On the threshold of adulthood: a new approach for the use of maturation indicators to assess puberty in adolescents from medieval England

Article

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On the threshold of adulthood: A new approach for the use of maturation indicators to assess puberty in adolescents from medieval England.

Mary Lewis, MSc, PhD (m.e.lewis@reading.ac.uk)

Fiona Shapland, MSc, PhD (fionashapland@gmail.com)

Rebecca Watts, MSc, PhD (r.watts@pgr.reading.ac.uk)

Department of Archaeology, University of Reading, Whiteknights, Reading, England, UK, RG6 6AB.

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Author for correspondence: Dr Mary Lewis (address and email as above), Tel: 0118 378 8927; fax 0118 378 6718

Abstract

Objectives*:* This study provides the first large scale analysis of the age at which adolescents in medieval England entered and completed the pubertal growth spurt. This new method has implications for expanding our knowledge of adolescent maturation across different time periods and regions.

Methods: In total, 994 adolescent skeletons (10-25 years) from four urban sites in medieval England (AD 900-1550) were analysed for evidence of pubertal stage using new osteological techniques developed from the clinical literature (i.e. hamate hook development, CVM, canine mineralisation, iliac crest ossification, radial fusion).

Results*:* Adolescents began puberty at a similar age to modern children at around 10-12 years, but the onset of menarche in girls was delayed by up to 3 years, occurring around 15 for most in the study sample and 17 years for females living in London. Modern European males usually complete their maturation by 16-18 years; medieval males took longer with the deceleration stage of the growth spurt extending as late as 21 years.

Conclusions: This research provides the first attempt to directly assess the age of pubertal development in adolescents during the tenth to seventeenth centuries. Poor diet, infections, and physical exertion may have contributed to delayed development in the medieval adolescents, particularly for those living in the city of London. This study sheds new light on the nature of adolescence in the medieval period, highlighting an extended period of physical and social transition.

Keywords: epiphyseal fusion, dental age, hamate hook, CVM, menarche

Introduction

Today, ‘adolescence’ is a term used to cover the uniquely human period that falls between childhood and adulthood. Biologically this encompasses the timing of the growth spurt, sexual maturation and the completion of physical development (or puberty), but also refers to the period in which an individual transitions between childhood dependency and functioning as an independent adult (Marshall and Tanner, 1986; Viner, 2008; Hochberg and Belsky, 2013). In the medieval period, this period of transition was often defined by the individual leaving home for work and gaining economic autonomy (Hanawalt,1993). Adolescents often began paid work, apprenticeships and other periods of service from around 12 years of age, or sometimes earlier (Goldberg, 2004, Alexandre-Bidon and Lett, 1999). The inclusion of 14 year olds in the English poll tax of AD 1377 suggests that by this age individuals were considered to be of independent means (Fenwick, 1998). In the 12th century, Cluniac orders placed ‘adolesencia’ at 15 years, and considered this the time at which boys entered puberty (Alexandre-Bidon and Lett, 1999). Undoubtedly, these physical changes must have been important in deciding how an individual was viewed; puberty would have signalled a wealthy female’s suitability for marriage and childbirth (Philips 1999), and reported incidents such as the raising of girls’ skirts to determine whether they were of poll tax age (Goldberg, 2004) suggest that sexual maturation stood as a proxy for true age in this society. Gilchrist (2000: 42) called for more research to be carried out into the medieval adolescent life course and suggested that both the ‘extended male adolescence’ and north-western European marriage pattern highlighted by historians may be related to delayed maturation in medieval adolescents. Despite these rare glimpses, medieval documentary sources are relatively silent on biological matters, and little is known about the age at which medieval individuals started to show the outward signs of puberty, such as breast development, increased musculature, menarche and the breaking of the voice.

Modern European adolescents normally experience the onset of puberty at round 10-12 years (Aksglaede et al., 2008), and maturation it is often complete by 13-17 years for girls and 15-18 years for boys (Hägg and Taranger, 1982), although there can be considerable individual variation (Tanner, 1989). When compared to records from the nineteenth century, the age of puberty appears to have undergone a significant decline in modern populations. As the age of menarche is a clear indicator that puberty is underway it is often used to estimate its onset. In the 1860s, menarche occurred between the ages of 14 years (USA) and 17 years (Finland) depending on social status (Eveleth and Tanner, 1990). Since then, the age at menarche has fallen consistently, with females in modern industrialised countries experiencing their menarche at around 13 years (Marshall and Tanner, 1986). This decrease is usually ascribed to improvements in health, nutrition and environmental conditions (de Muinck Keizer-Schrama and Mul, 2001), and there is evidence that this decline has now begun to stabilise (Coleman and Coleman, 2002; Dorn and Biro 2011). Thomas et al. (2001) argue that variability in the age at menarche is largely determined by extrinsic factors, and studies have consistently shown a link between poor nutritional status and a delay in menarche regardless of the child's ancestry or climate (Zacharias and Wurtman, 1969; Gluckman and Hanson, 2006; Karapanou and Papadimitriou, 2010; Goyal et al., 2012). In addition, acute and chronic illness and accumulated childhood hardships (e.g. poverty, poor nutrition, exposure to alcoholism or tobacco smoke, physical neglect, death of a parent) delay menarche as a stress response (Karapanou and Papadimitriou, 2010; Boynton-Jarrett and

Harville, 2012; Dossus et al., 2012). It is likely that the high levels of disease and poor nutrition associated with rapid social and economic change in the nineteenth century pushed the mean age to artificially high levels, providing an uneven picture of pubertal development in the past. In the medieval period for example, the age of menarche was reported to be similar to modern estimates. In the eleventh century, Trotula (Green, 2001), in a treatise on female medicine, placed it at 14-15 years, and by the thirteenth century this age was reduced to 12-13 years, similar to modern levels (Post, 1971). Only after the 1550s was the age of menarche reported to increase to post-medieval levels (Backman,1947). Until recently, these accounts are all the evidence we have had for the timing of puberty prior to the nineteeth century. Detailed analysis using direct evidence of adolescent skeletons from medieval cemetery sites have been hindered by small sample sizes, with low numbers of individuals dying between 10-17 years.

Recent large scale excavations have provided the first opportunity for direct research into the growth, maturation and health of the medieval adolescent. In 2013 and 2014, Shapland and Lewis modified a series of maturational traits used by clinicians to record pubertal stages for application in bioarchaeology. Analysis of a small sample of medieval adolescents suggested that both males and females began puberty around 10-12 years, as today, but that the tempo of pubertal growth was longer, with females achieving menarche between 13-16 years, and individuals being as old as 16-20 years before they were fully mature. This current study aims to explore the utility of these methods on a larger sample of medieval adolescents from three contrasting urban sites.

Assessing pubertal stage from skeletal and dental markers

The adolescent growth spurt and onset of puberty follows a well-mapped sequence. Growth is accelerated until 'peak height velocity' (PHV) has been reached (Marshall and Tanner, 1986). As growth begins to decelerate girls will experience their menarche and boys develop a full adult voice (Hägg and Taranger, 1982). The growth spurt ends with the fusion of the long bone epiphyses and final maturation of the pelvis (Marshall and Tanner, 1986). Maturational markers used to establish 'bone age' in relation to a child's position within the pubertal sequence in clinical practice have recently been adapted for use in archaeological skeletal remains. Shapland and Lewis (2013; 2014) outlined methods based on the dentition, hand, wrist, pelvis and cervical vertebrae. Certain of these indicators have the potential to enable us to examine at what age important stages of pubertal development were reached in past populations. In boys, peak height velocity signals an increase in weight and musculature that improves their physical capacity (Philippaerts et al., 2006). In girls, PHV also corresponds to an increase in breast size (Marshall and Tanner 1969) signalling their transition to womanhood in medieval society. The hook of the hamate in the wrist is completed (Stage I) around six months before peak height velocity (Grave and Brown, 1976), and attainment of Demirjian et al.'s Stage G for the canine (root complete or apex 1/2) has been shown to occur between 0.4 years and 1.3 years before PHV for girls and boys, respectively (Coutinho et al., 1993). Stages 3 and 4 of cervical vertebra morphology have been correlated with PHV (Franchi et al., 2000). Roche (1976) reported that fusion of the proximal ulna epiphysis preceded PHV in males and females. Shortly after PHV, we should expect to see fusion of the phalangeal epiphyses and capitulum at the lateral distal humerus (Houston, 1980; Roche, 1976).

Females tend to achieve menarche after PHV and during the deceleration phase (Tanner, 1989). While ossification of the iliac crest is a strong signal that menarche has recently begun, in archaeological contexts, this thin strip of bone rarely survives. Where an ossified iliac crest is present, however, or where subsequent fusion of the epiphysis has begun, this indicates that menarche has been achieved. Menarche has also been found to occur around the time that the first (distal) hand phalangeal epiphyses and the distal phalanx of the second metacarpal begins to fuse (Buehl and Pyle, 1942; Frisancho et al., 1969).

Materials

Four medieval sites were selected for the study and represent a variety of different living and working environments (Figure 1, Table I). Barton-upon-Humber (Barton) was a relatively wealthy small town in the Lincolnshire countryside, located on the Southern bank of the river Humber and surrounded by good quality agricultural land (Waldron, 2007). Despite the existence of a port and a ferry, the majority of residents are believed to have been born locally, occupied in agriculture or river trade (Waldron, 2007). Documentary evidence indicates that the richer and middle class members of the population were buried in the cemetery of St. Peter's Church (AD 950-1700) (Tyszka, 2006). Isotopic analysis of the assemblage indicates that the population were well-nourished, with diets consisting of meat, vegetables, and fish (Beavan et al., 2011). By contrast, the 90 adolescents from the cemeteries of Fishergate House (AD 950-1700) and St. Helen-on-the-Walls (AD 950-1550) in York represent individuals who lived in the poorest areas of the urban centre (Dawes and Magilton, 1980). Archaeological and documentary evidence suggests that living conditions here were crowded, with dwellings being used for both residential and industrial purposes (Palliser, 1980). As well as inhabiting an environment conducive to the spread of disease, it is unlikely that the poorer residents of York were able to afford a nutritionally adequate diet, or grow much produce of their own. Instead, they would have been reliant on meals purchased from the city's cook shops and markets, with bread, porridge and ale being common medieval staples (Roberts and Cox, 2003). The final study group was derived from St. Mary Spital, London (AD 950-1500). The site contains an unusually large proportion of adolescents and young adults, and this may reflect its use as a hospital cemetery which took in unmarried pregnant women and invalids as well as migrant workers who had nowhere else to turn to in times of illness (Connell et al., 2012). The total sample comprised 994 individuals aged between 10-25 years.

Table I, Figure 1 here

Methods

Age and sex determination

Age-at-death was determined using calcification of the permanent mandibular dentition (excluding the mandibular canine, see below) based on a large reference sample of white Canadians of European descent (Moorrees et al.,1963). A mean age-at-death was then calculated by averaging ages of attainment for all observed teeth. Where only the third molar was observable, the revised age estimates provided by Liversidge and Marsden (2010) were used. In order to provide some consistency in age estimates where the sex of the individual was unknown, all ages were estimated using the combined male and female average for each tooth. Individuals were then placed into one-year age categories (i.e. 10.0-10.9 etc.)

ranging from 10 to 19 years. The use of a single mean age at death has the potential to introduce an error by as much as 2-4 years around actual chronological age (Liversidge and Marsden, 2010). However, this approach was necessary in order for a more detailed assessment of age at pubertal stage to be carried out. While the degree of error is likely to be similar for the archaeological samples, it needs to be taken into account when attempting to compare the archaeological with the modern children where their age is known.

Once dental development was complete, individuals were aged based on skeletal maturation, excluding those areas used to assess puberty. Those aged 20-21 years were defined as having fused long bone diaphyses; an extended epiphysis of the ischio-pubic ramus (18-21 years); an open junction between S1 and S2 on the sacrum (closes 20-25 years); an unfused or flaked epiphysis at the medial clavicle (18-21 years) and a fused or fusing ischial epiphysis and vertebral annular rings (complete 18-23 years) (Scheuer and Black, 2000; Albert and McCallister, 2004). Those assigned to the 22-25 year category demonstrated complete fusion of the vertebral annular rings, ischial epiphysis and sacrum, and a fusing epiphysis at the medial clavicle (c. 21-25 years). Anyone with a fused S1-S2 junction and fused medial clavicle epiphysis were considered to be over 25 years of age. While these age assignments are subject to population variation and may be delayed in environmentally adverse conditions, they served to divide the young adults into a more defined group and allow an end point of maturation to be identified.

As the timing of puberty varies between males and females, it was desirable to examine stages in as many sexed individuals as possible, especially around 10-12 years when modern children commonly start the process. Sex determination in immature skeletal remains is problematic due to changes in morphology during growth and development of the skull and pelvis, and the variations in growth trajectories and rates of maturation that exist in males and females, and in different populations (Wilson et al., 2015). Several methods have been shown to be more sex-related with increasing age, with the best results reported for the ilium (Sutter, 2003; Wilson et al., 2015). Skeletons aged 10.0-13.9 years were sexed based on features on the pelvis and humerus, and 'male' or 'female' assigned when both traits agreed. Reported accuracies for predicting sex vary depending on the population studied and the age of the sample. Only traits that achieved over 70% accuracy in individuals over 10 years of age were selected (ilium: sciatic notch angle (72%), sciatic notch depth (81%), auricular elevation (72-85%); humerus: trochlear symmetry (81.5%), olecranon fossa shape (85%), medial epicondyle angle (78%); mandible: chin prominence (73%)) (Sutter, 2003; Falys et al., 2005). After the age of 15 years, only standard methods used to sex adults based on pelvis were used (Buikstra and Ubelaker, 1994), as many cranial features will still be unpronounced in young males (Walker et al., 1988).

Assessment of pubertal stage

An assessment of pubertal stage was carried out using a series of skeletal and dental developmental features identified in the clinical literature (Table 2) and developed for skeletal analysis (Shapland and Lewis, 2013; 2014). In dry bone, the epiphyseal union is scored on a three stage scale: 1) no union, 2) partial union where fusion has begun and the junction between the epiphysis and metaphysis is still clearly visible, and 3) complete union, where the fusion line is faint or completely obliterated (Buikstra and Ubelaker, 1994). Cervical vertebra morphology was scored for all samples except Barton, which was studied before the CVM method was developed. A pubertal stage was assigned where three or more features could be observed. Commencement of fusion of the phalangeal epiphyses was considered to indicate that PHV had been passed and that, in females, menarche had been achieved. The presence of the ossified superior iliac crest was also taken as an indicator that PHV had been passed, and that menarche had occurred.

Table II here

Results

Demography

Of the original 994 individuals in the study, 645 were assigned a mean dental age. Of these 470 (72.8%) could be assigned a sex, with 283 males and 187 females (Table III). In the 18 and 19 year categories, 49 individuals (26 males and 26 females) were assigned a mean age based on the development of the third molar alone. In the original sample, the phalanges were the most common bone observed (n=449 individuals) followed by the canine (n=392), iliac crest (n=391), distal radius (n=370) the cervical vertebrae (n=322) and the hamate (n=138). Eighty individuals had data for all five areas. An unfused ossified iliac crest epiphysis was identified in 26 cases, and in nine females. Three individuals presented with a malformed or absent hamate hook. Pubertal stage was determined for 348 (78.2%) of the dentally aged individuals displaying three or more traits, 236 (67.8%) of whom could be assigned a sex (152 males; 84 females). In the 20-21 and 22-25 year categories, where dental ageing was no longer possible, there were 187 individuals for whom a pubertal stage was assessed. The results are summarised in Table III and Figures 2-4.

Table III here

The onset of puberty

Observations of the mandibular canine, the hamate hook, and cervical vertebrae suggest that adolescents were experiencing the onset of the pubertal growth spurt by 10-12 years of age. Fifty-four percent of 10 year olds, 22% of 11 year olds and just 6% of 12 year olds were pre-pubertal based on Demirjian et al. (1976) Stage G for the mandibular canine. For the hamate, Stage G (no hook) was only observed in three cases, two 10 year olds and one adolescent aged 11 years. Pre-pubertal individuals would also be expected to display CVM at Stage 1 (initiation) (Hassel and Farman, 1995), and of the 40 individuals showing this stage, 87.5% were around 10-11 years, and 10% were 12 years of age. One individual from London still displayed a Stage 1 cervical vertebra at around 14 years. Stage H (hook appearing) coincides with the early stages of the pubertal growth spurt (Grave and Brown, 1976), and in 96% (n=22 of 23) of cases was noted in adolescents aged 10-12 years. One 13 year old, again from London still displayed Stage H. Both of the London individuals with a later onset were female.

Acceleration of the growth spurt

The acceleration phase of the pubertal growth spurt is difficult to identify in skeletal remains. Analysis of those with a canine at G or H, hamate hook at H or H.5 and CVM Stage 2, revealed a wide age range, spanning 10-16 years. The majority (70%) of adolescents considered to be at this stage were 10-12 years (n=85/121), 17% had reached acceleration by 15 years, while 10 (8.2%) took between 15-17 years to achieve this phase. All of these individuals were from London, with the exception of a 16 year old from York, who had a paralysed arm (disuse atrophy). Where sex could be assessed (n=6), all except one of these later developers were male. In the cervical vertebrae, Stage 2 (acceleration) was achieved between 10 to 13 years of age in 93% cases, although five individuals with Stage 2 had a mean age of 15.6 years. Sixty percent of the individuals who were behind their peers in entering the acceleration phase had a chronic pathology (i.e. rickets, osteomyelitis, or tuberculosis).

Peak height velocity

Peak height velocity (PHV) was determined by a Stage I hamate hook and a Stage 3 CMV in combination with a fused or fusing proximal ulna or fusing capitate epiphysis at the distal humerus. PHV was suggested in 53 cases. This phase spanned the whole growth period with individuals aged between 11-19 years showing skeletal traits that indicated they had entered or had just completed PHV. By 11-13 years 22.6% individuals had reached PHV, the majority (39%) were aged 15 years, with 24% aged 16-17.5 years. Both males and females experienced PHV over the same extended period, with females (n=7) aged between 12-17 years and males (n=26) aged between 11-18 years. Two males from London with skeletal traits that suggested they were around PHV were 18.4 and 19.3 years. The eldest had a chronic infection in his shoulder.

Age of menarche

Whether a female had achieved menarche could be assessed in 201 individuals. The presence of an ossified but unfused iliac crest epiphysis in nine females aged between 15-17 years indicates that these girls had begun to menstruate. The evidence of distal hand phalangeal fusion supports this finding, which began around the age of 15 years. The 69 females yet to achieve menarche when they died were aged 10-17 years. By 15-17 years only 10 (14%) were pre-menarche; two females from Barton and eight from London. When she died in London at 17 years, a female with severe congenital curvature of the spine had still not achieved menarche.

Deceleration of the growth spurt and start of maturation

The majority of individuals (78%) began deceleration of the growth spurt by 15-18 years (Figures 2-4). Unfused phalangeal epiphyses were observed as late as 19 years in the London males, although in most cases fusion commenced at around 17 years in both males and females. Complete fusion was observed in individuals aged from 15 to19 years, however three females (one from London and two from Barton) had complete fusion of their phalangeal epiphyses earlier, by 12, 13 and 14 years respectively.

Partial fusion of the iliac crest and distal radius commenced between 15-19 years of age, with a mean age of 18 years in both males and females. This is similar to the modern pattern where the iliac crest fuses between 14-18 years in females and 17-20 years for males (Schaefer et al., 2009). For CVM (Stage 4: deceleration; Stage 5: maturation) deceleration was suggested in one London female aged 12 years, but the average age was 17 years for both males and females. Two London females, both estimated to be 22-25 years were still in the deceleration phase of the growth spurt when they died.

Puberty complete

Of the 25 individuals that could be dentally aged, complete maturation (post-puberty) was seen individuals aged between 15-19 years, but there was no variation in the male and female scores, perhaps suggesting a delay in medieval females who usually finish maturing around two years before the males. However, the sample size is small. Complete fusion of the iliac crest was seen between the ages of 16-19 in males and 17-19 in females, with the radius complete between 16-19 years in both sexes. Individuals with the latest ages for iliac crest fusion were the St Mary Spital females, where 67% (4 of 6) individuals in whom it was observed were 19 years of age. While CMV (Stage 6), radial and phalangeal fusion data suggested that all of those aged 22-25 in Barton and York were through puberty, 29% (34/117) individuals from London (17 males and 17 females) still demonstrated partial fusion of the iliac crest indicating that while deceleration had occurred, puberty was not yet complete.

Figures 2-4 here

Discussion

This research provides the first attempt to directly assess the age of pubertal development in adolescents during the tenth to seventeenth centuries. The employment of modern clinical markers to track the progress of puberty in archaeological skeletal remains is not without its problems. Many modern studies use longitudinal data and growth velocity to calculate the onset and tempo of puberty in healthy living children of known age and sex. Archaeological data is cross-sectional and based on children who died during adolescence either through acute or chronic diseases or fatal injury. We cannot assess velocity of growth and therefore rely on individual independent measures of canine development, epiphyseal fusion and skeletal morphological changes. The link between the age of epiphyseal fusion of the radius and iliac crest and pubertal stage in modern practice is based on radiographic assessments that may record 'fusion' slightly earlier than it is observed in dry bone (Krogman and Iscan, 1986; Cardoso, 2008). In addition, our ability to accurately assign a biological sex to skeletal material is limited before the secondary sexual characteristics associated with pubertal maturation are established. While sexing children over the age of 10 years has been found to be more accurate than in younger individuals, we can only be confident we have achieved between 72-85% accuracy. Dental age assessment in the older adolescents relied on the third molar, a tooth that is notoriously variable. Individuals estimated to have a mean age of 17 years could actually be between 14-21 years (Liversidge and Marsden, 2010: 4), making direct comparisons with modern populations difficult. Nevertheless, when ages of pubertal attainment are compared between the medieval samples, the degree of error introduced by using modern methods is likely to be the same. Taking a robust approach that required three or more traits to be observed in individuals with a dental mean age considerably reduced the sample size from an initial 994 to a sexed and dentally aged sample of just 236 individuals. Hence, any attempt to study puberty in future archaeological populations will require a large original sample.

Despite these caveats, the results demonstrated considerable variation in the data, with the expected presence of early and late maturers seen in the modern data. This indicates that the variation in the traits we recorded is reflecting changes during puberty. Marshall and Tanner (1969; 1970) outlined the variations in onset and tempo of pubertal development in 192 and 228 British boys and girls assessed between 1951 and 1970. In girls they recorded that puberty commenced between 8.5-13.0 years, with PHV reached at approximately 12 years, menarche around 13 years, with the end of puberty falling between 11.8 to 18.9 years. Although girls of a lower social economic status could be a year behind in menarche compared to their wealthier peers (Marshall and Tanner, 1969). For boys puberty phases were 9.5-13.5 years (start), 14 years (PHV) and 13-17 years (finish), respectively. Boys could take anywhere between 1.8 to 4.7 years to reach full maturity from its outset. The wide degree of variation in these timings in children with no reported clinical history is notable. In the archaeological data, the group of adolescents we anticipate experienced the most physiological and psychological stress, those living in medieval London, showed a greater delay in the age at menarche and final maturation when compared to their peers from Barton and York. The results show that in medieval England, adolescents experienced the onset of the pubertal growth spurt at a similar age as in Europe today (Table IV).

Table IV here

A study of 156,835 modern Danish children demonstrated that the onset of the pubertal growth spurt occurred at 10 years on average in females, and 12 years in males (Aksglaede et al., 2008). In the combined sex group, medieval adolescents experienced the onset of puberty at much the same age, between 10-12 years.

Although two females had still not started their pubertal growth when they died aged 13 years old. That the onset of puberty displays such little variation among groups which experienced a diverse range of living conditions suggests that the biological triggers which activate the hormonal changes at the start of puberty, may not strongly inhibited by environmental factors (Aksglaede et al., 2008). The acceleration phase of the growth spurt is estimated to have continued to 16 years of age for some, compared to 12 or 14 for modern girls and boys. Of those with traits that suggested they were still experiencing acceleration at 15-16 years, 60% suffered a chronic infection such as tuberculosis, and of the sexed individuals, 83% were male. The largest numbers of adolescents were achieving PHV by 15 years of age, but ages spanned 11-17 years. One London male had not achieved PHV when he died at 19 years old, and this may have been due to physiological stress as the result of a chronic infection in his shoulder. PHV in modern populations is usually reached by 12 years in girls and 14 in boys (Tanner, 1989) and so the majority of our medieval adolescents are not too far behind. This stage of development is associated with increased physical strength in boys and greater breast development in girls. If the average medieval adolescent was showing an increase in their height, weight and musculature at around 15 years, then this fits with the ecclesiastical view of when a male was mature enough to take the pledge to be a monk. However, for those starting work around 12 years of age, they may have been required to start heavy manual labour before they were physically able, having implications for their overall health and physical development (Thomas et al., 2001). Changes associated with the deceleration of the growth spurt, such as menarche for girls and the breaking of the voice for boys, were more delayed. The results indicate that 86% of medieval females achieved menarche at 15 years, compared to 13 years in well-nourished modern females, in London this age was as late as 17 years. Similarly, several London males were dying in the deceleration phase at 18-19 years, around two years later than the age estimates for modern Europeans. In our sample, 41.6% of females and 34.2% of males died during the deceleration and maturation phases. However, there was also evidence that some females were maturing more quickly with three females entering deceleration between 12-14 years of age. While the majority of medieval adolescents completed puberty by 15-19 years (16-19 for females and 17-19 for males), based on the fusion of their pelvis and cervical spine morphology, 29% of Londoners had still not achieved complete maturation by the time they died at 22-25 years of age.

This period of physical and sexual development is at odds with medieval canon law, where the legal age at which boys and girls could consent to marriage was 14 and 12 years respectively. This encompasses a time when both would have experienced the onset of puberty, but predates the period in which the majority of females would have been fertile (c.15-16 years). In practice, it seems males and females in thirteenth to fifteenth century England married between 18-23 years (Hallam, 1985) when our data shows the majority were fully mature, with urban females marrying slightly later, perhaps reflecting their greater financial and social independence (Goldberg, 1992).

Today, early and late maturing adolescents can suffer psychological stress and low self-esteem as the result of being different from their peers (Tanner et al., 1975; Dorn and Biro, 2011). While we cannot directly assess psychological stress from skeletal remains, the existence of such late maturing Londoners this would have had implications in terms of the age of transition to adulthood, their ability to carry out an adult workload and to bear children.

While medieval adolescents experienced the onset of puberty at similar time to their modern day counterparts, it took them considerably longer to reach PHV, deceleration and final maturation. In London, where the differences are most pronounced, it is likely that a poor diet, chronic disease, manual labour and stressful environmental conditions influenced the tempo of puberty in adolescence. Today when a child might be expected to have finished their development by 18 years, London adolescents took up to four years longer to reach maturity.

Conclusions

This study represents the first large scale study of puberty in medieval England. While the modern data for the ages at which children enter and progress through puberty cannot be directly compared, the results suggest that medieval adolescents experienced the onset of puberty at around the same time (10-12 years), but that they fell slightly behind achieving the other milestones. Medieval adolescents achieved menarche around 15 years and final maturation between 19 to 22 years, with 26% of individuals in medieval London dying aged 22-25 years, before they had reached full maturity.

An inadequate diet, exposure to disease and a heavy physical workload are likely to have contributed to the delayed development of the medieval adolescents, suggesting the potential of this method to measure environmental stress in the past. The variability in the ages at which adolescents reached the different pubertal stages, and the presence of early and late maturers in all groups, reflects modern patterns and emphasises the ability of these clinical markers to accurately track puberty in skeletal remains. This research was based on a uniquely large adolescent sample, but in many cases skeletons were only preserved well enough of only one or two traits to be observed. Future research should seek to improve the link between individual markers, such as CVM, with PHV menarche, to reduce the impact of poor preservation and increase the number of individuals for whom such stages can be assessed, allowing much smaller samples to be analysed. Comparisons exploring the timing of pubertal development in individuals from earlier and later periods, and urban and rural comparisons should help us to further elucidate the environmental and genetic factors affecting puberty, the adolescent life-course and ultimately, fertility in the past.

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Declaration of Interest

There are no conflicts of interest

References

Acheson RM. 1957. The Oxford method of assessing skeletal maturity. *Clin Orthop Relate R.* 10:19-39.

Aksglaede L, Olsen L, Sorensen T, Juul A. 2008. Forty years trends in timing of pubertal growth spurt in 157,000 Danish school children. *PloS ONE* 3 (7):e2728.

Albert AM, McCallister K. 2004. Estimating age at death from thoracic and lumbar vertebral ring epiphyseal union data. *Am J Phys Anth.* 38:51.

Alexandre-Bidon D, Lett D. 1999. *Children in the Middle Ages, 5-15th century*. Paris, Hachette Littérature.

Baccetti T, Franchi L, McNamara J. 2002. An improved version of the cervical vertebral maturation (CMV) method for the assessment of mandibular gowth. *Angle Orthod.* 72:316-323.

Baccetti T, Franchi L, McNamara J. 2005. The cervical vertebral maturation (CVM) method for the assessment of optimal treatment timing in dentofacial orthopedics. *Semin Orthod.*11:119-129.

Backman G. 1947. Die beschleunigte entwicklung der jugend. Verfrühte menarche, verspätete menopause, verlängerte lebensdauer. *Acta Anat.* 4:421-480.

Beavan N, Mays S, Cook G, Ditchfield D. 2011. Stable isotope analysis. In: Rodwell W, Atkins C, editors. *St Peter's Barton-upon-Humber, Lincolnshire. A Parish Church and its Community, History, Archaeology and Architecture. Part 2.* Oxford, Oxbow. 762-767pp

Boynton-Jarrett R, Harville E. 2012. A prospective study of childhood social hardships and age at menarche. *Ann Epidemio.* 22:731-737.

Buehl C, Pyle S. 1942. The use of age at first appearence of three ossification centers in determining the skeletal status of children. *J Pediatr.* 21:335-342.

Buikstra J, Ubelaker D, eds. 1994. *Standards for Data Collection from Human Skeletal Remains.*, *Arkansas Archaeological Survey Research Series 44*. Fayetteville, Arkansas Archeological Survey.

Cardoso H. 2008. Epiphyseal union at the innominate and lower limb in a modern Portuguese skeletal sample, and age estimation in adolescent and young adult male and female skeletons. *Am J Phys Anthrop.*135:161-170.

Chertkow S. 1980.Tooth mineralization as an indicator of the pubertal growth spurt. *Am J Orthod.* 77:79-91.

Clapson R. 2005.The later history of Barton-upon-Humber.In: Workers' Educational Association, editors. *Barton and the River Humber 1086-1900*, Gainsborough, G.W. Belton Ltd. 123-157pp

Coleman L, Coleman J. 2002. The measurement of puberty: a review. *J Adolescence* 25:535-550.

Connell B, Gray Jones A, Redfern R, Walker D. 2012. *A Bioarchaeological Study of Medieval Burials on the site of St Mary Spital*. Monograph 60. London, Museum of London Archaeology.

Coutinho S, Buschang P, Miranda F. 1993. Relationships between mandibular canine calcification stages and skeletal maturity. *Am J Orthod Dentofac.* 104 (3):262-268.

Dalla Palma L, Giusti C, Borghi A. 1967. Skeletal development in gonadal dysgenesis, female in phenotype. *Am J Roentogen.* 101 (4):876-83.

Dawes J, Magilton J. 1980. *The Cemetery of St. Helen-on-the-Walls, Aldwark.* London, Council for British Archaeology.

de Muinck Keizer-Schrama S, Mul D. 2001.Trends in pubertal development in Europe. *Human Reprod Update* 7 (3):287-291.

Demirjian A, Goldstein H, Tanner J. 1973. A new system of dental age assessment. *Hum Biol.* 45 (2):211-227.

Demirjian A. 1990. Dentition. In: Falkner F, Tanner J, editors. *Human Growth. A Comprehensive Treatise*. New York, Plenum Press 269-297pp

Dorn L, Biro F. 2011. Puberty and its measurement: a decade review. *J Res Adolescence* 21 (1):180-195.

Dossus L, Kvaskoff M, Bijon A, Fervers B, Boutron-Ruault M-C, Mesrine S, Chavel-Chapelon F. 2012. Determinants of age at menarche and time to menstral cycle regularity in the French E3N cohort. *Ann Epidemiol.*198.

Eveleth P, Tanner J. 1990. *Worldwide Variation in Human Growth.* 2nd ed. Cambridge, Cambridge University Press.

Falys C, Schutkowski H, Weston D. 2005.The distal humerus - a blind test of Rogers' sexing technique using a documented skeletal collection. *J Forensic Sci.* 50 (6):1289-1294.

Fanchi L, Baccetti T, McNamara J. 2000. Mandibular growth as related to cervical vertebral maturation and body height. *Am J Orthod Dentofac.* 118 (3):335-40.

Fenwick C. 1998. *Part 1: Bedfordshire-Leicestershire*. Oxford, Oxford University Press.

Fishman LS. 1982. Radiographic evaluation of skeletal maturation. A clinically orientated method based on hand-wrist films. *Angle Orthod.* 52 (2):88-112.

Flores-Mir C, Burgess C, Chamney M, Jensen R, Pitcher M, Major P. 2006. Correlation of skeletal maturation stages determined by cervical vertebrae and hand-wrist evaluations. *Angle Orthod.* 76:1-5.

Frisancho A, Garn S, Rohnmann C. 1969. Age at menarche: a new method of predicting and retrospective assessment based on hand X-rays. *Hum Biol.* 41: 42-50.

Gilchrist R. 2000. Archaeological biographies: realizing human lifecycles, -courses and -histories. World Archaeology 31(3):325-328.

Gluckman P, Hanson M. 2006. Evolution, development and timing of puberty. *Trends Endocrin Met.* 17(1):7-12.

Goldberg P. 1992. *Women, Work, and Life Cycle in a Medieval Economy: Women in York and Yorkshire c. 1300-1520.* Oxford, Clarendon Press.

Goldberg P. 2004. Migration, youth and gender in later medieval England. In: Goldberg P, Riddy F, editors. *Youth in the Middle Ages*. Rochester, York Medical Press, 85-99pp.

Goyal R, Mehta P, Kaur G. 2012. Nutritional status and menarche in adolescents of Punjab. *J Life Sci.* 4 (1):63-66.

Grave K, Brown T. 1976. Skeletal ossification and the adolescent growth spurt. *Am J Orthod.* 69 (6):611-619.

Green M. 2001. *The Trotula: a medieval compendium of women's medicine.* Pennsylvania, University of Pennsylvania Press.

Hägg U, Taranger J. 1982. Maturation indicators and the pubertal growth spurt. *Am J Orthod.* 82 (4):299-309.

Hallam H. 1985. Age at first marriage and age at death in the Lincolnshire Fenland, 1252-1478. *Popul Stud.* 39:55-69.

Hanawalt B. 1993. *Growing up in Medieval London*. Oxford, Oxford University Press.

Hassel B, Farman A. 1995. Skeletal maturation evaluation using cervicle vertebrae. *Am J Orthod Dentofac.*107 (1):58-66.

Hewitt D, Acheson R. 1961a. Some aspects of skeletal development through adolescence. I. Variations in the rate and pattern of skeletal maturation at puberty. *Am J Phys Anthrop*. 19 (4):321-331.

Hewitt D, Acheson R. 1961b. Some aspects of skeletal development through adolescence. II. The inter-relationship between skeletal maturation and growth at puberty. *Am J Phys Anthrop*.19 (4):333-344.

Hochberg Z, and Belsky J. 2013. Evo-devo of human adolescence: beyond disease models of early puberty. BMC Medicine 11(113):on-line journal.

Houston W. 1980. Relationships between skeletal maturity estimated from hand-wrist radiographs and the timing of the adolescent growth spurt. *Eur J Orthodont.* 2 (2):81-93.

Karapanou O, Papadimitriou A. 2010. Determinants of menarche. *Repod Biol Endocrin.* 8:115-122.

Khan R, Ijaz A. 2011. Correlation of dental mineralisation and skeletal maturity indicators. *Ann King Edward Med School* 17:22-26.

Krogman W, Iscan M. 1986. *The Human Skeleton in Forensic Medicine*. 2nd ed. Illinois, Charles C. Thomas.

Lamparski D. 1972. Skeletal Age Assessment Utlizing Cervical Vertebrae. PhD Thesis, Pittsburgh, University of Pittsburgh.

Lewis ME. 2007. *The Bioarchaeology of Children*. Cambridge, Cambridge University Press.

Liversidge HM, Marsden P. 2010. Estimating age and the likelihood of having attained 18 years of age using mandibular third molars. *Brit Dent J.* 209 (8):E13.

Marshall W, Tanner J. 1986. Puberty. In: Falkner F, Tanner J, editors. *Human Growth. A Comprehensive Treatise*. New York, Plenum Press, 171-209pp

Marshall W, Tanner J. 1969. Variations in pattern of pubertal changes in girls. *Arch Dis Child.* 44 (235):291.

Marshall W, Tanner J. 1970. Variations in the pattern of pubertal changes in boys. *Arch Dis Child.* 45 (239):13-23.

Mays S, Lees B, Stevenson J. 1998. Age-dependent bone loss in the femur in a medieval population. *Int J Osteoarchaeol.* 8 (2):97-106.

Moorrees C, Fanning E, Hunt E. 1963. Age variation of formation stages for ten permanent teeth. *J Dent Res.* 42:1490-1502.

Morrissy R, Weinstein S. 2006. *Lovell and Winter's Pediatric Orthopaedics*. Vol. 1: New York, Lippincott Williams & Wilkins.

Özer T, Kana J, Özer S. 2006. A practical method for determining pubertal growth spurt. *Am J Orthod Dentofac.*130:131-e1.

Palliser D. 1980. Location and history. In: Magilton J editor. *The Archaeology of York: The Medieval Walled City North-east of the Ouse.* London, Council for British Archaeology 2-14pp

Philippaerts R, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, Bourgois J, Vrijens J, Beunen G, Malina R. 2006. The relationship between peak height velocity and physical performance in youth soccer players. *J Sport Sci.* 24 (3):221-230.

Philips K. 1999. Maidenhood as the perfect age of woman's life. In: Lewis K, Mengue N, Philips K, editors.*Young Medieval Women*, Gloucester, Sutton Publishing, 1-24pp

Post J. 1971. Ages at menarche and menopause: some medieval authorities. *Popul Stud.* 25:83-87.

Roberts C, Cox, M. 2003. *Health and Disease in Britain*. Gloucestershire, Sutton Publishing Ltd.

Roche A. 1976. Growth after puberty. In: Fuchs E, editor. *Youth in a Changing World: cross-cultural perspectives on adolescence. New York, Walter de Gruyter,* 8:17pp.

San Román P, Palma J, Oteo M, Nevedo E. 2002. Skeletal maturation determined by cervical vertebrae development. *Eur J Orthodont* 24:303-311.

Schaefer M, Black S, Scheuer L. 2009. *Juvenile Osteology*. London, Academic Press.

Scheuer L, Black S. 2000. *Developmental Juvenile Osteology*. London, Academic Press.

Scoles P, Salvagno R, Villalba K, Riew D. 1987. Relationship of iliac crest maturation to skeletal and chronologic age. *J Pediatric Orthop.* 8 (6):639-644.

Shapland F, Lewis ME. 2013. Brief communication: A proposed osteological method for the estimation of pubertal stage in human skeletal remains. *Am J Phys Anthrop*. 151 (2):302-310.

Shapland F, Lewis ME. 2014. Brief communication: A proposed method for the assessment of pubertal stage in human skeletal remains using cervical vertebrae maturation. *Am J Phys Anthrop*.153 (1):144-153.

Soegiharto B, Moles D, Cunningham S. 2008. Discriminatory ability of the skeletal maturation index and the cervical vertebrae maturation index in detecting peak pubertal growth in Indonesian and white subjects with receiver operating characteristics analysis. *Am J Orthod Dentofac.* 134 (2):227-237.

Sutter RC. 2003. Nonmetric subadult skeletal sexing traits: I. A blind test of the accuracy of eight previously proposed methods using prehistoric known-sex mummies for Northern Chile. *J Forensic Sci.* 48 (5):on line.

Tanner JM. 1989. *Foetus into Man*. London, Open Books Publications Ltd.

Tanner JM, Healy J, Goldstein H, Cameron N. 2001. *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3)*. London, WB Saunders.

Tanner JM, Whitehouse R, Marshall W, Healy J, Goldstein H. 1975. *Assessment of Skeletal Maturity and Prediction of Adult Height*. London, Academic Press.

Thomas F, Renaud F, Benefice E, de Meeus T. 2001. International variability of ages at menarch and menopause: patterns and main determinants. *Hum Biol.* 73 (2):271-290.

Tyszka D. 2006. *The Later History of Barton-on-Humber. Part Six. Church and People in a Victorian Country Town. Barton Parish 1830–1900*. Gainsborough, Workers' Educational Association, GW Belton.

Uysal T, Ramoglu S, Basciftci F, Sari Z. 2006. Chronologic age and skeletal maturation of the cervical vertebrae and hand-wrist: is there a relationship? *Am J Orthod Dentofac.*130 (5):622-628.

Viner R. 2008. Adolescent medicine. In: McKintosh N, Helms P, editors. *Forfel and Arnell's Textbook of Pediatrics*. London, Churchill Livingstone,1757-1768pp

Waldron T. 2007. *St Peter's, Barton-upon-Humber, Lincolnshire, Vol 2. The Human Remains*. Oxford, Oxbow Books.

Walker P, Johnson J, and Lambert P. 1988. Age and sex biases in the preservation of human skeletal remains. *Am J Phys Anthrop*. 76:183-188.

Wilson L, Ives R, Cardoso H, Humphrey L. 2015. Shape, size and maturity trajectories of the human ilium. *Am J Phys Anthrop*.156:19-34.

Zacharias L, Wurtman R. 1969. Age at menarche: genetic and environmental influences. *New Eng J Med.* 280:868-875.

Zhang S, Liu G, Liu L, Ma Z, Han Y, Shen X, Xu R. 2008. Relationship of certain skeletal maturity indicators of hand and wrist with adolescent growth spurt. *Zhong Yi Xue Za Zhi* 88 (31):2198-2200.

Captions

Table I. Characteristics of the archaeological study samples

Table II. Skeletal and dental features associated with the stages of maturation in boys and girls

Table III: Mean age distribution of the sub-sample based on dental development

Table IV: Estimation of the average age (years) at which puberty milestones were achieved in the medieval sample

Figure 1. Location of the sites from which the skeletal remains were derived

Figure 2. Age at attainment for puberty milestones: York (sexes combined)

Figure 3. Age at attainment for puberty milestones: Barton (sexes combined)

Figure 4. Age at attainment for puberty milestones: London (sexes combined)

Table I. Characteristics of the archaeological study samples

Site	Date	Type	Number of individuals
Barton-on-Humber, Lincs	AD 950-1700	Urban, high status	200
York sites combined	AD 950-1700	Urban, low status	90
St. Mary Spital, London	AD 950-1500	Urban, low status	704
Total			**994**

Table II. Skeletal and dental features associated with the stages of maturation in boys and girls

Stage	Canine Mineralisation[1]	Hamate Hook[2]	Phalanges and Distal Radius[3]	Iliac Crest[4]	CMV[5]
Initiation or pre-puberty	F Root ½ to 3/4	Stage G Hook absent	Stage 1 Proximal epiphysis of MC2 (PP2) narrower than shaft Distal radius unfused	Risser 1 Epiphysis not present	1
Acceleration	G/H Root complete to apex 1/2	Stages H or H.5 Hook appearing or increased	Stage 2 Proximal phalanx of PP2 and epiphyses of equal width Distal radius unfused	Risser 2 Epiphysis 50% complete, unfused	2
PHV or transition	H Apex complete	Stage I Hook complete	Stage 3 Increased width of PP2 Distal radius unfused Proximal ulna fusing/fused Capitate of distal humerus fusing	Risser 2-3 Epiphysis 50-75% complete, Unfused (1)	3
Deceleration	H Apex complete	Stage I Hook complete	Stage 4 Capping of phalangeal epiphyses Distal radius unfused (1)	Risser 3-4 Epiphysis 75-100% complete, Non to partial union (2-3)	4-5
Maturation	H Apex complete	Stage I Hook complete	Stage 5 Fusing of MC3 proximal epiphysis (PP3) Distal radius partially fused (2)	Risser 4 Epiphysis 100% complete, partial union (2)	5-6
Completion or post-puberty	H Apex complete	Stage I Hook complete	Stage 6 Phalanges fused Distal radius fused (3)	Risser 5 Fusion complete (3)	6

[1]Cherkow (1980) based on Demirjian et al.'s dental stages (1973); Grave and Brown (1976); Chertkow (1980); [2]Shapland and Lewis (2013); Grave and Brown (1976); [3]Hägg and Taranger (1982) for the phalangeal epiphyses; Hägg and Taranger (1982) and Zhang et al. (2008) for the distal radius; [4]Hewitt and Anderson (1961a,b); Scoles et al. (1987); Scheuer and Black (2000); [5]Hassel and Farman (1995) for cervical 3, Baccetti et al. (2002) for cervical 2-4.

Table III. Mean age distribution of the sub-sample based on dental development

Age (yrs)	**Total sample**		**Male**		**Female**		**Estimated pubertal status**	
	n	*%*[1]	*n*	*%*	*n*	*%*	*n*	*%*
10.0-10.9	65	10.1	15	2.3	13	2.0	61	9.4
11.0-11.9	59	9.1	22	3.4	8	1.2	47	7.3
12.0-12.9	45	6.9	17	2.6	9	1.4	32	4.9
13.0-13.9	45	6.9	20	3.1	7	1.1	25	3.8
14.0-14.9	13	2.0	9	1.4	1	0.1	9	1.4
15.0-15.9	82	12.7	18	2.8	17	2.6	56	8.7
16.0-16.9	42	6.5	17	2.6	12	1.8	31	4.8
17.0-17.9	48	7.4	27	4.2	18	2.8	40	6.2
18.0-18.9	15	2.3	6	0.9	7	1.1	14	2.2
19.0-19.9	40	6.2	23	3.6	15	2.3	37	5.7
20-21	34	5.3	19	2.9	14	2.2	31	4.8
22-25	157	24.3	90	13.9	66	10.2	156	24.2
Total	**645**		**283**		**187**		**539**	

[1] Percent of total 645 individuals.

Table IV. Average age (years) at which puberty milestones are achieved

Pubertal Stage	**York**		**Barton**		**London**		**Average Medieval**
	males	females	males	females	males	females	
Initiation	10-12	10-12	10-12	10-12	10-12	10-12	10-12
Acceleration	12-16	10-11	12-14	10-12	10-16	10-13	10-13
PHV	**12-16**	**12-16**	**11-16**	**11-16**	**12-17**	**12-18**	**15-16**
Menarche		**10-15**		**12-16**		**15-17**	**15-17**
Deceleration/Maturation	14-21	15-11	13-19	14-17	14-25	12-25	15-17
Completion	16-19	16-19	17-19	16-22	17-25	18-25	16-22

Figure 1.

Figure 2. Age attainment for puberty milestones: York (sexes combined)

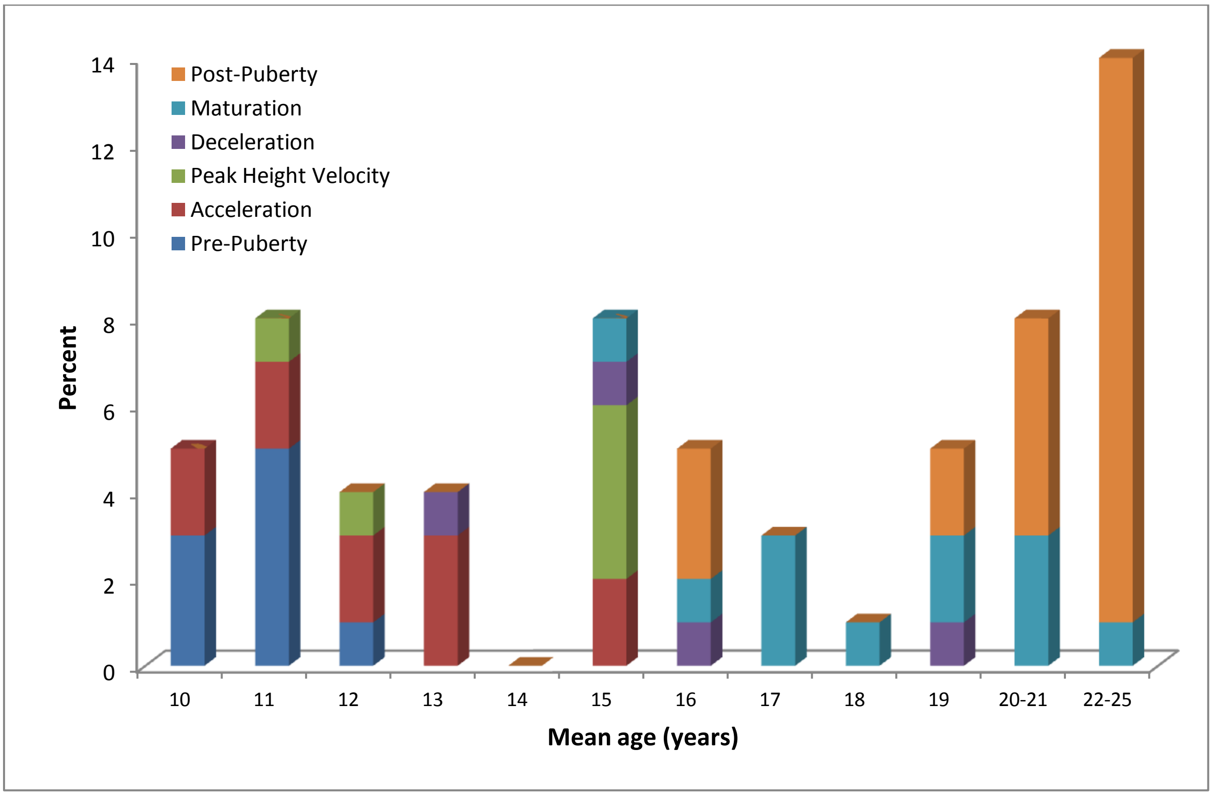

Figure 3. Age attainment for puberty milestones: Barton (sexes combined)

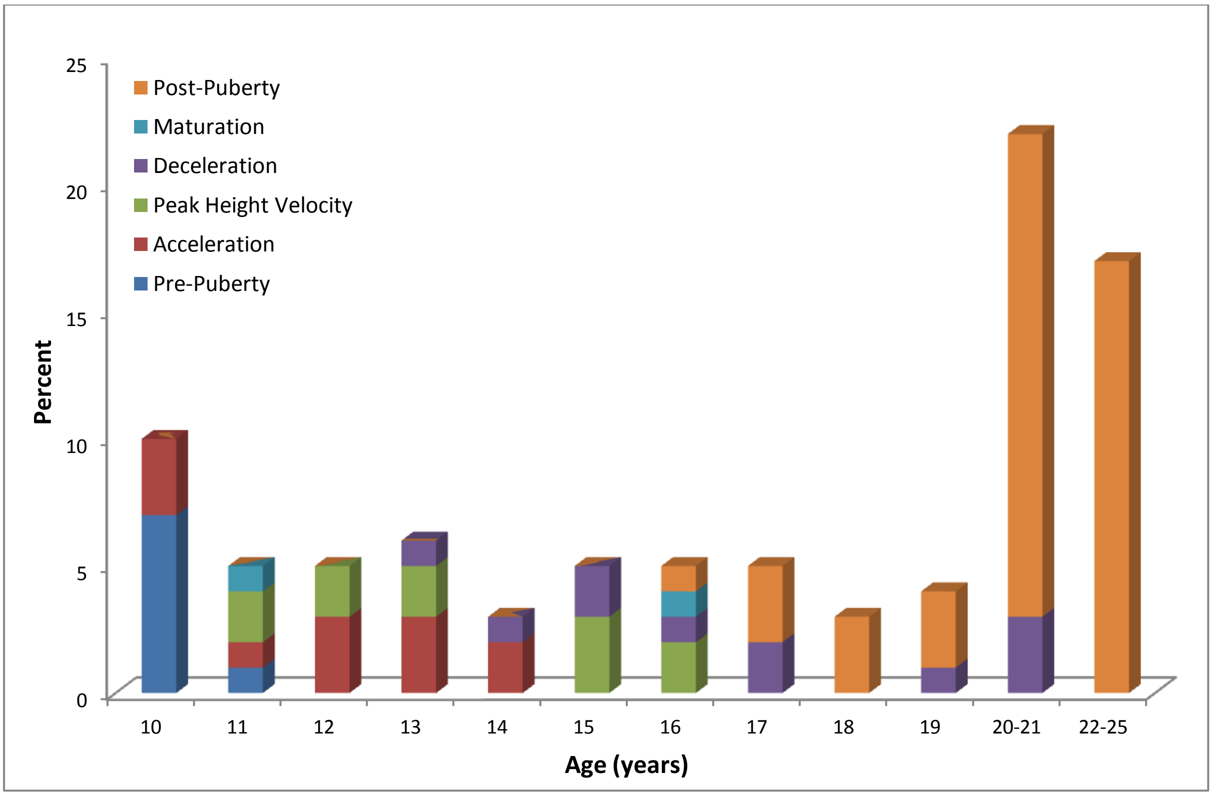

Figure 4. Age attainment for puberty milestones: London (sexes combined)