuring CI between two independent recording events made by the same observer. A sample (n=20) of the Anglo-Saxon site of Great Chesterford was selected and re-photographed after the initial recording attempt, for both maxillary and mandibular molars. This sample followed the above 'ideal' camera set-up recommendations (Figure 6.3.3). 5-7% of the sample variance was made up of measurement error for upper and lower molars (Table 6.3.4), suggesting that CI measurement can be recorded reliably.

Table 6.3.4. Repeatability of results crown index measurements between two independent recording events.

Tooth	N	Sm	S	R	%
LMaxM1	17	3.279	14.455	0.051	5.14
LMaxM2	16	3.224	14.060	0.053	5.26
LMaxM3	7	3.697	16.879	0.048	4.80
RMaxM1	14	3.368	18.863	0.032	3.19
RMaxM2	11	2.551	10.256	0.062	6.19
RMaxM3	7	3.640	15.529	0.055	5.49
LManM1	16	2.254	10.567	0.045	4.55
LManM2	14	2.751	10.745	0.066	6.56
LManM3	9	3.076	12.644	0.059	5.92
RManM1	17	2.192	8.464	0.067	6.71
RManM2	17	2.684	10.168	0.070	6.97
RManM3	8	2.985	12.531	0.057	5.68

Sm, method error statistic
S, Sample standard deviation
R, sample variance
%, sample variance expressed as a percentage of total variance
L, left. R, right
Max, maxillary molar. Man, mandibular molar
M1, first molar. M2, second molar. M3, third molar

6.3.3 Percentage of Dentine Exposure (%DE)

Percentage of exposed dentine (%DE) was measured following Clement and Freyne (2012). Digital photographs of the occlusal surface of the maxillary and mandibular molars were taken and two measurements recorded using ImageJ (Ferreira and Rasband 2012). The occlusal area was measured by drawing a line around the occlusal surface of each tooth. ImageJ determined the area of the occlusal surface by counting the number of pixels within this perimeter (Figure 6.3.4).

Each area of exposed dentine on a single tooth was measured in the same way and all areas summed, giving the total area of exposed dentine. %DE was calculated by dividing the summed area of dentine exposure by the area of the occlusal surface (Clement and Freyne 2012). It was decided to express this value as a percentage, following Mays and Pett (2014), for easy interpretation.

6.3.3.1 Camera Set-Up: Percent of exposed dentine (%DE)

The same camera settings used for CI measurements were applied to measure %DE. Each jaw or cranium was placed in a sand bath with the occlusal surface in a horizontal position, i.e. facing up, with the camera lens in a vertical position to obtain clear images of the occlusal surface (Figure 6.3.5). Molars were photographed in their sockets or, if loose, in a sand bath.

Figure 6.3.4.Percent of exposed dentine (%DE) measurements. The dashed line represents the outline of the occlusal surface and the areas of exposed dentine are shaded in black.

6.3.3.2 Methods test: Percent of exposed dentine (%DE)

Two aspects of the method were tested for error when measuring percent of exposed dentine (%DE). The first examined the reliability of measuring %DE between two recording attempts using the same set of photographs. This approach tested the ability of a single observer to reliability identify the occlusal and dentine areas. The second evaluated the reliability of measuring %DE between independent recording events, once the dentitions had been repositioned.

Figure 6.3.5. Ideal positions for camera set when recording percent of dentine exposure (%DE) for the A & B. maxillary molars and C & D. mandibular molars.

An Anglo-Saxon sample (n=57) was used to test the reliability of measuring dentine proportion between two recording attempts using the same set of photographs. 0-6% of sample variance was made up of measurement error for both maxillary and mandibular molars (Table 6.3.5), indicating a high degree of reliability when measuring dentine proportions. However, the original error measurement for the left maxillary first molar (LMaxM1) was relatively high at 16%. Reviewing the %DE measurements identified a large error for individual Gr. 93. The first recording attempt recorded a proportion of 22% of exposed dentine on the LMaxM1, and a %DE of 93% in the second recording attempt. This equates to a 71% difference in exposed dentine between recording events. Re-examination of Gr. 93 LMaxM1 showed areas covered by thin enamel had been recorded as exposed dentine. Re-measuring the molar produced a %DE of 21%, decreasing the sample variance to 2% between the original recording event and the corrected event (Table 6.3.5).

Table 6.3.5. Proportion of exposed dentine (%DE) testing the reliability for recording %DE on mandibular and maxillary molars using the same set of photographs.

	n	*Sm*	*S*	*R*	*%*
LMaxM1	30	3.151	24.337	0.016	1.7
LMaxM2	21	0.816	18.241	0.002	0.2
LMaxM3	9	0.359	3.937	0.008	0.8
RMaxM1	27	3.561	19.651	0.033	3.3
RMaxM2	18	2.763	15.768	0.031	3.1
RMaxM3	4	-	-	-	-
LManM1	30	1.925	13.497	0.020	2.0
LManM2	23	0.861	15.758	0.003	0.3
LManM3	16	0.848	14.364	0.003	0.3
RManM1	30	1.512	19.923	0.006	0.6
RManM2	24	1.222	24.685	0.002	0.2
RManM3	17	0.564	16.076	0.001	0.1

Sm, method error statistic
S, Sample standard deviation
R, sample variance
%, sample variance expressed as a percentage of total variance
L, left. R, right
Max, maxillary molar. Man, mandibular molar
M1, first molar. M2, second molar. M3, third molar

The low TEM values in Table 6.3.5 indicates the method for measuring the proportion of exposed dentine on the occlusal surface was reliable for all molars. However, care must taken to identify molars with thin layers of enamel present. When examining a molar, it is usually easy to identify whether a dentine area is exposed or whether there is an enamel layer present. Photographs do not always capture this distinction, as seen in individual Gr. 93.

It could be argued that the tooth under study should be directly observable to accurately measure exposed dentine proportions, i.e. to record measurements on site with the remains in-hand. This, however, increases the time required to measure large sample sizes as photographs must be taken and uploaded before any measurements are taken. To test whether this was a necessary step a TEM test was performed between measurements of exposed dentine when the tooth was directly observable and again when the tooth was not present. A sub-sample of adults from Great Chesterford (n=10) and sub-sample of juvenile individuals from Butler's Field (LBF n=15) was employed for this methods test. This sample allowed molars with high and low levels of dental wear to be observed. Approximately 2-3% of sample variance was found likely to be made up of measurement error (Table 6.3.6). This indicates that although layers of thin enamel may be problematic in individual cases, it was not a consistent problem across a sample.

Table 6.3.6. Reliability results for recording the calculated proportion of dentine exposure (%DE) when a tooth is directly observable compared to when it is not using two samples: Great Chesterford and Butler's Field.

Sample	*Sm*	*S*	*R*	*%*
Great Chesterford	1.288	10.056	0.016	1.6
Butler's Field	0.126	0.720	0.031	3.1

Sm, method error statistic
S, Sample standard deviation
R, sample variance
%, sample variance expressed as a percentage of total variance

There are two explanations for the low measurement error in Table 6.3.6. The camera, with additional magnification filters, produced high-quality images facilitating identification of exposed dentine. Alternatively, the test sample may not have included any individuals with thin layers of enamel over dentine. Therefore, it was proposed that individuals displaying thin layers of enamel would have %DE measured on site, with the molar directly observable. The remaining specimens would be measured off-site. This approach allows accurate assessment of problematic specimens while keeping recording time to a minimum.

The use of an ordinal scale alongside recording dentine exposed is also advised. An ordinal scale records the pattern of exposed dentine when a specimen is in-hand, providing a guide for measuring dentine exposure. For example, Figure 6.3.6 shows a potential area of exposed dentine when viewed in a photograph. However, a wear stage with no exposed dentine was assigned when using the ordinal scale and indicates to the observer that no measurement of %DE should be made (Table 6.3.8). Therefore, applying the ordinal scale alongside recording areas of exposed dentine is helpful for identifying areas of thin enamel.

Figure 6.3.6. Gr. 66 right maxillary third molar demonstrating difficulty of identifying dentine exposure in molars with a thin layer of enamel. Photograph indicates possible area of exposed dentine but was assigned Wear Stage 3 (no dentine exposure, flattened cusps), indicating minimal dentine exposure.

The reliability of recording dentine proportion between two recording events after repositioning of the specimens was also tested. A sample of Anglo-Saxon molars was re-positioned, re-photographed and the proportion of exposed dentine measured. The molars were grouped in mouth quadrants for two reasons; the first being to increase sample size and secondly, the focus of this test was to establish whether variation of measurements occurred between two sets of photographs (not the ability to measure a particular tooth). The TEM results indicate a high reliability for measuring exposed dentine, with under 2% of sample variance being made up of measurement error (Table 6.3.7).

Table 6.3.7. Proportion of exposed dentine (%DE) testing the reliability for recording the %DE on repositioned maxillary and mandibular molars.

Tooth	n	Sm	S	R	%
LMax	31	1.760	13.327	0.017	1.7
RMax	23	1.944	15.563	0.016	1.6
LMan	40	1.448	14.776	0.010	1.0
RMan	36	1.111	15.959	0.005	0.5

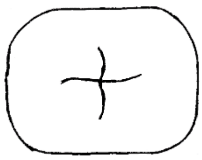
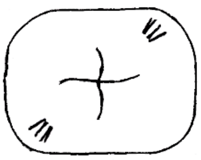
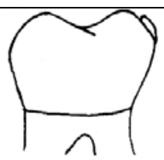
Sm, method error statistic
S, Sample standard deviation
R, sample variance
%, sample variance expressed as a percentage of total variance
L, left. R, right
Max, maxillary molar. Man, mandibular molar

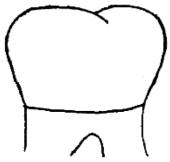
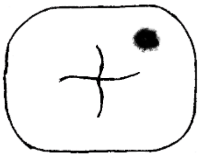
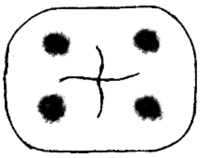
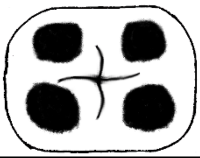
6.3.4 Ordinal Scale

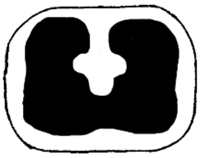
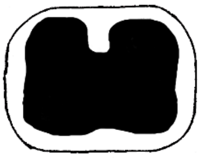
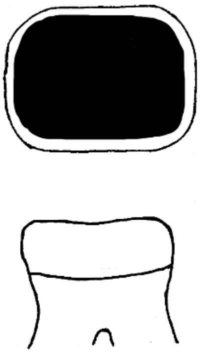
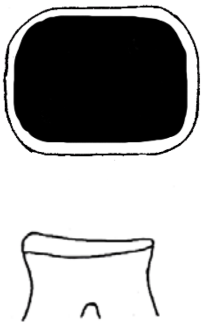
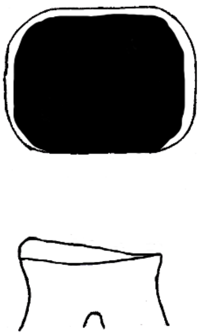
An ordinal scale was produced to assign stages of dental wear to each permanent molar. Table 6.3.8 provides descriptions and pictorial representation of each stage of wear. This single scale was applied to both maxillary and mandibular molars to reduce recording time. Previous studies identified a similar pattern of wear for both sets of molars (Murphy 1959a; Lovejoy 1985), supporting the use of a single ordinal scale. Following Brothwell (1963) the fifth mandibular cusp was excluded from the scale. The fifth cusp has been shown to coalesce early in the dental wear process (Miles 1962; Smith 1984), producing a simple, single wear scale that can be applied to all permanent molars.

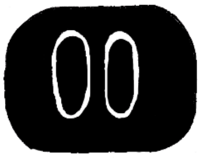
The ordinal scale produced for this study combined the wear stages of Brothwell (1963) with the diagrams and descriptions of Murphy (1959a). The addition of further stages allowed recording of enamel wear (before dentine exposure) and ante-mortem tooth loss (AMTL). Suggestions by Mays et al. (1995) were also included, such as the use of secondary dentine as a distinguishing feature between two stages. If a molar fell between two stages of wear the lower stage was selected following Bartlett et al. (2011 p.183). Stages 1 to 18 are a general progression of the dental wear process. Stages 19 and 20 capture information regarding ante-mortem tooth loss and are not necessarily a progression of the dental wear process as they may interrupt the earlier stages of wear. This approach captured the entire dental wear process while remaining comparable to the stages used by Brothwell (1963).

Table 6.3.8. Ordinal scale used to record dental wear

Wear Stage	Pictorial Diagram	Description
0		Tooth at occlusal level but no wear is visible
1		Enamel Faceting. Attrition is visible as tiny planes or facets that reflect light.
2		Enamel Rounding. The cusps of the molars are slightly rounded and have lost their peaks and angular faceting.

3		Enamel Flattening. The molar cusps are flattened but there is no dentine exposure.
4		Dentine exposed on one cusp only.
5		Dentine exposed on two cusps.
6		Dentine exposed on three cusps.
7		Dentine exposed on four cusps, but the dentinal areas are discrete. These dentine areas consist of small points of exposure.
8		Dentine exposed on four cusps, but the dentinal areas are discrete. These dentine areas consist of differing amounts of exposure. Typically, two cusps have large areas of dentine exposure and two cusps have small areas of dentine exposure.
9		Dentine exposed on four cusps. These dentine areas consist of large points of exposure, which are equal in size, that are approaching coalescence but remain as discrete areas.
10		Two dentinal areas coalesced
11		Three dentinal areas coalesced

12		Four dentinal areas coalesced connected by small bridges of exposed dentine.
13		Four dentinal areas coalesced, leaving a small island of enamel
14		The total occlusal surface of the tooth has the dentine exposed, with an enamel rim remaining.
15		The total occlusal surface of the tooth has the dentine exposed, with an enamel rim remaining. This enamel rim low in height and close to reaching the cement-enamel junction. Secondary dentine is visible.
16		The total occlusal surface of the tooth has the dentine exposed. The crown height has nearly reached the cement enamel junction (CEJ) and secondary dentine is visible. An enamel rim is visible, although it is broken.

17		Wear has reached the root trunk. There is no enamel of the crown remaining.
18		Wear has extended past the tooth trunk. The individual roots are now separate from each other.
19		Ante-mortem tooth loss has occurred. The alveolar bone has started to remodel. The tooth socket is still visible.
20		Ante-mortem tooth loss has occurred. The alveolar bone completely remodelled and not tooth socket is visible.

6.3.4.1 Methods test: the ordinal scale

Terminology for the ordinal scale was evaluated before method testing occurred. The stages of Brothwell (1963, 1972b, 1981) and Murphy (1959a) were used as a starting point for the production of the ordinal scale. These charts, however do not have stages depicting wear specific to the enamel. A literature review identified three wear scales describing dental wear to the enamel, in advance of dentine exposure (Seligman et al. 1988; Fares et al. 2009; Dawson and Robson-Brown 2013). A preliminary review applied these scales to an Anglo-Saxon sample (n=24) to assess their usability. The descriptions of Dawson and Robson-Brown (2013) were determined to be the most suitable due to ease of use and clarity. The descriptions of Seligman et al. (1988) were less informative compared with the Dawson and Robson-Brown (2013) scale. For example, Seligman et al. (1988 p.1323) use the term “slight” to describe minimal enamel wear, while Dawson and Robson-Brown (2013 p.436) detail ‘Enamel faceting’ as “tiny planes or facets which reflect the light.” The descriptions of Fares et al. (2009 p.120) employ specific quantities of enamel wear, such as “less than 10%,” to distinguish between enamel wear stages. This approach allows to a greater degree of subjective interpretation compared with the Dawson and Robson-Brown (2013) scale.

A method test of the ordinal scale was performed to evaluate its suitability and reliability using a linear weighted Cohen's Kappa test. The molars of 24 individuals from the Great Chesterford sample were selected at random and re-measured by the same observer.

Linear weighted Cohen's Kappa measures the agreement between two observations, compared with how much agreement would be expected to be present by chance alone (Viera and Garrett 2005). A linear weighted Cohen's Kappa was preferred over an unweighted kappa. A weighted kappa penalises any disagreements in terms of their seriousness, compared with an unweighted kappa that treats all disagreements equally (Sim and Wright 2005; Vanbelle and Albert 2009). It was decided to apply a weighted kappa as the dental wear ordinal scale consists of ordered categories (a tooth must have passed through the lower stages of wear before reaching the higher stages). A linear weighting, rather than a quadratic weighting, was chosen as it is less sensitive when using a large number of categories (Brenner and Kliebsch 1996). A low kappa value (i.e. close to 0) indicates low agreement between recording attempts, while a kappa value close to 1 indicates a high agreement (Brennan and Silman 1992).

The ordinal scale had a linear weighted kappa value of 0.95, indicating it was reliable for assigning wear stages between recording attempts. Appendix B provides the formula and raw outputs for the linear kappa statistic for testing the reliability of the ordinal scale between recording attempts.

6.4 Analysis employed

This section describes the analysis undertaken during the current study. Each statistical test is described below, presented in alphabetical order. The research questions outlined in Chapter 1 with their associated hypothesises are then provided. Finally, Table 6.4.1 details the analyses run to answer each of the research questions.

All tests were performed using either SPSS (IBM 2016) or GraphPad Prism (Graphpad 2017). Each stated null hypothesis (H_0) was rejected at the traditionally accepted alpha level of 0.05, and the alternative hypothesis (H_1) provided. Corrections were made for controlling the false discovery rate due to the high number of pair-wise comparisons produced during the analysis.

6.4.1 Statistical tests

Analysis of Covariance (ANCOVA)

It is possible to compare the equality of regression equations calculated for two or more populations using an approach equivalent approach to an analysis of covariance (Zar 2009). This test effectively tests whether the slopes from multiple regressions are parallel. If the slopes of the compared lines are not significantly different it is possible to test whether the y-intercepts between samples are similar. In effect, this test compares the constants α and β in the linear equation $Y=\alpha + \beta X$ between populations for any significant difference.

The hypothesis regarding equality of slopes is tested first:

H_0: there is no significant difference in slopes between temporal samples

H_1: there is a significant difference in slopes between temporal samples

If there is no significant between the slopes the null hypothesis is accepted and a comparison of y-intercepts is performed, where:

H_0: there is no significant difference in y-intercepts between samples

H_1: there is a significant difference in y-intercepts between samples

If there is a significant difference between either the slopes or the y-intercepts a series of pairwise comparisons are made to determine which groups differ from one another. Adjustment for multiple comparisons was made using the Bonferroni correction.

An ANCOVA consists of at least one categorical independent variable and at least one ratio independent variable.

Benjamini-Hochberg procedure

Any time a null hypothesis is rejected based on the p-value falling below the critical value there is a chance that the null hypothesis may really be true and the significant result is due to chance (McDonald 2009). For example, if 100 statistical tests are performed and all null hypothesises found to be true at the $p<0.05$ level approximately five tests will be significant due to chance. These are false positives. A false positive is a result that wrongly indicates the presence of a condition, otherwise known as a Type I error (Vogt 2011). Therefore, false positive results are possible when performing multiple statistical tests. This thesis uses the Benjamini-Hochberg procedure, which, controls for this false discovery rate, in place of the highly conservative Bonferroni correction (Nakagawa 2004).

Following the Benjamini-Hochberg procedure p-values within a family of tests were sorted and ranked (Benjamini and Hochberg 1995; McDonald 2009). The smallest p-value received rank 1, the second rank 2, etc. Each p-value is multiplied by the total number of tests and divided by its assigned rank, producing adjusted p-values. All the adjusted p-values below the chosen critical value are deemed to be significant, and reject the null hypothesis. A family of tests was defined as an entire collection of comparisons performed throughout this thesis organised by type of statistical test.

There are no comparable studies that use Benjamini-Hochberg procedure, however studies examining dental microwear and tooth employ a critical value between 0.5 and 0.25 (Krueger et al. 2017; Purnell et al. 2017; Yamada and Tagaya 2018). This thesis uses a critical value of 0.05 following Benjamini and Hochberg (1995). An increase in critical value made little difference to the number of false discoveries identified in this thesis. Appendix C provides the adjusted p-values for this study. P-values identified as false discoveries according to the Benjamini-Hochberg procedure were identified in-text.

The Benjamini-Hochberg procedure can be applied to both ratio and ordinal data.

<u>Box and Whisker plot</u>

Each box represents the inter-quartile range (IQR), i.e. the middle 50% of scores within a sample. The ends of each box represent the upper and lower quartile values. The line within the box represenst the median and the whiskers the overall range of values. Outliers are represented by circle and asterisk symbols and indicate values that are separated from the upper or lower quartiles by 1.5 (circle) or 3 (asterisk) times the length of the IQR. Figure 6.4.1 provides an explanatory diagram of a box and whisker plot.

Box and whisker plots can display a summary for both ratio and ordinal data. Categorical data can be applied to compare data distributions across groups.

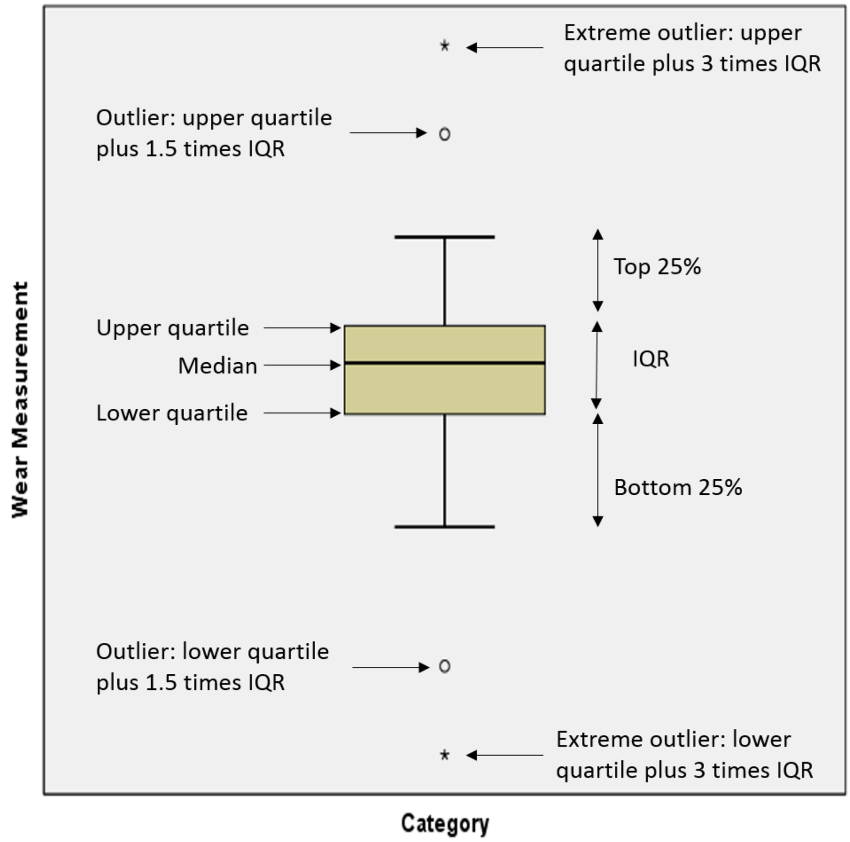


Figure 6.4.1. Explanatory diagram for box and whisker plot

Chi-square test of independence

The Chi-square test' for independence is used to explore the relationship between two categorical variables. It is used to determine whether there is a significant association between the two variables.

Independent T-test

The independent T-Test is used to compare the mean scores of two different groups by comparing the values of some continuous variable (Zar 2009; Salkind 2010). Normality was checked using a Shaprio-Wilk test and examination of Q-Q plots to ensure the assumptions of this parametric test were met. A Levene’s test tested the equality of variance within SPSS. A Levene’s test examines whether the groups included in the independent t-test have equality of variances.

In an independent T-Test, the dependent variable is measured on a continuous scale, while the independent variable consists of two categorical, independent groups.

Kruskal-Wallis test

This test is a rank-based non-parametric alternative to the one-way analysis of variance. The test determines whether the medians of two or more groups are significantly different. As a non-parametric test, scores are converted to ranks and the median rank compared.

The dependent variable in a Kruskal-Wallis test can consist of ordinal data or continuous data that does not have a normal distribution. The independent variable should consist of three or more categorical groups.

Mann-Whitney test

The Mann-Whitney test is a non-parametric equivalent to the independent T-Test. This test was employed for data that did not have a normal distribution; this includes data measured on an ordinal scale (Vogt 2011). Rather than comparing means, the Mann-Whitney test compares the median values of two groups and converts the scores into ranks. These ranks are compared to determine if the values for the two groups differ significantly.

One-way Analysis of variance (ANOVA)

This test is used where an independent variable has three or more groups and allows comparison between groups of a dependent continuous variable. This test will inform the user if there is significance between the groups, but not where the significance falls. Therefore, a post hoc test needs to be performed to determine between which groups the difference lies. Each sample is compared to one another in a series of pairwise comparisons. Adjustment for multiple comparisons was made using the Bonferroni correction.

Pearson’s correlation coefficient (r)

The Pearson correlation coefficient is a measure of the strength of a relationship between two continuous variables and tests whether this relationship is significant. The Pearson correlation coefficient (r) ranges in value from -1 to +1. A r value close to 1 indicates a very strong relationship between the variables, while a r value of 0 indicates no relationship. A positive correlation coefficient indicates that as one variable increases, so does the second variable. A negative correlation coefficient indicates an increase in one variable was associated with a decrease in the second variable. A correlation between two variables does not mean that there is a causal relationship between them, only that there is an association.

Polynomial regression analysis

Polynomial regression investigates whether a relationship exists between two continuous variables and whether this relationship is linear or non-linear. Regression analysis determines the line of best fit using the concept of least squares to minimise the vertical distance between the line and the data points. Least squares regression considers the vertical deviation of each data point from the line and defines the line of best fit as that which results in the smallest values for the sum of the squares of these vertical deviations (Zar 2009).

Polynomial regression analysis is a sequential analysis. A linear regression is first evaluated and then a quadratic term added. It was assessed whether the added term was justified and whether it provided a significant improvement over the linear model. Subsequent terms were added and evaluated until a model that best explained the data was identified. A significant change in the *F* statistic ($p<0.05$) indicated a significant improvement in the model with the addition of a power term.

The simplest functional relationship between one variable and another in a population is a simple linear regression. The equation of a straight line is given by the equation: $Y= \alpha + \beta X$, where Y is the dependent variable (wear measurement), X is the dependent variable (age), α is the y-intercept and β is the slope of the line. Both α and β are constants. A polynomial equation has X raised to integer powers so: $Y= \alpha + \beta_1 X + \beta_2 X^2 \ldots \beta_{nx}{}^n$ (McDonald 2009; Zar 2009). Before performing regression analysis normality was checked using a Shaprio-Wilk test and examination of Q-Q plots.

Shapiro-Wilks test

The Shapiro-Wilks test examined whether the sample data had been drawn from a normal distribution, and was therefore used to check for normality. If this test indicated the data came from a normally distributed population a parametric test could be used. If not, a non-parametric equivalent would be applied.

Spearman's rank correlation (r_s)

The Spearman's rank correlation is the non-parametric alternative to a Pearson's correlation coefficient. Spearman's rank was applied when using two ranked variables, or one ranked and one measurement variable, and the data did not have a normal distribution. This statistic shows the degree of monotonic relationship, where an increase in one variable always results in an increase or decrease in another, between two ranked variables (Vogt 2011).

A Spearman's rank correlation is applied when testing the association between two variables, at least one of which consists of ordinal data.

6.4.2 Research Questions

Research Question 1: do molars of the same type wear at a similar rate?

A. H_0: left and right molar partners wear at a similar rate
   H_1: left and right molar partners do not wear at a similar rate
B. H_0: occlusal partners wear at a similar rate
   H_1: occlusal partners do not wear at a similar rate

Research Question 2: do all molar types have a similar rate of wear?

A. H_0: there is a similar rate of wear between molar types
   H_1: there is a different rate of wear between molar types

A further question was proposed: if molars wore a different rate, does the rate of wear between molars remain constant relative to one another?

B. H_0: the rate of wear between molars remain constant
   H_1: the rate of wear between molars do not remain constant

Research Question 3: how strongly is dental wear associated with age?

A. H_0: there is a relationship between dental wear and juvenile age
   H_1: there is no relationship between dental wear and juvenile age
B. H_0: there is a relationship between dental wear and bony age estimates
   H_1: there is no relationship between dental wear and bony age estimates

Research Question 4: do populations dating from the British Neolithic to Post-Medieval archaeological periods have a similar rate of wear?

A. H_0: there is no significant difference in ante-mortem tooth loss frequency between temporal samples
   H_1: there is a significant difference in ante-mortem tooth loss frequency between temporal samples
B. H_0: Ante -mortem tooth loss frequency occurs at a similar age in all temporal samples

H_1: Ante-mortem tooth loss frequency does not occur at a similar age in all temporal samples

C. H_0: Ante-mortem tooth loss does not have any effect on dental wear

   H_1: Ante-mortem tooth loss does have any effect on dental wear

D. H_0: Populations dating from the British Neolithic to Post-Medieval periods do not have similar dental wear distributions

   H_1: Populations dating from the British Neolithic to Post-Medieval periods have similar dental wear distributions

E. H_0: Populations dating from the British Neolithic to Post-Medieval periods have similar juvenile dental wear rates

   H_1: Populations dating from the British Neolithic to Post-Medieval periods do not have similar juvenile dental wear rates

F. H_0: Populations dating from the British Neolithic to Post-Medieval periods have similar adult dental wear rates

   H_1: Populations dating from the British Neolithic to Post-Medieval periods do not have similar adult dental wear rates

Table 6.4.1 Data used and analysis undertaken by research question

Research Question	**Data Used**	**Analysis undertaken**
Research Question 1: Do molars of the same type wear at a similar rate?	Wear measurements: CH, CI, %DE, WS Molar types: All Max, Man, Left, Right Temporal samples: Sub-sample of each pooled	Pearson's correlation coefficient Spearman's correlation coefficient Shapiro-Wilks test Independent T-test Mann-Whitney test Two scatter plots illustrated the relationship between occlusal and left-right pairs. The first plotted wear measurements taken for molar pairs against one another, for example plotting the left first mandibular molars against the right first mandibular molar. A line of absolute symmetry, where y=1, was also plotted. It was expected that data points would fall closely around line of symmetry if two molars within a pair wore at a similar rate. The second plot showed the wear difference between two molar partners (y-axis) against wear measurements on one molar within a pair (x-axis). For example, the difference in wear measurement between the left and right first mandibular molars was plotted against the wear measurement on the left first mandibular molar. The difference in wear measurement was expected to remain constant if two molars within a pair wore at a similar rate. This analysis compared molar pairs within the same dentition, e.g. a specific skeleton's LMaxM1 vs RManM1 and MaxM2 vs ManM2.

Table 6.10 (continued). Data used and analysis undertaken by research question		
Research Question	**Data Used**	**Analysis undertaken**
Research Question 2: do all molar types have a similar rate of wear?	Wear measurements: CH, CI, %DE, WS Molar types: LMan Temporal samples: All	Pearson's correlation Spearman's rank correlation Two scatter plots illustrated the wear relationship between molar types. The first scatter plot plotted the degree of wear of the earlier erupting molar (x-axis) against the degree of wear on the later erupting molar (y-axis). A line depicting the relationship expected if two molars wore at a similar rate was plotted, henceforth the line of similar wear. It is expected that points will fall on this line, with a slope of 1, if the two molars wore at a similar rate. If the points fell in a straight line with a slope other than one, this would suggest the two molars wore at a difference rate but this difference remained constant throughout life. The y-intercept of the line of similar wear is calculated as the difference in wear measurement between the two molars observed when the later molar within a pair erupts. A second scatter plot examined the wear difference between two molar regions (x-axis) against the earlier erupting molar wear measurement (y-axis). This analysis compared molar pairs within the same dentition, e.g. a specific skeleton's ManM1 vs ManM2. Analysis was repeated for each temporal sample.

Table 6.10 (continued). Data used and analysis undertaken by research question		
Research Question	**Data Used**	**Analysis undertaken**
Research Question 3: how strongly is dental wear associated with age?	Wear measurements: Hypothesis A: CH, CI, WS Hypothesis B: CH, CI, %DE, WS Molar types: Hypothesis A: LManM1, LManM2 Hypothesis B: All LMan Temporal samples: Hypothesis A: All Hypothesis B: Neo excluded	Polynomial regression analysis Pearson's correlation coefficient Spearman's rank correlation. Box and whisker diagrams examined wear measurement distributions associated with each age category as defined in Table 6.1.1. Analysis was repeated for each temporal sample.

Table 6.10 (continued). Data used and analysis undertaken by research question		
Research Question	**Data Used**	**Analysis undertaken**
Research Question 4: do populations dating from the British Neolithic to Post-Medieval archaeological periods have a similar rate of wear?	<u>Wear measurements</u>: CH, CI, %DE, WS <u>Molar types</u>: LManM1, LManM2, LManM3 <u>Temporal samples:</u> Hypothesis A: All Hypothesis B: Neo excluded Hypothesis C: All pooled Hypothesis D: All Hypothesis E: All Hypothesis F: All	Chi-square test of independence Independent T-Test Mann-Whitney test Analysis of covariance One-way analysis of variance Kruskal-Wallis test. Box and whisker diagrams showing wear measurement distributions by age category across period samples were also compared. Estimated wear rates following the Modified Miles Method (Gilmore and Grote 2012) for each period sample were produced and compared.

CH, average crown height. CI, crown index. %DE, percent of exposed dentine. WS, wear stage
L, left. R, right
Max, maxillary molar. Man, mandibular molar
M1, first molar. M2, second molar. M3, third molar

Chapter 7 Results

The choices made during the current analysis were dictated by the desire to develop skeletal ageing methods that are suited for commercial archaeologists. It was therefore decided to evaluate the under-lying principles of the most widely cited dental wear ageing methods. Such an approach intends to provide bioarchaeologists with confidence that the methods they choose to use are reliable.

This chapter analyses and visualises dental wear relationships by wear measurement in juveniles (6-17 years old) and adults (18+ years old) from temporal samples dating from the British Neolithic to the Post-Medieval period. The first section of this chapter examines the wear relationship between left-right, and occlusal molar pairs. Section 7.2 evaluates whether a single rate of wear can be applied to all molar types, or if independent wear rates are required. Section 7.3 analyses the strength of the relationship between dental wear in juvenile and adult individuals by temporal sample. The final section of this chapter compares wear rates across temporal samples.

Prior to evaluating dental wear relationships it must be established whether male and female molars wear at a similar rate. Some studies have identified a difference in wear rates between males and females (Molnar et al. 1983b; Berbesque et al. 2012; Masotti et al. 2017), while others have not (Kieser et al. 2001; Mays 2002). To ensure a single wear rate can be applied to an entire population the difference between males and females was examined.

Individuals with a relatively fast dental wear rate will show a greater wear difference between the first (ManM1) and second (ManM2) molars compared to individuals with a slower wear rate. This follows the logic that an individual with a fast wear rate will experience greater wear on their ManM1 before eruption of the ManM2, and therefore a greater difference in wear between the two molars. Thus, significant variation in mean difference between ManM1 and ManM2 wear in males and females indicates a variation in dental wear rates. Difference in mean wear measurement between males and females was compared using Independent T-Tests and Mann-Whitney tests. This analysis was repeated for the three wear measurements, average crown height (CH), crown index (CI), and wear stage (WS), by temporal sample. Percent of exposed dentine (%DE) was excluded from analysis as %DE difference between the ManM1 and ManM2

Table 7.1 Comparison of male and female mean difference between the first and second mandibular molars by temporal sample

		CH				CI				%DE				WS			
	Sex	n	mean difference	SD	p-value [a]	n	mean difference	SD	p-value [a]	n	mean difference	SD	p-value [b]	n	mean difference	SD	p-value [b]
Neolithic	M	13	-0.41	1.17	0.578	10	-7.25	9.60	0.907	6	14.79	13.85	0.302	12	3.3	1.5	0.883
	F	3	-0.80	0.22		3	-7.94	4.45		3	28.02	23.10		3	5.0	4.0	
Bronze Age	M	31	-0.44	0.43	0.596	28	-8.45	7.28	0.162	14	14.28	9.60	0.524	34	3.4	1.9	0.435
	F	9	-0.53	0.46		8	-4.65	3.02		4	20.93	17.92		11	2.8	1.5	
Iron Age	M	17	-0.28	0.58	0.510	15	-4.88	8.62	0.197	15	9.31	16.39	0.558	23	2.1	2.0	0.546
	F	18	-0.41	0.61		18	-1.71	4.96		17	7.61	11.38		20	2.4	2.3	
Romano-British	M	32	-0.46	0.75	0.273	31	-8.14	8.77	0.430	26	10.85	10.95	0.450	34	2.8	2.0	0.736
	F	14	-0.70	0.49		13	-10.31	6.82		9	15.84	15.31		14	2.8	1.5	
Anglo-Saxon	M	18	-0.37	0.67	0.910	18	-1.71	3.89	0.263	11	16.50	13.33	0.196	20	3.2	1.6	0.104
	F	24	-0.34	0.75		24	-3.72	7.39		17	12.46	12.12		24	2.2	2.0	
Medieval	M	15	-0.72	0.62	0.058	15	-7.00	11.91	0.599	13	14.50	11.19	0.277	16	2.3	2.3	0.955
	F	14	-0.21	0.76		14	-4.94	8.58		8	8.47	7.05		16	2.5	3.0	
Post-Medieval	M	16	-0.64	0.55	0.630	16	-8.74	9.65	0.536	8	7.16	9.07	0.307	16	2.4	2.1	0.797
	F	8	-0.15	0.66		7	-6.02	9.28		3	9.11	6.45		9	2.6	1.8	

a P-values given for independent t-test

b P-values given for iMann-Whitney test

Mean difference between first and second mandibular wear measurements by sex

SD: standard deviation

Sex: Male (M), Female (F)

Wear measurement: Waverage crown height (CH), crown index (CI), ear stage (WS), percent of exposed dentine (%DE) increased throughout the life of the dentition. The above analysis was not performed for the juvenile individuals due to the inability to reliably assign sex to juvenile remains.

Some variation in mean difference between the ManM1 and ManM2 wear was observed between males and females in all temporal samples. However, this difference was not significant, with p-values falling above the alpha level of 0.05 for both the independent T-Tests and Mann-Whitney tests (Table 7.1). This result held true for all wear measurements and all temporal samples indicating no significant variation in dental wear rates between males and females for the studied samples. Thus, wear on male and female molars may be pooled and the analysis from this point forward presents results for males and females combined.

7.1 Comparing molars of the same type

Previous studies have assessed the similarity of wear rates between antimere and occlusal partners (Section 4.2.1) . These approaches include the examination of correlation coefficients (Deter 2006), comparing the average difference (Clement 2008), or forming conclusions based on direct observation (Hojo 1954; Murphy 1959a). However, these methods are not precise and potentially hide differences between molar partners. This section aims to apply a more rigorous approach for assessing the similarity in wear rates between molar pairs through the application of multiple analysis.

Correlation coefficients between molar pairs measure the strength of the wear relationship. Scatter plots, plotting one molar against its partner (i.e. left vs. right, upper vs. lower), visualise the wear relationship between molar partners, with a line representing absolute symmetry (y=x). Data points falling on this line indicate identical wear measurements on two molars within a pair. This method reveals the similarity in wear measurements between two molars. However, it is not possible to determine if any observed differences are a result of a difference in wear rate or a difference in molar morphology. To overcome this, the difference in wear measurement between two molars is plotted against wear on one molar. For example, the difference in wear between the left (LManM1) and right (RManM1) mandibular molars (x-axis) is plotted against wear on the LManM1 (y-axis). This allowed for easy assessment of any differences in wear measurement. A wear difference between molar pairs that remained constant indicated a similar wear rate on both molars within a pair. Data points falling on the line y=0, henceforth the line of equality, indicates no difference in wear measurement between two molars. A constant difference in wear that did not sit on the line of equality indicated a difference in wear measurement between two molars that remained constant, but not a difference in wear rate. A wear difference that increased or decreased indicated a difference in wear rate on the two molars within a pair. See Figure 7.1.1 for a visual description of this relationship.

Independent T-Tests and Mann-Whitney tests compared the mean wear measurement between two molars, establishing if any observed differences were significant. A non-significant difference at the 5% alpha level supported a similar wear rate between molars pairs.

Analysis used a combined sub-sample of individuals taken from each temporal sample. This approach reduced the number of pairwise comparisons, thereby reducing the chance of a Type I error (i.e. chance of rejecting a true null hypothesis). Mean wear measurements were plotted by temporal sample to ensure pooling samples did not obscure any real differences between molar pairs. Analysis was repeated for each pair for each wear measurement: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

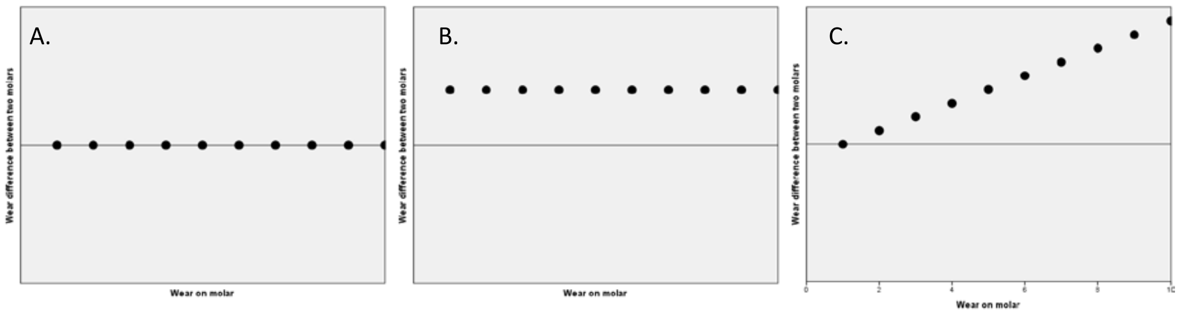


Table 7.1.1 Visual description for plots showing the difference in wear between two molars against wear on one molar

A. No difference in wear measurement between two molars, indicating a similar rate of wear.
B. A constant difference in wear measurement between two molars, indicates a similar wear rate.
C. Difference in wear measurement between two molars, indicates a difference in wear rate.

7.1.1 Comparing wear rates in left-right molar pairs

Null hypothesis: left and right molar partners wear at a similar rate

The analysis described in Section 7.1 was repeated for each antimere pair, by molar type.

Based on existing assumptions it was expected that:

- Molars within a left-right pair will have strong correlation coefficients
- The wear difference between molars within a left-right pair will be remain constant in relation to one another
- Molars within a left-right pair will show statistically similar measurements of dental wear

7.1.1.1 Comparing left and right first maxillary molar (MaxM1) wear

Average crown height (CH)

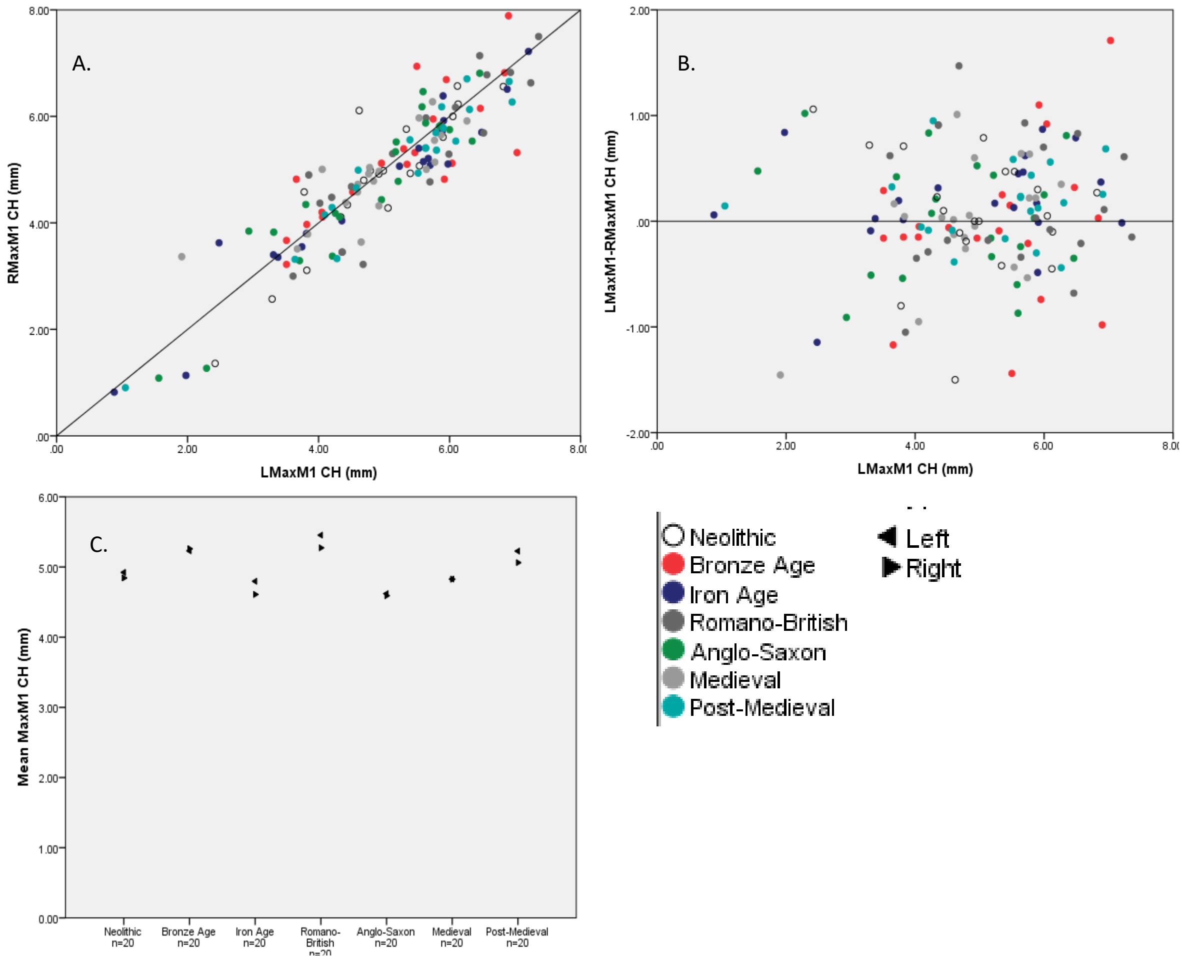


Figure 7.1.1. Plots of average crown height (CH) of the left first (LMaxM1) and right first (RMaxM1) maxillary molars

A. Scatter plot of LMaxM1 CH by RMaxM1 CH, with plotted line of absolute symmetry (y=x).
B. Scatter plot of CH difference between LMaxM1 and RMaxM1 against LMaxM1 CH, with plotted line of equality (y=0).
C. Plotted mean CH for LMaxM1 and RMaxM1, by temporal sample

A significant Pearson correlation coefficient supports a good association between maxillary left and right first molar CH measurements ($n=140$, $r=0.91$, $p<0.001$). Figure 7.1.1A. shows that, in general, the points for upper first molars clustered around the line of absolute symmetry. The points do not fall particularly heavily above or below the line, suggesting a relatively strong degree of symmetry. Figure 7.1.1B. shows points falling around the line of equality, indicating some difference in CH measurement between upper first left-right molar pairs. These differences, however, were not significant (Independent T-Test $t(278)=0.56$, $p=0.579$). Figure 7.1.1C. shows mean CH between left-right MaxM1s were not substantially different for any temporal sample. These results support a similar rate of wear, in terms of CH, between left and right MaxM1s.

Crown index (CI)

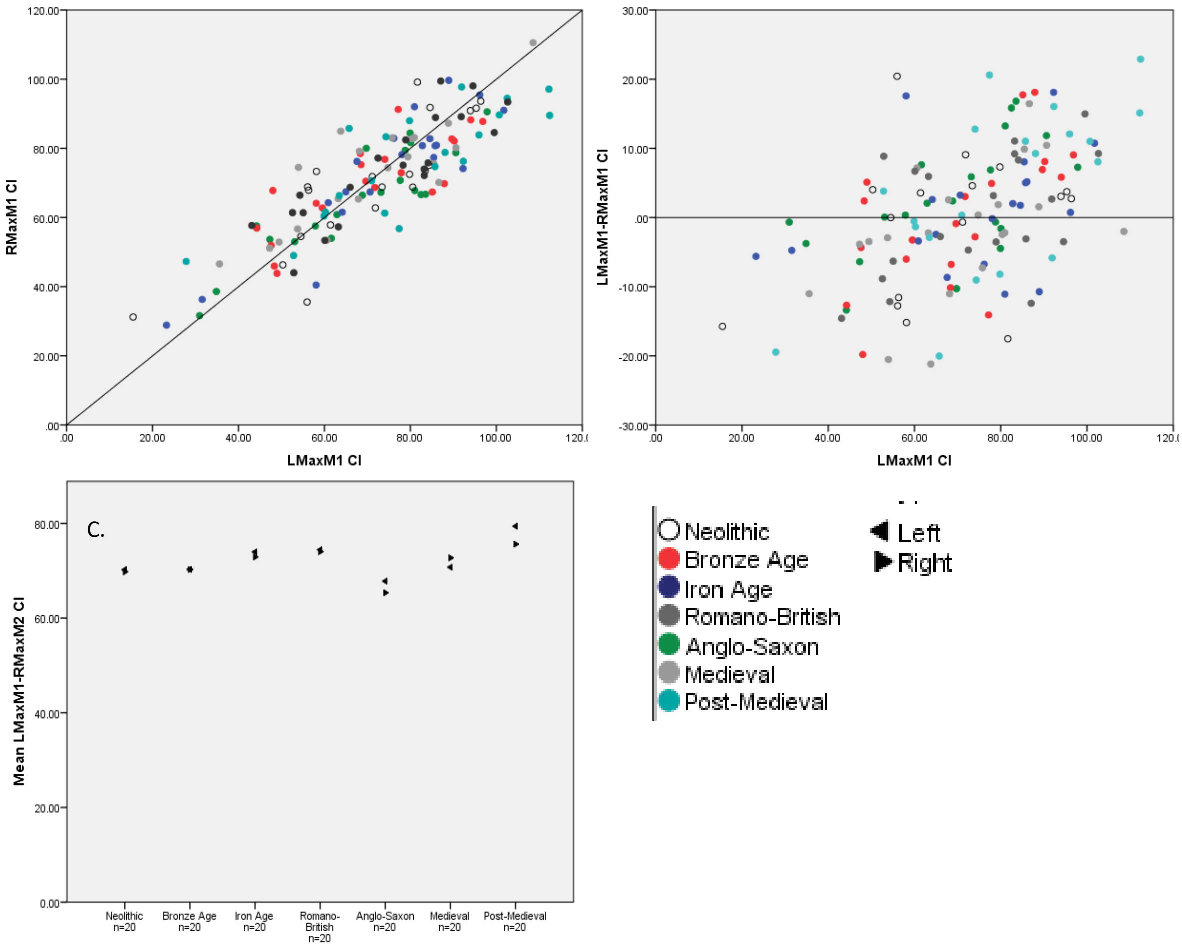


Figure 7.1.2. Plots of crown index (CI) of the left first (LMaxM1) and right first (RMaxM1) maxillary molars

A. Scatter plot of LMaxM1 CI by RMaxM1 CI, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CI difference between LMaxM1 and RMaxM1 against LMaxM1 CI, with plotted line of equality (y=0)
C. Plotted mean CI for LMaxM1 and RMaxM1, by temporal sample

A significant Pearson correlation coefficient supports an association in CI measurements between upper first left-right molars (n=140, r=0.86, p<0.001). The points in Figure 7.1.2A. fall around to the line of absolute symmetry. Figure 7.1.2B suggests some difference in CI between left-right MaxM1s, with points falling around the line of equality. These differences, again, were not significant (Independent T-Test t(278)=0.42, p=0.673). Figure 7.1.2C shows mean CI between left-right MaxM1s did not differ greatly for any temporal sample.

Percent of exposed dentine (%DE)

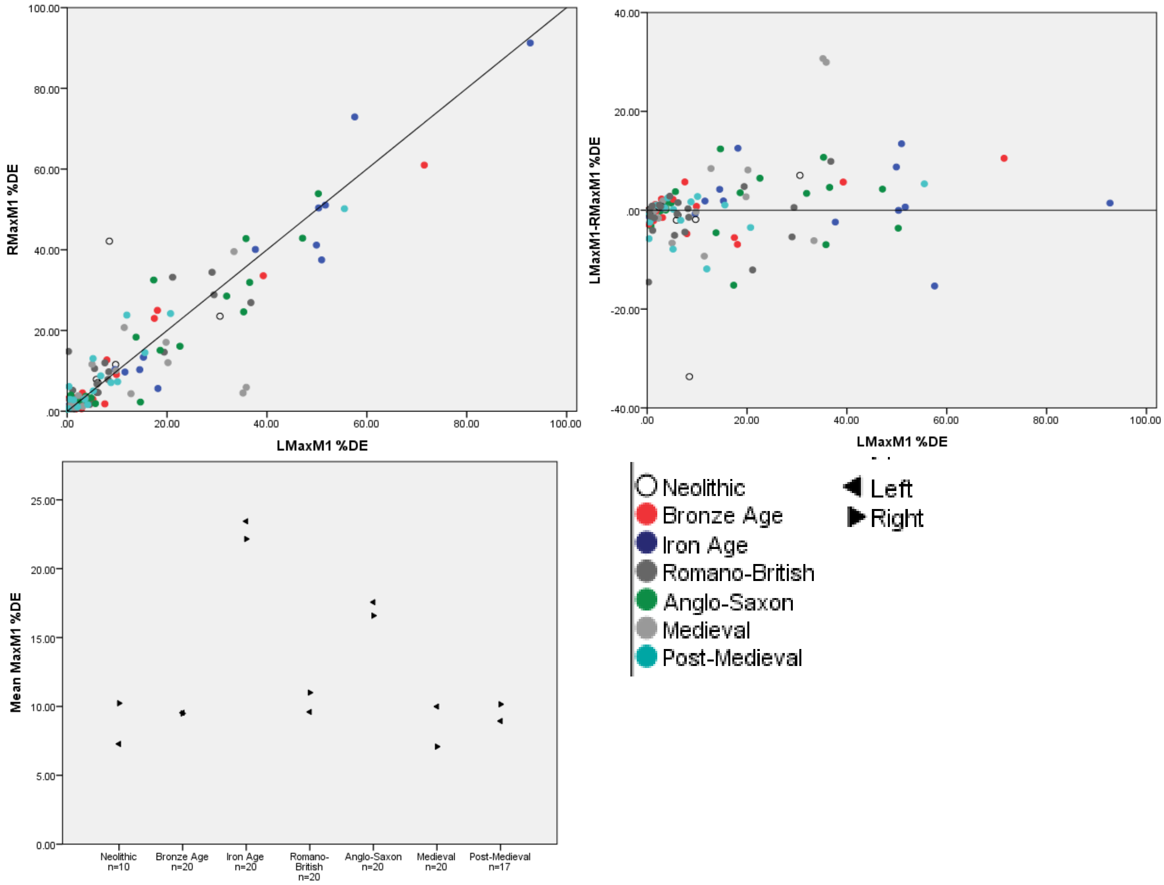


Figure 7.1.3. Plots of percent of dentine exposure (%DE) of the left first (LMaxM1) and right first (RMaxM1) maxillary molars

A. Scatter plot of LMaxM1 %DE by RMaxM1 %DE, with plotted line of absolute symmetry (y=x).

B. Scatter plot of %DE difference between LMaxM1 and RMaxM1 against LMaxM1 %DE, with plotted line of equality (y=0).

C. Plotted mean %DE for LMaxM1 and RMaxM1, by temporal sample

Figure 7.1.3A. shows that as one MaxM1 increased in %DE so did its antimere. A significant Spearman correlation coefficient supports this relationship (n=127, r_s=0.87, p<0.001). Points fell around the line of absolute symmetry, supporting a similar degree of wear between left and right MaxM1s. %DE difference between upper first left-right molars was minimal at low levels of wear. This difference increased at higher levels of wear, but remained constant (Figure 7.1.3B). The overall difference between left and right upper first molars was not significant (Mann-Whitney z=-0.23, p=0.817). Figure 7.1.3C shows mean %DE between left-right MaxM1s was not great for any temporal sample.

Wear stage (WS)

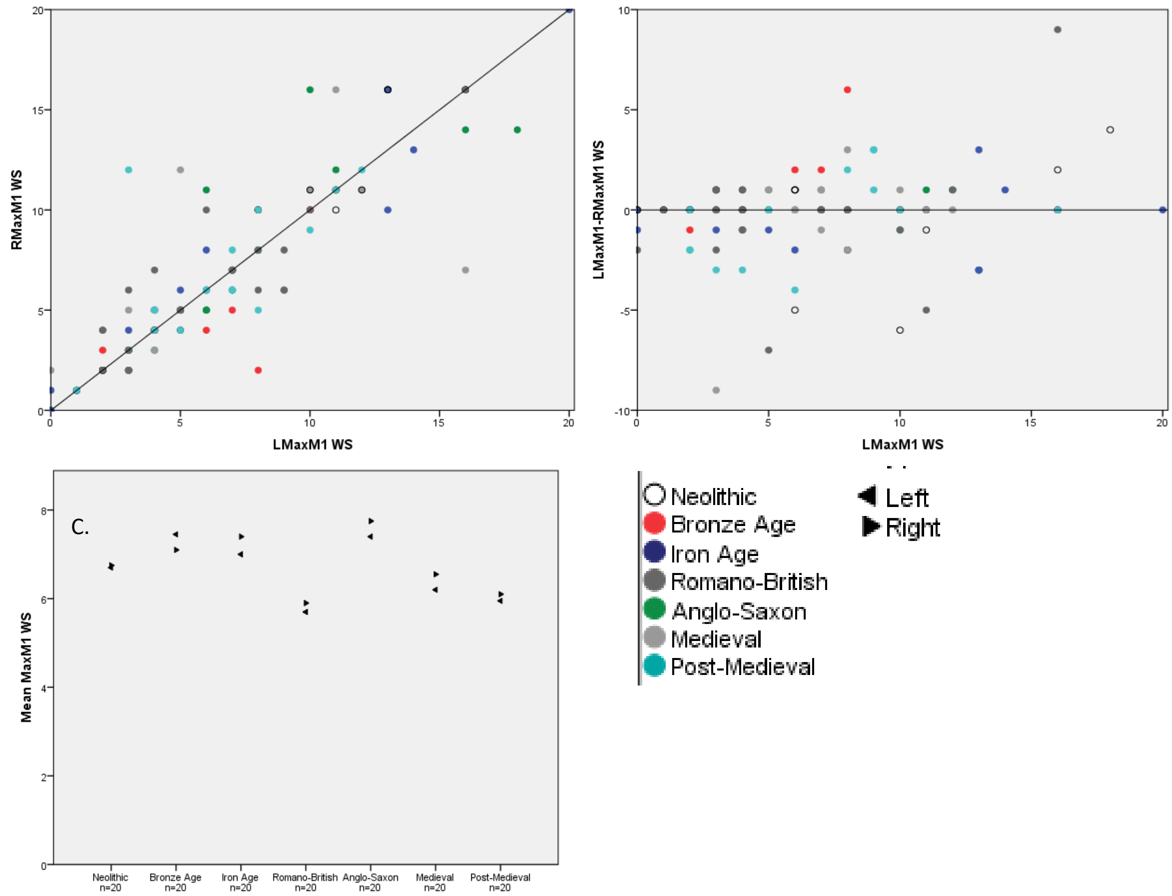


Figure 7.1.4. Plots of wear stage (WS) of the left first (LMaxM1) and right first (RMaxM1) maxillary molars

A. Scatter plot of LMaxM1 WS by RMaxM1 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between LMaxM1 and RMaxM1 against LMaxM1 WS, with plotted line of equality (y=0).
C. Plotted mean WS for LMaxM1 and RMaxM1, by temporal sample

The significant Spearman correlation coefficient supports a good association between LMaxM1 and RMaxM1 WS (n=140 r_s=0.91, p<0.001). Figure 7.1.4A shows as one MaxM1 experienced wear so did its antimere, and that the points clustered around the line of absolute symmetry. Left and right MaxM1s WS difference remained constant in relation to LMaxM1 (Figure 7.1.4A B), supporting a similar rate of wear between left and right MaxM1s. Some variation between molars was observed, shown by points falling around the line of equality. These differences were not significant (Mann-Whitney z=-0.18, p=0.854). Figure 7.1.4AC shows mean WS measurements between left-right MaxM1s did not differ greatly for any temporal sample.

7.1.1.2 Comparing left and right second Maxillary Molar (MaxM2) wear

Average crown height (CH)

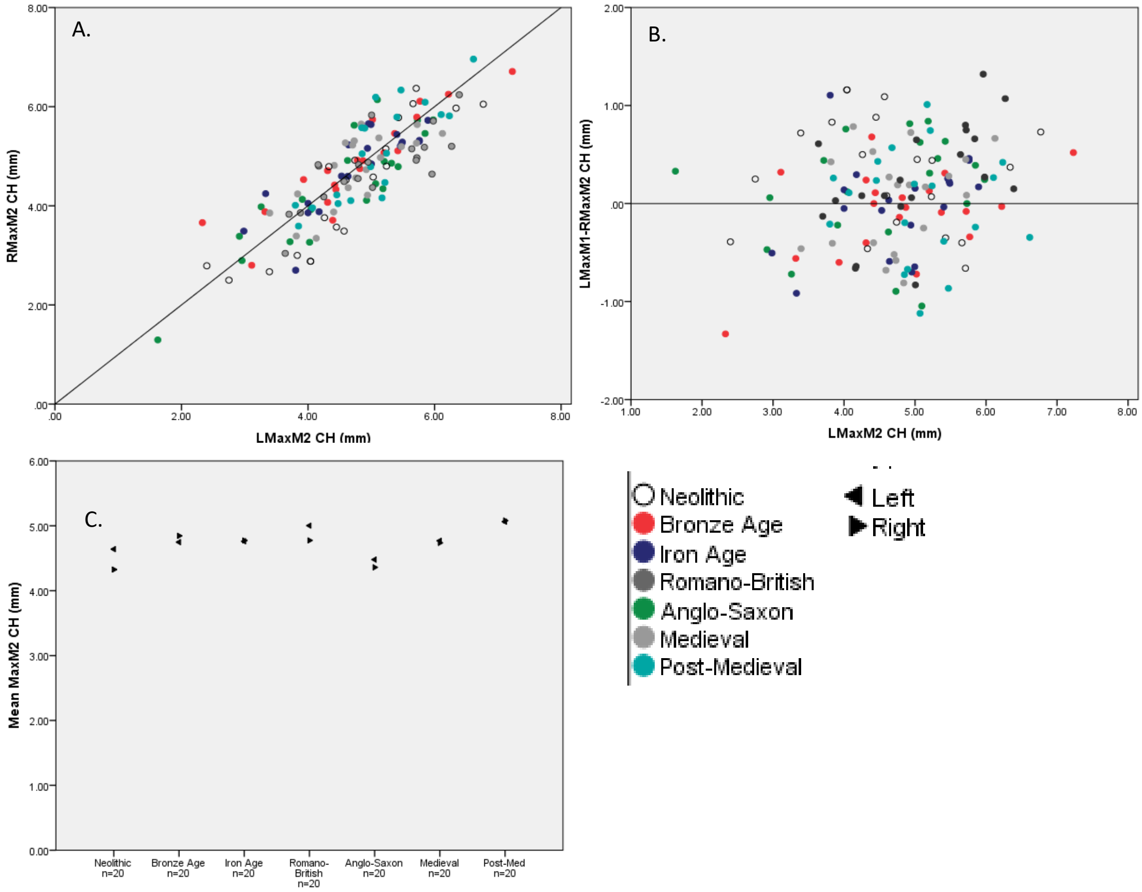


Figure 7.1.5. Plots of average crown height (CH) of the left second (LMaxM2) and right second (RMaxM2) maxillary molars

A. Scatter plot of LMaxM2 CH by RMaxM2 CH, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CH difference between LMaxM2 and RMaxM2 against LMaxM2 CH, with plotted line of equality (y=0).
C. Plotted mean CH for LMaxM2 and RMaxM2, by temporal sample

A significant Pearson's correlation coefficient supports a good association CH in left-right MaxM2 pairs (n=140, r=0.85, p<0.001), suggesting as one molar experienced wear so did its antimere. Data points for upper second molars fell around the line of absolute symmetry (Figure 7.1.5A). Figure 7.1.5B shows some difference between left-right CH measurements in the MaxM2, with points falling around the line of equality. This difference remained constant supporting a similar rate of wear. Mean difference in CH between left-right MaxM2 pairs was not significant (Independent T-Test t(278)=0.67, p.503). Figure 7.1.5C indicates no great difference in mean CH between left-right MaxM2s any temporal sample.

Crown index (CI)

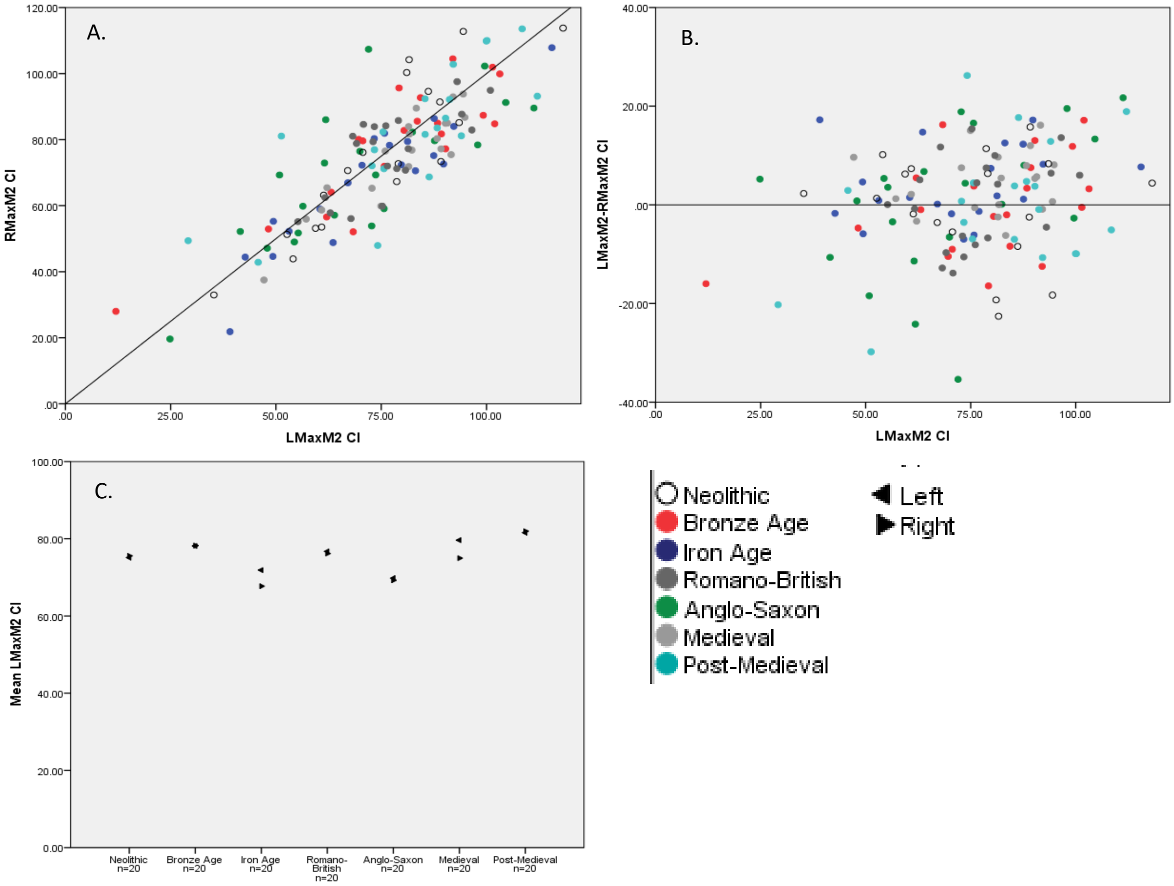


Figure 7.1.6. Plots of crown index (CI) of the left second (LMaxM2) and right second (RMaxM2) maxillary molars
A. Scatter plot of LMaxM2 CI by RMaxM2 CI, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CI difference between LMaxM2 and RMaxM2 against LMaxM2 %DE, with plotted line of equality.
C. Plotted mean %DE for LMaxM2 and RMaxM2, by temporal sample

MaxM2 antimere partners had a significant Pearson correlation coefficient for CI, suggesting as one molar experienced wear so did its antimere (n=140, r=0.84, p<0.001). Figure 7.1.6A shows some agreement between left-right MaxM2 CI; with points falling around the line of absolute symmetry. Figure 7.1.6B suggests CI measurements were not identical within upper second left-right molar pairs as points fell around the line of equality. This difference was not significant (Independent T-Test t(278)=0.58, p=0.564). The difference in CI wear remained constant, supporting a similar rate of wear between left-right upper second molar pairs. Figure 7.1.6C shows mean CI did not differ greatly between left-right MaxM2s for any temporal sample.

Percent of exposed dentine (%DE)

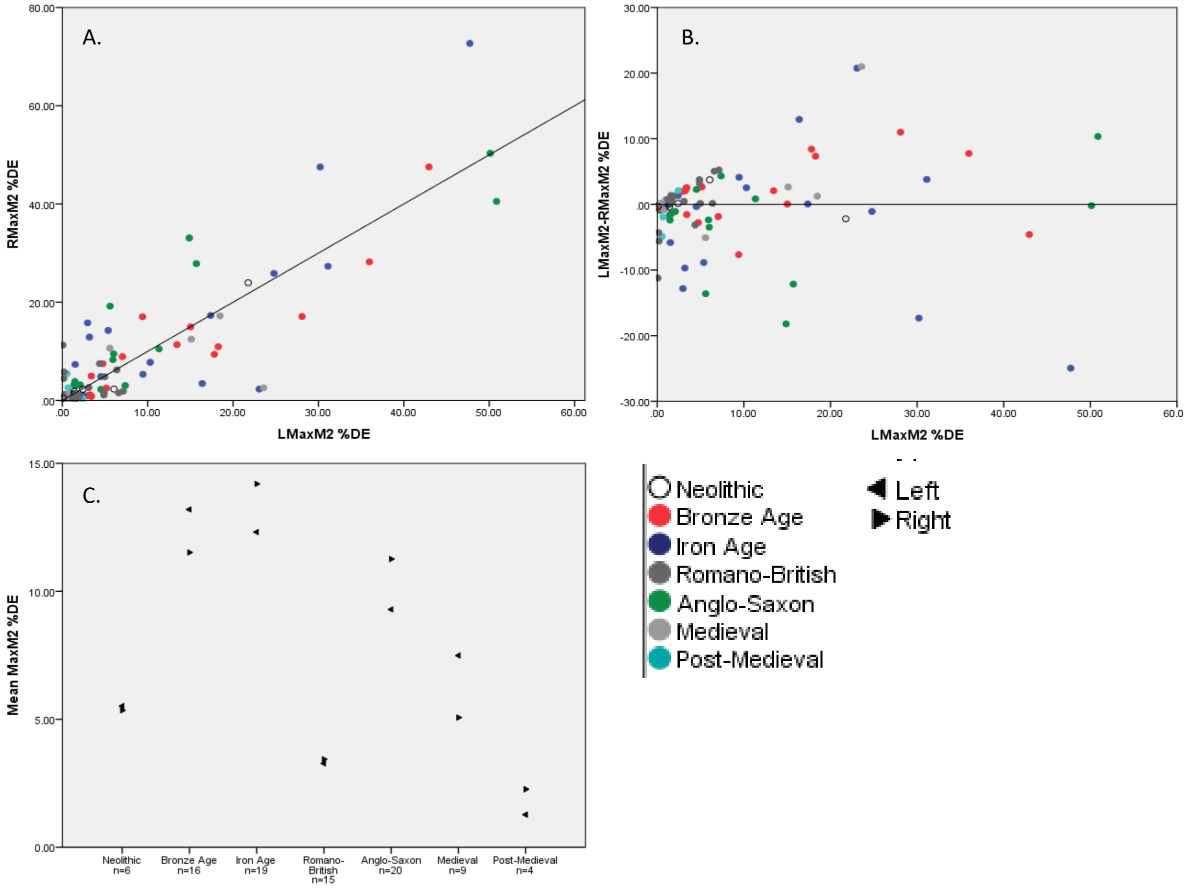


Figure 7.1.7. Plots of percent of exposed dentine (%DE) of the left second (LMaxM2) and right second (RMaxM2) maxillary molars

A. Scatter plot of LMaxM2 %DE by RMaxM2 %DE, with plotted line of absolute symmetry (y=x).
B. Scatter plot of %DE difference between LMaxM2 and RMaxM2 against LMaxM2 %DE, with plotted line of equality (y=0).
C. Plotted mean %DE for LMaxM2 and RMaxM2, by temporal sample

A significant Spearman correlation coefficient indicates an association between %DE measurements in left-right MaxM2 pairs (n=89, r_s=0.71, p<0.001). This means as one MaxM2 experienced wear so did its antimere. The points in Figure 7.1.7A fall around the line of absolute symmetry, indicating similar amounts of %DE on left and right MaxM2s. Figure 7.1.7B, however, shows %DE was not identical on left-right upper second molar pairs. Points did not fall on the line of equality, showing some difference in %DE measurements between molars, although this difference was not significant (Mann-Whitney z=-0.15, p=0.909). The difference between molars remained constant, supporting a similar rate of wear. Figure 7.1.7AC shows little difference in mean %DE between MaxM2 left-right pairs for the Neolithic, Romano-British and Post-Medieval samples. The remaining temporal samples showed some difference in mean %DE.

Wear stage (WS)

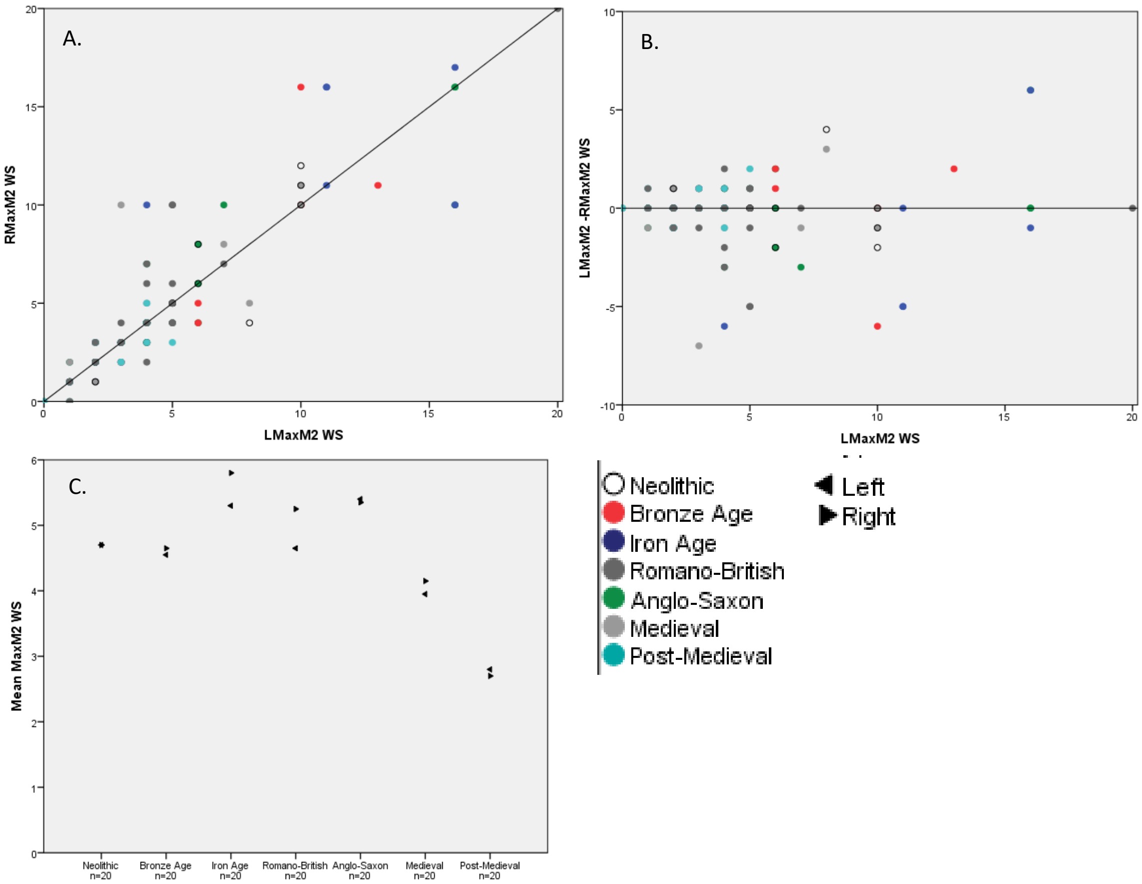


Figure 7.1.8. Plots of wear stage (WS) of the left second (LMaxM2) and right second (RMaxM2) maxillary molars

A. Scatter plot of LMaxM2 WS by RMaxM2 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between LMaxM2 and RMaxM2 against LMaxM2 WS, with plotted line of equality (y=0).
C. Plotted mean WS for LMaxM2 and RMaxM2, by temporal sample

Figure 7.1.8A shows left and right MaxM2s were highly associated, in terms of WS, meaning that as one MaxM2 experienced wear so did its antimere. This was supported by a significant Spearman correlation coefficient (n=140, r_s=0.92, p<0.001). The points in Figure 7.1.8A cluster around the line of absolute symmetry, indicating similar amounts of wear on left and right MaxM2s. Figure 7.1.8B shows any differences in WS between left-right MaxM2s were not substantial, falling on and around the line of equality, and remained constant. This was supported by a Mann-Whitney test (Mann-Whitney z=-0.01, p=0.996), suggesting a similar rate of wear in left-right MaxM2s. Figure 7.1.8C shows mean WS between left-right MaxM2s did not differ greatly for any temporal sample.

7.1.1.3 Comparing left and right third maxillary molar (MaxM3) wear

Average crown height (CH)

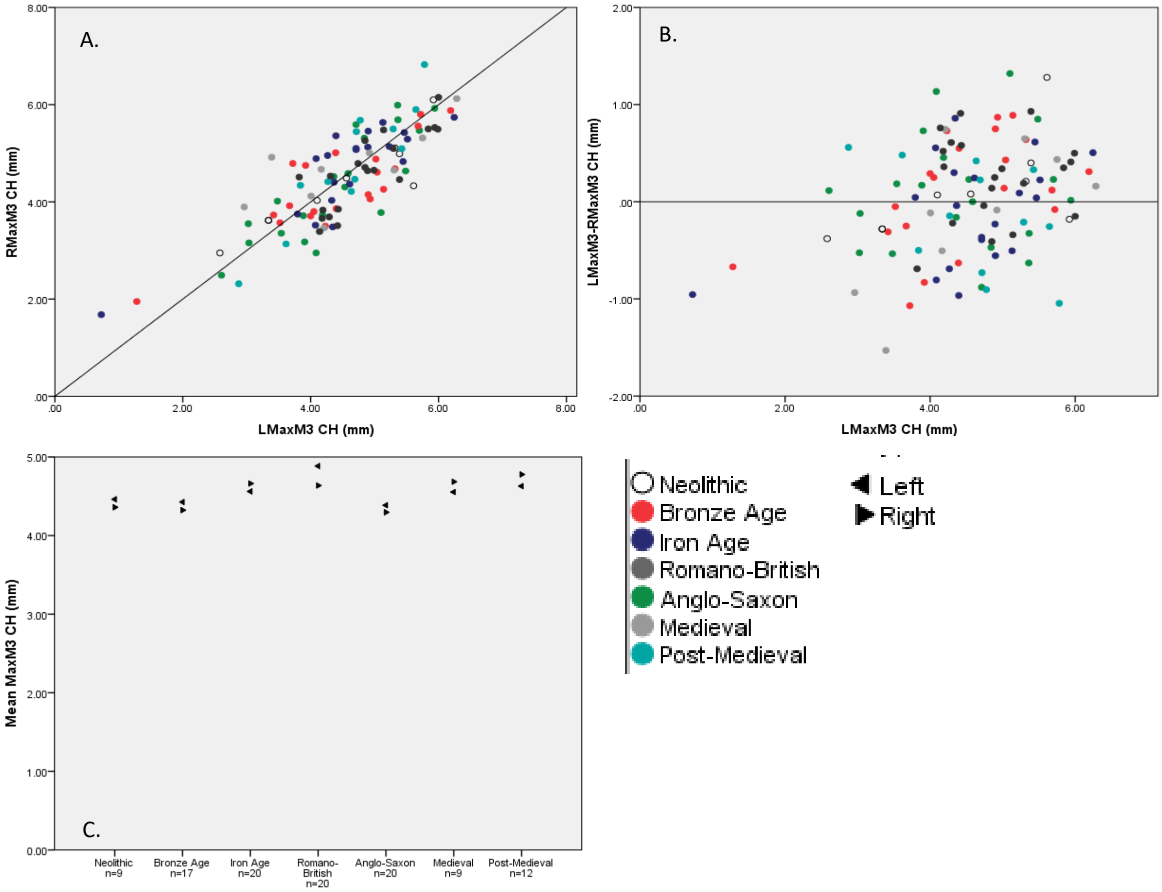


Figure 7.1.9. Plots of average crown height (CH) of the left third (LMaxM3) and right third (RMaxM3) maxillary molars

A. Scatter plot of LMaxM3 CH by RMaxM3 CH, with plotted line of absolute symmetry (y=x).
B. Scatter plot of CH difference between LMaxM3 and RMaxM3 against LMaxM3 CH, with plotted line of equality (y=0).
C. Plotted mean CH for LMaxM3 and RMaxM3, by temporal sample

Figure 7.1.9A shows as one MaxM3 experienced wear so did its antimere, supported by a significant correlation coefficient (n=107, r=0.83, p<0.001). Data points fell around the line of absolute symmetry, indicating a similar amount of CH on left-right MaxM3 pairs. CH difference between upper third left-right molars remained constant, supporting a similar rate of wear (Figure 7.1.9B). Points fell around the line of equality, showing some difference between molars. This difference was not found to be significant (Independent T-Test t(218)=0.33, p=0.740). Figure 7.1.9C shows the difference in mean CH between left-right MaxM3s was not great for any temporal sample.

Crown index (CI)

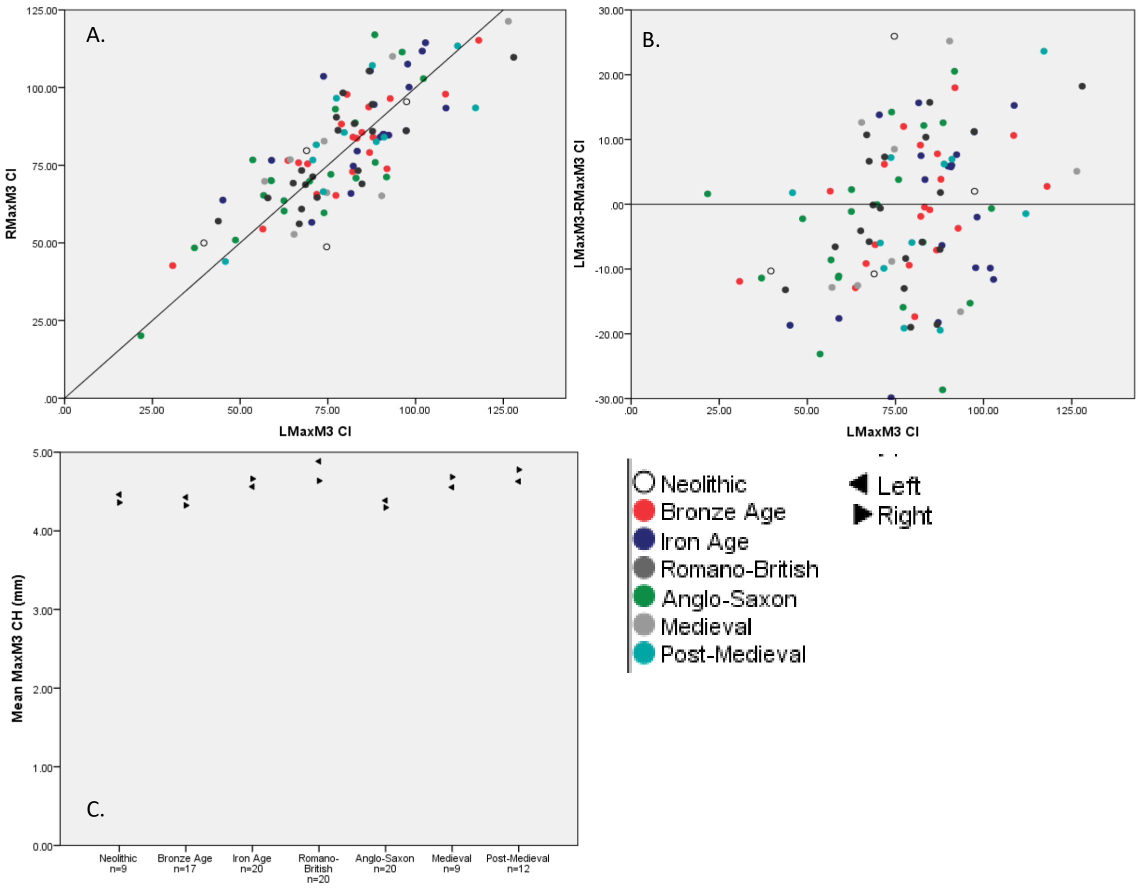


Figure 7.1.10. Plots of crown index (CI) of the left third (LMaxM3) and right third (RMaxM3) maxillary molars
A. Scatter plot of LMaxM3 CI by RMaxM3 CI, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CI difference between LMaxM3 and RMaxM3 against LMaxM3 CI, with plotted line of equality (y=0)
C. Plotted mean CI for LMaxM3 and RMaxM3, by temporal sample

A significant Pearson correlation coefficient supports an association in CI between left and right MaxM3s (n=106, r=0.78, p<0.001). Data points fell around the line of absolute symmetry, indicating a similar amount of wear on both left and right MaxM3s (Figure 7.1.10A). CI measurements were not identical in left-right upper third molar pairs, demonstrated by points falling around the line of equality (Figure 7.1.10B). This difference was not significant (Independent T-Test t(210)=-0.22, p=0.827), and remained constant supporting a similar rate of wear on molars within a pair. Figure 7.1.10C shows mean CI between left-right MaxM3s did not substantially differ for any temporal sample.

Percent of dentine exposure (%DE)

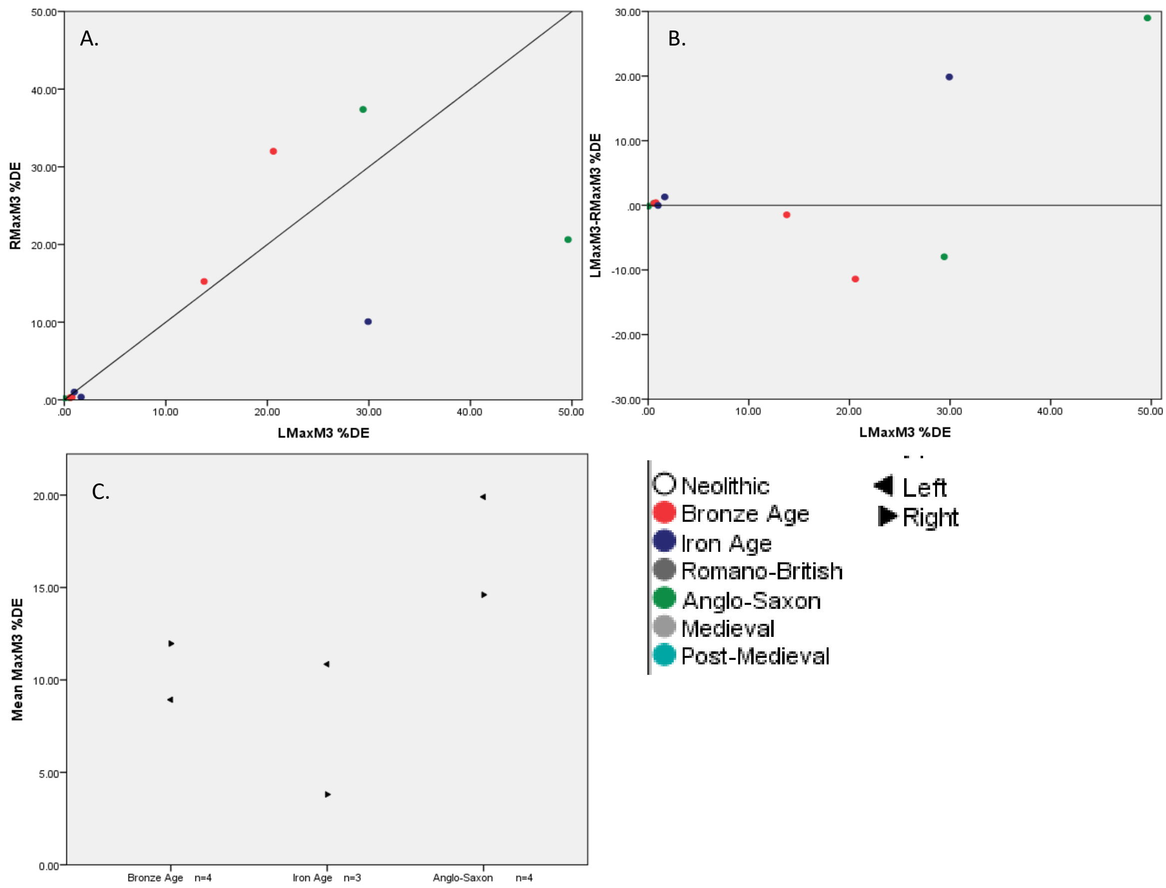


Figure 7.1.11. Plots of percent of dentine exposure (%DE) of the left third (LMaxM3) and right third (RMaxM3) maxillary molars

A. Scatter plot of LMaxM3 %DE by RMaxM3 %DE, with plotted line of absolute symmetry (y=x)
B. Scatter plot of %DE difference between LMaxM3 and RMaxM3 against LMaxM3 %DE, with plotted line of equality (y=0).
C. Plotted mean %DE for LMaxM3 and RMaxM3, by temporal sample

A significant Spearman's correlation coefficient for %DE in left-right upper third molar pairs supports a trend that as one molar experienced wear so did its antimere (n=111, r_s=0.89, p<0.001). Points fell loosely around the line of absolute symmetry, particularly at higher levels of exposed dentine (Figure 7.1.11A). This is more clearly observed in Figure 7.1.11B. At low levels of exposed wear, the difference in %DE between left-right MaxM3s is close to the line of equality. This becomes more varied with higher levels of exposed dentine. There was no significant difference in %DE between molar pairs (Mann-Whitney z=-0.62, p=0.533), indicating an overall similar degree of exposed dentine in left-right MaxM3 pairs. Figure 7.1.11C shows a difference in mean %DE between upper third left-right molars for three temporal samples. The remaining samples could not be observed due to a lack of molar pairs with exposed dentine. Figure 7.1.11B indicates the non-significant Mann-Whitney result may be misleading, and left-right upper third molar pairs do not show a similar amount of %DE.

Wear stage (WS)

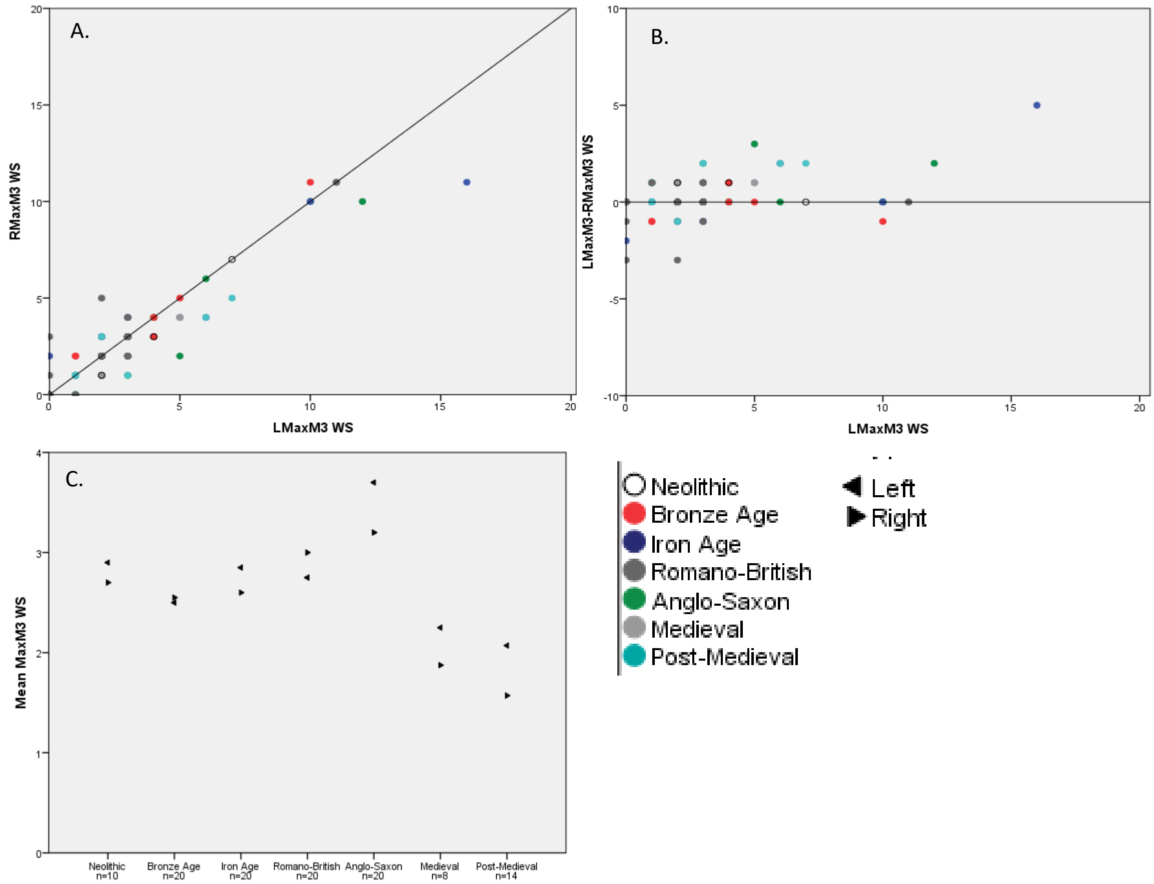


Figure 7.1.12. Plots of wear stage (WS) of the left third (LMaxM3) and right third (RMaxM3) maxillary molars

A. Scatter plot of LMaxM3 WS by RMaxM3 WS, with plotted line of absolute symmetry (y=x)

B. Scatter plot of WS difference between LMaxM3 and RMaxM3 against LMaxM3 WS, with plotted line of equality (y=0)

C. Plotted mean WS for LMaxM3 and RMaxM3, by temporal sample

A significant Spearman's coefficient supports an association between left-right upper third molar pairs (n=112, r_s=0.89, p<0.001). Data points clustered around the line of absolute symmetry, indicating a similar amount of wear on both left and right MaxM3s Figure 7.1.12A. WS difference between MaxM3s left-right pairs remained constant against ManxM3 WS, supporting a similar rate of wear (Figure 7.1.12B). Points fell around the line of equality, showing some difference in WS between molars (Figure 7.1.12B). This difference was not significant (Mann-Whitney z=-0.39, p=0.696). Figure 7.1.12C shows difference in mean WS between left-right MaxM3s was not great for any period sample.

7.1.1.4 Comparing left and right first mandibular molar (ManM1) wear

Average crown height (CH)

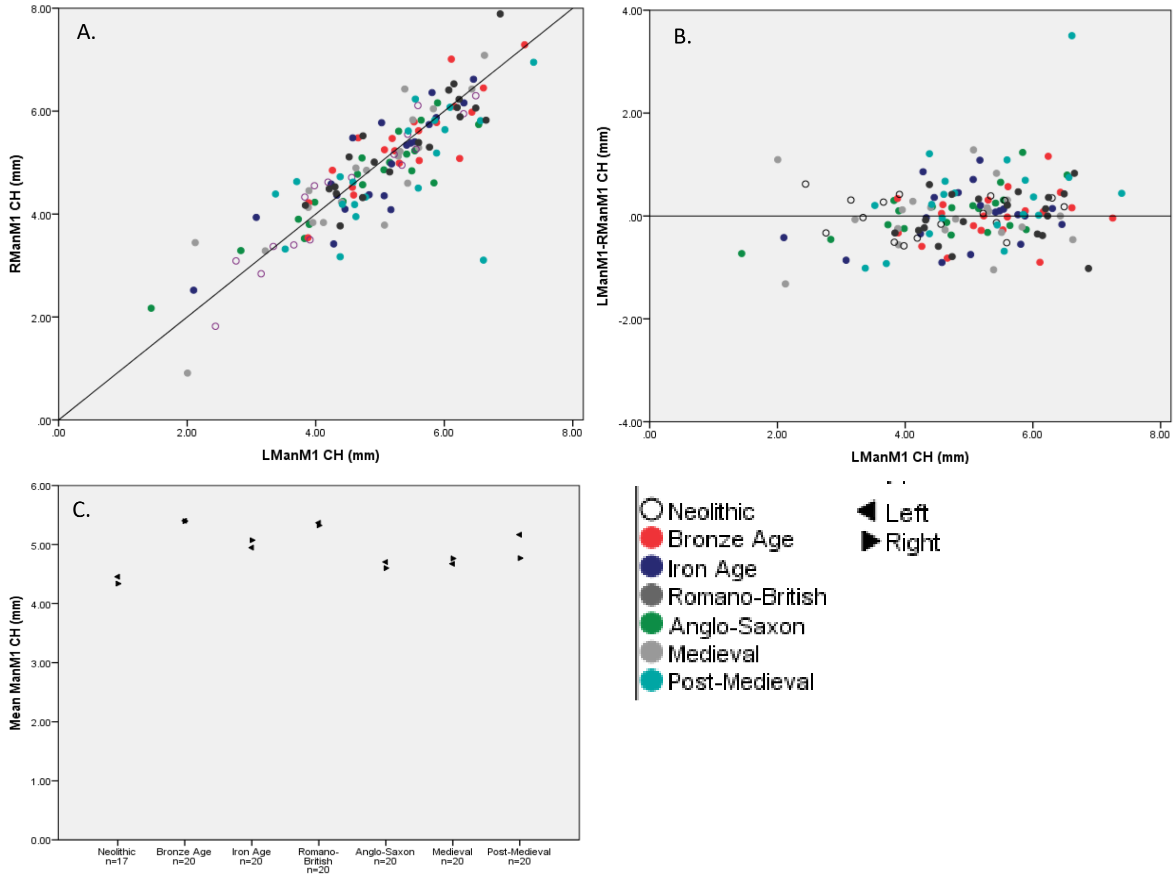


Figure 7.1.13. Plots of average crown height (CH) of the left first (LManM1) and right first (RManM1) mandibular molars

A. Scatter plot of LManM1 CH by RManM1 CH, with plotted line of absolute symmetry (y=x)

B. Scatter plot of CH difference between LManM1 and RManM1 against LManM1 CH, with plotted line of equality (y=0)

C. Plotted mean CH for LManM1 and RManM1, by temporal sample

There was a significant Pearson correlation coefficient between left-right lower first molar pairs for CH ($n=137$, $r=0.86$, $p<0.001$). Points fell around the line of absolute symmetry in Figure 7.1.13A, supporting a similar CH on left-right ManM1 pairs. Figure 7.1.13B shows CH was not identical between these molars, with points falling around the line of equality. These differences were not significant (Independent T-Test $t(271)=0.45$, $p=0.651$), and remained constant compared to LManM1 CH. These results support a similar rate of wear, in terms of CH, for left-right lower first molar pairs. Figure 7.1.13C shows mean CH between left-right ManM1s were similar for all temporal samples.

Crown index (CI)

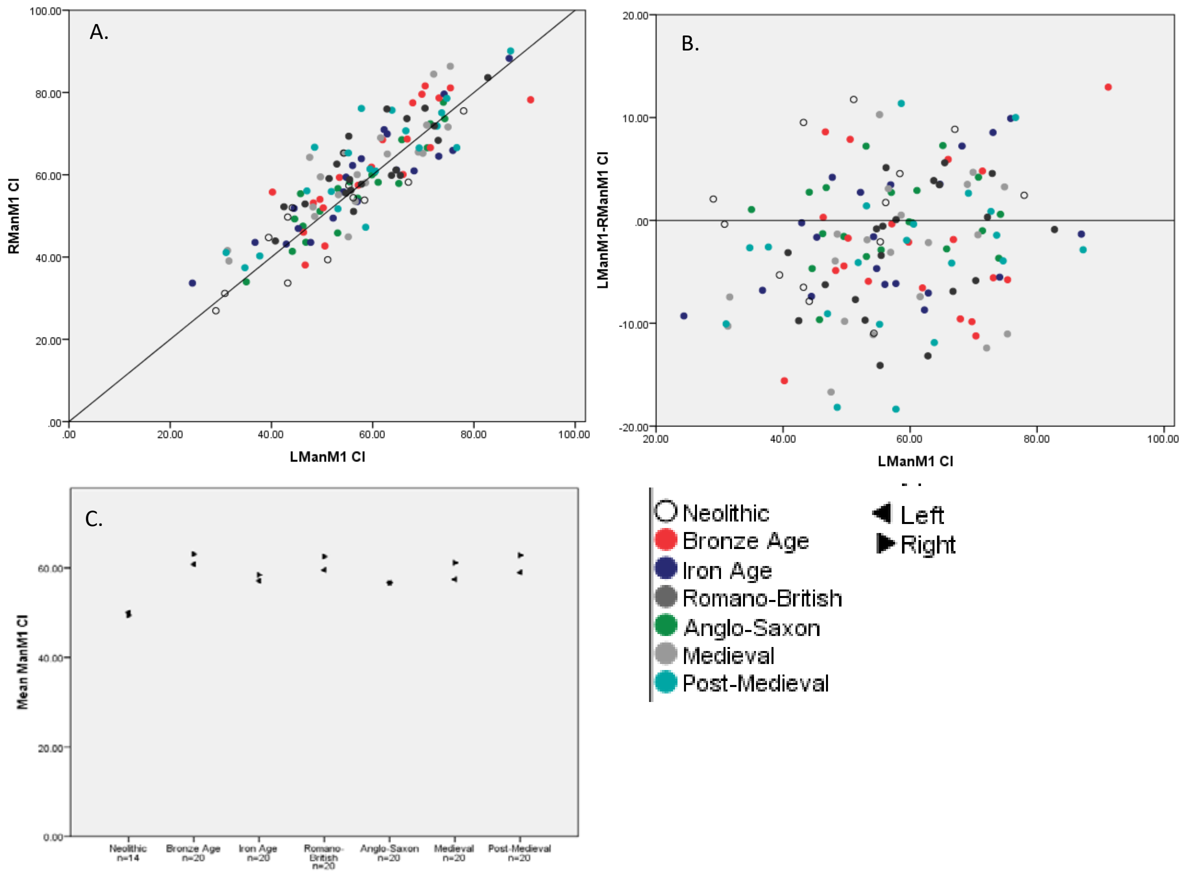


Figure 7.1.14. Plots of crown index (CI) of the left first (LManM1) and right first (RManM1) mandibular molars

A. Scatter plot of LManM1 CI by RManM1 CI, with plotted line of absolute symmetry (y=x)

B. Scatter plot of CI difference between LManM1 and RManM1 against LManM1 CI, with plotted line of equality (y=0)

C. Plotted mean CI for LManM1 and RManM1, by temporal sample

A significant Pearson correlation coefficient supports a good association between lower first left-right molar pairs in terms of CI ($n=134$, $r=0.87$, $p<0.001$). Points clustered around the line of absolute symmetry, supporting a similar degree of wear between left and right ManM1s (Figure 7.1.14A). CI measurements were not identical for left-right ManM1 pairs, demonstrated by points falling around the line of equality (Figure 7.1.14B). However, these differences were not significant (Independent T-Test $t(266)=-0.28$, $p=0.200$), and remained constant in relation to LManM1 CH, supporting a similar rate of wear on both the LManM1 and RManM1. Figure 7.1.14C shows mean CH between left-right MaxM1s did not differ substantially for temporal sample.

Percent of exposed dentine (%DE)

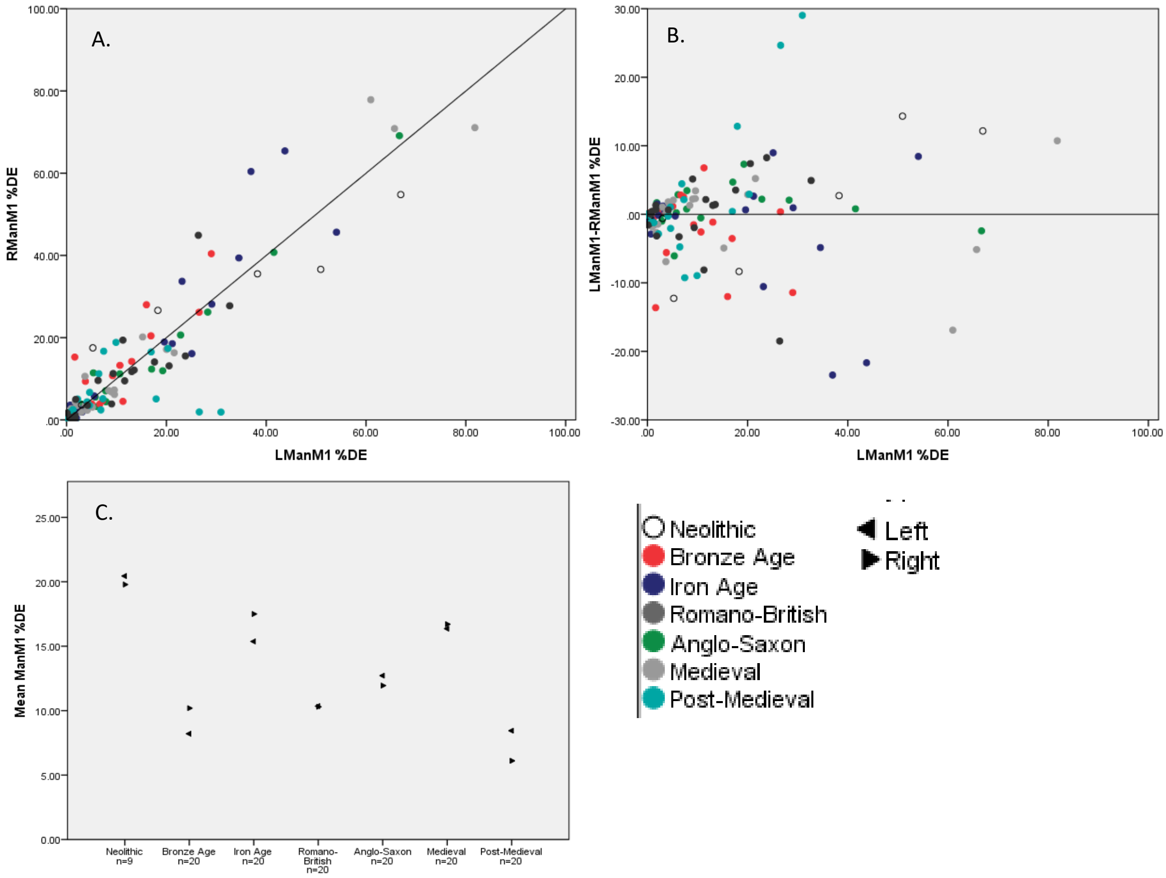


Figure 7.1.15. Plots of percent of exposed dentine (%DE) of the left first (LManM1) and right first (RManM1) mandibular molars

A. Scatter plot of LManM1 %DE by RManM1 CI, with plotted line of absolute symmetry (y=x)

B. Scatter plot of %DE difference between LManM1 and RManM1 against LManM1 %DE, with plotted line of equality (y=0).

C. Plotted mean %DE for LManM1 and RManM1, by temporal sample

An increase in %DE on ManM1 was associated with an increase in %DE on its antimere (Figure 7.1.15A). This was supported a significant Spearman correlation coefficient (n=129, r_s=0.89, p<0.001). Points fell around the line of absolute symmetry at low levels of %DE, becoming more varied at higher levels of %DE (Figure 7.1.15A). This is more clearly demonstrated in Figure 7.1.15B, where %DE difference between left-right ManM1 pairs is greater at higher degrees of wear on left ManM1s. This difference remained constant, and was not significantly different between left and right lower first molars (Mann-Whitney Mann-Whitney z=-0.06, p=0.947). Figure 7.1.15C shows minimal difference in mean %DE between left-right ManM1s for each period sample. These results support a similar rate of wear in %DE between lower first left-right molars.

Wear stage (WS)

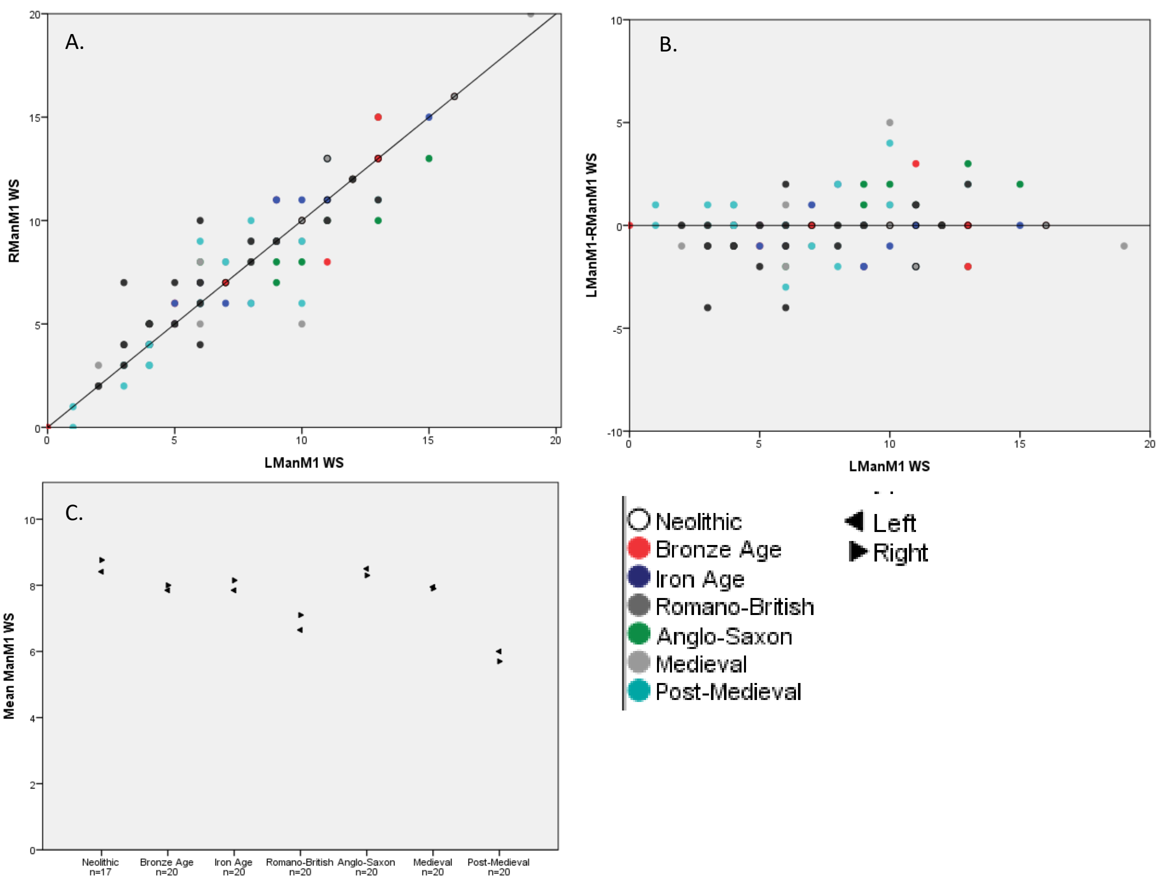


Figure 7.1.16. Plots of wear stage (WS) of the left first (LManM1) and right first (RManM1) mandibular molars
A. Scatter plot of LManM1 WS by RManM1 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between LManM1 and RManM1 against LManM1 WS, with plotted line of equality (y=0)
C. Plotted mean WS for LManM1 and RManM1, by temporal sample

A significant Spearman correlation coefficient supports a good association between lower left and right first WS measurements (n=137, r_s=0.93, p<0.001). Figure 7.1.16A shows points clustered around the line of absolute symmetry, supporting a similar degree of wear between left and right ManM1s. Figure 7.1.16B shows WS measurements between left-right ManM1 pairs were not identical, with points falling around the line of equality. These differences, however, were not significant (Mann-Whitney Mann-Whitney z=-0.21, p=0.837), and remained constant, supporting a similar rate of wear. Figure 7.1.16C shows mean WS between left-right ManM1s were not substantially different for any temporal sample.

7.1.1.5 Comparing left and right second mandibular molar (ManM2) wear

Average crown height (CH)

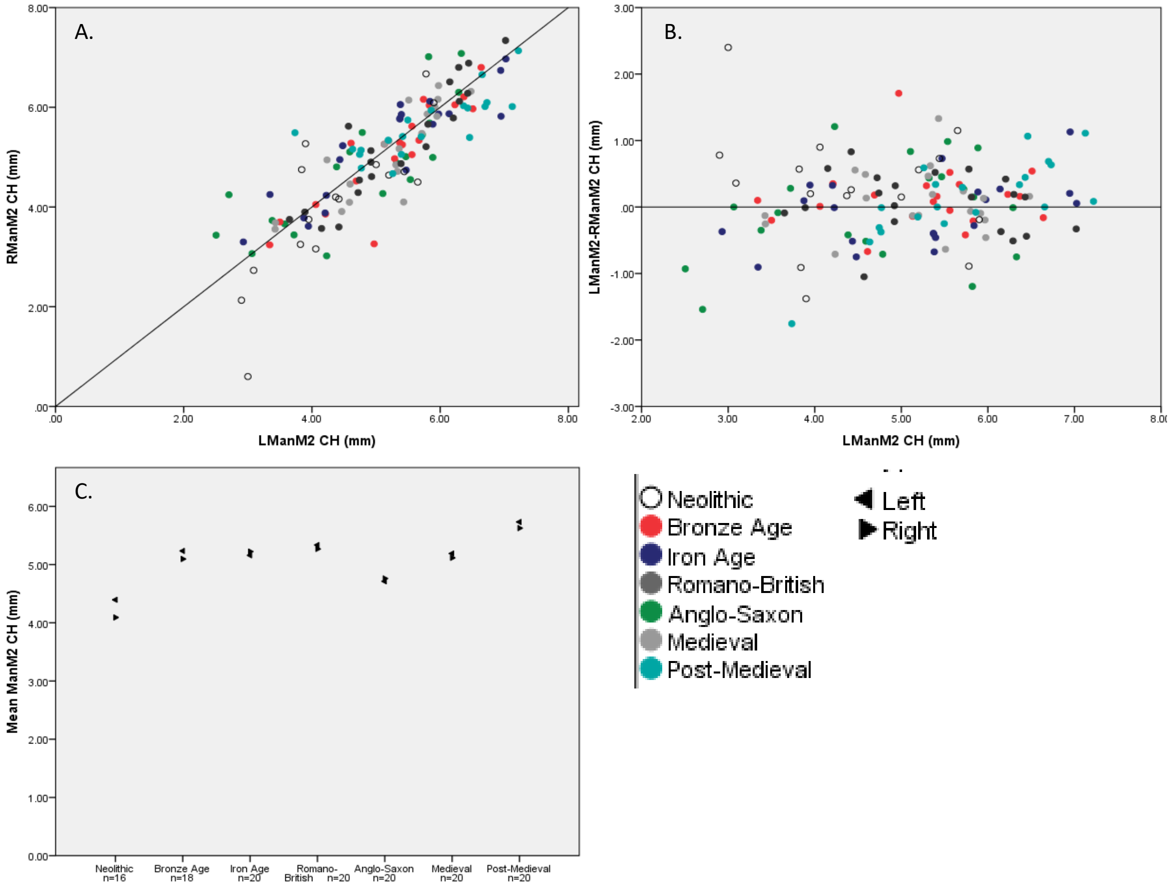


Figure 7.1.17. Plots of average crown height (CH) of the left second (LManM2) and right second (RManM2) mandibular molars

A. Scatter plot of LManM2 CH by RManM2 CI, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CH difference between LManM2 and RManM2 against LManM2 CH, with plotted line of equality (y=0)
C. Plotted mean CH for LManM2 and RManM2, by temporal sample

A significant Pearson correlation coefficient supports a good association between lower left and right second molar CH measurements (n=136, r=0.85, p<0.001). Points for lower ManM2s clustered around the line of absolute symmetry (Figure 7.1.17A). Figure 7.1.17B shows points falling around the line of equality, indicating some difference in CH measurement between upper first left-right molar pairs. These differences, however, were not significant (Independent T-Test t(270)=0.57, p=0.571), and remained constant. Figure 7.1.17C shows mean CH between left-right ManM2s did not differ greatly for any temporal sample. These results support a similar rate of wear, in terms of CH, between left and right ManM2s.

Crown index (CI)

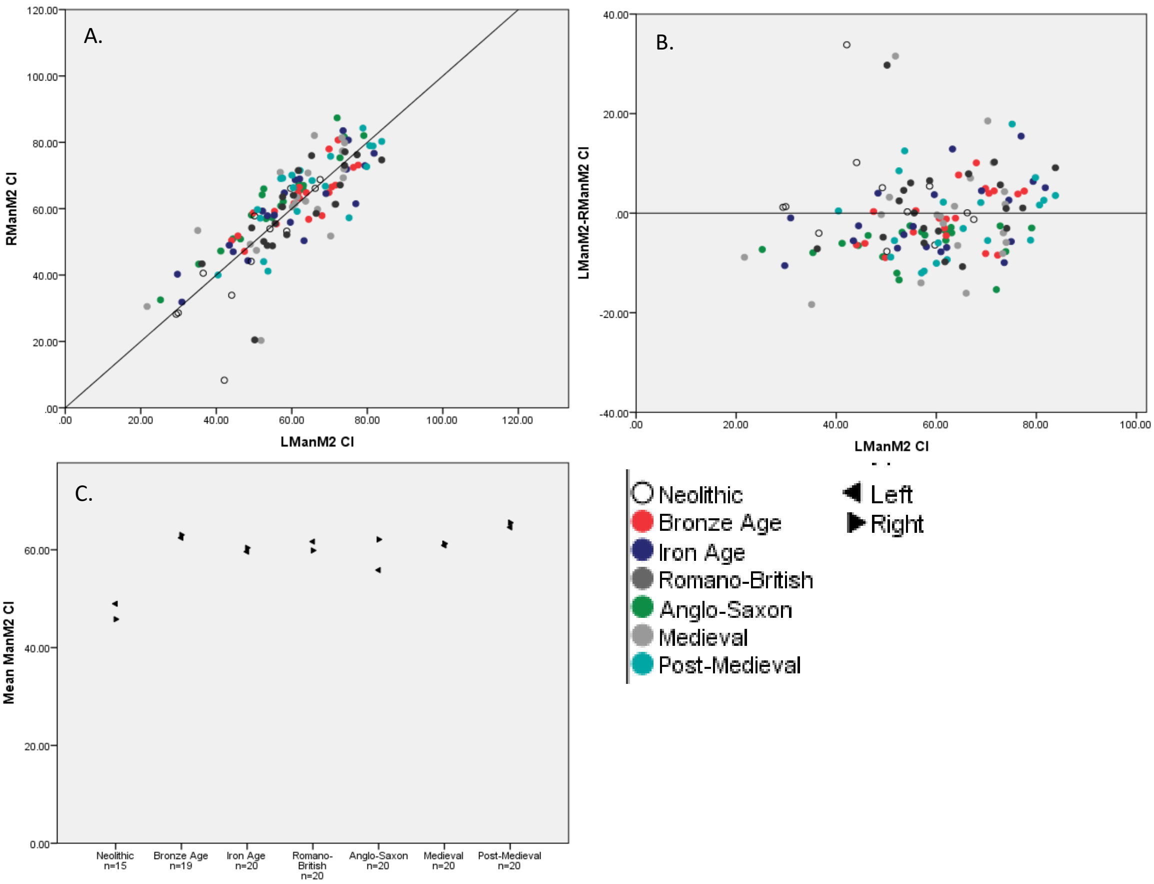


Figure 7.1.18. Plots of crown index (CI) of the left second (LManM2) and right second (RManM2) mandibular molars

A. Scatter plot of LManM2 CI by RManM2 CI, with plotted line of absolute symmetry (y=x)

B. Scatter plot of CI difference between LManM2 and RManM2 against LManM2 CI, with plotted line of equality (y=0)

C. Plotted mean CI for LManM2 and RManM2, by temporal sample

Lower second left-right molars had a significant Pearson correlation coefficient for CI, suggesting as one molar experienced wear so did its antimere (n=134, r=0.81, p<0.001). Figure 7.1.18A shows some agreement between left-right MaxM2s CI; with points falling around the line of absolute symmetry. Points fell around the line of equality, suggesting CI measurements were not identical between lower second left-right molar pairs (Figure 7.1.18B). These differences were not significant (Independent T-Test t(266)=0.58, p=0.564), and remained constant supporting a similar rate of wear between left-right upper second molar pairs. Figure 7.1.18C shows mean CI did not differ substantially between left-right ManM2s for any temporal sample.

Percent of dentine exposure (%DE)

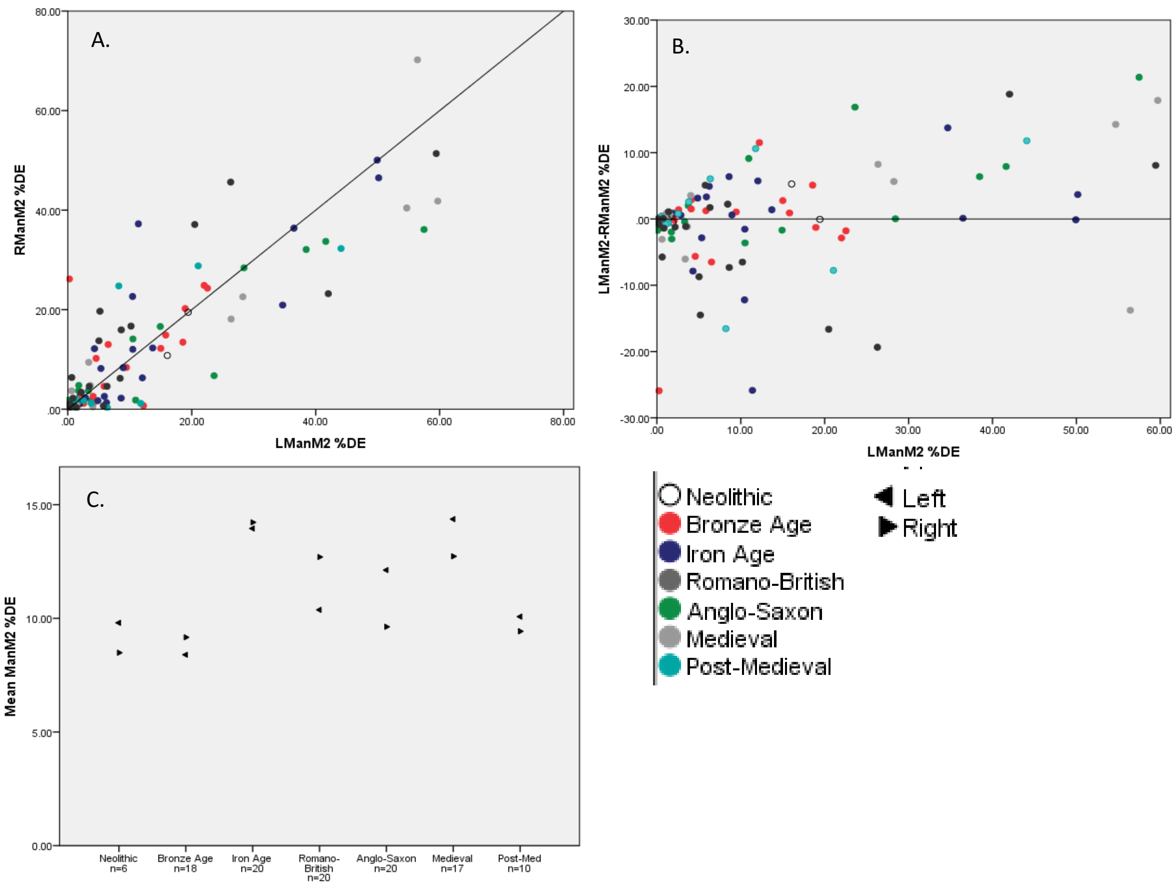


Figure 7.1.19. Plots of percent of dentine exposure (%DE) of the left second (LManM2) and right second (RManM2) mandibular molars

A. Scatter plot of LManM2 %DE by RManM2 %DE, with plotted line of absolute symmetry (y=x)
B. Scatter plot of %DE difference between LManM2 and RManM2 against LManM2 %DE, with plotted line of equality (y=0)
C. Plotted mean %DE for LManM2 and RManM2, by temporal sample

A significant Spearman correlation coefficient indicates an association in %DE measurements between lower second left-right molars (n=111, r_s=0.81, p<0.001). Points in Figure 7.1.19A fall around the line of absolute symmetry, suggesting similar amounts of %DE on left and right ManM2s. Figure 7.1.19B shows %DE was not identical for lower second left-right molar pairs. With minimal wear, %DE difference clustered on the line of equality. As %DE increased on the left ManM2 the different in %DE between left-right ManM2 pairs increased, with more wear on the left mandibular molars. These differences were not found to be significant (Mann-Whitney z=-0.15, p=0.909). Figure 7.1.19C shows some differences in mean %DE between MaxM2 left-right pairs for all temporal samples, expect the Iron Age sample. This suggests some variation between left-right ManM2 pairs that was consistent across all temporal samples.

Wear stage (WS)

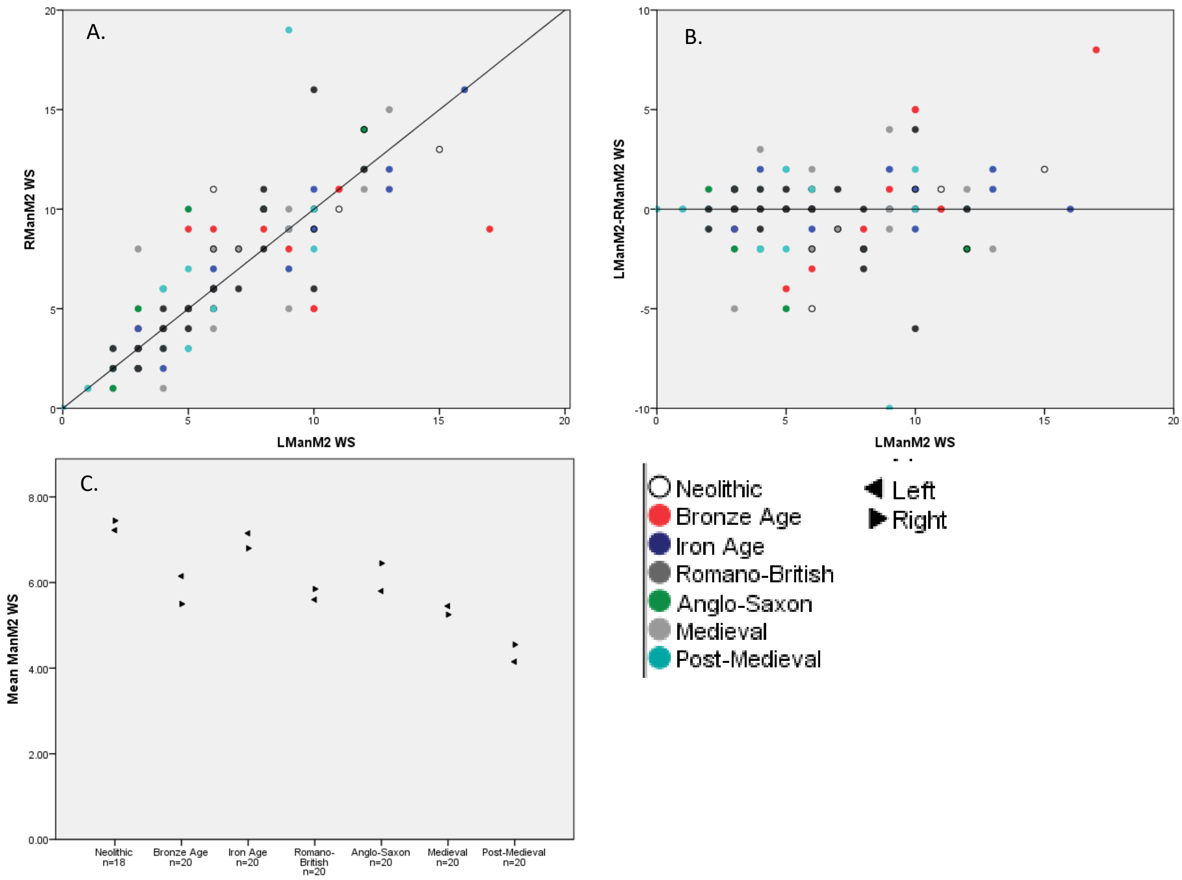


Figure 7.1.20. Plots of wear stage (WS) of the left second (LManM2) and right second (RManM2) mandibular molars.
A. Scatter plot of LManM2 WS by RManM2 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between LManM2 and RManM2 against LManM2 WS, with plotted line of equality (y=0)
C. Plotted mean WS for LManM2 and RManM2, by temporal sample

A significant Spearman's correlation coefficient supports a good association between lower left and right second molar WS measurements (n=138, r_s=0.90, p<0.001). Points clustered around the line of absolute symmetry, suggesting a relatively strong degree of symmetry (Figure 7.1.20A). Figure 7.1.20. Plots of wear stage (WS) of the left second (LManM2) and right second (RManM2) mandibular molars.B shows points fell around the line of equality, indicating some difference in WS measurement between lower second left-right molar pairs (Figure 7.1.20B). These differences, however, were not significant (Mann-Whitney z=-0.35, p=0.726), and remained constant supporting a similar rate of wear. Figure 7.1.20C shows mean WS between left-right ManM2s were not substantially different for any temporal sample. These results support a similar rate of wear, in terms of WS, between left and right ManM2s.

7.1.1.6 Comparing left and right third mandibular molar (ManM3) wear

Average crown height (CH)

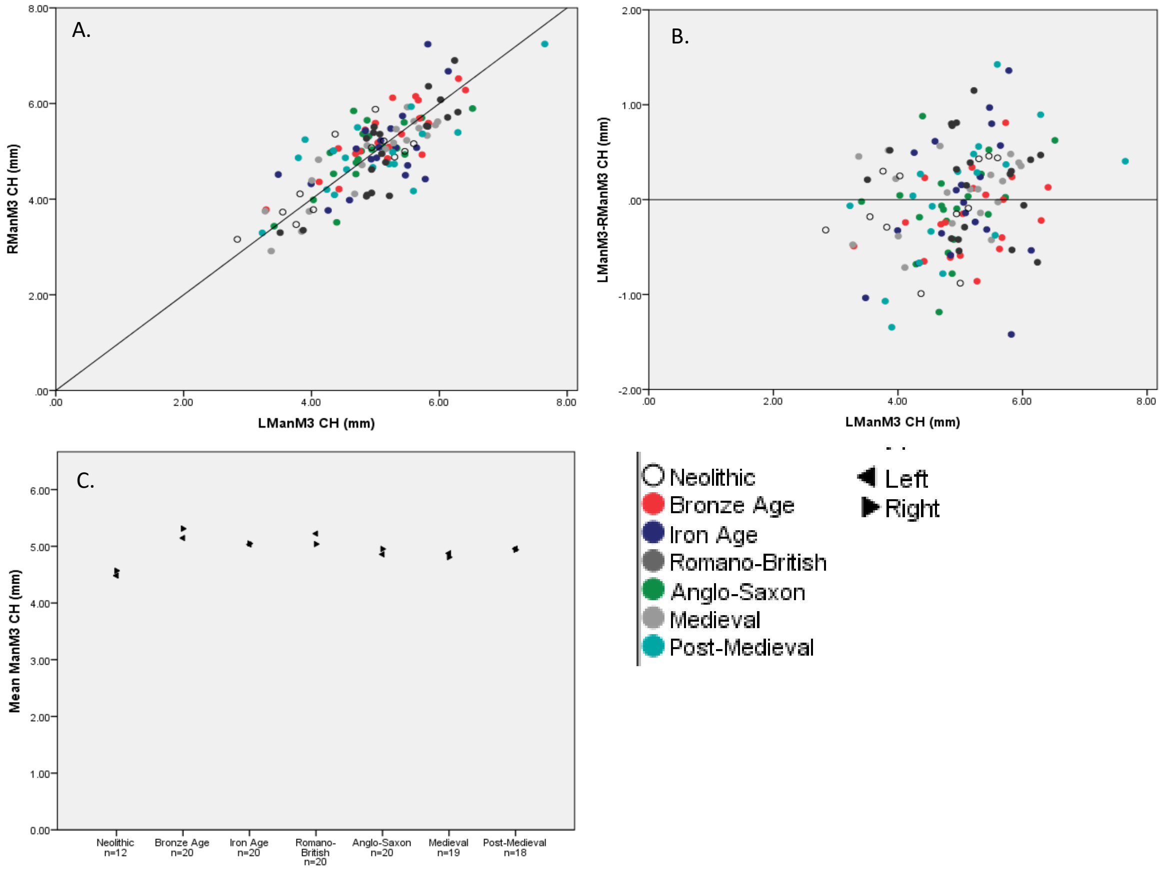


Figure 7.1.21. Plots of average crown height (CH) of the left third (LManM3) and right third (RManM3) mandibular molars

A. Scatter plot of LManM3 CH by RManM3 CH, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CH difference between LManM3 and RManM3 against LManM3 CH, with plotted line of equality (y=0)
C. Plotted mean CH for LManM3 and RManM3, by temporal sample

A significant Pearson's correlation coefficient supports a good association between lower third left-right molars (n=129, r=0.779, p<0.001), suggesting as one molar experienced wear so did its antimere. Figure 7.1.21A shows points clustered around the line of absolute symmetry, indicating a similarity in CH between left-right ManM3s. Figure 7.1.21B shows CH measurements were not identical between these molars with points falling around the line of equality. This difference in CH was not significant (Independent T-Test t(256)=-0.09, p=0.925). The difference in CH remained constant supporting a similar rate of wear. Figure 7.1.21C shows mean CH between left-right ManM3s did not greatly differ for any temporal sample.

Crown index (CI)

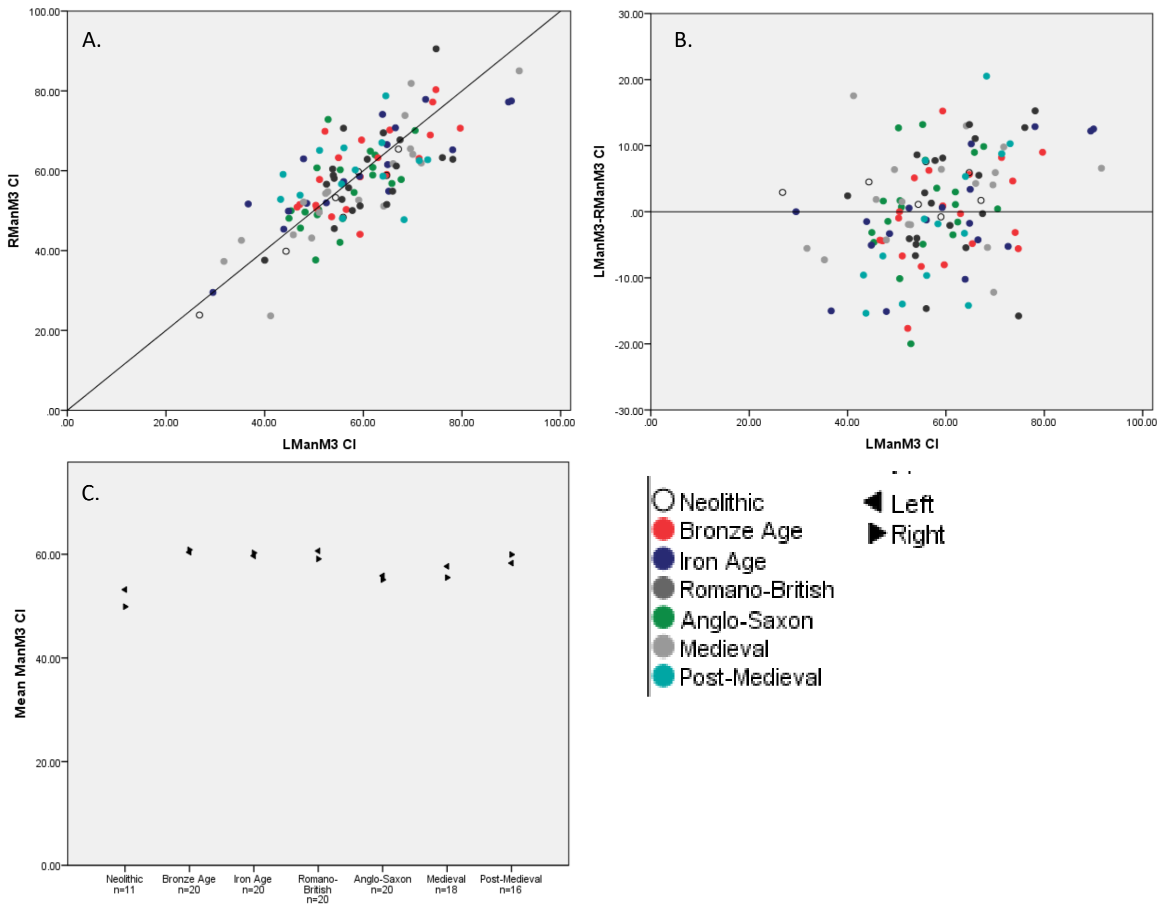


Figure 7.1.22. Plots of crown index (CI) of the left third (LManM3) and right third (RManM3) mandibular molars

A. Scatter plot of LManM3 CI by RManM3 CI, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CI difference between LManM3 and RManM3 against LManM3 CI, with plotted line of equality (y=0)
C. Plotted mean CI for LManM3 and RManM3, by temporal sample

A significant Pearson correlation coefficient supports an association in CI between left and right ManM3s (n=125, r=0.76, p<0.001). Data points fell around the line of absolute symmetry, indicating a similar amount of wear on both left and right MaxM3s (Figure 7.1.22A). CI measurements were not identical in left-right upper third molar pairs, demonstrated by points falling around the line of equality (Figure 7.1.22B). This difference was not significant (Independent T-Test t(248)=0.37, p=0.714), and remained constant supporting a similar rate of wear on molars within a pair. Figure 7.1.22C shows mean CI between left-right ManM3s did not substantially differ any temporal sample.

Percent of dentine exposure (%DE)

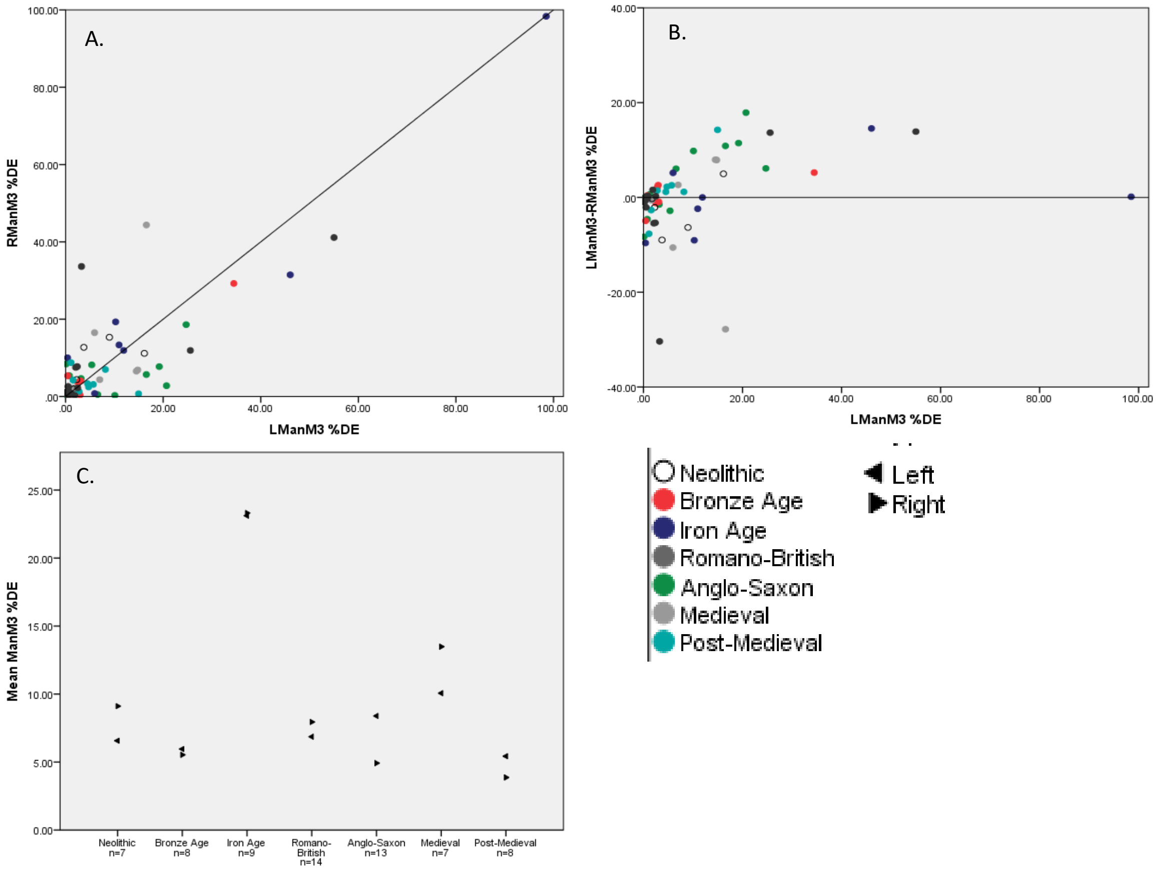


Figure 7.1.23. Plots of percent of dentine exposure (%DE) of the left third (LManM3) and right third (RManM3) mandibular molars
A. Scatter plot of LManM3 %DE by RManM3 %DE, with plotted line of absolute symmetry (y=x)
B. Scatter plot of %DE difference between LManM3 and RManM3 against LManM3 %DE, with plotted line of equality (y=0)
C. Plotted mean %DE for LManM3 and RManM3, by temporal sample

Few individuals showed more than 30%DE on either their left or right lower third molars, but a moderate significant Spearman's correlation coefficient indicates the presence of a wear relationship between these molars (n=66, r_s=0.57, p<0.001). The points of left-right pairs of lower third molars are somewhat less strongly clustered around the line of absolute symmetry (Figure 7.1.23A). Figure 7.1.23B indicates a slightly higher %DE on the left lower second molars compared to their antimere partner. This difference was not significant (Mann-Whitney z=-0.15, p=0.879), and remained constant supporting a similar rate of wear on both molars. Figure 7.1.23C shows a small difference in mean %DE between lower third left-right molars in all temporal samples.

Wear stage (WS)

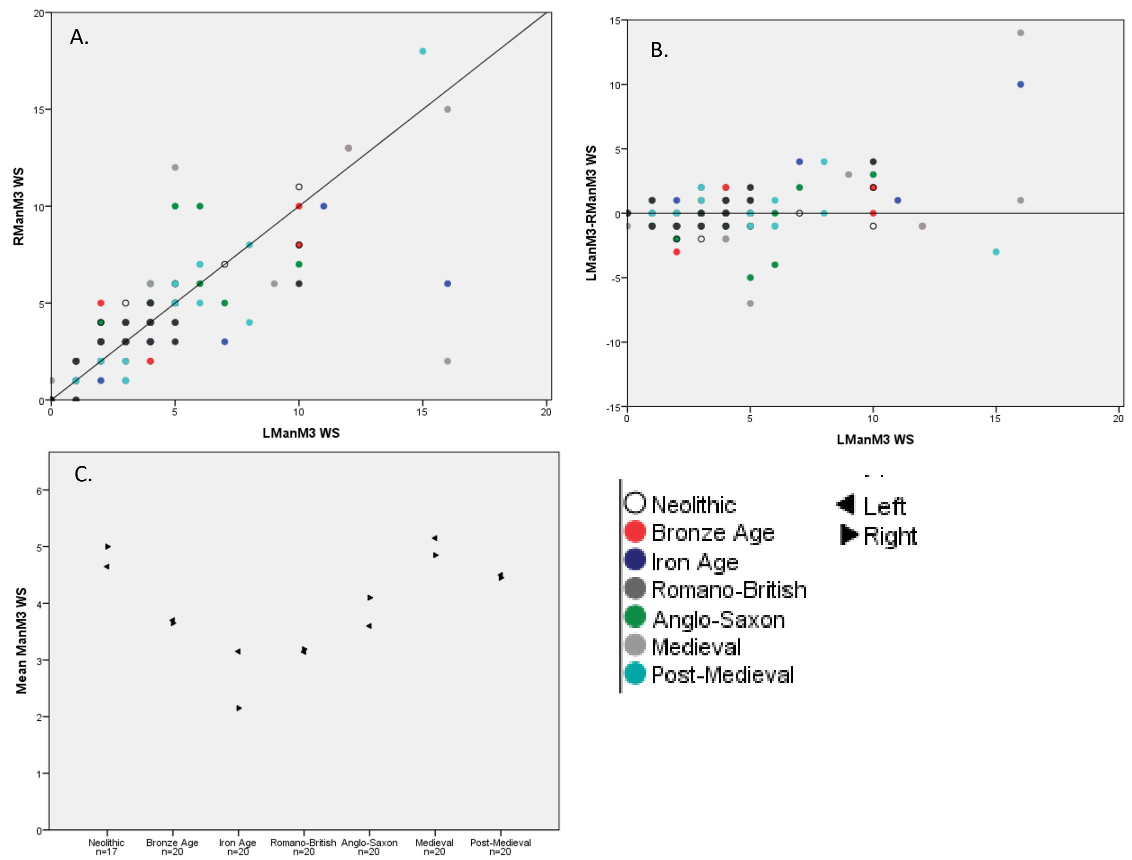


Figure 7.1.24. Plots of wear stage (WS) of the left third (LManM3) and right third (RManM3) mandibular molar

A. Scatter plot of LManM3 WS by RManM3 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between LManM3 and RManM3 against LManM3 WS, with plotted line of equality (y=0)
C. Plotted mean WS for LManM3 and RManM3, by temporal sample

The significant Spearman correlation coefficient supports a good association between lower third left-right molar WS (n=138, r_s=0.86, p<0.001). Figure 7.1.24A shows as one ManM3 experienced wear so did its antimere, and that the points clustered around the line of absolute symmetry. WS difference between left and right ManM3s remained constant in relation to LMaxM1 WS supporting a similar rate of wear between left and right ManM3s in both the occlusal (Figure 7.1.24B). Some variation between molars was observed, shown by points falling around the line of equality. These differences, however, were not significant (Mann-Whitney z=-0.17, p=0.876). Figure 7.1.24C shows mean WS measurements between left-right ManM3s did not differ greatly for any temporal sample.

7.1.1.7 Summary

The above results show as one molar within an antimere pair experienced wear, so did its partner. Data points typically fell closely around the line of absolute symmetry supporting a similarity in wear measurement across molar pairs. The wear difference between left and right molars within a pair remained constant, in relation to the left molar wear measurements. This was true for all wear measurements, supporting a similarity in wear rate between molars. Wear between left and right molar pairs was similar but not identical, indicated by points falling around the line of equality. This difference, however, was not statistically significant. Thus, these results support the null hypothesis that left and right molar partners wear at a similar rate.

A comparison of left and right molars supports the traditional practice of using either the left or right molars to investigate dental wear, substituting its antimere when missing. Therefore, the analysis from this point onwards adopts this practice, i.e. using the left molars and the right molars when the lefts are missing or damaged.

7.1.2 Comparing wear rates in occlusal pairs

This section evaluates whether a single rate of wear can be applied to upper and lower molar partners, or if independent wear rates are required. The analysis described in 7.1 is repeated for each occlusal pair by molar type, and repeated for the four wear measurements: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

Null hypothesis: upper and lower molar partners wear at a similar rate

Based on the existing assumptions it is expected that:

- Molars within an occlusal pair will have strong correlation coefficients
- The wear difference between molars within an occlusal pair will be remain constant in relation to one another
- Molars within an occlusal pair will show statistically similar measurements of dental wear

7.1.2.1 Comparing upper and lower first molar wear

Average crown height (CH)

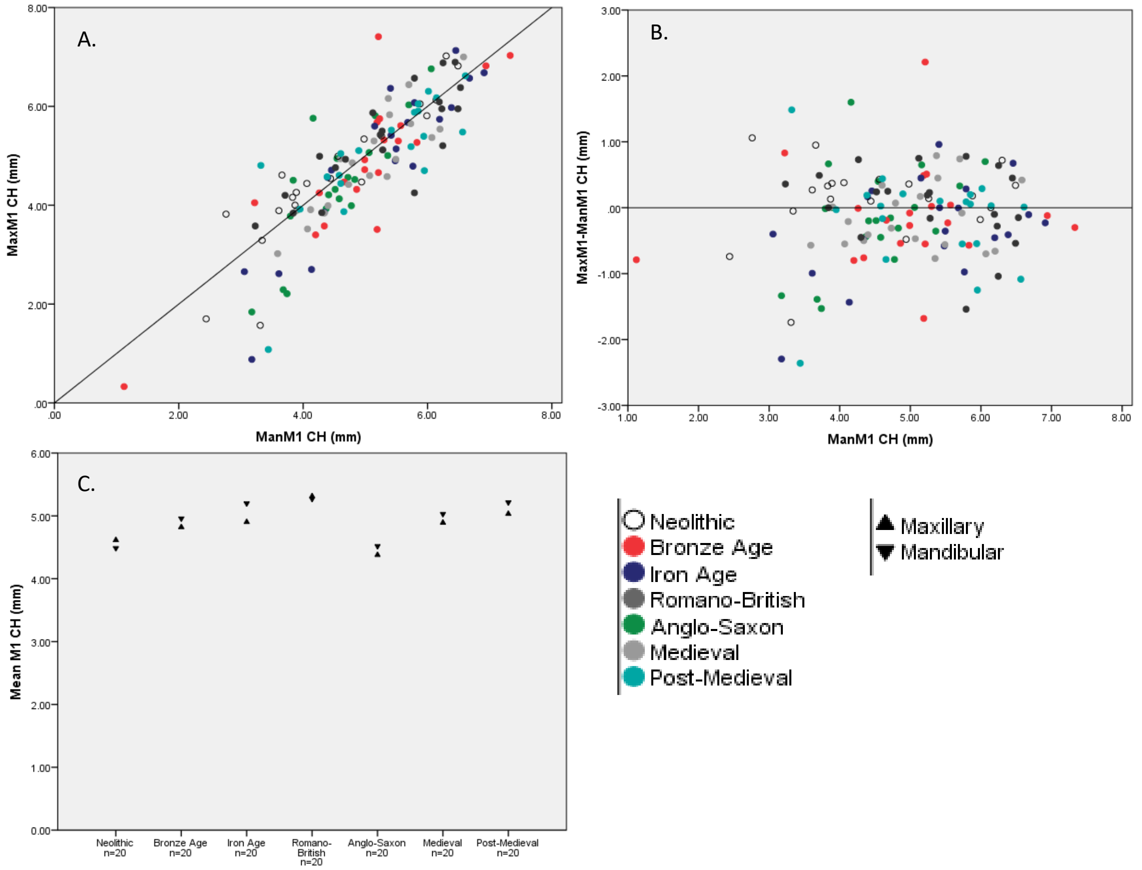


Figure 7.1.25. Plots of average crown height (CH) of the first upper (MaxM1) and first lower (ManM1) molars.

A. Scatter plot of MaxM1 CH by ManM1 CH, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CH difference between MaxM1 and ManM1 against ManM1 CH, with plotted line of equality (y=0)
C. Plotted mean CH for MaxM1 and ManM1, by temporal sample

Figure 7.1.25A shows that as one molar decreased in CH so did its occlusal partner. This was supported by a significant Pearson's correlation coefficient (n=140, r=0.86, p<0.001). The points fell around the line of absolute symmetry, supporting a similar CH on both upper and lower M1s. Figure 7.1.25B shows any difference in CH between upper and lower M1s remained constant in relation to ManM1 CH, supporting a similar wear rate on both molars. Points fell around the line of equality indicating CH was not identical in the first occlusal pair. This difference was not significant (Independent T-Test t(278)=-0.73, p=0.468). Mean CH between upper and lower first molars did not differ greatly for any temporal sample (Figure 7.1.25C).

Crown Index (CI)

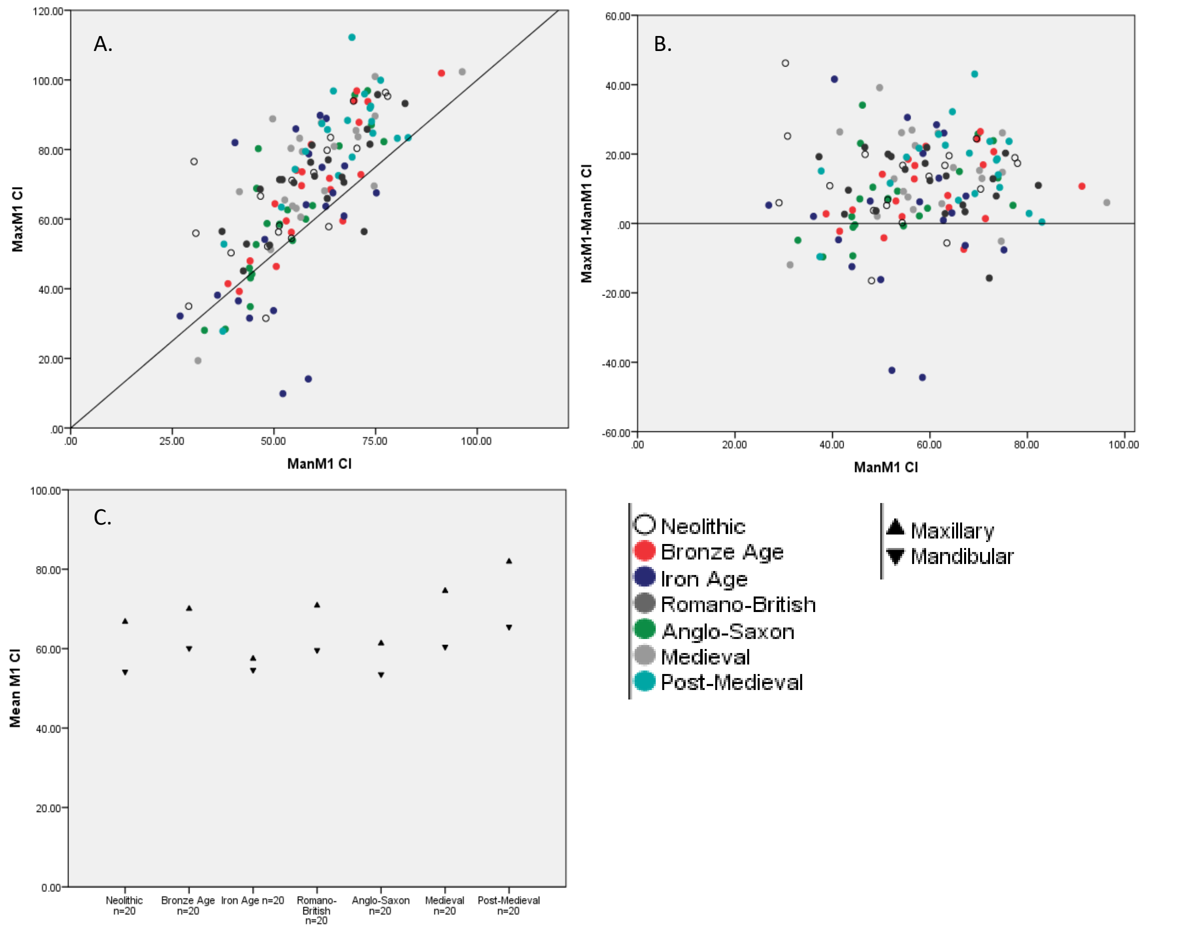


Figure 7.1.26. Plots of crown index (CI) of the first upper (MaxM1) and first lower (ManM1) molars

A. Scatter plot of MaxM1 CI by ManM1 CI, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CI difference between MaxM1 and ManM1 against ManM1 CI, with plotted line of equality (y=0)
C. Plotted mean CI for MaxM1 and ManM1, by temporal sample

Figure 7.1.26A shows that as one molar experienced CI loss so did its occlusal partner. This was supported by a significant Pearson's correlation coefficient (n=140, r=0.74, p<0.001). Points fell in a linear pattern above the line of absolute symmetry indicating a difference in CI. Figure 7.1.26B shows 117/140 (84%) points fell above the line of equality, with upper first molars having a larger CI compared to their occlusal partner. This difference was found to be significant (Independent T-Test t(278)=5.18, p<0.001). The difference between upper and lower M1s remained constant in relation to ManM1 CI indicating a similar rate of wear on both molars. Therefore, the difference in CI can be contributed to a difference in molar morphology between the upper and lower ManM1s. Figure 7.1.26C shows mean CI was greater in the MaxM1 compared to the ManM1 for all temporal samples.

Percent of exposed dentine (%DE)

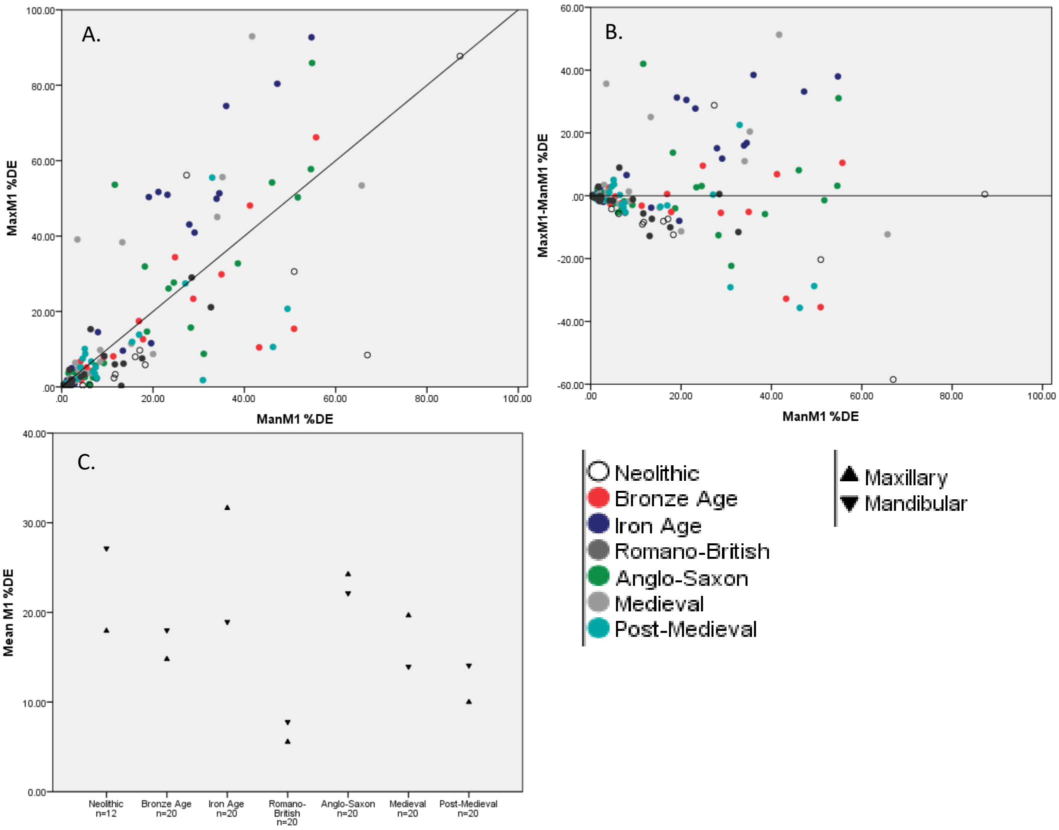


Figure 7.1.27. Plots of percent of exposed dentine (%DE) of the first upper (MaxM1) and first lower (ManM1) molars

A. Scatter plot of MaxM1 %DE by ManM1 %DE, with plotted line of absolute symmetry (y=x)

B. Scatter plot of %DE difference between MaxM1 and ManM1 against ManM1 %DE, with plotted line of equality (y=0)

C. Plotted mean %DE for MaxM1 and ManM1, by temporal sample

Plotting MaxM1 %DE against ManM1 %DE showed as one molar experienced dental wear so did its occlusal partner (Figure 7.1.27A). This was supported by a significant Spearman's coefficient (n=132, r_s=0.85, p<0.001). Points clustered around the line of absolute symmetry when dentine exposure was below 20%DE, but became more varied and were less strongly clustered around the line of symmetry as more dentine was exposed. This is further demonstrated in Figure 7.1.27B, where points fell close to the line of equality with minimal wear. At higher levels of exposed dentine, %DE difference between upper and lower molars increased. This difference, however, was not significant (Mann-Whitney z=-1.15 p=0.252). The broadly horizontal pattern in Figure 7.1.27B indicates a similar rate of wear on both upper and lower M1s, which remained constant in relation to one another.

Figure 7.1.27C shows minimal difference in mean %DE for upper and lower first molar by temporal sample. Only the Neolithic and Iron Age samples showed a large difference in mean %DE. Figure 7.1.28 shows a single individual (HBG HN1) may be skewing the mean %DE value for the Neolithic sample. Iron Age molars had a higher %DE on their upper first molars compared to their occlusal partners. Independent T-Tests for both the Neolithic and Iron Age sample, however, were not significant (Table 7.1.2).

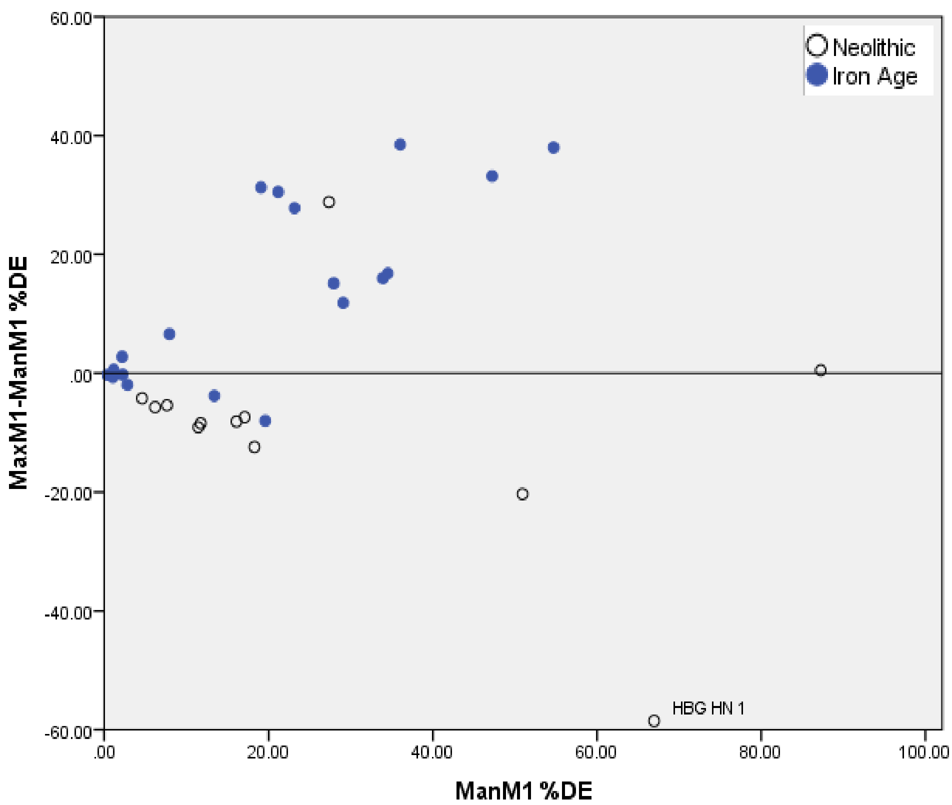


Figure 7.1.28. Scatter plot of %DE difference between MaxM1 and ManM1 against ManM1 %DE, with plotted line of equality (y=0)

Table 7.1.2. Results for Independent T-Test for percent of exposed dentine in first occlusal pairs for the Neolithic and Iron Age sample.

Sample	n pairs	Independent T-Test
Neolithic	12	t(22)=-0.83, p=0.414
Iron Age	20	t(38)=1.64, p=0.110

Wear Stage (WS)

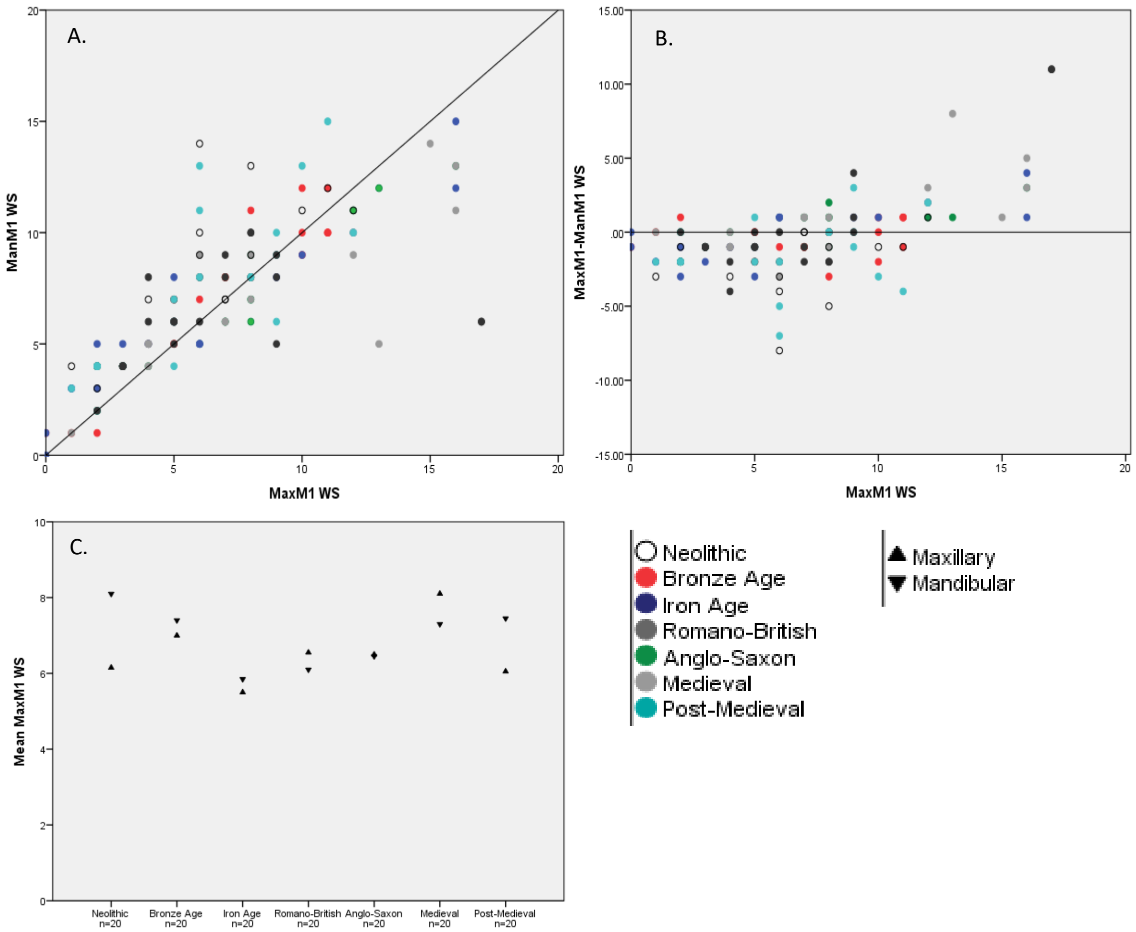


Figure 7.1.29. Plots of wear stage (WS) of the first upper (MaxM1) and first lower (ManM1) molars

A. Scatter plot of MaxM1 WS by ManM1 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between MaxM1 and ManM1 against ManM1 WS, with plotted line of equality (y=0)
C. Plotted mean WS for MaxM1 and ManM1, by temporal sample

Figure 7.1.29A shows as one molar experienced dental wear so did its occlusal partner. This was supported by a significant Spearman's correlation coefficient (n=140, r_s=0.85, p<0.001). Points fell around the line of absolute symmetry, suggesting a similar WS on first molar occlusal partners. Figure 7.1.29B shows WS was not identical on upper and lower M1s with points falling around the line of equality. This difference was not significant (Mann-Whitney z=-1.35, p=0.178) and remained constant, suggesting a similar rate of wear on both molars. Mean WS wear measurements between upper and lower M1s did not differ greatly for any temporal sample (Figure 7.1.29C).

7.1.2.2 Comparing upper and lower second molar wear

Average crown height (CH)

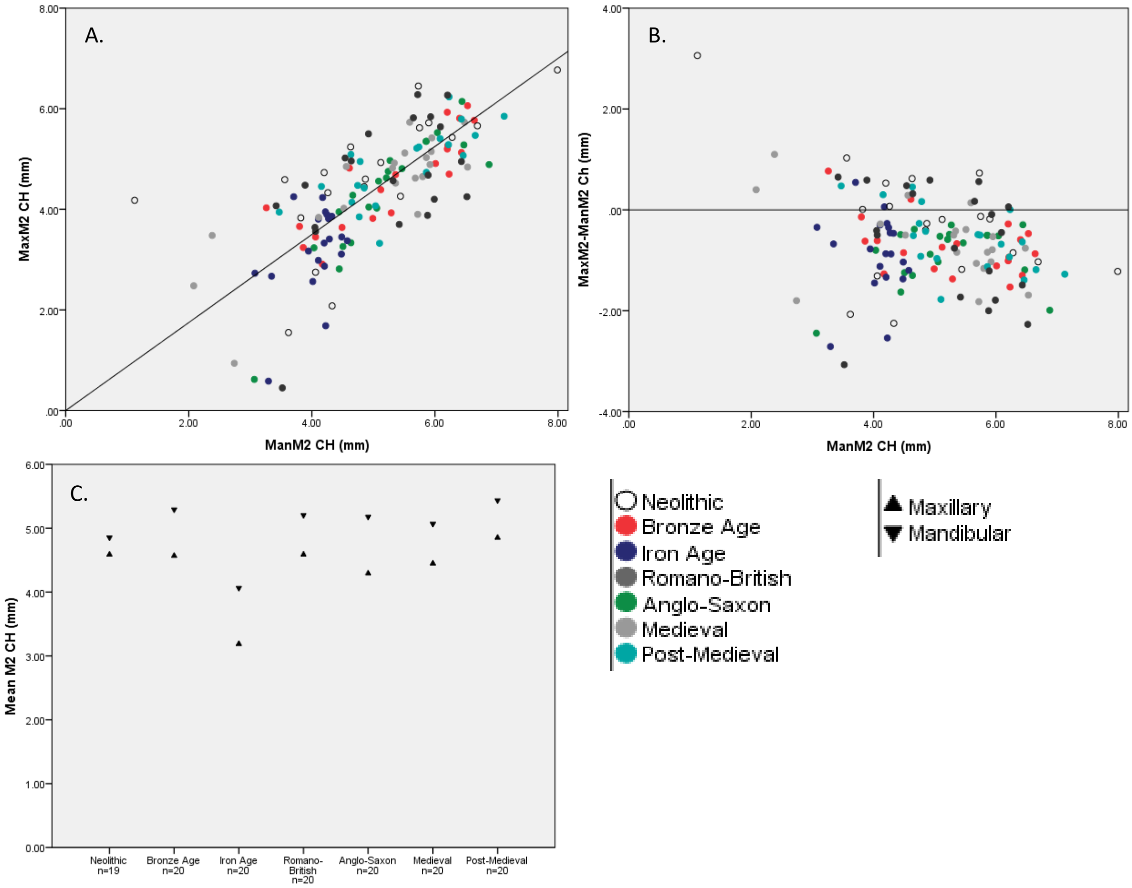


Figure 7.1.30. Plots of average crown height (CH) of the second upper (MaxM2) and second lower (ManM2) molars

A. Scatter plot of MaxM2 CH by ManM2 CH, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CH difference between MaxM2 and ManM2 against ManM2 CH, with plotted line of equality (y=0)
C. Plotted mean CH for MaxM2 and ManM2, by temporal sample

Plotting upper and lower M2 CH showed as one molar lost CH so did its occlusal partner (Figure 7.1.30A). This was supported by a significant Pearson's correlation coefficient (n=139, r=0.74, p<0.001). Points clustered quite around the line of absolute symmetry, indicating a difference in CH between the molars. An examination of Figure 7.1.30B shows the majority of points, n=111/139 (80%), fell below the line of equality, indicating individuals had a larger CH in their lower second molars compared with their upper M2. This difference in CH was significant according to an Independent T-Test (Independent T-Test t(276)=-4.74, p<0.001). The horizontal pattern of points in Figure 7.1.30B indicates the difference in CH between upper and lower M2s remained constant in relation to ManM2 CH, supporting a similar rate of wear. Figure 7.1.30C shows a difference in mean CH for upper and lower second molars, indicating a difference in crown height between M2 molar partners. This pattern was observed in all temporal samples. These results suggests a difference in molar morphology between upper and lower M2s.

Crown index (CI)

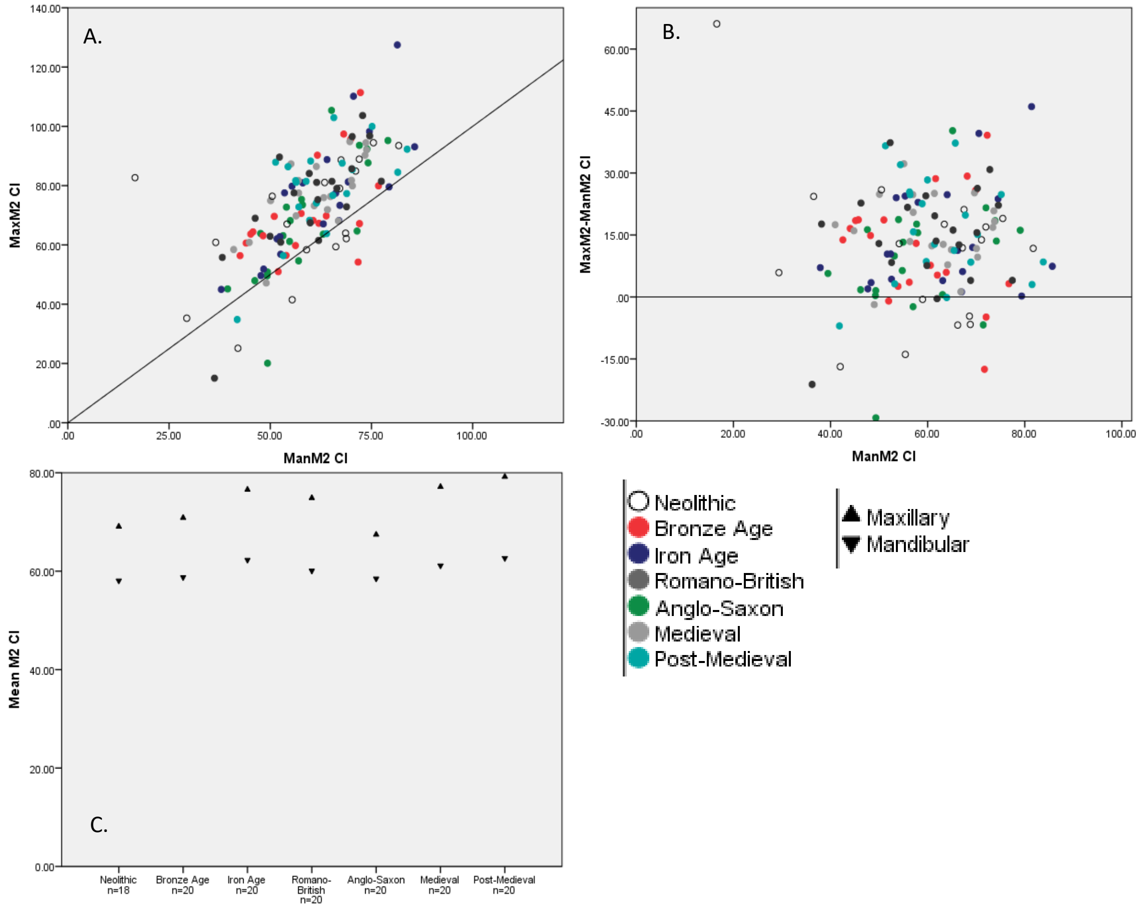


Figure 7.1.31. Plots of crown index (CI) of the second upper (MaxM2) and second lower (ManM2) molars

A. Scatter plot of MaxM2 CH by ManM2 CI, with plotted line of absolute symmetry (y=x)
B. Scatter plot of CI difference between MaxM2 and ManM2 against ManM2 CI, with plotted line of equality (y=0)
C. Plotted mean CI for MaxM2 and ManM2, by temporal sample

Figure 7.1.31A shows as one molar lost CI so did its occlusal partner. This was supported by a significant Pearson's correlation coefficient (n=138, r=0.67, p<0.001). Points fell in a linear pattern above the line of absolute symmetry, indicating a difference in CI between the molars. The majority of individuals, n=122/138 (88%), fell above the line of equality, indicating a larger CI in the maxillary molars in contrast to their occlusal partner. An Independent T-Test shows that this difference was significant (Independent T-Test t(274)=7.31, p<0.001). The horizontal pattern in Figure 7.1.31B shows difference in CI between the upper and lower M2s remained constant in relation to ManM2 CI, supporting a similar wear rate for both molars. Upper M2s consistently showed a larger mean CI across the temporal samples (Figure 7.1.31C).These results suggests a difference in molar morphology between upper and lower M2s.

Percent of exposed dentine (%DE)

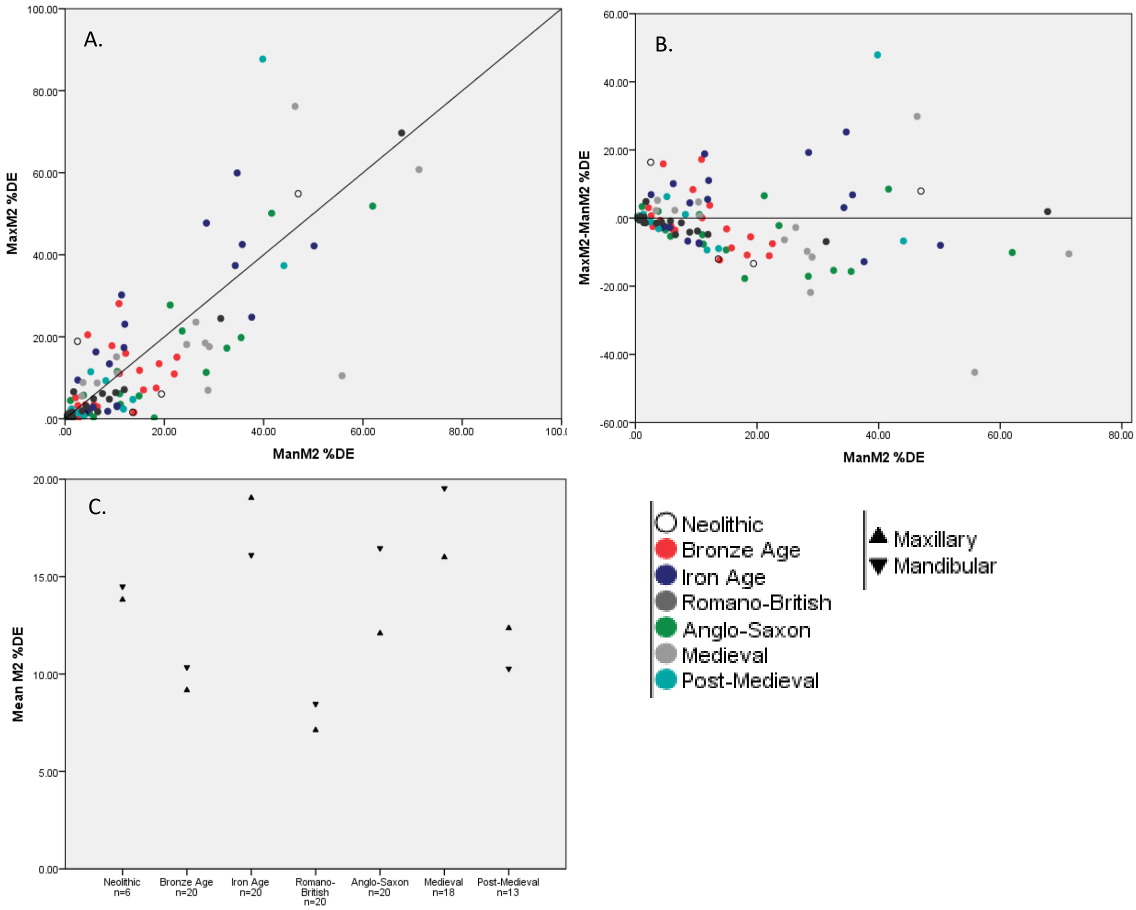


Figure 7.1.32. Plots of percent of exposed dentine (%DE) of the second upper (MaxM2) and second lower (ManM2) molars

A. Scatter plot of MaxM2 %DE by ManM2 %DE, with plotted line of absolute symmetry (y=x)

B. Scatter plot of %DE difference between MaxM2 and ManM2 against ManM2 %DE, with plotted line of equality (y=0)

C. Plotted mean %DE for MaxM2 and ManM2, by temporal sample

As one M2 increased in %DE so did its occlusal partner (Figure 7.1.32A). This was supported by a significant Spearman's coefficient (n=117, r_s=0.81, p<0.001). The points formed a tight cluster around the line of absolute symmetry at low values of %DE, increasing in spread as %DE increased. This suggests %DE was similar on both molars with minimal wear, but became varied with increased wear. Figure 7.1.32B supports this, with points clustering around the line of equality at low ManM2 %DE, becoming more varied as %DE increased on the ManM2. This indicates at low %DE the molars are unlikely to differ greatly in %DE, but this becomes varied as dental wear increases. A broadly horizontal pattern in Figure 7.1.32B indicates a similar rate of wear on both upper and lower M2s. There was no significant difference in %DE between the upper and lower M2s (Mann-Whitney z=-0.47, p=0.638). Figure 7.1.32C shows a small difference between mean %DE in all temporal samples.

Wear stage (WS)

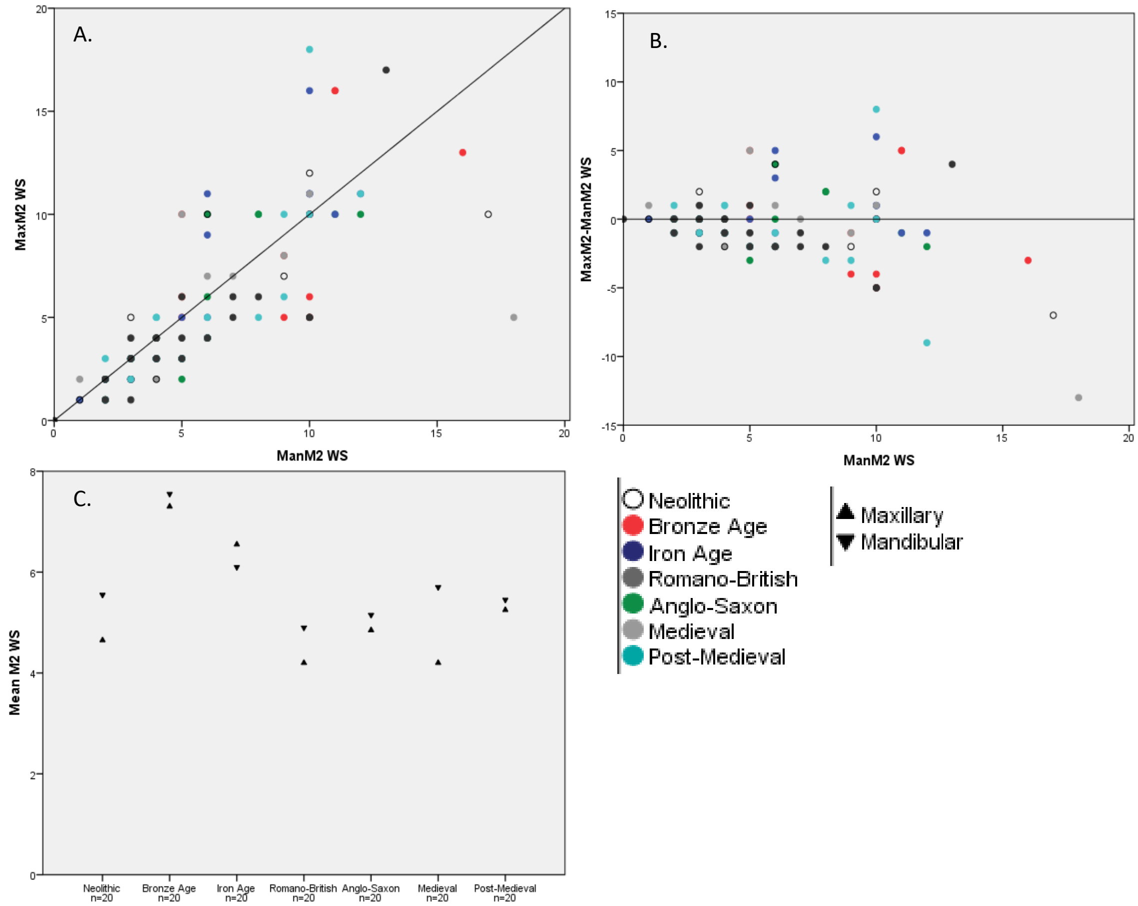


Figure 7.1.33. Plots of wear stage (WS) of the second upper (MaxM2) and second lower (ManM2) molars

A. Scatter plot of MaxM2 WS by ManM2 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between MaxM2 and ManM2 against ManM2 WS, with plotted line of equality (y=0)
C. Plotted mean WS for MaxM2 and ManM2, by temporal sample

Plotting WS for upper and lower M2s showed as one molar experienced wear so did its occlusal partner (Figure 7.1.33A). This was supported by a significant Spearman's coefficient (n=140, r_s=0.82, p<0.001). Points fell clustered around the line of absolute symmetry, suggesting similarity in WS between the two molars. Figure 7.1.33B shows a broadly horizontal pattern, indicating WS difference between upper and lower M2 remained constant and molars wore at a similar rate. Points fell around the line of equality, showing some difference between upper and lower M2s. This difference was not significant (Mann-Whitney z=-1.70, p=0.089). Figure 7.1.33C shows the difference in mean WS for upper and lower second molars was not great for any temporal sample.

7.1.2.3 Comparing upper and lower third molar wear

Average crown height (CH)

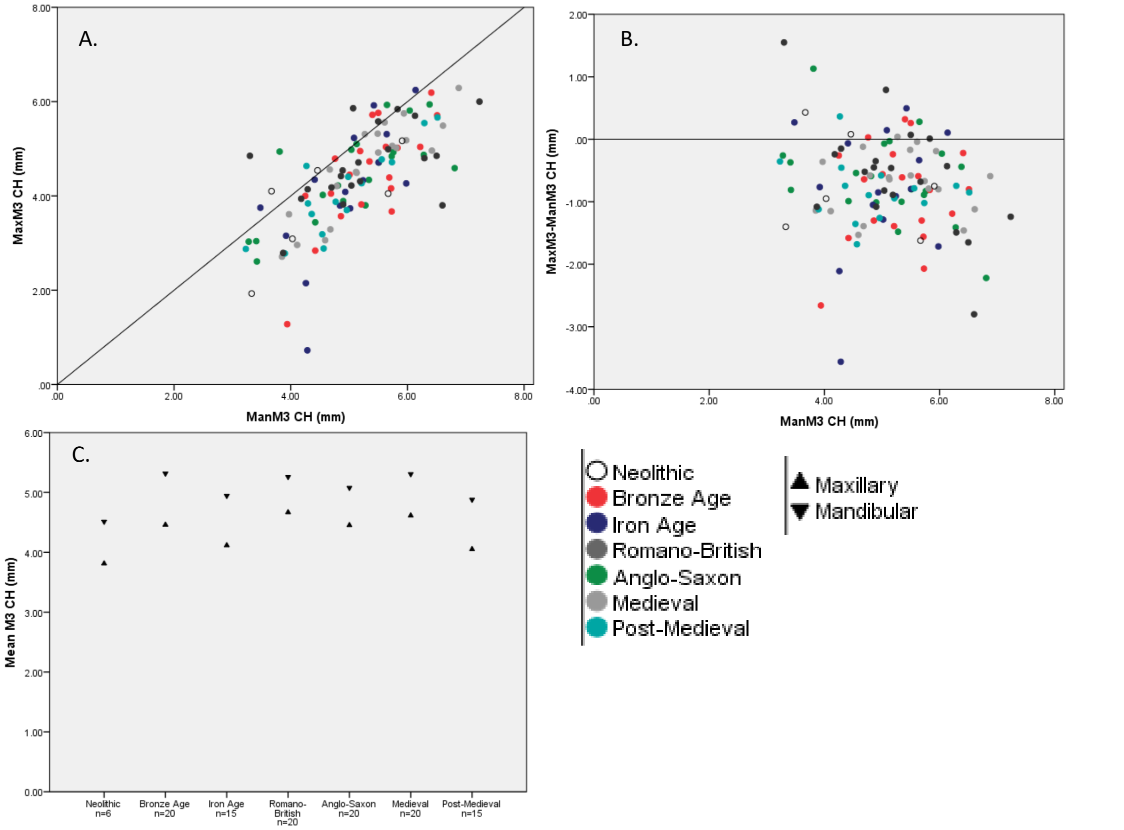


Figure 7.1.34. Plots of crown index (CH) of the third upper (MaxM3) and third lower (ManM3) molars

A. Scatter plot of MaxM3 CH by ManM3 CI, with plotted line of absolute symmetry (y=x)

B. Scatter plot of CH difference between MaxM3 and ManM3 against ManM3 CH, with plotted line of equality (y=0)

C. Plotted mean CH for MaxM3 and ManM3, by temporal sample

Figure 7.1.34A shows as one molar decreased in CH so did its occlusal partner, this was supported by a significant Pearson's correlation coefficient (n=116, r=0.72, p<0.001). These points fell in a linear pattern below the line of absolute symmetry, indicating some difference in CH between the molars. The broadly horizontal pattern in Figure 7.1.34B suggests CH difference between upper and lower M3s remained constant, supporting a similar rate of wear between the molars. The majority of points, n=99/116 (85%), fell below the line of equality, showing a difference in CH with the lower molars having a larger CH compared to their occlusal partner. This difference in CH was significant (Independent T-Test t(230)=- 5.67, p<0.001). These results support a similar rate of wear between upper and lower M3s that remained constant. Each period sample shows a consistent difference in mean CH between the upper and lower M3s, with a larger CH in the lower third molars (Figure 7.1.34C).The difference between upper and lower M3s is therefore a result of difference in molar morphology rather than a difference in wear rate.

Crown index (CI)

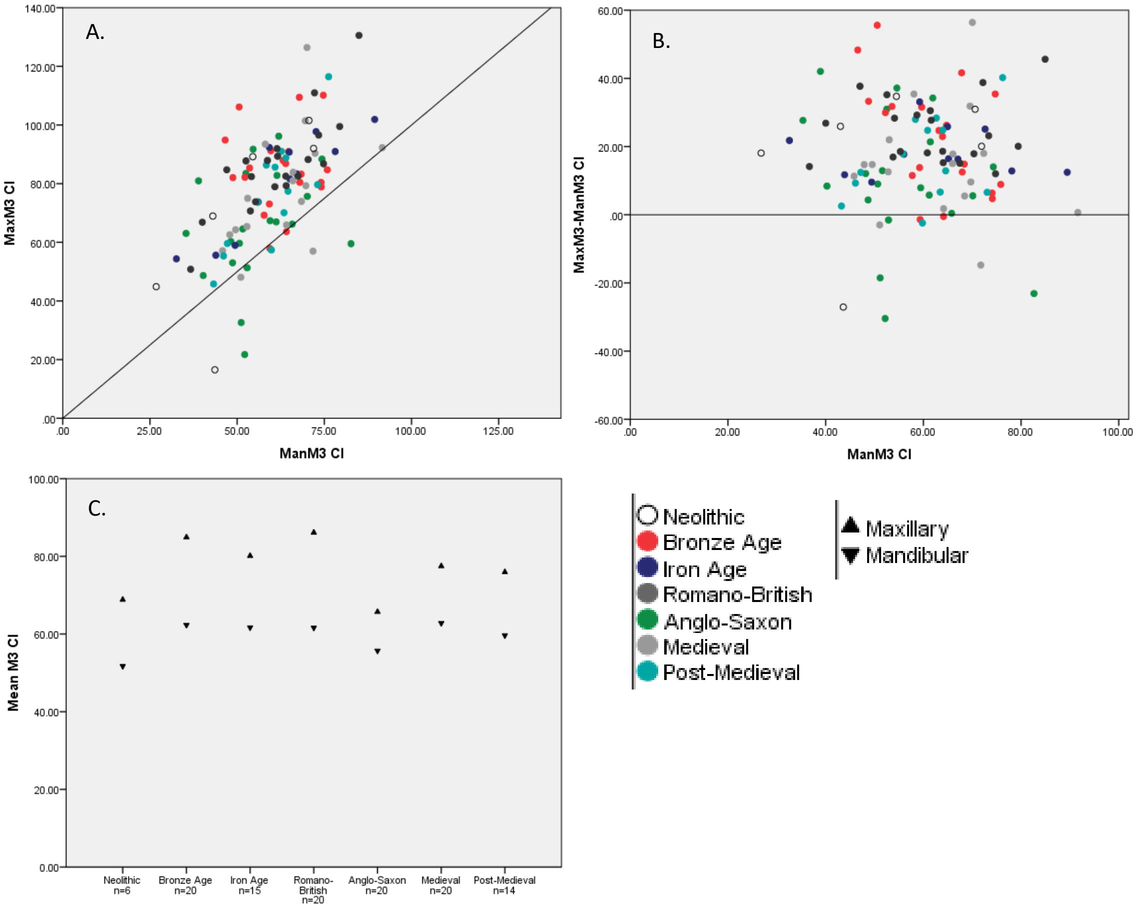


Figure 7.1.35. Plots of average crown height (CI) of the third upper (MaxM3) and third lower (ManM3) molars

A. Scatter plot of MaxM3 CI by ManM3 CI, with plotted line of absolute symmetry (y=x)

B. Scatter plot of CI difference between MaxM3 and ManM3 against ManM3 CI, with plotted line of equality (y=0)

C. Plotted mean CI for MaxM3 and ManM3, by temporal sample

Plotting upper and lower M3 CI showed an association between the molars, and as one molar experienced wear so did its occlusal partner (Figure 7.1.35A). This was supported by a significant Pearson’s coefficient ($n=115$, $r=0.60$, $p<0.001$). Points fell above the line of absolute symmetry, showing a difference in CI between the molars. The majority of individuals, n=97/115 (84%), in Figure 7.1.35B fell above the line of equality, indicating a larger CI in the upper molars in contrast to their occlusal partner. This difference in CI between molars was found to be significant (Independent T-Test $t(228)=8.05$, $p<0.001$). The broadly horizontal pattern, however, suggests a similar rate of CI wear for the upper and lower M3s and that this difference remained constant. Each temporal sample showed a larger mean CI in their upper M3 compared with their lower M3

(Figure 7.1.35C). These results suggests a difference in morphology between upper and lower M3s.

Percent of exposed dentine (%DE)

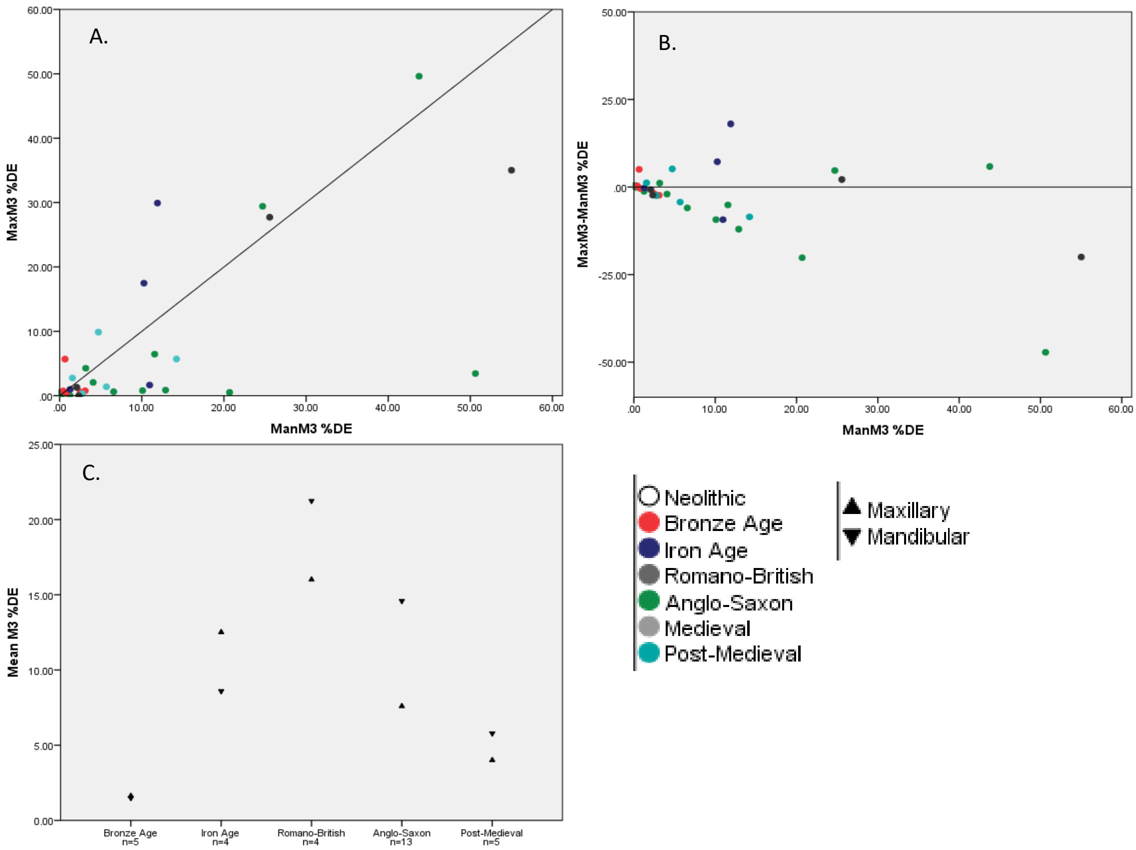


Figure 7.1.36. Plots of percent of dentine exposure (%DE) of the third upper (MaxM3) and third lower (ManM3) molars

A. Scatter plot of MaxM3 %DE by ManM3 %DE, with plotted line of absolute symmetry (y=x)

B. Scatter plot of %DE difference between MaxM3 and ManM3 against ManM3 %DE, with plotted line of equality(y=0)

C. Plotted mean %DE for MaxM3 and ManM3, by temporal sample

A significant Spearman's correlation coefficient supports a relationship between upper and lower third molar %DE measurements (n=31, r_s=0.64, p<0.001). As one M3 increased in %DE so did its occlusal partner (Figure 7.1.36A). Points fell around the line of absolute symmetry at low values of %DE, increasing in spread as %DE increased. This suggests %DE was similar on both molars with minimal wear, but became varied with increasing wear. A similar pattern was observed in Figure 7.1.36B, suggesting some difference in %DE between upper and lower M3s. A Mann-Whitney test just missed significance (z=-1.91, p=0.056), indicating the overall difference was between molars was not statistically significant. Figure 7.1.36C shows a difference in mean %DE for each temporal sample, excluding the Neolithic and Medieval samples as they lacked any M3 pairs with measurable %DE. The largest difference was 7%DE in the Anglo-Saxon sample. This indicates mean %DE difference was not large between upper and lower third molars, and that third molars wore at a similar rate.

The sample size for examining the wear relationship between upper and lower M3s was small for each temporal sample compared to the other wear measurements. The Neolithic and Medieval samples were excluded due to no individuals having exposed dentine on both the third upper and lower molars. Figure 7.1.36A shows few individuals with more than 20%DE on either molar, indicating that few individuals obtained a high level of exposed dentine on the third molars.

Wear Stage (WS)

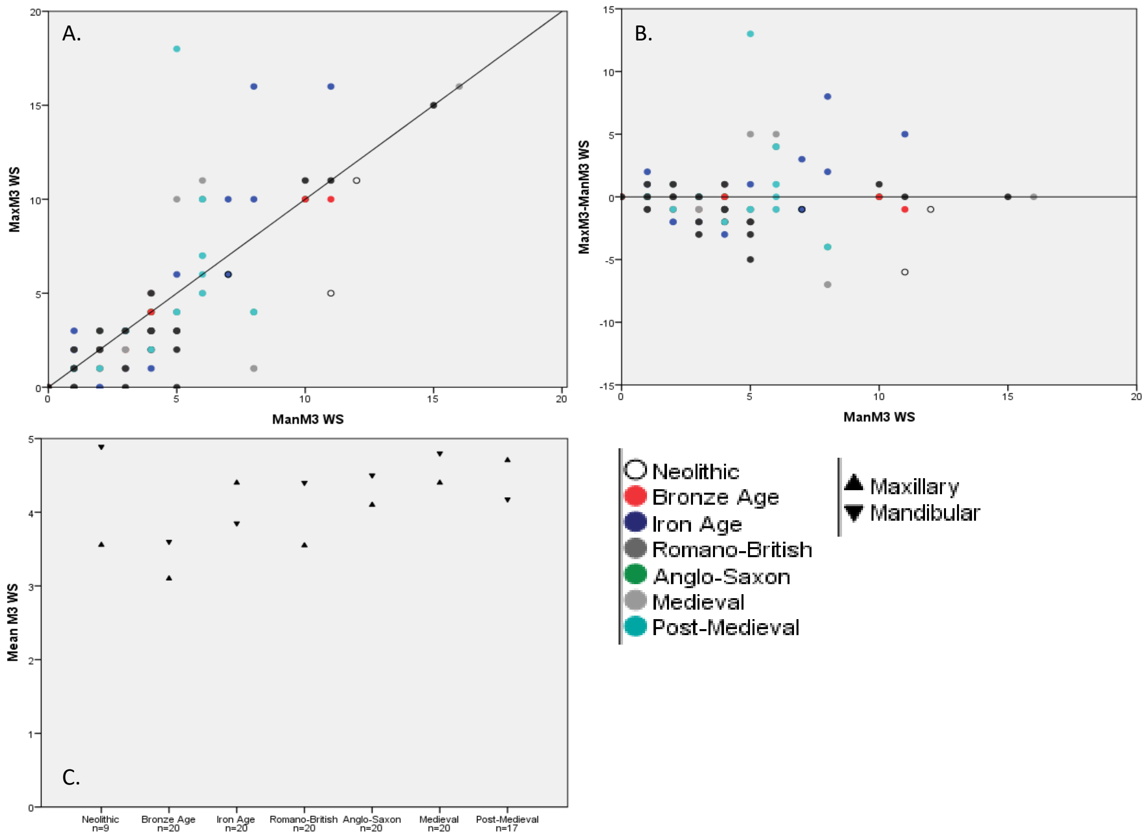


Figure 7.1.37. Plots of wear stage (WS) of the third upper (MaxM3) and third lower (ManM3) molars

A. Scatter plot of MaxM3 WS by ManM3 WS, with plotted line of absolute symmetry (y=x)
B. Scatter plot of WS difference between MaxM3 and ManM3 against ManM3 WS, with plotted line of equality (y=0) C. Plotted mean WS for MaxM3 and ManM3, by temporal sample

The third occlusal pair was significantly correlated for WS (n=126, r_s=0.79, p<0.001). This supports the relationship in Figure 7.1.37A that as WS increased on one molar WS also increased in its occlusal partner. Points fell around the line of absolute symmetry indicating a degree of similarity between the molars. A broadly horizontal pattern in Figure 7.1.37B suggests WS difference between upper and lower M3s remained constant and indicates a broadly similar wear rate on third molars. A Mann-Whitney test showed a significant difference in WS between the third molars (Mann-Whitney z=-2.19, p=0.028), although this was not deemed significant when using the Benjamini-Hochberg procedure to control the false discovery rate (Appendix B). However, Figure 7.1.37C and Table 7.1.3 shows a maximum difference in mean WS of one stage, indicating an overall small difference in WS between upper and lower M3s across the temporal samples. These results suggest the overall difference in wear stage between upper and lower M3s is not great and that they wear at a similar rate.

Table 7.1.3 Mean Wear Stage (WS) for the upper (Max) and lower (Man) third molars (M3) by temporal sample

Sample	MaxM3 Mean WS	ManM3 Mean WS	Difference in Mean WS
Neolithic	3.6	4.9	-1.3
Bronze Age	3.1	3.6	-0.5
Iron Age	4.4	3.9	0.6
Romano-British	3.6	4.4	-0.9
Anglo-Saxon	4.1	4.5	-0.4
Medieval	4.4	4.8	-0.4
Post-Medieval	4.7	4.2	0.5

7.1.2.4 Summary

As one molar within an occlusal experienced wear so did its occlusal partner. This was true for all wear measurements and all molar pairs. Data points for the crown height measurements, including average crown height (CH) and crown index (CI) did not necessarily cluster around the line of absolute symmetry. CH was similar in upper and lower first molars, but showed a greater CH in lower molars for the second and third occlusal pair. CH wear difference between upper and lower molars remained constant for all occlusal pairs, in relation to lower CH, supporting a similar rate of CH wear between all occlusal partners and all temporal periods. This pattern was also observed in the CI measurements. Crown Index was significantly different across all occlusal partners, with a larger CI in the upper molars. This pattern was observed in all temporal samples. This difference remained constant, in relation to lower CI measurements, supporting a similar rate of CI wear between occlusal partners.

Differences in CH and CI measurements that remained constant between occlusal partners support a difference in molar morphology rather than a difference in wear rate. The larger CH measurements in lower molars but larger CI measurements in upper molars indicated maxillary molars are smaller both in crown height and tooth width compared to mandibular molars. Occlusal partners are therefore different in size and shape. This difference in crown height measurements was observed throughout the life of the dentition indicating a difference was present before either molar within a pair experienced wear. As occlusal partners erupt at approximately the same age any differences must result from a difference in starting crown height. The observation means occlusal partners wear at a similar rate despite having a difference in morphology.

The occlusal wear measurements, percent of exposed dentine (%DE) and wear stage (WS), were not significantly different between upper and lower molars. Data points typically fell around the lines of absolute symmetry and equality supporting a similarity in wear measurements across occlusal pairs. Wear difference between upper and lower molars remained constant, in relation to lower molar wear. These results support a similar rate of occlusal wear between occlusal partners.

7.2 Wear rates across molar types

Section 7.1 established that occlusal and antimere molar pairs wear at a similar rate. This section examines wear rates along the tooth row and aims to establish if a single rate of wear can be applied to all molar types, or if molar-specific wear rates are required. This section also aims to investigate whether the wear rates between molars along a tooth row remain constant throughout the life of the dentition, a key assumption of the Miles Method and Modified Miles Method.

Section 7.2.1 examines the wear relationship between the first mandibular (ManM1) and second (ManM2) molars, while 7.2.2 evaluates the wear relationship between the second and third (ManM3) molars. Finally, the relationship between wear on the first and third molars is examined (Section 7.2.3).

Correlation coefficients between two molars measure the strength of the relationship. These relationships were visualised using scatter plots, plotting the earlier erupting molar against the later erupting molar (i.e. ManM1 vs ManM2, ManM2 vs ManM3, ManM1 vs ManM3). It is expected that the earlier erupting molar will show a more advanced degree of wear compared to the later erupting molar. Thus, a line depicting the relationship expected if two molars wore at a similar rate was plotted, henceforth named the line of equal wear. Points falling on this line of equal wear, with a slope of one, indicates two molars wear at a similar rate. Points falling in a linear pattern with a slope other than one this indicates two molars wore at different rates, but that this difference remained the same throughout life. A non-linear relationship suggests the two molars wore at different rates, which varied throughout life.

If two molars wore at a similar rate it is expected that the difference in wear measurement observed which exists when the later molar within a pair erupts is maintained throughout life. This difference in wear between two molar forms the y-intercept for the line of equal wear.

To confirm the results observing the wear relationship between two molars within a tooth row, the wear difference between molars was plotted against wear of the earlier erupting molar. For example, the wear difference between the first and second mandibular molar (y-axis) was plotted against wear on the first mandibular molar (x-axis). A wear difference between two molars that remained constant indicated a similar rate of wear on both molars. A wear difference that increased or decreased as wear on the earlier erupting molar increased suggests a difference in wear rate on the two molars that remained constant. No clear patterning indicates a difference in wear rate on the two molars that did not remain constant.

Thus, thus section tests two hypotheses:

Null hypothesis A: there is a similar rate of wear on all molar types
Null hypothesis B: the rate of wear between molars remains constant throughout life of the dentition

The wear relationship between molars along the tooth row were examined using all wear measurements: average crown height (CH), crown index (CI), percent of exposed dentine (%DE), and wear stage (WS). Analysis was repeated for each pair of molars along the tooth row by temporal sample. It was decided to analyse the wear relationship by temporal sample as this thesis did not want to assume that all samples had a similar wear rate. Pooling samples has the potential obscure any difference in wear rates between molar pairs.

Based on existing assumptions it was expected that:

- Molar pairs along the tooth row will have significant correlation coefficients
- The earlier erupting molars will show a more advanced degree of wear compared to later erupting molars
- The wear gradient between two molars will remain constant throughout the life of the dentition

7.2.1 Comparing wear rates between the first and second mandibular molars

Average crown height (CH)

There was a clear relationship between ManM1 and ManM2 CH for all temporal samples, as ManM1 CH decreased ManM2CH also decreased. Pearson correlation coefficients supported this relationships (Figure 7.2.2A). All correlations were significant at the 1% level (Table 7.2.1).

Points clustered around the line of equal wear for the Neolithic, Iron Age, Anglo-Saxon, Medieval and Post-Medieval samples supporting a similar wear rate on the ManM1 and ManM2 for these samples (Figure 7.2.2A). A CH difference between the ManM1 and ManM2 that remained constant with increasing wear on the ManM1 further supports a similar CH wear rate the ManM1 and ManM2 (Figure 7.2.2B).

Table 7.2.1. Pearson correlation coefficients examining the wear relationship between first and second mandibular molar average crown height.

Sample	n	Pearson's coefficient (r)	P-value	Equation for the line of equal wear
Neolithic	61	0.75	<0.001	M2 CH = M1 CH + 0.7
Bronze Age	66	0.90	<0.001	M2 CH = M1 CH + 0.5
Iron Age	74	0.85	<0.001	M2 CH = M1 CH + 0.4
Romano-British	74	0.79	<0.001	M2 CH = M1 CH + 0.5
Anglo-Saxon	86	0.78	<0.001	M2 CH = M1 CH + 0.4
Medieval	56	0.85	<0.001	M2 CH = M1 CH + 0.6
Post-Medieval	46	0.84	<0.001	M2 CH = M1 CH + 0.3

The Bronze Age and Romano-British samples showed a slight increase in CH difference between the ManM1 and ManM2, which remained constant. This pattern indicates a difference in wear rate on the two molars (Figure 7.2.2B). However, the points clustered around the line of equal wear (Figure 7.2.2A), suggesting only a slight difference in CH wear rate.

A single outlier in the Romano-British sample (AC SK269) showed extensive wear to the buccal side of the ManM1, producing a low CH (Figure 7.2.1). This extensive wear was not observed on the ManM2, producing a large difference in CH. The ManM1 of individual AC SK269 had an oblique pattern of wear in a linguobuccal direction, causing a reduced crown height on the buccal side of the tooth.

The majority of points fell below the line of equality for all temporal samples, indicating a larger CH on the ManM2 compared with ManM1 CH (Figure 7.2.2B)

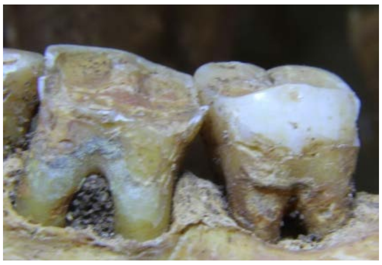


Figure 7.2.1 Buccal aspect of the ManM1 and ManM2 of Romano-British individual AC SK269 showing a larger difference in CH between the two molars

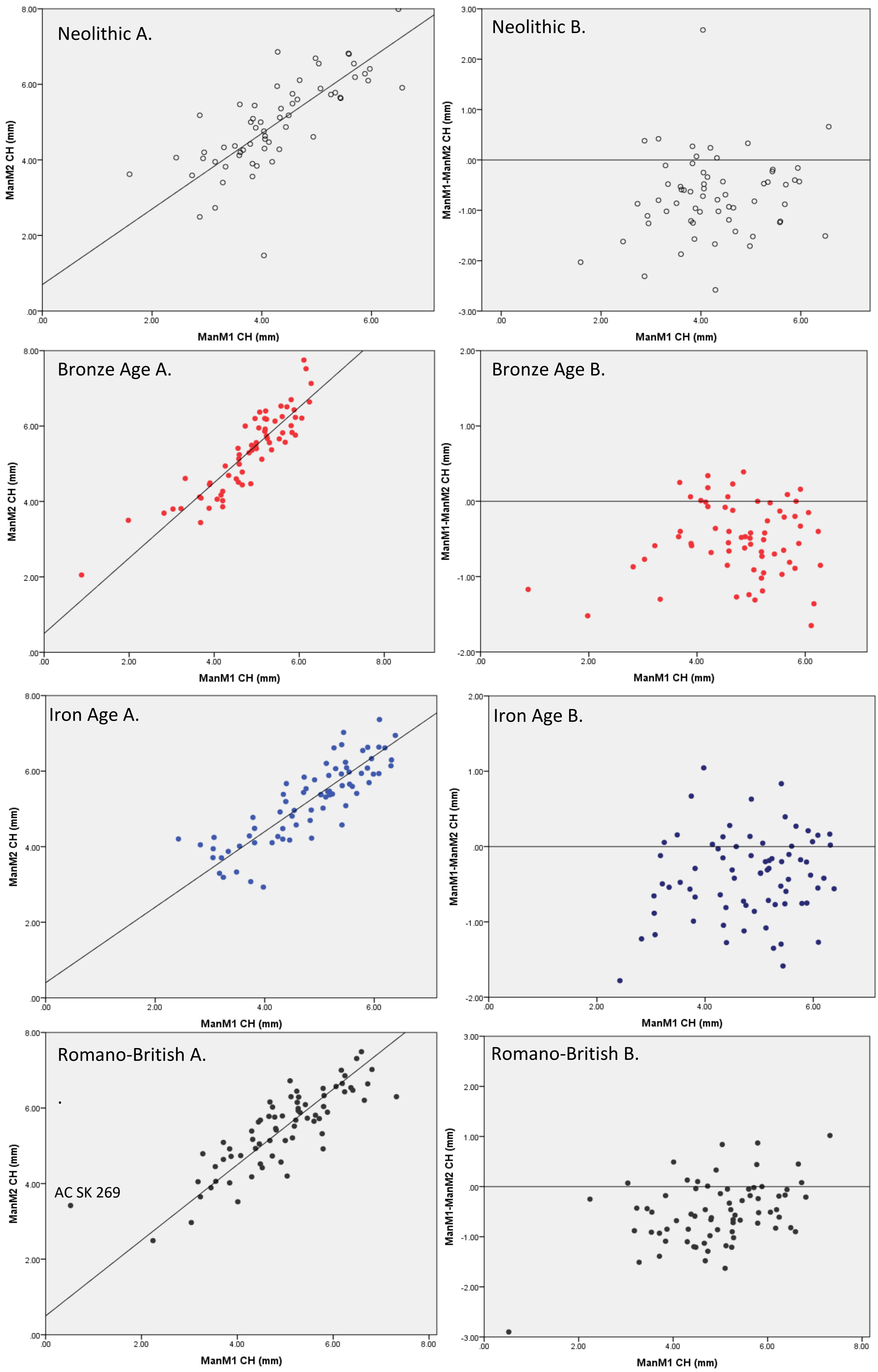


Figure 7.2.2. Plots of average crown height (CH) of the first (ManM1) and second (ManM2) molars by temporal sample.

A. scatter plot of ManM2 CH against ManM1 CH. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate.

B. Difference between ManM1 and ManM2 CH against ManM1 CH with a plotted line of equality (y=0).

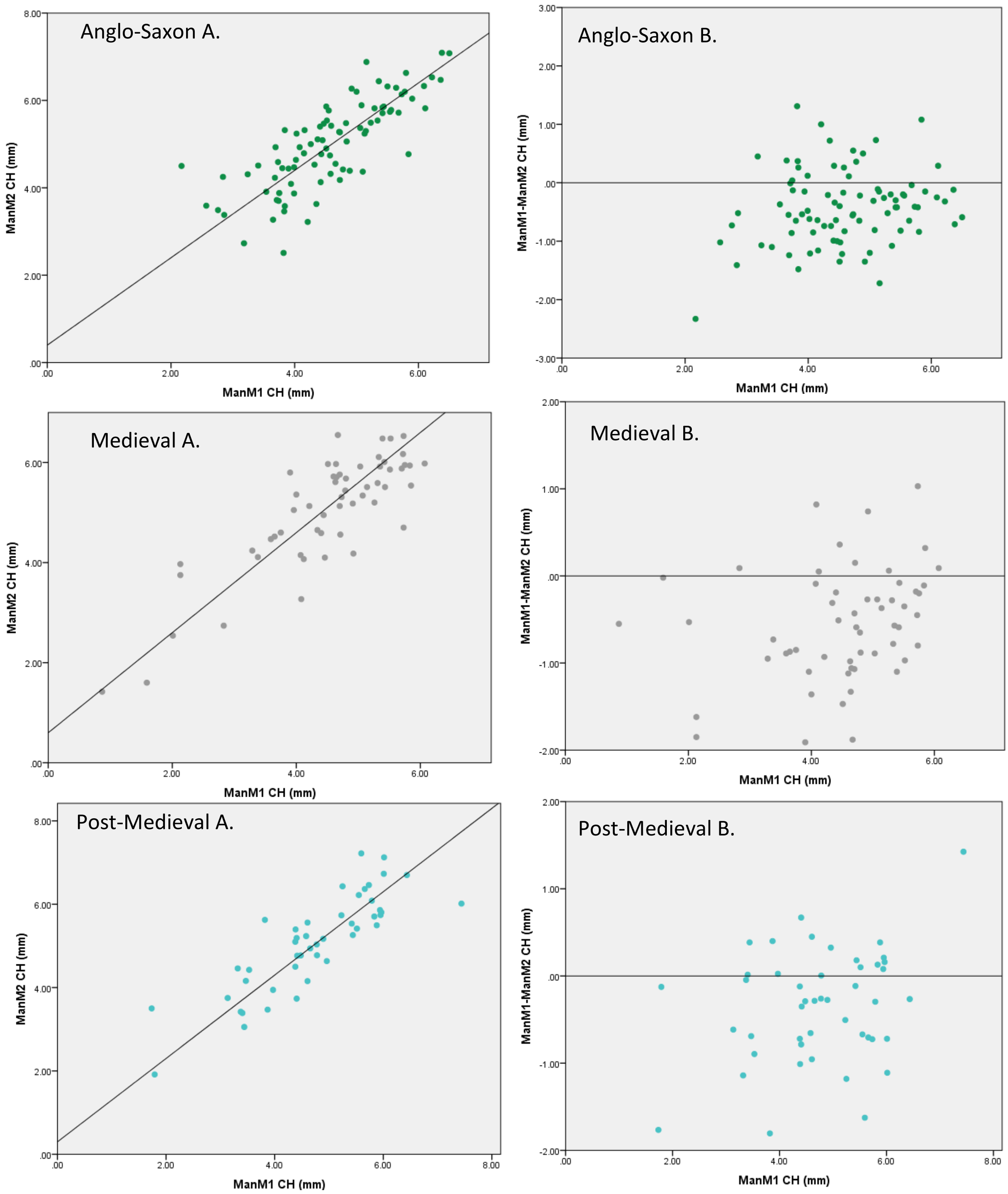


Figure 7.2.2 Continued. Plots of average crown height (CH) of the first (ManM1) and second (ManM2) molars by temporal sample.
A. scatter plot of ManM2 CH against ManM1 CH. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate.
B. Difference between ManM1 and ManM2 CH against ManM1 CH with a plotted line of equality (y=0).

Crown index (CI)

There was a good association between ManM1 and MAnM2 CI wear across all temporal samples. As the ManM1 experienced wear so did its partner ManM2. This relationship was supported by Pearson correlation coefficients, which were significant at the 1% level (Table 7.2.2). The majority of points fell below the line of equality in all temporal samples, indicating a larger CI in the ManM2 regions, compared to its ManM1 partner region as expected.

Points clustered around the line of equal wear for the Neolithic, Bronze Age, Iron Age Romano-British and Anglo-Saxon samples (Figure 7.2.3A). This indicates a similar rate of CI wear on the ManM1 and ManM2 for these samples. Figure 7.2.3B further supports this relationship showing the CI difference between the ManM1 and ManM2 remained constant relative to ManM1 CI.

The Medieval and the Post-Medieval samples had a wide spread of points around the line of similar wear (Figure 7.2.3A). It is therefore difficult to determine whether ManM1 and ManM2 had a similar CI wear rate. Figure 7.2.3B shows an increase in CI difference between the two molar regions relative to ManM1 CI for the Medieval and the Post-Medieval samples, indicating a difference in wear rate that remained constant.

A single outlier in the Romano-British sample, showing a comparatively large CI difference between the ManM1 and ManM2. This was the same outlier for the CH wear measurement (AC SK269). This ManM1 had an oblique pattern of wear, which was not observed in the ManM2, producing a small amount of enamel on the buccal side of the tooth.

Table 7.2.2. Pearson correlation coefficients examining the wear relationship between first and second mandibular molar crown index.

Sample	n	Pearson's coefficient (r)	P-value	Equation for the line of equal wear
Neolithic	59	0.69	<0.001	M2 CI = M1 CI + 8.1
Bronze Age	64	0.81	<0.001	M2 CI = M1 CI + 7.6
Iron Age	71	0.85	<0.001	M2 CI = M1 CI + 3.9
Romano-British	71	0.78	<0.001	M2 CI = M1 CI + 8.5
Anglo-Saxon	83	0.85	<0.001	M2 CI = M1 CI + 3.9
Medieval	53	0.76	<0.001	M2 CI = M1 CI + 6.5
Post-Medieval	44	0.74	<0.001	M2 CI = M1 CI + 6.3

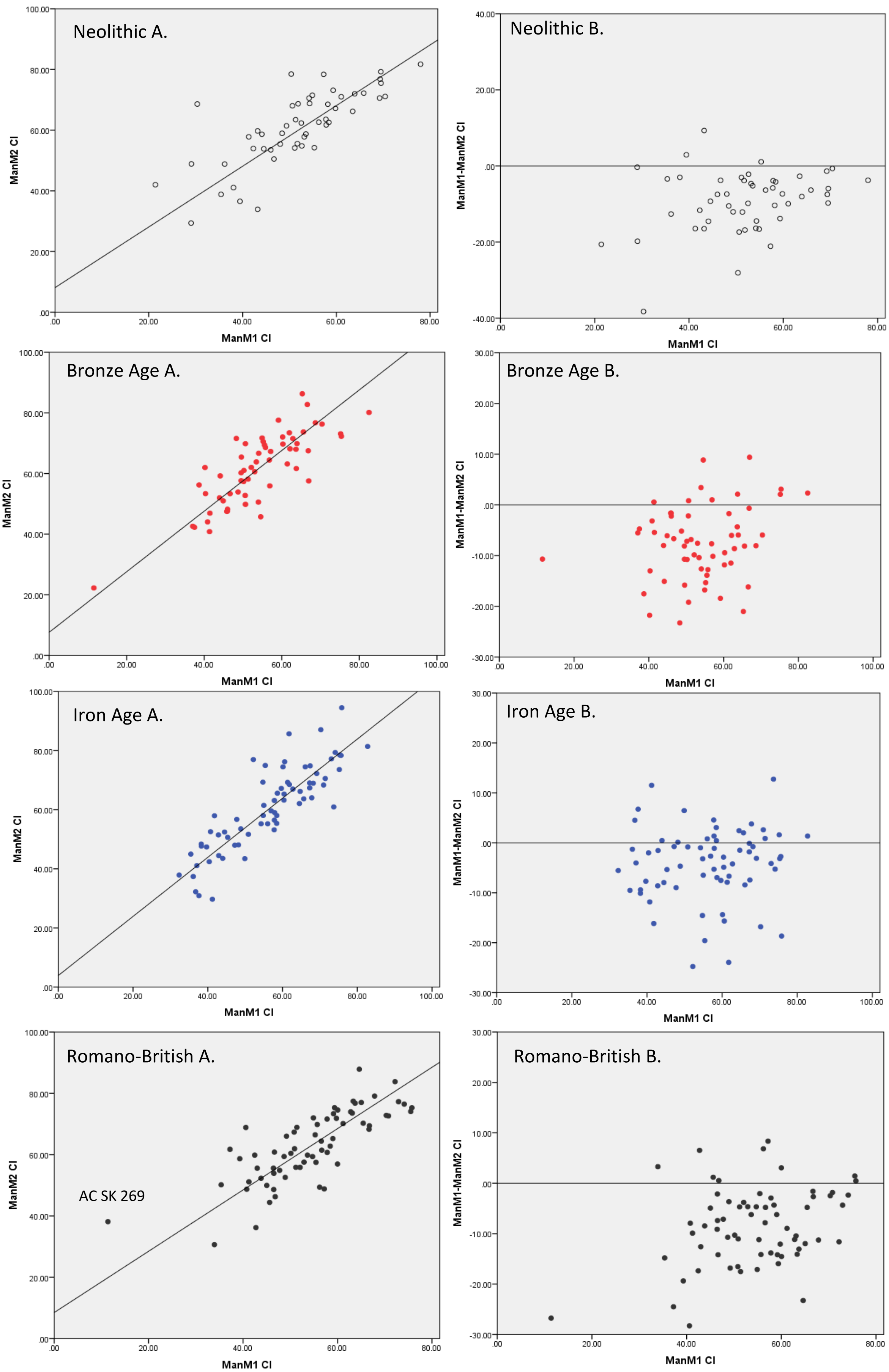


Figure 7.2.3. Plots of crown index (CI) of the first (ManM1) and second (ManM2) molars by temporal sample.

A. scatter plot of ManM1 CI vs ManM2 CI. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate.
B. Difference between ManM1 and ManM2 CI against ManM1 CI with a plotted line of equality (y=0).

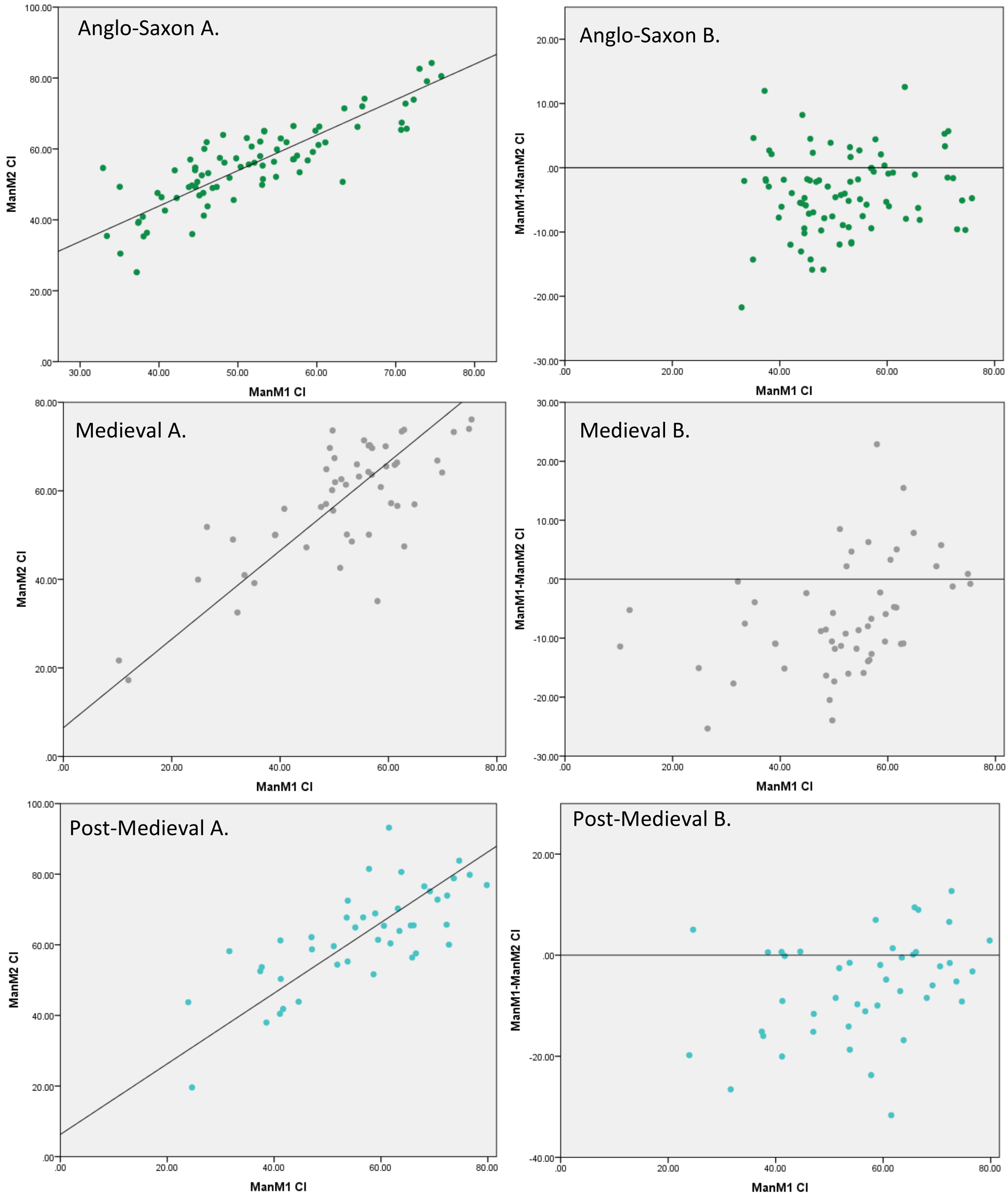


Figure 7.2.3 Continued. Plots of crown index (CI) of the first (ManM1) and second (ManM2) molars by temporal sample.

A. scatter plot of ManM1 CI vs ManM2 CI. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate.

B. Difference between ManM1 and ManM2 CI against ManM1 CI with a plotted line of equality (y=0).

Percent of exposed dentine (%DE)

Figure 7.2.4A shows that as ManM1 %DE increased so did ManM2 %DE. Spearman's correlation coefficients supported this relationship, which were significant at the 1% level. (Table 7.2.3).

The majority of points fell below the line of equal wear, in all temporal samples (Figure 7.2.4A), supporting a difference in %DE wear rate on the first and second mandibular molars. Points falling below the line of equal wear indicate a faster %DE wear rate on the ManM1 compared to the ManM2. Due to the spread of points it is difficult to determine whether this difference in wear rate remained constant or varied throughout the life of the dentition.

All temporal samples showed an increase in %DE difference between ManM1 and ManM2 regions as %DE increased on the ManM1 (Figure 7.2.4B). The linear pattern indicates a difference in %DE wear rate on both molars, which remained constant.

The majority of points fell above the line of equality, showing %DE was larger on the ManM1 compared to its ManM2 partner (Figure 7.2.4B).

Table 7.2.3. Spearman correlation coefficients examining the wear relationship between first and second mandibular molar percent of exposed dentine.

Sample	n	Spearman's coefficient (r_s)	P-value	Equation for the line of equal wear
Neolithic	22	0.58	0.005	M2 %DE = M1 %DE - 2.1
Bronze Age	21	0.73	<0.001	M2 %DE = M1 %DE
Iron Age	40	0.74	<0.001	M2 %DE = M1 %DE – 0.2
Romano-British	41	0.80	<0.001	M2 %DE = M1 %DE
Anglo-Saxon	43	0.84	<0.001	M2 %DE = M1 %DE – 0.5
Medieval	28	0.72	<0.001	M2 %DE = M1 %DE – 0.2
Post-Medieval	19	0.75	<0.001	M2 %DE = M1 %DE

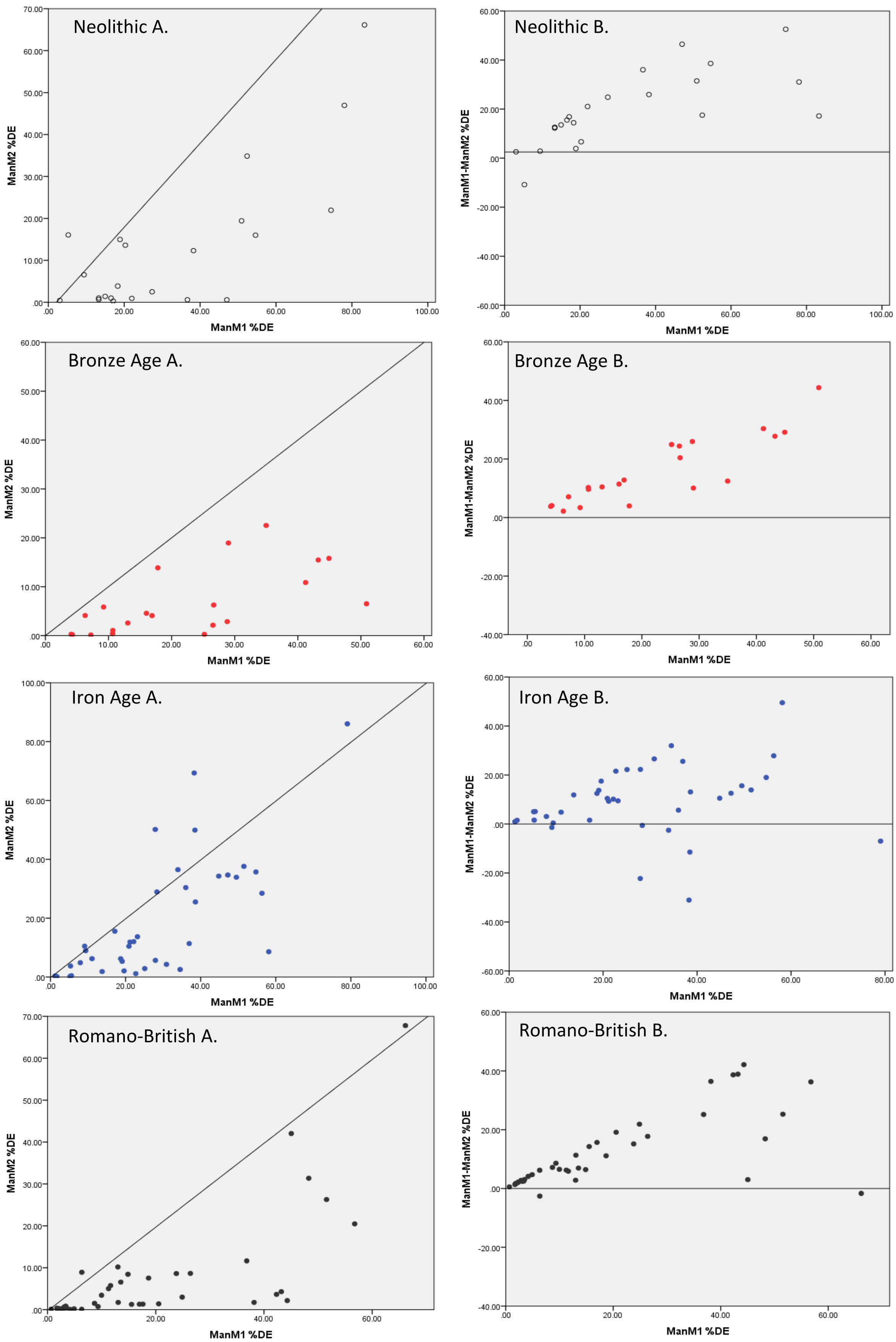


Figure 7.2.4. Plots of percent of exposed dentine (%DE) of the first (ManM1) and second (ManM2) molars by temporal sample.

A. scatter plot of ManM1 %DE vs ManM2 %DE. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate.

B. Difference between ManM1 and ManM2 %DE against ManM1 %DE with a plotted line of equality (y=0).

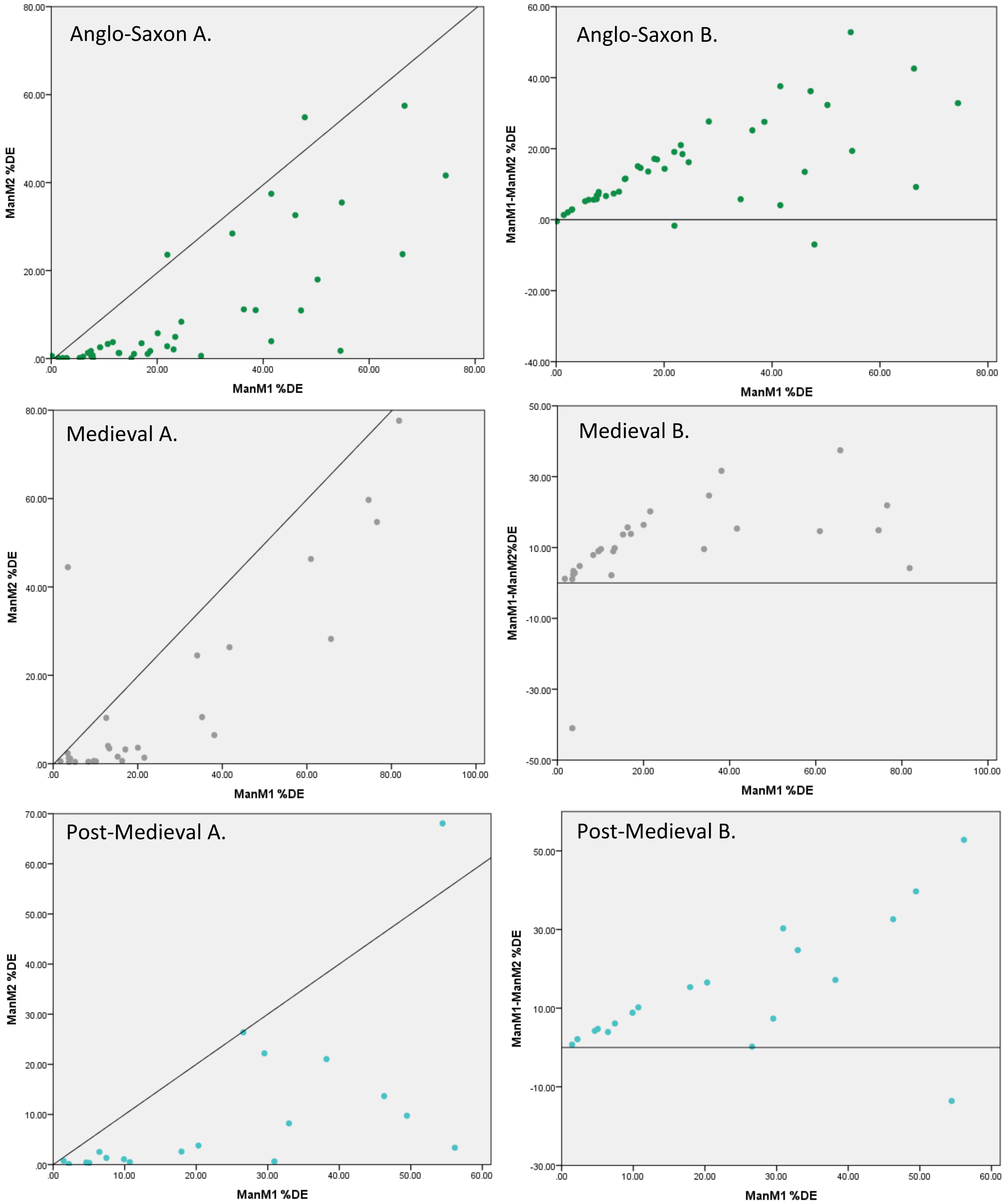


Figure 7.2.4 Continued. Plots of percent of exposed dentine (%DE) of the first (ManM1) and second (ManM2) molars by temporal sample.
A. scatter plot of ManM1 %DE vs ManM2 %DE. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate.
B. Difference between ManM1 and ManM2 %DE against ManM1 %DE with a plotted line of equality (y=0).

Wear stage (WS)

As ManM1 WS increased so did ManM2 WS for all temporal samples (Figure 7.2.5A). This was supported by Spearman's correlation coefficients that were significant at the 1% level (Table 7.2.4).

All points clustered around the line of equal wear supporting a similar WS wear rate on both the first and second mandibular molar (Figure 7.2.5A). This wear relationship was further supported by a WS difference between the ManM1 and ManM2 regions that remained constant relative to ManM1 WS (Figure 7.2.5B). This relationship was observed in all temporal samples.

The majority of points fell above the line of equality, showing a higher WS on the ManM1 compared to its partner ManM2 (Figure 7.2.5B).

Table 7.2.4. Spearman's correlation coefficients examining the wear relationship between first and second mandibular molar wear stage.

Sample	n	Spearman's coefficient (r_s)	P-value	Equation for the line of equal wear
Neolithic	66	0.86	<0.001	M2 WS = M1 WS - 3
Bronze Age	74	0.90	<0.001	M2 WS = M1 WS - 3
Iron Age	86	0.86	<0.001	M2 WS = M1 WS - 3
Romano-British	75	0.84	<0.001	M2 WS = M1 WS - 3
Anglo-Saxon	89	0.83	<0.001	M2 WS = M1 WS - 3
Medieval	62	0.80	<0.001	M2 WS = M1 WS - 3
Post-Medieval	47	0.82	<0.001	M2 WS = M1 WS - 3

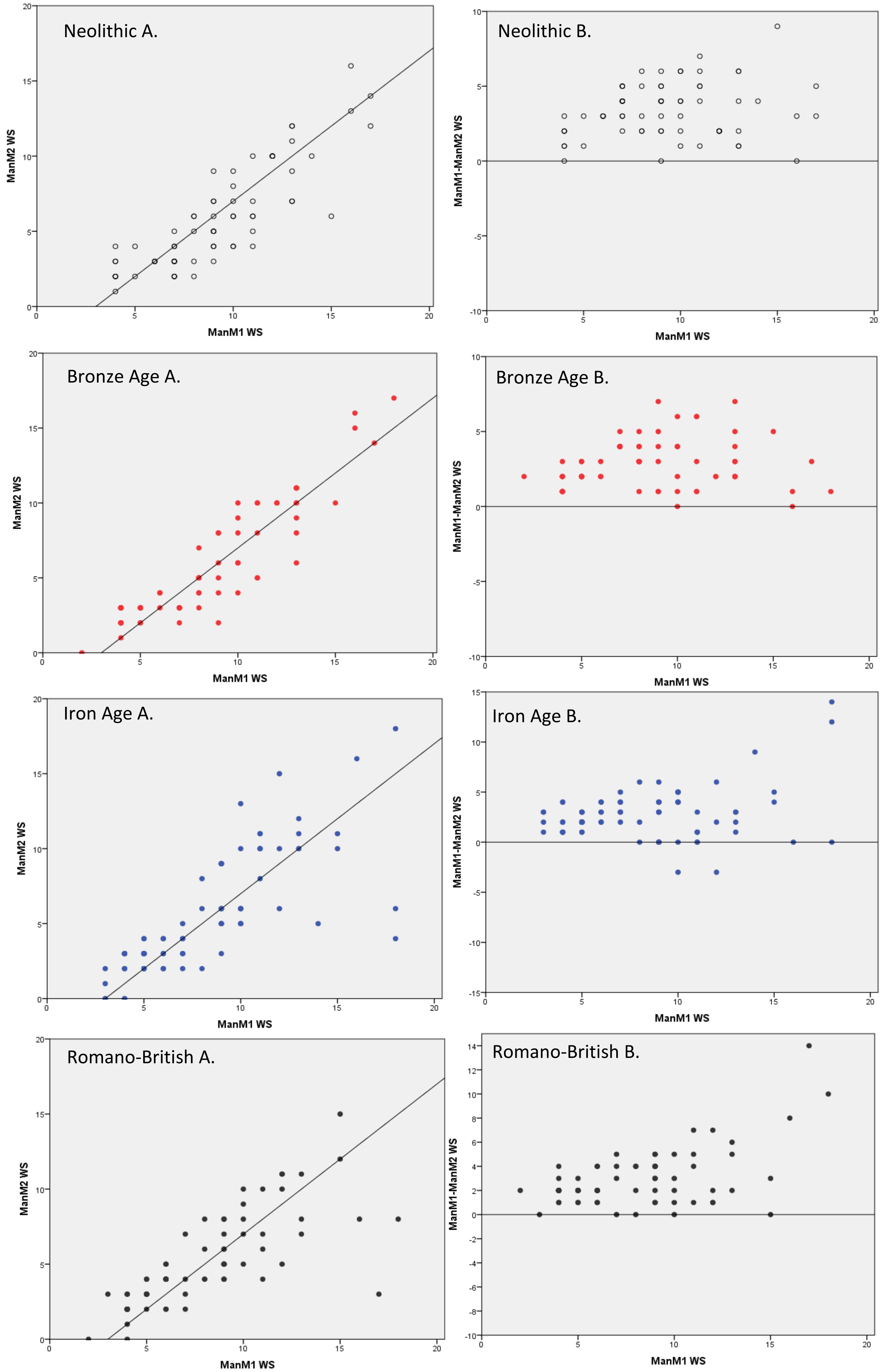


Figure 7.2.5. Plots wear stage (WS) of the first (ManM1) and second (ManM2) molars by temporal sample

A. scatter plot of ManM1 WS vs ManM2 WS. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate. B. Difference between ManM1 and ManM2 WS against ManM1 WS with a plotted line of equality (y=0).

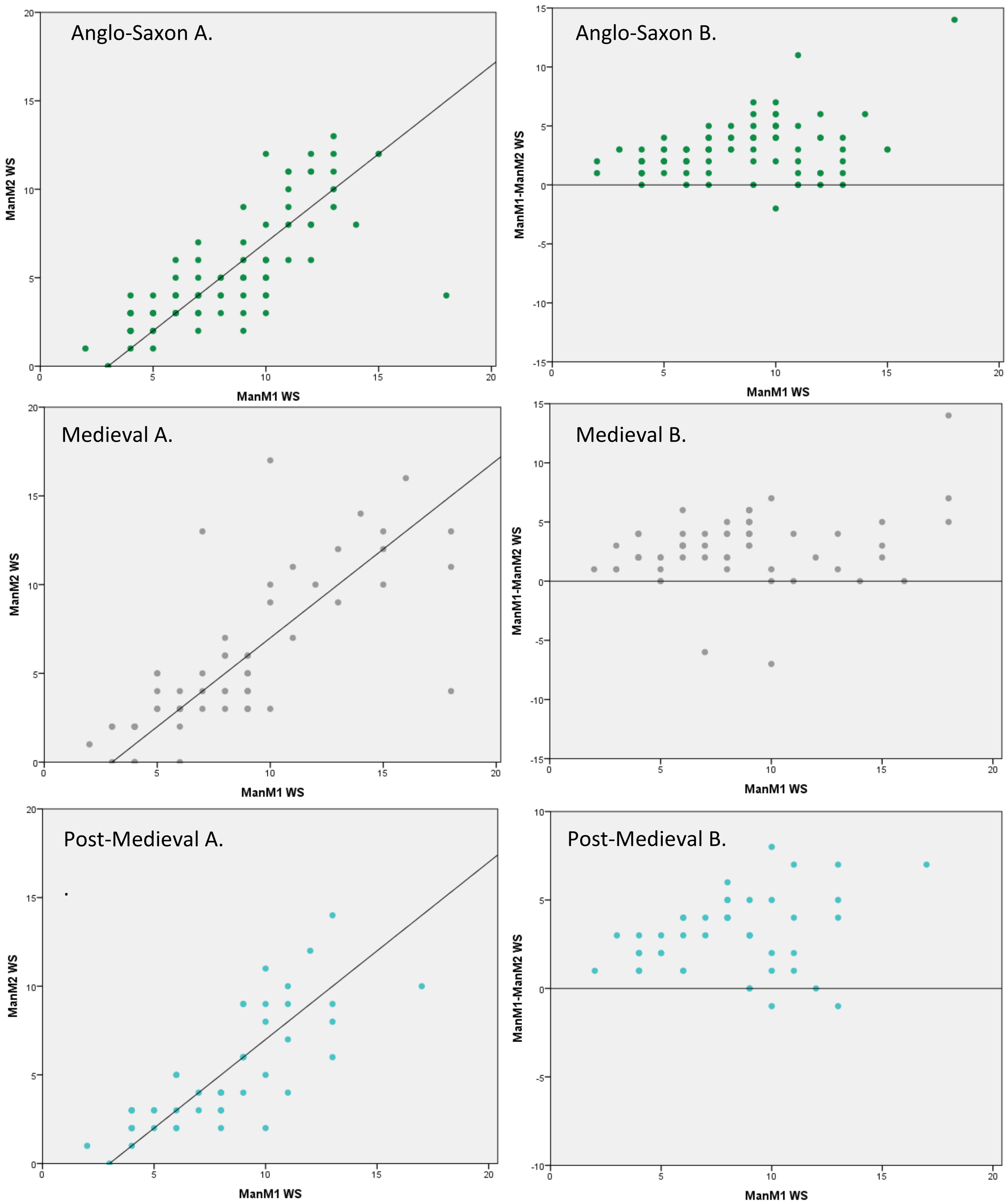


Figure 7.2.5 Continued. Plots wear stage (WS) of the first (ManM1) and second (ManM2) molars by temporal sample.

A. scatter plot of ManM1 WS vs ManM2 WS. The line on the scatterplot is the relationship expected if the M1 and M2 wear at the same rate.

B. Difference between ManM1 and ManM2 WS against ManM1 WS with a plotted line of equality (y=0).

7.2.2 Comparing wear rates between the second and third mandibular molars

Average crown height (CH)

All temporal samples showed a relationship between ManM2 and ManM3 CH, where a decrease in ManM2 CH was associated with a decrease in ManM3 CH (Figure 7.2.6A). This was supported by significant Pearson's correlation coefficients (Table 7.2.5).

Points clustered around the line of equal wear for the Neolithic and Romano-British samples, indicating a similar CH wear rate on the second and third mandibular molars (Figure 7.2.6A). This was further supported by a CH difference that remained constant relative to the ManM2 CH (Figure 7.2.6B).

The Iron Age, Anglo-Saxon, Medieval and Post-Medieval samples showed an increase in CH difference between the second and third mandibular molars as ManM2 CH decreased (Figure 7.2.6B). The linear pattern in Figure 7.2.6B supports a difference in CH wear rate on the molars that remained constant. This was supported by points falling close to, but not tightly on, the line on similar wear (Figure 7.2.6A).

The majority of points for the remaining period samples fell below the line of equality, indicating ManM3 CH was larger compared to its ManM2 partner. The Romano-British sample fell around the line of equality, indicating either ManM2 CH or ManM3 could be larger.

Table 7.2.5. Pearson correlation coefficients examining the wear relationship between second and third mandibular molar average crown height.

Sample	n	Pearson's coefficient (r)	P-value	Equation for line of equal wear
Neolithic	37	0.59	<0.001	M3 CH = M2 CH + 0.7
Bronze Age	49	0.79	<0.001	M3 CH = M2 CH + 0.5
Iron Age	28	0.59	0.001	M3 CH = M2 CH + 0.4
Romano-British	53	0.80	<0.001	M3 CH = M2 CH + 0.1
Anglo-Saxon	62	0.73	<0.001	M3 CH = M2 CH + 0.4
Medieval	34	0.83	<0.001	M3 CH = M2 CH + 0.5
Post-Medieval	35	0.72	<0.001	M3 CH = M2 CH + 0.1

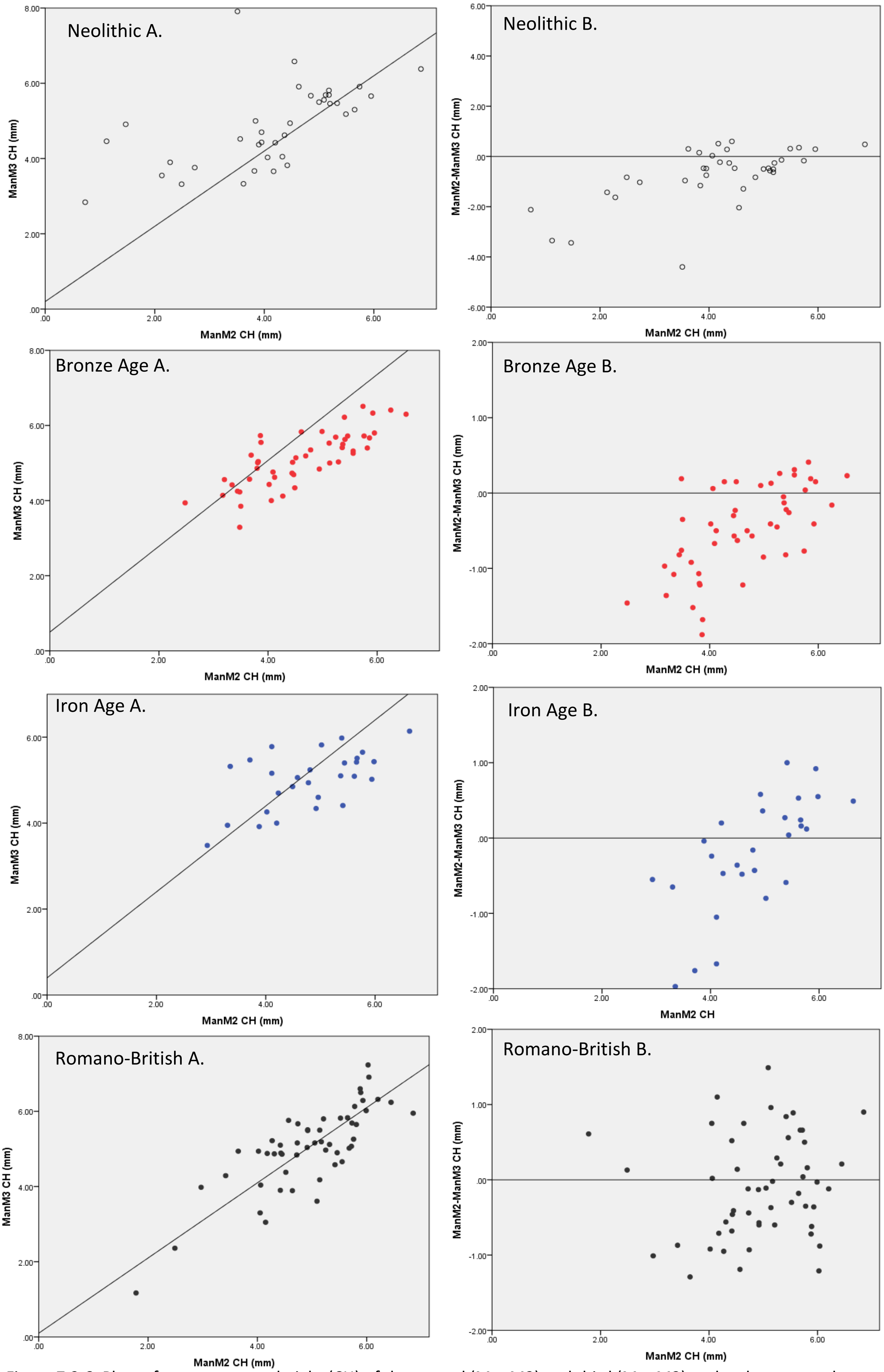


Figure 7.2.6. Plots of average crown height (CH) of the second (ManM2) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM2 CH vs ManM3 CH. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.

B. Difference between ManM2 and ManM3 CH against ManM2 CH with a plotted line of equality (y=0).

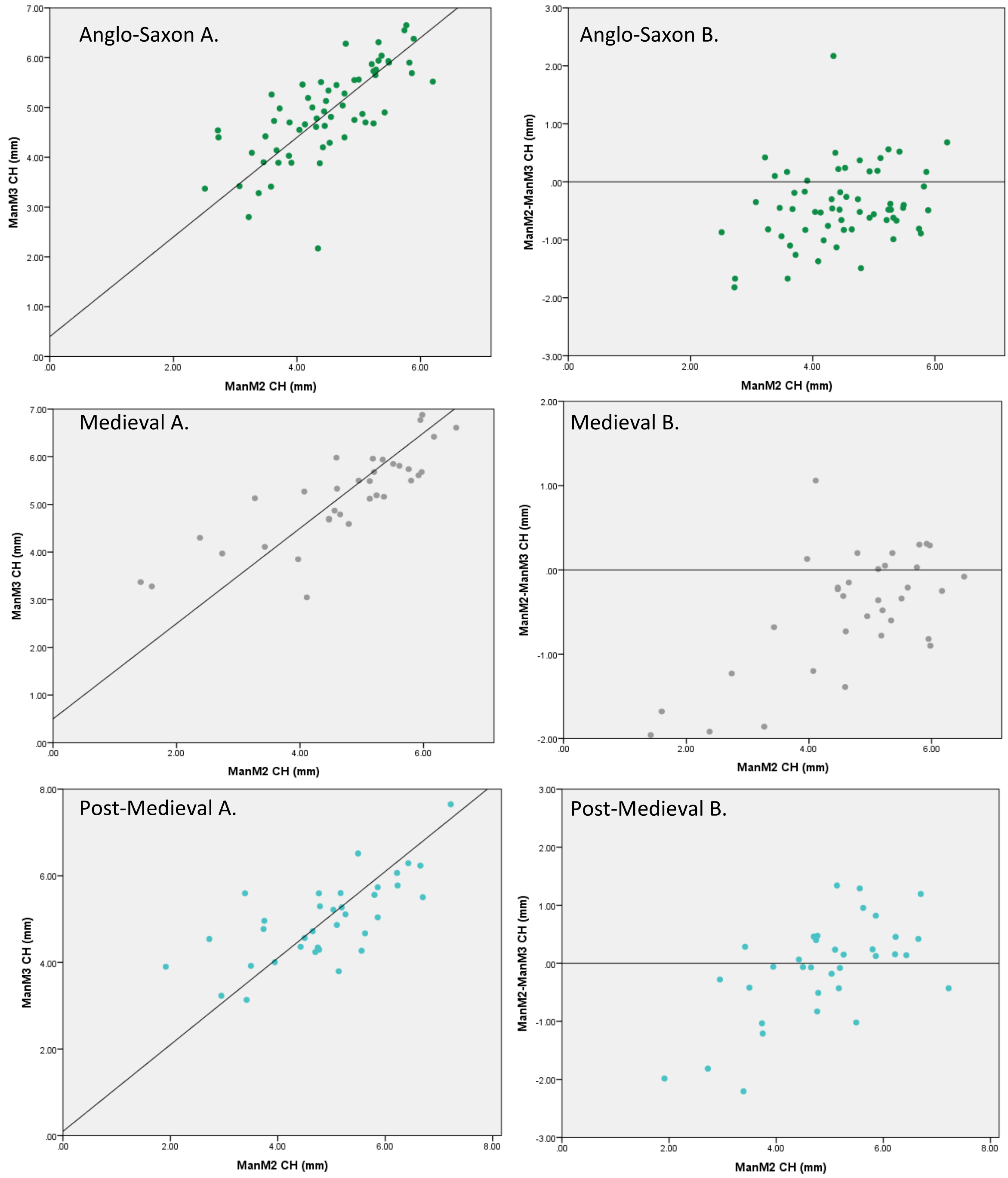


Figure 7.2.6 Continued. Plots of average crown height (CH) of the second (ManM2) and third (ManM3) molars by temporal sample.
A. scatter plot of ManM2 CH vs ManM3 CH. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.
B. Difference between ManM2 and ManM3 CH against ManM2 CH with a plotted line of equality (y=0).

Crown index (CI)

ManM3 CI decreased as ManM2 CI decreased (Figure 7.2.7A). This was true for all temporal samples, supported by significant Pearson correlation coefficients (Table 7.2.6).

Points fell around the line of equal wear for all temporal samples (Figure 7.2.7A). The spread of points makes it difficult to determine whether CI wear rates for the ManM2 and ManM3 were similar. However, plots of CI difference against ManM2 CI provide some clarification.

CI difference between the ManM2 and ManM3 remained constant, in relation to ManM2 CI, for the Neolithic, Iron Age samples, Anglo-Saxon, Medieval and Post-Medieval samples (Figure 7.2.7B). This indicates a similar rate of CI wear on both molars for these samples.

The Bronze Age and Romano-British samples showed an increase in CI difference between ManM2 and ManM3 as ManM2 CI decreased (Figure 7.2.7B). These results suggest ManM2 and ManM3 wore at a different CI rate, which remained constant. However, the points clustered around the line of similar wear suggesting only a slight difference in CI wear rate.

Table 7.2.6. Pearson correlation coefficients examining the wear relationship between second and third mandibular molar crown index.

Sample	n	Pearson's coefficient (r)	P-value	Equation for line of equal wear
Neolithic	34	0.65	0.001	M3 CI = M2 CI + 8.5
Bronze Age	47	0.71	<0.001	M3 CI = M2 CI + 6.5
Iron Age	25	0.85	<0.001	M3 CI = M2 CI + 3.7
Romano-British	53	0.61	<0.001	M3 CI = M2 CI + 2.3
Anglo-Saxon	62	0.72	<0.001	M3 CI = M2 CI + 3.7
Medieval	34	0.80	<0.001	M3 CI = M2 CI + 10.3
Post-Medieval	35	0.74	<0.001	M3 CI = M2 CI + 2.5

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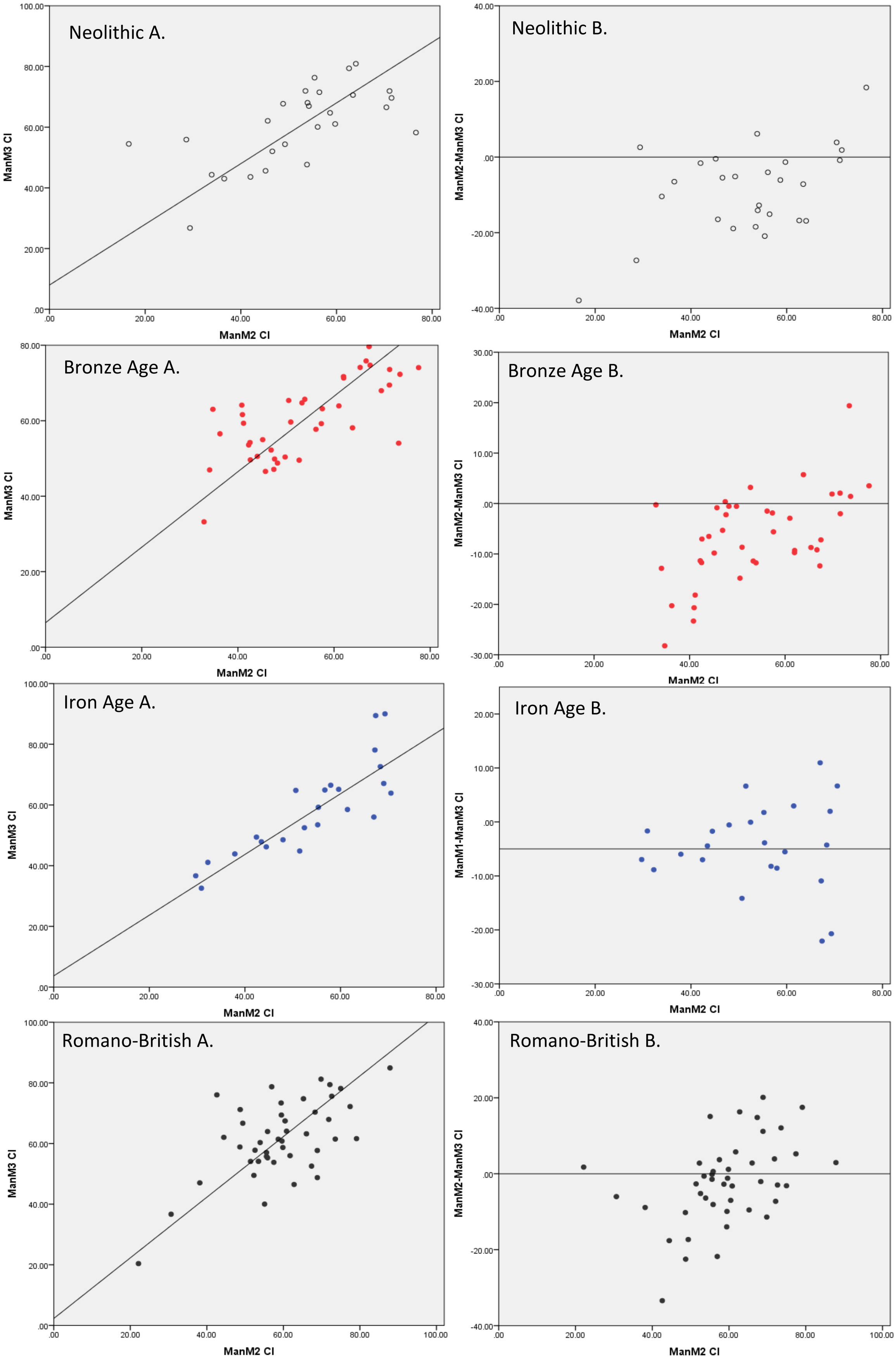

Figure 7.2.7. Plots of crown index (CI) of the second (ManM2) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM2 CI vs ManM3 CI. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.

B. Difference between ManM2 and ManM3 CI against ManM2 CI with a plotted line of equality (y=0).

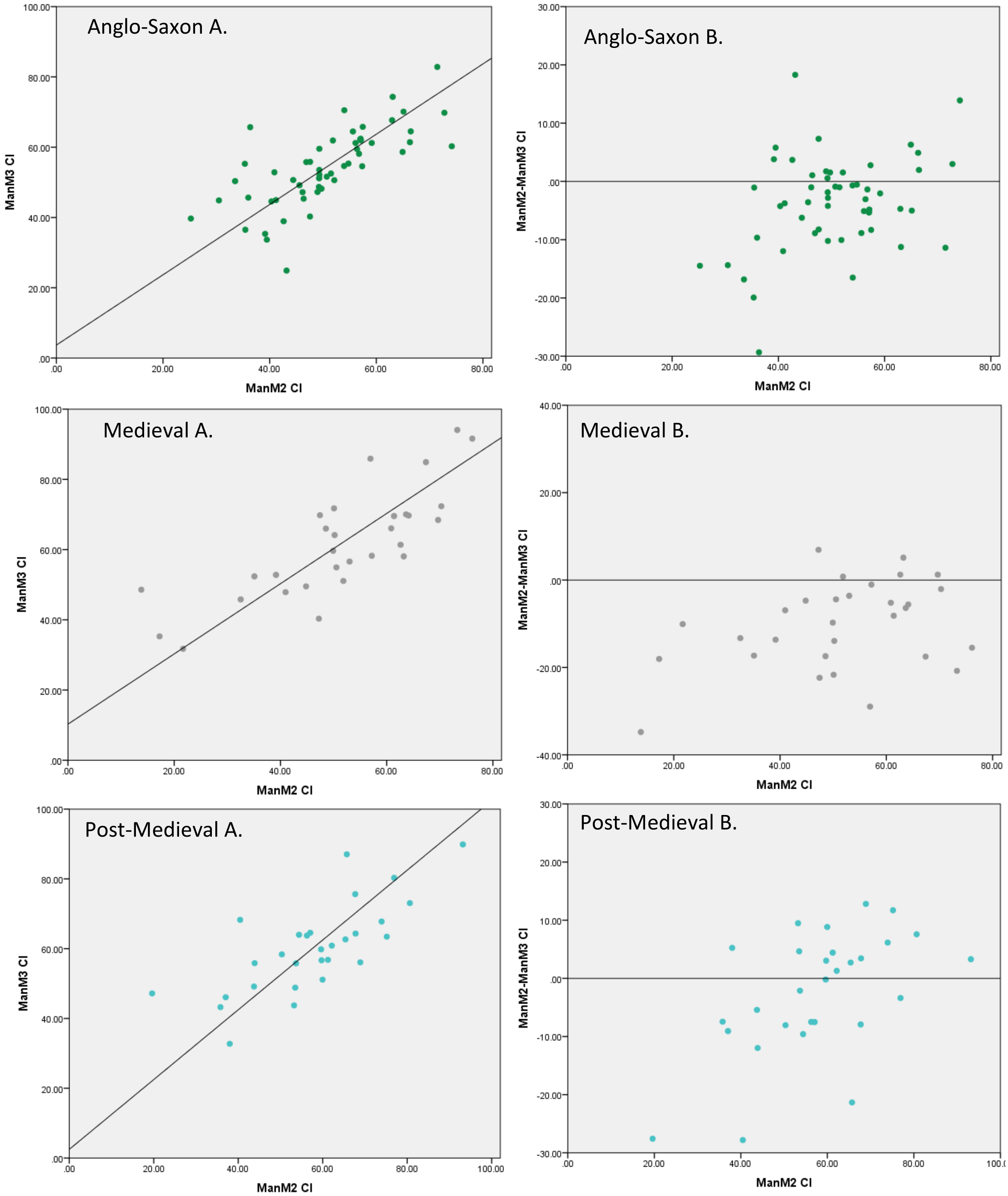

Figure 7.2.7 Continued. Plots of crown index (CI) of the second (ManM2) and third (ManM3) molars by temporal sample.
A. scatter plot of ManM2 CI vs ManM3 CI. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.
B. Difference between ManM2 and ManM3 CI against ManM2 CI with a plotted line of equality (y=0).

Percent of exposed dentine (%DE)

All temporal samples showed an increase in ManM2 %DE was associated with an increase in ManM3 %DE (Figure 7.2.8A). However, this increase was minimal. Only the Spearman's correlation coefficients for the Neolithic, Anglo-Saxon and Medieval samples were significant (Table 7.2.7).

Figure 7.2.8A shows wear was minimal on the ManM3, with few individuals showing more than 20%DE for any temporal sample. This explains the low correlation coefficients in Table 7.2.7.

The majority of points fell below the line of equal wear supporting a difference in %DE wear rate between the second and third mandibular molars, for all temporal samples (Figure 7.2.8A). Points falling below the line of equal wear suggest a faster %DE wear rate on the ManM2 compared with the ManM3. Figure 7.2.8B further supports this, as %DE difference between the ManM2 and ManM3 increased as ManM2 %DE increased. These results indicate a difference in %DE wear rate on the two molars that remained constant.

The majority of points fell above the line of equality, suggesting a higher degree of %DE on the ManM2 compared with its ManM3 partner.

Table 7.2.7. Spearman correlation coefficients examining the wear relationship between second and third mandibular molar percent of exposed dentine.

Sample	n	Spearman's coefficient (r_s)	P-value	Equation for line of equal wear
Neolithic	13	0.70	0.008	M3 %DE = M2 %DE – 4
Bronze Age	13	0.53	0.061	M3 %DE = M2 %DE – 1.1
Iron Age	12	0.48	0.112	M3 %DE = M2 %DE – 0.8
Romano-British	23	0.56	0.005	M3 %DE = M2 %DE – 0.1
Anglo-Saxon	24	0.85	<0.001	M3 %DE = M2 %DE – 0.2
Medieval	9	0.92	0.001	M3 %DE = M2 %DE – 0.2
Post-Medieval	14	0.07	0.805	M3 %DE = M2 %DE – 0.8

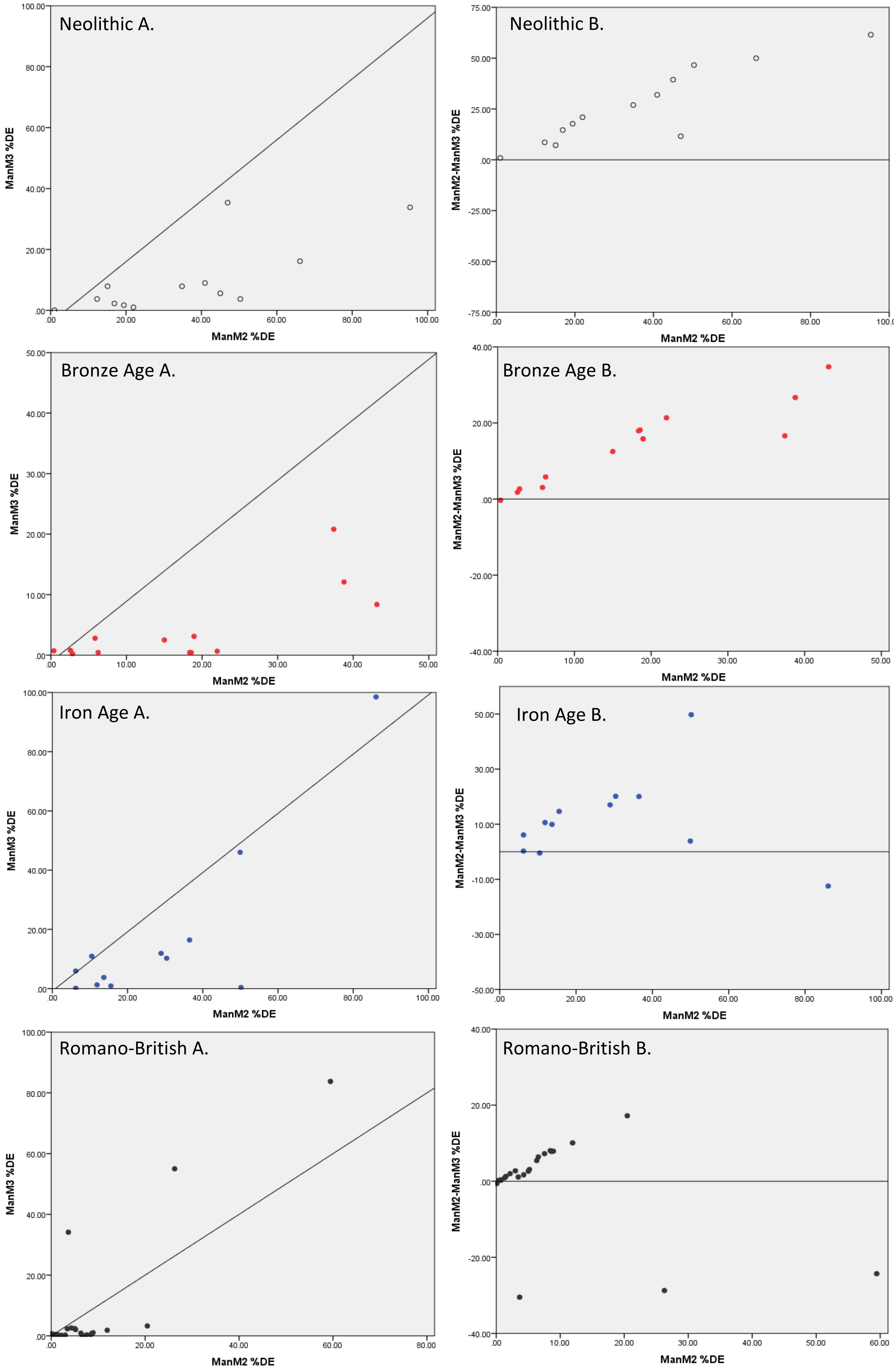

Figure 7.2.8. Plots of percent of exposed dentine (%DE) of the second (ManM2) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM2 %DE vs ManM3 %DE. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.

B. Difference between ManM2 and ManM3 %DE against ManM2 %DE with a plotted line of equality (y=0).

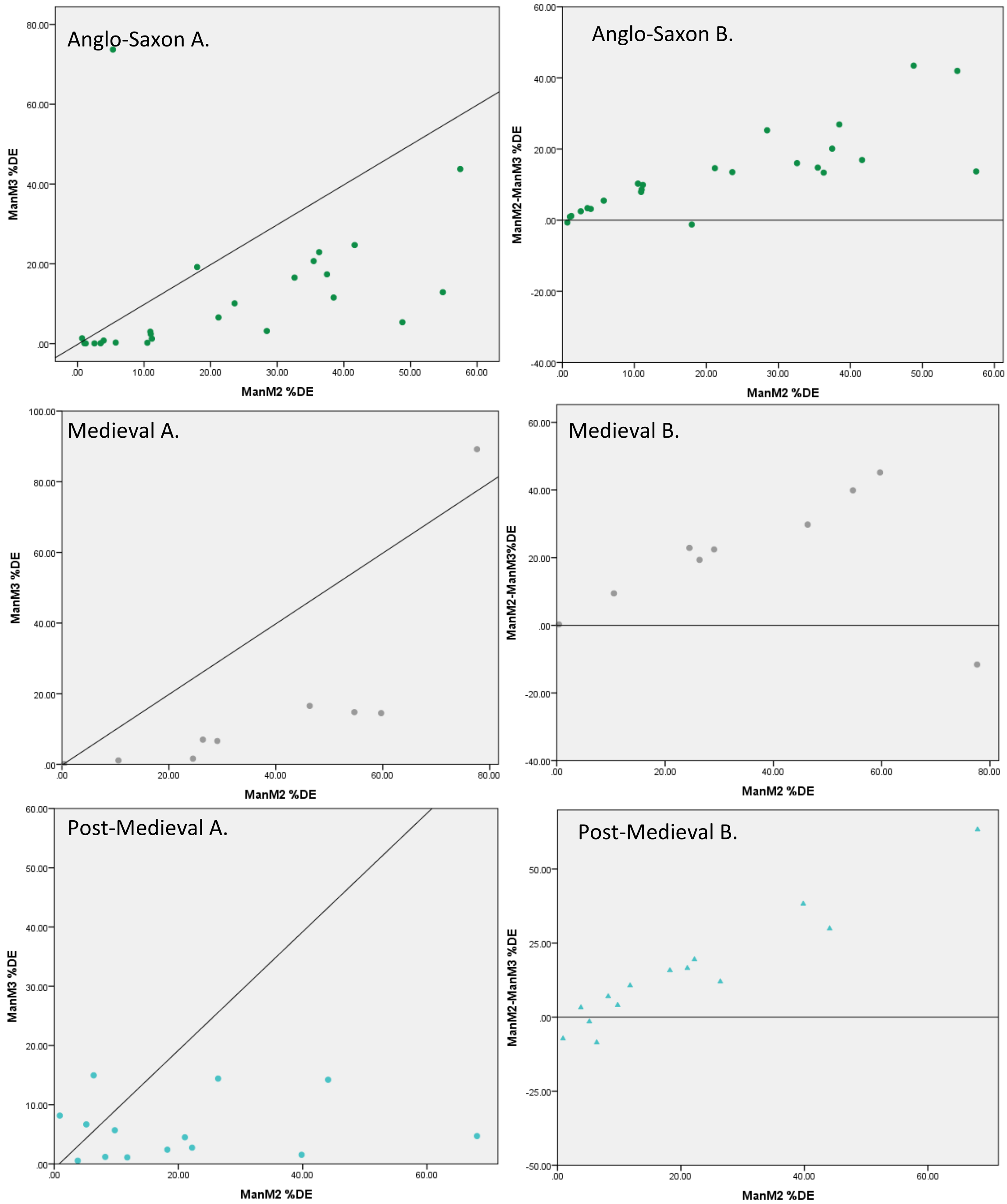

Figure 7.2.8 continued. Plots of percent of exposed dentine (%DE) of the second (ManM2) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM2 %DE vs ManM3 %DE. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.

B. Difference between ManM2 and ManM3 %DE against ManM2 %DE with a plotted line of equality (y=0).

Wear stage (WS)

ManM3 WS increased as ManM2 WS increased in all temporal samples (Figure 7.2.9A), which were supported by significant Spearman's coefficients supported this (Table 7.2.8).

All points fell around the line of equal wear making it difficult to determine whether WS wear rate was similar or different for the second and third mandibular molars (Figure 7.2.9A). Figure 7.2.9B provides some clarification for the relationship between ManM2 and ManM3 WS.

WS difference between the ManM2 and ManM3 increased as WS increased on the ManM2 (Figure 7.2.9B). This was true for all samples except the Anglo-Saxon sample, which showed a WS difference that remained constant in relation to ManM2 WS (Figure 7.2.9B). This suggests all temporal samples, except the Anglo-Saxon group, had a difference in rate of WS wear on the ManM2 and ManM3 that remained constant. In contrast, the Anglo-Saxon sample had a similar WS wear rate on both molars that remained constant. As all points fell around the line of equal wear (Figure 7.2.9A) suggesting only a slight difference in WS wear rate.

The majority of points fell above the line of equality in all temporal samples, indicating a higher WS on the ManM2 compared with its ManM3 partner.

Table 7.2.8. Spearman correlation coefficients examining the wear relationship between second and third mandibular molar wear stage.

Sample	n	Spearman's coefficient (r_s)	P-value	Equation for line of equal wear
Neolithic	48	0.81	<0.001	M3 WS = M2 WS – 3
Bronze Age	59	0.76	<0.001	M3 WS = M2 WS – 3
Iron Age	42	0.82	<0.001	M3 WS = M2 WS – 3
Romano-British	57	0.77	<0.001	M3 WS = M2 WS – 3
Anglo-Saxon	63	0.87	<0.001	M3 WS = M2 WS – 3
Medieval	43	0.80	<0.001	M3 WS = M2 WS - 3
Post-Medieval	39	0.83	<0.001	M3 WS = M2 WS - 3

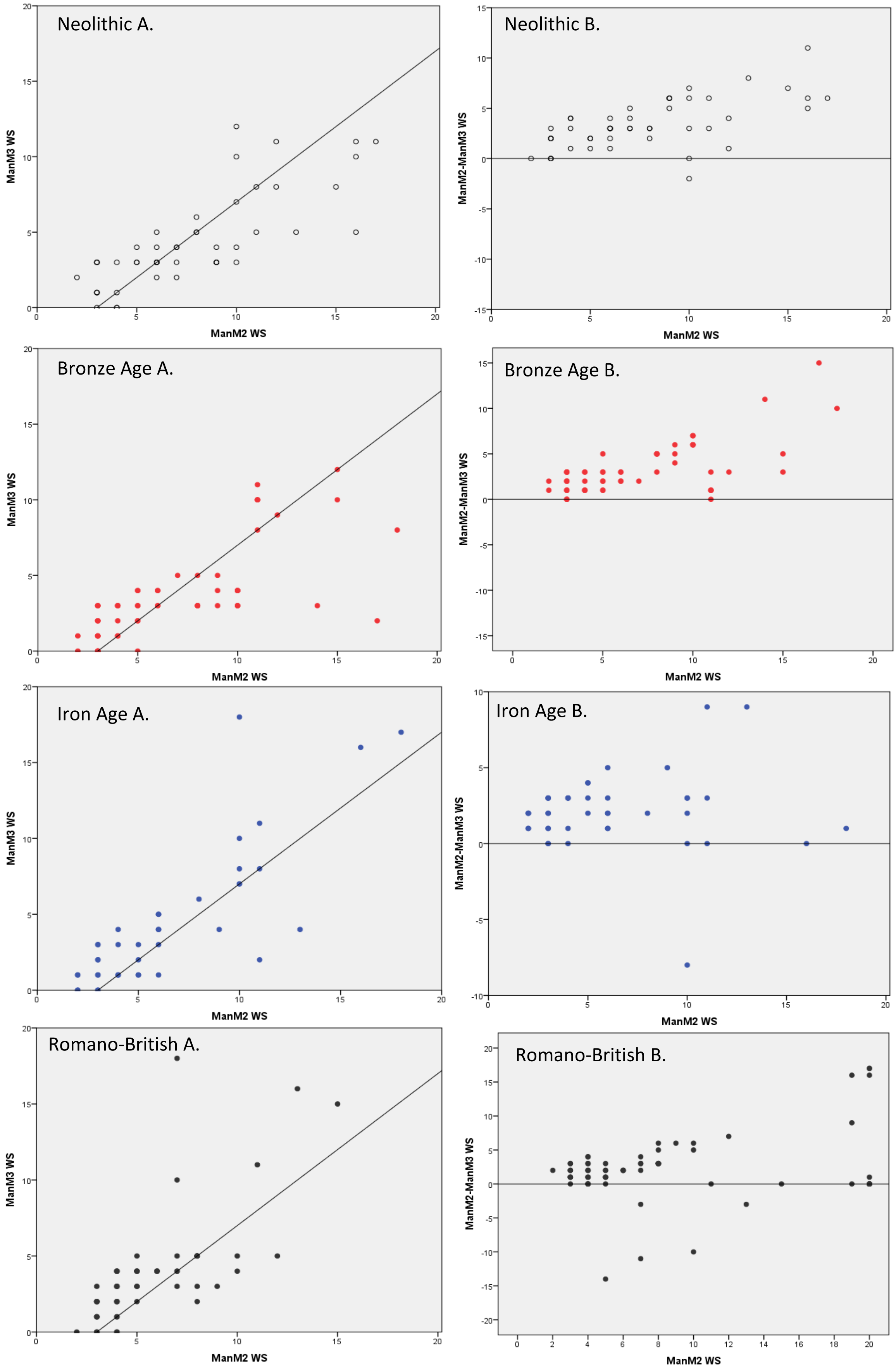

Figure 7.2.9. Plots wear stage (WS) of the second (ManM2) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM2 WS vs ManM3 WS. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.

B. Difference between ManM2 and ManM3 WS against ManM2 WS with a plotted line of equality (y=0).

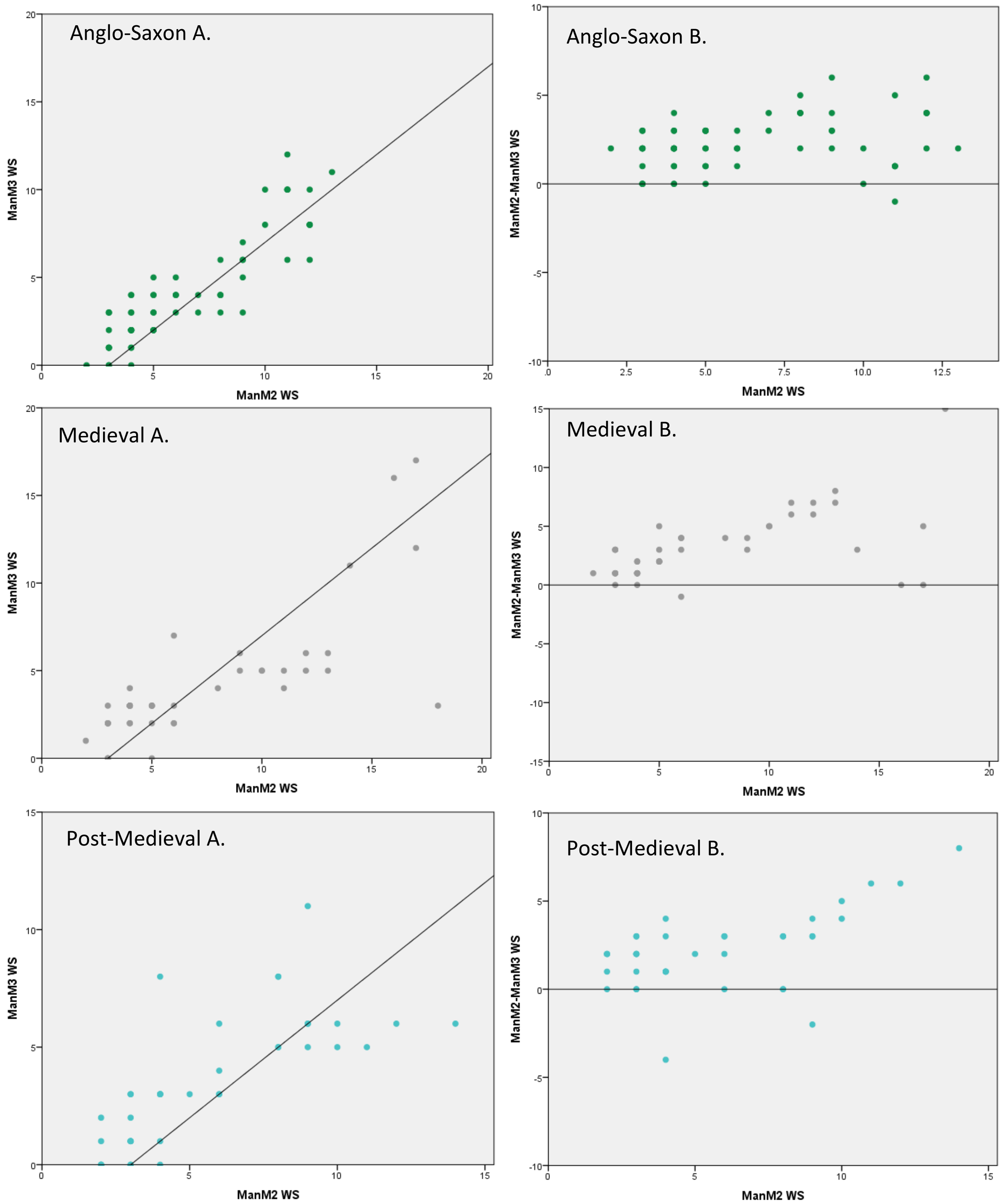

Figure 7.2.9 Continued. Plots wear stage (WS) of the second (ManM2) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM2 WS vs ManM3 WS. The line on the scatterplot is the relationship expected if the M2 and M3 wear at the same rate.

B. Difference between ManM2 and ManM3 WS against ManM2 WS with a plotted line of equality (y=0).

7.2.3 Comparing wear rates between the first and third mandibular molars

Average crown height (CH)

All temporal samples showed an association between ManM1 CH and ManM3 CH, where ManM3 CH decreased as ManM1 CH decreased (Figure 7.2.10A). These were supported by Pearson correlation coefficients, which were significant at the 5% level (Table 7.2.9). For all temporal samples the majority of points in Figure 7.2.10B fell below the line of equality, showing ManM3 CH was larger compared with ManM1 CH.

Points did not cluster on the line of equal wear making it difficult to determine whether first and third mandibular molars had a similar rate of CH wear (Figure 7.2.10A). Figure 7.2.10B shows CH difference between the ManM1 and ManM3 remained constant as ManM1 CH decreased for the Bronze Age, Romano-British, Anglo-Saxon and Post-Medieval samples, indicating a similar CH wear rate on the ManM1 and ManM3, which remained constant.

The Iron Age and Medieval samples showed a slight increase in CH difference as ManM1 CH decreased, supporting a difference in CH wear rate. However, the points did not fall far from the line of equal wear suggesting the difference in CH wear rate may not have been great (Figure 7.2.10A). The Neolithic sample showed some evidence of a non-linear pattern in both Figure 7.2.10A and Figure 7.2.10B, indicating a difference in CH wear rate on the ManM1 and ManM3 that did not remain constant.

There was a single outlier in the Romano-British sample (AC SK269) that showed extensive wear to the buccal side of the ManM1, producing a low CH. This extensive wear was not observed on the ManM3, producing a large difference in CH. This is the same outlier observed in Figure 7.2.2 and Figure 7.2.3.

Table 7.2.9. Pearson correlation coefficients examining the wear relationship between first and third mandibular molar average crown height.

Sample	n	Pearson's coefficient (r)	P-value	Equation for line of equal wear
Neolithic	29	0.58	0.001	M3 CH = M1 CH + 1.2
Bronze Age	42	0.62	<0.001	M3 CH = M1 CH + 0.9
Iron Age	29	0.46	0.013	M3 CH = M1 CH + 0.8
Romano-British	45	0.67	<0.001	M3 CH = M1 CH + 0.5
Anglo-Saxon	58	0.46	<0.001	M3 CH = M1 CH + 0.9
Medieval	30	0.90	<0.001	M3 CH = M1 CH + 1.2
Post-Medieval	24	0.68	<0.001	M3 CH = M1 CH + 0.6

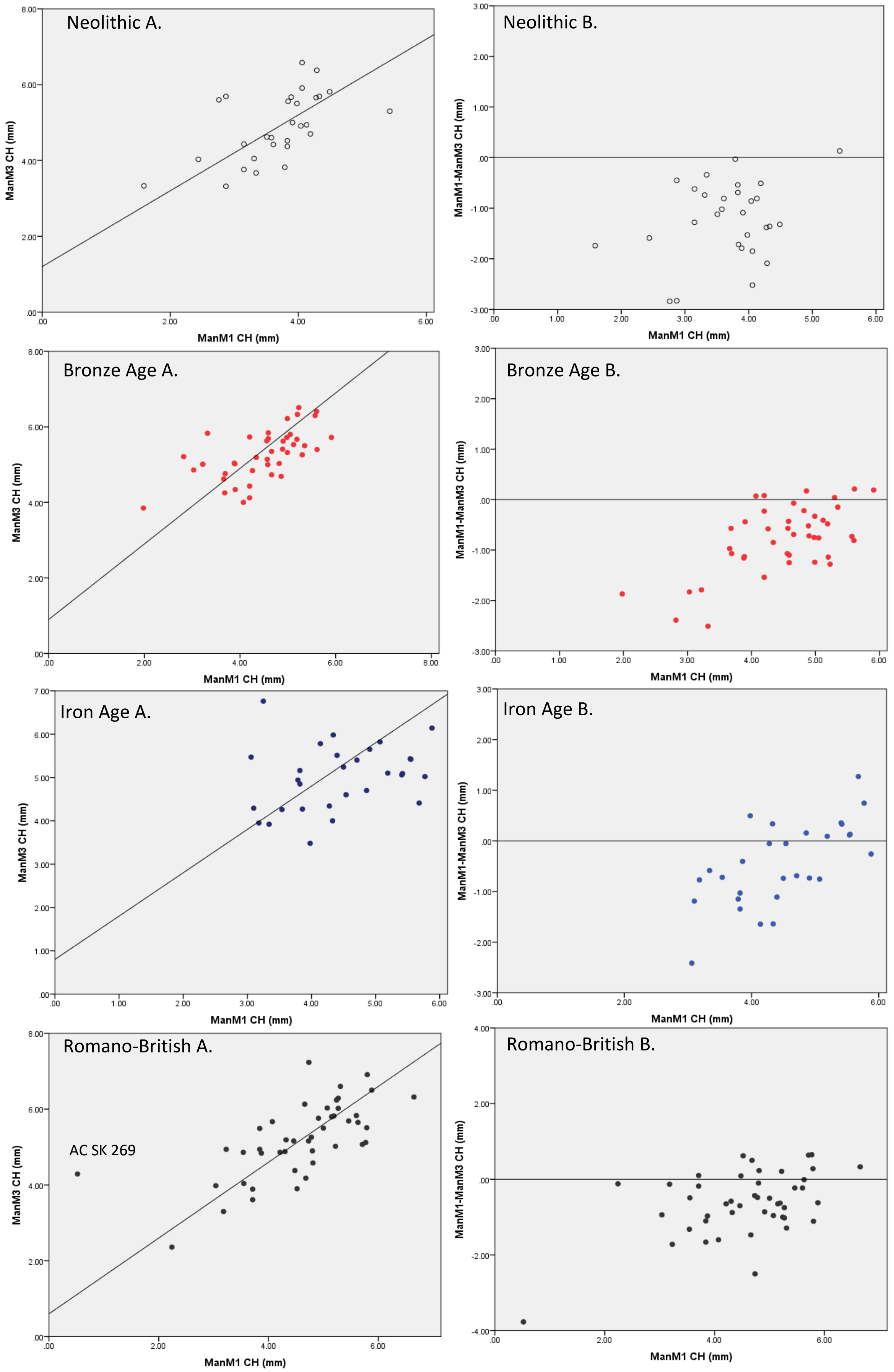

Figure 7.2.10. Plots of average crown height (CH) of the first (ManM1) and third (ManM3) molars by temporal

A. scatter plot of ManM1 CH vs ManM3 CH. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.
B. Difference between ManM1 and ManM3 CH against ManM3 CH with a plotted line of equality (y=0).

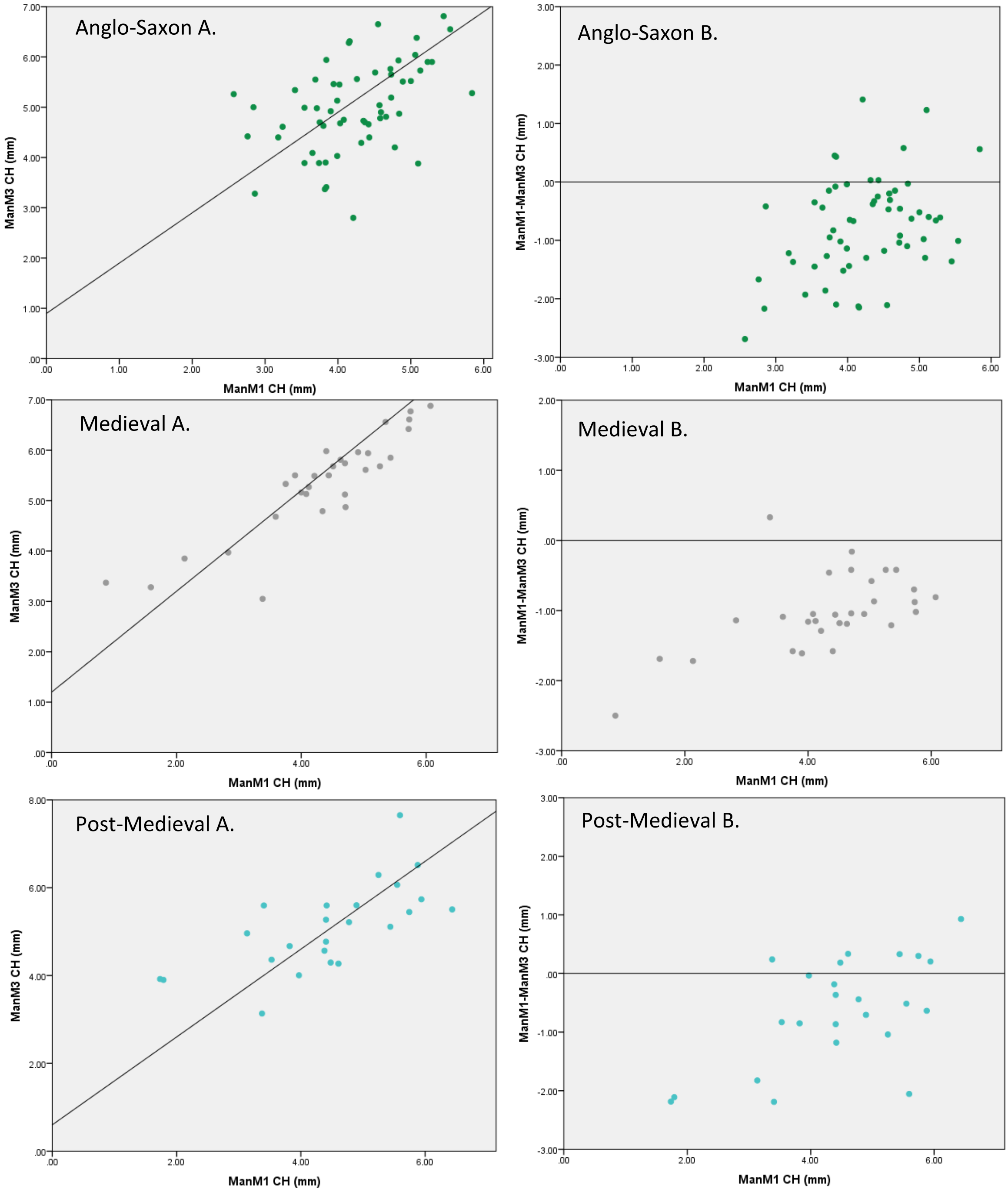

Figure 7.2.10 Continued. Plots of average crown height (CH) of the first (ManM1) and third (ManM3) molars by temporal sample.
A. scatter plot of ManM1 CH vs ManM3 CH. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.
B. Difference between ManM1 and ManM3 CH against ManM3 CH with a plotted line of equality (y=0).

Crown index (CI)

All temporal samples showed a relationship between ManM1 and ManM3 CI. Positive Pearson correlation coefficients supported this, which were significant at the 5% level (Table 7.2.10). Therefore, all temporal samples showed an association where one molar region decreased in CI so did the other molar region (Figure 7.2.11A).

The spread of points in both Figure 7.2.11A and Figure 7.2.11B make it difficult to state the CI wear relationship between first and third molars with any certainty for any of the temporal samples.

Figure 7.2.11B shows a broad pattern where CI difference between the ManM1 and ManM3 remained constant relative to ManM1 CI in the Iron Age and Anglo-Saxon samples. This indicates a similar wear rate on both the ManM1 and ManM3, which remained constant.

The Bronze Age, Romano-British and Post-Medieval samples show a linear pattern, indicating CI difference increased between the two molar regions relative to ManM1 CI (Figure 7.2.11B). This pattern supports a difference in CI wear rate that remained constant. The pattern for the Neolithic sample is unclear, thus it is not possible to determine the wear relationship for this group.

The majority of points fell below the line the line of equality, indicating a larger CI in the ManM1 regions, compared to its ManM3 partner.

Table 7.2.10. Pearson correlation coefficients examining the wear relationship between first and third mandibular molar crown index (CI).

Period	n	Pearson's coefficient (r)	P-value	Equation for line of equal wear
Neolithic	27	0.53	0.021	M3 CI = M1 CI + 14.5
Bronze Age	40	0.46	0.006	M3 CI = M1 CI + 13.4
Iron Age	26	0.77	<0.001	M3 CI = M1 CI + 8.0
Romano-British	42	0.59	<0.001	M3 CI = M1 CI + 11.4
Anglo-Saxon	57	0.63	<0.001	M3 CI = M1 CI + 8.0
Medieval	27	0.78	<0.001	M3 CI = M1 CI + 13.6
Post-Medieval	22	0.75	<0.001	M3 CI = M1 CI + 14.5

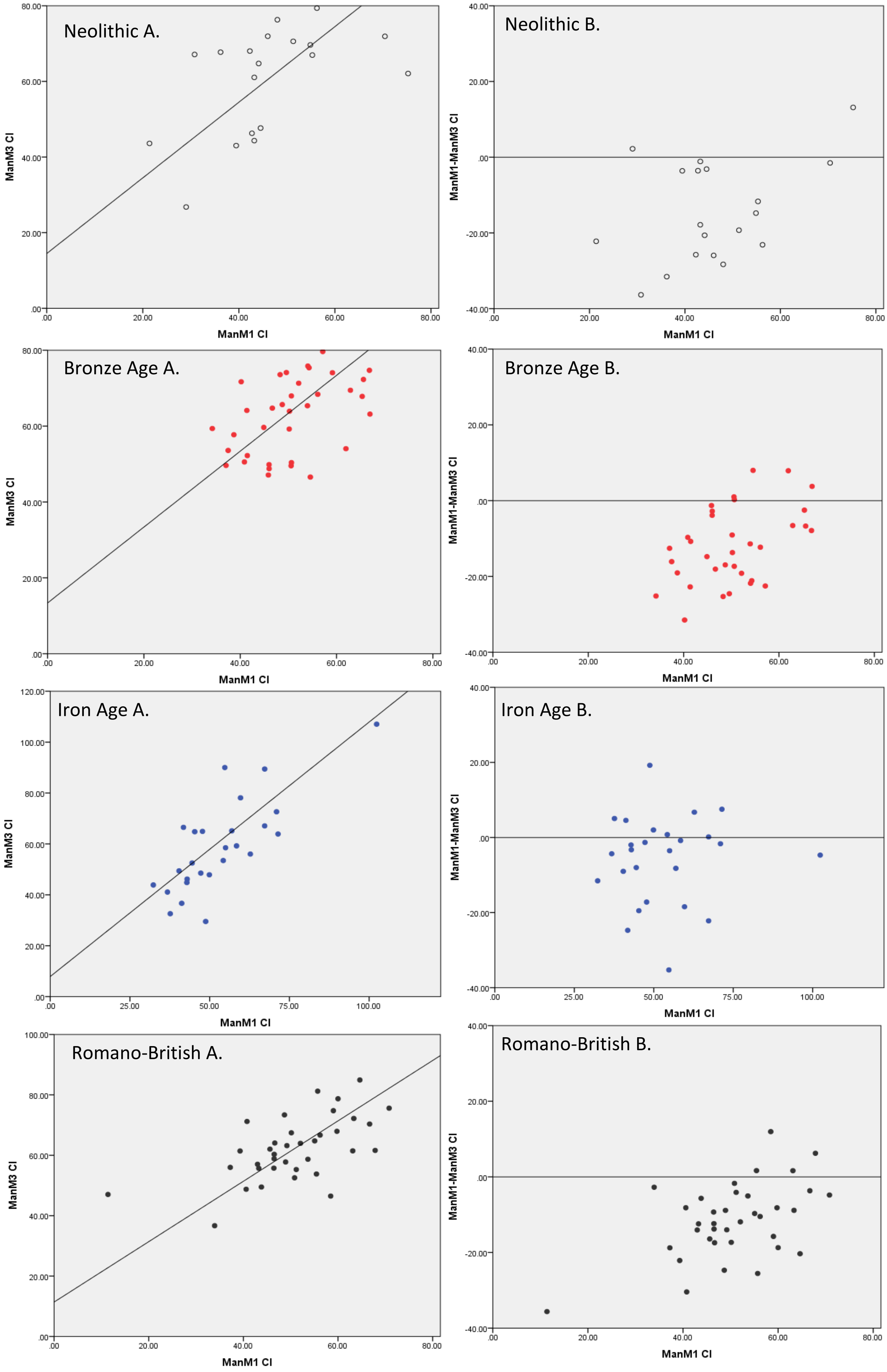

Figure 7.2.11. Plots of crown index (CI) of the first (ManM1) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM1 CI vs ManM3 CI. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.

B. Difference between ManM1 and ManM3 CI against ManM3 CI with a plotted line of equality (y=0).

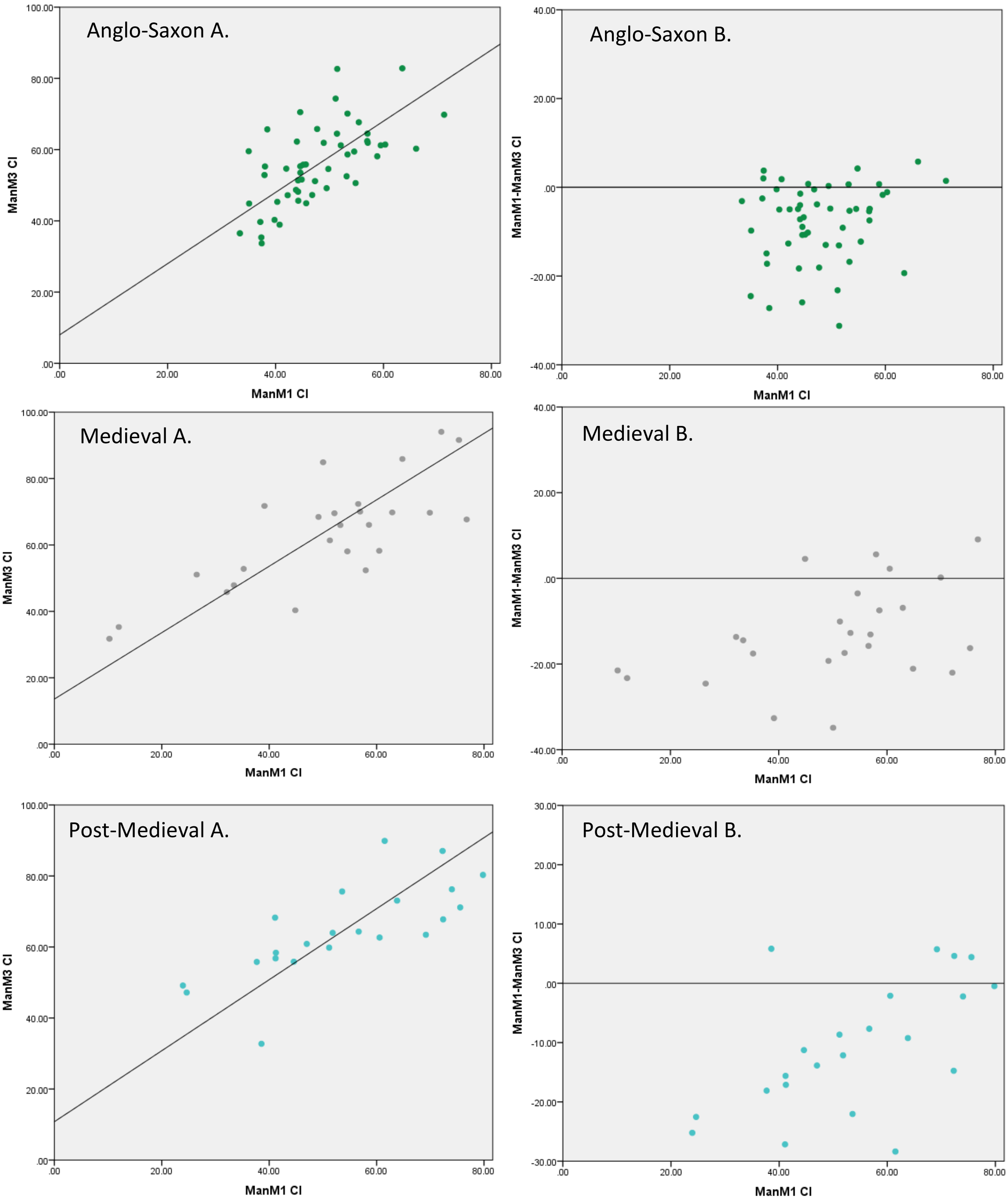

Figure 7.2.11 Continued. Plots of crown index (CI) of the first (ManM1) and third (ManM3) molars by temporal sample.
A. scatter plot of ManM1 CI vs ManM3 CI. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.
B. Difference between ManM1 and ManM3 CI against ManM3 CI with a plotted line of equality (y=0).

Percent of exposed dentine (%DE)

Overall the relationship between ManM1 %DE and ManM3 %DE was weak (Figure 7.2.12A, Table 7.2.11). The Iron Age, Romano-British, Anglo-Saxon and Medieval samples had a significant Spearman's correlation coefficient between the two variables, although few individuals had more than 20% of exposed dentine on their ManM3. The Neolithic, Bronze and Post-Medieval samples did not show a significant association between ManM1 and ManM3 %DE. Figure 7.2.12A shows minimal %DE on the ManM3 as ManM1 %DE increased for all samples.

The majority of points fell below the line of equal wear (Figure 7.2.12A). This indicates a faster %DE wear rate on the ManM1 compared with the ManM3, which was further supported by Figure 7.2.12B. All samples showed an increase in %DE difference between the ManM1 and ManM3 as ManM1 %DE increased, suggesting a difference in wear rate on the two regions that remained constant.

The majority of points fell above the line of equality (Figure 7.2.12B), indicating a larger %DE in the ManM1 compared to its ManM3 partner.

Table 7.2.11. Spearman's correlation coefficients examining the wear relationship between first and third mandibular molar percent of exposed dentine (%DE).

Period	n	Spearman's coefficient (r_s)	P-value	Equation for line of equal wear
Neolithic	7	0.71	0.071*	M3 %DE = M1 %DE – 8.5
Bronze Age	6	-0.09	0.872*	M3 %DE = M1 %DE – 3.2
Iron Age	13	0.73	0.005	M3 %DE = M1 %DE – 6.0
Romano-British	22	0.53	0.011	M3 %DE = M1 %DE – 1.1
Anglo-Saxon	22	0.86	0.001	M3 %DE = M1 %DE – 7.4
Medieval	9	0.83	0.005	M3 %DE = M1 %DE – 2.0
Post-Medieval	8	0.41	0.320*	M3 %DE = M1 %DE – 8.0

*indicates a non-significant correlation between ManM1 and ManM3 %DE

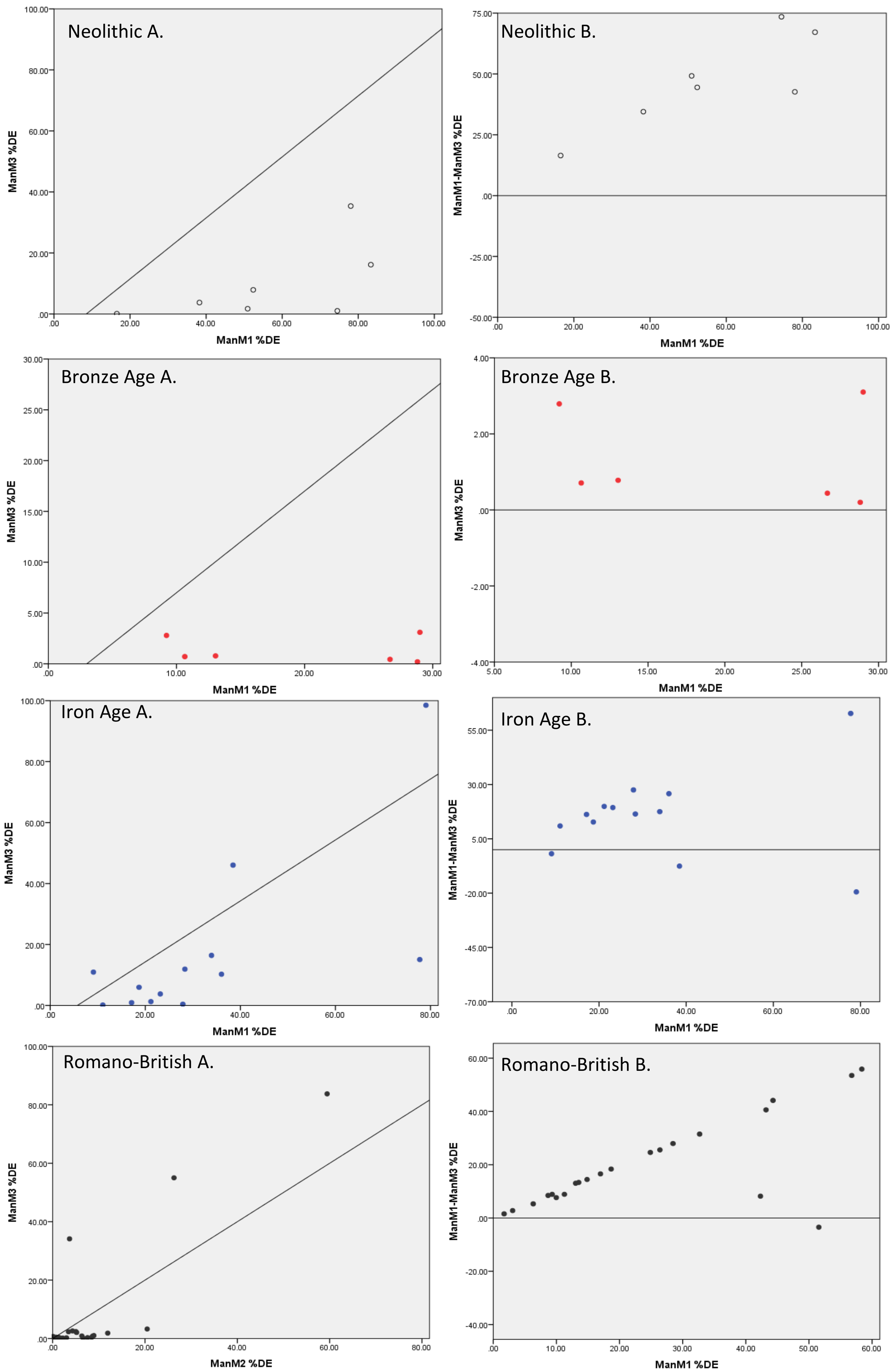

Figure 7.2.12. Plots of percent of exposed dentine (%DE) of the first (ManM1) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM1 %DE vs ManM3 %DE. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.

B. Difference between ManM1 and ManM3 %DE against ManM3 %DE with a plotted line of equality (y=0).

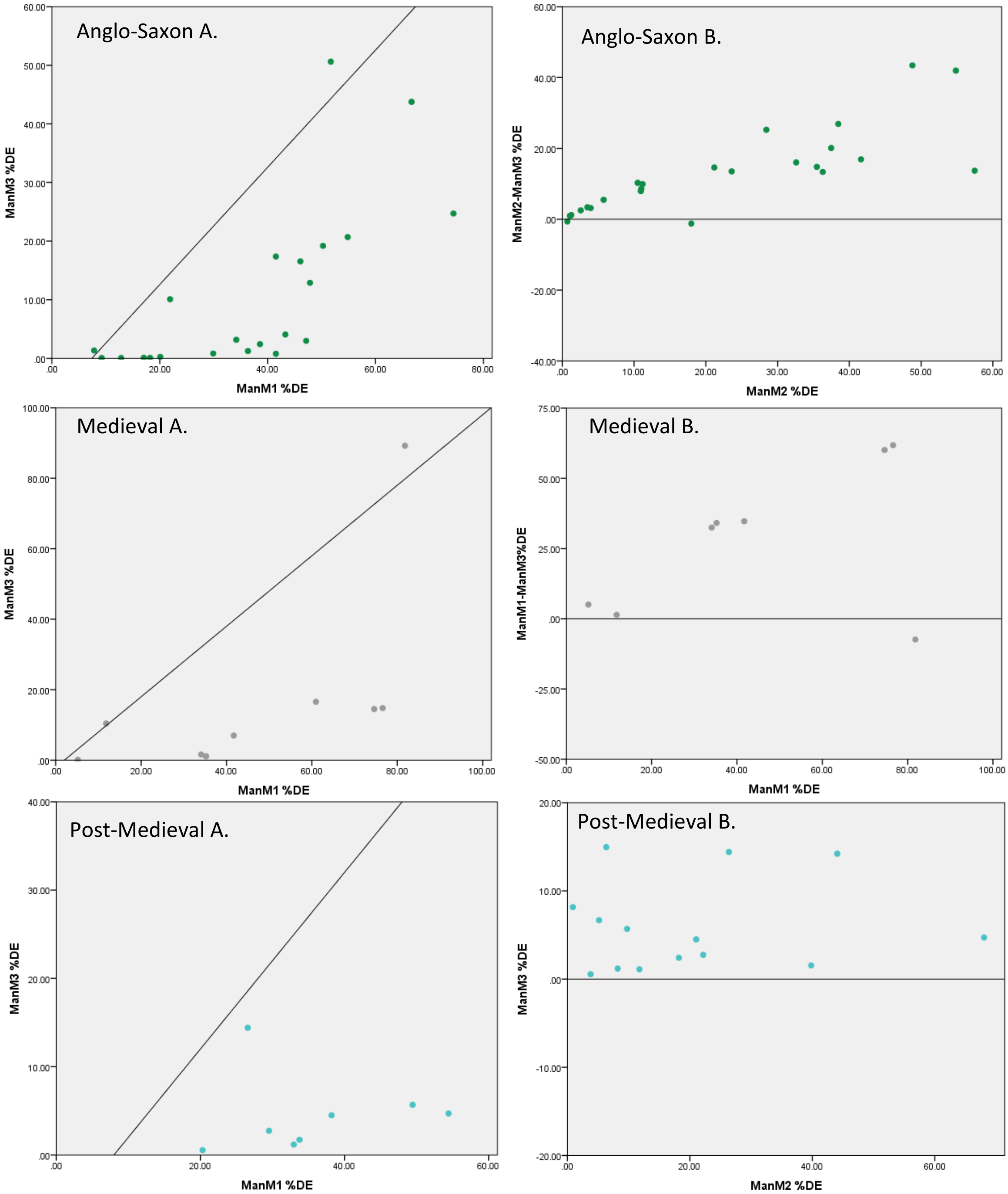

Figure 7.2.12 Continued. Plots of percent of exposed dentine (%DE) of the first (ManM1) and third (ManM3) molars by temporal sample.
A. scatter plot of ManM1 %DE vs ManM3 %DE. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.
B. Difference between ManM1 and ManM3 %DE against ManM3 %DE with a plotted line of equality (y=0).

Wear stage (WS)

Figure 7.2.13A shows that as ManM1 WS increased, so did ManM3 WS. This was true for all temporal samples and was supported by significant Spearman coefficients (Table 7.2.12).

Points fell around the line of equal wear for all temporal samples making it difficult to determine whether the WS wear rate was similar on the first and third mandibular molars (Figure 7.2.13A). Figure 7.2.13B shows WS difference between the ManM1 and ManM3 increased relative to ManM1 WS for all samples. This pattern was most obvious in the Bronze Age, Romano-British and Post-Medieval samples. These results indicate a difference in WS wear rate on the two molars, which remained constant. However, as the points fell near the line of equal wear (Figure 7.2.13A) it is unlikely that the wear rate differed greatly between the two molars.

The majority of points fell above the line of equality (Figure 7.2.13B). All temporal samples had a higher WS on the ManM1 compared to its ManM3 partner.

Table 7.2.12. Spearman correlation coefficients examining the wear relationship between first and third mandibular molar wear stages (WS).

Period	n	Spearman's coefficient (r_s)	P-value	Equation for line of equal wear
Neolithic	40	0.66	<0.001	M3 WS = M1 WS – 7
Bronze Age	54	0.60	<0.001	M3 WS = M1 WS – 6
Iron Age	44	0.70	<0.001	M3 WS = M1 WS – 6
Romano-British	52	0.71	<0.001	M3 WS = M1 WS – 6
Anglo-Saxon	63	0.65	<0.001	M3 WS = M1 WS – 6
Medieval	39	0.55	<0.001	M3 WS = M1 WS – 6
Post-Medieval	32	0.69	0.001	M3 WS = M1 WS – 6

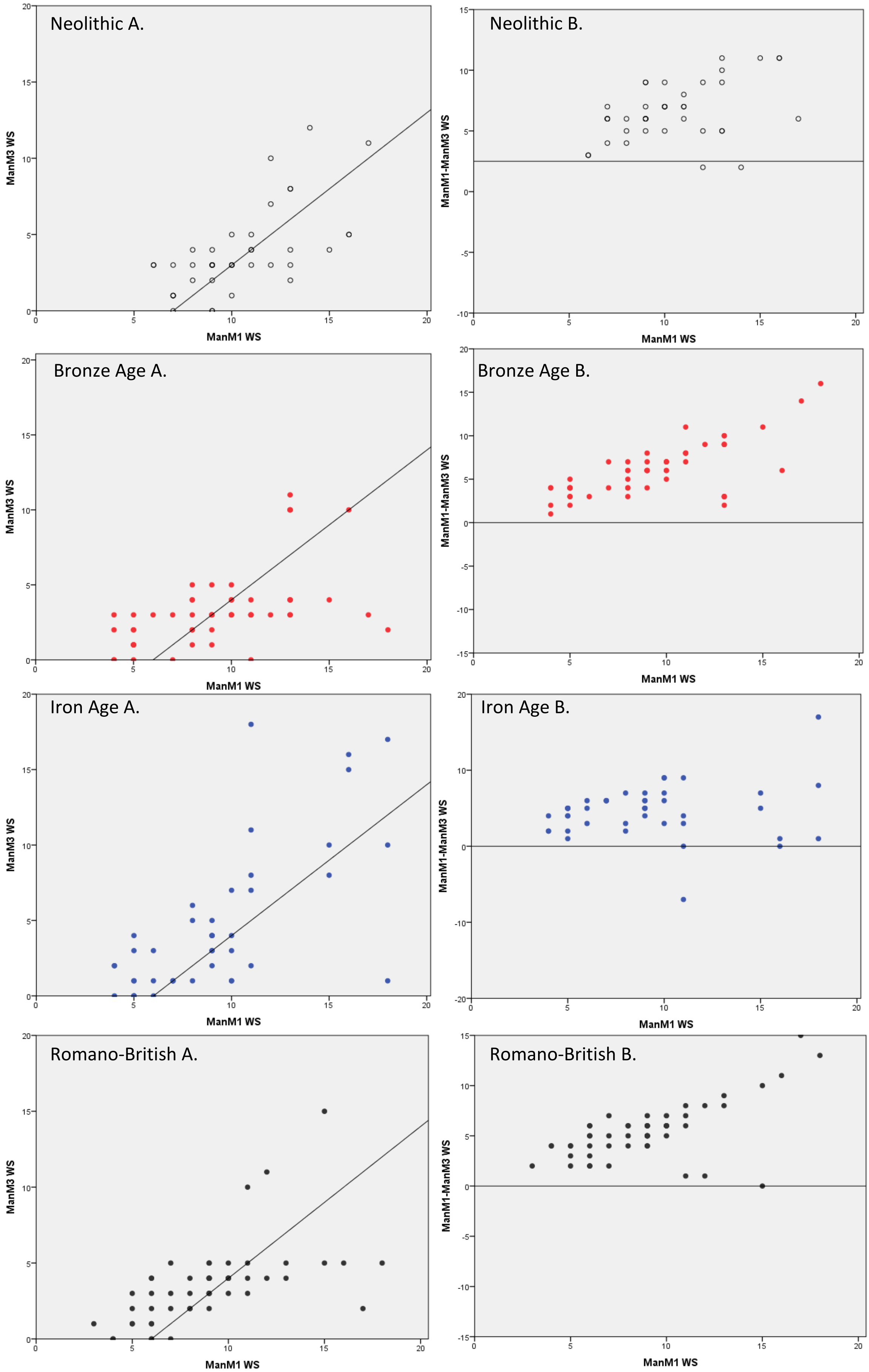

Figure 7.2.13. Plots wear stage (WS) of the first (ManM1) and third (ManM3) molars by temporal sample.

A. scatter plot of ManM1 WS vs ManM3 WS. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.

B. Difference between ManM1 and ManM3 WS against ManM3 WS with a plotted line of equality (y=0).

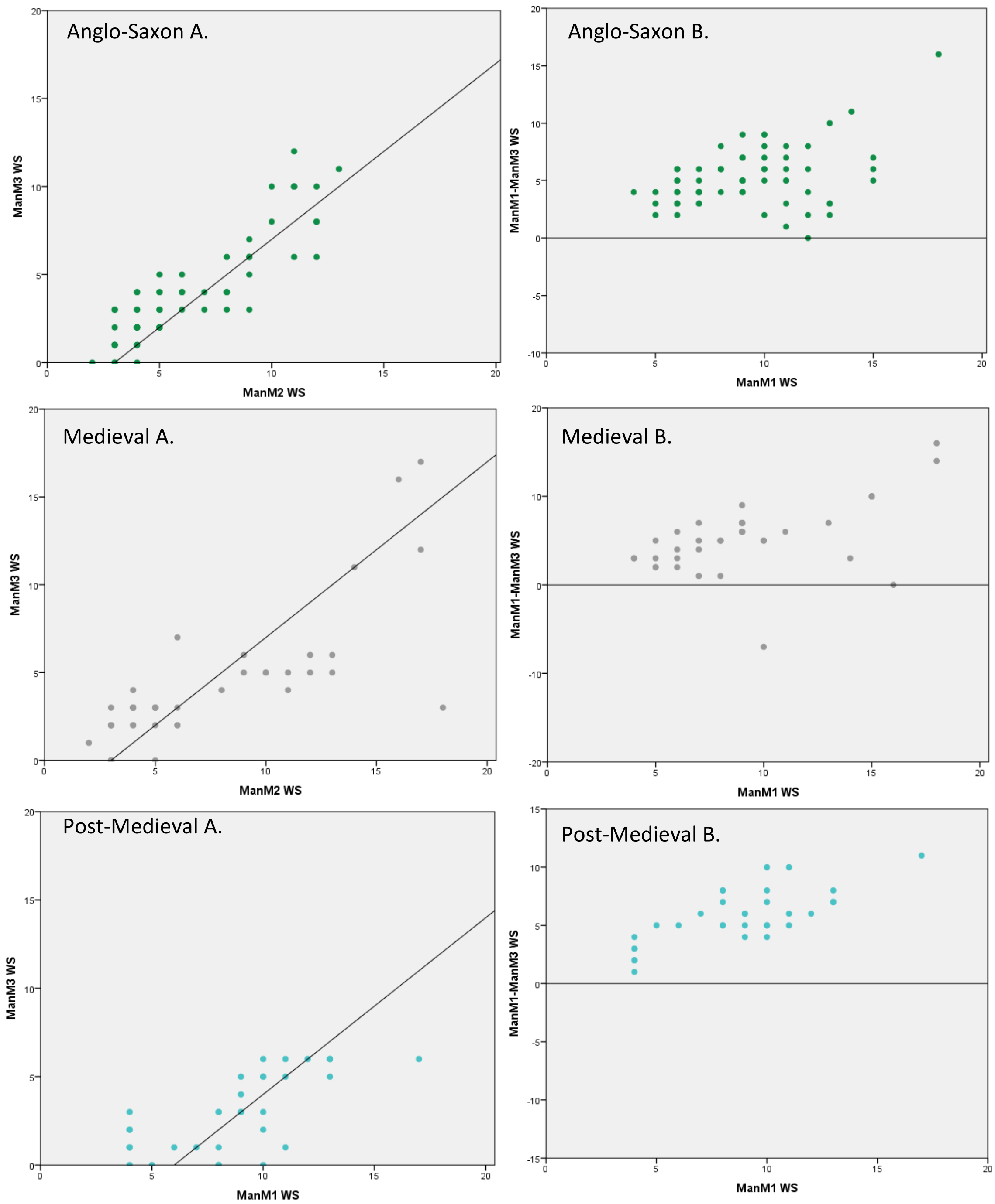

Figure 7.2.13 Continued. Plots wear stage (WS) of the first (ManM1) and third (ManM3) molars by temporal sample.
A. scatter plot of ManM1 WS vs ManM3 WS. The line on the scatterplot is the relationship expected if the M1 and M3 wear at the same rate.
B. Difference between ManM1 and ManM3 WS against ManM3 WS with a plotted line of equality (y=0).

7.2.4 Summary

The wear relationship between molars along the tooth row were examined to establish whether all molar types wore at a similar rate, and whether this relationship remained constant throughout the life of the dentition. The analysis showed that as the ManM1 experienced wear so did its ManM2 partner. This was true for all temporal samples, which were supported by significant correlation coefficients. Overall, there was a similar rate of wear on the both molars regarding the average crown height (CH), crown index (CI) and wear stage (WS) measurements. The ManM1 showed a greater rate of %DE wear compared to the ManM2.

All temporal samples showed a relationship where an increase in wear on the ManM2 was associated with an increase in wear on its ManM3 partner. These relationships were supported by significant correlation coefficients. Some temporal samples showed a difference in CH or CI wear rate on the ManM2 compared with the ManM3, while other samples showed a similar rate of wear on both molars. Any difference in wear rate was not great as points fell near the line depicting the relationship expected if both the ManM2 and ManM3 wore at similar rates. All temporal samples showed a difference in rate of %DE wear across the two molars, where the ManM2 showed a greater %DE wear rate compared with the ManM3 %DE. All temporal samples also showed a difference in rate of WS wear. WS points fell around the line of equal wear, suggesting the difference in WS wear rate between two molars was not great.

Section 7.2.3 showed that there was a relationship between the ManM1 and the ManM3 for the CH, CI and WS wear measurements. All temporal samples showed that an increase in wear on the ManM1 was associated with an increase in wear on the ManM3. As with the ManM2 and ManM3 wear relationship, some samples showed a similar CH or CI wear of rate on the ManM1 and ManM3 while others showed a difference. Any difference in wear rate was not great as the majority of points fell near the line of equal wear. The relationship between ManM1 and ManM3 %DE wear was weak, due to a minimal degree of exposed dentine on either molar. However, the results indicate a faster rate of %DE wear on the ManM1 compared with the ManM3. All temporal samples showed a difference in WS wear rate on the first and third molar.

The ManM3 did not experience high degrees of wear. The loss of the ManM1 or ManM2 due to ante-mortem tooth loss (AMTL) may provide an explanation. AMTL of the earlier erupting molars means it is no longer possible to observe the wear relationship on the ManM3. The ManM3 may still be experiencing wear, but it would not be possible to observe in the current analysis. It may also be argued that individuals died before the ManM3 experienced high levels of dental wear.

Table 5.1.2, however, shows a number of individuals were estimated to be over 45 years old in all temporal samples except the Neolithic and Bronze Age. This suggests it is likely that the loss of the earlier erupting molars prevents observation of the entire wear process of the ManM3 during this analysis rather individuals dying young. The ManM3 is therefore of limited use when estimating age of archaeological samples. Dental wear ageing methods such as Miles (1962) relies on the wear relationship between molars to estimate age. Once molars are lost to AMTL this approach is not possible.

These results reject the null hypothesis that all molars have a similar rate of wear. Although a difference in wear rate was observed across the three molars this thesis argues that this was not great, supported by points falling close to the line of equal wear. The second null hypothesis stated in section 7.2, that the rate of wear between molars remained constant, was accepted.

7.3 Relationship between dental wear and age

To ensure that dental wear is a reliable method for estimating age at death in British archaeological remains the relationship between the dental wear and age must be examined. Section 7.3 examines the relationship between dental wear and age for each studied sample, dating from the British Neolithic to Post-Medieval period. Following previous work, a relationship between the two variables is expected, where dental wear increases with increasing age.

To fully examine the relationship between dental wear and age individuals were divided into two groups: juvenile and adult. Juveniles were classified as an individual with developing dentition and had at least one erupted permanent, maxillary or mandibular, molar present for recording. An individual was considered an adult if any third molar was in full occlusion, or the fusion of long bone epiphyses was complete. The relationship between dental wear and juvenile age is first examined (Section 7.3.1). Age at death for juvenile individuals was based on their dental development. Dental development is tightly controlled by genetics and minimally affected by extrinsic factors and is therefore a reliable method for ageing juveniles (Smith 1991; Liversidge et al. 1998; White et al. 2011). Section 7.3.2 examines the relationship between dental wear and age in adult individuals, using bony age estimates as a proxy for age. Although there are issues associated with estimating age using bony age estimates (Chapter 2) this approach examines whether dental wear progresses with age in the studied samples.

7.3.1 Relationship between dental wear and juvenile age

Section 7.3.1 examines the strength of the relationship between juvenile age and dental wear for the wear measurements; average crown height (CH), crown index (CI) and ordinal wear stage (WS). Few juvenile individuals had any dentine exposed, thus the relationship between juvenile age and the percentage of dentine exposed (%DE) could not be examined. The wear relationship between juvenile age and dental wear was examined for the first (ManM1) and second (ManM2) mandibular molars by temporal sample. The third molar (ManM3) was excluded from this analysis as it was a marker of an adult individual. Regression analysis investigated the relationship between juvenile age and the CH and CI measurements, with a coefficients of determination (r^2) produced to measure the strength of a relationship between the two variables. Spearman's correlation coefficients examined the relationship between juvenile age and WS.

Null hypothesis: there is a relationship between dental wear and juvenile age

It was expected that:

- There is a relationship between juvenile age and dental wear in the first and second mandibular molars
- Measurements of crown height will decrease with age
- The WS measurement will increase with age

7.3.1.1 First mandibular molar (ManM1)

Average crown height (CH)

Regression analysis examined the relationship between first mandibular molar average crown height (ManM1 CH) and juvenile age. Table 7.3.1 reports the results of the regression analysis. Figure 7.3.1A shows the scatter plots for ManM1 CH against juvenile age and the regression line that best fits the scattered points by temporal sample. Figure 7.3.1B shows the scatter plots for the standardized residuals of ManM1 CH against juvenile age.

Table 7.3.1. Regression results for average crown height (CH) upon estimated juvenile age for the first mandibular molar (ManM1) by temporal sample.

Sample	n	Regression equation	Pearson's correlation coefficient (r)	Coefficient of determination (r^2)	P-value
Neolithic	27	ManM1 CH = 7.10 - 0.14*age	-0.49	0.24	0.009
Bronze Age	27	ManM1 CH = 7.27 - 0.12*age	-0.61	0.37	0.001
Iron Age	35	ManM1 CH = 6.86 - 0.09*age	-0.49	0.24	0.003
Romano-British	37	ManM1 CH = 6.96 - 0.08*age	-0.37	0.14	0.022
Anglo-Saxon	34	ManM1 CH = 6.80 - 0.08*age	-0.47	0.22	0.005
Medieval	32	ManM1 CH = 7.39 - 0.15*age	-0.72	0.52	0.001
Post-Medieval	22	ManM1 CH = 7.03 - 0.11*age	-0.67	0.22	0.001

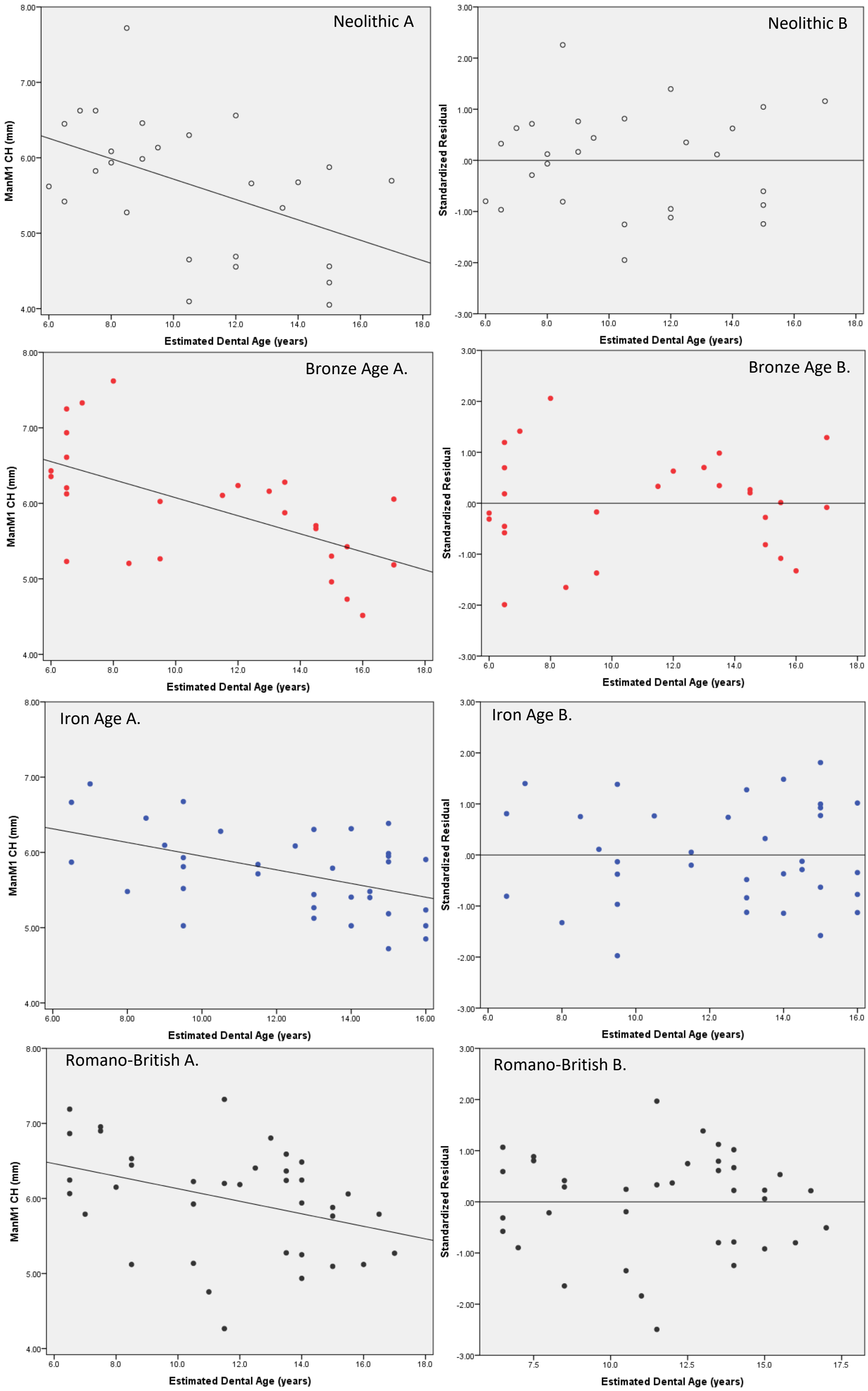

Figure 7.3.1. Scatter plots depicting results of the regression analysis for average crown height (CH) of the first mandibular molar (ManM1) against estimated juvenile age by temporal sample.

A. Scatterplot with regression line.

B. Standardized residuals of CH of the ManM1 against estimated juvenile age.

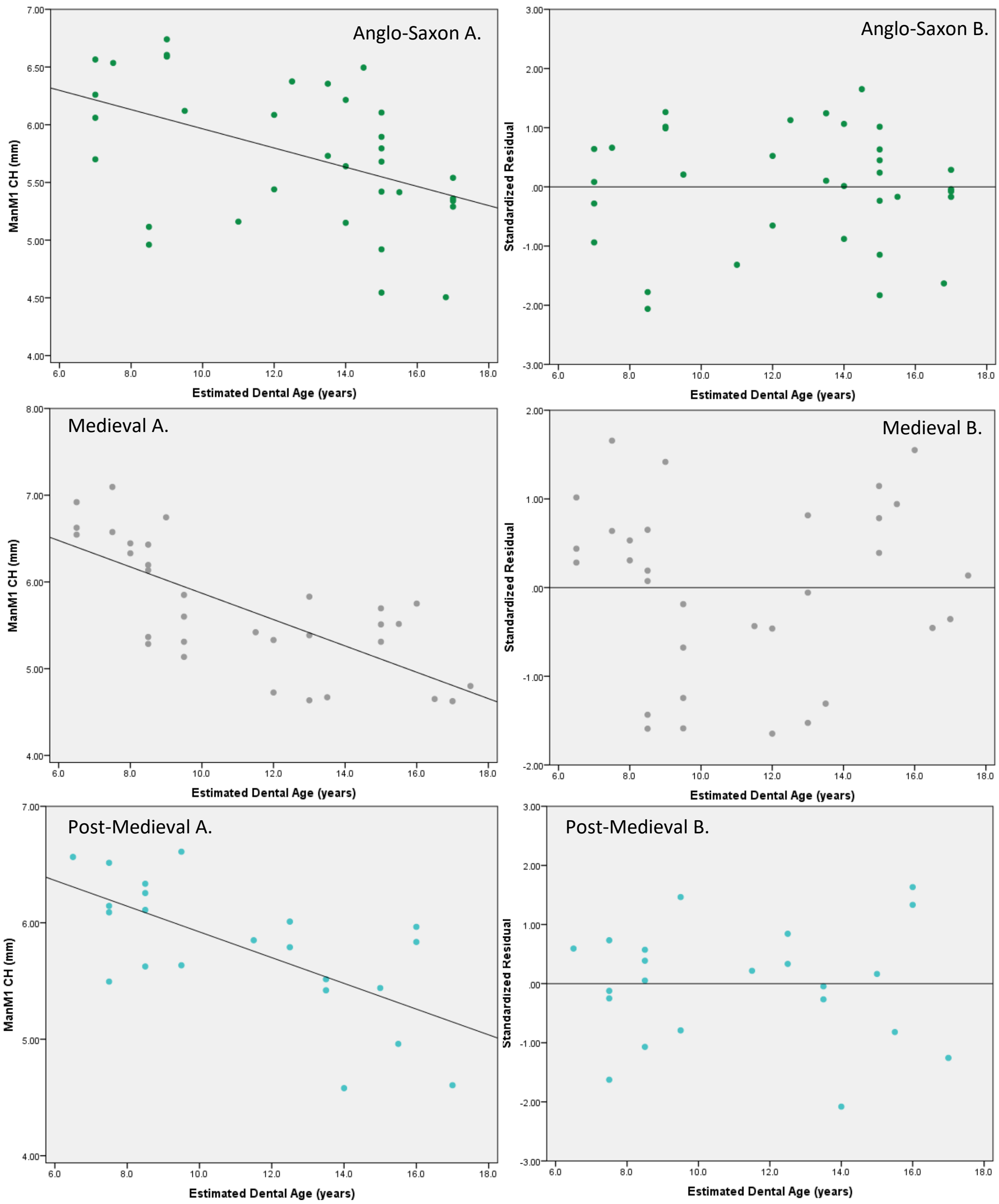

Figure 7.3.1 Continued. Scatter plots depicting results of the regression analysis for average crown height (CH) of the first mandibular molar (ManM1) against estimated juvenile age by temporal sample.
A. Scatterplot with regression line
B. Standardized residuals of CH of the ManM1 against estimated juvenile age.

Results of a regression analysis indicated a significant, linear relationship between ManM1 CH and juvenile age for all temporal samples. Figure 7.3.1A shows as juvenile age increased ManM1 CH decreased, this was supported by significant, negative Pearson correlation coefficients (Table 7.3.1). Inspection of the residual plots supported a linear regression model of ManM1 CH and juvenile age (Figure 7.3.1B). The r-square values show 14-52% of the variation observed in ManM1 CH was explained by an increase in juvenile age for all temporal samples.

The residual plot for the Medieval sample showed a patterning of points, where a V-shape was detectable. Figure 7.3.1B shows a decrease in ManM1 CI with juvenile age until around the age of 12 years, which then plateaued. The ManM2 erupts around the age of 12 years, potentially slowing the rate of wear on the ManM1. However, performing the regression analysis using a quadratic model did not greatly improve the fit of the data. These results suggest that caution is required before accepting the relationship between the variables is precisely linear. However, manipulation of the data failed to find a model that provided a better description of the relationship between ManM1 CH and juvenile age.

The above findings support an overall good relationship between ManM1 CH and juvenile age within each temporal sample. These results support the use of ManM1 juvenile wear rates in methods for estimating age at death.

Crown index (CI)

Regression analysis examined the relationship between first mandibular molar crown index (ManM1 CI) and juvenile age. Table 7.3.2 reports the results of the regression analysis. Figure 7.3.2A shows the scatter plots for ManM1 CI against juvenile age and the regression line that best fits the scattered points by temporal sample. Figure 7.3.2B shows the scatter plots for the standardized residuals of ManM1 CI against juvenile age.

Table 7.3.2. Regression results for crown index (CI) upon estimated juvenile age for the first mandibular molar (ManM1) by temporal sample.

Sample	n	Regression equation	Pearson's correlation coefficient (r)	Coefficient of determination (r^2)	p-value
Neolithic	26	ManM1 CI = 83.25 - 1.51*age	-0.54	0.29	0.004
Bronze Age	24	ManM1 CI = 92.74 - 1.98*age	-0.65	0.42	0.001
Iron Age	33	ManM1 CI = 83.16 - 1.32*age	-0.53	0.18	0.024
Romano-British	33	ManM1 CI = 79.39 - 0.93*age	-0.42	0.18	0.015
Anglo-Saxon	34	ManM1 CI = 92.83 - 2.04*age	-0.74	0.55	<0.001
Medieval	30	ManM1 CI = 86.17 - 1.84*age	-0.69	0.59	<0.001
Post-Medieval	22	ManM1 CI = 81.40 - 0.94*age	-0.45	0.20	0.033

As with ManM1 CH, there was a statistically significant linear relationship between ManM1 CI and juvenile age for all temporal samples (Table 7.3.2). Pearson correlation coefficients between ManM1 CI and juvenile age ranged from -0.2 to -0.6, which were significant at the 5% level. The r-square values indicate 18-59% of the variation observed ManM1 CI was explained by an increase in juvenile age.

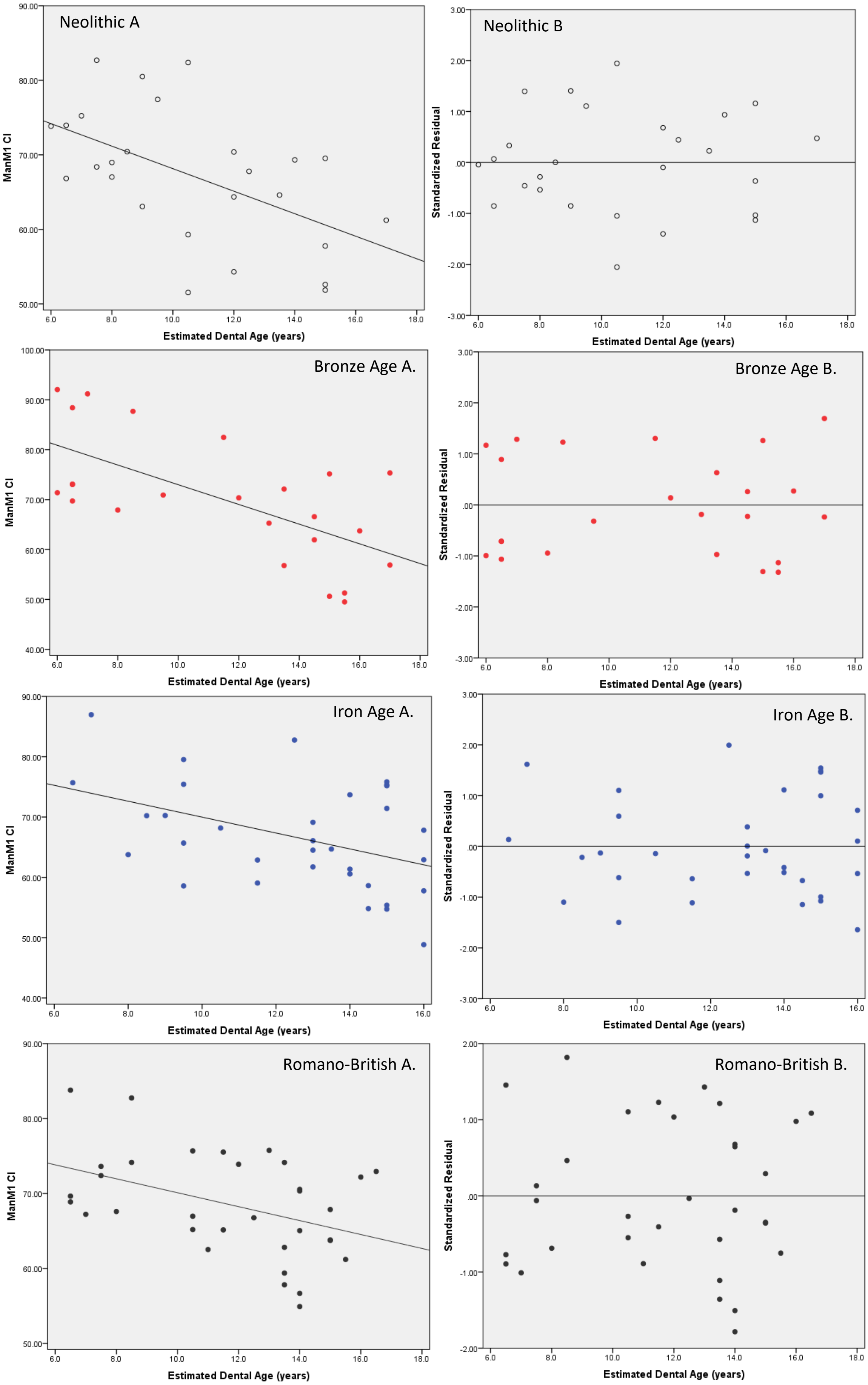

Figure 7.3.2. Scatter plots depicting results of the regression analysis for crown index (CI) of the first mandibular molar (ManM1) against estimated juvenile age by temporal sample.

A. Scatterplot with regression line
B. Standardized residuals of CI of the ManM1 against estimated juvenile age.

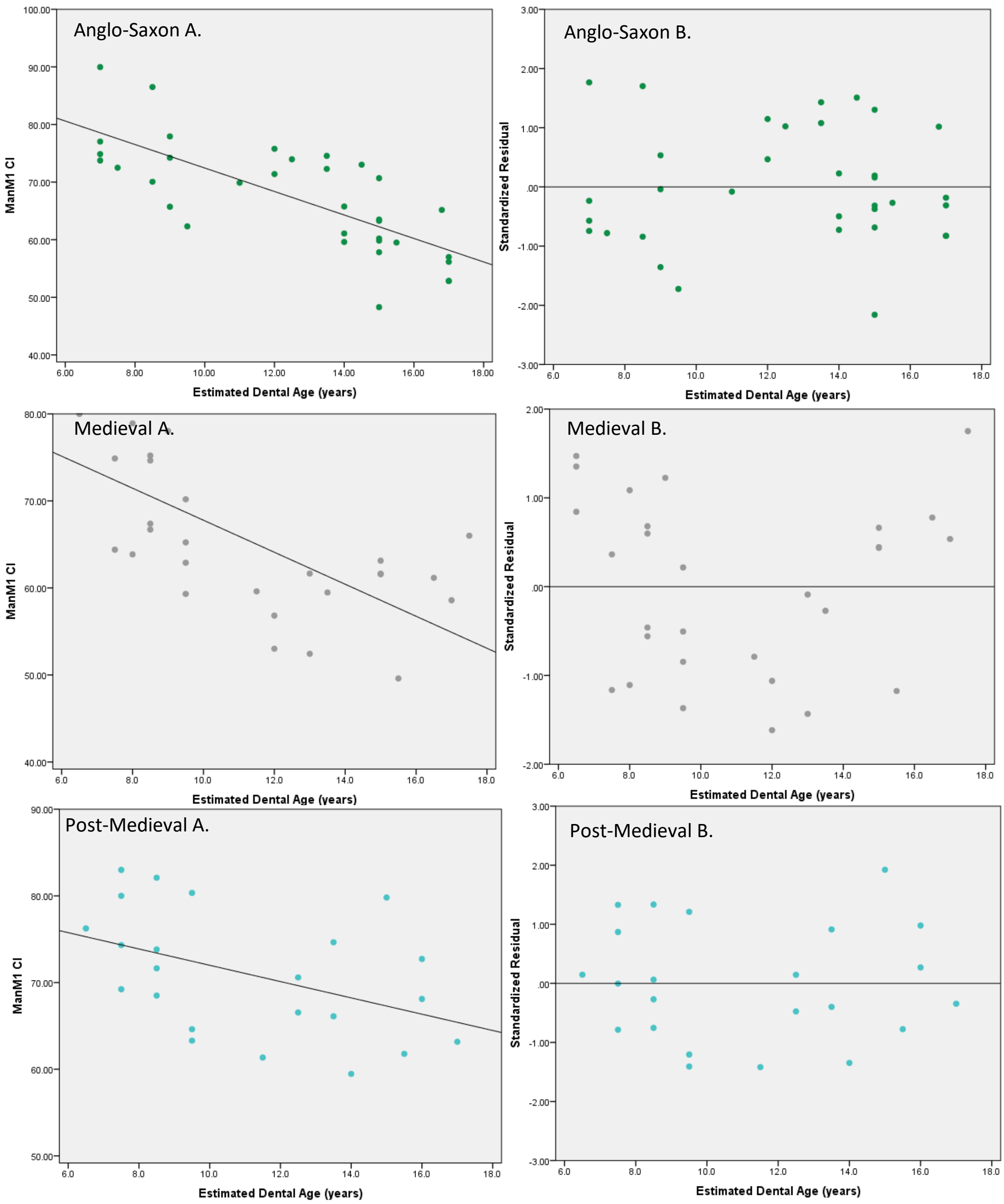

Figure 7.3.2 Continued. Scatter plots depicting results of the regression analysis for crown index (CI) of the first mandibular molar (ManM1) against estimated juvenile age by temporal sample.
A. Scatterplot with regression line
B. Standardized residuals of CI of the ManM1 against estimated juvenile age.

The regression procedure indicated that, for the Medieval sample, the relationship between ManM1 CI and juvenile age was negative, and statistically significant at the 5% level. This procedure also indicated that the relationship was adequately described by a linear regression (Table 7.3.2, Figure 7.3.2). However, examination of the Medieval plot of standardized residuals shows a V-shape pattern. As with ManM1 CI, Figure 7.3.2Medieval A shows a decrease in ManM1 CI with juvenile age until around the age of 12 years, which then plateaued. The ManM2 erupts around this age, potentially slowing the rate of wear on the ManM1. Performing the regression analysis with a quadratic model did not greatly improve the fit of the data. These results indicate the relationship between Medieval ManM1 CI and juvenile age may not be precisely linear, however, manipulation of the data failed to find a model that better described the relationship.

The above findings support a relationship between ManM1 CI and juvenile age, further supporting the use of ManM1 wear in juvenile individuals in methods for estimating age at death.

Wear stage (WS)

Due to the ordinal nature of the Wear Stage (WS) measurement, regression analysis could not be performed between ManM1 WS and juvenile age. Figure 7.3.3 shows the scatter plots for ManM1 WS against juvenile age by temporal sample. Spearman's correlation coefficients evaluated the strength of the relationship between the two variables (Table 7.3.3). All temporal samples showed a relationship between ManM1 WS and juvenile age, where ManM1 WS increased with juvenile age. These were supported by significant Spearman's correlation coefficients (Table 7.3.3).

These results support a good relationship between ManM1 WS and juvenile age, further supporting the use of ManM1 wear in methods for estimating age.

Table 7.3.3. Spearman's correlation coefficients for wear stage (WS) upon estimated juvenile age for the first mandibular molar (ManM1) by temporal sample

Sample	n	Spearman's correlation coefficient (r_s)	p-value
Neolithic	28	0.77	<0.001
Bronze Age	28	0.77	<0.001
Iron Age	35	0.63	<0.001
Romano-British	39	0.72	<0.001
Anglo-Saxon	34	0.78	<0.001
Medieval	32	0.75	<0.001
Post-Medieval	24	0.81	<0.001

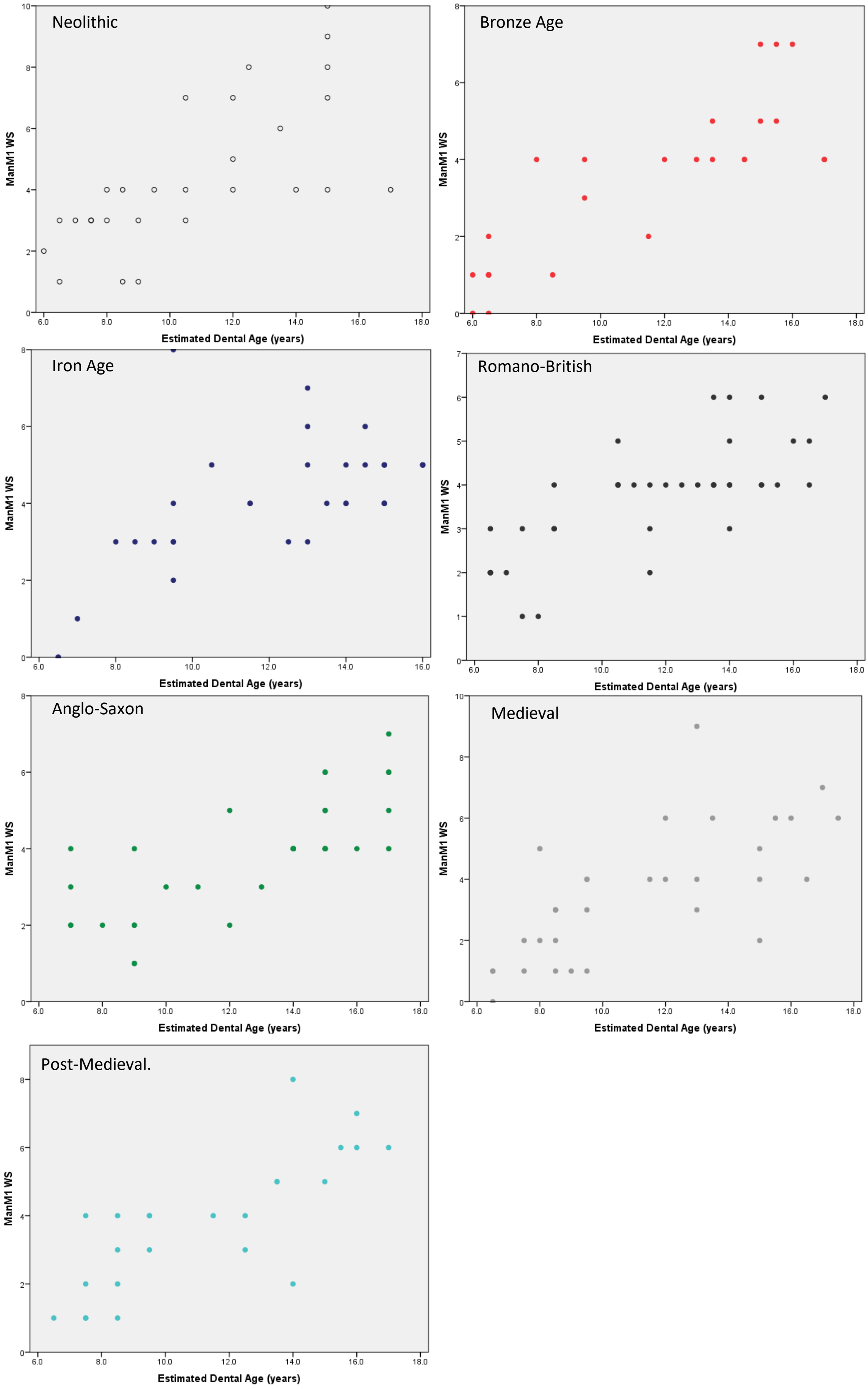

Figure 7.3.3. Wear stage (WS) of the first mandibular molar (ManM1) against estimated juvenile age by temporal sample.

7.3.1.2 Second mandibular molar (ManM2)

Average crown height (CH)

Regression analysis examined the relationship between second mandibular molar average crown height (ManM2 CH) and juvenile age. Table 7.3.4 reports the results of the regression analysis. Figure 7.3.4A shows the scatter plots for ManM2 CH against juvenile age and the regression line that best fits the scattered points by temporal sample. Figure 7.3.4B show the scatter plots for the standardized residuals of ManM2 CH against juvenile age.

Table 7.3.4. Regression equations for average crown height (CH) upon estimated juvenile age for the second mandibular molar (ManM2) by temporal sample.

Sample	n	Regression equation	Pearson's correlation coefficient (r)	Coefficient of determination (r^2)	p-value
Neolithic	11	ManM2 CH = 6.00 - 0.005*age	-0.03	0.001	0.943*
Bronze Age	13	ManM2 CH = 13.18 - 0.48*age	-0.78	0.61	0.002
Iron Age	19	ManM2 CH = 10.73 - 0.33*age	-0.69	0.48	0.001
Romano-British	19	ManM2 CH = 8.10 - 0.11*age	-0.31	0.09	0.104*
Anglo-Saxon	22	ManM2 CH = 8.24 - 0.14*age	-0.43	0.18	0.049
Medieval	13	ManM2 CH = 7.53 - 0.11*age	-0.56	0.30	0.052*
Post-Medieval	13	ManM2 CH = 8.29 - 0.18*age	-0.45	0.20	0.128*

* indicates a non-significant relationship between ManM2 CH and juvenile age

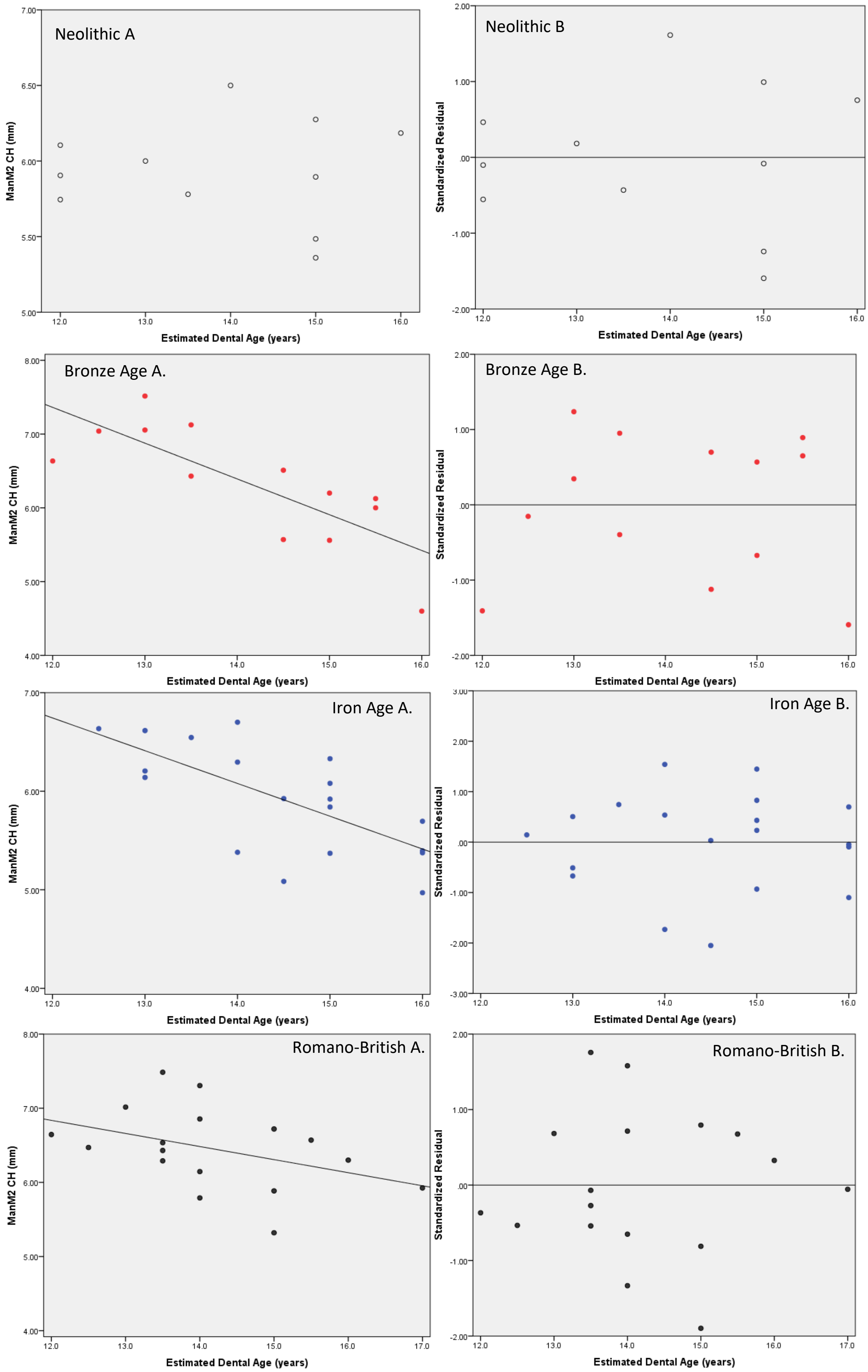

Figure 7.3.4. Scatter plots depicting results of the regression analysis for average crown height (CH) of the second mandibular molar (ManM2) against estimated juvenile age by temporal sample

A. Scatterplot with regression line
B. Standardized residuals of CH of the ManM2 against estimated juvenile age

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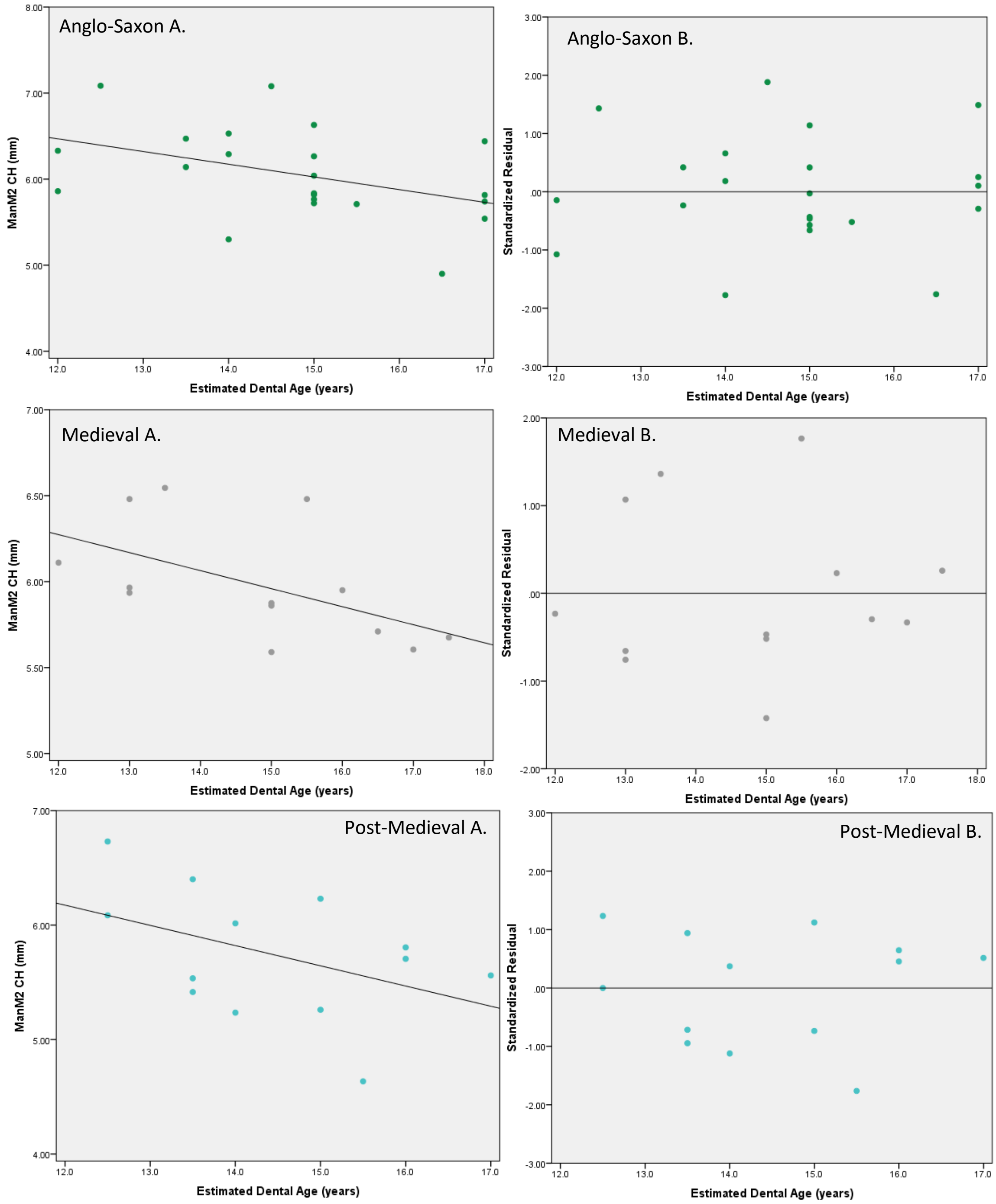


Figure 7.3.4 Continued. Scatter plots depicting results of the regression analysis for average crown height (CH) of the second mandibular molar (ManM2) against estimated juvenile age by temporal sample.
A. Scatterplot with regression line
B. Standardized residuals of CH of the ManM2 against estimated juvenile age.

Results of the regression analysis indicate a significant, linear relationship between ManM2 CH and juvenile age for the Bronze Age, Iron Age and Anglo-Saxon samples. Figure 7.3.4A shows as juvenile age increased ManM1 CH decreased. This was supported by a significant, negative Pearson correlation coefficients (Table 7.3.4). Inspection of the residual plots supported a linear regression model of ManM1 CH and juvenile age. The r-square values show 18-61% of the variation observed in ManM1 CH was explained by an increase in juvenile age for the Bronze Age, Iron Age, and Anglo-Saxon samples.

The Neolithic, Romano-British and Post-Medieval samples did not have a statistically significant linear relationship between ManM2 CH and juvenile age. The Neolithic did not show a pattern in the plot of ManM2 CH by juvenile age. There was no evidence of patterning in the Neolithic plot of standardized residuals. Transformations of the data set did not identify a significant relationship between Neolithic ManM2 CH and juvenile age.

The linear equation for the Romano-British, Medieval and Post-Medieval samples were not significant. However, plotting the regression line shows a pattern of decreasing ManM2 CH with an increase in juvenile age. The Medieval sample only just missed significance at the 5% level, and a random pattern in the standard residuals plots supports a linear model. Various transformations of the data did not improve the fit of the data to a straight line.

These results suggest a weak relationship between ManM2 CH and juvenile age, thus the ManM2 CH and juvenile age may not be reliable when employed in methods for estimating age. A possible explanation for this relatively weak relationship, compared with ManM1 CH, is the comparatively shorter period of time to examine wear on the ManM2 during the juvenile period. Wear on the ManM2 is only observable for six years during the juvenile period, compared to twelve years on the ManM1. Therefore, only a minimal amount of ManM2 dental tissue loss is observed.

Crown index (CI)

Regression analysis examined the relationship between second mandibular molar crown index (ManM2 CI) and juvenile age. Table 7.3.5 reports the results for the regression analysis. Figure 7.3.5A shows the scatter plots for ManM2 CI against juvenile age and the regression line that best fits the scattered points by temporal sample. Figure 7.3.5B shows the scatter plots for the standardized residuals of ManM2 CI against juvenile age.

Table 7.3.5. Regression equations for crown index (CI) upon estimated juvenile age for the second mandibular molar (ManM2) by temporal sample.

Sample	n	Regression equation	Pearson's correlation coefficient (r)	Coefficient of determination (r^2)	p-value
Neolithic	8	ManM2 CI = 84.63 - 0.99*age	-0.29	0.09	0.481*
Bronze Age	12	ManM2 CI = 159.30 - 6.09*age	-0.64	0.41	0.024
Iron Age	18	ManM2 CI = 130.59 - 4.32*age	-0.53	0.28	0.024
Romano-British	15	ManM2 CI = 120.67 – 2.98*age	-0.44	0.19	0.116*
Anglo-Saxon	19	ManM2 CI = 118.86 - 3.55*age	-0.56	0.31	0.013
Medieval	11	ManM2 CI = 92.73 - 1.71*age	-0.52	0.27	0.100*
Post-Medieval	11	ManM2 CI = 77.48 - 0.51*age	-0.08	0.01	0.817*

* indicates a non-significant relationship between ManM2 CI and juvenile age

Regression analysis indicated the relationship between ManM2 CI and juvenile age was negative, and was adequately described by a linear regression for the Bronze Age, Iron Age and Anglo-Saxon samples. These relationship were statistically significant at the 5% level. The r-square values show 28-40% of the variation observed in ManM2 CI was explained by an increase in juvenile age.

The Neolithic, Romano-British, Medieval and Post-Medieval samples did not have a statistically significant linear relationship between ManM2 CI and juvenile age. The Neolithic and Post-Medieval samples did not show a trend in the plot of ManM2 CI by juvenile age, and there was no evidence of patterning in the plots of standardized residuals. Applying various regression models to these data sets did not identify a significant relationship between ManM2 CI and juvenile age. These results indicates minimal loss of ManM2 CI during the juvenile period for the Neolithic, Romano-British, Medieval and Post-Medieval samples.

The linear equation for the Romano-British and Medieval samples were not significant but showed evidence of patterning when plotting ManM2 CI against juvenile age. A random pattern in the standard residuals plots supports a linear model. Various transformations of the data did not improve the fit of the data to a straight line. The r^2 values of 0.19 and 0.21 respectively for the Romano-British and Medieval samples indicates approximately 20% of the variation observed in ManM2 CI was explained by an increase in juvenile age.

The above results suggest there is a weak relationship between ManM2 CI and juvenile age. Thus, ManM2 rates based on juvenile individuals may not be reliable in methods for estimating age at death. As with ManM2 CH wear, the short occlusion time of the ManM2 during the juvenile period may explain these results.

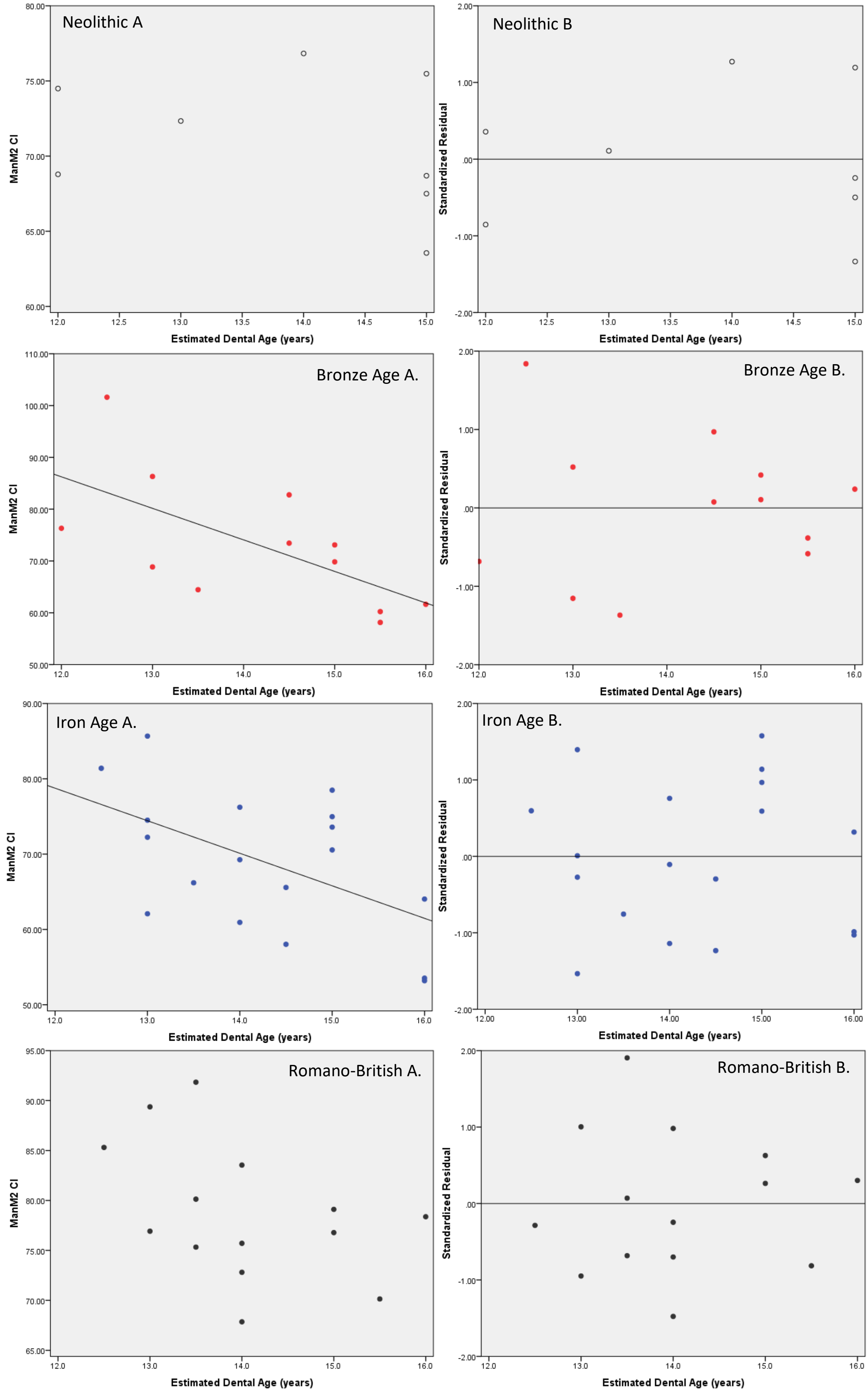


Figure 7.3.5 Scatter plots depicting results of the regression analysis for crown index (CI) of the second mandibular molar (ManM2) against estimated juvenile age by temporal sample

A. Scatterplot with regression line

B. Standardized residuals of CI of the ManM2 against estimated juvenile age

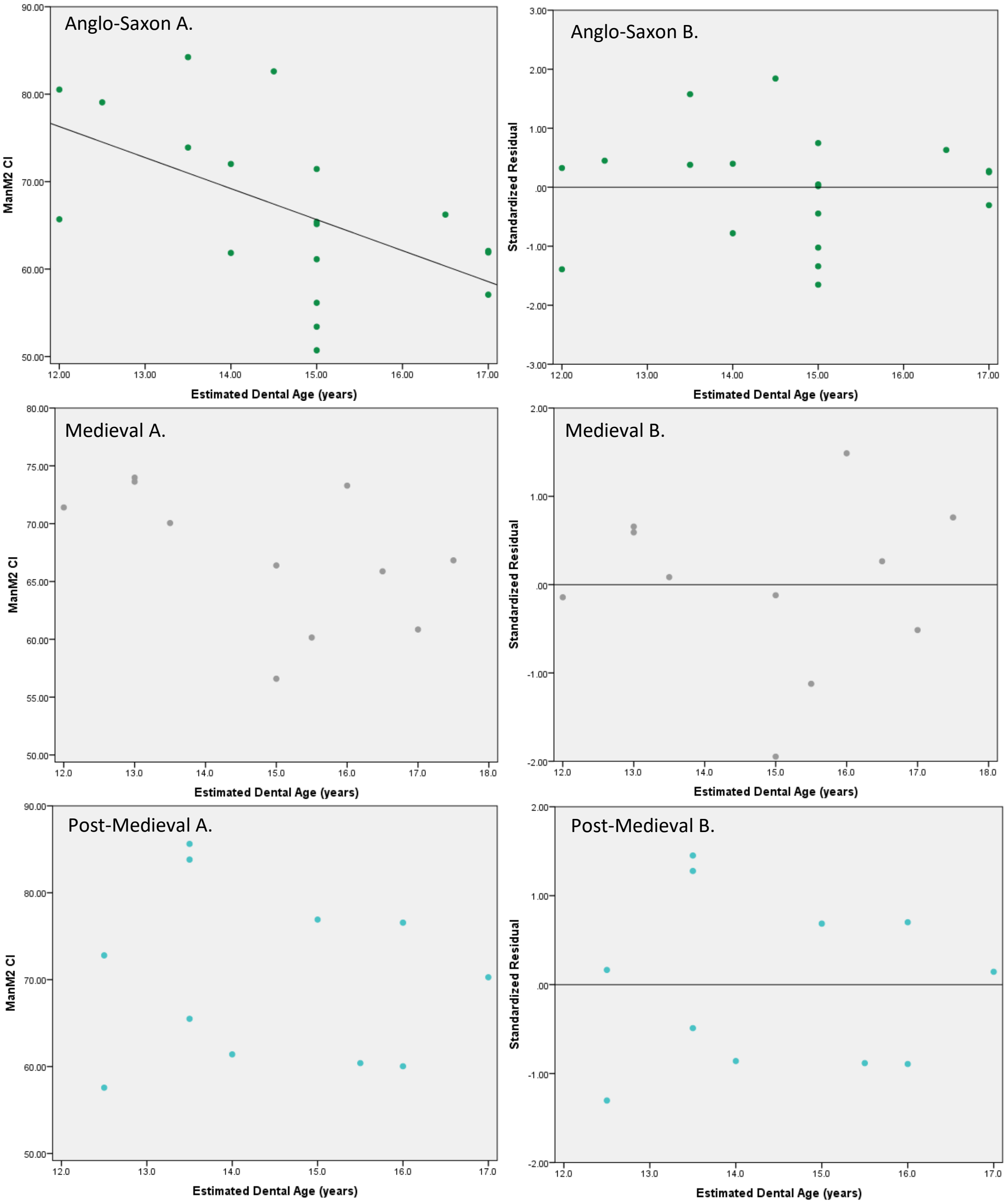


Figure 7.3.5 Continued. Scatter plots depicting results of the regression analysis for crown index (CI) of the second mandibular molar (ManM2) against estimated juvenile age by temporal sample.
A. Scatterplot with regression line
B. Standardized residuals of CI of the ManM2 against estimated juvenile age.

Wear stage (WS)

Due to the ordinal nature of the Wear Stage (WS) measurement, regression analysis could not be performed for ManM2 WS against juvenile age. Figure 7.3.6 shows the scatter plots for ManM2 WS versus juvenile age by temporal sample. Spearman correlation coefficients evaluated the strength of the relationship between ManM2 WS and juvenile age (Table 7.3.6) All temporal samples, except the Iron Age sample, showed a relationship between ManM2 WS and juvenile age, where ManM2 WS increased with juvenile age. These were supported by Spearman's correlation coefficients, which were significant at the 5% level. The Spearman correlation coefficients were weak compared with the coefficients for ManM1 WS and juvenile age, indicating a relatively weaker relationship in ManM2 wear for the juvenile period.

Spearman's correlation coefficient between ManM2 WS and juvenile age for the Iron Age sample was not significant (Table 7.3.6). The plot of ManM2 WS versus juvenile age shows minimal ManM2 wear an increase in juvenile age.

These results suggest there is a relationship between ManM2 WS and juvenile age, although this is comparatively weaker than the ManM1 WS relationship. Thus, the use of ManM2 WS juvenile wear in methods for estimating age is supported.

Table 7.3.6. Spearman's correlation coefficients for wear stage (WS) upon estimated juvenile age for the second mandibular molar (ManM2) by temporal sample.

Sample	n	Spearman's correlation coefficient (r_s)	p-value
Neolithic	11	0.70	0.016
Bronze Age	15	0.74	0.002
Iron Age	20	0.25	0.283*
Romano-British	20	0.50	0.026
Anglo-Saxon	22	0.74	<0.001
Medieval	14	0.55	0.044
Post-Medieval	13	0.60	0.030

* indicates a non-significant relationship between ManM2 WS and juvenile age

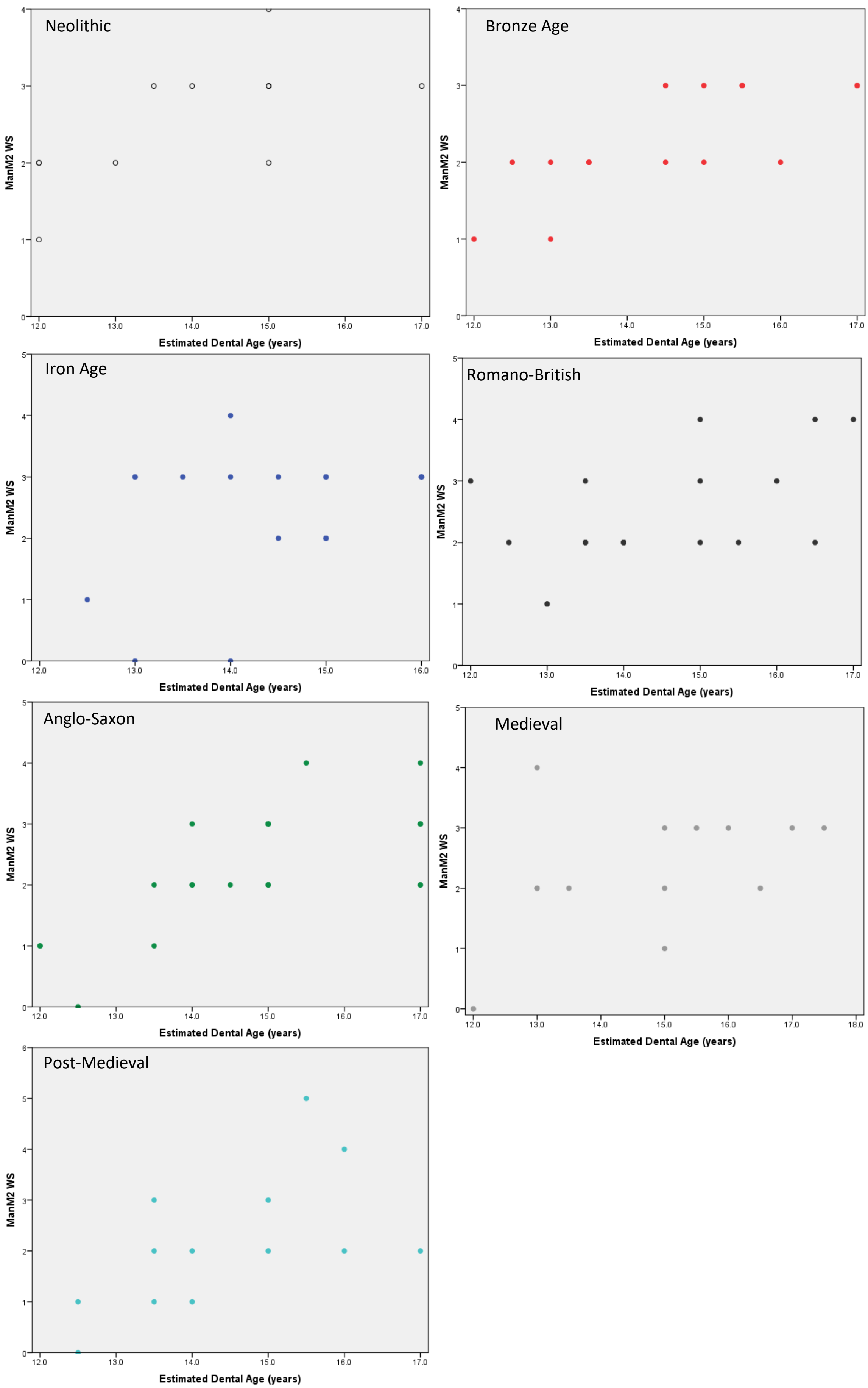


Figure 7.3.6. Wear stage (WS) of the second mandibular molar (ManM2) against estimated juvenile age by temporal sample.

7.3.1.3 Summary: the relationship between dental wear and juvenile

Section 7.3.1 examined the relationship between dental wear and juvenile age by temporal sample. This section aimed to ensure the expected relationship between the two variables was observed in the studied samples, and to evaluate the strength of the relationship between dental wear and juvenile age.

The first mandibular molar had a significant relationship between wear measurement and juvenile age in all temporal samples. This was true for all wear measurements employed (CH, CI and WS). There was an overall linear pattern, indicating as juvenile age increased wear also increased on the ManM1.

The second mandibular molar had a significant relationship between ManM2 average crown height (CH) and juvenile age in the Bronze Age, Iron Age, Anglo-Saxon and Medieval samples. There was a general trend of decreasing ManM2 CH with increasing juvenile age for the Romano-British and Post-Medieval samples, which was significant. Neolithic ManM2 CH remained constant with an increase in juvenile age. These results suggest that the wear relationship between ManM2 CH and juvenile age is weak compared with relationship between ManM1 CH and juvenile age.

The relationship between second mandibular molar crown index (ManM2 CI) and juvenile age was significant in the Bronze Age, Iron Age and Anglo-Saxon samples. ManM2 CI remained constant with an increase in juvenile age in the Neolithic and Post-Medieval samples. A pattern of decreasing ManM2 CI with an increase in juvenile age was observed in the Romano-British and Medieval samples, which was not significant. These results suggest that the relationship between ManM2 CI and juvenile age is weak compared with relationship between ManM1 CI and juvenile age.

There was a significant relationship between ManM2 WS and juvenile age for all temporal samples, except the Iron Age sample. The Iron Age showed a general trend of increasing ManM2 WS with an increase in juvenile age.

These results support acceptance of the null hypothesis for the ManM1 but rejection of the null hypothesis for the ManM2. This conclusion suggests the relationship between ManM1 dental wear and juvenile wear may be reliably used in methods for estimating age at death, however the use of the ManM2 juvenile wear relationship will be less reliable. While the ManM2 showed an overall pattern of increasing dental wear with an increase in juvenile age, the relatively short time span to view this relationship prevents one to be confident in using it to estimate age.

7.3.2 Relationship between dental wear and adult age

Section 7.3.1 examined the relationship between dental wear and juvenile age. The below analysis examines the relationship between age category and dental wear measurements by temporal sample. Bony age estimates were used as a proxy for estimated age, allowing individuals to be assigned into an age category. Chapter 2 discusses the issues associated with bony age estimation techniques, however, this analysis ensures that the relationship between dental wear and age continues into adulthood. This is particularly important for the CI and %DE wear measurements, which have not previously been employed in studies examining the relationship between dental wear and age. This approach ensures that dental wear is progressive with age and that dental wear as an ageing method may be applied to British archaeological remains.

Box and whisker diagrams illustrated wear measurement distributions by age category for each temporal sample. Each box represents the middle 50% of scores in the distribution (the interquartile range) and the whiskers show the top and bottom 25% of scores. Any scores outside this range were outliers and the thick line represents the median value. Spearman's correlation coefficients determined the strength of the association between age categories and wear measurement. This analysis was repeated for four wear measurements, average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS), by temporal sample. The Neolithic sample was excluded due to the inability to assign sex to dental remains as a result of Neolithic burial practices.

Null hypothesis: there is a relationship between dental wear and adult age

It is expected that:

- There is a progressive loss of dental tissue with an increase in age category across all molar types
- There is a significant correlation between dental wear measurements and age categories.
- Within each age category, the first molar shows greater wear compared to the second molar and the second molar shows more wear compared to the third molar.

Bronze Age sample

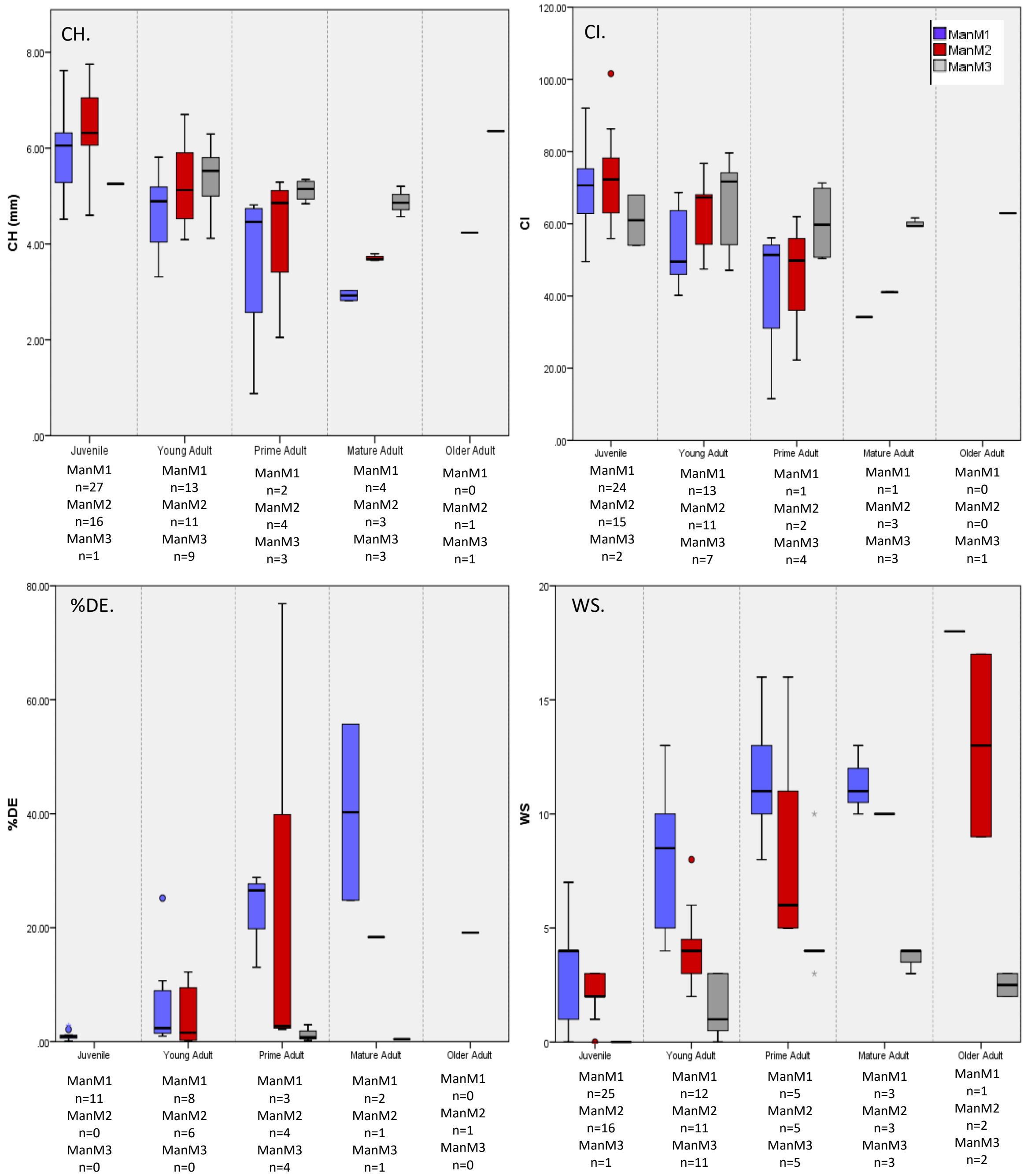


Figure 7.3.7. Box and whisker diagrams representing the relationship between age and dental wear measurement for the Bronze Age sample by molar type.

Each diagram represents a wear measurement: average crown height (CH), crown Index (CI), percent of dentine exposure (%DE) and wear stage (WS).

Figure 7.3.7 shows an association between all dental wear measurements and age category for the Bronze Age sample. CH and CI decreased with age, while %DE and WS increased with age. This was true for three mandibular molars. This relationship was observed until the Mature Adult age category, where small samples sizes prevented further examination. Spearman's correlation coefficients supported the relationship observed in Bronze Age first and second mandibular molars, and were significant at the 5% level (Table 7.3.7). Spearman's correlation coefficients were not significant between ManM3 crown height measurements and age, although a pattern of decreasing CH with an increase in age was observed. The relationship between ManM3 %DE and age category could not be examined due to a small sample size. Finally, the relationship between ManM3 WS and age category was significant.

The first molars consistently showed a greater degree of wear compared to the second molars. The second molars showed a greater degree of wear compared to the third morals. This was true for all wear measurements.

The inter-quartile range (IQR) for the ManM1 and ManM2 remained constant for the CH and CI measurements. The %DE and WS measurements showed an increase in inter-quartile range with an increase in age. This suggests the amount of exposed dentine on the occlusal surface became more varied as individuals increased in age. This variation has the potential to decrease the reliability of age estimates when using occlusal wear measurements to estimate age.

These results support the expectation that dental wear increased with age for the Bronze Age sample, although occlusal wear becomes more varied with increasing age. Furthermore, these results support the use of dental wear as an ageing technique in Bronze Age Individuals.

Table 7.3.7. Spearman's correlation coefficients for age category by wear measurement and molar type for the Bronze Age sample.

Wear Measurement	Molar	n	Spearman correlation coefficients (r_s)	p-value
CH	ManM1	46	-0.73	<0.001
	ManM2	35	-0.74	<0.001
	ManM3	18	-0.14	0.572*
CI	ManM1	42	-0.66	<0.001
	ManM2	31	-0.61	<0.001
	ManM3	17	-0.13	0.615*
%DE	ManM1	24	0.83	<0.001
	ManM2	12	0.64	0.024
	ManM3	4	-	-
WS	ManM1	46	0.82	<0.001
	ManM2	37	0.86	<0.001
	ManM3	22	0.58	0.006

Wear measurement: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

* indicates a non-significant relationship between wear measurement and adult age

Iron Age sample

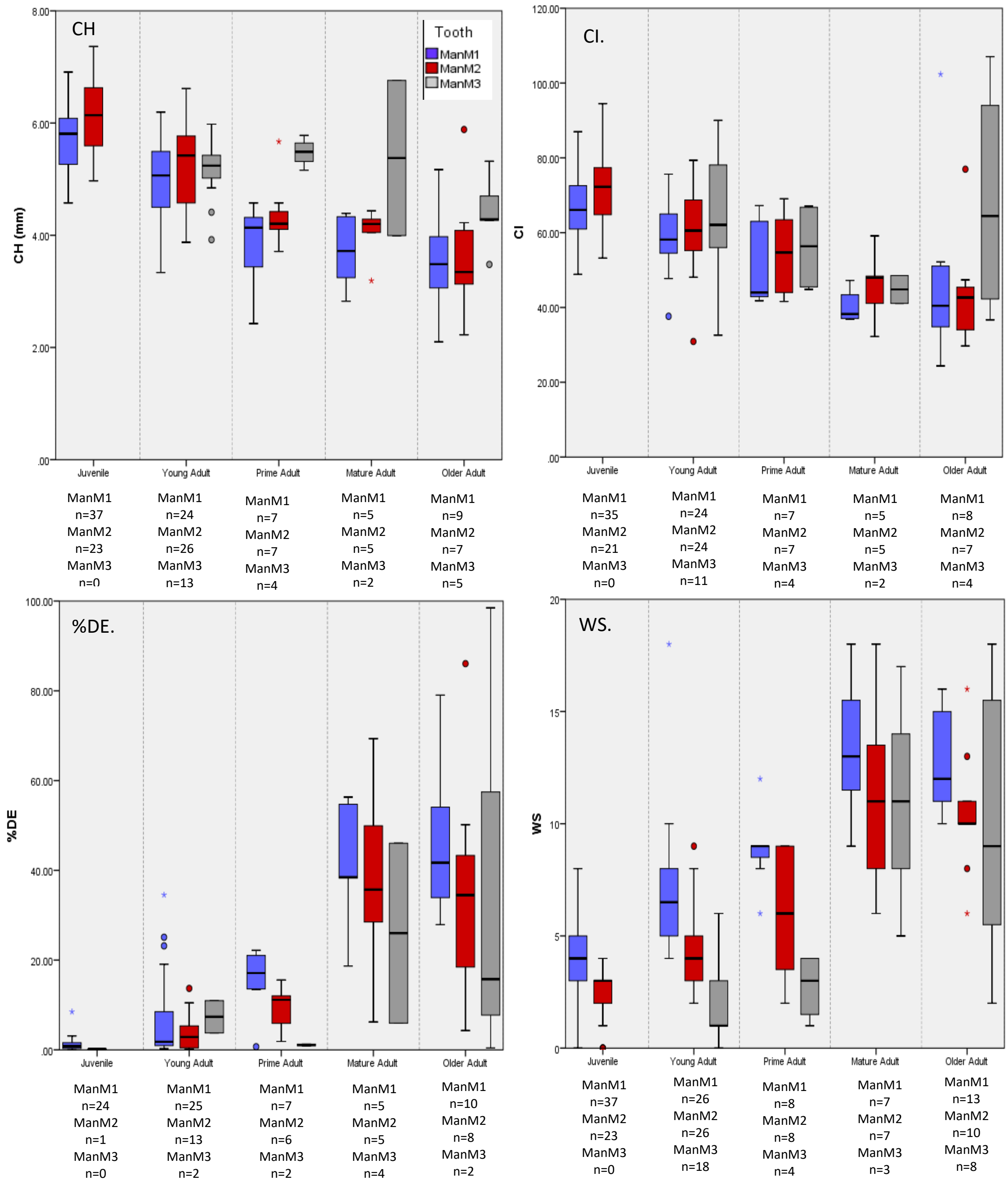


Figure 7.3.8. Box and whisker diagrams representing the relationship between age and dental wear measurement for the Iron Age sample by molar type.

Each diagram represents a wear measurement: average crown height (CH), crown Index (CI), percent of dentine exposure (%DE) and wear stage (WS).

Figure 7.3.8 shows an association between all dental wear measurements and age category for the Iron Age sample. CH and CI decreased with age, while %DE and WS increased with age. This was true for all molars and was observed across age categories. The relationship between dental wear measurements and age category were supported by significant Spearman's correlation coefficients in the first and second mandibular molars (Table 7.3.8). Wear on the ManM1 was consistently greater compared to the ManM2, and wear on the ManM2 was greater compared to wear on the ManM3. This was true across all wear measurements.

Only the WS measurement showed a significant relationship with age category in the ManM3. Figure 7.3.8 does not show a clear pattern of increasing wear with age for either the ManM3 CH or ManM3 %DE measurements. ManM3 CI appears to show a pattern of decreasing CI with age, although this become varied in the oldest age category.

The inter-quartile range for ManM1 CH remained constant across the age categories, while the ManM2 CH IQR varied. CI measurements had comparable IQR across age categories, for each molar. %DE and WS showed an increase in IQR with an increase in age, indicating exposed dentine became more varied with an increase in age. This variation has the potential to decrease the reliability of age estimates when using occlusal wear measurements to the estimate age of Iron Age remains.

These results support a relationship between dental wear and age for the Iron Age sample, although the occlusal wear measurements became more varied with increasing age.

Table 7.3.8. Spearman's correlation coefficients for age category by wear measurement and molar type for the Iron Age sample.

Wear Measurement	Molar	n	Spearman's correlation coefficients (r_s)	p-value
CH	ManM1	82	-0.74	<0.001
	ManM2	68	-0.72	<0.001
	ManM3	24	-0.27	0.207
CI	ManM1	79	-0.61	<0.001
	ManM2	65	-0.62	<0.001
	ManM3	20	-0.16	0.499*
%DE	ManM1	71	0.77	<0.001
	ManM2	33	0.76	<0.001
	ManM3	10	0.35	0.316*
WS	ManM1	91	0.85	<0.001
	ManM2	74	0.78	<0.001
	ManM3	33	0.70	<0.001

Wear measurement: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

* indicates a non-significant relationship between wear measurement and age

Romano-British sample

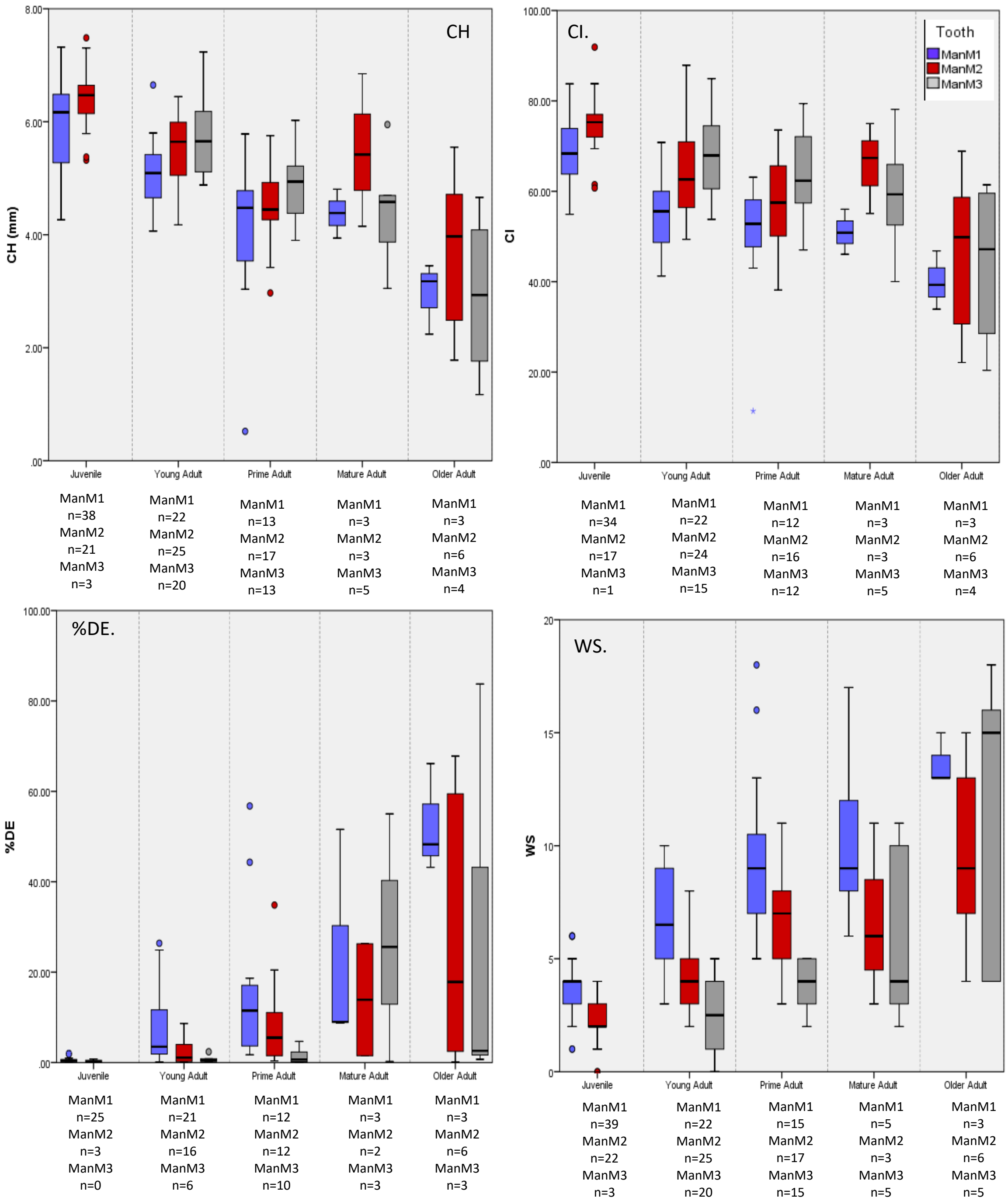


Figure 7.3.9. Box and whisker diagrams representing the relationship between age and dental wear measurement for the Romano-British sample by molar type.

Each diagram represents a wear measurement: average crown height (CH), crown Index (CI), percent of dentine exposure (%DE) and wear stage (WS).

The Romano-British sample showed an association between all dental wear measurements and age category (Figure 7.3.9). This was true for all mandibular molars. CH and CI decreased as age increased, while %DE and WS increased as age increased. The relationships in Figure 7.3.9 was supported by Spearman's correlation coefficients, which were significant at the 5% level for all molar types and all wear measurements (Table 7.3.9).

The first mandibular molar showed a larger degree of wear compared to the second mandibular molar across all age categories. The second mandibular molar typically showed a greater amount of wear compared with the third mandibular for the first three age categories. In the Mature Adult age category CH and CI were greater on the ManM2 compared with the ManM3. One individual (LH 1022), estimated to be a Mature Adult, had no dentine exposure on their ManM2 and experienced ante-mortem loss of their ManM1 due to periodontal disease. It may be that individual LH 1022 was incorrectly assigned a higher age category, therefore skewing the results for ManM2 CH and CI wear distributions. This individual may also be skewing the Mature Adult ManM2 WS measurement, which has a lower median compared to the ManM2 WS Prime Adult age category.

ManM1 inter-quartile ranges were comparable for the CH and CI measurements across the age categories. In comparison, the IQR for ManM2 and ManM3 crown height measurements varied. %DE and WS IQR increased with higher age categories, indicating the amount of exposed dentine became more varied as individuals increased in age. This variation has the potential to decrease the reliability of age estimates when using occlusal wear measurements to estimate age of Romano-British individuals.

These results support a relationship between dental wear and adult age for the Romano-British sample. Occlusal wear measurements were found to become varied with increasing age.

Table 7.3.9. Spearman's correlation coefficients for age category by wear measurement and molar type for the Romano-British sample.

Wear Measurement	Molar	n	Spearman's correlation coefficients (r_s)	p-value
CH	ManM1	80	-0.75	<0.001
	ManM2	73	-0.73	<0.001
	ManM3	56	-0.75	<0.001
CI	ManM1	75	-0.77	<0.001
	ManM2	67	-0.60	<0.001
	ManM3	45	-0.44	0.003
%DE	ManM1	66	0.72	<0.001
	ManM2	49	0.60	<0.001
	ManM3	31	0.40	0.028
WS	ManM1	84	0.82	<0.001
	ManM2	73	0.74	<0.001
	ManM3	48	0.64	<0.001

Wear measurements include: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

Anglo-Saxon sample

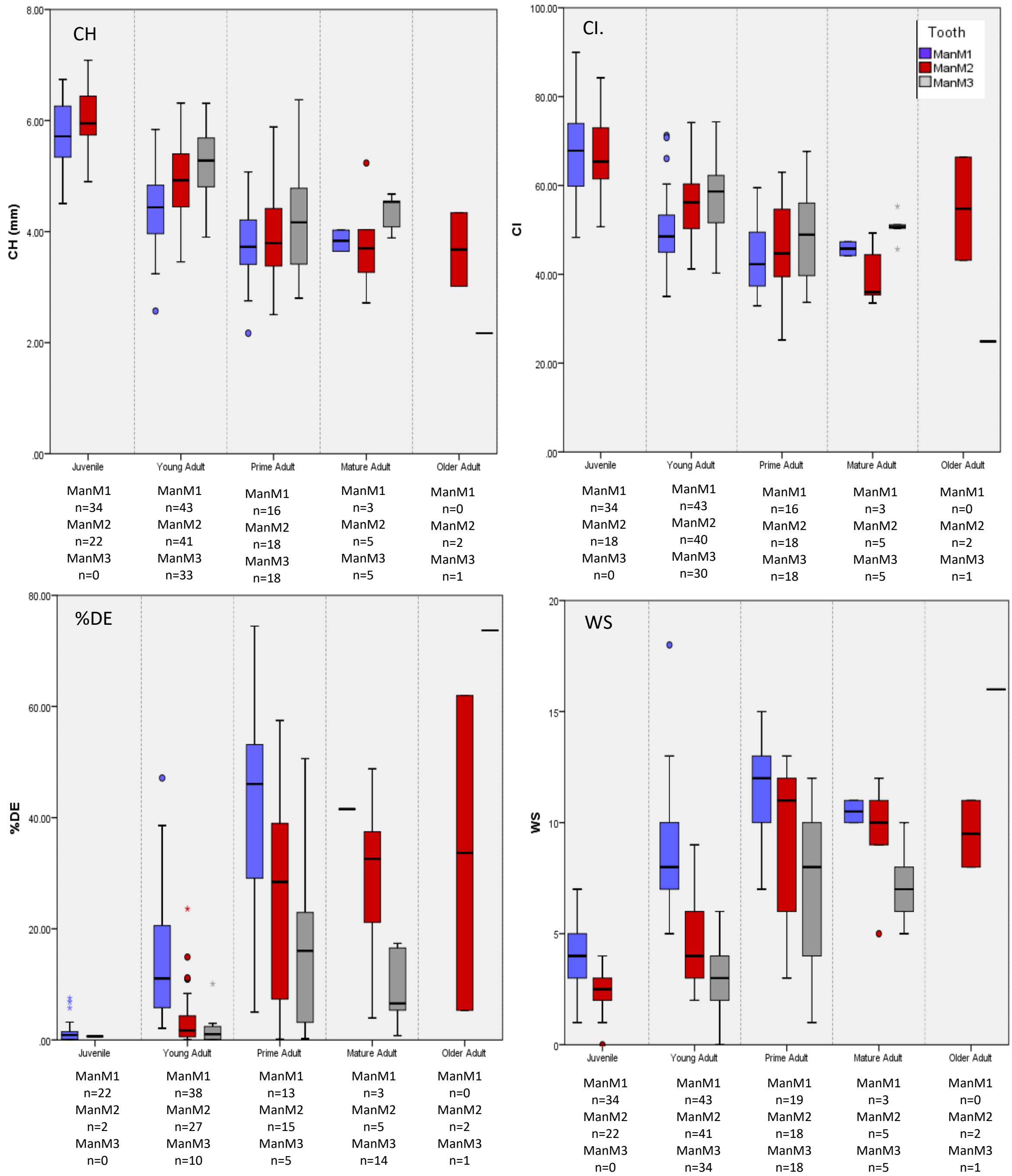


Figure 7.3.10. Box and whisker diagrams representing the relationship between age and dental wear measurement for the Anglo-Saxon sample by molar type.
Each diagram represents a wear measurement: average crown height (CH), crown Index (CI), percent of dentine exposure (%DE) and wear stage (WS).

Figure 7.3.10 shows an increase in age was associated with a higher degree of dental wear across all wear measurements for each molar type in the Anglo-Saxon sample. CH and CI decreased with an increase in age category, showing a decrease in crown height with age. This was true for all molar types and was supported by significant Spearman's correlation coefficients (Table 7.3.10).

ManM1 CH was greater compared to ManM2 wear, and ManM2 wear was greater than ManM3 wear.

The interquartile range remained constant across age categories for ManM1 and ManM2 CH and CI measurements. IQR varied across the age groups for the ManM3. As with the previous temporal samples, %DE and WS IQR increased with increasing age, indicating the amount of exposed dentine became varied with an increase in age. This variation has the potential to decrease the reliability of age estimates when using occlusal wear measurements to estimate age in Anglo-Saxon individuals.

These results support a relationship between dental wear and age for the Anglo-Saxon sample, although there was an increase in variation with increasing age for the occlusal wear measurements. These results support the use of dental wear as an ageing technique in Anglo-Saxon individuals.

Table 7.3.10. Spearman's correlation coefficients for age category by wear measurement and molar type for the Anglo-Saxon sample.

Wear Measurement	Molar	n	Spearman's correlation coefficients (r_s)	p-value
CH	ManM1	96	-0.75	<0.001
	ManM2	88	-0.76	<0.001
	ManM3	57	-0.62	<0.001
CI	ManM1	96	-0.71	<0.001
	ManM2	84	-0.64	<0.001
	ManM3	49	-0.46	<0.001
%DE	ManM1	76	0.74	<0.001
	ManM2	51	0.63	<0.001
	ManM3	30	0.53	<0.001
WS	ManM1	99	0.81	<0.001
	ManM2	88	0.77	<0.001
	ManM3	58	0.69	<0.001

Wear measurements include: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

Medieval sample

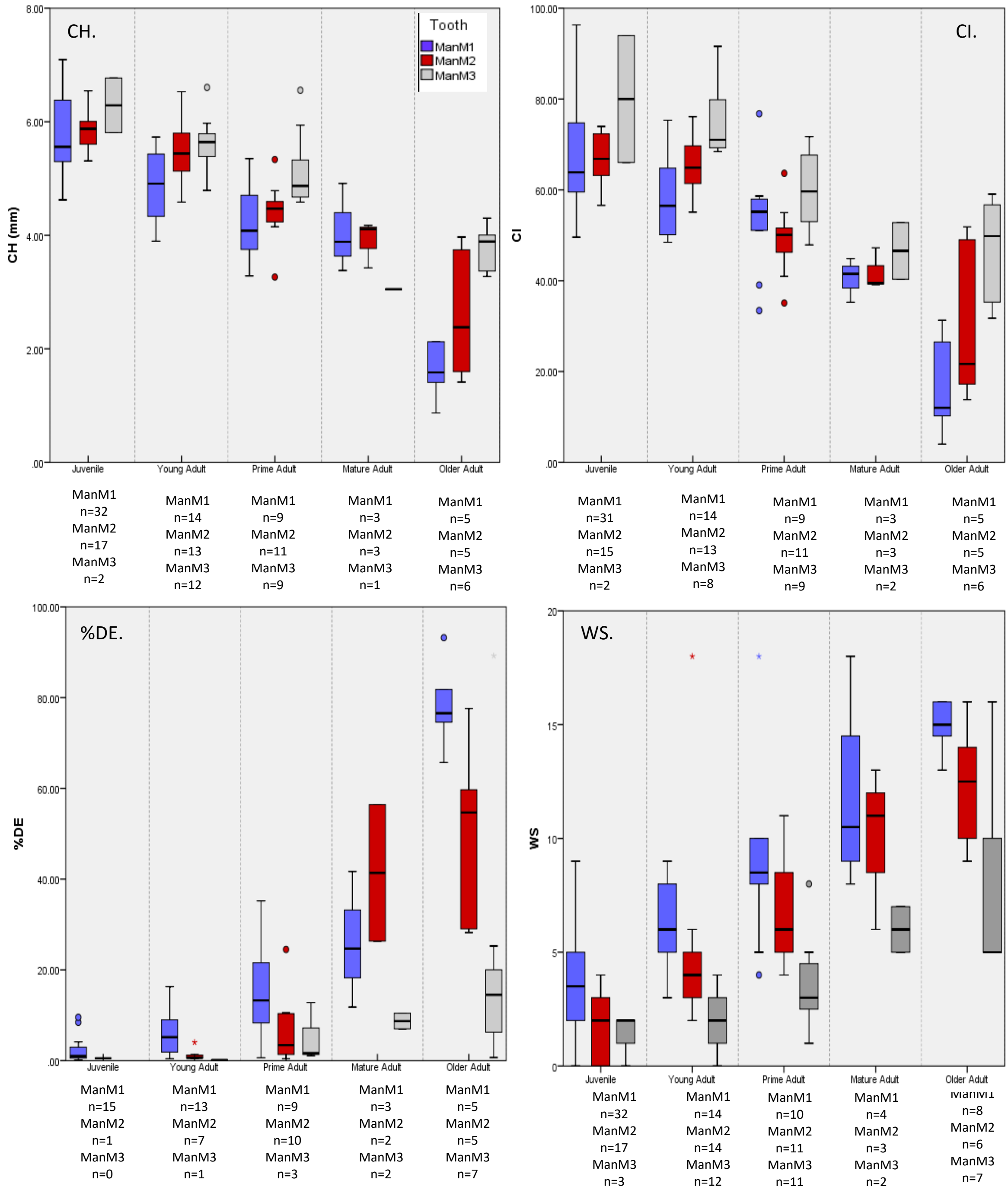


Figure 7.3.11. Box and whisker diagrams representing the relationship between age and dental wear measurement for the Medieval sample by molar type.

Each diagram represents a wear measurement: average crown height (CH), crown Index (CI), percent of dentine exposure (%DE) and wear stage (WS).

Figure 7.3.11 shows an association between all dental wear measurements and an increase in age category for the Medieval sample. CH and CI decreased with age, while %DE and WS increased with age. This was true for three mandibular molars. Spearman's correlation coefficients supported this relationship in the first and second mandibular molars, which were significant at the 5% level (Table 7.3.11). The relationship between ManM3 wear measurement and age category was significant for the CH, CI and WS data. ManM3 %DE did not show a significant relationship with age category, although Figure 7.3.11 shows evidence of an increase in %DE with age for the oldest three age categories.

The first molars consistently showed a greater degree of wear compared to the second molars. The second molars showed a greater degree of wear compared to the third morals. This was true for all wear measurements.

The inter-quartile range (IQR) for the ManM1 and ManM2 remained constant for the CH and CI measurements. The %DE and WS measurements showed an increase in inter-quartile range with an increase in age. This suggests the amount of exposed dentine on the occlusal surface became more varied as individuals increased in age. However, %DE and WS IQRs were less varied than for the previous temporal samples. This variation has the potential to decrease the reliability of age estimates when using occlusal wear measurements to estimate age of Medieval remains.

These results confirm a relationship between Medieval dental wear and age. However, the occlusal wear measurements became more varied with increasing age. These results support the use of dental wear as an ageing technique in Medieval individuals.

Table 7.3.11. Spearman's correlation coefficients for age category by wear measurement by molar type for the Medieval sample.

Wear Measurement	Molar	n	Spearman's correlation coefficients (r_s)	p-value
CH	ManM1	63	-0.73	<0.001
	ManM2	49	-0.86	<0.001
	ManM3	30	-0.79	<0.001
CI	ManM1	62	-0.65	<0.001
	ManM2	47	-0.80	<0.001
	ManM3	27	-0.79	<0.001
%DE	ManM1	45	0.77	<0.001
	ManM2	25	0.81	<0.001
	ManM3	13	0.51	0.076*
WS	ManM1	68	0.81	<0.001
	ManM2	51	0.86	<0.001
	ManM3	35	0.74	<0.001

Wear measurements include: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

* indicates a non-significant relationship

Post Medieval sample

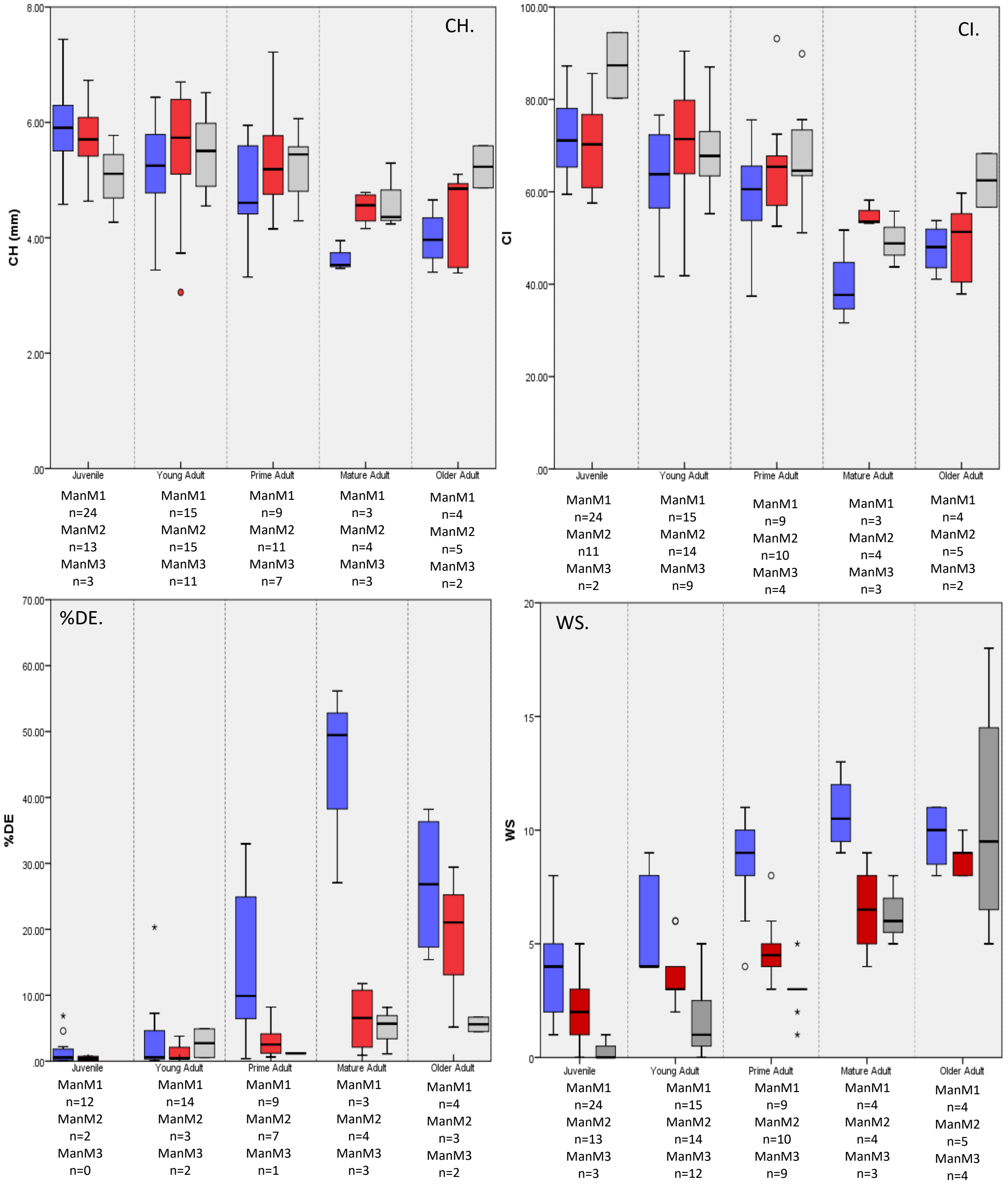


Figure 7.3.12. Box and whisker diagrams representing the relationship between age and dental wear measurement for the Post-Medieval sample by molar type.

Each diagram represents a wear measurement: average crown height (CH), crown Index (CI), percent of dentine exposure (%DE) and wear stage (WS).

Figure 7.3.12 shows an association between all dental wear measurements and age category for the Post-Medieval sample. CH and CI decreased with age, while %DE and WS increased with age. This was true for all molars and was observed across age categories. The relationship between dental wear measurements and age category were supported by significant Spearman’s correlation coefficients in the first and second mandibular molars (Table 7.3.12). CH and %DE measurements did not show a significant relationship with age category in the ManM3. Figure 7.3.12 suggests CH and %DE remained constant in the ManM3 as age increased.

Wear on the ManM1 was greater compared to the ManM2, and wear on the ManM2 was greater compared to wear on the ManM3. This was true across the wear measurements and within each age category.

These results support a relationship between dental wear and age in the Post-Medieval sample, and supports the use of dental wear as an ageing technique in Post-Medieval individuals.

Table 7.3.12. Spearman's correlation coefficients for age category by wear measurement and molar type for the Post-Medieval sample.

Wear Measurement	Molar	n	Spearman's correlation coefficients (r_s)	p-value
CH	ManM1	55	-0.64	<0.001
	ManM2	48	-0.48	0.001
	ManM3	27	-0.13	0.513*
CI	ManM1	55	-0.64	<0.001
	ManM2	44	-0.54	<0.001
	ManM3	23	-0.51	0.013
%DE	ManM1	42	0.72	<0.001
	ManM2	19	0.74	<0.001
	ManM3	8	0.46	0.255*
WS	ManM1	78	0.74	<0.001
	ManM2	63	0.76	<0.001
	ManM3	44	0.79	<0.001

Wear measurements include: average crown height (CH), crown index (CI), percent of exposed dentine (%DE) and wear stage (WS).

* indicates a non-significant relationship

7.3.2.1 Summary: the relationship between dental wear and adult age

Section 7.3.2 examined the relationship between dental wear and adult age, using bony age estimates as a proxy for estimated age. This section aimed to establish whether dental wear was progressive with age for the studied samples, and whether dental wear should be employed as a method for estimating age at death in archaeological remains.

Box and whisker diagrams illustrated wear measurement distributions by age category for each temporal sample. These plots confirmed the presence of a relationship between age category and dental wear measurements in all studied samples, where an increase in age was associated with a higher degree of dental wear. This relationship was strongest in the first and second molars, with the third molar being comparatively weaker.

ManM1 consistently showed a higher degree of wear compared to the ManM2, and the ManM2 had a higher degree of wear compared to the ManM3. The inter-quartile remained constant across age categories for the CH and CI wear measurements for all temporal samples. In contrast, there was an increase in the inter-quartile range with age for the %DE and WS measurements, indicating older individuals were associated with a larger degree of variation in the amount of exposed dentine compared to young individuals. This variation has the potential to decrease the reliability of age estimates when using occlusal wear measurements to estimate age of archaeological remains.

These results support acceptance of the null hypothesis that there is a relationship between dental wear measurements and adult age, and supports the use of dental wear to estimate age for the studied samples.

7.4 Comparing dental wear rates of multiple British temporal periods

Brothwell (1989 p.304) writes "As regards [to] ancient samples, my guess is that there was likely to be more homogeneity in rates of wear, as social differentials would have generally been less (and the same kinds of coarse foods would have been generally eaten)." This conclusion, that there is a similar rate of wear across multiple archaeological periods, has never been validated. This thesis has reviewed the wear rates of archaeological samples dating from the Neolithic to Medieval, with a Post-Medieval sample included for comparison. This section tests Brothwell's conclusion through the comparison of dental wear rates across temporal samples.

Before comparing wear rates the frequency of ante-mortem tooth loss (AMTL) within each temporal sample was compared. AMTL is tooth removal before death through injury or surgery, the loss of the supporting bone, or through dental pathology and periodontal disease (Hillson 2001; Ortner 2003; Lukacs 2007; Roberts and Manchester 2007). AMTL may occur at any point during the dental wear process and becomes more frequent with increasing age (Durić et al. 2004; Esclassan et al. 2009; Lucas et al. 2010). Therefore, the frequency of AMTL rates across the studied samples, and effect of AMTL on dental wear rates must be considered.

The presence of dental caries may also affect dental wear rates in a similar way to AMTL, however, the frequency of individuals with caries was low. For example, the Post-Medieval sample had the highest frequency of caries but only 14% (13/95) of Post-medieval individuals had caries on the first mandibular molar (ManM1). Thus, reliable conclusions regarding the effect of caries on the dental wear rate could not be made.

After a comparison of AMTL rates three approaches examined the similarity of dental wear rates across the studied samples. The first compares wear distributions within age categories to provide a general overview of the wear pattern for each temporal sample (Section 7.4.2). Section 7.4.3 compares juvenile dental wear rates, while Section 7.4.4 examines wear rates obtained from adult individuals. However, each approach has a limitation. While a comparison of wear distributions within age categories can provide an overall view of the wear patterns of multiple samples, it is not precise and heavily relies on the accuracy of bony age estimates. A comparison of juvenile wear rates only examines part of the wear process, and similarity in juvenile wear rates across the studied samples does not guarantee that this rate will persist into adulthood. Finally, the method of Gilmore and Grote (2012) assumes all molars in a tooth row experience wear at a similar rate, and that this rate remains constant throughout the life of the individual, i.e. wear rate is linear with age. Section 7.2 indicated molars along the tooth row wear at a similar rate, however, it was not possible to assess whether this rate was linear with age. By pooling the results from this analysis a robust conclusion can be formed regarding Brothwell's conclusion.

7.4.1 Ante-mortem tooth loss (AMTL)

Ante-mortem tooth loss (AMTL) was observed in all temporal samples. This section first examines whether the frequency of AMTL differs across the studied samples. Section 7.4.1.2 then investigates AMTL frequency by age group, to examine at which point AMTL approximately occurs in an individual's life, and whether this differs between the temporal samples. Finally, the effect of AMTL on dental wear was examined by comparing the mean wear measurements of mandibular molars that have lost their occlusal partner ante-mortem, to the mean wear measurements of mandibular molars that have a present occlusal partner.

7.4.1.1 Comparing ante-mortem tooth loss (AMTL) by temporal sample

This section compares the rate of AMTL between the samples by molar type. Following Brothwell (1959), it is expected that the rate of AMTL will increase from the Neolithic period onwards (see Figure 4.2.4, Section 4.2.3). A higher rate of AMTL in the ManM1 is also expected. The first molar is the first to erupt, thus it is expected that it will be the first molar to be lost ante-mortem. The frequency of AMTL by temporal sample was examined by plotting the percentage of molars lost to AMTL by temporal sample for each molar type, and differences tested using a Chi-square test of independence.

Null hypothesis: there is no significant difference in AMTL frequency between temporal samples

It is expected that:

- The ManM1 will have a higher AMTL frequency compared to the later erupting molars
- Samples dating to earlier temporal periods will have a lower AMTL frequency compared to samples dating to later temporal periods

As expected, the ManM1 consistently showed a higher frequency of AMTL compared with the later erupting molars. Then second mandibular molar (ManM2) showed a higher AMTL frequency compared with the third mandibular molar (ManM3). This pattern was observed in all samples except the Iron Age sample, which showed a similar AMTL frequency across all molars (Table 7.4.1, Figure 7.4.1).

Table 7.4.1. Percentage (%) of molars lost to ante-mortem tooth loss (AMTL) for each temporal sample by molar type

	ManM1			ManM2			ManM3		
Sample	n AMTL	total n	%	n AMTL	total n	%	n AMTL	total n	%
Neolithic	11	102	11%	8	99	8%	6	79	8%
Bronze Age	10	100	10%	3	99	3%	5	87	6%
Iron Age	8	114	7%	8	112	7%	9	95	9%
Romano-British	31	132	23%	20	125	16%	13	105	12%
Anglo-Saxon	15	119	13%	12	115	10%	7	98	7%
Medieval	21	105	20%	19	104	18%	13	84	15%
Post-Medieval	31	102	30%	25	101	25%	16	87	18%

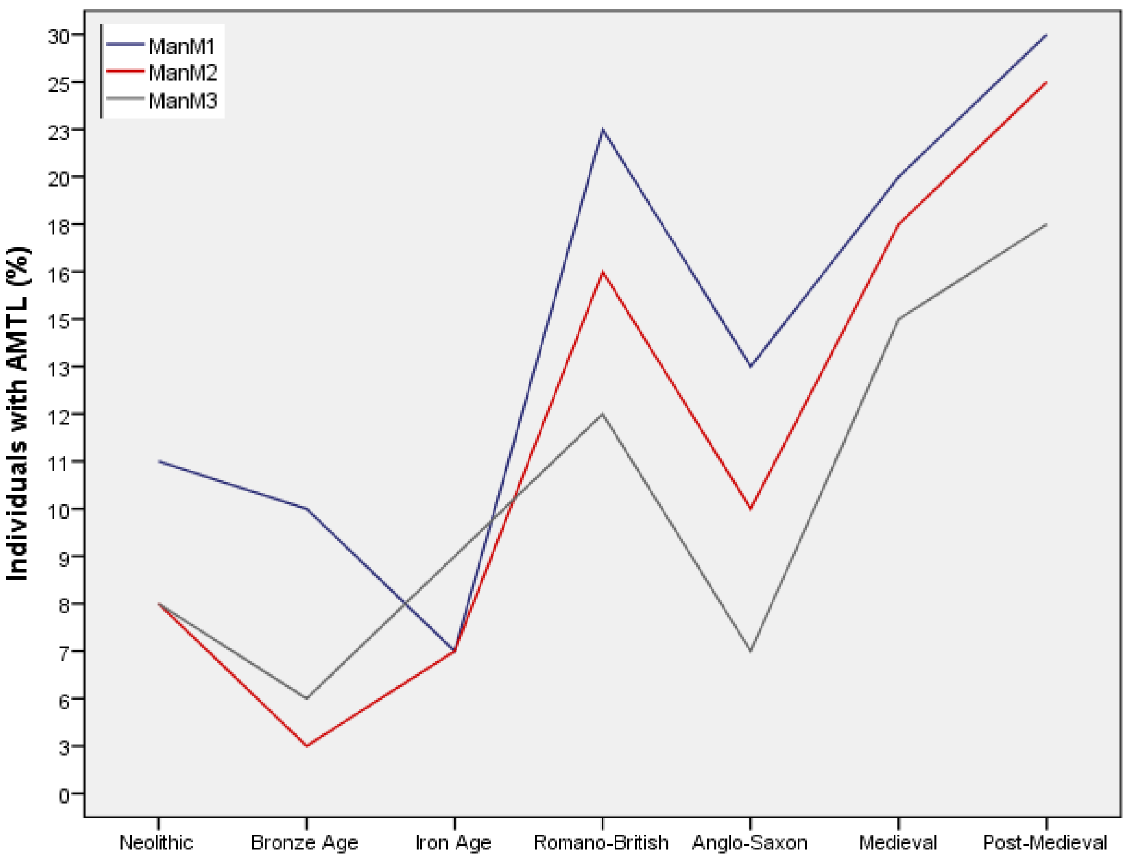


Figure 7.4.1. Percent of molars lost to ante-mortem tooth (AMTL) loss by temporal sample and molar type

The Bronze Age sample showed a lower rate of AMTL across all three molars compared with the Neolithic sample. Compared to the Bronze Age, the Iron Age sample showed an increase in AMTL in the second and third molars. The Romano-British sample showed a higher frequency of AMTL across all molar types, potentially indicating a decline in oral health. The rate of AMTL decreased in the Anglo-Saxon sample, but remained higher than the pre-Roman samples. There was a large in the percent of molars lost to AMTL increase from the Anglo-Saxon to Medieval period, returning to a similar AMTL rate as the Romano-British sample. This increased again, with the Post-Medieval sample showing the highest rate of AMTL across all three molars. All three molars showed a similar pattern of ante-mortem tooth loss, suggesting any change in oral health had a similar affect for all molars.

The pattern observed in Figure 7.4.1 indicates an increase in AMTL frequency over time for each molar type, with a relatively lower rate in earlier temporal samples compared to later temporal samples. Chi-square tests of independence indicated AMTL frequency was significantly different between temporal samples for the ManM1 and ManM2, but were not significantly different for the ManM3 (Table 7.4.2). These results reject the null hypothesis that AMTL frequency is similar across temporal samples, and indicates AMTL frequency has the potential to be a contributing factor to any observed differences in dental wear rates between temporal samples.

Table 7.4.2. Results of chi-square test of independence comparing AMTL frequencies between temporal samples

Tooth	Chi-square	Degrees of freedom	p-value
ManM1	34.28	6	<0.001
ManM2	31.52	6	<0.001
ManM3	12.00	6	0.062

7.4.1.2 Ante-mortem tooth loss (AMTL) by age

Figure 7.4.1 demonstrated overall AMTL frequency by temporal sample but does not show at which point in an individual's life AMTL occurs. AMTL may occur as a result of dental caries or periodontal disease, meaning that tooth loss can occur at any point during the wear process. However, it is expected that molar-loss is age progressive (Tal and Tau 1984; Deas 1992; Gandhi 2002; Mays 2002). The higher AMTL rates of the Post-Medieval sample may represent a higher number of individuals with tooth loss only in the oldest age groups or a higher frequency of tooth loss in the younger age groups.

Frequency of tooth loss was plotted by age group for each molar type to examine at which age AMTL occurred. The Neolithic sample was excluded due to the inability to assign adults to an age category based on the bony age estimates. Difference in AMTL frequency between temporal samples by age group were compared using a Chi-square test of independence.

Null hypothesis: AMTL frequency occurs at a similar age in all temporal samples

It is expected that:

- AMTL frequency increases with an increase in age for all temporal samples

As expected, there was a general increase in tooth loss with an increase in age for all samples studied and each molar type (Table 7.4.3, Figure 7.4.2).

The Post-Medieval sample had a relatively high AMTL ManM1 and ManM2 frequency in the Young Adult (18-25 years old) age group, compared to the earlier temporal samples. This difference was supported by significant Chi-square tests of independence (Table 7.4.4). The Post-Medieval AMTL frequency for the ManM3 in this age group was comparable to the earlier temporal samples.

In the Prime Adult (25-35 years old) age group, the Post-Medieval sample had the highest AMTL frequency across all three molars. This difference, however, was not significant (Table 7.4.4).

The Mature Adult (35-45 years old) age group showed a general increase in AMTL frequency across all temporal samples, and all molar types (Table 7.4.3, Figure 7.4.2). The Anglo-Saxon samples had the highest AMTL frequency of the ManM1, while the Romano-British sample had highest AMTL rate for the ManM2 and ManM3. Chi-square tests of independence found no significant difference in AMTL frequency between the studied samples across the three molars (Table 7.4.4).

The Anglo-Saxon had the highest AMTL rate within the Older Adult (45+ years) age group for all three molars. The Bronze Age and Iron Age samples had relatively low AMTL rates for this age group. Chi-square tests indicated a significant difference in ManM1 AMTL frequency between temporal samples. This result may be a due to the relatively low AMTL rate observed in Iron Age sample, and suggests Iron Age individuals retained their ManM1 molars into old age.

Table 7.4.3. Percentage (%) of individuals with ante-mortem tooth loss (AMTL) for each temporal sample by age group and molar type

	ManM1			
	Young Adult % of AMTL	**Prime Adult % of AMTL**	**Mature Adult % of AMTL**	**Older Adult % of AMTL**
Neolithic	-	-	-	-
Bronze Age	0% (0/13)	20% (1/5)	0% (0/3)	50% (1/2)
Iron Age	4% (1/27)	0% (0/8)	22% (2/9)	13% (2/16)
Romano-British	8% (2/25)	20% (4/20)	50% (5/10)	85% (11/13)
Anglo-Saxon	0% (0/42)	0% (0/20)	78% (7/9)	100% (6/6)
Medieval	7% (1/15)	27% (4/15)	20% (1/5)	50% (8/16)
Post-Medieval	25% (5/20)	31% (4/13)	50% (4/8)	67% (8/12)
	ManM2			
	Young Adult % of AMTL	**Prime Adult % of AMTL**	**Mature Adult % of AMTL**	**Older Adult % of AMTL**
Neolithic	-	-	-	-
Bronze Age	8% (1/12)	0% (0/5)	0% (0/3)	0% (0/2)
Iron Age	0% (0/26)	0% (0/8)	22% (2/9)	31% (5/16)
Romano-British	0% (0/25)	5% (1/20)	67% (6/9)	58% (7/12)
Anglo-Saxon	0% (0/42)	5% (1/19)	56% (5/9)	67% (4/6)
Medieval	6% (1/16)	14% (2/14)	40% (2/5)	63% (10/16)
Post-Medieval	20% (4/20)	15% (2/13)	50% (4/8)	58% (7/12)
	ManM3			
	Young Adult % of AMTL	**Prime Adult % of AMTL**	**Mature Adult % of AMTL**	**Older Adult % of AMTL**
Neolithic	-	-	-	-
Bronze Age	9% (1/11)	17% (1/6)	0% (0/3)	0% (0/2)
Iron Age	0% (0/19)	17% (1/6)	40% (2/5)	25% (2/8)
Romano-British	0% (0/20)	12% (2/17)	63% (5/8)	50% (5/10)
Anglo-Saxon	0% (0/35)	0% (0/18)	50% (4/8)	75% (3/4)
Medieval	8% (1/13)	9% (1/11)	33% (1/3)	50% (7/14)
Post-Medieval	7% (1/14)	22% (2/9)	57% (4/7)	64% (7/11)

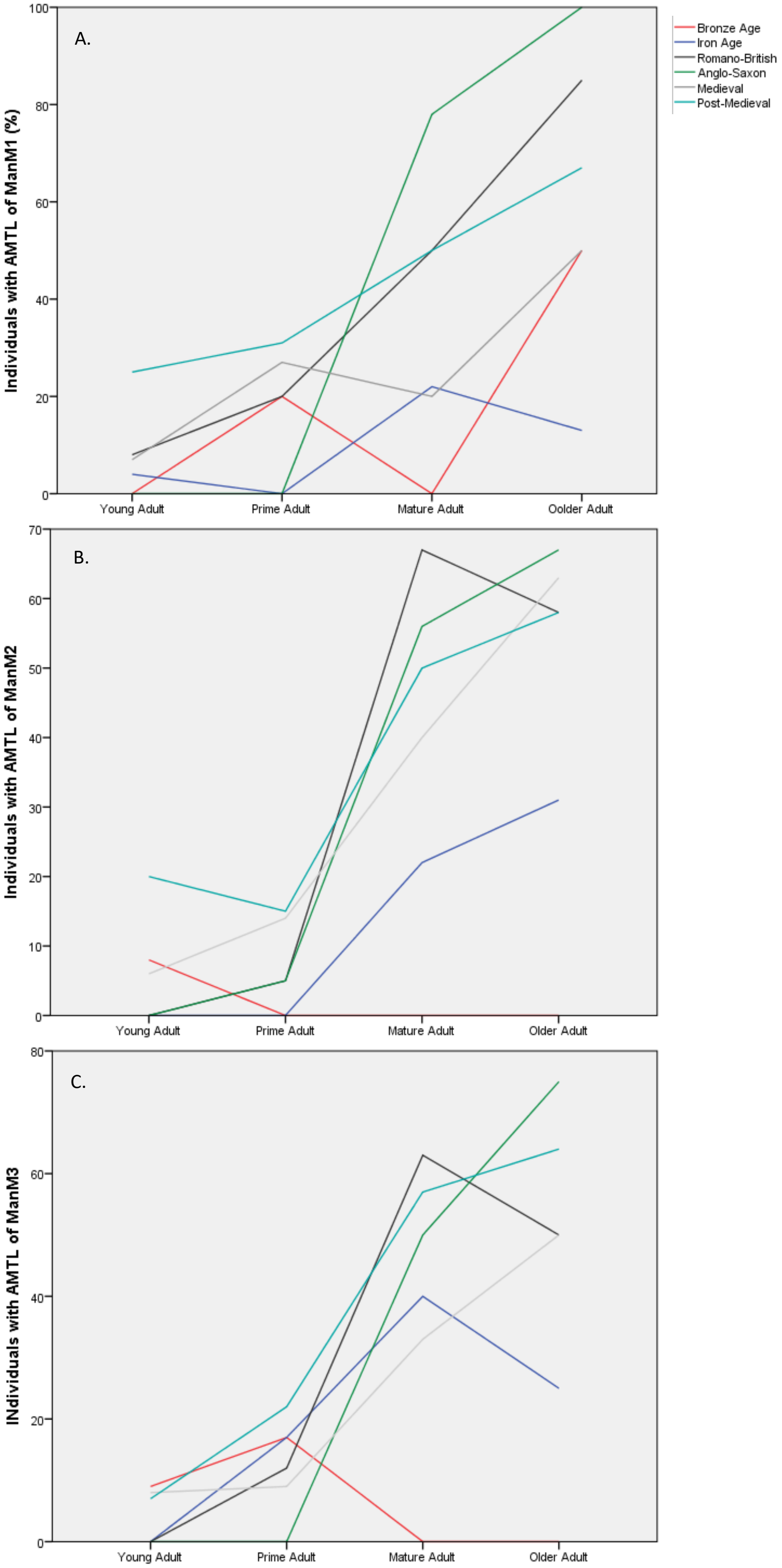


Figure 7.4.2. Percentage of individuals with ante-mortem tooth loss (AMTL) by age group for each temporal sample. A. First mandibular molar (ManM1). B. Second mandibular molar (ManM3). C. Third mandibular molar (ManM3).

These results show tooth loss increased with age, as expected. The Post-Medieval sample had a comparatively higher percentage of AMTL in younger individuals compared to other samples, particularly for the ManM1 and ManM2. This indicates the higher overall AMTL loss observed in Figure 7.4.1 for the Post-Medieval sample is the result of a higher rate of tooth loss in younger individuals. Furthermore, these results suggest Post-Medieval individuals experience AMTL at a relatively younger age compared to the earlier dating samples. These results reject the null hypothesis that AMTL occurs at a similar age for all temporal samples, and suggests any difference in wear rate between the samples may be a result of when AMTL occurs within a population.

Table 7.4.4. Results of chi-square test of independence comparing AMTL frequencies with age groups between temporal samples

Molar	Age Group	Chi-square	Degrees of freedom	p-value
ManM1	Young Adult	15.89	5	0.007*
	Prime Adult	8.99	5	0.109
	Mature Adult	9.72	5	0.084
	Older Adult	22.07	5	<0.001*
ManM2	Young Adult	16.95	5	0.005*
	Prime Adult	3.43	5	0.635
	Mature Adult	6.60	5	0.252
	Older Adult	6.53	5	0.258
ManM3	Young Adult	6.10	5	0.297
	Prime Adult	3.98	5	0.552
	Mature Adult	4.07	5	0.539
	Older Adult	5.80	5	0.326

*indicates a significant difference in AMTL frequency between temporal samples

7.4.1.3 Effect of ante-mortem tooth loss (AMTL) on dental wear

As AMTL may occur during any point during the dental wear process, AMTL has the potential to affect dental wear rates. It may be expected that teeth that had lost their occlusal partner ante-mortem will display a lower wear signature than expected for their age. For example, CH and CI measurements may be greater and WS and %DE measurements may be lower in molars where the occlusal partners have been lost ante-mortem compared to those with occlusal partners that are present.

Wear measurements of molars with an occlusal partner lost ante-mortem were compared to wear measurements of molar where their occlusal partner remained in situ using independent t-tests and Mann-Whitney tests. Due to small samples size temporal samples were pooled. Although pooling samples is not ideal, due to some observed difference in AMTL frequencies between the studied samples, this analysis provides a tentative investigation of the effect of AMTL on dental wear.

Null hypothesis: AMTL does not have any effect on dental wear

It is expected that:

- AMTL will not have any effect on dental wear measurements
- Mandibular molar dental wear measurements will not be significantly difference between molars that have lost their occlusal partner ante-mortem from those molars that have their occlusal partner in situ

There was no evidence of reduced wear in molars whose occlusal partner had been lost ante-mortem, which was supported by non-significant Independent T-tests and Mann-Whitney tests. Mandibular molars showed a similar degree of dental wear whether their occlusal partner had been lost ante-mortem, or was present. This pattern was observed across all age groups. This was true for all wear measurements, including average crown height (Table 7.4.5), crown index (Table 7.4.6), percent of exposed dentine (Table 7.4.7), or wear stage (Table 7.4.8), and for all molar types. The only exception was a significant Mann-Whitney test comparing %DE wear on the ManM3 (Table 7.4.7, $z=-0.43$, $p=0.023$). However, this result was not significant according to the Benjamini-Hochberg procedure (Appendix C).

These results below indicate, in the present study group, AMTL had no demonstrable effect on the process of dental wear. However, due to the use of small sample sizes, these results must be viewed with caution, and further investigation of the effect of AMTL on dental wear is recommended.

Table 7.4.5. Independent T-Test results comparing average crown height (CH) measurements for mandibular molars with their occlusal partner present and those with their occlusal partner lost ante-mortem. Comparisons made by tooth type and by age group.

Tooth	Age Group	Occlusal Partner	n	Mean CH (mm)	T-Test	p-value
ManM1	Young Adult	Present	121	4.72	0.57	0.570
		AMTL	4	4.47		
	Prime Adult	Present	51	3.97	-1.91	0.061
		AMTL	3	5.15		
	Mature Adult	Present	11	3.32	-0.79	0.443
		AMTL	9	3.72		
	Older Adult	Present	14	3.25	0.41	0.688
		AMTL	5	2.98		
ManM2	Young Adult	Present	125	5.25	-	-
		AMTL	0	-		
	Prime Adult	Present	58	4.44	1.04	0.305
		AMTL	4	3.98		
	Mature Adult	Present	15	4.30	0.30	0.771
		AMTL	7	4.19		
	Older Adult	Present	19	3.83	-0.64	0.531
		AMTL	4	4.19		
ManM3	Young Adult	Present	66	5.02	-	-
		AMTL	0	-		
	Prime Adult	Present	33	4.66	1.55	0.130
		AMTL	3	5.44		
	Mature Adult	Present	12	4.54	-0.55	0.591
		AMTL	2	4.16		
	Older Adult	Present	7	3.96	1.25	0.236
		AMTL	6	4.65		

Table 7.4.6. Independent T-Test results comparing crown index (CI) measurements for mandibular molars with their occlusal partner present and those with their occlusal partner lost ante-mortem. Comparisons made by tooth type and by age group.

Tooth	Age Group	Occlusal Partner	n	Mean CI	T-Test	p-value
ManM1	Young Adult	Present	119	55.00	0.67	0.503
		AMTL	4	51.60		
	Prime Adult	Present	50	48.51	-1.94	0.059
		AMTL	3	63.09		
	Mature Adult	Present	10	39.88	-1.20	0.249
		AMTL	8	44.60		
	Older Adult	Present	13	37.58	-0.72	0.480
		AMTL	5	45.94		
ManM2	Young Adult	Present	120	61.50	-	-
		AMTL	0	-		
	Prime Adult	Present	57	52.57	-0.29	0.774
		AMTL	3	54.58		
	Mature Adult	Present	14	48.66	-0.65	0.527
		AMTL	7	51.83		
	Older Adult	Present	19	46.94	0.220	0.828
		AMTL	3	44.83		
ManM3	Young Adult	Present	59	62.91	-	-
		AMTL	0	-		
	Prime Adult	Present	31	56.00	1.13	0.269
		AMTL	3	64.32		
	Mature Adult	Present	13	53.33	-1.03	0.321
		AMTL	2	47.24		
	Older Adult	Present	6	51.79	1.33	0.214
		AMTL	6	65.23		

Table 7.4.7. Mann-Whitney results comparing percent of exposed dentine (%DE) measurements for mandibular molars with their occlusal partner present and those with their occlusal partner lost ante-mortem. Comparisons made by tooth type and by age group.

Tooth	Age Group	Occlusal Partner	n	Median %DE (%)	Mann-Whitney score	p-value
ManM1	Young Adult	Present	108	6.06	-6.00	0.548
		AMTL	3	11.17		
	Prime Adult	Present	45	17.12	-1.68	0.092
		AMTL	3	4. 23		
	Mature Adult	Present	11	41.53	-1.47	0.137
		AMTL	8	28.48		
	Older Adult	Present	14	38.40	-1.27	0.203
		AMTL	4	65.04		
ManM2	Young Adult	Present	69	1.30	-	-
		AMTL	0	-		
	Prime Adult	Present	47	5.90	-0.20	0.984
		AMTL	3	5.27		
	Mature Adult	Present	12	19.77	-0.28	0.779
		AMTL	6	18.02		
	Older Adult	Present	17	19.13	-0.51	0.649
		AMTL	5	29.05		
ManM3	Young Adult	Present	17	0.45	-	-
		AMTL	0	-		
	Prime Adult	Present	24	1.73	-1.39	0.166
		AMTL	1			
	Mature Adult	Present	10	6.78	-0.43	0.667
		AMTL	2	12.77		
	Older Adult	Present	7	6.67	-0.43	0.023*
		AMTL	4	0.09		

Table 7.4.8. Mann-Whitney results comparing wear stage (WS) measurements for mandibular molars with their occlusal partner present and those with their occlusal partner lost ante-mortem. Comparisons made by tooth type and by age group.

Tooth	Age Group	Occlusal Partner	n	Median WS	Mann-Whitney score	p-value
ManM1	Young Adult	Present	121	7	-1.50	0.134
		AMTL	4	9.5		
	Prime Adult	Present	57	9	-1.09	0.277
		AMTL	4	7.5		
	Mature Adult	Present	13	11	-0.94	0.347
		AMTL	10	10		
	Older Adult	Present	18	11.5	-1.47	0.143
		AMTL	7	15		
ManM2	Young Adult	Present	125	4	-	-
		AMTL	0	-		
	Prime Adult	Present	60	6	-1.52	0.128
		AMTL	5	9		
	Mature Adult	Present	15	10	-0.16	0.870
		AMTL	8	6.5		
	Older Adult	Present	22	10	-0.17	0.865
		AMTL	6	9		
ManM3	Young Adult	Present	75	2	-	-
		AMTL	0	-		
	Prime Adult	Present	13	5	-0.94	0.347
		AMTL	2	9		
	Mature Adult	Present	37	4	-0.45	0.655
		AMTL	4	3.5		
	Older Adult	Present	9	9	-0.76	0.939
		AMTL	11	8		

7.4.1.4 Summary: Ante-mortem tooth loss

Section 7.4.1 examined the frequency of ante-mortem tooth loss (AMTL) across temporal samples and whether AMTL had any effect on the dental wear process. AMTL was observed in all temporal samples. The Post-Medieval samples had the highest frequency of AMTL across all mandibular molars. AMTL was progressive with age, with the Post-medieval samples showing a relatively higher rate of tooth loss in the younger age groups compared to the other studied samples. A comparison of mean wear measurements did not identify any significant difference in wear measurements between molars whose partner had been lost ante-mortem and molars whose partner was still in occlusion. These results suggest that while AMTL frequency differs between temporal samples, the effect on the dental wear rate is minimal.

It may be argued that the difference in AMTL rates across the temporal samples are a reflection of a difference in age distribution. In the current study, age distributions were similar across the samples (Table 5.1.2) and is therefore unlikely that the difference in AMTL occurrence was due to a difference in demography. It must be noted however, that the research sample was selected to represent the entire wear process experienced by a temporal period rather than its actual demographic profile. Thus, any conclusions from this analysis much be regarded with caution when applied to populations with a different demographic profile.

7.4.2 Comparing dental wear distributions by age category

To examine whether a single dental wear rate can be reliably applied to multiple archaeological samples dental wear patterns was first compared using box and whisker diagrams. Following Brothwell (1963), it was expected that there would be a similarity in wear distributions, and therefore wear pattern, within age categories across temporal samples. Wear distributions were produced and compared for the first (ManM1), second (ManM2) and third (ManM3) mandibular molars by each wear measurement; average crown height (CH), crown index (CI), percent of exposed dentine (%DE), and wear stage (WS). The Neolithic sample was excluded from analysis, except in the juvenile age category, due to the lack of adult individuals that could be assigned an age estimate.

Null hypothesis: temporal samples show a similar wear pattern in relation to age category

It is expected that:

- temporal samples will show a similar wear distribution within each age category
- temporal samples will show similar median values and inter-quartile ranges (IQR) within each age category

7.4.2.1 First mandibular molar (ManM1)

Average crown height (CH)

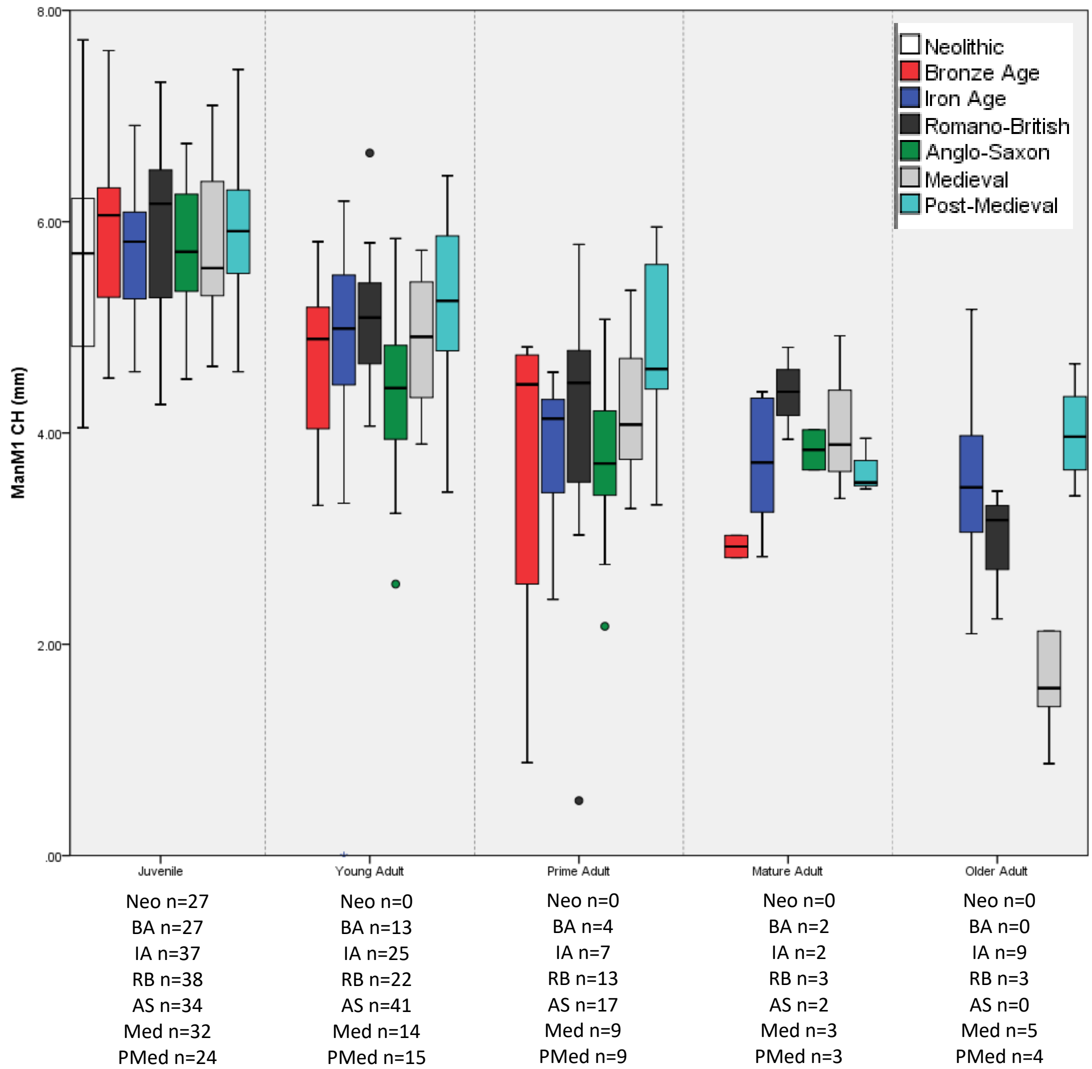


Figure 7.4.3. Box and whisker diagrams representing the relationship between first mandibular molar (ManM1) average crown height (CH) and age category by temporal sample.

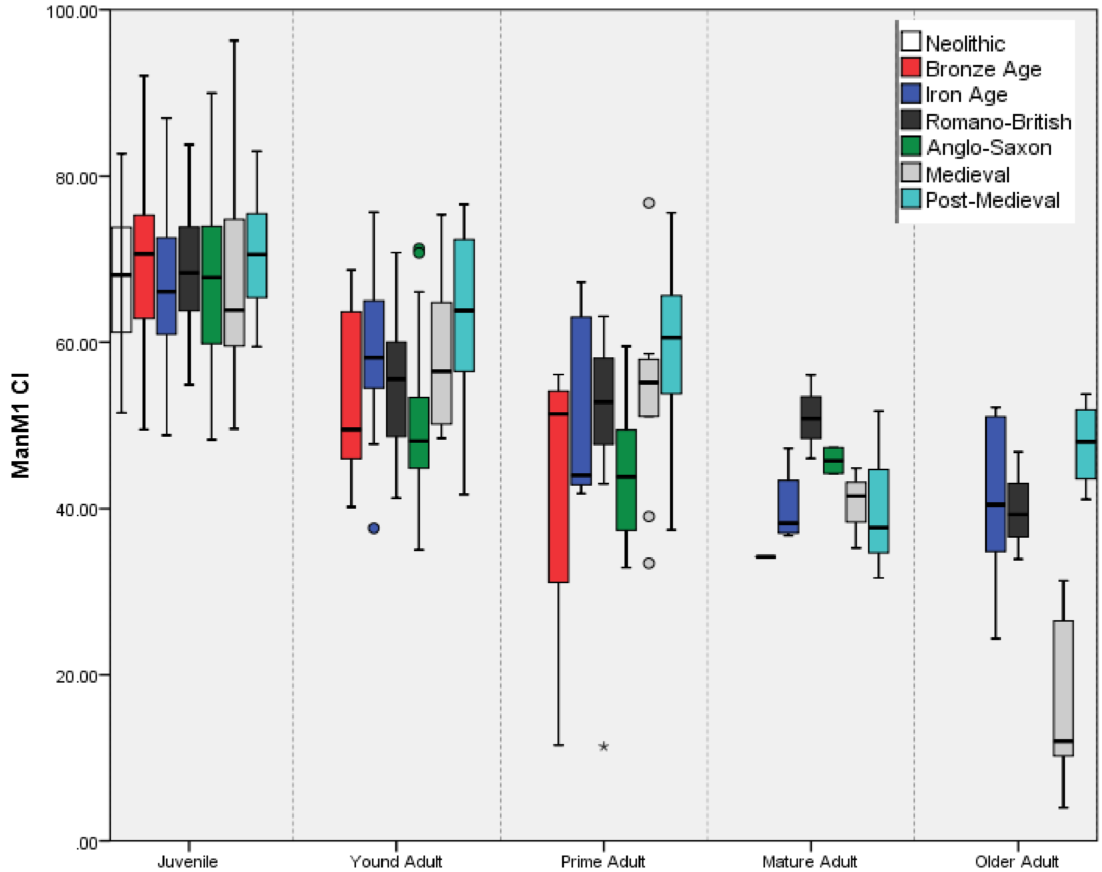
Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

ManM1 CH wear distributions overlapped considerably for the Juvenile age group, including similar median values and inter-quartile ranges for all temporal samples (Figure 7.4.3). With increasing age ManM1 CH wear distributions became more varied, indicating some difference in wear pattern between the temporal samples with increasing age. This was evidenced by a decrease in overlap in IQR between the studied samples, and an observable difference in median values with an increase in age. The smallest degree of overlap was observed in the Older Adult age group, with little overlap of IQRs between samples and a greater degree of distance between median values, compared to the younger age groups. Wear distributions within the Young Adult, Prime Adult and Mature Adult showed a smaller degree of overlap in IQRs compared to the Juvenile age group, but a greater degree of overlap compared to the Older Adult age group.

It should be noted that all Older Adult individuals within the Bronze Age and Anglo-Saxon samples either experienced AMTL or had no enamel present on the ManM1. In contrast, the comparatively low boxplot for the Medieval sample suggests any ManM1 that remained in occlusion experienced a high degree of dental crown height loss.

These results suggest the application of a single wear pattern for estimating age to multiple archaeological population may by reliable for individuals up to the age of 35, but less reliable for older individuals. It is therefore recommended that populations-specific ManM1 CH wear patterns are developed and used.

Crown Index (CI)



Juvenile	Young Adult	Prime Adult	Mature Adult	Older Adult
Neo n=26	Neo n=0	Neo n=0	Neo n=0	Neo n=0
BA n=24	BA n=13	BA n=4	BA n=1	BA n=0
IA n=35	IA n=24	IA n=7	IA n=5	IA n=8
RB n=34	RB n=22	RB n=12	RB n=3	RB n=3
AS n=34	AS n=41	AS n=17	AS n=2	AS n=0
Med n=31	Med n=14	Med n=9	Med n=3	Med n=5
PMed n=23	PMed n=15	PMed n=9	PMed n=3	PMed n=4

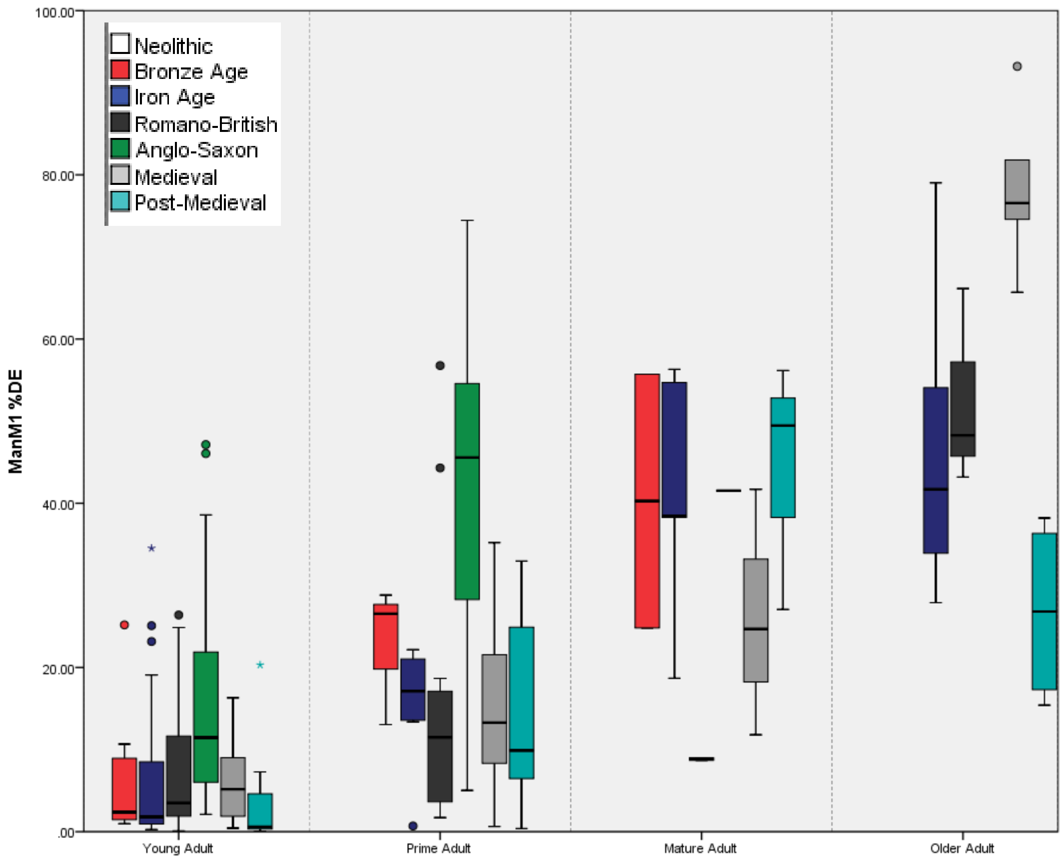
Figure 7.4.4. Box and whisker diagrams representing the relationship between first mandibular molar (ManM1) crown index (CI) and age category by period sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

Figure 7.4.4 shows ManM1 CI wear distributions overlapped considerably in the Juvenile age group, including similar median values and IQRs. This supports a similar wear pattern across all temporal samples during the Juvenile period. As with the ManM1 CH wear pattern, ManM1 CI wear distributions became more varied with increasing age. The degree of overlap between temporal samples wear distributions decreased in the Young Adult and Prime Adult age groups, with an observable difference in ManM1 CI medians, suggesting a slight difference in wear pattern between temporal samples. The Mature Adult age group showed a large similarity in ManM1 CI IQR for the Iron Age, Medieval and Post-Medieval samples, but a higher wear distribution for the Romano-British and Anglo-Saxon samples. The Older Adult age group showed the greatest difference in ManM1 CI wear distributions, with the Medieval samples having a relatively low IQR and median compared to the Iron Age, Romano-British and Post-Medieval samples. Figure 7.4.4 therefore shows a similarity in ManM1 CI wear pattern between temporal samples in younger individuals, but with increasing age this wear pattern differs.

These results support the use of a single pattern of dental wear to estimate age in younger individuals belonging to difference archaeological populations. However, the application of a single wear pattern to estimate age in older individuals may be unreliable. These results, thus, supports the use of population-specific dental wear patterns and wear rates to estimate age.

Percent of dentine exposure (%DE)



Young Adult	Prime Adult	Mature Adult	Older Adult
Neo n=0	Neo n=0	Neo n=0	Neo n=0
BA n=8	BA n=3	BA n=2	BA n=0
IA n=24	IA n=7	IA n=5	IA n=10
RB n=21	RB n=12	RB n=1	RB n=3
AS n=37	AS n=14	AS n=1	AS n=0
Med n=13	Med n=9	Med n=3	Med n=5
PMed n=14	PMed n=9	PMed n=3	PMed n=4

Figure 7.4.5. Box and whisker diagrams representing the relationship between first mandibular molar (ManM1) percent of dentine exposure (%DE) and age category by period sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

The Juvenile age group was excluded from analysis due to few juvenile individuals with any exposed dentine on their first mandibular molar.

ManM1 %DE medians were similar across temporal samples in the Young Adult group, except the Anglo-Saxon sample which was relatively higher (Figure 7.4.5). The wear distributions in this age group overlapped, supporting a similar wear pattern for this age groups across the studied samples.

The Anglo-Saxon sample had a higher wear distribution compared to the remaining samples in the Prime Adult, indicating some difference in wear pattern. A similar wear distribution, including similar medians and overlapping IQRs, for the remaining samples support some similarity in wear patterns between the studied samples. This pattern was also observed in the Mature Adult age group.

The Older Adult age group showed the greatest degree of variation in wear distributions between samples. The Medieval sample had a comparatively high wear distribution, while the Post-Medieval sample had a relatively low manM1 %DE wear distribution. This suggests some difference in ManM1 %DE wear pattern between the studied samples for older individuals.

Figure 7.4.5 shows ManM1 %DE wear distributions became more varied with increasing age, indicating a difference in wear pattern between temporal samples with an increase in age. These results suggest it may be unreliable to use a single pattern of wear to estimate age of multiple archaeological populations. Thus, it is recommended that population-specific wear patterns are produced to obtain the most reliable estimates of age.

Wear stage (WS)

The Juvenile age group had a similar ManM1 WS wear pattern across the samples, with a large degree of overlap in IQRs (Figure 7.4.6) Each sample had a median score of 4 (one discrete area of exposed dentine) except the Medieval sample, which had a ManM1 WS median score of 3 (no exposed dentine, flattened cusps). With increasing age ManM1 WS wear distributions became more varied, indicating some difference in wear pattern between the temporal samples with increasing age. This is evidenced by a decrease in the degree of overlap in IQRs between temporal samples. While the Young Adult age group shows a large degree of overlap in wear distributions, it is reduced compared to the Juvenile age group. The largest difference in wear distributions between temporal samples was observed in the Older Adult age group, with little overlap of IQRs between samples and a greater degree of distance between median values, compared to the younger age groups.

As with the previous ManM1 dental wear measurements, Figure 7.4.6 suggests the studied samples have a similar pattern of wear in young individuals, but is likely to differ in older individuals. These results, therefore, support the use of a single pattern of wear to estimate age in juvenile individuals across multiple archaeological populations. However, it is recommended that population-specific wear patterns are used in methods for estimating age to obtain the most reliable estimates of age.

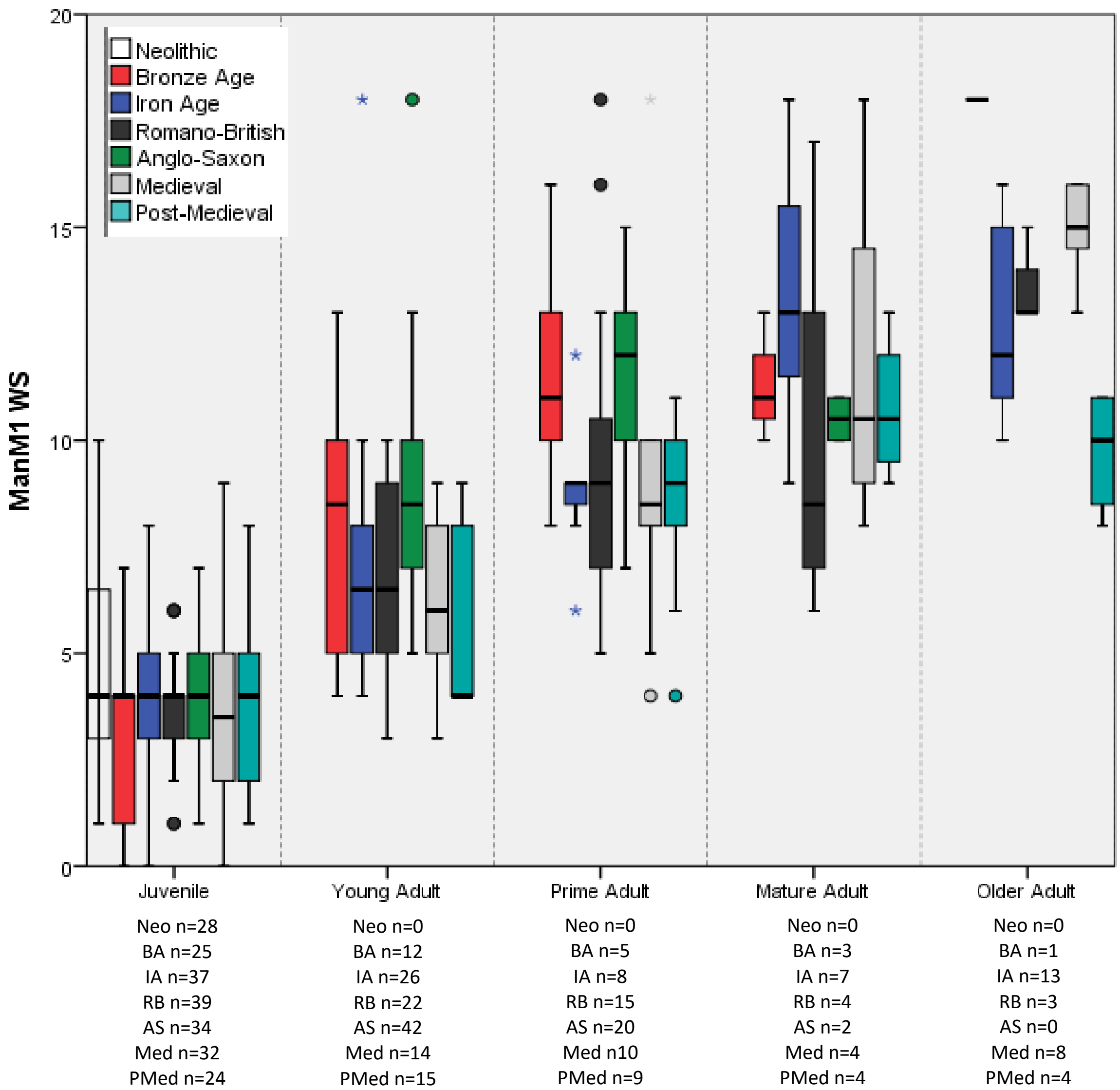


Figure 7.4.6. Box and whisker diagrams representing the relationship between first mandibular molar (ManM1) wear stage (WS) and age category by period sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

7.4.2.2 Second mandibular molar (ManM2)

Average crown height (CH)

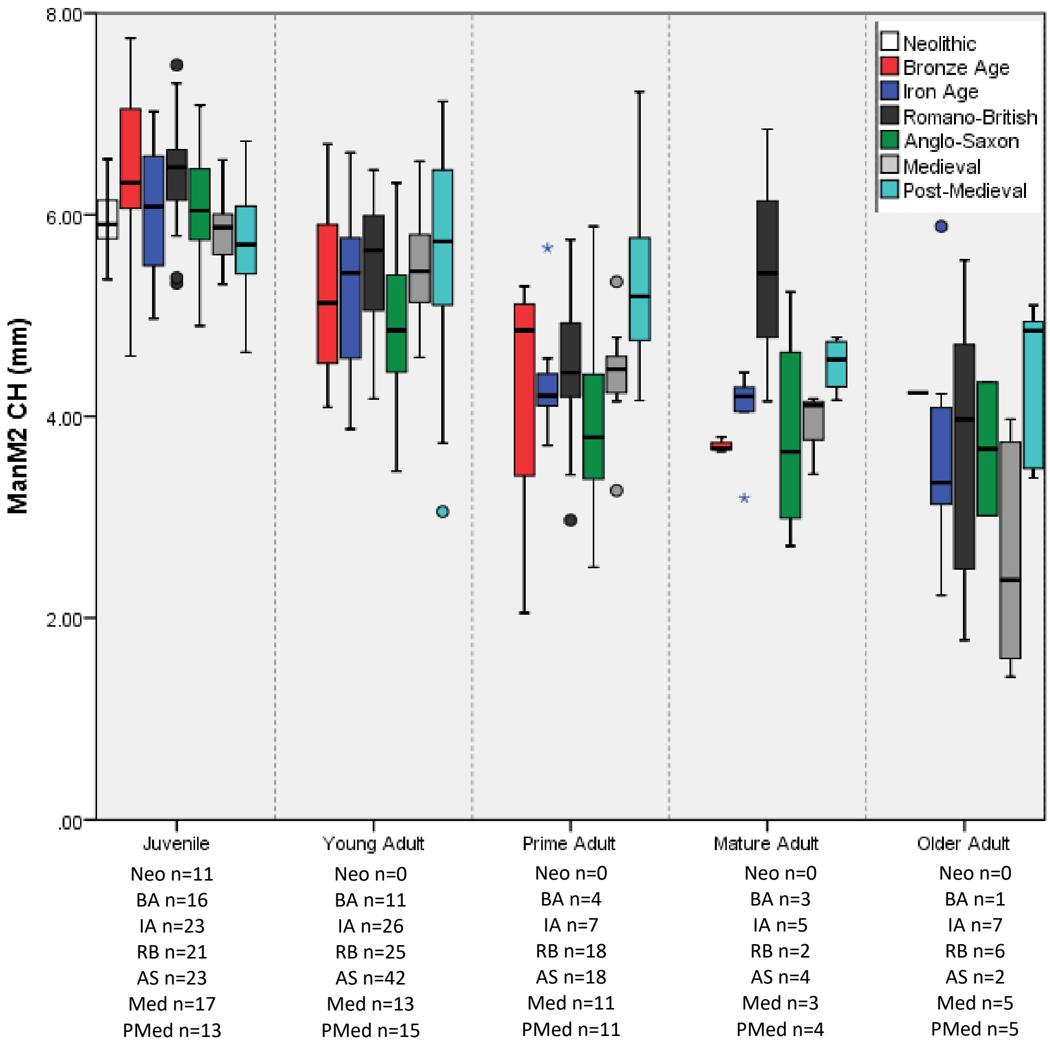


Figure 7.4.7. Box and whisker diagrams representing the relationship between second mandibular molar (ManM2) average crown height (CH) and age category by temporal sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

There was considerable overlap of ManM2 CH wear distributions in the Juvenile age group, including similar median values and inter-quartile ranges for all temporal samples (Figure 7.4.7). With increasing age ManM1 CH wear distributions became more varied, indicating some difference in wear pattern between the temporal samples with increasing age. This was evidenced by an observable difference in median values with an increase in age and a decrease in overlap in IQR between the studied samples. However, this difference was not as great as that observed when comparing ManM1 CH wear distributions.

These results suggest that the use of a single wear pattern to estimate age in multiple archaeological may be reliable. However, the presence of slight differences in ManM2 CH wear distributions between samples supports the development and use of population-specific dental wear charts.

Crown Index (CI)

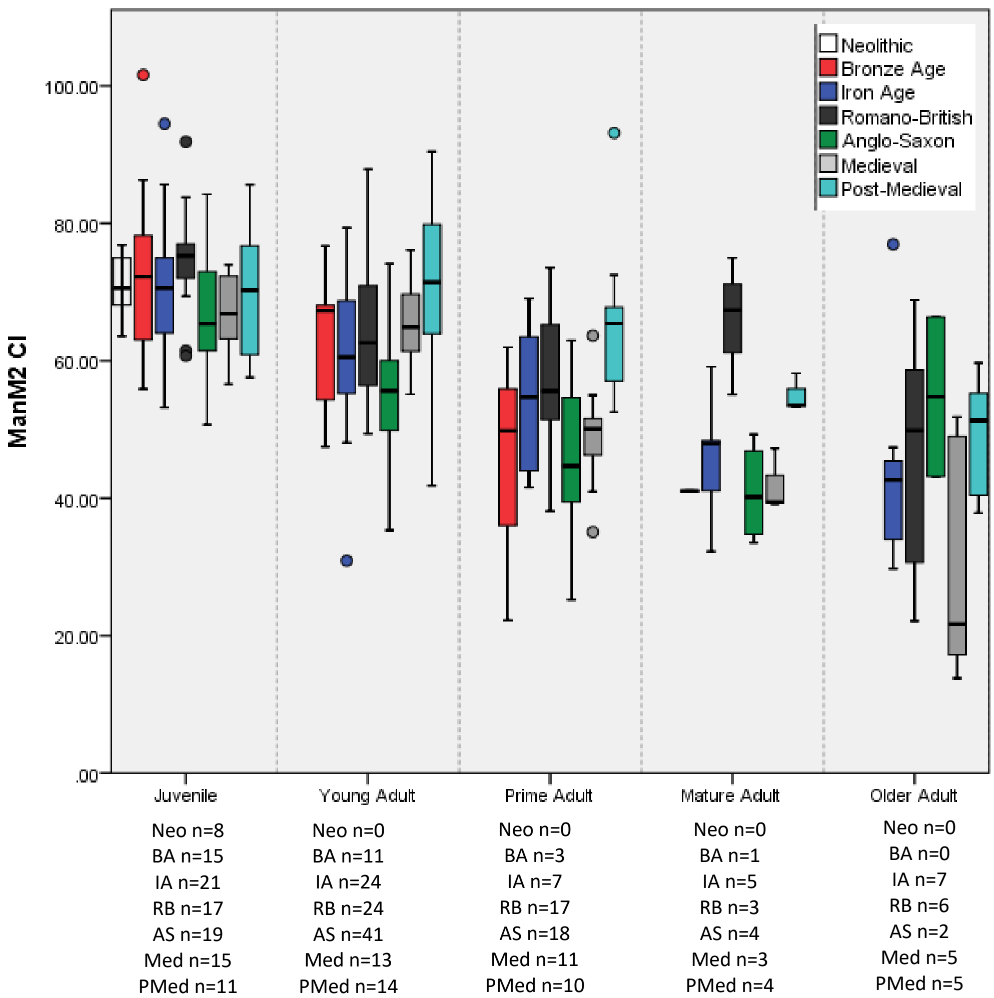


Figure 7.4.8. Box and whisker diagrams representing the relationship between second mandibular molar (ManM2) crown index (CI) and age category by temporal sample.
Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

Figure 7.4.8 shows a similar ManM2 CI wear distribution for all temporal samples in the Juvenile age group, indicated by similar medians and IQRs. The Young Adult age group indicates a similar pattern of wear across the studied samples, demonstrated by similar IQRs that overlap. Some difference in wear pattern between the samples can be observed in the Prime Adult age group, indicated by a slightly smaller degree of overlap in IQRs, and a larger difference between ManM2 CI medians. Some similarity in wear distributions for the Iron Age, Anglo-Saxon and Medieval samples in the Mature Adult group supports a similar pattern of wear for these samples. There was a degree of overlap in ManM2 CI wear distributions for individuals in the Older Adult group, although this was to a lesser extent compared to the younger age groups. The larger difference between ManM2 CI medians in the oldest age group suggests some difference in wear pattern between the studied samples.

These results suggest the application of a single wear pattern for estimating age to multiple archaeological population may by reliable for younger individuals, but less reliable for older individuals. Thus, it is recommended that population-specific dental wear patterns are used to estimate age in archaeological remains.

Percent of dentine exposure (%DE)

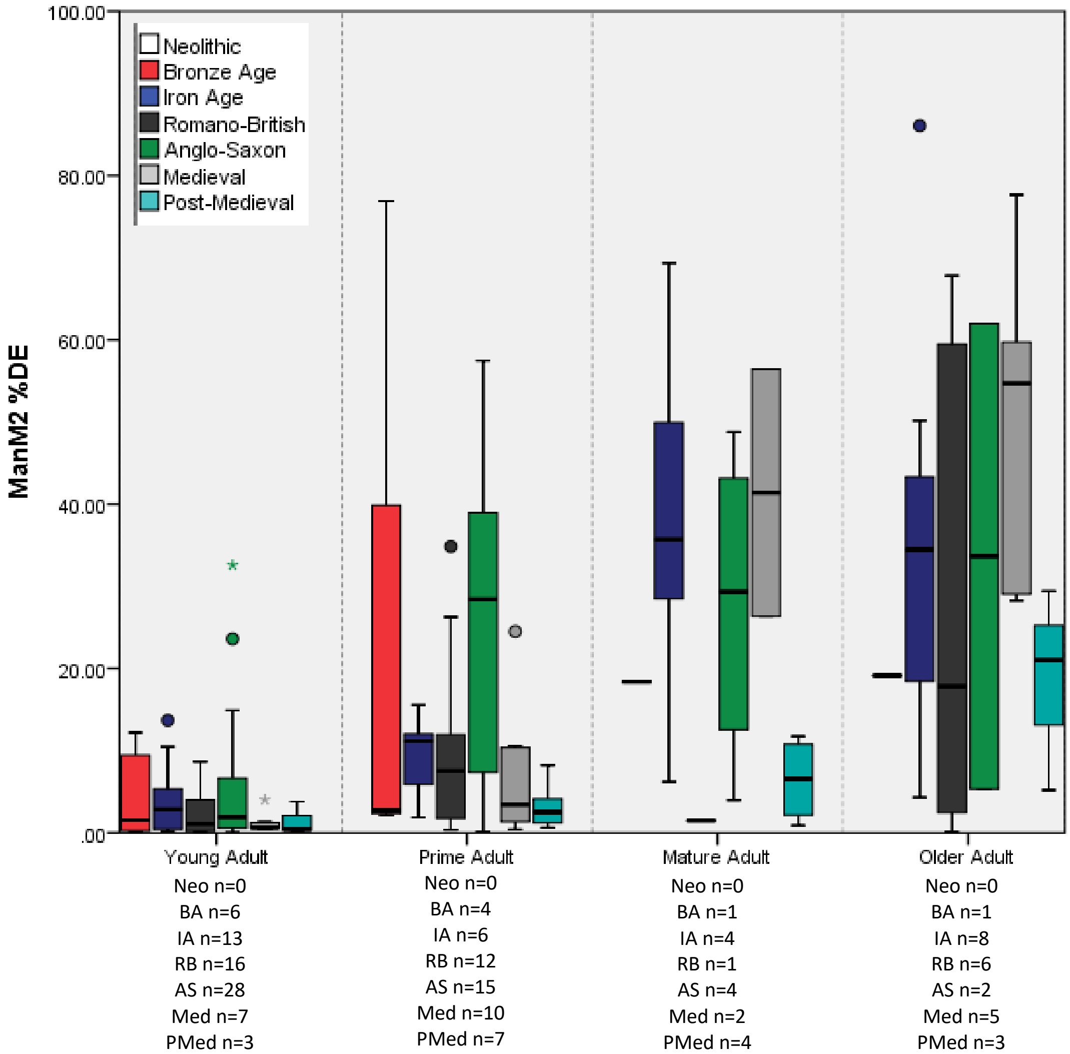


Figure 7.4.9. Box and whisker diagrams representing the relationship between ManM2 percent of dentine exposure (%DE) and age category by temporal sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

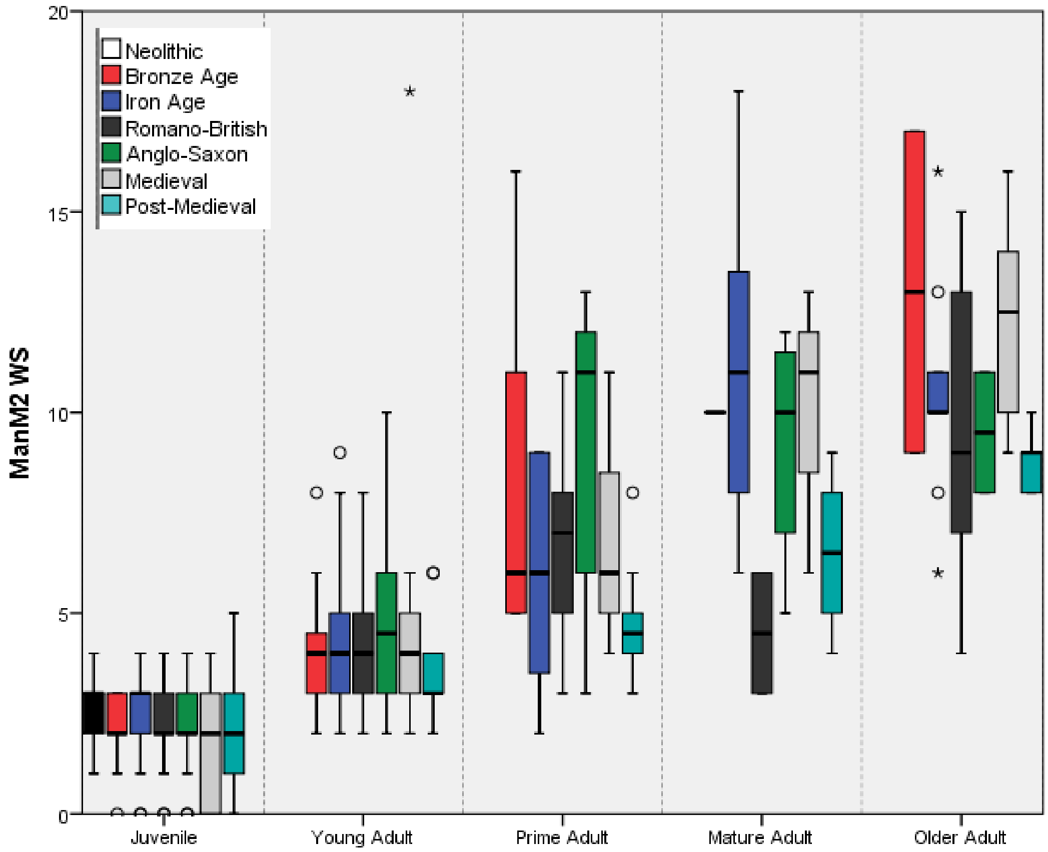
The Juvenile age group was excluded from analysis due to few juvenile individuals with any exposed dentine on their second mandibular molar.

ManM2 %DE medians were similar across temporal samples in the Young Adult group (Figure 7.4.9). The large degree of overlap between wear distributions in this age group support a similar wear pattern across the studied samples. This pattern was also observed in the Prime Adult age group, although the Bronze Age and Anglo-Saxon samples had a relatively large IQR. This suggests an overall similarity in ManM2 %DE wear pattern between the studied samples for the Prime Adult age group.

The Mature Adult and Older Adult age groups showed some variation in wear distributions between temporal samples. Although there was a degree of overlap in the wear distributions the studied samples had large IQRs and a greater difference between ManM2 %DE medians compared to the younger age groups. These results suggest some difference in wear pattern between temporal samples.

These results support the use of population-specific dental wear patterns in methods for estimating age of archaeological populations. While the studied samples showed a broad similarity in ManM2 %DE wear distributions, this becomes more varies with increasing age. Thus, it is likely that population-specific dental wear patterns will be more reliable for estimating age.

Wear Stage (WS)



Juvenile	Young Adult	Prime Adult	Mature Adult	Older Adult
Neo n=11	Neo n=0	Neo n=0	Neo n=0	Neo n=0
BA n=13	BA n=11	BA n=5	BA n=3	BA n=2
IA n=23	IA n=26	IA n=8	IA n=7	IA n=10
RB n=22	RB n=25	RB n=18	RB n=2	RB n=6
AS n=23	AS n=42	AS n=18	AS n=4	AS n=2
Med n=17	Med n=14	Med n=11	Med n=3	Med n=6
PMed n=13	PMed n=14	PMed n=10	PMed n=4	PMed n=5

Figure 7.4.10. Box and whisker diagrams representing the relationship between second mandibular molar (ManM2) wear stage (WS) and age category by temporal sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

Figure 7.4.10 shows a broad similarity in ManM2 WS wear distributions between temporal samples in the Juvenile and Young adult age groups. This was supported by similar ManM2 WS medians and IQRs, which overlapped. As with the previous measurements, there was more variation observed between samples with increasing age.

ManM2 WS medians were similar across the majority of temporal samples in the Prime Adult age group, although the Anglo-Saxon median was relatively high. A large degree in overlap between the IQRs, however, supports a broad similarity in ManM2 WS wear pattern between the samples for this age group.

The Mature Adult and Older Adult age groups showed some variation in wear distributions between the studied samples. The smaller degree of overlap in IQRs and the greater difference between ManM2 WS medians indicated some difference in wear pattern between the samples.

These results suggest the application of a single wear pattern for estimating age to multiple archaeological population may by reliable for younger individuals, but less reliable for older individuals. It is therefore recommended that populations-specific ManM2 WS wear patterns are developed and used to obtain the most reliable age estimates in archaeological remains.

7.4.2.3 Third mandibular molars (ManM3)

The third mandibular molar erupts around the age of 18 years old. As a result, juvenile individuals do not have a ManM3 in occlusion and were therefore excluded from analysis.

Average crown height (CH)

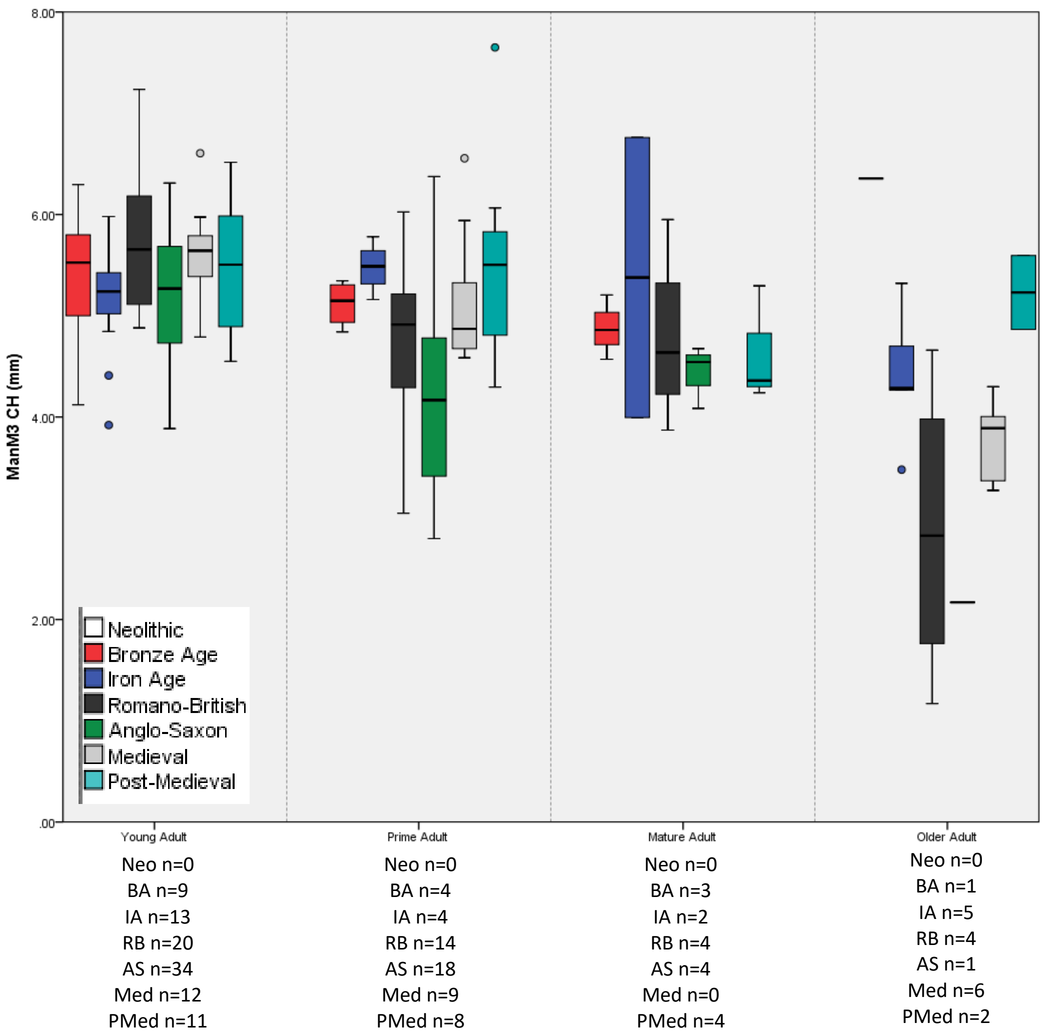


Figure 7.4.11. Box and whisker diagrams representing the relationship between third mandibular molar (ManM3) average crown height (CH) and age category by temporal sample.
Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

All samples had a similar ManM3 CH median and inter-quartile range, which overlapped, in the Young Adult age group (Figure 7.4.11). This pattern was also observed in the Prime Adult age group, although there was a greater degree of variation between samples. For example, the Anglo-Saxon sample had a relatively IQR and low ManM3 CH median, but there was some overlap with the Romano-British sample. These results support a similar wear pattern for ManM3 CH in both the Young adult and Prime Adult age groups.

The Mature Adult age group showed a similar pattern to the Prime Adult age group. ManM3 CH medians were similar across the samples, and there was a degree of overlap in IQRs. However, the Iron Age sample showed a comparatively larger IQR and a higher median, suggesting some difference in wear pattern. The Medieval sample had no individuals with measureable crown height in this age group.

The Older Adult age group showed the most variation between samples. This was evidenced by little overlapping of IQRs, and a large difference in ManM3 CH medians. These results indicate a difference in ManM3 CH wear pattern for the Older Adult age group.

These results suggest using a single dental wear pattern to estimate age in multiple archaeological populations may only be reliable for estimating age of young individuals. Figure 7.4.11 suggests that wear patterns may differ between temporal samples in older individuals, thus estimating age using a single wear pattern may be unreliable. It is therefore suggested that population-specific dental wear charts are used.

Crown index (CI)

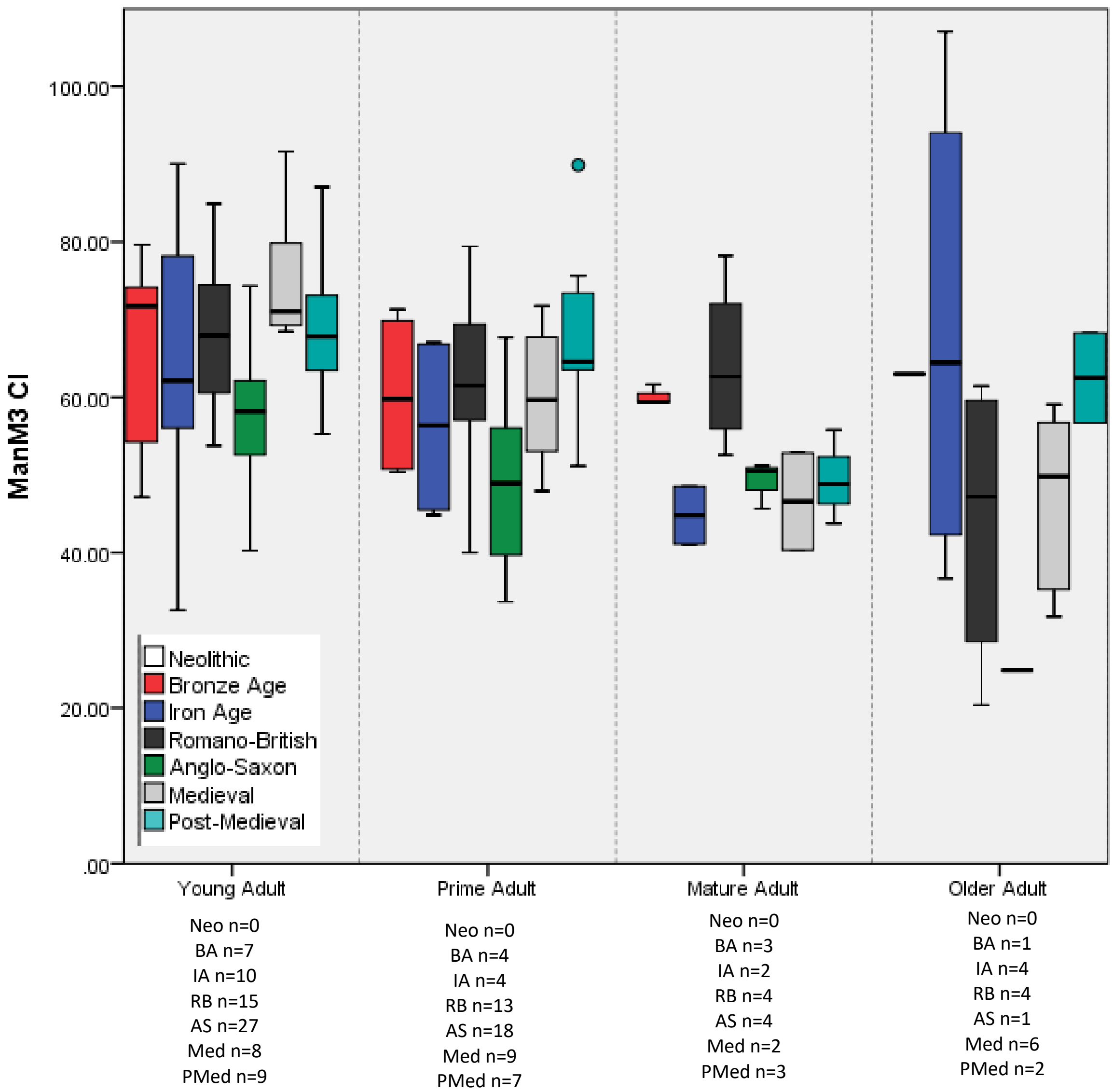


Figure 7.4.12. Box and whisker diagrams representing the relationship between third mandibular (ManM3) crown index (CI) and age category by temporal sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

Figure 7.4.12 shows a broad similarity in ManM3 CI wear pattern across the samples for the Young Adult and Prime Adult age categories, although there was some variation. In both age groups, the Anglo-Saxon showed a relatively lower value for the median. ManM3 medians were similar across and there was a large degree of overlap in IQRs for the remaining periods. This pattern was observed in both the Young Adult and Prime Adult age groups.

The Iron Age, Anglo-Saxon, Medieval and Post-Medieval samples had similar ManM3 CI inter-quartile ranges and medians, in the Mature Adult sample. The Bronze Age and Romano-British samples had higher median, indicating a difference in ManM3 CI wear pattern across the samples. The Romano-British sample also had a large IQR, compared with the other samples.

The greatest degree of variation between samples in ManM3 CI wear pattern was observed in the Older Adult age category. ManM3 CI IQRs were larger compared to the younger age groups, but there was a smaller degree of overlap between samples. Furthermore, there was a greater difference between ManM3 CI medians, suggesting some difference in wear pattern between the samples.

These results support the use of population-specific wear patterns for estimating age. While a single wear pattern designed to estimate age in multiple archaeological populations may be reliable for estimating age of younger individuals, it is highly likely decrease in reliability with increasing age.

Percent of dentine exposure discussion (%DE)

ManM3 %DE inter-quartile ranges and medians were similar for the Romano-British, Anglo-Saxon and Post Medieval samples in the Young Adult group (Figure 7.4.13). The Iron Age sample had a relatively higher median and larger IQR, indicating some difference in ManM3 %DE wear pattern... The Bronze Age had no individuals with measureable ManM3 %DE so could not be included in the analysis.

All temporal samples, except the Anglo-Saxon sample, had similar ManM3 %DE values for the Prime Adult age category. The Anglo-Saxon sample had a comparatively higher wear IQR and median. These results indicate the majority of temporal samples had a similar ManM3 %DE wear pattern for the Prime Adult age category.

The Anglo-Saxon, Medieval and Post-Medieval samples had a similar wear distribution for the Mature Adult age category. The relatively large IQRs and higher ManM3 %DE medians indicate some difference in wear pattern between the samples.

There was no individuals with measureable ManM3 %DE in the Older Adult age group for the Bronze Age and Anglo-Saxon samples. ManM3 %DE IQRs were larger compared to the younger age groups, although there was a degree of overlap between samples. There was a greater difference between ManM3 %DE medians in the Older Adult age group, suggesting some difference in wear pattern between the samples.

These results suggest the application of a single wear pattern for estimating age to multiple archaeological population may by reliable for younger individuals, but less reliable for older individuals. It is therefore recommended that populations-specific ManM3 %DE wear patterns are developed.

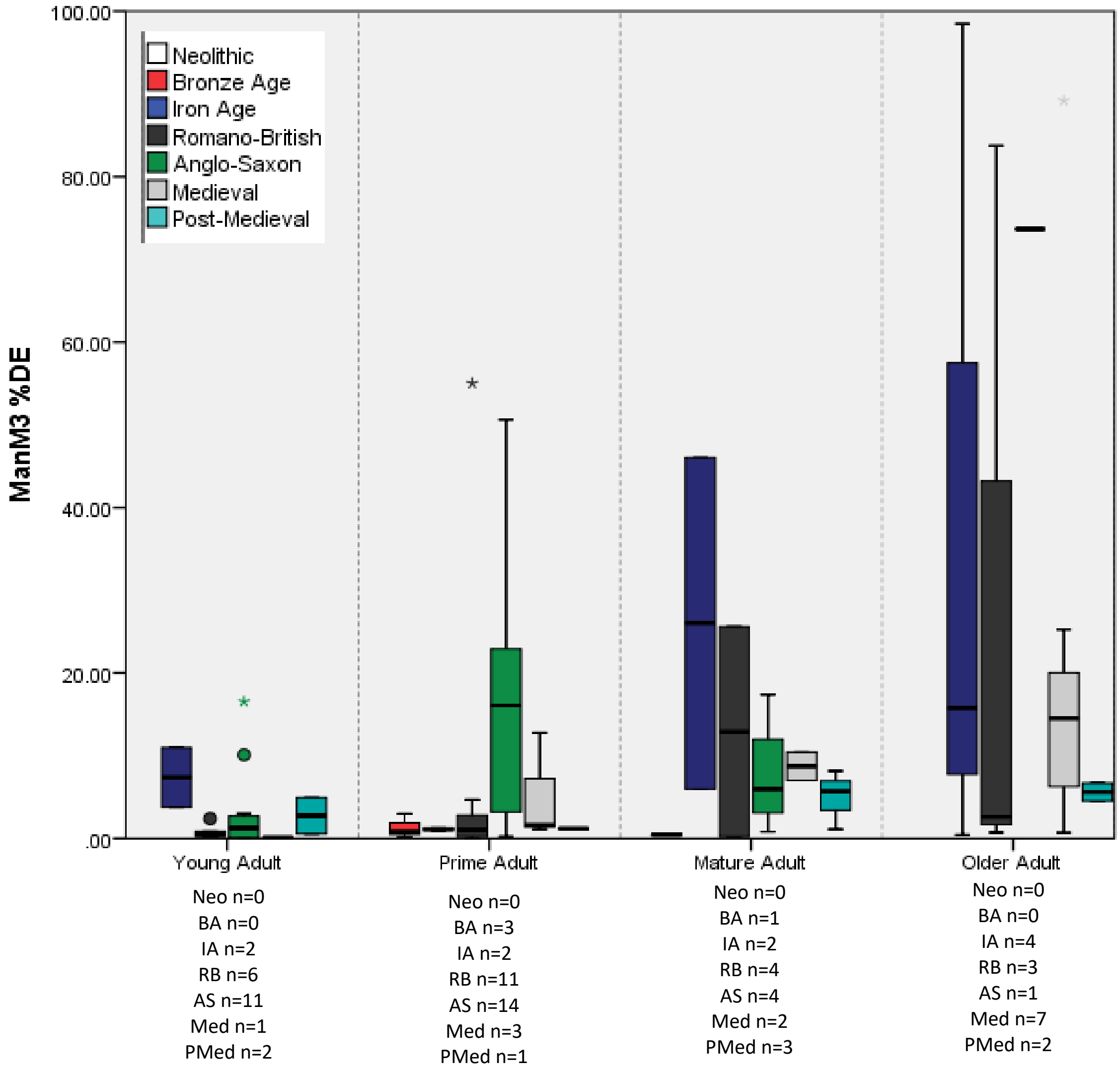


Figure 7.4.13. Box and whisker diagrams representing the relationship between third mandibular molar (ManM3) percent of dentine exposure (%DE) and age category by temporal sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

Wear stage (WS)

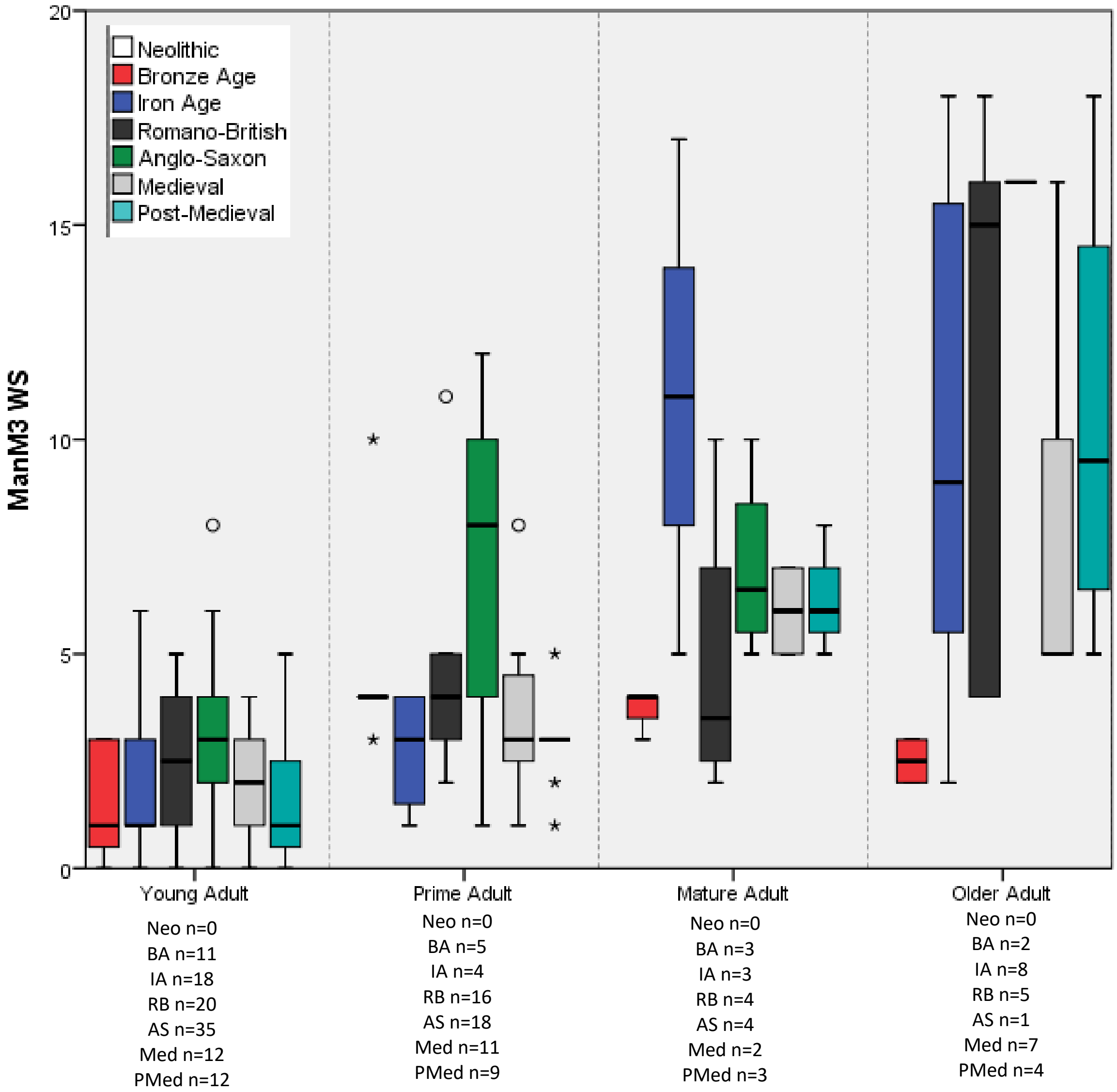


Figure 7.4.14. Box and whisker diagrams representing the relationship between third mandibular molar (ManM3) wear stage (WS) and age category by temporal sample.

Sample: Neo = Neolithic, BA = Bronze Age, IA = Iron Age, RB = Romano-British, AS = Anglo-Saxon, Med = Medieval, PMed = Post-Medieval

The Young Adult age group had a similar ManM3 WS wear pattern across temporal samples, with a large degree of overlap in IQRs (Figure 7.4.14. With increasing age ManM3 WS wear distributions became more varied, indicating some difference in wear pattern between the temporal samples with increasing age. This is evidenced by a decrease in the degree of overlap in IQRs between temporal samples and a difference between ManM3 medians. The large ManM3 WS IQRS observed in the Older Adult age group make comment on the similarity of wear patterns between samples difficult, however, the relatively large difference in medians suggests a difference in wear pattern.

As with the other ManM3 wear measurements, these results support use of population-specific dental wear patterns to estimate age. While a single wear pattern for estimating age in multiple archaeological populations may by reliable for young individuals, it may be less reliable for older individuals.

7.4.2.4 Summary: comparing dental wear distributions

Section 7.4.2 compared wear distributions by age category across temporal samples. Inter-quartile ranges overlapped between the studied samples, particularly in the Juvenile and Young Adult age group. However, this degree of overlap decreased with increasing age. Furthermore, there was a greater difference between median values with increasing age. This pattern was observed in all wear measurements and all molar types. Dental wear appears to increase steadily until middle age where it then appears to plateau. This finding suggests dental wear may not be precisely linear with age as assumed by some dental wear ageing methods, including Gilmore and Grote (2012). A decrease in dental wear rate in older individuals may result from a change in the proportion of exposed dental tissue. Alternatively, the tooth may be reaching its capacity to withstand wear, causing a reduction in dental wear rate, and is may to be lost imminently. This finding suggests older individuals may be assigned a lower age estimate when using dental wear ageing methods that rely on the assumption that dental wear is linear with age.

These results support a single pattern of dental wear to estimate age in younger individuals belonging to difference archaeological populations. However, the application of a single wear pattern to estimate age in older individuals may be unreliable.

7.4.3 Comparing Juvenile wear rates

This section compares juvenile dental wear rates to test the validity of using a single rate of wear to estimate age in multiple archaeological populations. Juvenile wear rates produced during linear regression analysis (Section 7.3) were compared by first examining the equality of slopes. A significant result ($p<0.05$) indicates a difference between at least two of the slopes, and thus a difference in wear rate in juvenile individuals between at least two temporal samples. A non-significant result indicated a similarity in wear rates during the juvenile period. If the test of equality of slopes was not significant a comparison of the y-intercepts was performed. This examined whether the starting crown heights of molars (i.e. unworn molars) were significantly different between temporal samples. This comparison of slopes and y-intercept is equivalent to an analysis of covariance (ANCOVA). An ANCOVA was performed to compare juvenile wear rates on both the first and second mandibular molars, using the measurements of average crown height (CH) and crown index (CI).

The ANCOVA requires the dependent variable (i.e. the wear measurement) to be a continuous measurement, this analysis therefore did not include the Wear Stage data. WS wear rates were compared using distribution plots with 95% confidence intervals plotted and a Kruskal-Willis test performed. The Kruskal-Willis test determines whether the medians of multiple groups are different. Thus, it is expected that a significant difference in WS wear rates between juveniles will produce a difference overall population median. %DE could not be analysed due to the lack of dentine that is exposed during the juvenile period.

Null hypothesis: juvenile wear rates do not significantly differ between temporal samples

It is expected that:

- temporal samples will have a similar juvenile dental wear rate
- temporal samples will have a similar starting crown height of unworn molars
-

7.4.3.1 First mandibular molar (ManM1)

Average crown height (CH)

All temporal samples had a significant relationship between ManM1 CH and estimated juvenile age according to the regression analysis (Table 7.4.9, Figure 7.4.15). The Neolithic and Medieval samples had the largest slope coefficients, indicating a faster rate of wear. The Romano-British and Anglo-Saxon samples had the smallest slope coefficients, suggesting a slower rate of wear. However, an ANCOVA of ManM1 CH juvenile rates was not significant (F=0.74, p=0.619), supporting a similar rate of ManM1 CH wear across the studied samples.

Table 7.4.9. Regression equations and Pearson's correlation coefficients (r) for first mandibular molar (ManM1) average crown height (CH) against estimated juvenile age by temporal sample.

Sample	n	Linear Regression Equation	r	P-value
Neolithic	27	ManM1 CH = 7.10 - 0.14*age	-0.49	0.009
Bronze Age	27	ManM1 CH = 7.27 - 0.12*age	-0.61	0.001
Iron Age	35	ManM1 CH = 6.86 - 0.09*age	-0.49	0.003
Romano-British	37	ManM1 CH = 6.96 - 0.08*age	-0.32	0.022
Anglo-Saxon	34	ManM1 CH = 6.80 - 0.08*age	-0.47	0.005
Medieval	32	ManM1 CH = 7.39 - 0.15*age	-0.70	0.001
Post-Medieval	22	ManM1 CH = 7.03 - 0.11*age	-0.47	0.001

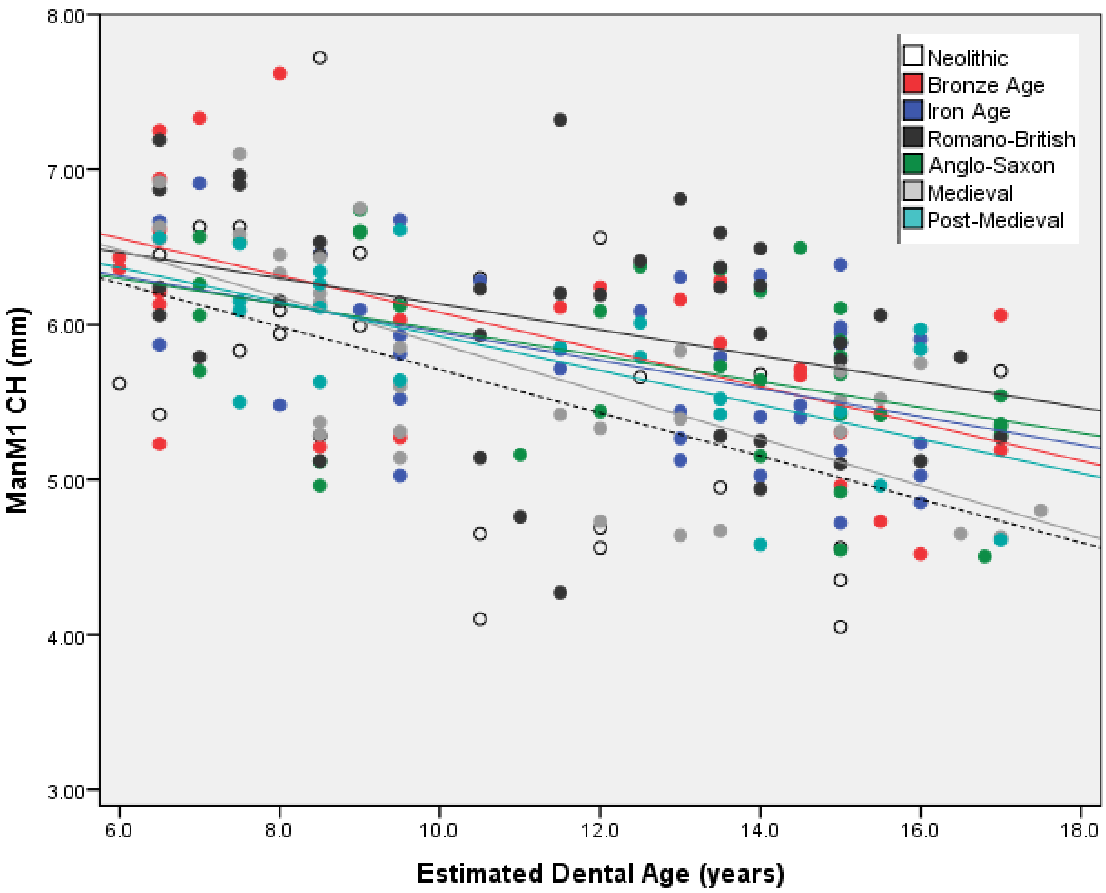


Figure 7.4.15. Comparison of first mandibular molar (ManM1) average crown height (CH) wear rates against juvenile age by temporal sample. The linear regression lines of ManM1 CH upon dental age for each temporal sample are superimposed.

A comparison of ManM1 CH y-intercepts just obtained significance at the 5% alpha level (F=2.23, p=0.041), indicating a significant difference between at least two of the studied samples. A post-hoc test of pairwise comparisons was performed with a Bonferroni adjustment to determine significance among temporal samples. The alpha level was set to 0.007 (0.05/7). Table 7.4.10 shows a significant difference in ManM1 CH y-intercepts between the Neolithic and Romano-British samples (p=0.002).

These results support a similarity in ManM1 CH juvenile wear rates between temporal samples. Any difference between the studied samples is a result of a difference in starting CH of unworn first mandibular molars. These results support the use of a single dental wear rate to estimate age of multiple archaeological populations.

Table 7.4.10. Post-hoc test of pairwise comparisons of y-intercepts for ManM1 CH against juvenile age by temporal sample.

Sample	Neolithic	Bronze Age	Iron Age	Romano-British	Anglo-Saxon	Medieval	Post-Medieval
Neolithic	-	0.021	0.050	0.002*	0.028	0.385	0.174
Bronze Age	0.021	-	0.629	0.478	0.820	0.121	0.399
Iron Age	0.050	0.629	-	0.198	0.786	0.251	0.665
Romano-British	0.002*	0.478	0.198	-	0.316	0.016	0.118
Anglo-Saxon	0.028	0.820	0.786	0.316	-	0.162	0.504
Medieval	0.385	0.121	0.251	0.016	0.162	-	0.553
Post-Medieval	0.174	0.399	0.665	0.118	0.504	0.553	-

*indicates a significant difference in y-intercepts between two temporal samples when adjusted for multiple comparisons

Crown index (CI)

All temporal samples had a significant, linear relationship between ManM1 CI and juvenile age (Table 7.4.11,Figure 7.4.16). The slopes of the regression lines for the Bronze Age and Anglo-Saxon samples were greater than those for the other samples. However, an ANCOVA was not significant (F=1.27, p=0.272), supporting a similar rate of ManM1 CI wear across temporal samples.

Table 7.4.11. Regression equations and Pearson's correlation coefficients (r) for first mandibular molar (ManM1) crown index (CI) against estimated juvenile age by temporal sample.

Sample	n	Linear Regression Equation	r	P-value
Neolithic	26	ManM1 CI = 83.25-1.51*age	-0.54	0.004
Bronze Age	24	ManM1 CI = 92.74-1.98*age	-0.65	0.001
Iron Age	33	ManM1 CI = 83.16-1.32*age	-0.53	0.024
Romano-British	33	ManM1 CI = 79.39-0.93*age	-0.42	0.015
Anglo-Saxon	35	ManM1 CI = 92.83-2.04*age	-0.74	<0.001
Medieval	30	ManM1 CI = 86.17-1.84*age	-0.69	<0.001
Post-Medieval	23	ManM1 CI = 81.40-0.94*age	-0.45	0.033

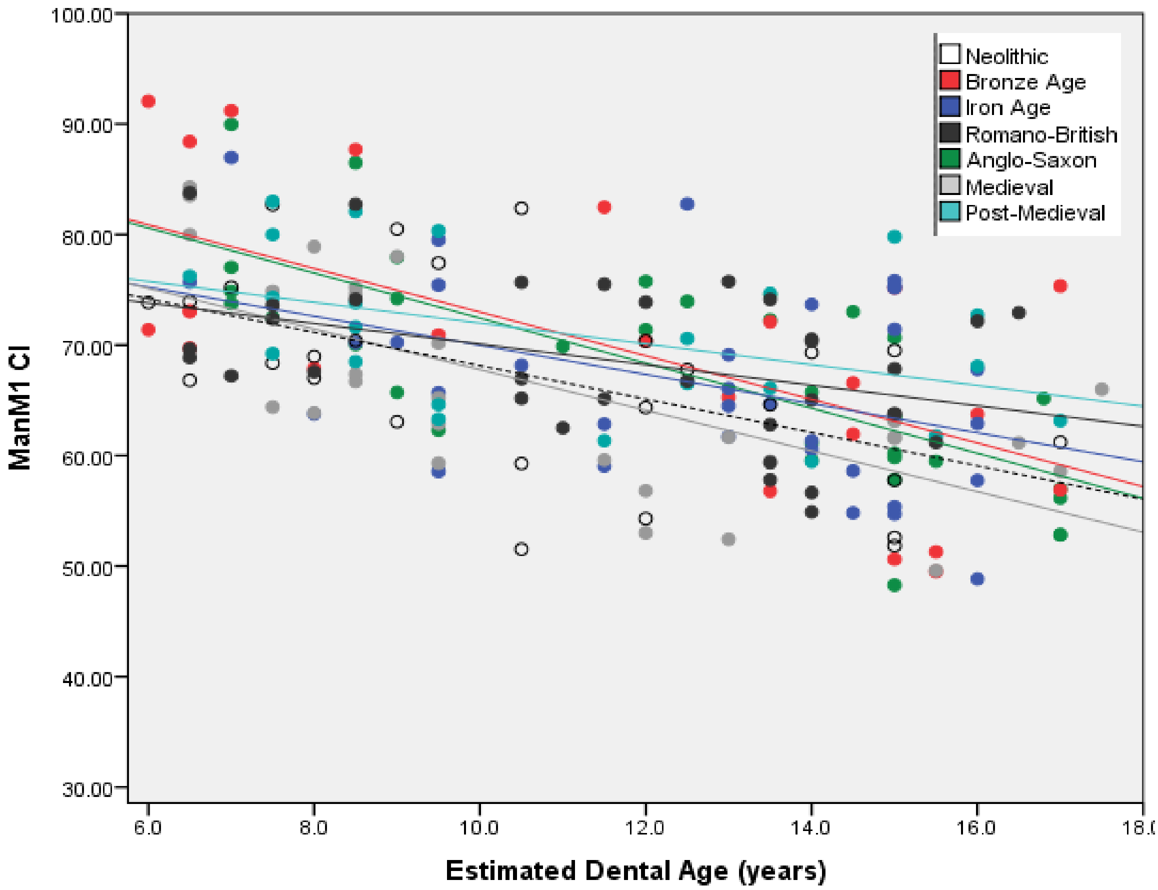


Figure 7.4.16. Comparison of first mandibular molar (ManM1) crown index (CI) wear rates against juvenile age by temporal sample. The linear regression lines of ManM1 CI upon dental age for each temporal sample are superimposed.

A comparison of ManM1 CI y-intercepts was not significant (F=1.91, p=0.081). At 6 years of age, when the ManM1 erupts, ManM1 CI y-intercept was approximately 75 for all studied samples, except the Bronze Age and Anglo-Saxon populations, which were slightly higher. These results support a similar starting ManM1 CI of unworn molars.

These results suggest all temporal samples had a similar rate of ManM1 CI juvenile, with a similar starting CI of unworn first mandibular molars. Thus, a single wear rate is reliable for estimating age in multiple archaeological populations.

Wear stage (WS)

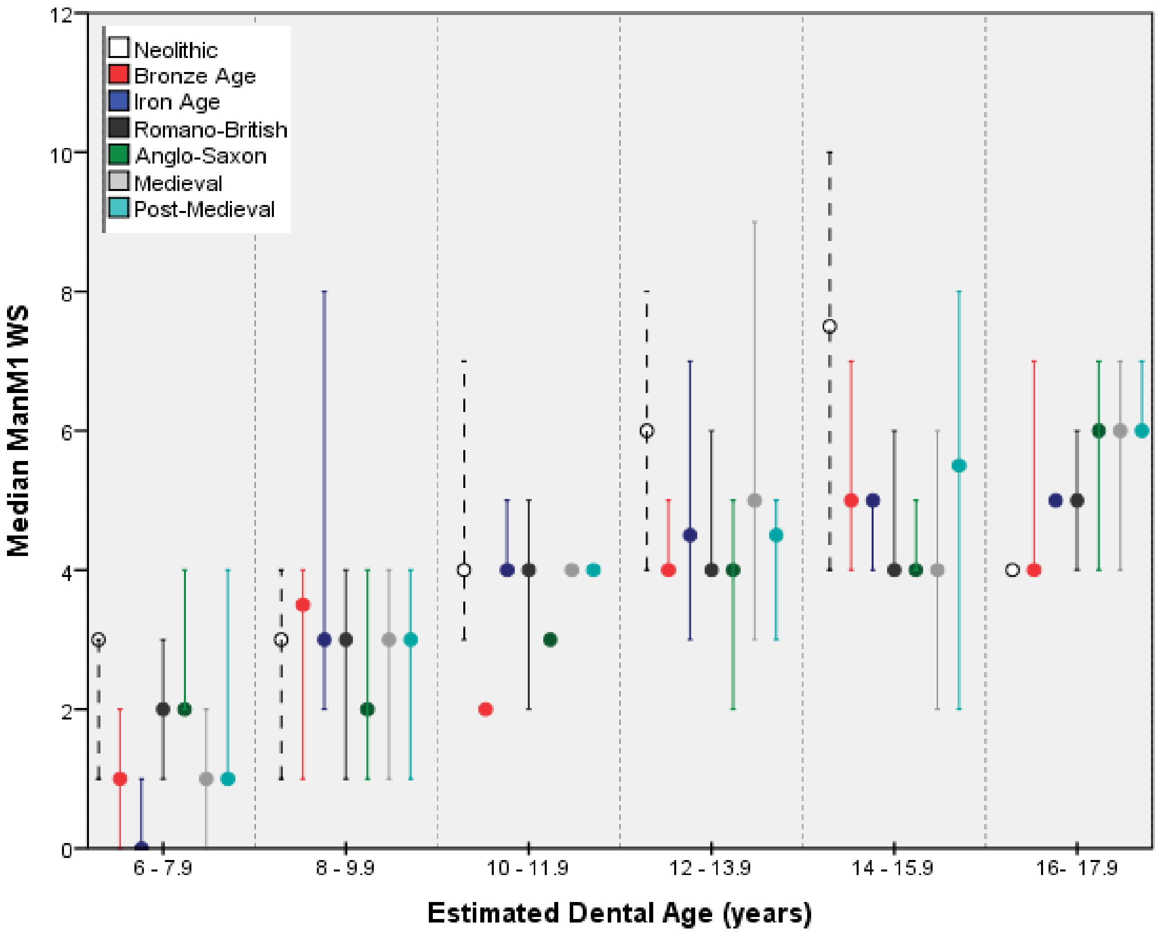


Figure 7.4.17. Median first mandibular molar (ManM1) wear stage (WS) by juvenile age across temporal samples. Bars represent 95% confidence intervals.

All temporal samples had a positive association between ManM1 WS and juvenile age (Figure 7.4.17). Neolithic individuals had the highest ManM1 WS median for individuals aged between 10 and 15.9 years old, while the other samples clustered together. By the end of the juvenile period the Neolithic and Bronze Age samples had a median ManM1 WS of 4 (one discrete area of exposed dentine). The Iron Age and Romano-British samples had a median ManM1 WS of 5 (two discrete areas of exposed dentine) by the end of the juvenile period. The Anglo-Saxon, Medieval and Post-Medieval samples had the highest median ManM1 WS of 6 (three discrete areas of exposed dentine) by the end of the juvenile period. These results suggest a broad similarity in ManM1 WS wear rate during the juvenile period for the majority of period samples. This was supported by a non-significant Kruskal-Wallis test ($\chi^2(6)$ 4.19, p=0.650).

These results suggest all temporal samples had a similar ManM1 WS wear rate, and thus a single wear rate may be reliably used to estimate age in multiple archaeological populations.

7.4.3.2 Second mandibular molar (ManM2)

Average crown height (CH)

Regression analysis identified a significant, linear relationship between ManM2 CH and juvenile age for the Bronze Age, Iron Age and Anglo-Saxon samples (Table.7.4.12, Figure 7.4.18). A linear pattern of decreasing ManM2 CH with an increase in juvenile age was identified in the Romano-British, Medieval and Post-Medieval samples, although this was not significant. The Neolithic did not show a pattern of decreasing ManM2 with an increase in juvenile age.

Table.7.4.12. Regression equations and Pearson's correlation coefficients (r) for second mandibular molar (ManM2) average crown height (CH) against estimated juvenile age by temporal sample.

Sample	n	Linear Regression Equation	r	P-value
Neolithic	11	ManM2 CH = 6.00 - 0.005*age	-0.03	0.943
Bronze Age	13	ManM2 CH = 13.18 - 0.48*age	-0.78	0.002
Iron Age	19	ManM2 CH = 10.73 - 0.33*age	-0.69	0.001
Romano-British	19	ManM2 CH = 8.10 - 0.11*age	-0.31	0.202
Anglo-Saxon	22	ManM2 CH = 8.11 - 0.14*age	-0.43	0.049
Medieval	13	ManM2 CH = 7.53 - 0.11*age	-0.56	0.052
Post-Medieval	13	ManM2 CH = 8.29 - 0.18*age	-0.45	0.128

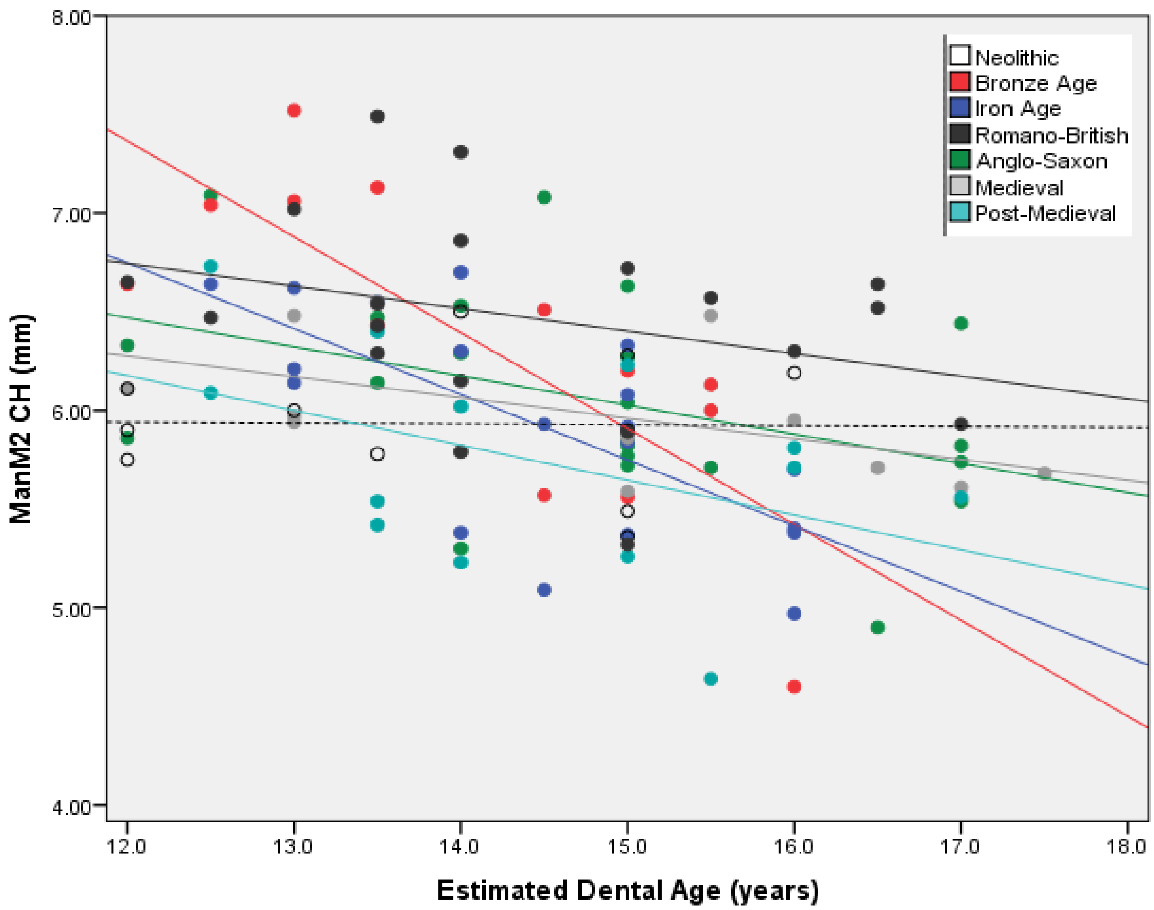


Figure 7.4.18. Comparison of second mandibular molar (ManM2) average crown height (CH) wear rates against juvenile age by temporal sample. The linear regression lines of ManM2 CH upon dental age for each temporal sample are superimposed.

An ANCOVA identified a significant difference between ManM2 CH regression slopes (F=2.72, p=0.017). The Bronze Age and Iron Age samples slope coefficients were greater than the remaining temporal samples, producing a difference in the linear regression lines of ManM2 CH upon juvenile age (Table.7.4.12, Figure 7.4.18). These results indicate that the Bronze Age and Iron Age samples had a faster rate of ManM2 CH wear compared to the other studied samples during the juvenile period. As there was a significant difference between regression lines there is no need to compare ManM2 CH y-intercepts.

These results a single ManM2 CH wear rate to estimate age of multiple archaeological periods will not be reliable. Furthermore, the lack of a significant linear relationship between ManM2 CH and juvenile age in some of the studied samples (Section 7.3.1) suggests ManM2 CH juvenile wear rates may not reliable for estimating age. Thus, this thesis recommends the use of ManM1 CH juvenile wear rates to estimate age in archaeological remains.

Crown Index (CI)

The Bronze Age, Iron Age and Anglo-Saxon samples had a significant, linear relationship between ManM2 CI and juvenile age. A linear pattern of decreasing ManM2 CI with an increase in juvenile age was identified in the Romano-British, Medieval and Post-Medieval samples, although this was not significant. The Neolithic did not show a pattern of decreasing ManM2 with an increase in juvenile age. Slopes and y-intercepts were compared for ManM2 CH against juvenile age (Table 7.4.13,Figure 7.4.19).

Table 7.4.13. Regression equations and Pearson's correlation coefficients (r) for second mandibular molar (ManM2) crown index (CI) against estimated juvenile age by temporal sample

Sample	n	Linear Regression Equation	r^2	P-value
Neolithic	11	ManM2 CI = 84.63 - 0.99*age	-0.29	0.481
Bronze Age	12	ManM2 CI = 159.30 - 6.09*age	-0.64	0.024
Iron Age	18	ManM2 CI = 130.59 - 4.32*age	-0.53	0.024
Romano-British	15	ManM2 CI = 120.67 – 2.98*age	-0.44	0.116
Anglo-Saxon	19	ManM2 CI = 118.86 - 3.55*age	-0.56	0.013
Medieval	11	ManM2 CI = 92.73 - 1.71*age	-0.52	0.100
Post-Medieval	11	ManM2 CI = 77.48 - 0.51*age	-0.08	0.817

*indicates a significant difference in ManM2 CH regression slopes between two temporal samples when adjusted for multiple comparisons

A comparison of ManM2 CI regression slopes was not significant following an ANCOVA (F=1.25, p=0.292). These results suggest a similarity in ManM2 CI wear rates over the juvenile period for all samples. However, a comparison of ManM2 CI y-intercepts was significant (F=2.61, p=0.023). A post-hoc test of pairwise comparisons was performed using a Bonferroni adjustment to determine significance among temporal samples. The alpha level was set to 0.007 (0.05/7). Table 7.4.14 shows a significant difference in ManM2 CI y-intercepts between the Iron Age and Romano-British samples (p=0.002), The Romano-British and Anglo-Saxon samples (p=0.001), and between the Romano-British and Medieval samples (p=0.007).

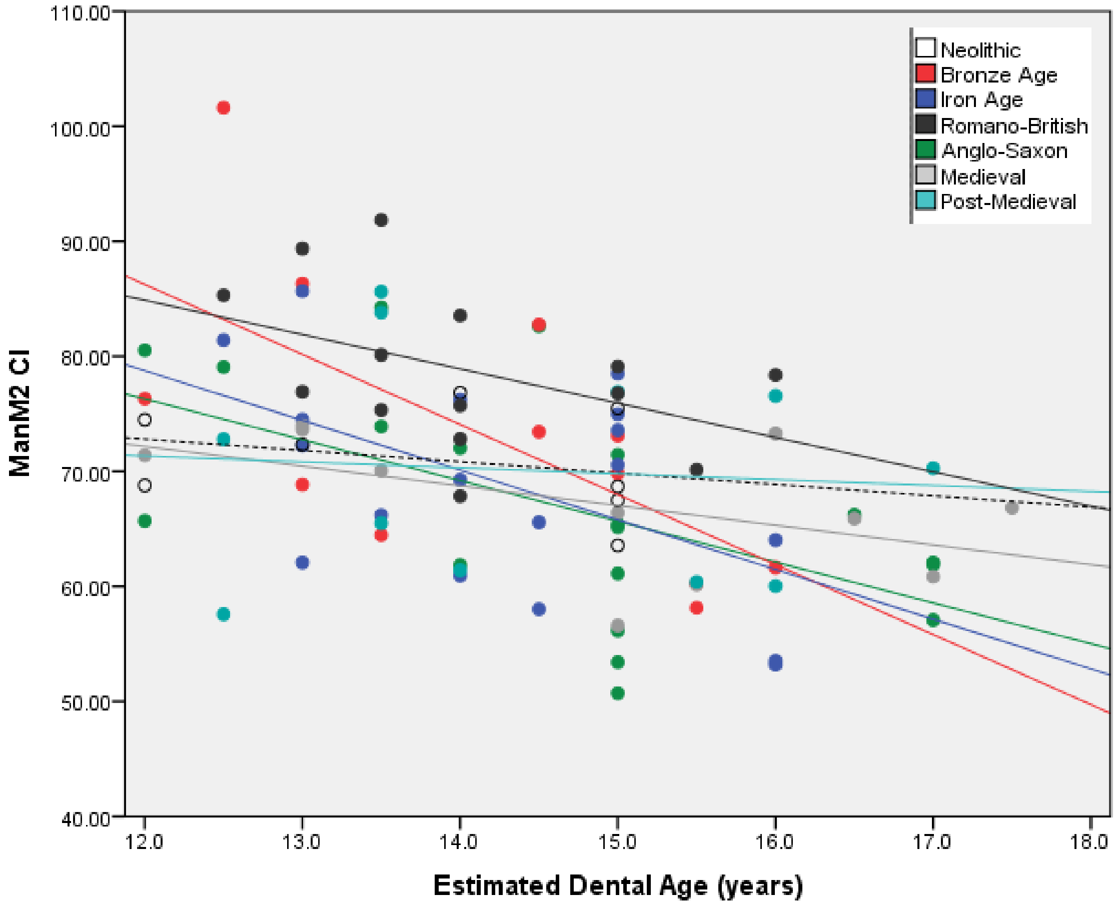


Figure 7.4.19. Comparison of second mandibular molar (ManM2) crown index (CI) wear rates against juvenile age by temporal sample. The linear regression lines of ManM2 CI upon dental age for each temporal sample are superimposed.

These results show temporal samples have a similar rate of wear when ManM2 crown height is normalised for tooth width. Any difference between the studied samples is a result of a difference in starting CI of unworn first mandibular molars. These results conflict with those comparing ManM2 CH juvenile wear rates, and cast doubt on the reliability of ManM2 juvenile wear rates when estimating age. Although no significant difference was observed between ManM2 CI juvenile wear rates it must be noted that not all temporal samples showed a significant linear relationship with juvenile age. ManM2 juvenile wear rates are likely to reflect wear solely to the molar cusps, before dentine is exposed or wear is experience across the entire tooth surface. Thus, ManM2 juvenile wear rates may not be a true representation of dental wear rates, and will not be reliable for estimating at age death.

Table 7.4.14. Post-hoc test of pairwise comparisons of y-intercepts of ManM2 CI against juvenile age by temporal sample

Sample	Neolithic	Bronze Age	Iron Age	Romano-British	Anglo-Saxon	Medieval	Post-Medieval
Neolithic	-	0.428	0.801	0.023	0.601	0.842	0.832
Bronze Age	0.428	-	0.209	0.096	0.117	0.280	0.529
Iron Age	0.801	0.209	-	0.002*	0.727	0.972	0.590
Romano-British	0.023	0.096	0.002*	-	0.001*	0.007*	0.024
Anglo-Saxon	0.601	0.117	0.727	0.001*	-	0.734	0.397
Medieval	0.842	0.280	0.972	0.007*	0.734	-	0.653
Post-Medieval	0.832	0.529	0.590	0.024	0.397	0.653	-

*indicates a significant difference in ManM2 CI y-intercepts between two temporal samples when adjusted for multiple comparisons

Wear stage (WS)

Figure 7.4.20 shows all temporal samples increased in ManM2 WS wear rate with an increase in juvenile age. By the end of the juvenile period most samples had a median ManM2 WS of 3 (enamel flattening, no exposed dentine). The Romano-British sample had a ManM2 WS of 4 (one discrete area of exposed dentine) and the Post-medieval sample had a WS of 2 (enamel rounding) at the end of the juvenile period. These results suggest few individuals showed exposed dentine on their ManM2 during the juvenile period, but, showed a similar rate of ManM2 WS wear during the juvenile period. These results were supported a non-significant Kruskal-Wallis test ($\chi^2(6)=5.03$, p=0.540).

These results support the use of a single ManM2 WS wear rate to estimate age in multiple archaeological populations. However, the relatively short time span to examine the relationship between ManM2 WS and juvenile age suggests it may be less reliable compared with ManM1 WS wear rates.

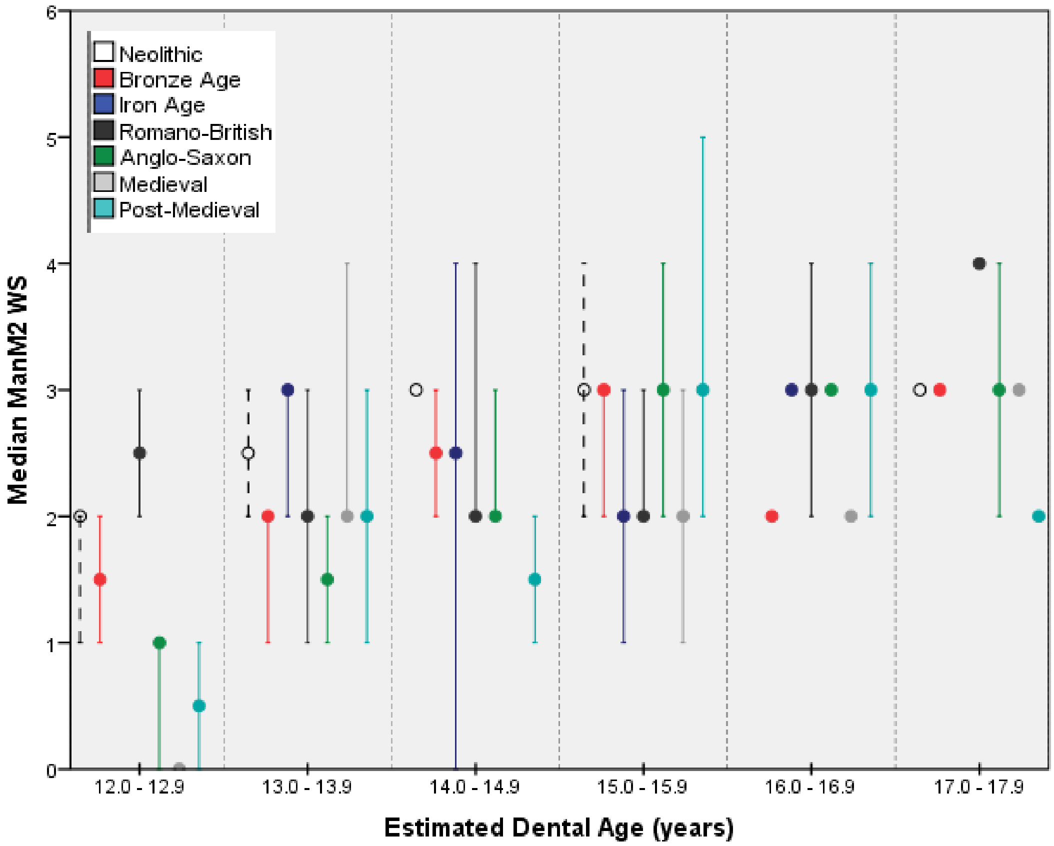


Figure 7.4.20. Median second mandibular molar (ManM2) wear stage (WS) by juvenile age across temporal samples. Bars represent 95% confidence intervals.

7.4.3.3 Summary: comparing juvenile dental wear rates

Section 7.4.3 compared the wear rates of the ManM1 and ManM2 observed during the juvenile period. Following an analysis of covariance, temporal samples showed a similar CH, CI and WS rate of wear in the ManM1. These results support the application of a single rate of wear to multiple British archaeological samples for estimating age at death.

The ManM2 showed an overall similarity in wear rate for the CI and WS measurements, but some difference in the ManM2 CH wear rate. These conflicting results suggest that ManM2 crown height measurements only show a similar rate of wear across multiple archaeological samples when normalised for tooth width. ManM2 wear during the juvenile period is confined to the molar cusps, with few individuals showing any exposed dentine by the end of the juvenile period. The wear rate observed on juvenile ManM2s may therefore not be reliable for estimating age in adult individuals. Furthermore, not all temporal samples showed a significant linear relationship between ManM2 crown height measurements and juvenile age. These results, therefore, suggest caution before applying a single ManM2 wear rate to multiple archaeological samples.

7.4.4 Comparing adult dental wear rates

A comparison of juvenile dental wear rates between the studied samples only examines a small part of the dental wear process. This section compares adult dental wear rates between temporal samples, to further test the conclusion of Brothwell that a single wear chart can estimate age in multiple British archaeological populations.

Adult molar wear rates were produced following the Modified Miles Method (Gilmore and Grote 2012). The Modified Miles Method averages the overall wear difference between two molars for adult individuals within a population, producing an estimated rate of wear. Estimated rate of wear for each studied sample was calculated using the mean wear difference between the ManM1 and ManM2. While estimated wear rates may also be calculated using the mean difference between the ManM2 and ManM3, or the ManM1 and ManM3 Section 7.2 demonstrated the wear relationship between the ManM1 and ManM2 was the strongest. This, the most reliable estimates of age will be produced using this relationship.

Following Gilmore and Grote (2012 p.189) individual wear differences were calculated as: $D_i = wearM1_i - wearM2_I$ within each studied sample. ManM1-ManM2 differences within each sample were then average to produce a mean wear difference. To calculate the average wear per year this mean wear difference was divided by the number of years between eruption of the ManM1 and ManM2. The ManM1 erupts around the age of 6 years of age, while the ManM2 erupts around 12 years of age. Thus, the difference in age between eruption events is 6 years. This process was repeated to give the estimated wear rate for each studied sample. For example, the Neolithic sample had a mean difference in average crown height (CH) of -0.73 mm between the ManM1 and ManM2. Dividing this mean difference by 6 years produced an estimated CH wear rate of 0.12mm lost per year for Neolithic adult individuals, following the Modified Miles Method.

Plots show the calculated rates of wear (y-axis) against years of functional age (x-axis). Following the Modified Miles Method, it was assumed that molars within a pair wore at a similar rate, i.e. they had a ratio of 1:1, and that this was linear with age. Estimated wear rates were produced CH, CI, and WS wear measurements. Section 7.2 showed a difference in %DE wear rate across the first, second and third mandibular molars. Thus, estimated wear rates were not produced for the %DE wear measurement.

A one-way analysis of variance (ANOVA) examined whether there was a significant difference between estimated adult wear rate between samples for the CH and CI wear measurements. A Kruskal-Wallis test examined the differences between samples for the WS measurement.

Null hypothesis: adult individuals have a similar rate of wear across temporal samples

It is expected that:

- temporal samples will have a similar adult dental wear rate

Average crown height (CH)

Section 7.2 showed the difference between ManM1 CH and ManM2 CH remained constant regardless of ManM1 CH, indicating a similar rate of CH wear on both molars. This was true for the majority of the temporal samples. The Bronze Age and Romano-British samples showed a slight increase in CH difference between the ManM1 and ManM2 with a decrease in ManM1 CH, however, the data points fell close to the line of equal wear indicating only a slight difference in wear rate between molars. For the purpose of this analysis, and following Gilmore and Grote (2012), all studied samples were assumed to have a wear gradient of 1:1.

The Iron Age sample had the smallest mean difference between the ManM1 and ManM2 CH of 0.35mm, while the Neolithic sample had the largest of 0.73mm (Table 7.4.15). This indicates the Iron Age sample had a relatively slow wear rate, while the Neolithic sample had a relatively fast rate of CH wear. Mean CH difference was divided by 6 years, producing an estimated rate of wear for each studied sample (Table 7.4.16). Estimated rate of wear ranged from 0.06-0.12mm loss in CH per year following the Modified Miles Method. However, an ANOVA indicates there was no significant difference in wear rates ($F=1.58$, $p=0.152$). Figure 7.4.21 plots the estimated rate of wear upon the ManM1 as:

CH wear = starting CH – estimated wear rate*functional years of wear.

Table 7.4.15. Mean average crown height (CH) difference between the first (ManM1) and second (ManM2) mandibular molars by temporal sample

Sample	n pairs	Mean difference between ManM1 and ManM2 CH (mm)	Standard Deviation (mm)
Neolithic	51	-0.73	0.84
Bronze Age	51	-0.45	0.45
Iron Age	50	-0.35	0.56
Romano-British	52	-0.54	0.65
Anglo-Saxon	62	-0.44	0.77
Medieval	39	-0.51	0.68
Post-Medieval	34	-0.44	0.63

Table 7.4.16. Mean starting average crown height (CH) for unworn molars and estimated rate of CH wear.

Sample	ManM1 starting CH		Estimated rate of CH wear (mm/year)	Equation for plotting estimated CH rate of wear upon the ManM1
	n	Mean ± 1SD		
Neolithic	3	6.72 ± 0.90	-0.12	CH wear = 6.72 - 0.12*functional years of wear
Bronze Age	7	6.18 ± 0.74	-0.07	CH wear = 6.18 - 0.07*functional years of wear
Iron Age	3	6.48 ± 0.54	-0.06	CH wear = 6.48 - 0.06*functional years of wear
Romano-British	2	6.55 ± 0.57	-0.09	CH wear = 6.55 - 0.09*functional years of wear
Anglo-Saxon	2	6.67 ± 0.10	-0.07	CH wear = 6.67 - 0.07*functional years of wear
Medieval	3	6.70 ± 0.20	-0.07	CH wear = 6.70 - 0.07*functional years of wear
Post-Medieval	4	6.37 ± 0.20	-0.07	CH wear = 6.37 - 0.07*functional years of wear

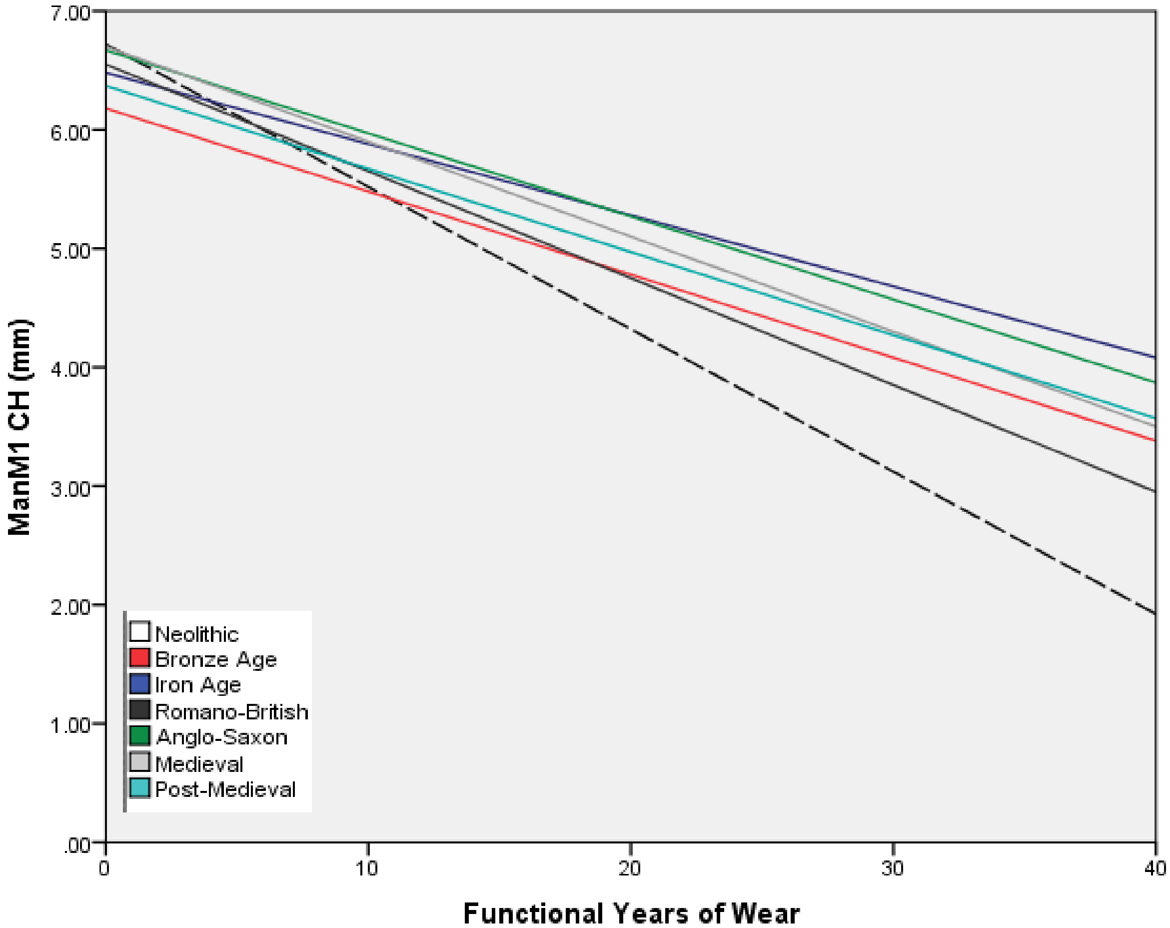


Figure 7.4.21. Estimated rates of wear following Gilmore and Grote (2012) for average crown height (CH) upon the first mandibular molar (ManM1) by temporal sample.

These results support the use of a single wear rate to estimate age of individuals dating to multiple British archaeological periods. However, population-specific dental wear rates are recommended to obtain the most reliable age estimates.

Crown Index (CI)

Section 7.2 showed CI difference between ManM1 and ManM2 remained constant in relation to ManM1 CI. This was true for all samples except the Medieval and Post-Medieval samples, which showed an increase in CI with a decrease in ManM1 CI. However, the data points for the Medieval and Post-Medieval samples fell close to the line of equal wear suggesting the difference in wear rate on the ManM1 and ManM2 was not great. For the purpose of this analysis, and following Gilmore and Grote (2012), all studied samples were assumed to have a wear gradient of 1:1.

The Anglo-Saxon sample had the smallest mean CI difference between the ManM1 and ManM2 of 4.35 CI. The Bronze Age sample had the largest of 7.78 CI (Table 7.4.17). Mean CI difference was divided by 6 years, producing an estimated rate of wear (Table 7.4.18). Estimated rate of wear ranged from 0.73-1.30 loss in CI per year following the Modified Miles method. The Anglo-Saxon sample had the slowest estimated rate of wear, while the Bronze Age sample had the fastest estimated rate of wear. However, an ANCOVA suggested these differences were not significant ($F=1.77$, $p=0.104$). Figure 7.4.22 plots the estimated CI wear rates upon the ManM1 against functional year of age was given by:

CI wear = starting CI – estimated wear rate*functional years of wear.

These results support the use of a single wear rate in methods for estimating age using dental wear, which can be applied to multiple archaeological populations. However, population-specific dental wear rates are recommended to obtain the most reliable age estimates.

Table 7.4.17. Mean crown index (CI) difference between the first (ManM1) and second (ManM2) mandibular molars by temporal sample

Sample	n pairs	Mean difference between ManM1 and ManM2 CI	Standard Deviation (mm)
Neolithic	44	-7.22	8.95
Bronze Age	47	-7.78	6.91
Iron Age	47	-4.41	6.63
Romano-British	51	-7.64	6.52
Anglo-Saxon	62	-4.35	6.31
Medieval	38	-6.09	10.26
Post-Medieval	33	-7.55	9.82

Table 7.4.18. Mean starting crown index (CI) for unworn molars and estimated rate of CI wear

Sample	ManM1 starting CI		Estimated rate of CI wear (CI/year)	Equation for plotting estimated CI rate of wear upon the ManM1
	n	Mean ± 1SD		
Neolithic	2	68.51 ± 7.70	-1.20	CI wear = 68.61 - 1.35*functional years of wear
Bronze Age	6	80.95 ± 9.38	-1.30	CI wear =80.95 - 1.30*functional years of wear
Iron Age	2	81.33 ± 7.98	-0.74	CI wear =81.33 - 0.66*functional years of wear
Romano-British	2	69.98 ± 3.39	-1.27	CI wear =69.98 - 1.48*functional years of wear
Anglo-Saxon	2	71.83 ± 8.63	-0.73	CI wear =71.83 - 0.72*functional years of wear
Medieval	3	88.04 ± 7.18	-1.02	CI wear =88.04 - 1.01*functional years of wear
Post-Medieval	4	78.26 ± 4.05	-1.26	CI wear =78.26 - 1.26*functional years of wear

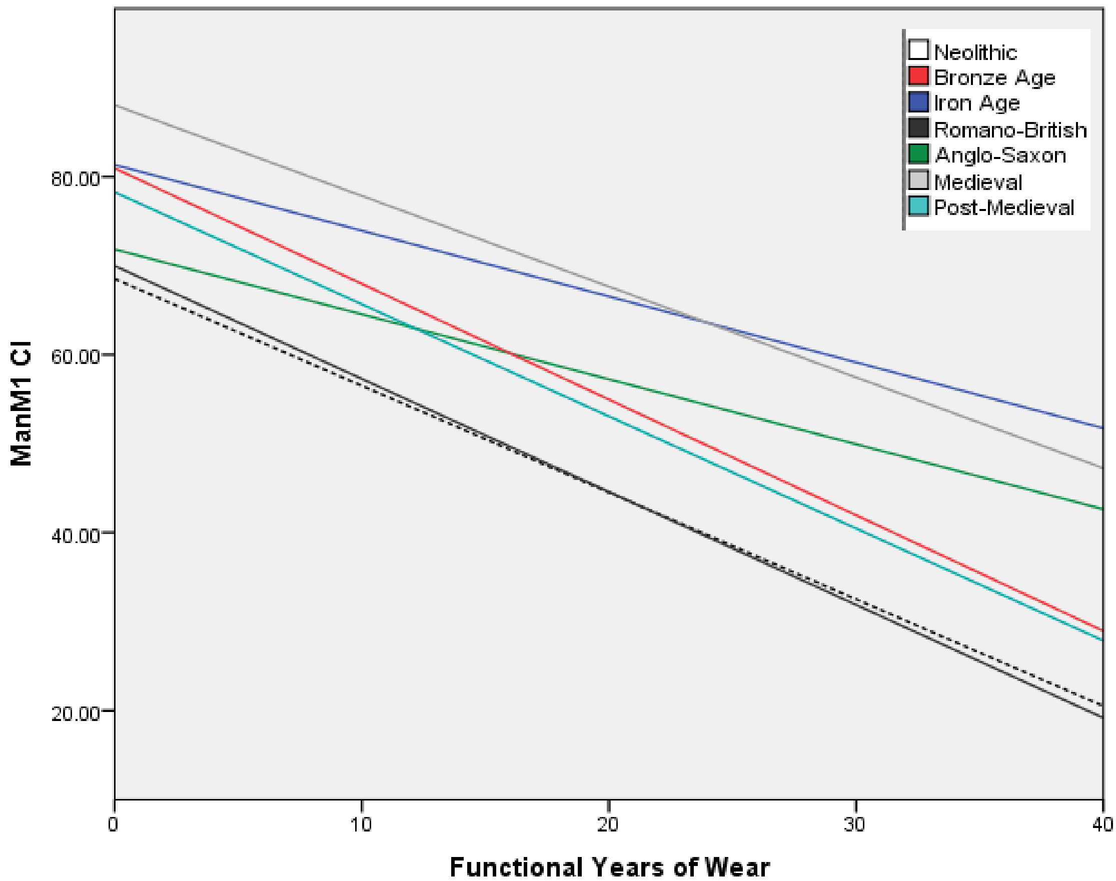


Figure 7.4.22. Estimated rates of wear following Gilmore and Grote (2012) for crown index (CI) upon the first mandibular molar (ManM1) by temporal sample.

Wear stage (WS)

Section 7.2 showed the difference between ManM1 and ManM2 WS remained constant regardless of the degree of wear on the ManM1, supporting a similar rate of WS wear on both molars. This was true for all samples studied.

Estimated WS wear rate ranged from 0.4-0.6 WS per year across temporal samples (Table 7.4.19). The Iron Age sample had the slowest wear rate, and Neolithic had the fastest. Plotting the estimated WS wear rates upon the ManM1 against functional year of age shows a broad similarity across the samples (Figure 7.4.23), given by:

WS wear = estimated wear rate*functional years of wear

All molars start life with no occlusal wear so there was no need to put in a starting stage of wear into the linear equation.

Table 7.4.19. Estimated wear stage (WS) wear rate following Gilmore and Grote (2012) using the mean difference between the first (ManM1) and second (ManM2) mandibular molars by temporal sample.

Sample	n	Mean difference (WS)	Standard Deviation (WS)	rate of wear per year (WS/year)
Neolithic	53	3.5	1.9	0.6
Bronze Age	58	2.8	1.7	0.5
Iron Age	58	2.4	2.2	0.4
Romano-British	54	2.7	1.9	0.5
Anglo-Saxon	65	3.0	1.9	0.5
Medieval	41	2.7	2.4	0.5
Post-Medieval	35	2.9	2.2	0.5

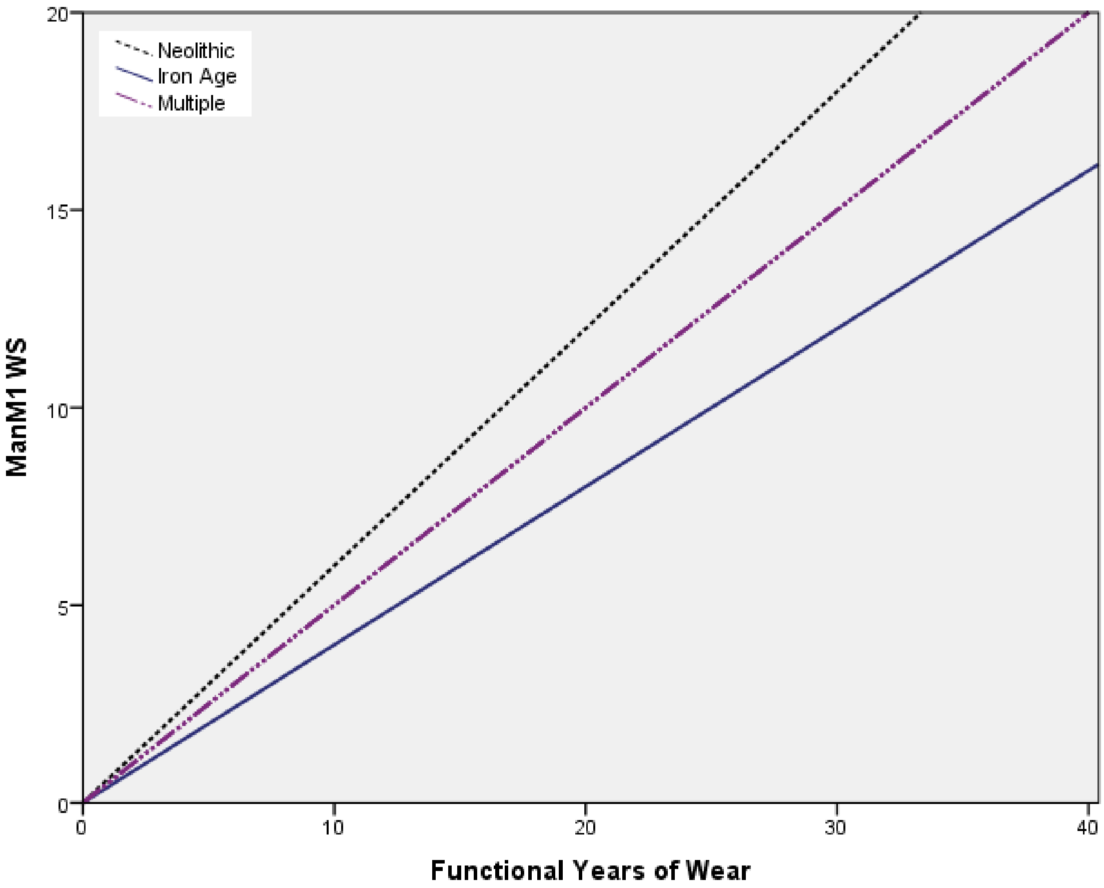


Figure 7.4.23. Estimated rates of wear by following Gilmore and Grote (2012) for wear stage (WS) upon the first mandibular molar (ManM1) temporal[a] sample.

[a] A single line represents the Bronze Age, Romano-British, Anglo-Saxon, Medieval and Post-Medieval samples, with an estimated wear rate of 0.5 WS per year.

Figure 7.4.23: shows the estimated wear rate for the Neolithic and the Iron Age samples, with an additional line illustrating the estimated wear rate for multiple samples. The Bronze Age, Romano-British, Anglo-Saxon, Medieval and Post-Medieval samples all had a wear rate of 0.5 increase in WS per year. These results indicate an overall similarly in WS wear rate between the studied samples.

Independent samples Kruskal-Wallis test was not significant (p=0.313), supporting the null hypothesis that the distribution of WS is comparable across temporal samples. Results support a similarity in WS wear rate.

These results supports the use of a single wear rate to estimate age at death for multiple British archaeological populations. However, the slight difference in estimated rates of WS wear recommend the development and use of population-specific wear rates to obtain the most reliable age estimates.

7.4.4.1 Summary: comparing adult dental wear rates

Section 7.4.4 examined the similarity in adult wear rates of the studied samples. Estimated rates of wear were produced following the Modified Miles Method, using the mean difference in wear measurements between the ManM1 and ManM2 using adult individuals. A comparison of CH, CI and WS estimated wear rates showed a similarity in wear rates. These results indicate a similar rate of wear across all temporal samples, supporting the use of a single dental wear rate to estimate age. However, slight differences in wear rate were observed between the studied samples in all wear measurements. Thus, these results support the use and development of population-specific dental wear rates for us in methods for estimating age in order to obtain the most reliable estimates of age for archaeological remains.

7.5 Producing a dental wear profile

This thesis has employed a visual diagram of seriated wear stages (Figure 6.9). While Section 7.3.2 shows this wear scale effectively tracks age estimates from pelvic indicators it does not attribute specific wear stage to any given age category. The current research has shown that the key principles of the Miles Method hold true, and thus may be used to produce an estimated actual age for each stage of wear.

The Miles Method requires physical seriation of individuals by increasing dental wear. The current study could not apply this approach as skeletal samples were curated by different institutions in varying locations. To overcome this, distributions plots with 95% confidence intervals were used. Data from all temporal samples was pooled due to their similarity in wear rate (Section 7.4).

The first step of the Miles Method identifies the rate of wear for the juvenile sample. In the current study ManM1 WS, followed by ManM2 WS, was plotted against juvenile age. These plots produced a series of skulls of 'known age' ranging from 6 to 18 years old showing the functional life of the ManM1, from the time it erupted at approximately 6 years of age to the end of its first twelve years of functional use (Figure 7.5.1A). This approach was repeated for the ManM2 to show its first six years of functional use (Figure 7.5.1B). Individuals estimated to be 18 years were identified by individuals with a ManM3 in full occlusion but with no signs of wear.

Making the assumption that the rates of wear between molars remained constant throughout the life of the dentition, confirmed by the analysis in Section 7.2, twelve years of functional wear on the ManM2 would show a similar degree of wear as twelve years of functional wear on the ManM1. Likewise, six years of wear on the ManM3 would show a similar degree of wear as six years of functional wear on the ManM1 and on the ManM2. Thus, Figure 7.5.2 shows after 12 years of functional wear the ManM1 displays WS 6. This means after 12 years of functional wear the ManM2 will also display WS 6. This information can be used to identify the ManM1 wear stage after 18 years of functional wear, as an individual with 12 years of wear on the ManM2 will have a ManM1 that has experienced 18 years of functional wear. Figure 7.5.2A shows when the ManM2 displays a WS of 6, representing 12 years of wear, the ManM1 has a WS of 10, representing the wear pattern of an individual with an estimated age of 24 years old.

The above process is repeated for progressively older individuals. For example, a ManM2 with 18 years of functional wear will have a WS of 10. This information can be used to identify the ManM1 wear stage of a 30 year old. The same process is applied to the ManM3 using Figure 7.5.4 and

Figure 7.5.3. This process of extrapolation was continued until teeth were lost ante-mortem and produced a wear profile for the pooled temporal samples (Figure 7.5.5).

Past the estimated age of 36 years, equivalent to thirty, twenty-four and eighteen functional years of wear on the ManM1, ManM2 and ManM3 respectively, estimation of wear stages became more difficult due to an increase in variation. It must be noted that the below dental profile uses relatively fine age divisions and is at risk of producing errors due to the inability to account for the observed variation in older adults (Section 7.3.2). Thus, it is recommended that dental wear ageing charts employ age ranges to account for this variation. While such an approach will decrease the precision of age estimates it will increase their reliability.

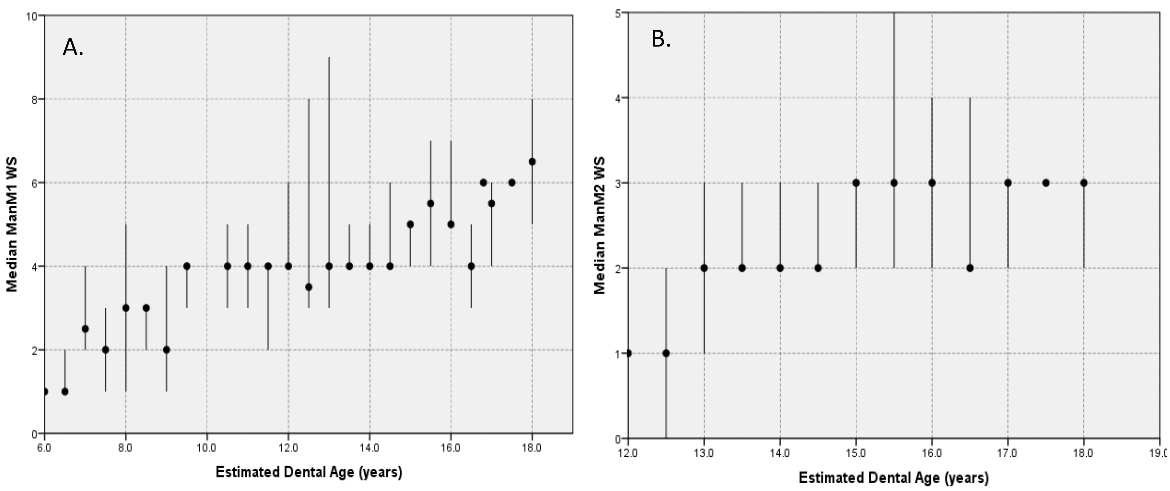


Figure 7.5.1. Median wear stage (WS) by juvenile age with all temporal samples pooled. Bars represent 95% confidence intervals. A. First mandibular molar (ManM1). B. Second mandibular molar (ManM2)

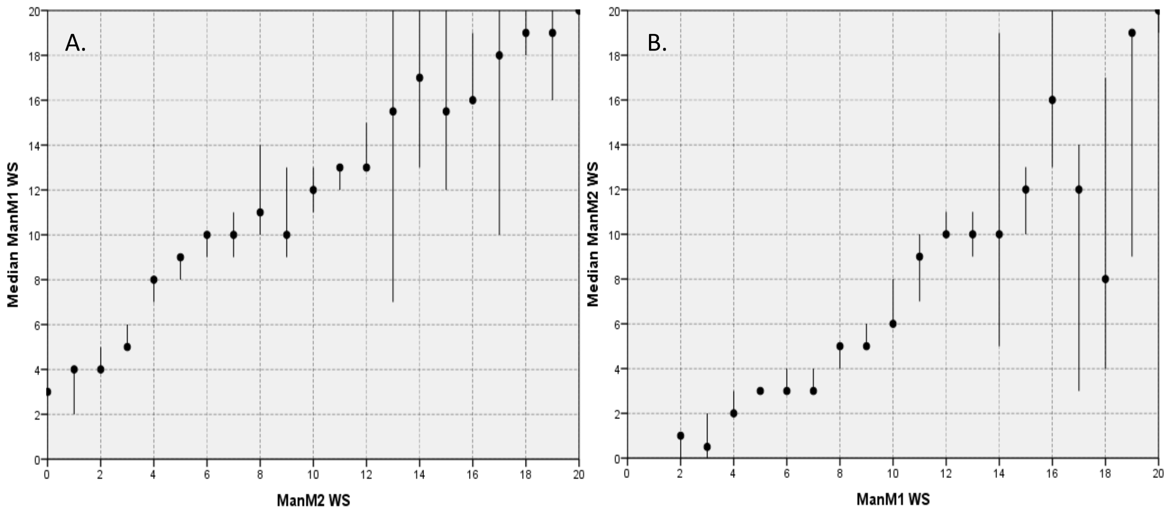


Figure 7.5.2. Wear stage (WS) distribution plots for the first (ManM1) and second (ManM2) mandibular molars. A. Median ManM1 WS against ManM2 WS. B. Median ManM2 WS against ManM1 WS.

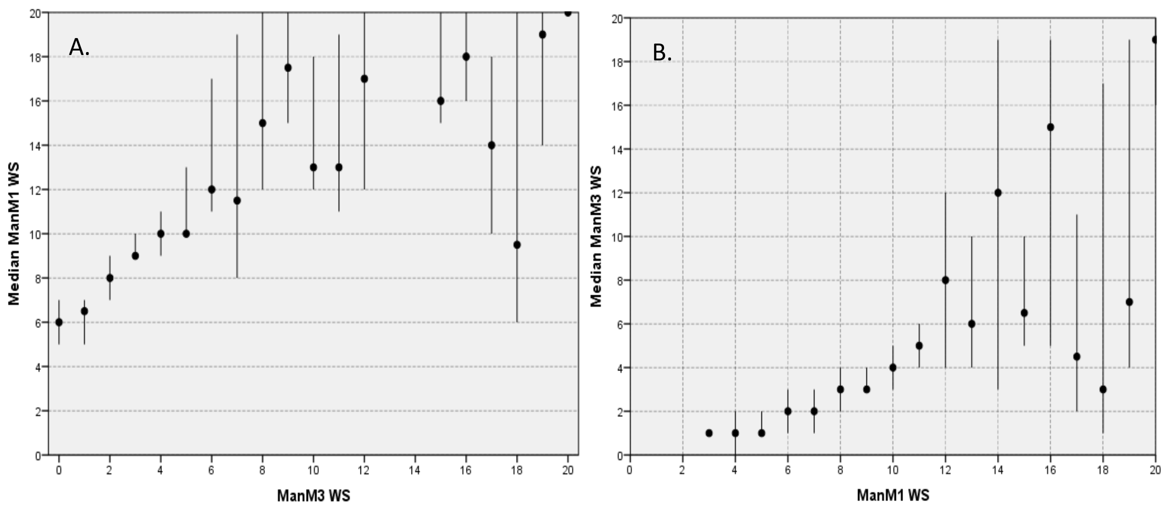


Figure 7.5.3. Wear stage (WS) distribution plots for the second (ManM1) and third (ManM3) mandibular molars. A. Median ManM1 WS against ManM3 WS. B. Median ManM3 WS against ManM1 WS.

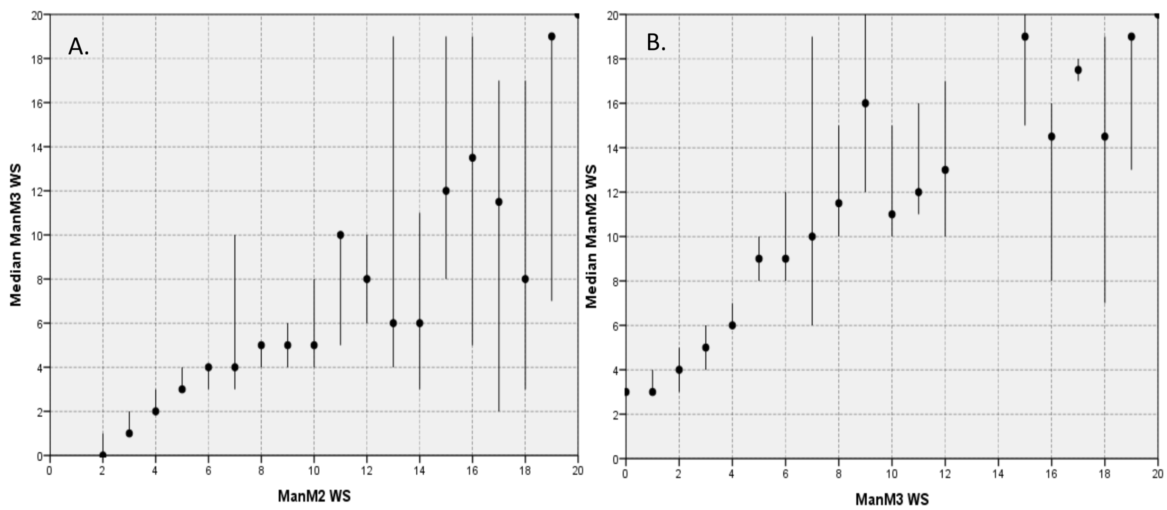


Figure 7.5.4. Wear stage (WS) distribution plots for the second (ManM2) and third (ManM3) mandibular molars. A. Median ManM3 WS against ManM2 WS. B. Median ManM2 WS against ManM3 WS.

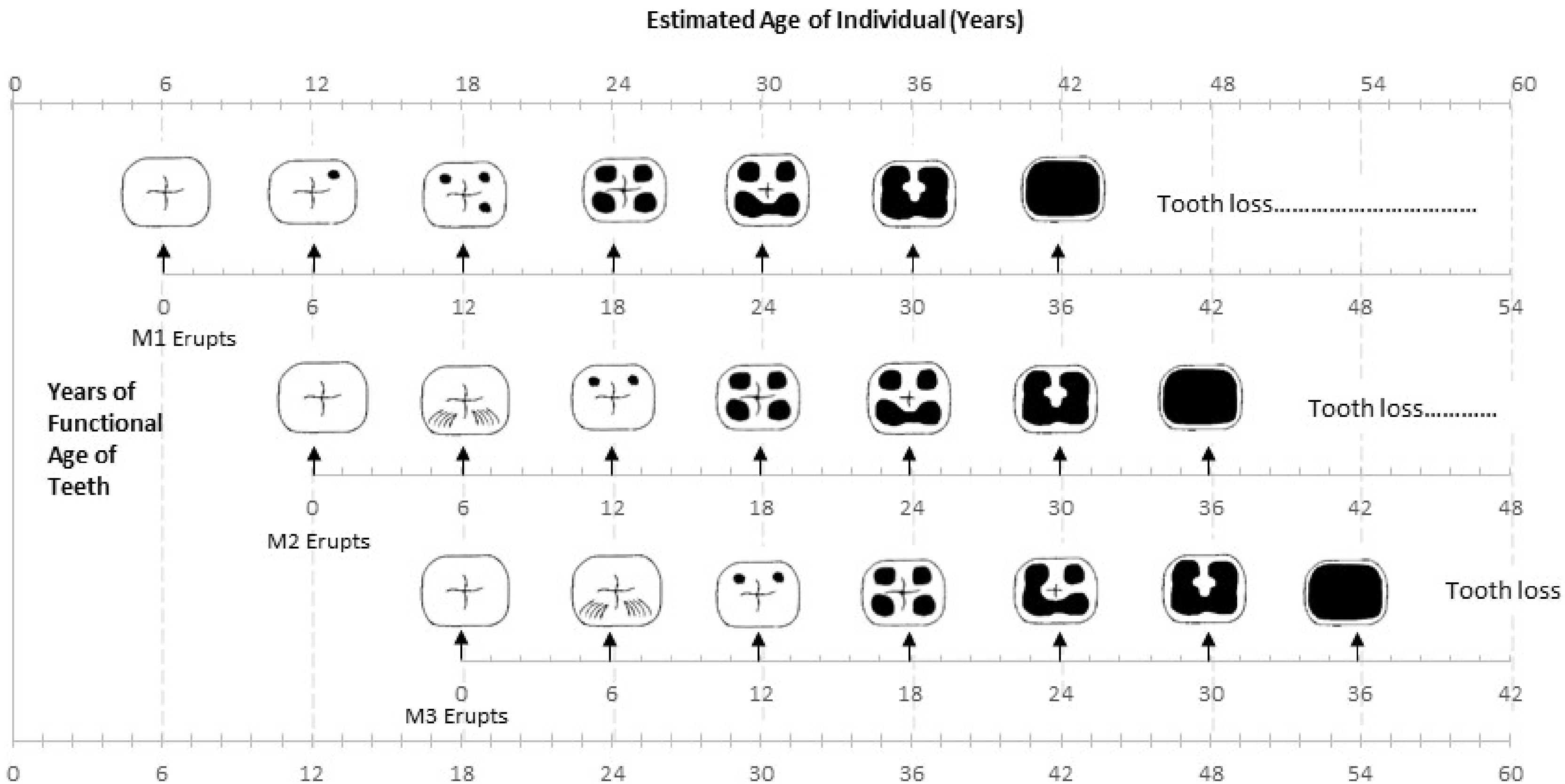


Figure 7.5.5. Diagram showing the systematic use of molar wear for age assessment. The stages of wear of the first (ManM1), second (ManM2) and third (ManM2) mandibular molars are depicted against time scales of estimated age of subject and functional age of tooth. Molars are depicted against time scales of estimated age of subject and function age of tooth.

The reliability of the dental wear profile was tested using a sample of 40 individuals with wear visible on all three molars. These individuals were selected at random from the pooled temporal samples. Age estimates obtained using the dental wear profile were compared to the age category based on bony age estimates for this random sample. It was expected that there would be a strong correlation and agreement between the dental wear age estimates and the bony age estimates.

A strong, positive, significant Spearman's correlation coefficient supports a good association between the two age estimates (r_s=0.73, $p<0.001$). 58% (23/40) individuals showed agreement between the age two age estimates. It is not possible from these results to state whether the dental profile is accurate as the individuals were of unknown age, and any disagreement in age may result from an inaccuracies of either the dental wear or the bony age estimates. However, the Spearman's correlation coefficient and degree of agreement between the two age estimates suggest the dental wear profile is still effectively tracking age estimated by traditional methods.

Section 7.5 therefore demonstrates how the Miles Method may be applied to produce a new dental wear profile for estimating age.

7.5.1 Comparing the Brothwell chart and dental wear profile

The production of a dental wear profile generated from multiple British archaeological samples allows assessment of Brothwell's (1963) chart. A level of agreement between the dental profile produced following the Miles Method (Figure 7.5.5) and Brothwell's chart provides support for the reliability of estimating age at death using Brothwell's chart. A high level of agreement, and a finding where the stages of Brothwell fall into the same age category of the dental profile, would suggest the Brothwell chart is reliable for estimate age at death.

The reliability of the Brothwell chart was tested through direct comparison to the dental profile produced in this thesis. The two charts were recreated in the style of Brothwell (1963 p69) and placed side-by-side (Figure 7.5.6). The wear stages that fell within each age category were then compared through simple observation.

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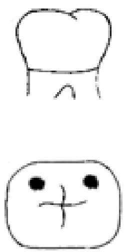
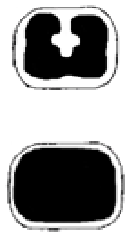
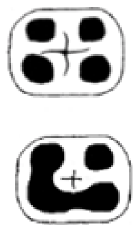
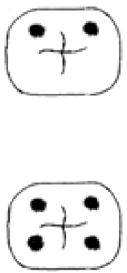
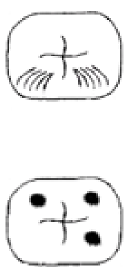
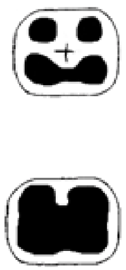
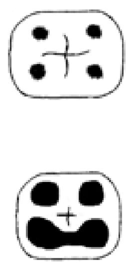
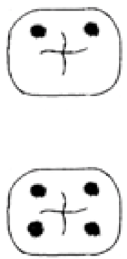
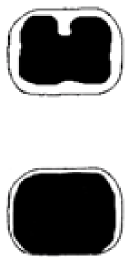
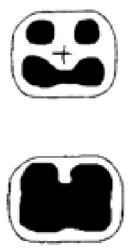
	M1	M2	M3	M1	M2	M3	M1	M2	M3	
Combined			Dentine not exposed. There may be some enamel polishing							Any greater degree of wear than in the previous columns.
	M1	M2	M3	M1	M2	M3	M1	M2	M3	
Brothwell			Dentine not exposed. There may be some enamel polishing							Any greater degree of wear than in the previous columns.

Figure 7.5.6. Dental wear stages with associated age category for the Combined Chart and Brothwell chart.
Molar types: M1 = first mandibular molar, M2 = second mandibular molar, M3 = third mandibular molar

Figure 7.5.6 show a good agreement between the dental profile and Brothwell chart in the 17-25 age category showed. Both charts showed a similarity in wear stage, with a maximum of four discrete areas of exposed dentine on the first molar, and two-to-three areas of exposed dentine on the second molar. 17-25 year old individuals showed wear confined to the enamel on the third molar in both the dental wear profile and Brothwell's chart.

The Miles Method only provides an estimated wear stage for the 25-35 age group, for an individual of an estimated age of 30 years old. The wear stage given for each molar type compares well to those provided in the Brothwell chart for the same age group.

The 35-45 year age group shows some agreement between the two dental wear charts, although Brothwell's chart shows a slightly higher wear stage compared to the produced dental profile. For example, the first molar shows a small island of remaining enamel for individuals within this age group but the Brothwell chart includes a pattern of wear of a rim of remaining enamel, which may be breached. It may be argued that the Brothwell chart represents a slightly higher wear rate in older individuals compared to the sample used in the current study. However, the distribution plots for wear stage by age category in Section 7.3.2 showed the wear pattern became increasingly varied in older individuals in each temporal samples. Furthermore, Section 7.4 demonstrated that the wear pattern became varied between temporal samples in the Mature and Older Adult age groups. This increase in variation both within and between the studied samples indicates suggest using a few stages of wear to depict these older age groups is unreliable. The differences observed between the produced dental profile and the Brothwell chart may therefore be a result of an increase in variation, rather a difference in wear rate.

The similarity observed between the Brothwell chart and the produced dental wear profile suggest dental wear charts are reliable for estimating age, although it is a system of decreasing accuracy. This means dental wear charts will be reliable for estimating age of individuals up to the age of 35 years, but is likely to decrease in reliability for ageing older individuals. The production of population-specific dental wear profiles may improve the reliability of both the Brothwell chart and the produced dental profile. Additionally, ante-mortem tooth loss (AMTL) may be considered as a marker for older individuals. Figure 7.4.2 showed the majority of individuals estimated than to be older than 45 years old had lost their first mandibular molar ante-mortem. These findings suggest that additional factors of the ageing process may be required alongside dental wear in order to obtain the most reliable age estimates for older individuals.

The comparison of the produced dental wear chart and Brothwell's chart is not perfect. It is unclear whether Brothwell included all molar types in his dental wear chart, potentially increasing the variation the chart had to include. The produced dental profile included only mandibular molar wear, although comparison tests to upper molars revealed little difference in the dental wear pattern (Section 7.1.2). It is also unclear how Brothwell combined individuals dating to multiple periods, or how Brothwell assigned individuals into any age group. None the less, a comparison of the Brothwell chart to the produced chart using a well-documented sample and clearly defined methodology indicates Brothwell's chart is reliable, at least for estimating age of individuals up to the age of 35 years.

7.6 Summary

This chapter has presented the results under several headings, each related to examining and testing the use of dental wear as a tool for estimating age at death in British archaeological remains.

To summarise, three key underlying principles of three dental wear ageing methods were tested and validated using a large sample of skeletal remains dating from the British Neolithic to the Post-medieval periods. The entire wear process was examined in a more precise manner than with traditional, ordinal methods using four wear measurements to record dental wear. The results from this thesis support the continued use of dental wear to estimate age of archaeological remains.

A comparison of dental wear rates between molars of the same types supports the substitution of one molar for its antimere if missing. While occlusal partners have a similar rate of wear a difference in crown height suggests dental wear on either the maxillary molars or the mandibular molars should be used for estimating age. Due to the relatively smaller degree of measurement error associated with recording dental wear, and a potentially closer relationship between dental wear with age, this thesis recommends age is estimated from dental wear observed on the mandibular molars.

A comparison of dental wear rates between mandibular molars along the tooth row indicated a similar wear rate in the first and second mandibular molars, with a relatively slower wear rate in the third mandibular molars. However, this thesis argued this difference in wear rate was not great. Additionally, molar wear rates remained constant in relation to one another throughout the life of the dentition, supporting a key principle of the Miles Method and Modified Miles Method.

Section 7.3 confirmed the presence of a relationship between dental wear and age within the studied sample, supporting the use of dental wear as an ageing method in archaeological populations. A comparison of wear rates between temporal samples supports an overall similarity in wear rate. These results indicate Brothwell's conclusion, that a single wear rate can be applied to estimate age in multiple British archaeological periods, is valid. As a result, a new dental wear profile was presented following the Miles Methods, pooling temporal samples. A comparison of this new chart with Brothwell's indicated Brothwell's chart is reliable for estimating age, but is a system of decreasing accuracy.

This thesis, however, recommends the development and use of population-specific wear rates for estimating age. While Section 7.4.1.3 indicated ante-mortem tooth loss had little effect on dental wear rates, a comparison of AMTL frequency indicated AMTL rate increased through time. Furthermore, a comparison of wear distributions between temporal samples showed wear patterns differed in older individuals. Finally, a difference in starting crown height of unworn molars indicates some difference in tooth morphology between archaeological populations. These differences have the potential to decrease the reliability of age estimates when using a single dental wear chart.

Chapter 8 Discussion

8.1 Introduction

Estimating age at death is fundamental to the fields of archaeology and anthropology, and although the ageing of adult remains is fraught with issues (Chapter 2), past studies have found dental wear correlates well with both known age and bony age estimates. However, previous tests of reliability fail to evaluate the underlying principles of dental wear ageing methods. Thus, this thesis aimed to re-evaluate the use of dental wear as an ageing method for British archaeological skeletal remains through the examination of these underlying principles.

The thesis identified and examined three underlying principles of three key methods for estimating age using dental wear: the Brothwell chart (Brothwell 1963, 1972a, 1981), the Miles Method (Miles 1962), and the Modified Miles Method (Gilmore and Grote 2012). Recording dental wear using ordinal and ratio measurements permitted a thorough investigation of the dental wear process, and the production of dental wear rates for multiple archaeological samples. Drawing on Chapter 7's findings, the extent to which dental wear can be considered a valid method for estimating age at death in skeletal remains will now be discussed.

Four research questions were outlined in Chapter 1, alongside proposed hypotheses in Chapter 6. The interpretation of each of these questions using the results presented in Chapter 7 will be discussed in this section. Before a discussion of the results a review of the methods employed to measure dental wear is provided.

8.2 A review of the dental wear measurements

The present study measured dental wear using four techniques permitting an examination of the relationship between dental wear and age on both the crown height and the occlusal surface. This section will review each technique in turn, evaluating their strengths and weaknesses, and their contribution to estimating age at death of archaeological remains.

8.2.1 Crown height measurements

Two approaches measured molar crown height: average crown height (CH) and crown index (CI). A key strength of these techniques is the ability to measure dental wear as a quantitative measurement, thereby removing the subjective nature of traditional methods (Chapter 4). As a result, robust statistical tests can be applied, such as regression analysis, and estimated dental wear rates can be produced. Dental wear and its relationship with age may therefore be examined in a more precise manner than when using traditional ordinal data.

Crown height measurements were quick and simple methods for recording dental wear, allowing many individuals to be processed quickly, adding minimal recording time to the dental inventory. Tests of repeatability showed CH and CI measurements were associated with low repeatability error (Section 6.3), indicating a low contribution to the overall variance within a sample. The repeatability of crown height measurements and their objective nature allows for cross-comparison studies of dental wear rates. This is a distinct advantage over traditional methods of recording wear, where multiple iterations of ordinal scales exist making cross-comparison studies difficult.

Of the two crown height measurements, CH has an advantage over CI. Although CI showed a significant, negative relationship with dental age across the mandibular molars, it is more time and resource expensive compared with the CH measurement. CH, thus, may be more beneficial for researchers with limited time and resources. Furthermore, CI measurements showed a greater degree of measurement error in tests of repeatability compared with CH measurements (Section 6.3.2.2). This has the potential to introduce additional variation into CI measurements, reducing its reliability when used in methods for estimating age at death.

Although crown height measurements can produce estimated rates of dental wear, age estimation for a single individual may be difficult. Unlike ordinal wear stages, where a wear stage on a single individual can be used to produce a dental wear chart, crown height measurements cannot. Section 7.4 showed archaeological populations differed in their starting crown height, therefore taking CH from a single individual and comparing this to a line of estimated CH wear will only be reliable when starting crown height of a population is taken into account. If the initial crown height in individuals could be reliably estimated, the removed crown height could be inferred and used to estimate age. Further study is required to explore how individual crown height data may be used to estimate age, and to consider how unworn teeth may differ from one another not only in size but also in shape. However, this thesis has demonstrated the potential value of crown height in the study of estimating age at death.

8.2.2 Occlusal wear measurements

Recording the percent of exposed dentine (%DE) was simple and allowed a quantitative measurement of exposed dentine on the occlusal surface of molars. However, few juvenile individuals had exposed dentine on either their first or second molars, meaning %DE dental wear rates could not be calculated for this age group. Furthermore, estimated adult %DE wear rates could not be calculated following the Modified Miles method for any samples in this thesis due to a difference in wear rate between the first and second molar (Section 7.2). These finding suggest %DE may be of limited use for estimating age at death.

Although %DE may not be able to produce estimated rates of dental wear for archaeological individuals, it can be employed to compare dental wear patterns. Using this method for recording dental wear, Clement and Hillson (2012) demonstrated the Igloolik Inuit of Canada (a recent hunter-gatherer group) possessed a pattern of extremely heavy anterior tooth wear, relative to the posterior teeth. The authors also identified statistically significant differences between wear patterns of males and females, which were attributed to sexual division of labour within the population. Thus, comparing %DE ratios can examine intra- and inter- population variation in dental wear patterns more precisely than traditional ordinal scales.

%DE may be a useful tool for evaluating stages of wear. In a study examining the dental wear on deciduous molars, Mays and Pett (2014) provided summary statistics for CI split by wear stage (WS). A similar approach may be applied using %DE to determine whether stages of wear are quantitatively equal across different molar types; for example, does a wear stage representing two discrete areas of exposed dentine on the first mandibular molar equal the same %DE as two discrete areas of exposed dentine on the ManM2. Such an approach would permit robust statistical analysis, as well as presenting a more accurate representation of exposed dentine. Therefore, %DE has the potential to be a precise tool for evaluating wear patterns rather than as a tool for estimating age at death in archaeological populations.

An ordinal scale was the second occlusal wear measurement to be employed in the current thesis. Stages of wear are the most frequently employed technique for recording dental wear (Chapter 5). Ordinal scales are simple to use but are highly subjective in the number of stages used, and therefore vary in the degree of detail they capture. This thesis combined the wear stages of Brothwell (1963) with the diagrams and descriptions of Murphy (1959a), as well as stages to capture wear on the enamel before any dentine is exposed, and to record ante-mortem tooth loss (AMTL). While this unique chart makes further cross-comparison studies difficult it recorded the dental wear process in greater detail, and allowed comparison with Brothwell's chart. The inability to perform cross-comparison studies is an issue inherent in all studies using an ordinal scale to record dental wear. It is clear an extensive review of existing dental wear scales is required to a scale appropriate for recording dental wear and estimating age at death across populations.

Few ordinal wear scales record dental wear that is confined to the enamel, before any dentine is exposed. AMTL is also rarely recorded in traditional ordinal scales. This thesis supports the inclusion of both conditions into ordinal scales. Section 7.3.1 showed few juvenile individuals had any exposed dentine on their molars. The ability to record enamel wear using the ordinal scale allowed a more precise assessment of juvenile dental wear, a key step in the Miles Method. AMTL is frequently recorded in a dental inventory, but it is rarely examined in relation to the dental wear process. While the current study found little evidence of the effect of AMTL on the rate of dental wear, it is an area that requires further exploration. Furthermore, AMTL is age progressive and, thus, has the potential as a marker of old age.

Although stages of wear are somewhat problematic for recording dental wear due to their subjective nature, they have their place for estimating age at death in human remains. The Miles Method has been found to be reliable for estimating age in populations with a large sample of juveniles (Nowell 1978; Kieser et al. 1983; Santini et al. 2017), while the Modified Miles Method offers a technique for estimating age in skeletal samples consisting of only adult remains. In addition, ordinal scales are easy to apply in the field and provide a simple method for inexperienced archaeologists. Further work is required, however, to identify a series of wear stages that truly reflects the continuous process of dental wear, and that best tracks the relationship with age.

8.3 Wear on molars of the same type

Research Question 1: do molars of the same type wear at a similar rate?

Neither Brothwell (1963) or Miles (1962) explicitly state whether their dental charts represent the left or right molars, or if they represent both the maxillary and mandibular molars. The Modified Miles Method averages the wear score of upper and lower molars, with dental wear only recorded for the left side unless lost. Thus, these three methods assume molars of the same type wear at a similar rate. This assumption was tested in the current thesis by comparing dental wear rates of left-right molar pairs by molar type, followed by a comparison of dental wear rates of occlusal pairs by molar type.

8.3.1 Left-right molar pairs

H_0: left and right molar partners wear at a similar rate

H_1: left and right molar partners do not wear at a similar rate

Section 7.1.1 showed left-right molar pairs had similar crown height and occlusal wear measurements. The difference between wear measurements in a left-right molar pair remained constant, falling around the line of equality (y=0). This pattern was observed across all molar types and all temporal samples. These results support the null hypothesis that left-right molar pairs wear at a similar rate. The similarity of wear rate between left-right molar pairs supports findings of previous work (Hojo 1954; Murphy 1959a; Lovejoy 1985; Santini et al. 1990; Clement 2008; Deter 2009; Esclassan et al. 2009).

A similarity in wear rate between left-right molar pairs supports the traditional method of scoring dental wear from one side of the dental arcade, substituting for its antimere when missing (Hinton 1982; Mays 2002; Benazzi et al. 2008; Gilmore and Grote 2012). This approach is advantageous for recording dental wear in fragmentary remains, allowing sample sizes to be maximized.

8.3.2 Occlusal molar pairs

H_0: Occlusal molar partners wear at a similar rate

H_1: Occlusal molar partners do not wear at a similar rate

Comparing dental wear in upper and lower molars showed an overall difference in crown height between occlusal partners, but a similarity in occlusal wear measurements (Section 7.1.2). Average crown height (CH) was relatively larger in mandibular molars compared with their maxillary partner, while maxillary molars had a larger crown index (CI) compared to their mandibular partner. However, the wear difference between occlusal partners remained constant for all wear measurements, indicating a similar rate of wear. These results suggest differences in dental wear were a result of a difference in crown height and shape between upper and lower molars, rather than a difference in dental wear rate. A constant difference indicates upper and lower molar partners differed in crown starting crown height, producing a difference that remained throughout the life of the dentition.

A similarity of rate of wear in occlusal partners is consistent with previous findings. Using a methodology involving gradients of exposed dentine, Lavelle (1970) reported no significant difference between molars across multiple populations. Other studies have noted a similarity in the degree of exposed dentine between occlusal partners in non-British archaeological populations (Dreier 1994; Esclassan et al. 2009). A comparison of average crown height for the Romano-British population of Poundbury, Dorset, also indicated maxillary and mandibular occlusal partners wore at a fairly similar rate (Mays et al. 1995). However, this pattern is not universal with some studies reporting a difference in wear rate between occlusal partners (Murphy 1959b; Molnar 1971b; Lunt 1978b; Molnar et al. 1983b; Lovejoy 1985; Gilmore and Grote 2012).

Occlusal partners clearly differ in their size and shape. Maxillary molars are larger in the buccolingual dimensions, compared to the mandibular molars (Kieser 1990a; Grine 2002; Smith et al. 2006), whereas mandibular molars are larger in their mesiodistal length (Kieser 1990a). Furthermore, using a sample of modern human molars, Smith et al (2006) identified significant differences in enamel thickness and dentine area between occlusal partners, with the upper molars consistently showing greater values compared to their mandibular partner. This difference appears to be consistent across populations, supported by all temporal samples showing larger CI and smaller CH measurements in the maxillary molars (Section 7.1). It is therefore expected that all studies comparing occlusal wear rates will show the same pattern. However, this is not the case.

While some studies identified a faster wear rate in mandibular molars (Murphy 1959b; Lunt 1978b; Molnar et al. 1983b; Lovejoy 1985), others show a faster wear rate in the maxillary molars (Molnar 1971b; Gilmore and Grote 2012). Due to the use of varying methods to record dental wear and variation in the samples employed it is not possible to identify a reason for this inconsistency across the studies. However, none of the aforementioned studies state the difference in occlusal partner wear rates is significant. Conclusions were made through visual observations and simple comparisons. It is therefore unclear whether the difference between wear rates was great. None theless, these studies support inspection of upper and lower wear rates before a single wear rate is applied to all molars to estimate age.

Traditionally, dental wear is either recorded solely on the mandibular molars (Helm and Prydso 1979; Mahoney 2006; Grimoud and Gibbon 2017), or on both the maxillary and mandibular molars (Murphy 1959a; Lovejoy 1985; Benfer and Edwards 1991; Mays 2002; Benazzi et al. 2008). Rarely, wear measurements from occlusal partners are combined to produce an average dental wear score for each molar type (Gilmore and Grote 2012). To my knowledge, a molar is not substituted for its occlusal partner when missing. The results from this thesis suggest the wear rate obtained from a first mandibular molar may be applied to the first maxillary molar, and vice versa, therefore producing a similar estimate of age. However, it may be asked; *which set of molars is more reliable for estimating age?*

At the time of writing, no study has been found indicating maxillary molars are more reliable than mandibular molars for estimating age. Previous studies reported similar age estimates when examining either the upper or lower molars (Nowell 1978; Molnar et al. 1983a; Kim et al. 2000), while others have identified a closer relationship with age in the lower molar wear patterns. For example, using a modern, high-attrition population from South America, Kieser et al. (1983) found estimated age from mandibular molars correlated better with actual age rather than with age estimates derived from the maxillary molars. Mays (2002) reported similar results, where Pearson correlation coefficients between average crown height and known age ranged between -0.33 to -0.37 for the maxillary molars, compared with -0.57 to -0.63 for the mandibular molars, in a 19th Century Dutch sample of documented age. These studies suggest age estimates based on dental wear of the mandibular molars bears a closer relationship with age, and thus are more reliable for estimating age at death. Furthermore, the current study showed the typical degree of measurement error when recording dental wear was markedly lower in the mandibular molars compared with the maxillary molars (Chapter 6.2). This means the degree of error expected to incur when taking a measurement was greater for the maxillary molars than the mandibular molars. Thus, mandibular dental wear measurements are associated with a smaller degree of error, potentially producing more reliable age estimates.

This thesis, therefore, recommends recording dental wear from molars from one side of the mandible, substituting for its antimere when missing. Dental wear rates from the mandibular molars may be tentatively applied to the maxillary molars only when a similarity in wear rates between occlusal partners has been confirmed.

8.4 Wear rates across molar types

Research Question 2: Do all molar types have a similar rate of wear?

The use of dental wear to estimate age at death relies on the presence of a wear relationship between molars along the tooth row. Miles (1962) concluded molars wore at a slightly different rate, while Gilmore and Grote (2012) assumed all molar types wore at a similar rate. Both methods assume that the ratio of wear rates between molars remains constant through the life of the dentition. This thesis examined the wear relationship between molar regions by plotting the earlier erupting molar against the later erupting molars (Chapter 7.2). This analysis examined whether molars wear at a similar rate and whether the gradient between molars remained constant.

8.4.1 Relationship between molars along the tooth row

The relationship between molar regions was examined before comparing wear rates along the tooth row. As expected, the first mandibular molar (ManM1) showed a higher degree of wear compared with the second mandibular molar (ManM2), and the second molar had a higher degree of wear compared with the third mandibular molar (ManM3). The current study also identified a relationship between molar pairs along the tooth row, where an increase in wear on one molar was associated with an increase in wear on a later erupting molar (Section 7.2). The strongest wear relationship was observed between the ManM1 and ManM2, across all wear measurements, while the ManM1-ManM3 had the weakest relationship. These results are consistent with previous findings (Benfer and Edwards 1991; Mays et al. 1995; Gilmore and Grote 2012).

The variable nature of the third molar may explain the relatively poor wear relationship between the ManM3 and the earlier erupting molars. Multiple studies have found the third molar to be the most variable in terms of size, shape and eruption times (Garn et al. 1962; Thorson and Hagg 1991; Mincer et al. 1993; Solari and Abramovitch 2002). In a study of 321 individuals from three archaeological sites in the Xi'an region, northern China, third mandibular molars showed a larger coefficient of variation (the ratio of the standard deviation to the mean) in mesiodistal, buccolingual, and root length compared with the first and second mandibular molars (Huang et al. 2012). This supports the consistently higher standard deviations (SD) of mesiodistal and buccolingual lengths of third molars provided in Kieser (1990a).

The ManM3 also shows a higher degree of variability in its development and formation compared to the earlier erupting molars. Using radiographs of 1050 healthy dental patients from London, aged between 2 and 22 years old, Liversidge (2009) identified a higher SD associated with mean age for entering a stage of molar development in the third molar compared to the first or second molars. Finally, eruption times for the third molar are more variable compared to the earlier erupting molars. Average age of clinical eruption of third mandibular molar is between 16 and 20 years of age, with a SD of around 2 years, based on a review of previous studies using world-wide populations (Liversidge 2008). This compares to an eruption age of between 5-7 years old ± 1 year for the first molar, and an eruption age of between 11-12 years old ± 1 year for the second molar, in a large sample of African and Asian living children (Hassanali and Odhiambo 1981). The variation in ManM3 is likely to result in a higher degree of variation in dental wear measurements, producing a weaker relationship with the earlier erupting molars.

The effect of ManM1 ante-mortem tooth loss (AMTL) may also explain the comparatively weaker relationship observed between ManM1 and ManM3. The ManM3 WS plots show the majority of individuals had a wear stage of 5 (two discrete areas of exposed dentine) or less (Figure 7.2.3.13). Individuals with a higher stage of wear on the ManM3 had typically lost their ManM1 ante-mortem, meaning only a small part of the relationship between the ManM1 and ManM3 could be examined. The effect of AMTL was also observed in the %DE measurement. The amount of %DE exposed on the ManM3 was low, with the majority of individuals showing less than 20%DE. This means only a small part of the relationship between the ManM1 %DE and ManM3 %DE was observed, and may provide some explanation for the poor correlations between ManM1 and ManM3 wear measurements.

The loss of a ManM1 ante-mortem means the higher stages of wear on the later erupting molar could not be examined in relation to wear rate, making it difficult to state with certainty what happens to the ManM3 at higher degrees of wear. This, along with the increased variability of the ManM3, indicates age estimates produced using the ManM3 will be less reliable than those produced using the ManM1 or ManM2. Thus, this thesis recommends using the ManM1-ManM2 wear relationship to estimate age, with the ManM2-ManM3 and ManM1-ManM3 relationship to support any conclusions.

8.4.2 Comparing wear rates between molar types

H_0: there is a similar rate of wear between molar types

H_1: there is a different rate of wear between molar types

A comparison of dental wear rates between the mandibular molars revealed an overall difference in wear rate. First and second molars showed a similar wear rate for the CH, CI and WS measurements, but a difference in %DE wear rate. This wear relationship was observed in all temporal samples (Section 7.2). All temporal samples had a relatively slower WS wear rate in the third molar compared with both the first and second molars. In contrast, some of the studied samples showed a relatively slower wear rate for the crown height measurements in the ManM3 compared to the ManM1 or ManM2, while others had a similar rate of wear across all molars. For example, the Bronze Age sample showed a difference in CH wear rate for the second and third molars, while the Neolithic had a similar rate of CH wear across all three molars. All molars in all temporal samples showed a difference in %DE wear rate.

The results of Section 7.2 reject the null hypothesis that all molar types have a similar rate of wear. The results from the current study indicate a similar wear rate in the first and second molars for the CH, CI and WS measurements, with a difference in the third molar. These results are similar to previous work. Using a large sample of medieval Danes, Helm and Prydso (1979) observed a similar rate of attrition for the first and second molar but a relatively slower rate of wear in the third molar. This is in contrast to some studies showing more rapid wear on the first molar compared with the later erupting molars (Miles 1962; Akpata 1975; Santini et al. 1990). However, this difference in molar wear rates is not universal, with other studies finding no difference in molar wear rates (Nowell 1978; Dreier 1994; Mays 2002).

Previous work has demonstrated molars along the tooth row vary in their size and shape. For example, upper and lower molars showed a decreasing trend in dentine area and an increasing trend in enamel cap area along the molar row, in a study using histological sections of modern human molars (Smith et al. 2006). This difference in morphology provides one explanation for a difference in wear rate between molar types. The increased proportion of enamel, a tissue that is extremely resistant to wear (Spears et al. 1993; Chun et al. 2014), may explain the relatively slower wear rate observed in the ManM3.

A second explanation for a difference in wear rates across molar types is a difference in biting force acting upon the teeth. When mechanically grinding a sample of extracted modern ManM3s, Burak et al. (1999) demonstrated enamel wear rates were less than those of dentine at lighter loads, whereas similar rates of wear were demonstrated for the two tissues at higher loads. Although the study sample was small and only examined wear on the ManM3s, the study by Burak et al. (1999) indicates at high mechanical loads molars will wear at a similar rate regardless of their dental properties. The mechanical load of molars in archaeological populations is unclear. It may be that British archaeological individuals experienced a similar dental load on the ManM1 and ManM2, which was different to that on the ManM3, producing a relatively slower wear rate on the ManM3. It would be useful to conduct in vitro work in this area simulating the conditions of antiquity to explore this further.

The results of the current study suggest molars along a tooth row do not wear at the same rate. In order to obtain the most reliable estimates of age, molar specific dental wear rates may be recommended, rather than to assume a single wear rate across all molars. However, this thesis argues the difference in wear rate between the ManM3 and the earlier erupting molars was not great when using the wear measurements CH, CI and WS. When plotting ManM3 wear against wear on the ManM1 or ManM2 data points fell close to the line representing the relationship expected if two molars wore at a similar rate. A large difference in wear rates would show points falling well above or below this line of equal wear. It is therefore unlikely that there would be a large difference to estimates of age if a single wear rate was applied to all molars along the tooth row. This supports a statement made by Miles (2001 p.975), "in practice, it does not make a large difference to estimates of age if this additional calculation [of molar specific wear rates] is omitted."

The conclusion that a single rate of wear may be applied to all molars along the tooth row only applies to the wear measurements of CH, CI and WS. Examination of %DE wear rates showed the ManM1 had a faster %DE wear rate compared to the ManM2, and the ManM2 had a faster %DE wear rate than the ManM3. This finding conflicts with the results produced when recording dentine exposure using an ordinal scale. Ordinal scales use wear stages to record the pattern of exposed dentine on a molar. The application of a single wear scale to all three molars assumes the same wear stage represents the same amount of exposed dentine on each type of molar. If this was true, however, both the %DE and WS measurements would show the same wear relationship between molars along the tooth row. The results from the current thesis do not show this and therefore suggests stages of wear represent different amounts of exposed dentine across the molars.

These results support the need for molar specific %DE dental wear rates if used in methods for estimating age, and a review of wear stages across molar types. Furthermore, the difference in the wear relationship observed using %DE and WS measurements indicate errors will be introduced to age estimates when using WS wear rates. It may be that a pattern of exposed dentine observed on the ManM2 will equal a smaller amount of %DE compared to the same pattern on the ManM1. This means stages on the ManM2 may be passed through more quickly and will result in under-aging of older individuals. Further research is required to identify an ordinal scale that accurately represents the wear process for each molar type. Using such an approach may produce a more rigorous ageing method based on the quantitative measurement of exposed dentine.

8.4.3 Do wear rates between molars remain constant?

H_0: the rate of wear between molars remain constant
H_1: the rate of wear between molars do not remain constant

Both the Miles Method and the Modified Miles Method require the assumption that the rate of wear between molars remains constant throughout the life of the dentition. Examination of the wear relationships in Chapter 7.2 support acceptance of the null hypothesis that the rate of wear between molars remained constant. This held true for all wear measurements and for all temporal samples.

Few studies have examined whether the wear rates between molars remain constant. In a study using average crown height, Mays et al. (1995) identified a similar rate of wear on the first and second mandibular molars that then remained constant. A similar analysis was attempted with the first and third molars, but it was not possible to determine whether these molars wore at a similar rate due to a greater degree of variability in the wear of the ManM3. The absence of a non-linear pattern, however, suggests wear rates between the molars did not vary throughout life (Mays et al. 1995). Thus, the results of the current study, alongside the work of Mays et al. (1995), validate the assumption of Miles (1962) and Gilmore and Grote (2012). It is worth stressing that this does not indicate whether dental wear rates were fast or slow, or that wear bears a linear relationship with age. However, if the wear rate did vary through life, it must have decreased or increased in tandem across all mandibular molars.

This thesis recommends employing the wear relationship between the first and second mandibular molars in methods for estimating age using dental wear, using the third mandibular molar to support any conclusions. Furthermore, a single wear rate may be applied to both the ManM1 and ManM2, and this wear rate between the molars remains constant throughout the life of the dentition. The results of this thesis therefore validate two key assumptions of the Miles Method, and the Modified Miles Method, providing support to their ability to reliably estimate age at death of archaeological remains.

8.5 Relationship between dental wear and age

Research Question 3: How strongly is dental wear associated with age?

Multiple studies have observed a relationship between dental wear and age (Miles 1962; Lunt 1978a; Nowell 1978; Lovejoy 1985; Walker et al. 1991; Mays 2002). A key aim of this thesis was to evaluate the strength of the relationship between age and dental wear measurements to assess the reliability of using dental wear as a tool to estimate age.

8.5.1 Relationship between dental wear and juvenile age

H_0: there is a relationship between dental wear and juvenile age

H_1: there is no relationship between dental wear and juvenile age

The results in Section 7.3 indicate a significant relationship between ManM1 wear measurements and juvenile age in all temporal samples. This was true for the wear measurements: CH, CI and WS. %DE was excluded due to the lack of exposed dentine on the ManM1 during the juvenile period. Comparatively few of the relationships between ManM2 wear measurements and juvenile age were statistically significant, but did show a pattern of increasing dental wear with age for all samples. These results support acceptance of the null hypothesis that there is a relationship between dental wear and juvenile age.

Few studies have examined the wear relationship of the permanent molars in juvenile individuals, making cross-comparison studies difficult. A study of ManM1 crown height in Romano-British individuals, aged between 6 and 18 years, identified a significant relationship between ManM1 crown height and dental age (Mays et al. 1995). This study did not examine the relationship between ManM2 wear and juvenile age. The results of the current study are therefore consistent with Mays et al. (1995) regarding the first mandibular molar, and support the presence of a relationship between dental wear and juvenile age in the ManM1.

Due to the lack of studies examining the relationship between ManM2 wear and juvenile age, it is difficult to place the results of the current study in context of the wider literature. While examining dental wear in the Libben population, Lovejoy (1985 p.51) described the ManM2 with "unworn to slight polish with infrequent small facets in older members," for individuals aged between 12-18 years old. Individuals aged between 16-20 years the ManM2 showed "No exposure...Polishing of remaining cusps with occasional small facets," (Lovejoy 1985 p.52). In the current study, all temporal samples had a single area of exposed dentine as the highest ManM2 wear stage during the juvenile period. The only exception was a single individual belonging to the Post-Medieval sample with a WS of 5 (two discrete areas of exposed dentine). Therefore, the degree of wear observed on juvenile ManM2s in the current study is consistent with Lovejoy (1985).

An increase in ManM2 dental wear with an increase in juvenile age was observed, although this pattern was not statistically significant across all temporal samples. The non-significant results may be attributed to the relatively short time span from which to examine any relationship between ManM2 dental wear and juvenile age. The ManM2 erupts around the age of 12 years and the juvenile period ends around the age of 18 years, producing a six year period to review any relationship between dental wear and age. Inspection of the Wear Stage data for the ManM1 reveals a similar degree wear after six years of wear. Section 7.3.2 demonstrated ManM2 increased with age in adult individuals. Therefore, it is likely that the relationship between ManM2 wear and age may become significant, but only after observing a longer period of wear. However, juvenile ManM2 dental wear rates reflect wear of the molar cusps, confirmed by the lack of ManM2 dentine exposed during this period. ManM2 juvenile wear rates may not be a true representation of dental wear rates, and it would be ill-advised to produce age estimates solely based on ManM2 juvenile wear rates.

The present results indicate that dental wear on the first mandibular molars bears a stronger relationship with juvenile age compared with the second mandibular molars. This suggests it is more reliable to estimate wear rate from the ManM1 than the ManM2. However, this does not mean that wear on the ManM2 should be excluded from dental wear ageing methods. Both the Miles Method and Modified Miles Method utilise the wear relationship between the ManM1 and ManM2 to estimate age at death. It has already been shown that there is a strong relationship between ManM1 and ManM2 wear, and that the wear difference remained constant throughout the life of the dentition. Overall, these results indicate that juvenile wear on the ManM2 is likely to be useful in the study of age at death but only when used together with the ManM1.

8.5.2 Relationship between dental wear and bony age estimates

H_0: there is a relationship between dental wear and bony age estimates

H_1: there is no relationship between dental wear and bony age estimates

The results in this thesis confirm a statistically significant relationship between dental wear and bony age estimates (Section 7.3.2). This was true for all wear measurements and all temporal samples. The null hypothesis is therefore accepted, indicating older individuals are associated with a higher degree of dental wear. These results are consistent with previous studies (Nowell 1978; Lovejoy 1985; Oliveira et al. 2006) and supports the use of dental wear as a tool for estimating age.

Although a relationship was observed between the occlusal wear measurements and age, these measurements become more varied with increasing age. This variation was evidenced by larger inter-quartile ranges (IQR) in the older age categories, compared to the younger age groups. This was not observed in the crown height measurements, with IQRs remaining relatively constant with increasing age. A possible explanation is a difference in the surface being measured. The %DE and WS measurements record wear in relation to the area of the occlusal surface, which changes in size and shape as more dental tissue is removed. Dental wear first acts on the molar cusps, which are small, discrete areas of enamel. Once the cusps have been worn dental wear acts upon the entire tooth surface. Figure 8.5.1 demonstrates that neither the enamel area nor the dentine area of a molar consists of a simple shape, but one that changes throughout the tooth. Occlusal wear measurements therefore include an additional source of variation, a change in tooth

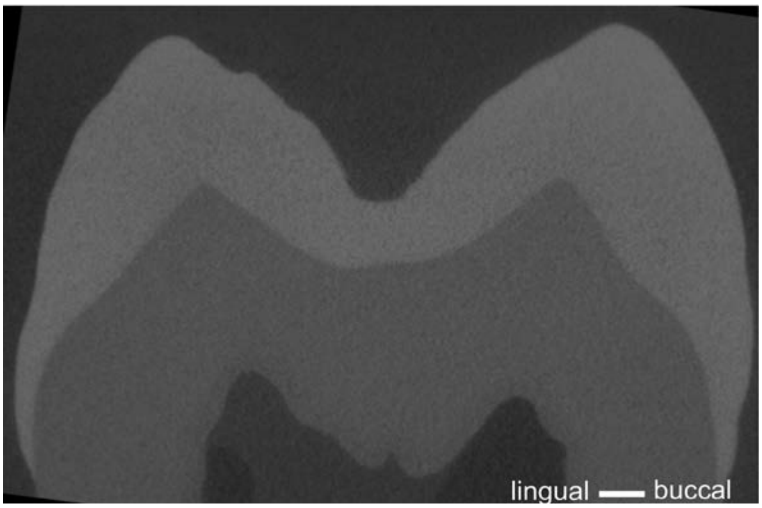


Figure 8.5.1. Cross section of third mandibular molar taken using micro-computed tomography. Light grey represents the enamel and darker grey the dentine. Image taken from Sova et al. (2018 p.6)

morphology with an increase in wear, which simple linear measurements of crown height do not need to account for.

These results suggest the degree of exposed dentine is likely to be more varied in older individuals, while a similar degree of variation in crown height is expected across all age groups. This increase in variation with increasing age will reduce the precision and accuracy of age estimates when using occlusal wear measurements. Crown height measurements may be less affected by change in tooth shape that occurs during the dental wear process. It is recommended that ageing methods using crown height are developed and assessed for their reliability, especially for estimating age of older individuals. However, the results from this thesis confirm the presence of a relationship between dental wear and age, validating the use of dental wear as a method to estimate age in archaeological remains.

8.5.3 Comparing juvenile and adult dental wear rates

The Miles Method states that the rate of wear on the permanent molars established from juvenile individuals of a population would continue during the adult period (Miles 1962; Miles 2001). However, previous studies examining the reliability of the Miles Method do not test this. The current study attempted to examine this assumption through the comparison of wear rates produced from juvenile and adult samples within each temporal grouping. Slope coefficients provided estimated rates of ManM1 wear for juvenile individuals (Section 7.2), while estimated rates of ManM1 wear for adult individuals were produced following the Modified Miles Method (Section 7.4.3). As the wear rates were produced using two separate methodologies no statistical test for comparison was performed, rather any differences in wear rate were examined in light of the standard deviation within each studied sample.

Due to the inability to perform regression analysis on ordinal data, no slope coefficients were produced for the relationship between WS and juvenile age. While an estimated rate of WS juvenile wear may be produced following the Modified Miles Method it is likely to be unreliable. The Modified Miles Method utilises the gradient between two molars to produce an estimated rate of wear. During the juvenile period both the ManM1 and ManM2 are in occlusion for 6 years before entering the Young Adult age group. Section 8.5.1 argued that 6 years was not long enough to produce a reliable wear rate for the ManM2, and it would be therefore ill-advised to produce an estimated juvenile wear rate following the Modified Miles Method. Furthermore, the approach of Miles (1962) extrapolated wear rates in a step-wise manner, foregoing the need for the assumption that WS is linear with age. This means when using the Miles Method the relationship between molars is more important than the similarity of wear rates in juvenile and adult individuals.

A comparison of the juvenile CH wear rates to the estimated adult rates of CH wear reveals no great difference in wear rate between the two age groups (Table 8.5.1). The slightly lower estimated wear rates in the adult group hints at a higher rate of wear in the ManM1 in juvenile individuals. This pattern has been observed in previous studies using CH, and was attributed to the relatively narrow cusp tips being worn down in the young individuals (Mays et al. 1995; Mays 2002). It may be argued that once dentine has been exposed, and the cusp tips removed, wear is experienced across the entire occlusal surface causing a slight reduction in wear rate. However, the difference in wear rates between age groups was relatively small when accounting for inter-individual population of a sample. Standard deviation for ManM1 starting CH of unworn molars fell between 0.20 and 0.90mm for the studied samples (Table 7.4.17, p.271). The standard deviation for mean CH difference between the ManM1 and ManM2 was between 0.45 and 0.84mm (Table 7.4.16, p.271). These results suggest that there may be some error when applying juvenile CH wear rates to adults of the same population but this will not be great when accounting for general inter-individual variation.

Table 8.5.1. Comparing first mandibular molar estimated average crown height (CH) wear rates for the juvenile and adult age groups by temporal sample.

Sample	Juvenile estimated CH wear rate (mm per year)	Adult estimated CH wear rate (mm per year)	Difference in wear rate (mm)
Neolithic	-0.14	-0.12	0.02
Bronze Age	-0.12	-0.07	0.05
Iron Age	- 0.09	-0.06	0.03
Romano-British	-0.08	-0.09	0.01
Anglo-Saxon	- 0.08	-0.07	0.01
Medieval	- 0.15	-0.07	0.08
Post-Medieval	- 0.11	-0.07	0.04

A comparison of juvenile and adult CI wear rates showed a similar pattern to the CH measurements, with the adults showing a slightly lower wear rate compared to individuals (Table 8.5.2). The difference in CI wear rate between the two age groups was relatively small when compared to the variation observed within each temporal sample. The standard deviation for

ManM1 starting CI was between 4.05 and 9.38 CI (Table 7.4.19, p.273), while the standard deviation for mean CI difference between the ManM1 and ManM2 was 6.35 to 11.29 CI (Table 7.4.18, p.273). These results suggest the overall difference in juvenile and adult CI wear rates was not great when accounting for inter-individual variation.

Table 8.5.2. Comparing first mandibular molar estimated crown index (CI) wear rates for the juvenile and adult age groups by temporal sample

Sample	Juvenile estimated wear rate (CI per year)	Adult estimated wear rate (CI per year)	Difference in wear rate (CI)
Neolithic	-1.51	-1.35	0.16
Bronze Age	-1.98	-1.30	0.68
Iron Age	-1.32	-0.66	0.66
Romano-British	-0.93	-1.48	0.55
Anglo-Saxon	-2.04	-0.72	1.32
Medieval	-1.84	-1.01	0.83
Post-Medieval	-0.94	-1.26	0.32

The above findings support the extrapolation of ManM1 juvenile wear rates to adult individuals of the same population to estimate age, further validating the approach of Miles (1962). It should be noted that the Modified Miles Methods relies on the assumption that wear is linear with age, i.e. an equal amount of dental tissue is lost each year. The results from the current study suggest this is true for juvenile individuals (Section 7.3.1), but this cannot be stated with certainty for adult individuals. The boxplots in Section 7.4.2 indicate a steady increase in dental wear with an increase in age, but this plateaus in older individuals. This suggests dental wear may be linear with age until certain point where it then slows and becomes more varied. This supports previous studies. Mays (2002) and Benazzi et al. (2008) indicate an approximately linear relationship between ManM1 CH and age, in samples of known-aged individuals ranging from 6-89 years old. However, both studies identified an increase in the spread of crown heights with age, indicating wear is more variable in older individuals and dental wear rates will become less reliable when applied to individuals of increasing age. If wear rates decrease or become highly variable with age, age estimates produced from juvenile dental wear rates will be unreliable in older individuals.

8.6 Comparing dental wear rates of multiple British archaeological samples

Research Question 4: do populations dating from the British Neolithic to Medieval periods have a similar rate of wear?

Brothwell (1963 p.68) stated "that the rates of wear in earlier British populations do not appear to have changed much from the Neolithic to mediaeval times." As a result, Brothwell produced a single chart for estimating age at death using dental wear, which he argued could be applied to British individuals dating from the Neolithic to the Medieval period. Due to the chart's simplicity, it is one of the most widely cited methods for estimating age using dental wear. However, the conclusion that individuals from multiple British archaeological periods have a comparable rate of wear has never been verified. Thus, validating Brothwell's statement was a key aim of this thesis.

Prior to the comparison of dental wear rates, ante-mortem tooth loss (AMTL) frequency was examined across the studied samples. A difference in AMTL frequency, and a difference in age at which AMTL occurs, between the studied samples has the potential to produce differences in the dental wear rate. Furthermore, the loss of a molar during an individual's lifetime has the potential to change dental wear distributions on the remaining teeth.

8.6.1 Comparing ante-mortem tooth loss (AMTL) rates

A. **H_0: there is no significant difference in ante-mortem tooth loss frequency between temporal samples**
   H_1: there is a significant difference in ante-mortem tooth loss frequency between temporal samples

B. **H_0: Ante -mortem tooth loss frequency occurs at a similar age in all temporal samples**
   H_1: Ante-mortem tooth loss frequency does not occur at a similar age in all temporal samples

C. **H_0: Ante-mortem tooth loss does not have any effect on dental wear**
   H_1: Ante-mortem tooth loss does not have any effect on dental wear

AMTL was observed in all temporal samples and was shown to increase in frequency with an increase in age (Section 7.4.1). A significant difference in AMTL rate and the age at which AMTL occurred was observed between the studied samples. The Post-Medieval sample had a higher percentage of individuals with AMTL for each molar type compared to the earlier dating samples, which is consistent with previous studies (Brothwell 1959 Fig. 2, p.62; Roberts and Cox 2003). The Post-Medieval sample also showed a comparatively high frequency of tooth loss in younger individuals (Figure 7.4.2). The higher rate of AMTL in the Post-Medieval sample may be an indicator of relatively poor health compared to earlier samples. AMTL can be a result of tooth removal through injury or surgery, the loss of the supporting bone, or dental pathology and periodontal disease (Hillson 2001; Ortner 2003; Lukacs 2007; Roberts and Manchester 2007). The relatively higher percentage of younger individuals with AMTL in the Post-Medieval sample suggests tooth loss is unlikely to be a result of dental wear, but rather a result of dental disease. The relatively high caries frequency observed in the Post-Medieval sample supports this (Figure 8.6.1).

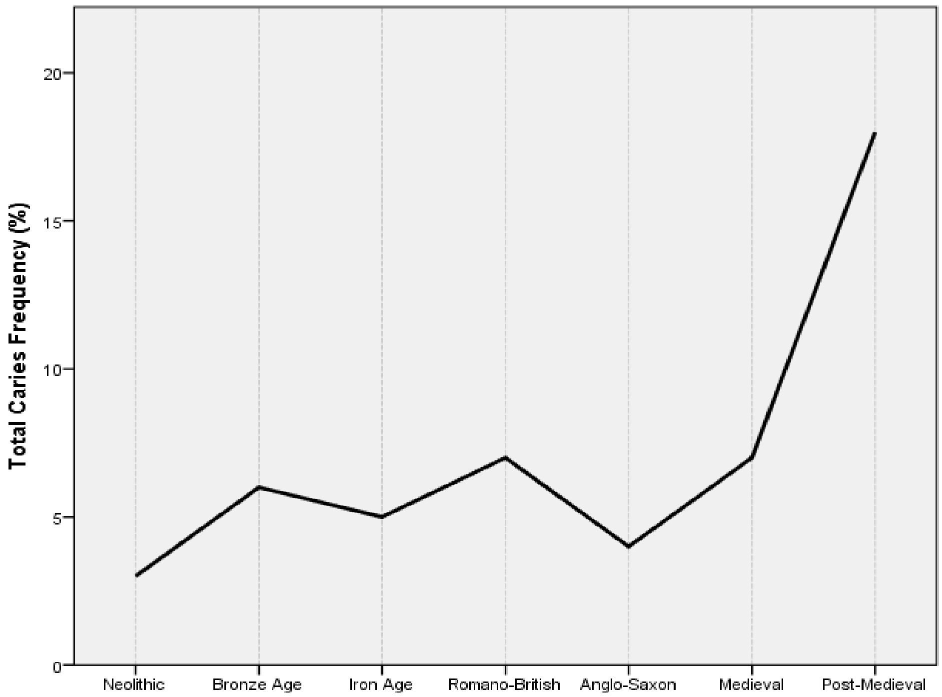


Figure 8.6.1. Total caries frequencies for all three molars by temporal sample.

The relatively higher rate of AMTL observed in the Post-Medieval sample has the potential to affect the rate of dental wear, and produce a difference between the studied samples. When a tooth loses its occlusal partner it no longer acts as a functioning unit during mastication. It may then be expected that wear on the occlusal surface will be greatly reduced. However, there was little evidence for any effect of AMTL on dental wear in the current study. Teeth that had lost their occlusal partner ante-mortem did not show a significant reduction in the degree of wear, compared to molars whose occlusal partner was present. These results are consistent with Mays (2002). Using multiple regression analysis, with crown height as the dependent variable and age and ante-mortem loss of occlusal partner as the independent variables, Mays (2002) failed to identify any effects of AMTL of occlusal partners on crown height. These results suggest that although the Post-Medieval sample from Barton showed a higher rate of AMTL it is unlikely that it had any observable effect of the process of dental wear.

The small sample sizes of the current study recommend further study of the effect of AMTL on dental wear rates. Both the current study, and the work of Mays (2002), examine the effect of AMTL on the occlusal partner of the missing molar. Wear on the remaining molars, however, may increase as wear forces are redistributed. Clinical studies suggest mastication predominance (chewing primarily on one side of the mouth) was increased in living individuals missing posterior teeth from one side of the dentition (Iwashita et al. 2014; Yamasaki et al. 2016). Such a change in wear distributions may result in a change in wear rates. However, if dental wear is only recorded from one side of the dentition, as in the current study and Mays (2002), this change in wear distributions may not be observed. It is clear that further work is required to understand how wear distributions may change across the whole dentition following AMTL of the molars, and how it may affect dental wear rates. This is particularly important for assessing the reliability of estimating age of older individuals who are likely to have experienced AMTL.

8.6.2 Comparing dental wear rates across temporal samples

D. H_0: Populations dating from the British Neolithic to Post-Medieval periods have similar dental wear distributions

H_1: Populations dating from the British Neolithic to Post-Medieval periods have similar dental wear distributions

The present study supports Brothwell's conclusion that dental wear rates were comparable across multiple British archaeological samples. This was confirmed by a comparison of juvenile and estimated adult wear rates using large, well-documented samples. A broad similarity in wear pattern across four different wear measurements further supports Brothwell's claim and supports a single wear rate for all individuals dating from the British Neolithic to the Medieval period. However, this thesis argues for the use of population-specific dental wear rates to obtain the most reliable estimates of age.

A comparison of dental wear distributions by age category showed a similarity in wear pattern between temporal samples (Section 7.4.2). However, with increasing age a difference between wear patterns was observed. It may be argued that there was a difference in dental wear rate between the studied samples, which only became apparent in older individuals. Samples which showed a large difference in wear rate might be expected to show a difference in wear pattern across all three molars, and for all four wear measurements. However, the large wear distributions for the older age groups makes this difficult to evaluate with certainty. Wear distributions in the older age groups were relatively large compared to the younger age group, indicating that wear is more variable in older individuals.

A finding of increased variation in the dental wear pattern with an increase in age is consistent with previous studies. Mays (2002) and Benazzi et al. (2008) found the variance of the residuals increased with age when examining the relationship between CH and known age. These studies indicate that the relationship between crown height and age becomes varied with increasing age. Mays (2002 p.865) argues an increased spread of crown heights with advancing age is an expected pattern, "given the idiosyncratic differences between individuals will tend to accumulate with age." Given this, estimating age of older individuals will be less reliable compared to age estimates for younger individuals when using dental wear ageing methods. The observed differences between the studied samples suggests using a single dental wear rate to estimate age of multiple archaeological populations will be unreliable. Thus, this thesis recommends the development and use of population-specific dental wear rates to estimate age.

E. H_0: Populations dating from the British Neolithic to Post-Medieval periods have similar juvenile dental wear rates

H_1: Populations dating from the British Neolithic to Post-Medieval periods do not have similar juvenile dental wear rates

A comparison of juvenile dental wear rates showed all temporal samples had a similar rate of wear for the ManM1, but some difference in ManM2 wear rates. Following an analysis of covariance, temporal samples showed a similar CH, CI and WS rate of wear in the ManM1. These results support the work of Brothwell, that dental wear rates were comparable across multiple British archaeological samples. However, a significant difference in ManM2 wear rates of average crown height (CH) supports the use of population-specific wear rates.

The Bronze Age and Iron Age samples showed a relatively faster rate of CH wear on the ManM2, compared to the remaining samples. However, a comparison of ManM2 CI juvenile wear rates was not significant. This suggests that when crown height on the ManM2 was normalised for tooth width, to produce a crown index (CI), the differences in wear rates was reduced. The Bronze Age sample had a relatively large ManM2 starting CH compared to the remaining samples (Figure 7.4.26), but this difference was reduced when normalised for tooth width (Figure 7.4.27). These results suggest ManM2s may have been larger in Bronze Age, and potentially in Iron Age, individuals compared to the remaining samples.

It is clear that populations vary in their tooth size and shape. Huang et al. (2012) showed that permanent dental dimensions varied when comparing three archaeological populations from Xi'an, northern China. The Chang'an (1000-1300 years BP) had the largest ManM1s in the mesial-distal dimension, while the Shaolingyuan (3000 years BP) had the smallest MaxM3s for the same dimension. Additional studies demonstrate a reduction in tooth size over time (e.g. Armelagos et al. 1989; Sciulli 1997; Sołtysiak 2007; Pinhasi et al. 2008). In a study analysing tooth size in skeletal samples dating to the Mesolithic-Neolithic Age, the Bronze Age, and from the Roman to Medieval times in Serbia, Pajević and Glišić (2017) demonstrated a decrease in the buccolingual diameter of the upper second and lower first molar from the earliest to the later groups. The current study further supports a difference molar morphology between the studied samples. Section 7.4.3.1 identified a significant difference ManM1 CH y-intercepts, indicating a difference in starting crown height of unworn molars. While it is unclear to which dental dimensions have the greatest effect on dental wear rates, these studies suggest molar morphology should be a consideration when using dental wear to estimate age.

The significant difference observed in ManM2 CH wear rates across temporal samples, but not in ManM2 CI wear rates, suggests molar morphology should be considered when using dental wear rates to estimate age. The results from the current study suggest juvenile dental rates do not differ greatly between multiple archaeological samples when normalised for tooth width. However, it is highly recommended that population-specific wear rates are employed to estimate age so any difference in tooth morphology is reflected.

F. H_0: Populations dating from the British Neolithic to Post-Medieval periods have similar adult dental wear rates
H_1: Populations dating from the British Neolithic to Post-Medieval periods do not have similar adult dental wear rates

A comparison of estimated adult wear rates further support a similarity of wear rate between the studied samples. However, this conclusion only holds true given the assumption that there is a linear relationship between dental wear and age, i.e. that dental tissue is lost at a consistent rate during an individual's life. The validity of this assumption is unclear.

Mays (2002) and Benazzi et al. (2008) demonstrated an approximately linear relationship between crown height and known age. However, these studies employed urban samples dating to the 19th and 20th Centuries, which may have a markedly slower wear rate compared to archaeological populations. Observations from the current study suggest dental wear may be linear with age but only in young and middle aged adults. The boxplots in Section 7.4.2 show a steady increase in dental wear with age, which then plateaus. These results suggest wear is unlikely to be linear with age in older individuals. Conclusions regarding the linearity of CH and age must therefore be applied to the current study with caution. Unfortunately, no study has examined the linearity of CI and age, therefore a similarity in CI wear rates is tentative.

The assumption of linearity is most likely to be violated in the relationship between WS and age. It is unclear whether stages of wear are passed through at a constant rate during an individual's life. Molleson and Cohen (1990) found the stages of Brothwell (1963, 1981) did not represent equivalent amounts of wear in terms of crown height, and suggested some stages may be passed through more quickly than others. In contrast, Kieser et al. (1985) showed an approximately linear relationship between Smith's (1972) system for scoring dental wear and age (from 19 to 39 years) for a known-age sample. The current study employs an ordinal scale based on the stages of Brothwell (1963) to record dental wear. It is therefore likely the estimated rate of WS produced following the Modified Miles Method is inaccurate, and thus results must be viewed with caution.

It is clear that further exploration is required to establish whether a linear relationship exists between dental wear and age. If wear rates decrease with age, the Modified Miles Method will systematically underestimate age in older adults. Nevertheless, a cautious conclusion may be drawn from a comparison of estimates adult dental wear rates. The non-significant results in Section 7.4.4 supports a similarity in adult wear rates across multiple archaeological samples. The results of Section 7.4 validate the conclusion of Brothwell that a single dental wear rate, and therefore a single dental wear chart, may be applied to estimate age of individuals dating to the British Neolithic to Medieval periods. The similarity in wear rates permits further evaluation of Brothwell's chart. However, the finding of a similar wear rate in the Post-medieval sample must first be discussed.

Brothwell (1963) states his dental wear chart may be applied to individuals dating from the British Neolithic to Medieval period. The Post-Medieval period is presumably excluded due to the introduction of new foods during this period, including potato, sugar and tea (Roberts and Cox 2003; Mant and Roberts 2015). The results from the current study suggest there was no significant difference between the Post-Medieval wear rate and the earlier groups. However, this may be a reflection of the Post-Medieval site chosen for study and may not apply to all Post-Medieval populations. The Post-Medieval sample consisted of individuals from St. Peter's Church, Barton-Upon-Humber, Lincolnshire. Barton was considered a rural community during the medieval period and did not experience significant urbanisation until the late 17th Century (Clapson 2005). For this reason, the diet consumed at Barton during the Post-Medieval period may not have differed greatly from the preceding Medieval period.

The results of the current study indicate a single chart or estimated rate of wear, obtained for samples dating from the British Neolithic to Medieval period, may be applied to Post-Medieval populations with caution. This approach is only recommended for Post-Medieval sites with a similar demographic and diet as earlier periods. For example, it would not be appropriate to apply the wear rate for Post-Medieval Barton to the remains of Broerenkerk, Zwolle, The Netherlands. The Zwolle material consists of known-aged, middle-class townsfolk interred from 1819 - 1828 AD with a slope coefficient of -0.04 for ManM1 CH against age (Mays 2002). In contrast, Barton had a slope coefficient of -0.11 for ManM1 CH against juvenile age (Table 7.4.9) and an estimated adult wear rate of -0.07 mm per year (Table 7.4.17). These results show the Zwolle sample had a relatively slow rate of dental compared to Barton. It would therefore be inaccurate to apply a dental wear rate from the rural site of Barton to the urban Dutch site to estimate age. Thus, this thesis recommends the use of population-specific dental wear rates when estimating age of Post-Medieval sites.

8.7 Testing the reliability of Brothwell's chart

The overall similarity in dental wear rates across multiple archaeological samples allows further evaluation of Brothwell's chart. Dental wear data for all temporal samples was pooled and a dental wear profile produced following the Miles Method (Figure 7.4.32). A comparison of the new dental profile and the Brothwell chart showed similar wear stages were obtained in individuals until the age of 35 years. The 35-45 year old age group then showed a higher degree of wear in the Brothwell chart across all three mandibular molars. These results suggest Brothwell's chart is reliable for estimating age at death in British archaeological remains, at least for individuals up to 35 years old.

This difference between the charts may indicate a faster wear rate in Brothwell's chart, compared to the new dental profile. However, the two charts differed by approximately one wear stage, suggesting the difference between the two charts was not great. Furthermore, the box and whisker diagrams for Wear Stage against age showed a higher inter-quartile range for older individuals (Section 7.3.2) and indicate that the dental wear pattern becomes more varied in older individuals. Without using a sample of known-aged individuals it is difficult to state with certainty whether the wear charts differ due to a difference in dental wear rate, or a result of increased variation with age.

The similarity between the two charts suggest dental wear charts are reliable for estimating age in younger individuals. However, wear is more variable in older individuals making dental wear charts a system of decreasing accuracy. The production of population-specific dental wear profiles may improve the reliability of both the Brothwell chart and the produced dental profile. Such an approach would capture any population-specific variations in dental wear, including differences in diet or tooth morphology. Thus, this thesis recommends that the Brothwell chart may be used to provide tentative age estimates for individuals where population-specific wear rates cannot be produced.

It is clear dental wear ageing charts have their place in bioarchaeology. However, in light of the current research adjustments can be made so dental wear ageing charts better represent the dental wear process.

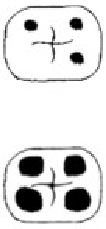
The Brothwell chart suggests age estimates can be produced from either the upper or the lower molars, although 'there are minor differences,' (Brothwell 1963 p69). The current research supports this (Section 8.3.2) but recommends obtaining an age estimate using wear on mandibular molars, only using the maxillary dentition when no lower molars are present. It is not recommended to mix the dentition within an individual due to the larger degree of error associated with the upper molars, i.e. to substitute a maxillary molar for a missing mandibular molar. Best practice would be to gain an age estimate from the lower molars and if incomplete or further clarification is needed an age estimate from the upper molars may be produced. Any new dental wear ageing chart should include an informative statement for clarification.

A second adjustment for dental wear ageing charts relates to the inclusion of the third molar (M3). This thesis has shown that dental wear on the M3 is more variable and has a weaker relationship with age compared to the earlier erupting molars (Section 7.3). These findings suggest the M3 is of limited use for estimating age, and it may be argued that this molar is excluded from ageing charts. However, inclusion of the M3 allows poorly preserved skeletons to be given a rough age estimate. It may be recommended that dental wear ageing charts include the M3 but must signpost any age estimate obtained using this molar are tentative. One suggestion is to move the M3 into its own section of an ageing chart with a statement of caution. Such an approach would decrease the weight given to M3 wear stages for estimating age but still allow estimates to be produced for poorly preserved skeletons.

A third adjustment relates to the age categories of an ageing chart. A bioarchaeologist can identify whether an individual is young (teeth are developing), elderly (many teeth lost ante-mortem), or somewhere in-between by looking at their teeth. The main purpose of dental wear ageing charts are therefore to divide this 'in-between' stage. This thesis has shown that wear stages may reliably indicate individuals aged between 17 and 25 years, and individuals aged between 25 and 35 years. Wear stages, however, are less reliable for estimating age of individuals over 35 years old. Dental wear ageing charts are therefore only able to distinguish individuals who are younger than 35 years old, but who are not juveniles, and individuals who are over 35 years old. It could be argued that the 35-45 years category is adjusted to 35+ years and to include Brothwell's statement; 'any degree of wear greater than in previous columns,' (Brothwell 196, p69).

A change to the 35-45 years category creates further consideration for the 45+ age group. It may be argued that the final dental wear ageing category is removed. However, the current study suggests information relating to ante-mortem tooth loss (AMTL) could be incorporated to extend the use of dental wear ageing charts. AMTL is routinely recorded in dental inventories but is rarely employed in studies of dental wear of age estimation. Tooth loss is strongly age progressive, with the majority of individuals over the age of 45 years in the current study having lost their ManM1 ante-mortem (Figure 7.4.2). The high frequency of AMTL in older individuals is consistent with previous studies (Tal and Tau 1984; Deas 1992; Gandhi 2002; Mays 2002). Gandhi (2002) found a dramatic increase in tooth loss in individuals aged over 55 years old for a group belonging to the Spitalfields collection, while Tal and Tau (1984) found many teeth were lost ante-mortem in individuals aged over about 50-60 years using a South African Bantu sample of known age at death. Although these samples are likely to have consumed a different diet compared to those studied in the current sample, a similar pattern of AMTL was observed. These studies suggest individuals in archaeological populations who have lost more than half of their teeth AMTL would most likely have been over 50-60 years old. Thus, the 45+ age group in a dental wear chart could include a statement such as; 'Ante-mortem tooth loss with greater degree of wear then in the previous columns on the remaining molars.

Figure 8.7.1 is an example of a dental wear chart that considers the adjustments discussed above. This new chart builds on Brothwell's (1963 p69) diagram but attempts to decrease the weight

N.B. Mandibular molars provide the most reliable age estimates. Age estimates can be made from the maxillary molars if mandibular molars are missing. It is not recommended to substitute a maxillary molar for a missing mandibular molar.							
17 – 25 years		**25 – 35 years**		**35+ years**		**45+ years**	
M1	M2	M1	M2	M1	M2	M1	M2
				Any greater degree of wear than in the previous columns.		Ante-mortem tooth loss with greater degree of wear than in the previous columns on the remaining molars	

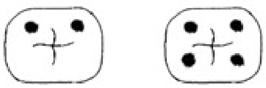
M3 N.B. Age estimates based on M3 Wear stages are only tentative	
Dentine not exposed. There may be some enamel polishing.	17-25 years
	25-35 years
Any greater degree of wear than in the previous row.	35 + years

Figure 8.7.1 Reimagined Brothwell (1963 p69) dental wear ageing chart including recommendations from the current research.

given to the M3 for estimating age and to provide more detailed instructions for its use. Such a chart would more accurately represent the dental wear process in relation to age while remaining simple.

Dental wear charts may always be the preferred method for estimating age at death in archaeological remains due to their ease of use. However, it is suggested that ageing techniques incorporating measurements of crown height are further explored. Section 7.4.2 and Section 8.5.2

argue measurements of crown height do not become as varied with increasing age as occlusal wear measurements. Thus, crown height measurements may be more reliable for estimating age. While a dental wear chart for crown height measurements cannot be produced, the Modified Miles Method offers an avenue for further research. A large sample of juvenile remains is required to produce a reliable dental wear chart for a given population, which is a rarity in excavated archaeological remains. This thesis has demonstrated, however, the ease in which an estimated wear rate may be calculated from adult dental remains following the Modified Miles Method (Section 7.4.4). It is therefore recommended that population-specific ageing methods utilising quantitative measurements are further investigated. Such an approach is likely to produce the most reliable estimates of age for British archaeological remains.

8.8 Using dental wear as a tool for estimating age

This thesis aimed to evaluate the use of dental wear as a tool for estimating age at death in British archaeological remains. The results from Chapter 7 support the fundamental principles of the most widely cited ageing techniques using dental wear, validating the methods of Miles (1962); Brothwell (1963, 1972a, 1981) and Gilmore and Grote (2012). Thus, this thesis recommends the continued use of dental wear for estimating age at death in archaeological remains. However, it is not a method without its flaws, with areas that require further investigation.

Although this thesis confirmed the presence of a relationship between dental wear and age it is imperfect. This means that dental wear is not perfectly correlated with age, and factors other than age introduce 'noise' into the relationship. To determine whether dental wear is suitable for estimating age the amount of 'noise' introduced into the wear relationship can be assessed using the coefficients of determination (r^2). The coefficient of determination is a measure of the strength of a monotonic relationship between two variables, measuring the amount of shared variance on a scale from 0-1. A r^2 close to 1 indicates a large proportion of the variation in dental wear rates are associated with variation in age, while a r^2 close to 0 indicates a large proportion of the variation in dental wear rates are associated with factors other than age.

Examination of the coefficients of determination for ManM1 dental wear and juvenile age indicated a large proportion of the variation may be attributed to factors other than age. For juvenile ManM1 CH wear rates, r^2 values ranged from 0.14 – 0.52, with a median of 0.24. Similar r^2 values were observed for ManM1 CI juvenile wear rates, producing a ranged of 0.18 – 0.59, with a median of 0.29. These values indicate only a quarter to a third of the variability in crown height was explained by an increase in age, with the majority of variation being attributed to factors other than age. This is consistent with previous work. In their study of molar crown height, Mays et al. (1995) reported a Pearson's correlation coefficient of -0.56 between ManM1 CH dental age for a large sample of Romano-British juveniles, producing a r^2 of 0.32. Furthermore, using a sample of Post-Medieval Dutch individuals with known ages of death ranging from 8-89 years old, Mays (2002) produced a ManM1 r^2 of 0.33. Similarly, Benazzi et al. (2008) identified a ManM1 r^2 of 0.23 in a 20th Century Sardinian sample aged from 18-84 years.

In contrast, r^2 values the relationship between ManM1 WS and juvenile age ranged from 0.40 – 0.66, with a median of 0.59. As discussed (Section 8.5.1), few studies examine the precise relationship of ManM1 in juvenile individuals, with no studies correlating WS with juvenile age. These values indicate approximately 60% of the variation in ManM1 WS was explained by an increase in age.

The ManM1 WS r^2 median is considerably higher compared with those for the ManM1 CH and CI measurements. The variation in starting crown height of unworn molars within a population may provide an explanation for this difference. While all molars start the dental wear process with a wear stage of zero, i.e. no wear on the occlusal surface, they do not have the same starting crown height. It is likely that variation in starting crown height of unworn molars within a population is an important factor for determining the spread of points around the regression line. Thus, age estimates produced from crown height measurements will only be reliable when starting crown height of a population is taken into account.

The above r^2 values suggests dental wear is only imperfectly correlated with age, and consequently, some may argue against the use of dental wear as an ageing method. However, a review of the coefficients of determination associated with bony ageing methods suggest a similar issue. In a review of 41 studies using bony age indicators, Mays (2015a) identified r^2 values that ranged from 0.03 – 0.90, with a median of 0.38. This means only 40% of the variation in bony age markers is explained by an increase in age.

An examination of the coefficients of determination shows the majority of variation in both dental and bony age indicators are associated with factors other than age. However, the extraneous factors that may affect dental wear rates are comparatively well understood. Once a tooth erupts it can only lose dental tissue. The mechanisms causing dental tissue loss are well understood, as are additional factors affecting dental wear rates (See Chapter 4). In contrast, age estimation using bony age markers is based on the degeneration and remodelling of bone at specific sites on the skeleton. The precise causes of these changes are unclear, as are the additional factors that may affect their expression. For example, an individual's lifestyle may contribute to degenerative changes of the joints used to estimate age. Physically demanding actives increases the risk of osteoarthritis, a condition that causes bone degeneration and formation (Roberts and Manchester 2007; White et al. 2011). Individuals undertaking highly physical tasks may therefore be more likely to develop osteoarthritis, potentially altering the timing of the later stages of the joints used to estimate age. Furthermore, Merritt (2015) suggests body size may influence skeletal age estimation, with low body size individuals attaining a given age-phase at the pubic symphysis earlier in life, compared to larger body sized individuals. The relationship between age and bone formation may therefore differ between individuals, introducing further variation into the relationship between bony age markers and age.

Dental wear ageing methods also have some distinct advantages over those using bony age indicators (Chapter 2). The most significant advantage is arguably the ability to produce population-specific dental wear profiles to estimate age. This is in contrast to bony ageing techniques, which rely heavily on reference collections that are unlikely to accurately represent the lifestyles of past individuals. Previous work has demonstrated that the age structure of a reference sample will be reflected in the age distribution of the target population, producing a bias and errors in estimates of age (Bocquet-Appel and Masset 1982; Usher 2002). This thesis has demonstrated the ability to produce population-specific dental wear charts and dental wear profiles with relative ease, removing a potential source of error.

This thesis also utilised quantitative measurements of dental wear. The majority of bony age markers rely on ordinal scales and morphological changes to determine the age of an individual. For example, the descriptions given by Lovejoy et al. (1985b) of changes in appearance of the auricular surface are subtle and expressive. For instance, the description for the appearance for an individual aged 25-29 years includes "changes from the previous phase are not marked and are mostly reflected an slight to moderate loss of billowing," while the stage for 45-49 years includes "Changes at apex are slight to moderate but are almost always present," (Lovejoy et al. 1985b p.22-26). These descriptions are imprecise and highly subjective. In contrast, quantitative measurements of dental wear are precise and requires fewer subjective decisions, minimising a further source of error and variation when estimating age.

The above discussion demonstrates the advantage of using dental wear to estimate age over bony skeletal markers. While dental wear is not perfectly correlated with age, dental wear ageing methods have the potential to overcome issues inherent in methods employing bony age markers. Thus, this thesis suggests dental wear is just as reliable for estimating age as alternative bony ageing techniques.

While the usefulness of dental wear as an ageing method has been demonstrated, particularly relating to archaeological remains, it is not without its flaws. One weakness is the ability to reliability estimate age of older individuals. The high frequency of AMTL observed in older individuals means dental wear is no longer a viable method for estimating age, and an alternative methods must be employed. Resorption of the mandibular alveolar bone may be one such approach. Following the loss of a tooth, the alveolar bone undergoes localised resorption and loss in vertical height (Hunter 1778). Mays (2014) explored the potential of using alveolar bone height in individuals showing tooth loss as an age indicator for older adults in skeletal populations. In a skeletal sample of known age at death from Zwolle, the Netherlands (1819-1828 AD) posterior corpus height of the mandibular showed a linear relationship with age at death in older individuals (Mays 2014). As with dental wear, the relationship between alveolar height and age is population specific. Further work by Mays (2017) found a poor relationship between alveolar height and age in a sample from Spitalfields. Spitalfields had a weaker association between molar loss and age compared to Zwolle, indicating alveolar height may not be appropriate for investigating age at death in all populations. None-the-less, the work of Mays (2014, 2017) provides a potential method for estimating age in older individuals when dental wear is no longer of use. Furthermore, this approach has the same advantages over alternative bony age indicators as dental wear, including superior preservation and the ability to produce population-specific standards (Chapter 3.2).

Chapter 9 Conclusion

Dental wear is one of the most frequently used methods for estimating age of archaeological remains, but the underlying principles of the technique have never been validated. Therefore, this thesis set out to identify, test and validate the key principles of three dental wear ageing techniques to ensure it is appropriate for ageing British archaeological remains.

Three dental wear ageing techniques were chosen for review due to their frequency and ease of use. The methods selected for evaluation included the Miles Method (Miles 1962), the Brothwell chart (Brothwell 1963), and the Modified Miles Method (Gilmore and Grote 2012). A review of these methods revealed three key underlying principles, which formed the bases of the research questions:

1. Do molars of the same type wear at a similar rate?
2. Do all molar types have a similar rate of wear?
3. How strong is the relationship between dental wear and age?

A fourth research question was proposed to investigate the conclusion of Brothwell (1963) - that a single dental wear chart for estimating age at death may be applied to multiple temporal samples:

4. Do populations dating from the British Neolithic to Medieval periods have a similar rate of wear?

Dental wear was measured in 861 individuals, including both juvenile and adult remains, using continuous measurements of crown height, percent of exposed dentine, and an ordinal scale in order to answer these questions. The study sample consisted of individuals derived from well-documented sites dating from the British Neolithic to the Medieval period. A Post-Medieval sample was also examined for further comparison.

9.1 Methodological Contribution

The first research question tested whether molars of the same type wore at a similar rate, thereby evaluating whether a single wear rate could be applied to molars of the same type. The wear relationship between left-right and occlusal molar pairs were examined using scatter plots, which demonstrated a similarity in wear rate across molars of the same type. A comparable wear rate between left-right molar pairs supports the traditional method of scoring dental wear on one side of the dental arcade, substituting for its antimere when missing. Occlusal molar partners showed a similar rate of wear but an overall difference in crown height. These results support the use of a single wear rate on upper-lower molar pairs, providing any difference in tooth morphology is considered.

Unlike left-right molar pairs, a molar is never substituted for its occlusal partner in studies of dental wear. A review of the literature indicates the mandibular molars may be preferable for recording dental wear. Furthermore, lower molars are likely to be more reliable in producing age estimates than those produced by maxillary molars. Maxillary molars have been shown to have a weaker relationship with known age (Kieser et al. 1983; Mays 2002), and have a greater degree of measurement error when recording dental wear (Chapter 6.2). This thesis, therefore, recommends the use of the mandibular molars to estimate age using dental wear, substituting its antimere when required. Dental wear rates from the lower molars may be tentatively applied to upper molars to estimate age in individuals with poor dental preservation.

The second research question examined whether molars of different types wore at a similar rate. Techniques using dental wear to estimate age rely on the presence of a wear relationship between molars along the tooth row. Examination of the wear relationship between earlier erupting molars and later erupting molars identified a similar rate of wear on the first and second mandibular molars. The third mandibular molar showed a relatively slower rate of wear compared to the earlier erupting molars. This thesis argued the difference in wear rate across the molars was not substantial, with data points falling close to the line of equal wear across all temporal samples. Thus, a single wear rate may be applied to all three molar types in methods for estimating age using dental wear.

This thesis demonstrated that a single wear rate may be applied to all molars in methods for estimating age using dental wear. The Miles Method and Modified Miles Methods, however, rely on a further assumption - that the rate of wear between molars remain constant throughout the life of the dentition. Examination of the wear difference between molars along the tooth row validated this key assumption.

The dental wear relationship was found to be strongest between the first and second mandibular molars, while the relationship between the first and third mandibular molars was relatively weak. Due to loss of the first mandibular molar ante-mortem it is not possible to examine the entire wear process of the third mandibular. These results suggest that while the wear relationship between the first and third mandibular molars may be used to estimate age at death, the wear relationship between the first and second mandibular molars is the most reliable.

Section 7.3 evaluated whether a relationship existed between dental wear and age in multiple British temporal samples. This thesis demonstrated a strong relationship between dental wear on the first mandibular molar and juvenile age. The relationship between dental wear on the second molar and juvenile age was comparatively weaker, and although a pattern of decreasing wear was observed with an increase in juvenile age this was not significant across all temporal samples. These results support the use of juvenile dental wear rates taken from the first mandibular molar in dental wear ageing methods. Dental wear rates of the second mandibular molars remain of use in studies of age at death but only when used together with the first mandibular molar. These findings further validate the Miles Method, which utilises juvenile dental wear rates to estimate age.

Examination of the relationship between dental wear and bony age markers showed biologically older individuals are associated with a higher degree of dental wear. This thesis demonstrated dental wear was age progressive for multiple temporal samples and, thus, supports the use of dental wear as an ageing method for archaeological remains.

Through the examination of the underlying principles in three methods of the Miles Method, the Brothwell chart, and the Modified Miles Method, this thesis has validated the methodology behind dental wear ageing techniques. This thesis has demonstrated dental wear rates can be calculated, and that the underlying principles for methods of estimating age using dental wear may be tested. Thus, supporting the use of dental wear as a reliable method for estimating age at death in British archaeological remains.

The final question of this thesis examined the reliability of Brothwell's chart. Brothwell (1963) stated multiple British temporal samples have a similar rate of wear, and thus a single dental wear chart for estimating age can be applied to multiple individuals. A comparison of dental wear patterns, juvenile wear rates and adult wear rates calculated from well-documented samples dating from the British Neolithic to Medieval periods validated Brothwell's conclusion. The finding of no significant difference in wear rates between temporal samples supports the use of a single dental wear chart for estimating age of British archaeological remains. However, a single wear chart is unlikely to account for all the variation observed when combining multiple populations, and thus, this thesis recommends the development and use of population-specific dental wear charts in order to produce the most reliable estimates of age.

The overall similarity in wear rates between the studied samples allowed production of a dental wear profile following the Miles Method, and an assessment of the widely cited chart of Brothwell

(1963). A simple comparison showed agreement between the two charts for individuals under 35 years of age. The Brothwell chart then displayed a higher degree of wear compared to the produced dental profile for individual's ages over 35 years old. This thesis argued the difference between the charts is a reflection of the decreasing accuracy that is associated with the Miles Method, and the increased variation in occlusal wear observed in older individuals. However, it is not possible to state which chart is more reliable for estimating age due to the use of individuals of unknown age. This thesis therefore suggests a single dental chart of estimating age, including Brothwell's, may be reliable for estimating age at death of individuals dating to multiple British archaeological periods, but with the understanding that it is a system of decreasing accuracy.

The findings of this thesis support the continued use of dental wear as a method for estimating age at death in archaeological remains. However, it is strongly recommended that population-specific wear rates are developed and applied to produce the most reliable estimates of age at death. The Modified Miles Method is currently under-used for producing estimates of age. This approach produces population-specific dental wear rates with relative ease and overcomes the issue of poor preservation of juvenile individual as in archaeological assemblages. For individuals where population specific wear rates cannot be produced, this thesis supports the continued use of the Brothwell chart. This thesis, therefore, argues while a single chart for estimating age at death may not be unreliable, the calculation and use of population-specific wear rates are likely to produce the most reliable age estimates.

9.2 Limitations and Future Research

It must be acknowledged that certain limitations were encountered during this research, however, these issues provide potential for future research projects. The first limitation is the use of skeletal remains of unknown age, and thus a reliance on bony age estimates. In a perfect study the method for estimating age using dental wear would be evaluated using a sample of known aged individuals. However, few archaeological collections consisting of known aged individuals exist, and those that do date to the Post-Medieval period and are not suitable for evaluating Brothwell's chart. This thesis was therefore unable to correlate dental wear with chronological age. Dental wear was instead correlated with skeletal age given by observing the dental development and bony age indicators. Such an approach meant it was not possible to measure the accuracy of using dental wear to estimate age only how well it reproduced ageing patterns in the skeleton. For this reason the current research is only able to confirm that dental wear is a reliable method for estimating age at death in archaeological remains.

Bony age estimates are frequently used as a proxy for chronological age, however these estimates are produced from multifactorial methods with their own inaccuracies and biases (Chapter 2). Consequently, when there is a disagreement between dental wear age and skeletal age it is not possible to say which indicator is more accurate for determining chronological age. For example, a Romano-British individual showed a relatively low crown height in the ManM1 for their age compared to the other Romano-British individuals (Chapter 7.4.1.1). It may be that this individual was placed into the incorrect age category, and was older than indicated by the bony age markers. Conversely, the bony age may be correct with the individual showing an advanced degree of wear. Without knowing the actual age of the individual it is not possible to state which conclusion is more likely.

It is vital that the most accurate age indicator is identified to produce the most accurate estimates of age. It is also important to identify which indicator, bony or dental, should be used to calibrate the other when using collections of unknown age. Repeating the work of Lovejoy et al. (1985a) using an archaeological sample, such as the Spitalfields Collection, rather than the modern Hamann-Todd collection may provide some clarification. This approach would examine and compare the inaccuracy and biases associated with each age indicator in relation to a single population, to provide insight into which indicatior is the most accurate for assessing age.

In addition to the limitations of using individuals of unknown age, another includes the issue of pooling multiple sites. The pooling of sites to form temporal samples was necessary to obtain the required sample size for analysis, however, the selection of sites dictates caution in the interpretation of the data set. While some temporal samples consist of rural and urban populations to produce a generalised dental wear, such as the Medieval sample, others do not. The Romano-British sample consists of individuals excavated from late Romano-British cemeteries associated with urban settlements. This means the rural and early Romano-British populations were not observed, and application of the dental wear rates from this thesis may produce unreliable age estimates for these groups. Further work is required to identify population-specific dental wear rates for these excluded groups.

A further limitation of pooling multiple sites is the inability to examine site-specific wear rates, and therefore the degree of variation within a temporal sample. The rate of dental wear is influenced by many factors, including diet and the use of teeth as tools. Although the sites chosen for the current study consumed a broadly similar diet and did not show evidence of using their teeth as tools, there is evidence of variation between sites dating to the same period. For example, individuals from the urban Medieval site of St. Helens-on-the-Wall may have consumed a different diet compared to those from the small, rural Medieval town of St. Peter's. It is unclear if any dietary difference existed, or whether it would make a difference to dental wear rates. It would be useful to produce site-specific dental wear rates to examine the degree of variation within British archaeological periods. This research has been previously limited by the inability to produce dental wear rates for sites lacking juvenile individuals. This thesis has demonstrated that the Modified Miles Method has the ability to produce dental wear rates from adult remains. The Modified Miles Method therefore provides an avenue for future research regarding site and population-specific dental wear rates.

This thesis employed the Modified Miles Method to compare wear rates between temporal samples. A limitation of this approach is the assumption that dental wear is linear with age. As discussed in Chapter 8, the validity of this assumption is unclear. This conclusion has already discussed the lack of archaeological samples consisting of known-aged individuals, which means it is difficult to assess the assumption of linearity using traditional collections. One approach may be to measure dental wear in living individuals who exhibit a relatively high rate of dental wear. An example of such a population is the Lengua Indians from the Chaco area of Paraguay, where stone casts of their dentitions have been produced and age known from official records (Kieser et al. 1985). While this population followed a hunter-gather subsistence strategy, rather than an agricultural lifestyle, it provides the opportunity to examine dental wear rates and their linearity with age using a known-aged population. This approach, alongside the work of Mays (2002) who argued there was little evidence for any great deviations from linearity in the relationship between crown height and age using a sample from Spitalfields, London, would provide an insight into the validity of the assumption that dental wear is linear with age.

A further limitation was the choice of ordinal scale employed to measure dental wear in the current study. This thesis demonstrated the usefulness of using an ordinal scale that incorporated ante-mortem tooth loss and wear to the enamel before dentine is exposed. No other studies use such an ordinal scale, limiting the ability to make cross-study comparisons. It would be useful to produce a universal scale, which could be applied to both archaeological remains and clinical patients, and has the ability to record the entire dental wear process. However, a key issue of ordinal scales must first be addressed. Stages within ordinal scales do not necessarily represent an equal degree of dental tissue loss (Chapter 4), which may mean some stages of wear will be passed through more quickly than others. This difference between wear stages potentially violates the assumption that dental wear is linear with age, a key principle in current dental wear ageing methods. Evaluating the percent of exposed dentine at each wear stage provides an avenue for further investigation. Such an approach has the potential to identify wear stages representing equal amounts of dental tissue loss. Furthermore, examining the percent of exposed dentine at each wear stage would indicate whether each wear stage represented comparable amounts of dental tissue loss across all molar types. A qualitative assessment of wear stages has the potential to produce a universal wear scale that is truly representative of the dental wear process.

Despite these limitations, this thesis has demonstrated that dental wear is a reliable method for estimating age at death. This thesis supports the continued use of dental wear as an ageing method for populations following an agricultural lifestyle, and supports the continued use of Brothwell's chart. The Modified Miles Method provides an alternative approach for estimating age of adult remains, and one that is currently under-used. This thesis has provided evidence that the underlying principles of dental wear ageing techniques are valid, and that a single rate of dental wear may be tentatively applied to multiple British archaeological periods. However, this thesis has expressed the need for the development of population-specific dental wear rates in order to produce the most reliable estimates of age.

Appendix A List of Museums visited

The author would like to thank all of the staff that assisted with inquiring regarding their museum collections, and for granting me access during the course of this PhD. Without their help and guidance this PhD would not have been possible. Below is a comprehensive list of all of the institutions visited, and where data collection was carried out.

- Bournemouth University
- Corinium Museum, Cirencester
- Cotswold Archaeology
- Dorset County Museum
- Duckworth Museum, University of Cambridge
- English Heritage
- Hampshire Cultural Trust
- Historic England
- Lancaster Maritime Museum
- Museum in the Park, Stroud
- Museums Sheffield
- National Museum Scotland
- National Museum Wales
- Natural History Museum
- The Wilson, Cheltenham
- University of Bristol Spelæological Society
- University of Bradford
- University of Manchester Museum
- University of Southampton
- Wiltshire Museum, Devizes
- York Museums Trust

Appendix B Formula and outputs testing the reliability of the ordinal scale

This section provides the results for the observed agreement between the first and second recording events, to assess the ordinal scale technique. This was to evaluate the reliability of the method to record dental wear. A description of the statistical process is provided, in addition to the observed agreement values produced for two versions of the original scale method.

The formula for a linear weighted Kappa is:

$$\frac{Po-Pe}{(1-Pe)}$$

Where *Po* is the proportion weighted observed agreement, and *Pe* is the proportion weighted chance agreement.

Before *Po* or *Pe* can be calculated the weight must be determined for each category. A Kappa can be weighted in two ways; linear and quadratic. A linear weighting was applied to the wear stage data as it is less sensitive to the number of categories being used, and is therefore preferred when using a large number of categories (Vanbelle and Albert 2009). A linear weighting is also more suitable as the difference between the first and second category has the same importance as between the second and third category.

To following equation was applied to calculate the weight:

$$1-\frac{i-j}{c-1}$$

Where *i-j* is the distance between the categories and *c* is the number of categories. For the categories in total agreement, i.e. where both observations have scored the same wear stage, the weight is 1, and in contrast the categories with most disagreement the weight is 0. Once the weighting has been calculated it can be applied to a table of observed values. A table of observed values represents the frequency of agreements between stages from the two different observations. The observed results are then converted into a proportion of the total number of incidents recorded.

To calculate *Po* each cell of the table of proportion of occurrence is multiplied by its corresponding weight. Every cell is then summed to produce the *Po*. The weighted change agreement (*Pe*) is given is determined by for each cell multiplying the sum of data for a row by the sum of data for a column, and then by multiplying its corresponding weight. Each cell is then summed to determine the *Pe*. The linear weighted Kappa is then calculated using the above equation.

Table A.1 below provides the observed agreements of assigning wear stage to mandibular and maxillary molars from the first and second recording events.

Table B.1. Observed agreement of assigning wear stage to mandibular and maxillary molars from the first and second recording events using the ordinal scale

Wear Stage	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
0	3	1																				4
1	1	6																				7
2	1	3	17	6	1																	28
3				23	1																	24
4				1	11	2																14
5				1	1	12																14
6							9	3														12
7							2	21	2													25
8								1	12	1	1											15
9								1		8	2											11
10						1			1		23										1	26
11											3	7			1					1		12
12													6	2								8
13													1	8								9
14																						0
15																						0
16																	2					2
17																		1				1
18																						0
19																				5		5
20																					24	24
Total	5	10	17	31	14	15	11	26	15	9	29	7	7	10	1	0	2	1	0	6	25	241

Appendix C Adjusted p-values

Following the Benjamini-Hochberg procedure (Benjamini and Hochberg 1995; McDonald 2009) p-values within a family of tests were sorted and ranked. The smallest p-value received rank 1, the second rank 2, etc, then each p-value is multiplied by the total number of tests and divided by its assigned rank, producing adjusted p-values. All the adjusted p-values below the chosen critical value of 0.5 were deemed to be significant.

As all contrasts came from a single data set, a 'family' of tests was defined by the type of test. Thus, all p-values produced within each set of tests (e.g. Independent T-Tests or Pearson correlation coefficients) were ranked and the Benjamini-Hochberg procedure performed.

Tables C.1-4 present adjusted p-values for Pearson correlation coefficients, Spearman correlation coefficients, independent T-Tests, and Mann-Whitney tests presented in Chapter 7. Each test is identified as 'significant' or 'not significant' according to the Benjamini-Hochberg procedure.

Key	
L	Left
R	Right
Max	Maxillary
Man	Mandibular
M1	First molar
M2	Second molar
M3	Third molar
Neo	Neolithic
BA	Bronze Age
IA	Iron Age
RB	Romano-British
AS	Anglo-Saxon
Med	Medieval
PMed	Post-Medieval
CH	Crown height
CI	Crown index
%DE	Percent of exposed dentine
WS	Wear stage

Table C.1 Adjusted p-values following the Benjamini-Hochberg procedure for Pearson correlation coefficients with a critical value of 0.5.

Sample	Comparison	Measurement	p-value	Rank	Adjusted p-value	
Pooled	LMaxM1 v RMaxM1	CH	4.17E-54	1	3.66529E-52	**significant**
Pooled	LManM1 v RManM1	CI	8.54E-43	2	3.75566E-41	**significant**
Pooled	LManM1 v RManM1	CH	8.55E-42	3	2.50862E-40	**significant**
Pooled	LMaxM1 v RMaxM1	CI	1.38E-41	4	3.02786E-40	**significant**
Pooled	MaxM1 v ManM1	CH	2.30E-41	5	4.05592E-40	**significant**
Pooled	LMaxM2 v RMaxM2	CH	1.49E-39	6	2.01671E-38	**significant**
Pooled	LManM2 v RManM2	CH	1.60E-39	7	2.01671E-38	**significant**
Pooled	LMaxM2 v RMaxM2	CI	3.20E-38	8	3.52066E-37	**significant**
Pooled	LManM2 v RManM2	CI	1.75E-32	9	1.71297E-31	**significant**
Pooled	LMaxM3 v RMaxM3	CH	3.05E-29	10	2.68127E-28	**significant**
Pooled	LManM3 v RManM3	CH	2.43E-28	11	1.94688E-27	**significant**
Pooled	MaxM1 v ManM1	CI	1.83E-25	12	1.33921E-24	**significant**
Pooled	MaxM2 v ManM2	CH	4.37E-25	13	2.95578E-24	**significant**
Bronze Age	Between ManM1 v ManM2	CH	1.91E-24	14	1.20045E-23	**significant**
Anglo-Saxon	Between ManM1 v ManM2	CI	2.19E-23	15	1.28222E-22	**significant**
Pooled	LManM3 v RManM3	CI	5.51E-23	16	3.02808E-22	**significant**
Pooled	LMaxM3 v RMaxM3	CI	1.47E-22	17	7.61304E-22	**significant**
Iron Age	Between ManM1 v ManM2	CH	1.10E-21	18	5.36409E-21	**significant**
Iron Age	Between ManM1 v ManM2	CI	1.34E-20	19	6.22716E-20	**significant**
Pooled	MaxM3 v ManM3	CH	1.58E-19	20	6.95112E-19	**significant**
Anglo-Saxon	Between ManM1 v ManM2	CH	2.39E-19	21	1.00056E-18	**significant**
Pooled	MaxM2 v ManM2	CI	2.57E-19	22	1.02636E-18	**significant**
Romano-British	Between ManM1 v ManM2	CH	1.30E-16	23	4.96052E-16	**significant**
Medieval	Between ManM1 v ManM2	CH	4.17E-16	24	1.53058E-15	**significant**
Bronze Age	Between ManM1 v ManM2	CI	3.41E-15	25	1.20169E-14	**significant**
Romano-British	Between ManM1 v ManM2	CI	9.85E-15	26	3.3328E-14	**significant**
Post-Medieval	Between ManM1 v ManM2	CH	2.30E-13	27	7.48065E-13	**significant**

Romano-British	Between ManM2 v ManM3	CH	9.34E-13	28	2.93625E-12	**significant**
Neolithic	Between ManM1 v ManM2	CH	2.70E-12	29	8.19857E-12	**significant**
Pooled	MaxM3 v ManM3	CI	7.35E-12	30	2.15653E-11	**significant**
Bronze Age	Between ManM2 v ManM3	CH	1.76E-11	31	4.8444E-11	**significant**
Anglo-Saxon	Between ManM2 v ManM3	CH	1.76E-11	32	4.8444E-11	**significant**
Medieval	Between ManM1 v ManM3	CH	2.38E-11	33	6.34107E-11	**significant**
Medieval	Between ManM1 v ManM2	CI	5.55E-11	34	1.43621E-10	**significant**
Anglo-Saxon	Between ManM2 v ManM3	CI	6.45E-10	35	1.62076E-09	**significant**
Medieval	Between ManM2 v ManM3	CH	1.84E-09	36	4.49338E-09	**significant**
Post-Medieval	Between ManM1 v ManM2	CI	5.41E-09	37	1.28575E-08	**significant**
Neolithic	Between ManM1 v ManM2	CI	1.74E-08	38	4.0304E-08	**significant**
Medieval	Between ManM2 v ManM3	CI	1.34E-07	39	3.01321E-07	**significant**
Iron Age	Between ManM2 v ManM3	CI	1.52E-07	40	3.34796E-07	**significant**
Anglo-Saxon	ManM1 v Juvenile age	CI	1.79E-07	41	3.84474E-07	**significant**
Bronze Age	Between ManM2 v ManM3	CI	2.88E-07	42	6.03869E-07	**significant**
Romano-British	Between ManM1 v ManM3	CH	4.09E-07	43	8.37596E-07	**significant**
Anglo-Saxon	Between ManM1 v ManM3	CI	9.22E-07	44	1.84334E-06	**significant**
Post-Medieval	Between ManM2 v ManM3	CH	0.000001	45	1.95556E-06	**significant**
Iron Age	Between ManM1 v ManM3	CI	4.00E-06	46	7.65217E-06	**significant**
Medieval	Between ManM1 v ManM3	CI	0.000005	47	9.16667E-06	**significant**
Post-Medieval	Between ManM2 v ManM3	CI	0.000005	48	9.16667E-06	**significant**
Medieval	ManM1 v Juvenile age	CI	0.000007	49	1.25714E-05	**significant**
Bronze Age	Between ManM1 v ManM3	CH	0.00001	50	1.72549E-05	**significant**
Romano-British	Between ManM2 v ManM3	CI	0.00001	51	1.72549E-05	**significant**
Post-Medieval	Between ManM1 v ManM3	CI	0.000067	52	0.000113385	**significant**
Neolithic	Between ManM2 v ManM3	CH	0.000123	53	0.000204226	**significant**
Romano-British	Between ManM1 v ManM3	CI	0.000142	54	0.000231407	**significant**
Post-Medieval	Between ManM1 v ManM3	CH	0.00026	55	0.000416	**significant**

Neolithic	Between ManM2 v ManM3	CI	0.000276	56	0.000433714	**significant**
Anglo-Saxon	Between ManM1 v ManM3	CH	0.000282	57	0.000435368	**significant**
Iron Age	Between ManM2 v ManM3	CH	1.00E-03	58	0.001375	**significant**
Neolithic	Between ManM1 v ManM3	CH	1.00E-03	59	0.001375	**significant**
Bronze Age	ManM1 v Juvenile age	CH	0.001	60	0.001375	**significant**
Bronze Age	ManM1 v Juvenile age	CI	0.001	61	0.001375	**significant**
Medieval	ManM1 v Juvenile age	CH	0.001	62	0.001375	**significant**
Post-Medieval	ManM1 v Juvenile age	CH	0.001	63	0.001375	**significant**
Iron Age	ManM2 v Juvenile age	CH	0.001	64	0.001375	**significant**
Bronze Age	ManM2 v Juvenile age	CH	0.002	65	0.002707692	**significant**
Iron Age	ManM1 v Juvenile age	CH	0.003	66	0.003940299	**significant**
Post-Medieval	ManM1 v Juvenile age	CI	0.003	67	0.003940299	**significant**
Neolithic	ManM1 v Juvenile age	CI	0.004	68	0.005176471	**significant**
Anglo-Saxon	ManM1 v Juvenile age	CH	0.005	69	0.006376812	**significant**
Bronze Age	Between ManM1 v ManM3	CI	6.00E-03	70	0.007542857	**significant**
Neolithic	ManM1 v Juvenile age	CH	0.009	71	0.01115493	**significant**
Iron Age	Between ManM1 v ManM3	CH	1.30E-02	72	0.015671233	**significant**
Anglo-Saxon	ManM2 v Juvenile age	CI	0.013	73	0.015671233	**significant**
Romano-British	ManM1 v Juvenile age	CI	0.015	74	0.017837838	**significant**
Bronze Age	ManM2 v Juvenile age	CI	0.017	75	0.019946667	**significant**
Neolithic	Between ManM1 v ManM3	CI	2.10E-02	76	0.024315789	**significant**
Romano-British	ManM1 v Juvenile age	CH	0.022	77	0.025142857	**significant**
Iron Age	ManM1 v Juvenile age	CI	0.024	78	0.026734177	**significant**
Iron Age	ManM2 v Juvenile age	CI	0.024	79	0.026734177	**significant**
Anglo-Saxon	ManM2 v Juvenile age	CH	0.049	80	0.0539	not significant
Medieval	ManM2 v Juvenile age	CH	0.052	81	0.056493827	not significant
Medieval	ManM2 v Juvenile age	CI	0.100	82	0.107317073	not significant

Romano-British	ManM2 v Juvenile age	CH	0.104	83	0.11026506	not significant
Romano-British	ManM2 v Juvenile age	CI	0.116	84	0.12152381	not significant
Post-Medieval	ManM2 v Juvenile age	CH	0.128	85	0.132517647	not significant
Neolithic	ManM2 v Juvenile age	CI	0.481	86	0.492186047	not significant
Post-Medieval	ManM2 v Juvenile age	CI	0.817	87	0.826390805	not significant
Neolithic	ManM2 v Juvenile age	CH	0.943	88	0.943	not significant

Table C.2 Adjusted p-values following the Benjamini-Hochberg procedure for Spearman correlation coefficients with a critical value of 0.5.

Sample	Comparison	Measurement	p-value	Rank	Adjusted p-value	
Pooled	LManM1 v RManM1	WS	3.24E-62	1	4.7E-60	**significant**
Pooled	LMaxM2 v RMaxM2	WS	2.83E-58	2	2.05E-56	**significant**
Pooled	LMaxM1 v RMaxM1	WS	2.71E-53	3	1.31E-51	**significant**
Pooled	LManM2 v RManM2	WS	4.44E-51	4	1.61E-49	**significant**
Pooled	MaxM2 v ManM2	WS	1.81E-49	5	5.24E-48	**significant**
Pooled	LManM1 v RManM1	%DE	7.37E-46	6	1.78E-44	**significant**
Pooled	LManM3 v RManM3	WS	4.25E-41	7	8.79E-40	**significant**
Pooled	LMaxM1 v RMaxM1	%DE	1.39E-39	8	2.46E-38	**significant**
Pooled	MaxM1 v ManM1	WS	1.52E-39	9	2.46E-38	**significant**
Pooled	LMaxM3 v RMaxM3	WS	4.51E-39	10	6.55E-38	**significant**
Pooled	MaxM1 v ManM1	%DE	1.1E-38	11	1.45E-37	**significant**
Anglo-Saxon	ManM1 v Age category	WS	1.01E-34	12	1.22E-33	**significant**
Romano-British	ManM1 v Age category	WS	2.06E-31	13	2.3E-30	**significant**
Pooled	MaxM2 v ManM2	%DE	3.17E-28	14	3.28E-27	**significant**
Pooled	MaxM3 v ManM3	WS	5.7E-28	15	5.29E-27	**significant**
Iron Age	ManM1 v Age category	WS	5.84E-28	16	5.29E-27	**significant**
Bronze Age	ManM1 v ManM2	WS	8.01E-28	17	6.83E-27	**significant**

Pooled	LManM2 v RManM2	%DE	2.13E-27	18	1.71E-26	**significant**
Iron Age	ManM1 v ManM2	WS	6.76E-26	19	5.16E-25	**significant**
Anglo-Saxon	ManM2 v Age category	WS	1.01E-25	20	7.34E-25	**significant**
Anglo-Saxon	ManM1 v ManM2	WS	7.2E-24	21	4.97E-23	**significant**
Medieval	ManM1 v Age category	WS	7.51E-23	22	4.95E-22	**significant**
Romano-British	ManM2 v Age category	WS	5.33E-22	23	3.36E-21	**significant**
Romano-British	ManM1 v ManM2	WS	1.71E-21	24	1.03E-20	**significant**
Iron Age	ManM2 v Age category	WS	2.51E-21	25	1.45E-20	**significant**
Neolithic	ManM1 v ManM2	WS	2.44E-20	26	1.36E-19	**significant**
Anglo-Saxon	ManM2 v ManM3	WS	6.62E-20	27	3.56E-19	**significant**
Anglo-Saxon	ManM1 v Age category	CH	1.12E-18	28	5.8E-18	**significant**
Medieval	ManM2 v Age category	WS	2.72E-18	29	1.36E-17	**significant**
Anglo-Saxon	ManM2 v Age category	CH	1.55E-17	30	7.47E-17	**significant**
Anglo-Saxon	ManM1 v Age category	CI	5.8E-16	31	2.71E-15	**significant**
Romano-British	ManM1 v Age category	CI	8.03E-16	32	3.64E-15	**significant**
Iron Age	ManM1 v Age category	CH	1.13E-15	33	4.98E-15	**significant**
Romano-British	ManM1 v Age category	CH	2.07E-15	34	8.81E-15	**significant**
Iron Age	ManM1 v Age category	%DE	2.44E-15	35	1.01E-14	**significant**
Medieval	ManM2 v Age category	CH	3.04E-15	36	1.22E-14	**significant**
Medieval	ManM1 v ManM2	WS	3.75E-15	37	1.47E-14	**significant**
Pooled	LMaxM2 v RMaxM2	%DE	5.9E-15	38	2.25E-14	**significant**
Post-Medieval	ManM1 v Age category	WS	1.41E-14	39	5.19E-14	**significant**
Anglo-Saxon	ManM1 v Age category	%DE	1.43E-14	40	5.19E-14	**significant**
Anglo-Saxon	ManM3 v Age category	WS	2.24E-14	41	7.91E-14	**significant**
Romano-British	ManM2 v Age category	CH	1.42E-13	42	4.92E-13	**significant**
Bronze Age	ManM1 v Age category	WS	1.8E-13	43	6.06E-13	**significant**
Post-Medieval	ManM2 v Age category	WS	9.29E-13	44	3.06E-12	**significant**

Post-Medieval	ManM1 v ManM2	WS	1.17E-12	45	3.77E-12	**significant**
Bronze Age	ManM2 v ManM3	WS	2.21E-12	46	6.97E-12	**significant**
Romano-British	ManM2 v ManM3	WS	2.57E-12	47	7.93E-12	**significant**
Neolithic	ManM1 v ManM2	WS	2.69E-12	48	8.13E-12	**significant**
Anglo-Saxon	ManM1 v ManM2	%DE	3.07E-12	49	9.07E-12	**significant**
Iron Age	ManM2 v Age category	CH	5.34E-12	50	1.55E-11	**significant**
Romano-British	ManM1 v Age category	%DE	8.11E-12	51	2.31E-11	**significant**
Medieval	ManM1 v Age category	CH	1.77E-11	52	4.95E-11	**significant**
Iron Age	ManM2 v ManM3	WS	2.3E-11	53	6.29E-11	**significant**
Medieval	ManM2 v Age category	CI	2.41E-11	54	6.48E-11	**significant**
Romano-British	ManM3 v Age category	CH	2.6E-11	55	6.86E-11	**significant**
Anglo-Saxon	ManM2 v Age category	CI	3.68E-11	56	9.52E-11	**significant**
Bronze Age	ManM2 v Age category	WS	5.28E-11	57	1.34E-10	**significant**
Post-Medieval	ManM2 v ManM3	WS	8.81E-11	58	2.2E-10	**significant**
Medieval	ManM2 v ManM3	WS	1.39E-10	59	3.43E-10	**significant**
Post-Medieval	ManM3 v Age category	WS	1.66E-10	60	4.01E-10	**significant**
Romano-British	ManM1 v ManM2	%DE	4.66E-10	61	1.11E-09	**significant**
Medieval	ManM1 v Age category	%DE	7.03E-10	62	1.64E-09	**significant**
Medieval	ManM3 v Age category	WS	1.29E-09	63	2.97E-09	**significant**
Romano-British	ManM1 v ManM3	WS	2.86E-09	64	6.48E-09	**significant**
Iron Age	ManM1 v Age category	CI	3.03E-09	65	6.75E-09	**significant**
Bronze Age	ManM1 v Age category	CH	8.9E-09	66	1.96E-08	**significant**
Anglo-Saxon	ManM1 v ManM3	WS	9.33E-09	67	2.02E-08	**significant**
Medieval	ManM1 v Age category	CI	1.13E-08	68	2.42E-08	**significant**
Iron Age	ManM2 v Age category	CI	3.99E-08	69	8.39E-08	**significant**
Iron Age	ManM1 v ManM2	%DE	4.64E-08	70	9.61E-08	**significant**
Anglo-Saxon	ManM1 v Juvenile age	WS	5.45E-08	71	1.11E-07	**significant**

Post-Medieval	ManM1 v Age category	%DE	1.04E-07	72	2.08E-07	**significant**
Romano-British	ManM2 v Age category	CI	1.09E-07	73	2.17E-07	**significant**
Post-Medieval	ManM1 v Age category	CI	1.14E-07	74	2.24E-07	**significant**
Bronze Age	ManM1 v Juvenile age	WS	1.17E-07	75	2.26E-07	**significant**
Anglo-Saxon	ManM1 v ManM3	%DE	1.53E-07	76	2.93E-07	**significant**
Post-Medieval	ManM1 v Age category	CH	1.59E-07	77	3E-07	**significant**
Iron Age	ManM1 v ManM3	WS	1.66E-07	78	3.08E-07	**significant**
Romano-British	ManM1 v Juvenile age	WS	2.22E-07	79	4.08E-07	**significant**
Anglo-Saxon	ManM3 v Age category	CH	2.6E-07	80	4.71E-07	**significant**
Medieval	ManM3 v Age category	CH	2.72E-07	81	4.86E-07	**significant**
Iron Age	ManM2 v Age category	%DE	3.76E-07	82	6.64E-07	**significant**
Bronze Age	ManM2 v Age category	CH	3.91E-07	83	6.84E-07	**significant**
Iron Age	ManM3 v Age category	WS	5.18E-07	84	8.94E-07	**significant**
Anglo-Saxon	ManM2 v Age category	%DE	7.15E-07	85	1.22E-06	**significant**
Bronze Age	ManM1 v Age category	%DE	7.34E-07	86	1.24E-06	**significant**
Medieval	ManM1 v Juvenile age	WS	8.41E-07	87	1.4E-06	**significant**
Medieval	ManM2 v Age category	%DE	9.01E-07	88	1.48E-06	**significant**
Medieval	ManM3 v Age category	CI	0.000001	89	1.63E-06	**significant**
Bronze Age	ManM1 v Age category	CI	0.000002	90	3.09E-06	**significant**
Bronze Age	ManM1 v ManM3	WS	0.000002	91	3.09E-06	**significant**
Pooled	LManM3 v RManM3	%DE	0.000002	92	3.09E-06	**significant**
Neolithic	ManM1 v Juvenile age	WS	0.000002	93	3.09E-06	**significant**
Post-Medieval	ManM1 v Juvenile age	WS	0.000002	94	3.09E-06	**significant**
Neolithic	ManM2 v ManM3	WS	0.000003	95	4.58E-06	**significant**
Romano-British	ManM3 v Age category	WS	0.000004	96	6.04E-06	**significant**
Romano-British	ManM2 v Age category	%DE	0.000005	97	7.47E-06	**significant**
Medieval	ManM1 v ManM2	%DE	0.000014	98	2.07E-05	**significant**

Anglo-Saxon	ManM2 v ManM3	%DE	0.000033	99	4.83E-05	**significant**
Iron Age	ManM1 v Juvenile age	WS	0.000057	100	8.27E-05	**significant**
Pooled	MaxM3 v ManM3	%DE	0.000105	101	0.000151	**significant**
Post-Medieval	ManM2 v Age category	CI	0.000134	102	0.00019	**significant**
Bronze Age	ManM1 v ManM2	%DE	0.000187	103	0.000263	**significant**
Post-Medieval	ManM1 v ManM2	%DE	0.000223	104	0.000311	**significant**
Pooled	LMaxM3 v RMaxM3	%DE	0.000233	105	0.000322	**significant**
Bronze Age	ManM2 v Age category	CI	0.000247	106	0.000338	**significant**
Medieval	ManM1 v ManM3	WS	0.000268	107	0.000363	**significant**
Post-Medieval	ManM2 v Age category	%DE	0.000336	108	0.000451	**significant**
Anglo-Saxon	ManM2 v Juvenile age	WS	0.000424	109	0.000564	**significant**
Anglo-Saxon	ManM3 v Age category	CI	0.001	110	0.001283	**significant**
Medieval	ManM2 v ManM3	%DE	0.001	111	0.001283	**significant**
Post-Medieval	ManM2 v Age category	CH	0.001	112	0.001283	**significant**
Post-Medieval	ManM1 v ManM3	WS	0.001	113	0.001283	**significant**
Anglo-Saxon	ManM3 v Age category	%DE	0.002	114	0.002522	**significant**
Bronze Age	ManM2 v Juvenile age	WS	0.002	115	0.002522	**significant**
Romano-British	ManM3 v Age category	CI	0.003	116	0.00375	**significant**
Iron Age	ManM1 v ManM3	%DE	0.005	117	0.006092	**significant**
Medieval	ManM1 v ManM3	%DE	0.005	118	0.006092	**significant**
Romano-British	ManM2 v ManM3	%DE	0.005	119	0.006092	**significant**
Neolithic	ManM1 v ManM3	%DE	0.005083	120	0.006142	**significant**
Bronze Age	ManM3 v Age category	WS	0.006	121	0.00719	**significant**
Neolithic	ManM1 v ManM3	%DE	0.008	122	0.009508	**significant**
Romano-British	ManM1 v ManM3	%DE	0.011	123	0.012967	**significant**
Post-Medieval	ManM3 v Age category	CI	0.013	124	0.015202	**significant**
Neolithic	ManM2 v Juvenile age	WS	0.016	125	0.01856	**significant**

Bronze Age	ManM2 v Age category	%DE	0.024	126	0.027619	**significant**
Romano-British	ManM2 v Juvenile age	WS	0.026	127	0.029685	**significant**
Romano-British	ManM3 v Age category	%DE	0.028	128	0.031719	**significant**
Post-Medieval	ManM2 v Juvenile age	WS	0.03	129	0.033721	**significant**
Medieval	ManM2 v Juvenile age	WS	0.044	130	0.049077	**significant**
Bronze Age	ManM2 v ManM3	%DE	0.061	131	0.067519	not significant
Neolithic	ManM2 v ManM3	%DE	0.071	132	0.077992	not significant
Medieval	ManM3 v Age category	%DE	0.076	133	0.082857	not significant
Iron Age	ManM2 v ManM3	%DE	0.112	134	0.121194	not significant
Iron Age	ManM3 v Age category	CH	0.207	135	0.222333	not significant
Post-Medieval	ManM3 v Age category	%DE	0.255	136	0.271875	not significant
Iron Age	ManM2 v Juvenile age	WS	0.282	137	0.298467	not significant
Iron Age	ManM3 v Age category	%DE	0.316	138	0.332029	not significant
Post-Medieval	ManM1 v ManM3	%DE	0.32	139	0.333813	not significant
Iron Age	ManM3 v Age category	CI	0.499	140	0.516821	not significant
Post-Medieval	ManM3 v Age category	CH	0.513	141	0.527553	not significant
Bronze Age	ManM3 v Age category	CH	0.572	142	0.584085	not significant
Bronze Age	ManM3 v Age category	CI	0.615	143	0.623601	not significant
Post-Medieval	ManM2 v ManM3	%DE	0.805	144	0.81059	not significant
Bronze Age	ManM1 v ManM3	%DE	0.872	145	0.872	not significant

Table C.3 Adjusted p-values following the Benjamini-Hochberg procedure for Independent-T-Tests with a critical value of 0.5.

Sample	Comparison	Measurement	p-value	Rank	Adjusted p-value	
Pooled	MaxM3 v ManM3	CI	5.68E-14	1	2.95E-12	**significant**
Pooled	MaxM2 v ManM2	CI	2.97E-12	2	7.73E-11	**significant**
Pooled	MaxM3 v ManM3	CH	3.90E-08	3	6.76E-07	**significant**
Pooled	MaxM1 v ManM1	CI	4.39E-07	4	5.71E-06	**significant**
Pooled	MaxM2 v ManM2	CH	0.000003	5	3.12E-05	**significant**

Medieval	Males v Females	CH	0.058	6	0.3965	not significant
Pooled	AMTL effect on DW - ManM1 PA	CI	0.059	7	0.3965	not significant
Pooled	AMTL effect on DW - ManM1 PA	CH	0.061	8	0.3965	not significant
Pooled	AMTL effect on DW - ManM3 PA	CH	0.13	9	0.751111	not significant
Bronze Age	Males v Females	CI	0.162	10	0.825659	not significant
Iron Age	Males v Females	CI	0.197	11	0.825659	not significant
Pooled	AMTL effect on DW - ManM3 OA	CI	0.214	12	0.825659	not significant
Pooled	AMTL effect on DW - ManM3 OA	CH	0.236	13	0.825659	not significant
Pooled	AMTL effect on DW - ManM1 MA	CI	0.249	14	0.825659	not significant
Anglo-Saxon	Males v Females	CI	0.263	15	0.825659	not significant
Pooled	AMTL effect on DW - ManM3 PA	CI	0.269	16	0.825659	not significant
Romano-British	Males v Females	CH	0.273	17	0.825659	not significant
Pooled	AMTL effect on DW - ManM2 PA	CH	0.305	18	0.825659	not significant
Pooled	AMTL effect on DW - ManM3 MA	CI	0.321	19	0.825659	not significant
Romano-British	Males v Females	CI	0.43	20	0.825659	not significant
Pooled	AMTL effect on DW - ManM1 MA	CH	0.443	21	0.825659	not significant
Pooled	MaxM1 v ManM1	CH	0.468	22	0.825659	not significant
Pooled	AMTL effect on DW - ManM1 OA	CI	0.48	23	0.825659	not significant
Pooled	LMaxM2 v RMaxM2	CH	0.503	24	0.825659	not significant
Pooled	AMTL effect on DW - ManM1 YA	CI	0.503	25	0.825659	not significant
Iron Age	Males v Females	CH	0.51	26	0.825659	not significant
Pooled	AMTL effect on DW - ManM2 MA	CI	0.527	27	0.825659	not significant
Pooled	AMTL effect on DW - ManM2 OA	CH	0.531	28	0.825659	not significant
Post-Medieval	Males v Females	CI	0.536	29	0.825659	not significant
Pooled	LMaxM3 v RMaxM3	CI	0.564	30	0.825659	not significant
Pooled	AMTL effect on DW - ManM1 YA	CH	0.57	31	0.825659	not significant
Pooled	LManM2 v RManM2	CH	0.571	32	0.825659	not significant

Neolithic	Males v Females	CH	0.578	33	0.825659	not significant
Pooled	LMaxM1 v RMaxM1	CH	0.579	34	0.825659	not significant
Pooled	AMTL effect on DW - ManM3 MA	CH	0.591	35	0.825659	not significant
Bronze Age	Males v Females	CH	0.596	36	0.825659	not significant
Medieval	Males v Females	CI	0.599	37	0.825659	not significant
Pooled	LManM1 v RManM1	CI	0.615	38	0.825659	not significant
Post-Medieval	Males v Females	CH	0.63	39	0.825659	not significant
Pooled	LManM2 v RManM2	CI	0.642	40	0.825659	not significant
Pooled	LManM1 v RManM1	CH	0.651	41	0.825659	not significant
Pooled	LMaxM1 v RMaxM1	CI	0.673	42	0.832	not significant
Pooled	AMTL effect on DW - ManM1 OA	CH	0.688	43	0.832	not significant
Pooled	LManM3 v RManM3	CI	0.714	44	0.843818	not significant
Pooled	LMaxM3 v RMaxM3	CH	0.74	45	0.855111	not significant
Pooled	AMTL effect on DW - ManM2 MA	CH	0.771	46	0.85634	not significant
Pooled	AMTL effect on DW - ManM2 PA	CI	0.774	47	0.85634	not significant
Pooled	LMaxM2 v RMaxM2	CI	0.827	48	0.878694	not significant
Pooled	AMTL effect on DW - ManM2 OA	CI	0.828	49	0.878694	not significant
Neolithic	Males v Females	CI	0.907	50	0.925	not significant
Anglo-Saxon	Males v Females	CH	0.91	51	0.925	not significant
Pooled	LManM3 v RManM3	CH	0.925	52	0.925	not significant

Table C. 4. Adjusted p-values following the Benjamini-Hochberg procedure for Independent-T-Tests with a critical value of 0.5

Sample	Comparison	Measurement	P-value	Rank	Adjusted p-values	
Pooled	AMTL effect on DW - ManM3 OA	%DE	0.023	1	0.63000	not significant
Pooled	AMTL effect on DW - ManM1 PA	%DE	0.092	5	0.64350	not significant

Pooled	AMTL effect on DW - ManM2 PA	WS	0.128	7	0.64350	not significant
Pooled	AMTL effect on DW - ManM1 YA	WS	0.134	8	0.64350	not significant
Pooled	AMTL effect on DW - ManM1 MA	%DE	0.137	9	0.64350	not significant
Pooled	AMTL effect on DW - ManM1 OA	WS	0.143	10	0.64350	not significant
Pooled	AMTL effect on DW - ManM3 PA	%DE	0.166	11	0.66750	not significant
Pooled	AMTL effect on DW - ManM1 OA	%DE	0.203	13	0.70269	not significant
Pooled	AMTL effect on DW - ManM1 PA	WS	0.277	15	0.83100	not significant
Pooled	AMTL effect on DW - ManM1 MA	WS	0.347	16	0.91853	not significant
Pooled	AMTL effect on DW - ManM3 PA	WS	0.347	17	0.91853	not significant
Pooled	AMTL effect on DW - ManM1 YA	%DE	0.548	21	0.99600	not significant
Pooled	AMTL effect on DW - ManM2 OA	%DE	0.649	23	0.99600	not significant
Pooled	AMTL effect on DW - ManM3 MA	WS	0.655	24	0.99600	not significant
Pooled	AMTL effect on DW - ManM3 MA	%DE	0.667	25	0.99600	not significant
Pooled	AMTL effect on DW - ManM2 MA	%DE	0.779	29	0.99600	not significant
Pooled	AMTL effect on DW - ManM2 OA	WS	0.865	35	0.99600	not significant
Pooled	AMTL effect on DW - ManM2 MA	WS	0.87	36	0.99600	not significant
Pooled	AMTL effect on DW - ManM3 OA	WS	0.939	41	0.99600	not significant
Pooled	AMTL effect on DW - ManM2 PA	%DE	0.984	43	0.99600	not significant
Anglo-Saxon	Male v Female	WS	0.104	6	0.64350	not significant
Bronze Age	Male v Female	WS	0.435	18	0.99600	not significant
Iron Age	Male v Female	WS	0.546	20	0.99600	not significant
Medieval	Male v Female	WS	0.995	44	0.99600	not significant
Neolithic	Male v Female	WS	0.883	39	0.99600	not significant

Pooled	MaxM3 v ManM3	WS	0.028	2	0.63000	not significant
Pooled	MaxM3 v ManM3	%DE	0.056	3	0.64350	not significant
Pooled	MaxM2 v ManM2	WS	0.089	4	0.64350	not significant
Pooled	MaxM1 v ManM1	WS	0.178	12	0.66750	not significant
Pooled	MaxM1 v ManM1	%DE	0.252	14	0.81000	not significant
Pooled	LMaxM3 v RMaxM3	%DE	0.533	19	0.99600	not significant
Pooled	MaxM2 v ManM2	%DE	0.638	22	0.99600	not significant
Pooled	LMaxM3 v RMaxM3	WS	0.696	26	0.99600	not significant
Pooled	LManM2 v RManM2	WS	0.726	27	0.99600	not significant
Pooled	LManM2 v RManM2	%DE	0.814	31	0.99600	not significant
Pooled	LMaxM1 v RMaxM1	%DE	0.817	32	0.99600	not significant
Pooled	LManM1 v RManM1	WS	0.837	33	0.99600	not significant
Pooled	LMaxM1 v RMaxM1	WS	0.854	34	0.99600	not significant
Pooled	LManM3 v RManM3	WS	0.876	37	0.99600	not significant
Pooled	LManM3 v RManM3	%DE	0.879	38	0.99600	not significant
Pooled	LMaxM2 v RMaxM2	%DE	0.909	40	0.99600	not significant
Pooled	LManM1 v RManM1	%DE	0.947	42	0.99600	not significant
Pooled	LMaxM2 v RMaxM2	WS	0.996	45	0.99600	not significant
Post-Medieval	Male v Female	WS	0.797	30	0.99600	not significant
Romano-British	Male v Female	WS	0.736	28	0.99600	not significant

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Appendix D Skeletal Materials

Appendix D presents the skeletal material and raw dental wear measurements recorded throughout the duration of this thesis (attached CD).

Key

\	Absent
%DE	Percent of exposed dentine measurement
C	caries
CA	Congenitally absent
Calc	Calculus
CH	Average crown height measurement
CI	Crown index measurement
D	Damage
F	Female
F?	Possible female
L	Left
M	Male
M?	Possible male
M1	First molar
M2	Second molar
M3	Third molar
Man	Mandibular molar
Max	Maxillary molar
P	present
R	Right
WS	Wear stage
X	Ante-mortem tooth loss

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