Title: Height and Health in Roman and Post-Roman Gaul, a Life Course Approach

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Abstract:

Objective: The present study explores growth and health in Roman (1st-3rd centuries CE) and Post-Roman (4th-7th centuries CE) Gaul, incorporating a life-course approach, to better understand the influence of Roman practices and lifestyles on health, and the impact of cultural change from the Roman to the Post-Roman period.

Materials and Methods: The skeletal remains of 844 individuals were analyzed for non-specific signs of physiological stress, including growth disruption (diaphyseal and adult maximum femur length), dental enamel hypoplastic defects (DEH), *cribra orbitalia* (CO), and periosteal reaction of the tibiae (Tibia PR).

Results: The Gallo-Roman sample demonstrated shorter femoral lengths, and higher rates of DEH and Tibia PR. Post-Roman groups demonstrated longer femoral lengths and higher rates of CO.

Conclusions: Gallo-Roman individuals may have been more regularly exposed to infectious pathogens throughout childhood, inhibiting opportunities for catch-up growth, resulting in high rates of DEH and shorter femoral lengths ('intermittent stress of low lethality'). This could be the result of overcrowding and insalubrious urban environments. Higher rates of CO in the Post-Roman samples may have been influenced by dietary changes between the periods.

Significance: The intertwined and often synergistic relationships between early life environment, nutrition and settlement structure is highlighted, helping to further understandings of life experiences during the Roman and Post-Roman periods.

Limitations: It was not possible to obtain sufficient data from northern regions during the Gallo-Roman period, limiting this analysis.

Suggestions for Further Research: Further application of life course approaches can reveal subtle patterns in stress indicators.

Keywords: Growth; Intermittent stress of low lethality; DOHaD (Developmental Origins of Health and Disease); Stature; Late Antiquity

Main Text

The impact of Roman practices on living conditions and health has received much attention. Some research has emphasized improvements in water supplies and sanitation during the period of Roman occupation, alongside increased economic activity, food diversity and trade networks, as factors positively impacting health status (Dermody et al., 2014; Hitchner, 2012; Jongman et al., 2019; Koloski-Ostrow, 2015; Kron, 2005, 2019; Lo Casio, 2006). Other work has argued that Roman urbanization, high population density and disease loads (and possible food shortages) negatively affected health (Frier, 1977; Harper, 2016; Morley, 2004; Porter, 1999; Scheidel, 2015, 2012a, 2012b; Scobie, 1986). Bioarchaeological studies demonstrate a pattern of reduced adult height across the Roman Empire when compared to both preceding and succeeding periods (Cleymans, 2019; Giannecchini and Moggi-Cecchi, 2008; Gowland, 2017; Gowland and Garnsey, 2010; Gowland and Walther, 2019; Koepke, 2014; Koepke and Baten, 2008; Redfern, 2008; Redfern and DeWitte, 2011; Roberts and Cox, 2003; Scheidel, 2012b; Stead et al., 2006). When assessed from skeletal remains, reduced stature is indicative of childhood physiological stress, but can also reflect enhanced survivorship (DeWitte and Hughes-Morey, 2012; Klaus and Tam, 2009; Vercellotti et al., 2014; Wood et al., 1992). As such, deeper contextualization of growth data is important for understanding how health and height were impacted during the Roman and Post-Roman periods. Growth disruption (and reduced adult stature) could stem from early life stressors and/or reflect recurrent periods of stress throughout the developmental period (Pezo-Lanfranco et al., 2020). This study examines skeletal stress indicators (long bone growth, dental enamel hypoplasia, *cribra orbitalia*, and tibial periosteal reactions) in 844 individuals from multiple sites from Roman and Post-Roman Gaul. Some analyzed lesions relate specifically to stress during childhood (e.g. growth stunting, enamel hypoplasia and *cribra orbitalia*), whilst others may occur up until the point of death (tibial periosteal reactions). This study aims to consider health across the life course and the effects of early life adversity on morbidity and mortality to improve understanding of health in Southern Roman Gaul.

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1.1 Research Context

Gaul (modern-day France, Belgium, parts of Germany, Italy, and Switzerland) occupied a unique position within the Roman Empire (Fig. 1). As an early trading partner and the first province north of the Alps to be conquered and colonized (late second century BCE), southern Gaul (*Gallia Narbonensis*) became strongly entrenched within Roman socio-political structures, trade and cultural ideals (Hitchner, 1999; Woolf, 1998). Northern Gaul was conquered much later (58-51 BCE) and, while it was integrated into the Empire, it remained a frontier zone, providing protection from and connection to 'barbarian' borderlands (Woolf, 1998). Roman integration was not a uniform process, although there are often great similarities in the monumental architecture of Romanized cities (baths, forum complexes, urban plans) (Aldrete, 2004). Southern Gaul tended to be wealthier, with more lavish villas and was more densely urbanized than northern regions (Woolf, 1998). Sanitation systems, including fresh water supplied through a system of aqueducts, public baths, regulations on keeping drains clear and the selling of spoiled food were implemented (Koloski-Ostrow, 2015; Porter, 1999). Vast communication networks facilitated travel, trade, access to resources and technologies, but also provided a conduit for the transmission of pathogens (Harper, 2016; Porter, 1999).

From the early 4th century, Roman authority and political control in northern regions was eroded through political intrigue, military defeats, civil wars and usurpations and an increasing 'barbarian' presence and influence (Halsall, 2004; Wickham, 2005). Urban areas contracted in size, traditional Roman construction methods and layouts were abandoned, systems of production, and communication and trade that had been established in the early empire deteriorated, reorienting what had been a large Imperial network to local forms of production and politics (Humphries, 2009; Mathisen, 2011; McCormick, 2015; Theuws, 2009; Van Ossel, 2006; Ward-Perkins, 1996; Wilkinson, 2015). Houses became more modest, public buildings and monumentalism were no longer invested in, and in some cases, were actively stripped away. Water supply and disposal systems were not maintained and eventually fell into disrepair and disuse (Bailey, 2016). Population density is thought to have dramatically decreased (Ando, 2008). This 'transition' is thought to have occurred more gradually in southern Gaul in the 4th and 5th centuries, as reflected by continued trade and Roman investment in the region. Roman power bases (capitals/prefects) in

Gaul were consolidated in the south when those in the north became too difficult to effectively manage (Laes and Vuolanto, 2016; Wickham, 2005). By the end of the 7th century, all of Gaul displayed markedly decreased wealth, social complexity and less integration via communication networks in comparison with the Roman period (Harries, 1994; Wilkinson, 2015). These events and trends highlight the diversity within Gaul during the Roman and Post-Roman periods, signaling the potential utility in examining health in southern and northern Gaul in relation to society-level changes occurring during these time periods. If features of Roman lifeways, such as urban living structures, higher population density and diet through trade networks (access to resources) were beneficial, then health and height are likely to have declined in the Post-Roman period, especially in northern regions. If, however, these practices were negatively influencing height and health in Gaul, then the opposite is to be expected.

1.2 Height and Health in the Western Roman Empire

Across the Western Roman Empire there is evidence of reduced adult stature, as compared to prior and later periods (Giannecchini and Moggi-Cecchi, 2008; Gowland, 2017; Gowland and Garnsey, 2010; Gowland and Walther, 2019; Koepke, 2016, 2014; Koepke and Baten, 2008; Redfern, 2008; Redfern and DeWitte, 2011; Roberts and Cox, 2003; Scheidel, 2012b; Stead et al., 2006). A person's potential for height is genetically dictated, but the ability to express or achieve that potential is mediated by environmental conditions, disease load and nutrition during childhood (Bogin, 1999a; Stinson, 2012; Vercellotti et al., 2014). On a population level, the systemic influences of environment, nutrition, emotional stress, disease and their interrelated effect on health or stature are more likely to be identified than genetic influences (Cardoso et al., 2019; Perkins et al., 2016; Steckel, 1995). As such, stature and growth are often used as an indicator of childhood health and wellbeing, as prolonged nutritional deficiencies and illness can negatively influence adult height (Goodman, 1991; Hoppa and Fitzgerald, 1999; Saunders and Hoppa, 1993; Steckel and Rose, 2002; WHO, 1998). Although growth disruption can take place at any time within the developmental period (prenatal-20 years for the femur- Scheuer and Black, 2000), delays in growth most often begin *in utero* or during infancy (Hoffman and Klein, 2012). Early childhood is a sensitive and precarious period of life, as growth processes are energetically demanding because there is high tissue turnover. This makes infants particularly sensitive to environmental conditions and fluctuations (Lewis, 2007). Growth stunting present by the age of two years can be retained through to adulthood, resulting in reduced adult stature (Kuzawa and Quinn, 2009). As a result, potentially faltered growth in the Roman period could have had its origins in infancy and early childhood, highlighting the importance of early life nutrition and environment.

In modern and past populations, stunted growth and reduced adult stature are associated with a reduction in immune function and increased morbidity and mortality throughout the life course, suggesting that populations with high degrees of growth stunting are more deeply affected by illness (Barker, 2012; Barker et al., 2002; McDade, 2012; Steckel, 2009, 2005; Steckel and Rose, 2002). However, when examining 'health' or stress states from human skeletal remains, reduced stature can be interpreted as a sign of survival, where more individuals with short stature were able to survive early life stressors (The Osteological Paradox) (Bogin, 1999b; DeWitte and Hughes-Morey, 2012; Klaus and Tam, 2009; Vercellotti et al., 2014; Wood et al., 1992). The recording and analysis of additional skeletal stress markers can provide critical insights into the timing, duration and cause of poor health and growth disruption within a population, helping to identify relationships between stature and enhanced or reduced frailty (Cameron and Demerath, 2002; Cohen et al., 1994; Goodman, 1993; Tanner, 1981). This approach has been exemplified in a number of previous studies (Gowland and Newman, 2017; Klaus and Tam, 2009; Newman and Gowland, 2015; Watts, 2013, 2011). Examining multiple stress indicators that develop at different life stages permits longitudinal analysis, even from cross-sectional data (Agarwal, 2016; Klaus and Tam, 2009; Roberts and Steckel, 2018; Temple, 2019; Vercellotti et al., 2014; Watts, 2013). For example, dental enamel defects can only form during the period of enamel development (from around six months to approximately nine years of age for the 2nd molar- AlQahtani et al., 2010). Like growth, dental enamel defects are non-specific, but because they can only form during a limited period of time, they can help identify when in the life course individuals and populations were affected. A biological life course approach, incorporating several skeletal stress indicators can augment growth data and may help to characterize the effects of Roman practices and lifestyles on health in Southern Gaul.

2 Materials and Methods

The skeletal remains of 844 individuals from 13 burial populations were analyzed for non-specific signs of physiological stress, including growth disruption (diaphyseal and adult maximum femur length), dental enamel hypoplastic defects (DEH), *cribra orbitalia* (CO), tibial periosteal reactions and (Tibia PR). Individuals were categorized into one of three groups (Gallo-Roman South, Post-Roman South, Post-Roman North) based on the date and location of their archaeological context (Table 1, Fig. 1). The separation of northern and southern regions of Gaul permits the examination of differences between the two regions based on different levels of integration in the Roman world and divergent trajectories in the Post-Roman period. Sites that displayed typical Gallo-Roman monumental or building features and burial rituals (Charon's obol- a coin placed near the mouth or eyes, sarcophagi, feasting vessels) or 'Post-Roman' rituals (row graves, weapon burials, jewelry) were prioritized. The Gallo-Roman South group includes individuals from two urban sites, Saintes, Rue Jacques Brel and Cirque Romain, Arles. Skeletal data for the Post-Roman South group derived from six archaeological sites located south of the Loire River. The Post-Roman North group is composed of individuals from five sites north of the Loire River. Both 'urban' and rural cemetery sites (as determined by archaeologists working with the sites and material) were included in the Post-Roman groups. Due to the prevalence of cremation as a funerary practice and associated preservation biases, it was not possible to obtain sufficient data from northern regions during the Gallo-Roman period. This limits the interpretations and scope of this analysis, but nevertheless data from the Post-Roman North is included here for comparison.

Both non-adult (<18 years old) and adult (>18 years old) individuals were examined in this research. Preservation of the remains was assessed using McKinley's (2004) scoring system. Individuals were included in this analysis if they had adequate preservation to estimate age-at-death and at least one bone element from which to assess the presence or absence of the non-specific stress indicators assessed in this study. For non-adults, age-at-death was estimated by the stage of dental development (AlQahtani et al., 2010). Adult age-at-death estimations were based on degenerative changes in the pelvis (Brooks and Suchey, 1990; Lovejoy et al., 1985; Schmitt et al., 2002) and dental wear (Brothwell, 1981). All individuals were assigned to standard broad age categories ("0-4 years", "5-9 years", "10-14 years", "15-17 years", "18-25 years", "26-35 years", “45+ years”, and “20+ years”). Only adult remains were assessed for sex, using sexually dimorphic features of the skull and pelvis (Bruzek, 2002; Phenice, 1969). Adult individuals were recorded as ‘female’, ‘probable female’, indeterminate’, probable male’, or ‘male’. To expand small sample sizes, individuals determined to be female or probable female were considered in the analysis as ‘female’ and likewise male and probable male individuals were pooled as male.

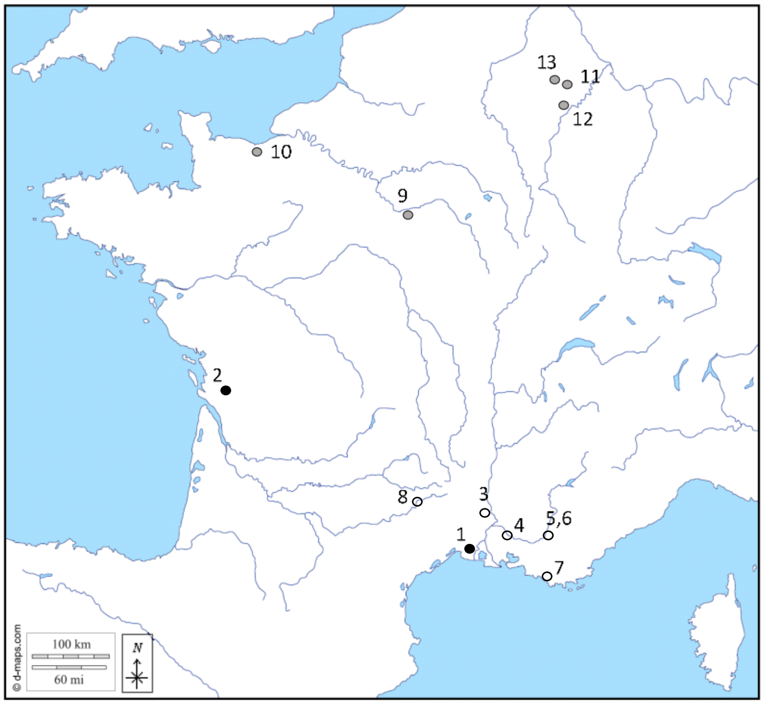

Fig. 1. Map of sites assessed in this analysis. Underlying map provided by dmaps.com. Black dots indicate Gallo-Roman South, white dots indicate Post-Roman South and gray dots indicate Post-Roman North. 1= Arles Cirque, 2= Saintes, Rue Jacques Brel, 3= La Grande Bastide de Cadarache, 4= Vaison la Romain. 5= Les Clavelles, 6= Saint-Martin (La Brillane), 7= Rues de Toulon, 8= La Granède, 9= Le Clos des Cordeliers, 10= St Martin de Fontenay, 11= Fontoy, 12= Rue du Tombois, 13= Cutry

Table 1. Sites included in the present research

Group	Site	Date	Context	Reference	Non-adults	Adults	Total Inds.
Gallo-Roman South (GRS)	Cirque Romain, Arles	2-4th c	Urban	(Sintès, 1989)	27	47	74
	Saintes, Rue Jacques Brel	1-3rd c	Urban	(Baigl et al., 1997)	22	60	82
	Total				49	107	156
Post-Roman South (PRS)	La Grande Bastide de Cadarache	4-7th c	Rural	(Pouyé et al., 1994)	27	79	106
	Colombier Vaison-la-Romain	5-6th c	Urban	(Carru, 1991)	15	65	80
	Les Clavelles	6-7th c	Rural	(Boiron, 1993)	5	7	12
	Rues de Toulon	4-7th c	Possibly urban?	(Pouget et al., 2002; Salicetti, 1998)	2	17	19
	Saint-Martin (La Brillane)	4-5th c	Rural	(Boiron, 1993)	1	9	10
	La Granède	4-7th c	Rural	(Saint-Pierre, 2010)	1	10	11
	Total				51	187	238
Post-Roman North (PRN)	Le Clos des Cordeliers	5-6th c	Rural	(Guignier, 1997)	16	40	56
	St Martin de Fontenay	4-7th c	Rural	(Pilet et al., 1994)	45	186	231
	Fontoy	4-7th c	Rural	(Seilly, 1995)	23	97	120
	Rue du Tombois	4th c	Urban	(De Filippo et al., 2000)	8	27	35
	Cutry	5-7th c	Rural/Villa	(Liéger and Cussenot, 1997)	1	7	8
	Total				93	357	450
				Total	**193**	**651**	**844**

2.1 Non-adult systemic stress

Growth disruption, DEH, CO, and Tibia PR were investigated in this analysis as these are considered to be reliable indicators of general health and reflect health during different stages of the life course (Redfern and DeWitte, 2011; Roberts and Cox, 2003; Steckel and Rose, 2002; Watts, 2013). Results are presented as both crude prevalence rate (CPR), the percentage of individuals displaying a lesion, and true prevalence rate (TPR), the percentage of observable bone elements or teeth displaying a lesion. Statistical analyses, including Kruskal-Wallis non-parametric and chi-squared tests, were applied to identify significant differences between groups in femoral length, CPR and TPR of the pathological conditions. Mann-Whitney U tests were used to examine the difference in mean age-at-death for individuals with and without growth disruption (comparatively shorter femoral length), DEH and CO to identify possible correlations between early mortality and these indicators of early life stress. Statistical significance was set at 0.05.

2.1.1 Growth disruption

For non-adults and adults, growth disruption was assessed through the maximum length of the femur. Femora that displayed traumatic lesions or evidence of metabolic disease were not included. The femur develops from the 7th-8th week *in utero* until the late teens or early twenties, when epiphyseal fusion occurs (Scheuer and Black, 2000). Femoral length therefore reflects growth and potential growth disruption throughout the developmental period. To assess small height-for-age, or potential growth disruption, skeletal growth profiles were created, where dental age was plotted against age estimations based on femoral diaphyseal lengths (Cardoso, 2007). Because dental development is least impacted by the environment (Cardoso, 2007; Lewis and Garn, 1960; Liversidge et al., 1998; Saunders, 2008), dental age estimates were used as a baseline against which to assess femoral growth. The mean of the dental age range was used in this analysis in common with other growth studies (Mays et al., 2008; Newman and Gowland, 2015). For non-adults, the diaphyseal length of the femur, without inclusion of the epiphyses, was measured. The utility of skeletal growth profiles has been debated, as both dental development and long bone growth age estimates are based on modern healthy populations (Saunders, 2008; Wood et al., 1992). However, other studies have identified that differences in growth between 'non-survivors' and those who died at older ages are likely to be small, especially in comparison with other biases affecting the study of archaeological skeletal remains (Saunders and Hoppa, 1993).

For adults, the maximum length of the femur was considered as a proxy for stature, as regression formulae for stature remain problematic due to population variability in body proportions (Klein Goldewijk and Jacobs, 2013; Vercellotti et al., 2009). Following similar analyses, short stature or disrupted growth was counted as 'present' for adult individuals that were below the median value for their sex within their respective group (Pezo-Lanfranco et al., 2020). Adult male and female femoral lengths were considered separately. Femora were measured to the nearest millimeter. Following standard practice, left femora were preferentially selected in all adult and non-adult analyses of femoral length (Buikstra and Ubelaker, 1994).

2.1.2 Dental enamel hypoplasia (DEH)

Dental enamel hypoplasia or defects form during periods of environmental or metabolic stress (illness, nutritional deficiencies or deprivation), where ameloblast function is inhibited, leaving an almost indelible mark of the stress episode (Fig. 2)(Goodman and Rose, 1990; King et al., 2005). Anterior and posterior permanent teeth were assessed for DEH presence, where DEH was scored as 'present', 'absent' or 'non-observable' (Goodman and Rose, 1990; Lukacs, 1989). Anterior teeth develop between one and six years of age, while posterior tooth crowns develop until around 14 years of age (AlQahtani et al., 2010). DEH presence would therefore reflect systemic stress between the ages of six months to 14 years. Although DEH can result from multiple etiologies, including genetic influences, trauma and biological stressors (both systemic and acute), the presence of DEH on multiple teeth suggests systemic origins (Klaus, 2020). Only individuals who displayed DEH on a minimum of three teeth were considered to have DEH present to avoid the inclusion of DEH based on trauma or genetic influences (Goodman and Rose, 1990). Where present, the number of observable DEH events were counted and recorded for each tooth.

2.1.3 *Cribra orbitalia* (CO)

Cribra orbitalia (CO) is characterized by hyperplasia of the diploë and a thinning of the outer table of the orbits in an effort to expand hematopoietic marrow surface area and produce more red blood cells (Brickley, 2018; Ortner, 2003). CO has an important relationship with diet, disease load, and several forms of anemia (iron deficiency, hemolytic and megaloblastic) and specific pathological conditions including thalassemia, rickets, scurvy and malaria (Gowland and Western, 2012; McIlvaine, 2015; Oxenham and Cavill, 2010; Piperata et al., 2014; Smith-Guzmán, 2015; Walker et al., 2009). Although similar appearing lesions can develop during adulthood as a result of inflammation of the eyes (Wapler et al., 2004), CO is most often developed during early childhood between the ages of six months and four years, with healed or healing lesions retained into adulthood (Blom et al., 2005; Brickley, 2018). CO is here assessed as a non-specific indicator of physiological stress (Belcastro et al., 2007; Brickley, 2018; Goodman and Martin, 2002; Redfern and DeWitte, 2011; Roberts and Cox, 2003; Steckel and Rose, 2002). *Cribra orbitalia* was recorded using the Stuart-Macadam (1991) method and only individuals recorded with a score of '3' or greater were counted as representative of this condition (Watts, 2013).

Fig. 2. Images of several non-specific stress indicators assessed in this research. A. Cribra orbitalia in the right orbit of Sepulture 84, Cadarache. B. Multiple dental enamel hypoplasias in Individual 12 from Saintes, Rue Jacques Brel (non-adult): C. Periosteal reaction of the tibia: woven bone in Individual 97 from Saintes, Rue Jacques Brel (non-adult)

2.2 Adult systemic stress

2.2.1 Periosteal reaction (Tibia PR)

Periosteal reaction refers to new bone formation on the outer-most surface of the bone in response to damage or inflammation of the periosteum, stemming from trauma, chronic infectious or inflammatory conditions (Fig. 2) (DeWitte, 2014; Klaus, 2014; Larsen, 1997; Ortner, 2003; Roberts and Manchester, 2005; Roberts, 2019; Weston, 2011, 2008). Despite complications in determining specific etiologies, this lesion, and in particular when it appears on the shaft of the tibiae, has been associated with increased frailty and premature mortality (DeWitte, 2014; DeWitte and Stojanowski, 2015; DeWitte and Wood, 2008; Klaus, 2014). Tibia PR can occur at any point during the life course. Periosteal reaction of the tibia was recorded if woven or lamellar new bone formation was present on the diaphyseal shaft. The location, type of bone formation and degree of healing were noted. Only the tibiae were systematically examined for periosteal new bone formation, as it is the long bone most commonly affected by these lesions (Klaus, 2014; Larsen, 1997).

3 Results

3.1 Demographics

All groups had age distributions broadly consistent with expectations for attritional burial samples (Fig. 3) (Margerison and Knüsel, 2002). As with many archaeological samples, there is an under-representation of infant individuals (e.g Stoodley, 1997; Ērkšķe, 2020), especially within the Post-Roman South group. This is likely the result of differential burial practices for the very young and excavation biases. There is a higher proportion of young adults (18-35 years) in both of the Post-Roman groups (30.2%, 30.8%) than in the Gallo-Roman group (17.9%). Determination of sex for adult individuals (18+ years), yielded slightly more males than females in the Gallo-Roman group and slightly more females than males in both Post-Roman groups (Fig. 4).

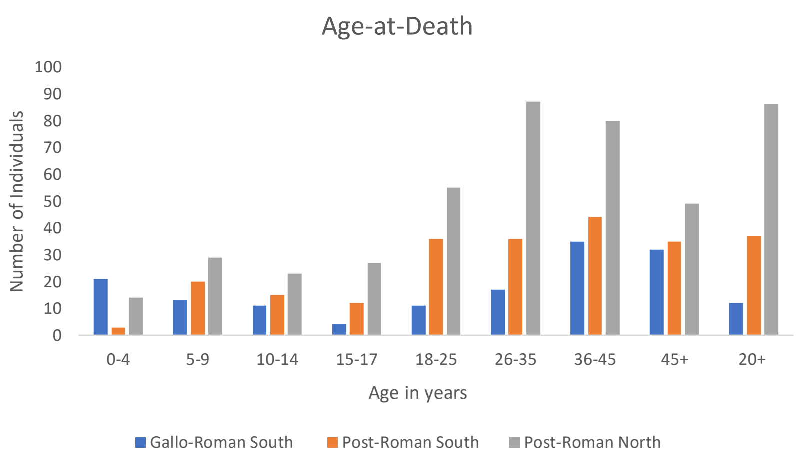

Fig. 3 Age distribution of Gallo-Roman South, Post-Roman South and Post-Roman North groups

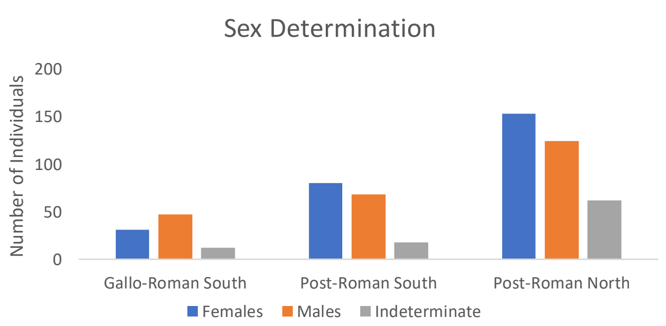

Fig. 4 Sex determination of adult individuals (> 18years) in this analysis

3.2 Growth disruption

Skeletal growth profiles permit analyses of differences in femoral length-for-age and potential growth disruption. All analyzed sample populations revealed dental ages that were nearly always estimated to be older (except three individuals, where dental and femoral age were estimated to be the same) (Fig. 5). This would suggest that in comparison with more recent child growth, nearly all non-adult individuals, regardless of context, were experiencing some degree of environmental stress, which had inhibited linear growth. Differences between dental and femoral age were not statistically significant between groups (P=0.879). Only four individuals aged 2 years or younger had teeth and femora adequately preserved for measurement, all of which derived from the Gallo-Roman context, preventing comparison with the other groups. Three of these four individuals displayed small height-for-age, indicating delayed growth. Although fusion of the femoral epiphyses can commence from as early as 10-12 years of age (Scheuer and Black, 2000), it is noteworthy that all groups have multiple adolescent individuals that show no signs of epiphyseal fusion.

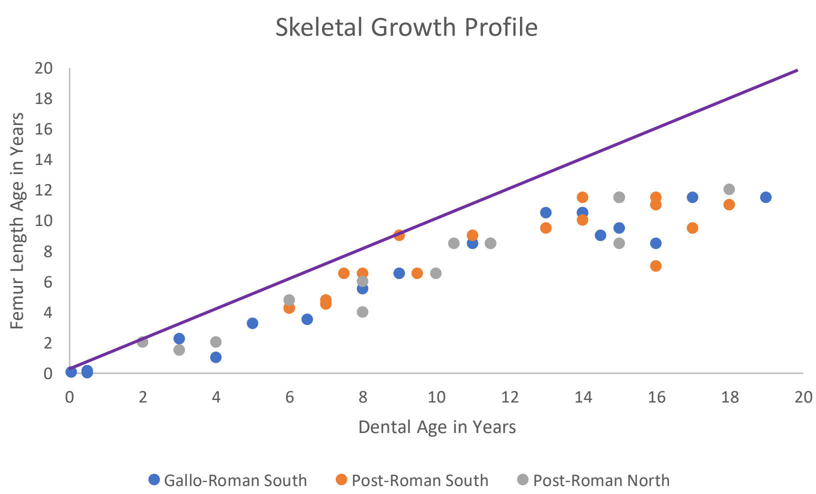

Fig. 5 Skeletal growth profile displaying age based on femoral length against age based on dental mineralization. Purple line displays a 1:1 ratio, when femoral and dental age are the same

Gallo-Roman females and males display the lowest mean and median femoral lengths (Fig. 6, Table 2). Average female Post-Roman femoral length only slightly increased, 0.6 cm and 1.1 cm in the south and north, respectively. These differences were not statistically significant (p=0.315).

Male average femoral length increased only in the Post-Roman North group; however, the increase of 1.8 cm was statistically significant (p=0.001).

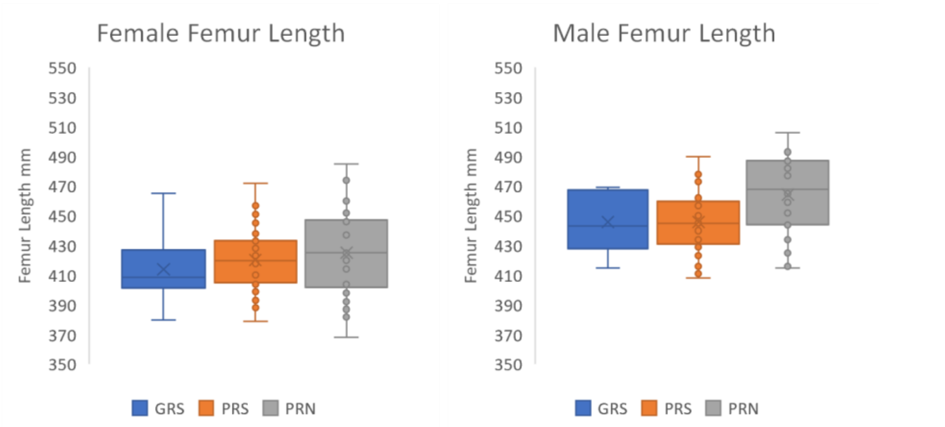

Fig. 6 Box and whisker plot of maximum femoral lengths. The line equals the median, the X is the mean, the box is quartiles 2 and 3 and whiskers are the maximum and minimum values, not including outliers. Additional dots are outliers. GRS= Gallo-Roman South, PRS= Post-Roman South, PRN= Post-Roman North

Table 2 Crude and True Prevalence Rates of non-specific stress indicators

Group		DEH		CO		Tibia PR		Mean Adult Femur Length mm	
		CPR	TPR	CPR	TPR	CPR	TPR	F	M
Gallo-Roman South	Affected n (n/N)	35 (22.4%)	196 (8.8%)	11 (7.1%)	13 (7.1%)	24 (15.4%)	72 (38.3%)	414	446
	Total (N)	156	2223	156	174	156	188	12	14
Post-Roman South	Affected n (n/N)	20 (8.4%)	136 (5.3%)	23 (9.7%)	41 (13.3%)	8 (3.4%)	30 (27.8%)	420	446
	Total (N)	238	2573	238	308	238	108	58	48
Post-Roman North	Affected n (n/N)	61 (13.6%)	400 (7.2%)	54 (12.0%)	80 (16.6%)	22 (4.9%)	74 (32.0%)	425	464
	Total (N)	450	5558	450	483	450	231	28	31
P-Value		**<0.001**	**<0.001**	0.197	**0.011**	**<0.001**	0.153	0.315	**0.001**

n= number affected individuals or bone elements; N=number of individuals or observable bone elements in group, F=Female, M=Male

3.3 Systemic stress indicators

Analysis of DEH revealed statistically significant differences between groups in both CPR and TPR, with the Gallo-Roman South group displaying the highest prevalence ($p<0.001$) (Table 2). The Gallo-Roman South group also had significantly higher proportions of individuals with multiple DEH (2, 3 and 4) events than Post-Roman groups ($p=0.001$) (Table 3). With respect to Tibia PR, the Gallo-Roman sample was again the most severely affected with a significant difference in CPR ($p= <0.001$), although TPR results were not significant ($p=0.153$) (Table 2). For CO, significant differences were found in TPR comparisons between groups, where disease prevalence was highest in the Post-Roman North group (Table 2). Individuals from the Post-Roman North context present the highest CPR in CO, but these results were not significant. The Post-Roman South context had the lowest frequencies of DEH and Tibia PR in CPR and TPR analyses. The Post-Roman South groups falls in-between the other groups in CPR and TPR of CO. Distributions of pathological conditions present similar patterns between the CPR and TPR of DEH, CO and Tibia PR.

Table 3 Number of DEH events per tooth

Number of DEH events per Tooth Crude Prevalence Rate						
Group	0	1	2	3	4	Total Number of Individuals
Gallo-Roman	106 (67.9%)	33 (21.2%)	11 (7.1%)	5 (3.2%)	1 (0.6%)	156
Post-Roman South	201 (84.5%)	31 (13.0%)	5 (2.1%)	0 (0.0%)	1 (0.4%)	238
Post-Roman North	337 (74.9%)	95 (21.1%)	13 (2.9%)	4 (0.9%)	1 (0.2%)	450

3.4 Mortality

In the Gallo-Roman sample, DEH presence was associated with earlier mean age-at-death ($P=0.007$) but was not associated with mean age-at-death in either of the Post-Roman groups (Table 4). In contrast, CO prevalence was correlated with mean age-at-death in Post-Roman samples and not in the Gallo-Roman sample. Short adult femur length was not associated with age-at-death in any of the groups.

Table 4 Mann-Whitney U p-values

Group	DEH	CO	Short adult femur length
Gallo-Roman South	**0.007**	0.120	0.793
Post-Roman South	0.936	**<0.001**	0.373
Post-Roman North	0.572	**0.013**	0.061

4 Discussion

Non-specific stress indicators were examined in multiple skeletal collections from Roman and Post-Roman Gaul to assess patterns in growth and health across the life course, elucidating the effects of Roman practices and lifestyles on health. This analysis revealed somewhat conflicting results. Adult Gallo-Roman males and females had shorter femoral lengths, but differences between dental and femoral age estimates in non-adults were not significant between groups (p=0.879). Frequencies of DEH and Tibia PR were significantly greater in the Gallo-Roman sample and DEH presence was correlated with earlier mortality. In both Post-Roman samples, frequencies of CO were significantly higher and CO presence was associated with earlier mortality. Short adult femur length was not associated with mortality in any of the groups. These results suggest that both Roman and Post-Roman samples experienced heightened frailty stemming from early life stressors, but the relationship with growth was less clear. Factors affecting health across the life course appear to have manifested in different ways between the groups, presumably due to variation in biocultural environments. These data are discussed in relation to the contextual and environmental factors impacting health throughout the life course in Roman and Post-Roman Gaul.

4.1 Life Course

4.1.1 Growth and early life adversity

Shorter adult femoral lengths were observed in the Gallo-Roman sample, aligning with previous research on height and health in the Roman Empire (Giannecchini and Moggi-Cecchi, 2008; Gowland, 2017; Gowland and Garnsey, 2010; Gowland and Walther, 2019; Koepke, 2016, 2014; Koepke and Baten, 2008; Redfern, 2008; Redfern and DeWitte, 2011; Roberts and Cox, 2003; Scheidel, 2012b; Stead et al., 2006). However, short femoral length was not associated with early mortality, indicating that growth data alone did not help to clarify if Roman lifestyles or environments negatively affected health in Gaul. In other analyses of multiple skeletal stress indicators, including growth, significant relationships or correlations were not always found where anticipated (Armelagos et al., 2009; Floyd and Littleton, 2006; Ribot and Roberts, 1996; Watts, 2013). Recent work has highlighted that the timing, duration and frequency of stress events affects the expression and severity of future health outcomes (Floyd and Littleton, 2006; Garland, 2020; Temple, 2019, 2014; Worthman and Kuzara, 2005). The earlier the exposure to stress, the more likely it is to manifest in negative adult health outcomes (Floyd and Littleton, 2006; Garland, 2020).

In addition to short femoral lengths, the Gallo-Roman South context had significantly higher proportions of individuals with DEH, higher numbers of teeth with DEH and more individuals displaying multiple DEH events. These individuals also had younger adult mortality (increased frailty). This indicates that the Gallo-Roman sample was exposed to early life adverse environments (before the age of 14) that affected mortality and could have impacted growth, contributing to the comparatively small femoral lengths observed in this analysis. In both Post-Roman groups, frequency of CO increased in comparison with the Gallo-Roman sample and was also correlated with early mortality. Because CO usually manifests before the age of four, this lesion typically represents the presence of early life stressors (Brickley, 2018). *Cribra orbitalia* can remodel over time, effectively disappearing in older individuals, potentially creating differences of comparison between archaeological populations. The samples here, however, showed no statistically significant difference in age structure. These findings indicate that individuals within each group experienced early life adversities, but the etiology of these likely differed, resulting in distinctly different skeletal manifestations.

4.1.2 Later life health outcomes

While growth stunting that commences in the womb and in infancy can have particularly profound effects on later life stature and health (Barker, 2012), the femur continues to grow until the late teens or early twenties, resulting in a comparatively long developmental period. During this time, an individual may be exposed to a variety of favorable or un-favorable environmental conditions, which may augment or hinder growth processes. Therefore, although all samples in this study experienced early life health insults, perhaps later childhood environments influenced the observed growth outcomes. ‘Catch-up’ or compensatory growth can occur in childhood or adolescence if negative conditions and/or dietary deficiencies improve, or if the growth period is prolonged (Bogin, 1999a; Tanner, 1981). It is therefore possible that individuals in this analysis could have experienced early life stressors (as evidenced through DEH and CO) that negatively influenced growth, but that conditions sufficiently improved to permit survival and compensatory growth (to varying degrees). In the Gallo-Roman South and both Post-Roman groups, a number of adolescents exhibited delayed epiphyseal fusion of the femur. Delayed fusion could be indicative of catch-up growth processes prior to death (Cameron and Demerath, 2002). Additionally, these data are cross- sectional, rather than longitudinal. Catch-up growth can exert a penalty on later health outcomes, as rapid compensatory growth consumes resources that might otherwise have gone to other systems and organs (Barker, 2012; Barker et al., 2011). None of the groups demonstrated a mortality penalty or advantage associated with femur length. This would suggest that if catch-up growth explains the differences in Gallo-Roman and Post-Roman growth patterns, it did not cause (detectable) negative later life outcomes in Post-Roman groups.

Recurrent periods of non-lethal stress could inhibit catch-up growth and continue to divert resources away from normal growth processes (Pezo-Lanfranco et al., 2020). As such, the short adult femoral lengths observed in the Gallo-Roman South sample could stem from early life stressors and also reflect regular or chronic periods of stress, which prevented catch-up growth (Pezo-Lanfranco et al., 2020). Examining the different growth patterns in males and females provides some support for this interpretation of the results. Females are thought to be more ‘buffered’ from infection, disease and growth disruption than males, where environmental stressors create greater disruptions to male skeletal growth (DeWitte, 2010; Stinson, 2012, 1985). In this analysis, female femoral lengths increased slightly (0.6 cm and 1.1 cm) from the Gallo-Roman to Post-Roman period. Male femoral lengths notably increased in the Post-Roman North group (1.8 cm). This could indicate that environmental stressors had suppressed growth in Gallo-Roman (and Post-Roman south) samples. If these pressures were reduced or relieved in the Post-Roman North, it could explain the increase in femoral lengths, but also differences in the magnitude of this increase between the sexes. In addition to overall shorter femur lengths and higher DEH frequencies, Gallo-Romans had higher crude prevalence rates of Tibia PR than the Post-Roman groups. This may represent increased frailty stemming from early life stressors or indicate the regular or chronic exposure to stressors throughout the life course and not only during development. TPR prevalence was not significant, but it does maintain the same overall pattern as CPR, with Gallo-Romans showing higher prevalence.

4.1.3 ‘Intermittent stress of low lethality’?

Short adult femur lengths, in combination with stress indicators from across the life course in the Gallo-Roman sample, could reflect early life adverse environments and also suggest regular and persistent negative environmental conditions throughout development (which prevented opportunities for catch-up growth as seen in Post-Roman samples). Following a recent study, it is argued that the Gallo-Roman data fit a newly formulated model of ‘intermittent stress of low lethality’ defined as ‘the adaptation to recurrent metabolic insults of low impact that allows survival to reproductive age with relative success, overcoming environmental aggressions in physiological, physical and cognitive terms‘ (Pezo-Lanfranco et al., 2020, p. 22). Complicating interpretations, exposure to early life stressors specifically during the first 1000 days after conception can make an individual more susceptible to poor health outcomes in later life (the Developmental Origins of Health and Disease (DOHaD paradigm) (Barker, 2012; Barker et al., 2002, 2011; Kuzawa and Quinn, 2009). The ability and energetic cost to survive a stressor in early childhood could have reduced the capacity of the body to mount an effective immune response later in life, potentially leading to increased/earlier morbidity and mortality (Goodman and

Redclift, 1988). This means that later life health outcomes could represent increased frailty from early life trade-offs or represent newly introduced stressors, but the two are not mutually exclusive. As such, Tibia PR seen in the Gallo-Roman sample could represent new or continual exposure to stressors, or represent individuals who were more frail, based on previous stress exposures in early life. Teasing apart this relationship may not be possible. However, because both Gallo-Roman and Post-Roman groups demonstrated early life stressors that impacted later mortality, this study does provide some evidence of DOHaD, indicating that individuals who survived early childhood stressors did so at the expense of mortality in adulthood. The effects of early life stressors on later health outcomes can be mitigated (positively or negatively) by cultural and environmental conditions (Amoroso et al., 2014; Garland, 2020; Temple, 2019). It is then worth considering how Roman practices and lifestyles, especially those surrounding urban environments and population density, may have contributed to the observed patterns in height and health.

4.2 Health in the Gallo-Roman and Post-Roman Periods

The Gallo-Roman South sample demonstrated shorter adult femoral lengths and higher rates of DEH and Tibia PR, suggesting the presence of early life stressors and potentially recurrent episodes of stress across the life course. In both Post-Roman groups, the high frequency of CO and its relationship with earlier mortality highlights the continued presence of early life stressors in this later time period, but also suggests a change. Different factors appear to be creating conditions with divergent impacts on health during Gallo-Roman and Post-Roman time periods with some regional variability. It has been suggested that features of Roman lifeways, such as urban living (houses and workplaces) and higher population density negatively affected health, despite improvements in water supplies, sanitation, and increased economic activity (Frier, 1977; Harper, 2016; Morley, 2004; Porter, 1999; Scheidel, 2015, 2012a; Scobie, 1986). Features of 'Roman' cultural and socio-political life are thought to have been more strongly present in southern Gaul and appear to have retreated more gradually than in northern regions.

4.2.1 Urbanization and Population Density

Several studies from across the Western Roman Empire have attributed perceived dips in health to high degrees of urbanization and population density, resulting in overcrowding and insalubrity (Gowland, 2017; Griffin, 2017; Jongman et al., 2019; Redfern and Roberts, 2005; Redfern and DeWitte, 2011; Rohnbogner and Lewis, 2016; Scheidel, 2012a). These conditions would have increased pathogen exposure and pathogen sustainability, including viruses, bacteria and parasites (Aldrete, 2004; Morley, 2004; Scheidel, 2015; Scobie, 1986). Although Roman towns often included a system for waste disposal, public facilities (baths, aqueducts) and flowing water, waste disposal and management in Roman cities was highly likely to have been inadequate and variable and could have led to food and water contamination and illness (Aldrete, 2004; Morley, 2004; Porter, 1999; Scobie, 1986). Housing within Roman cities could also have contributed to negative health outcomes through overcrowding, the use of indoor fires for warmth and food preparation, as well as owing to poor ventilation (Scobie, 1986). Additionally, high levels of migration to larger urban centers would have increased pathogen exposure, but also the number of vulnerable people within one place (Morley, 2004; Redfern et al., 2018; Scheidel, 2003; Stark, 2017). The same Roman road and communication networks that permitted travel, trade and access to new food sources, also could work to transmit and spread disease (Harper, 2017).

Within this study, the Gallo-Roman sample is composed of individuals from two major urban centers (Arles and Saintes). As a result, it is very possible (and even likely) that the present results reflect Roman urban influences on height and health. Although acute conditions would have led to death before the skeletal manifestation of disease, short femoral lengths, heightened DEH and Tibia PR observed in the Gallo-Roman sample might then have a relationship with repeated exposure to chronic infectious diseases, spread through Roman settlements with heightened population densities. This seems especially possible as the Gallo-Roman sample had many individuals with signs of repeated stress exposure (multiple DEH, short femoral length, Tibia PR). Although there are many possible (and synergistic) etiologies, growth disruption, DEH and Tibia PR can result from infection, especially when there are additional nutritional deficits (Resnick and Nakamura, 1995; Roberts, 2019). In the Post-Roman period, several features that might have created the repeated and regular exposure to pathogenic stressors declined. This includes a reduction in urban size and high population density, but also trade networks (and possibly migrants) (Kiple, 1993; McNeill, 1998; Morley, 2004). Similar to studies of rural environments in

Roman Britain (Redfern et al., 2015; Rohnbogner, 2015; Rohnbogner and Lewis, 2016, 2017), both Post-Roman samples in this study displayed high levels of CO, indicating a different underlying cause of early childhood stress compared to Roman urban centers.

4.2.2 Diet and Migration

Several studies have proposed that changes in diet between Roman and Post-Roman periods are the root cause for the observed patterns in growth and non-specific stress indicators (Koepke, 2014; Koepke and Baten, 2008; Lightfoot et al., 2012; Scheidel, 2012a). Isotopic, zooarchaeological and archaeobotanical data from across the Roman Empire suggest that diets were more diverse during the Roman period because of expanded trade routes, access to a wider variety of food and food production techniques (Bakels and Jacomet, 2003; Lightfoot et al., 2012; Mion et al., 2016; Müldner, 2013; Prowse et al., 2004; Redfern et al., 2010; Zech-Matterne et al., 2017). *Cribra orbitalia* was assessed as a non-specific stress indicator but has a relationship with diet and disease load (in addition to specific pathological conditions). Analysis of CO revealed comparatively higher prevalence in the Post-Roman groups. This finding could suggest differential dietary influences on health in Roman and Post-Roman Gaul. Isotopic analyses of diet (carbon and nitrogen) from Croatia and even from within northern Gaul have found that as Roman authority declined, diet became more heavily reliant on millet and other cereals (Lightfoot et al., 2012; Mion et al., 2016). This could have contributed to observed changes in the frequency and patterns of stress indicators observed in this study.

Migration has also been found to be a primary driver for patterns of disease in Roman Britain (Redfern et al., 2018; Redfern and DeWitte, 2011) and the presence of migrants within the site of Saintes, Rue Jacques Brel has been previously identified (Stark, 2017). Migrants expose local populations to new types of pathogens, but also experience heightened susceptibility to endemic diseases, potentially affecting mortality profiles (DeWitte et al., 2016; DeWitte and Stojanowski, 2015; Gowland and Redfern, 2010; McNeill, 1998). Migration was an important component of society in both Roman and Post-Roman periods in Gaul. Despite the clear significance of migration on health status in Roman and Post-Roman periods, it was not possible to adequately address this topic in this study.

5 Conclusion

Skeletal stress indicators from across the life course were analyzed to assess the effects of Roman practices and lifeways on health in Gaul. Early childhood stressors impacted both Gallo-Roman and Post-Roman samples with negative effects on mortality. However, the skeletal manifestations of both early life stressors and later health indicators were different between periods. Gallo-Roman individuals may have been more regularly exposed to infectious pathogens throughout childhood, through a long-term negative living environment that inhibited opportunities for catch-up growth, that resulted in shorter femoral lengths ('intermittent stress of low lethality'). This could be the result of overcrowding and insalubrity of the urban settlement environment. Post-Roman groups demonstrated longer femoral lengths and lower frequencies of DEH and Tibia PR. Higher rates of CO may have been influenced by dietary changes between the periods. However, the importance influence of migration on health during either period cannot be ruled out. The intertwined and often synergistic relationships between early life environment, nutrition and settlement structure and population density is highlighted, helping to further understandings of life experiences during the Roman and Post-Roman periods.

Acknowledgements:
The authors have no conflict of interest to declare. This work was supported by a Durham Doctoral Studentship, Durham University. Many thanks are due to Centre de Conservation et d'Etude de Lorraine, De la Préhistoire à l'Actuel : Culture, Environnement et Anthropologie, Le Centre de recherches archéologiques et historiques anciennes et médiévales, L'Ostéothèque Régionale Provence-Alpes-Côte d'Azur, especially Tanguy LeBorsicaud, Cecile Chapelain de Seréville-Niel, Patrice Courtaud, Yann Adragna, Bruno Touveron and Stephan Naji for access to the skeletal collections and their help in the development of the first author's PhD research.

Funding Sources:
This work was supported by a Durham Doctoral Studentship, Durham University.

Declarations of interest:
none.

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