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The Impact of Social, Economic and Political Change in Linear and Appositional Growth of Children from the Medieval Islamic and Christian Periods of the Algarve, Portugal

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A B S T R A C T

Archaeological data and historical research suggest that the Medieval Islamic Period (711-1249 A.D.) in Iberia was associated with conditions more favourable for child growth than the post-Islamic Christian Period (1249-1650 A.D.). This is due to agricultural prosperity, greater medical knowledge, and better hygienic practices of the former. As child growth is a sensitive indicator of environmental insults, it can be used as a proxy for the stress experienced by the whole population. The linear and appositional bone growth of 29 children (under the age of 12 years) recovered from archaeological sites in Silves and Cacela Velha - dating from the Medieval Islamic and Christian Period in the Algarve, Portugal - were compared to determine whether the environmental changes associated with the transition between these periods impacted the health and well-being of the populations. Age was estimated from tooth length. Linear growth of all long bones and the appositional growth of the femur and humerus at the midshaft were compared between periods using z-scores. Bone growth deficits were found among the medieval children in all samples. Overall, Islamic Period children had slightly greater growth deficits than Christian Period children, although these differences were not statistically significant. This finding suggests that neither Medieval Period was more favourable for growth. Statistically significant differences in appositional growth were found between the Medieval Santarém and Algarve populations, suggesting these differences to be related to the local environment, rather than religious or temporal differences within the Algarve or other regions of Portugal.

1. Introduction

With the transition between the Medieval Islamic Period (711 A.D.-1249 A.D.) and the Medieval Christian Period (1249 A.D.-1650 A.D.) in the Algarve, Portugal, came major changes to environmental and living conditions, including sanitation, proximity to vectors of disease, population density, and access to nutrition and medical care (Aceves 2019; Hollander and Staatsen 2003; Kennedy 1996; Knorr et al. 2019; Salas-Salvadó et al. 2006; Trindade 2007; Worman 2012). Despite the high frequency of political conflicts between different factions in the Islamic Period, there was immense socio-economic growth, and agricultural prosperity during this time (Kennedy 1996; Worman 2012). By contrast, with the Christian conquest, much of the farmlands in Portugal had been abandoned, there was widespread erosion, frequent droughts, and diets became much less diverse as cities became densely packed, and citizens were increasingly exposed to vectors of disease (Hollander and Staatsen 2003; Salas-Salvadó et al. 2006; Trindade 2007; Worman 2012). To explore how the dynamics of the social and political transition impacted the health and wellbeing of citizens in the Medieval Period, the growth of children recovered from Medieval Islamic and early post-Islamic Christian Period archaeological sites in Silves (an urban settlement) and Cacela Velha (a rural settlement) in the Algarve region of southern Portugal (see Figure 1) were examined.

Life-history theory dictates that the energy demands of malnutrition, disease load, activity, and physical and psychological trauma have a fundamental role in the trade-offs that occur in the energy allocated for growth, reproduction, maintenance, and survival. Under this theoretical model, bioarchaeologists can assess the impact of stress experienced by

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populations in the past by studying the physical growth and development of their children (Agarwal 2016; Bogin et al. 2007; Pomeroy et al. 2012; Stulp and Barett 2016). 'Stress' is defined as physiological disruptions to a person's homeostasis, including to growth, resulting largely from their physical, emotional, social, economic, and political environmental conditions (Bogin et al. 2007; Goodman et al. 1988). Children are the most vulnerable individuals of society and, simultaneously, the most phenotypically plastic in terms of growth and developmental outcomes, so the physiological signs of social and environmental stress manifest most prominently in them (Dhavale et al. 2017; Newman and Gowland 2017; Newman et al. 2019). Because children's growth is a sensitive indicator of their cumulative social and physical environment, the growth of children can be used as a proxy for the stress experienced by their whole population (Newman et al. 2019; Tanner 1987). Osteologically, stressors often manifest as a reduction in linear and appositional bone growth, and the resorption of cortical bone (Gooderham et al. 2019; Mays et al. 2009). In growing individuals, there is a strong relationship between delayed bone growth and cumulative exposure to stressors (Bogin et al. 2002; Ives and Humphrey 2020; Newman et al. 2019; Smith et al. 2003; Tanner 1987). By extension, the study of differences in the growth of past children, across populations, can be used to assess the quality of their environment (Bogin et al. 2002; Cardoso and Garcia 2009; Gooderham et al. 2019). The analysis found herein assumes that most of the variation in human growth is due to differences in environmental stressors rather than to genetics, as has been established by previous authors (see Bassino 2006; Bogin et al. 2002; Cardoso et al. 2021; Smith et al. 2003).

The current research expands on an earlier study of growth that evaluated how the transition from the Medieval Islamic Period to the Medieval post-Islamic Christian Period affected population-level stress in Santarém, Portugal (a major city in Central Portugal throughout the Medieval Era) (Gooderham et al. 2019). While individuals from the Christian Period typically experienced greater growth deficits than those from the Islamic Period, these differences were not considered statistically significant (Gooderham et al. 2019). The current study wishes to expand the previous published work, to include the analysis of human remains retrieved from other towns in Portugal that had undergone a similar cultural transition, and examine whether the same patterns could be observed. To further elucidate the question of whether there was a difference in the growth of children between the Late Medieval Islamic Period and the post-Islamic Christian Period in Portugal, the current study examines juvenile skeletal remains from archaeological sites in the Algarve region, in Southern Portugal.

2. Historical Context

Through a series of conquests beginning in 711 A.D., the Iberian Peninsula fell under Islamic rule. Faro, and later Silves, became the most important cities of the southwest part of the al-Gharb region (Catarino 2017). Silves was a major river port in the Medieval Era until the sixteenth century (Chanoca 2006; Gonçalves 2019). Cacela Velha became a fortified town important in maintaining maritime control over accesses to the Ria Formosa Lagoon and Guadiana River (Garcia 2015). Economic growth and urban development such as the fortification and expansion of large cities in the tenth century contribute to the idea of the 'Golden Age' of Islam; yet, there was a significant degree of turnover in the governors of cities and states due to infighting among the Islamic factions over land disputes (Garcia 2015; Kennedy 1996). Civilian revolts and uprisings for economic and religious reasons were also common. When a civil war broke out in the early to mid-eleventh century, Faro and Silves both became autonomous Taifas (small independent city states) (Catarino 2017). The fall of several major cities in the North to the Christian forces in the eleventh century encouraged the reunification of the Islamic state under the Almoravids (Garcia 2015). However, the struggle for power continued into the twelfth century. In about 1143/45 A.D., a new period of Taifas commenced, and these were gradually reincorporated into the Empire by the Almohads beginning in 1147 A.D. As a result of the near-continuous state of warfare and lack of political stability, food shortages were not uncommon in the Algarve during this time at the end of the Islamic rule (Garcia 2015).

In the eleventh century A.D., crusaders were moving south into the Iberian Peninsula, with Henry of Burgundy being given the area known as the *Condado Portucalense* (the county of Portugal) in 1096 A.D., which would later become the Kingdom of Portugal under the rule of his son, Afonso Henriques, in 1143 A.D. (Amaral 2008; Coelho 2000; Disney 2009). Recognition of his rule by the Pope came in 1179 A.D., thanks to his efforts to conquer the Al-Andalus, as it was viewed as a reconquest of Christian lands from Muslim occupiers (Disney 2009; Mattoso 2001). The major cities of Lisbon and Santarém fell under Christian rule permanently in 1147 A.D., but Silves was not taken permanently until 1248 A.D. (Disney 2009, Gonçalves and Oliveira 2020). Cacela Velha was taken by the Order of Santiago (Christian military-religious order) between 1238 and 1240 A.D. (Garcia 2015).

The transition between Islamic and Christian cultural periods in the Algarve led to significant changes in the political, religious, social, and economic structures and institutions. These in turn sparked important transformations in the lives of peoples, such as mobility, war environment, subsistence practices, diet, the design of rural and urban settlements, and the prevalence of diseases (Knorr et al. 2019; Martins 2017; Trindade 2007; Worman 2012). The dynamics of the Islamic occupation of the Iberian Peninsula towards the sea routes and consequent introduction of people, new products and techniques allowed for the expansion of settlements, simultaneously leading to an increase in the diversity and accessibility of food, and allowing cities to increase in number, size, and population (Catarino 1998; García Sánchez 2011; Kennedy 1996; Worman 2012).

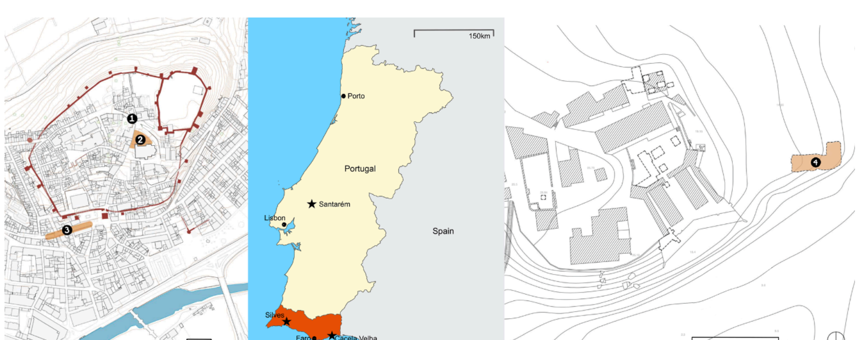

Figure 1. Map of Silves (Left) (Oliveira 2023), Portugal (Centre), and Cacela Velha (Right) (Garcia 2015). On the left, Silves city walls are shaded in dark brown sites are shaded in light brown and numbered: (1) is Rua A, (2) is Largo da Sé and Largo da Sé - Cisterna, (3) is Rua 25 de Abril. In the centre, the site locations are identified with a star. On the right, Poço Antigo (4) is located to the east of the town's fortifications and shaded in light brown.

As the Christian forces moved south, the threat of warfare meant that many of the Islamic citizens who could afford to leave migrated to the eastern and southern territories still under Islamic rule, and their agricultural lands often fell into disuse (Barros 2004; Birmingham 2003; Gonçalves 2019; Soyer 2010; Worman 2012). Under Christian rule, soils of the remaining farmlands often eroded due to the over-production of crops, such as wheat, that were ill-suited to the environment, ordered to support the military forces (Barros 2004; Birmingham 2003; Worman 2012). These soil issues were exacerbated by frequent natural disasters such as droughts and earthquakes, resulting in frequent famines during the Christian Period (Disney 2009; Worman 2012).

Diet may also have impacted the wellbeing of the Medieval populations. It is common for the historical narrative to state that the diets of Islamic Period citizens were more diverse, which would have been beneficial for ensuring a more balanced nutritional intake (Aceves 2019; García Sánchez 1983; Pereira 2014; Toso et al. 2019). By contrast, the Christian Period diet was far less balanced (Aceves 2019; Salas-Salvadó et al. 2006). Nutrition being an important factor in the maintenance of health, it is likely that food shortages and a lack of diversity in diet in the Christian Period would have adversely affected health.

The arrangement of the cities themselves could also have impacted the health of each population, through exposure to disease. Urban planning in the Islamic Period ensured that religious spaces, commercial districts, cemeteries, and waste deposits all had designated spaces, and were kept separate from residential areas, allowing for a greater distance between humans and areas where they could be exposed to potential vectors of disease, such as decaying bodies, pests, animals, and wastes (Catarino 2017; García 2001; Hollander and Staatsen 2003; Macias 2018; Trindade 2007). By contrast, in the Christian Period, there was a significant merging and overlap of the commercial and residential spaces (Catarino 2017; Llave 1998). For instance, and as per Christian custom, the dead were buried in, or near, churches (Garcia 2015; Kallio-Seppä and Tranberg 2021). Consequently, cemeteries were now within the inner city, exposing citizens in the surrounding area, as well as all those visiting the churches, to the decaying bodies, and the detrimental effects that the exposure could have had on their health (Kallio-Seppä and Tranberg 2021).

Exposure to harmful wastewater would have also been reduced in the Islamic period due to the common usage of latrines, septic pits, and drainage infrastructure (Garcia et al. 2015; Gonçalves and Oliveira 2020; Knorr et al. 2019; Macias 2018). By contrast, latrines became less common in Medieval Christian cities, with human wastes often being thrown directly into the streets, despite rules against this practice (Llave 1998). The lack of adequate means of disposal of human wastes, and the reduced division between urban and commercial spaces, suggests that the exposure of people in the Christian Period to disease vectors would likely have been greater.

Differences in sanitation practices between the periods may also have impacted health. For Islamic peoples, washing of hands, the body, and clothes was an important part of their daily ritual, and public baths were used frequently (Knorr et al. 2019). In the Christian Period, baths became unpopular even among remaining Islamic populations within Christian cities, and Christian individuals often avoided bathing and washing their clothing as an act of penance or devotion (Barros 2005; Oliveira Marques 1971). In spite of the focus on sanitation in the Islamic Period, their cleaning practices were likely ineffective at eliminating fecal-oral parasites (Knorr et al. 2019). The poor construction of latrines in some areas could have led to contamination of soil and wells, and historical documents assert that human feces, along with other manure and wastewater, were used to fertilize crops and gardens, perpetuating the life cycle of intestinal parasites (Gonçalves and Oliveira 2020; Knorr et al. 2019). The remains of intestinal parasites are commonly found in the archaeological sites of both Medieval populations (Knorr et al. 2019). In addition, other bacterial and viral infections that are undetectable archaeologically could have spread to people by the same means. Thus, the historical records from the Islamic Period indicating that people had an interest in or concern for sanitation may not actually equate to their level of success at sanitization.

Differences in medical knowledge could have affected the health of each population. In the Islamic Period, practitioners and medical scholars researched, studied, and wrote extensively about public health, preventative medicine, pediatric medicine, and treatments, sharing their findings across the Islamic world, and building on the knowledge of Greek and Roman scholars. In the Christian Period, medical practitioners were more concerned with the souls of patients (Silveira 2009). Religious orders established hospitals to care for the sick and poor as they conquered new lands, but the treatment of illness was not the priority of these hospitals (Martins 2017; Rodríguez-Picavea 2009; Silveira 2009). Patients often had to share their beds, and the sanitation practices would have been inadequate to prevent the spread of disease (Conde 1999). If a patient did not recover, their death was seen as the result of a divine punishment for their sins in life. Christian Period people relied heavily on prayer and folk remedies to protect themselves, some of which might have been more effective than others. Fasting, avoiding bathing, and the practice of maintaining filthy clothing to repent for sins (Oliveira Marques 1971) are now known to be more likely to cause, rather than prevent, disease (Cumming and Cairncross 2016; Headey et al. 2018). However, the Christian practice of avoiding people, removing corpses from public areas, and rubbing hands, faces, and surfaces in houses with vinegar (which can act as a disinfectant), may well have helped (Oliveira Marques 1971). Of course, without the means to understand the source of diseases and the methods of their transmission, epidemics often spread regardless.

The aim of this study is to contrast child growth between sites dated to the Late Medieval Islamic and post-Islamic Christian samples in the Southern Algarve region of Portugal, and with contemporary samples from Santarem, in Central Portugal. This contrast is carried out to assess whether the Islamic Period was more favourable to child growth and whether growth patterns in Medieval Algarve resembled those in Medieval Santarem. This research provides a unique and rare insight into the impact of social, economic and political changes on population-wellbeing associated with the Late Medieval transition from the Islamic to Christian Period in Portugal. Integration of the existing historical and archaeological evidence with the bioarchaeological data generated here will provide a further and richer understanding of living conditions in Medieval Portugal.

3. Materials and Methods

The skeletal remains of children from late Medieval Islamic Period and Medieval post-Islamic Christian Period archaeological sites within the Algarve, Portugal were examined. The Islamic Period sites include *Rua 25 de Abril*, located on the southern side of the Islamic city walls of Silves; and *Rua A*, located at the top of the hill, north of the Silves Cathedral, and west of the castle (see Figure 1). The Christian Period sites include *Largo da Sé* and *Largo da Sé - Cisterna*, which surround the Cathedral in Silves; and *Poço Antigo*, near the coastal fortress in Cacela Velha (see Figure 1).

All available juvenile skeletons from these sites with at least one unworn incompletely-formed mandibular tooth (used to estimate age at death), and one complete long bone with unfused epiphyses (used to measure linear growth) were examined (as per Gooderham et al. 2019). Relying on long bones with unfused epiphysis restricts the analysis to per-pubertal children (under the age of 12 years) and eliminates the difficulty of examining linear growth when either one or two epiphyses are fused. In addition, combining data from pre-pubertal individuals from both sexes is common practice in growth studies of the past, and is unlikely to have an impact in the analysis because sex-related differences in growth prior to puberty are negligible (Corron et al. 2021). No attempt was made to divide the sample by sex because, without DNA testing, sex cannot be reliably identified from juvenile remains. While the remains of over 100 children were initially screened, only 29 individuals were found suitable for this study due to poor preservation: nine of which were from the Islamic Period, and 20 of which were from the post-Islamic Christian Period (Table 1). Due to their preservation, not all teeth and/or bones were available from each individual.

Age was estimated based on tooth measurements following the procedures from Cardoso et al. (2016) for permanent dentition, and Cardoso et al. (2019) for deciduous dentition. Dental aging formulae for sexes combined were selected, because biological sex was unidentifiable since the children had not yet reached puberty and as such there were unlikely to be significant differences in their growth (Cardoso and Garcia 2009). The maximum length of each available unworn and incompletely-formed, deciduous and permanent mandibular tooth was measured to the nearest tenth of a millimetre. If a tooth was not socketed, then its maximum length was measured with a sliding digital caliper; otherwise, a scaled radiograph was made with a portable digital radiograph machine and ImageJ software was then used to measure each tooth. The age at death of each individual was then estimated by averaging their individual tooth ages (except those from the third molar), from all of their tooth types, since the mean age of multiple teeth was found to be more accurate than using individual teeth (Cardoso 2007).

The linear growth of all six long bones were examined as a proxy for stature, as periods of prolonged stress disrupt the expected growth rate of the long bones (Cardoso and Garcia 2009; Dhavale et al. 2017; Gooderham et al. 2019; Newman et al. 2019). The appositional growth of the humerus and femur were also examined because appositional growth can be more sensitive to environmental stress, such as malnutrition, than linear growth (Mays et al. 2009). The differences in appositional growth can help to detect differences in the growth environment that are too subtle to be seen by examining linear growth alone. If the Islamic Period in the Algarve was a more favourable environment for child growth, greater linear growth of all long bones would be expected during that period, along with greater cortical thickness.

To measure linear growth, the maximum diaphyseal length of each complete long bone, with unfused epiphyses, was measured and recorded to the nearest millimetre when using an osteometric board and sliding digital calipers. Appositional growth was measured by making scaled digital radiographs of the anteroposterior and mediolateral planes of the midshafts of the humerus and femur, using a portable digital radiograph machine, to mathematically estimate the cortical bone areas using the ellipse model method (O'Neill and Ruff 2004). The midshaft of juvenile humeri and femora are found at the 41% mark of the humerus and the 45.5% mark of the femur (measured from the distal end using sliding digital calipers) (O'Neill and Ruff 2004; Ruff 2003). These locations have the most elliptical shape and account for the difference from the midpoint due to the lack of epiphyses in juvenile individuals and allow for the deltoid tuberosity of the humerus to be avoided (Ruff 2000; Ruff 2003). ImageJ software was then used to measure the total width and the medullary width from the scaled mediolateral and anteroposterior radiographs, so that the total area, cortical area, medullary area, and cortical thickness of the humerus and femur could be estimated (O'Neill and Ruff 2004).

All linear and appositional bone measurements for each individual in each Islamic and Christian samples were then converted to z-scores, calculated with the Denver Growth Study Data as a reference (obtained from Maresh 1970 and the unpublished cortical bone data kindly provided by Dr. Christopher Ruff; corrected for radiographic distortion, as per Cardoso 2005). Z-scores standardize individual measurements so that differences in size due to age and sex are accounted for and allow comparisons to be made across samples, despite any unequal distribution in age or sex (Cardoso 2005; Gooderham et al. 2019; Spake and Cardoso 2021). The z-scores described how many standard deviations away from the mean growth of the reference sample, each individual measurement was. Z-scores are calculated by subtracting the age-specific mean from the individual value and dividing by the age-specific standard deviation. In the reference sample, there are only a set of age-specific means and standard deviations that do not always match the estimated age of the individual. For this reason, the age-specific mean and standard deviation used for the calculation of the z-scores were identified by assigning each individual to the age group from the reference data that immediately preceded the estimated age of that individual (Gooderham et al. 2019). If an individual has a positive z-score this indicated that the individual's growth was greater than the mean expected from the reference sample, while a negative z-score indicated that growth fell behind the mean of the reference sample.

The Denver Growth Study was chosen as a reference because it is the only study which has data available for assessing linear growth from all six long bones and for assessing appositional growth from cross-sectional measurements of the femur and humerus. While some other reference sample could theoretically have been used, since it is merely a tool for a relative comparison between the Islamic and Christian samples, calculating z-scores based on a different reference would carry no consequences to the analysis. Unfortunately, currently there are no alternate references that provide the same possibilities as the Denver Growth Study. In addition, the same reference was used by Gooderham et al. (2019) in their study of children from Medieval Santarém, and the z-scores calculated in that study can thus be directly compared to those calculated here. As long as the same reference collection and method is used for the calculation of the z-scores, the z-scores of any population can be compared.

Due to the small sample sizes, a Mann-Whitney test was used to test whether z-scores for linear and appositional growth differed between the Islamic and the post-Islamic Christian Period children from the Algarve, to assess any differences in growth between the periods. Lastly, z-score means for linear and appositional growth from this study were compared to those calculated from Medieval Santarém children (Gooderham et al. 2019) using unpaired two sample t-tests, to examine whether the regional differences in growth between Santarém and the Algarve during the Medieval Period were statistically significant. Since these regional comparisons had considerably larger sample sizes, t-tests

Table 1
Sample size distribution by site, period, age group, and skeletal element.

Location	Site Name	Chronology	Period	n	Age <2	Age >2	Humerus	Radius	Ulna	Femur	Tibia	Fibula	Femur Midshaft	Humerus Midshaft
Silves	Rua 25 de Abril	9th - mid 13th century	Medieval Islamic	8	5	3	6	5	6	5	4	2	5	6
Silves	Rua A	12th - mid 13th century	Medieval Islamic	1	0	1	1	1	1	0	0	0	0	1
Silves	Largo da Sé –Fase 1	13th - mid 16th century	Medieval Christian	4	0	4	4	2	1	3	2	0	2	4
Silves	Largo da Sé Cisterna	13th - mid 17th century	Medieval Christian	8	0	8	6	5	5	3	2	3	3	6
Cacela-Velha	Poço Antigo	Mid 13th – 14th century	Medieval Christian	8	5	3	6	5	8	4	2	1	3	4
Total				29	10	19	23	18	21	15	10	6	13	21

were conducted rather than non-parametric alternatives. Santarém was a very large urban centre throughout the Medieval Era and represents a more northerly Portuguese medieval population. By comparing our data with another location, we hoped to see whether there were regional differences in growth patterns across each Medieval Period, and whether the transition between the Islamic and post-Islamic Medieval Periods was consistent across regions.

Due to the small sample sizes, a power analysis was carried out to estimate the statistical power of our comparisons. Because sample size varied between comparisons, it was estimated that the power of the between-sample comparisons (Algarve vs. Denver) varied from 58% to 30%, with only a few as low as 17%. For between-period comparisons (Islamic vs. Christian) the statistical power dropped to a range of 41-23%, and as low as about 14% in a few cases. These comparisons have clearly low statistical power. Unfortunately, very little can be done to change these circumstances. Careful consideration of the impact of this lower power on the results is given later.

To visualize differences in growth between samples, skeletal growth profiles were constructed for each of various linear variables (the length of the humerus, radius, ulna, femur, tibia, and fibula) and appositional growth variables (the total area, cortical area, medullary area, and mediolateral and anteroposterior cortical thickness, at the midshaft of the humerus and femur). In each skeletal growth profile, a bone variable is plotted against age, and individuals are contrasted to a reference growth curve created from the mean age-specific reference data for the sexes-combined from the Denver Growth Study.

4. Results

On average, all long bones experienced a linear growth deficit, but the bones of the lower limb typically showed greater growth deficits than those of the upper limb (as seen in Table 2, and as illustrated in the skeletal growth profiles for the humerus in Figure 2, the radius in Figure 3, and the femur in Figure 4). In general, children in the Islamic Period show smaller z-scores and thus greater growth deficits in the diaphyseal lengths of the long bones. The radius showed the greatest difference in z-scores between the periods, but the differences in mean z-scores between the two samples did not reach statistical significance (Table 2). The skeletal growth profiles for the long bones did not show a clear visual difference in long bone growth between the periods (as seen in Figure 2, Figure 3, and Figure 4).

In general, for the femur, the total area, cortical area, mediolateral cortical thickness, and anteroposterior cortical thickness show a growth deficit, while the medullary area was larger for age (Table 3 and Figure 5, Figure 6, and Figure 7). The mean z-scores indicate that there were greater femoral appositional growth deficits among children from the Islamic Period, although these differences did not reach statistical significance (see Table 3). While children from both periods experienced growth deficits, the cortical bone of the Islamic Period children was typically thinner, the total area of their femora were generally smaller, and the medullary area of their femora were generally larger for age, than the Christian Period children.

Visually, the total area, cortical area, mediolateral cortical thickness, and anteroposterior cortical thickness of the midshaft of the humerus

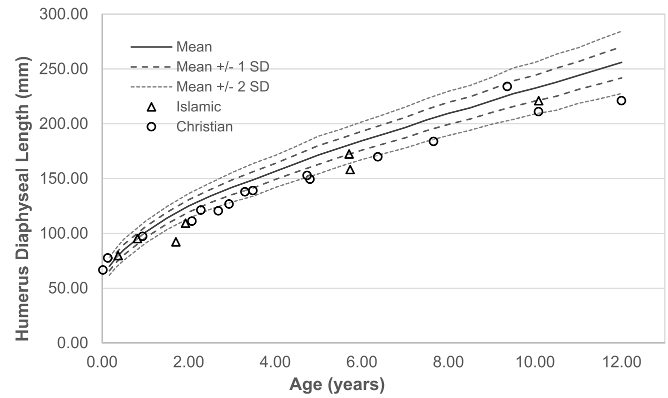

Figure 2. Scatterplot of humerus diaphyseal length for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

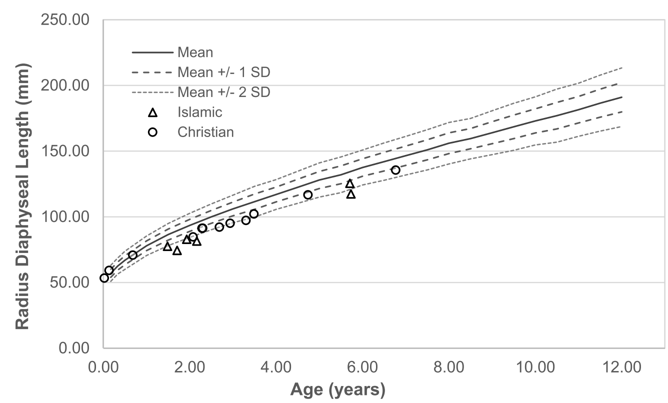

Figure 3. Scatterplot of radius diaphyseal length for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

show a growth deficit in the total Medieval sample of children relative to those in the Denver Study (Figure 8, Figure 9, and Figure 10). In general, there were greater growth deficits in the Islamic Period (see Table 4). While the mean z-scores indicate that the children from both periods had humeri with a similar total area at the midshaft, the Islamic Period children had slightly wider medullary cavities, and thinner cortical bone. These differences in medullary area and cortical bone thickness between the Periods were not statistically significant (Table 4).

Generally, the pattern of linear and appositional growth observed in this study is the reverse of what was observed by Gooderham et al. (2019). In the Algarve, the Islamic Period children tended to have greater linear growth deficits. By contrast, in Santarém, the Christian Period children tended to have greater linear growth deficits compared to their Islamic Period counterparts. Regardless, the differences in growth within each region were not found to be statistically significant. When the linear growth of children in the total samples from Santarém

Table 2
Sample size (n), mean (X̄), and standard deviation (SD) for long bone length z-scores, by Period. A Mann-Whitney test compares the Islamic and Christian Periods, and was computed as a z-score (z) to facilitate interpretation. If z-score is less than -1.96 or greater than 1.96, the null hypothesis is rejected at a significance level of 0.05.

	Total			Islamic			Christian			Mann-Whitney U test	
	n	X̄	SD	n	X̄	SD	n	X̄	SD	z	p
Humerus	21	-1.07	1.59	7	-0.92	1.98	14	-1.15	1.43	-0.671	0.535
Radius	16	-1.32	0.97	6	-1.93	0.84	10	-0.96	0.88	-1.952	0.056
Ulna	19	-0.92	1.53	7	-0.83	1.74	12	-0.98	1.47	-0.507	0.650
Femur	14	-1.94	1.04	5	-2.26	0.89	9	-1.76	1.13	-1.267	0.240
Tibia	10	-1.81	1.10	4	-2.01	0.87	6	-1.67	1.29	-0.213	1.000
Fibula	6	-1.57	1.22	2	-1.94	1.45	4	-1.38	1.28	-	-

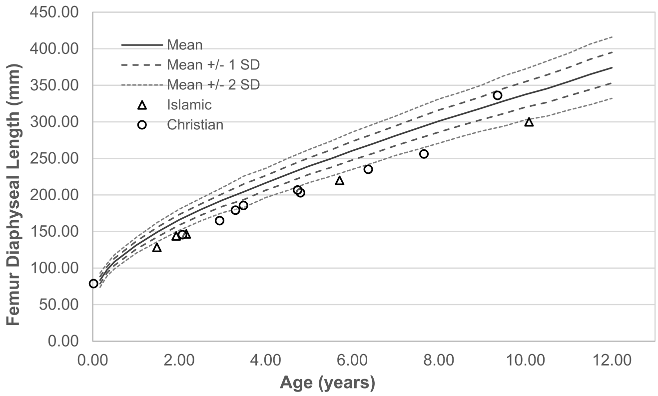

Figure 4. Scatterplot of femur diaphyseal length for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

(from Gooderham et al. 2019), were compared to the total samples from the Algarve, the Santarém samples had greater growth deficits (Table 5). Nonetheless, according to the t-tests, the differences in the linear growth between the regions were not statistically significant.

When the z-scores for each Period were compared between the regions, only the radius in the Christian Period showed a statistically significant difference between the Algarve and Santarém (p=0.04) samples. None of the other long bones demonstrated a statistically significant difference between the regions, although, there were generally greater growth deficits among the Christian Period children from Santarém than those from the Algarve.

When the appositional growth of the femur for the total samples from the Algarve and Santarém were compared, the z-scores for cortical area between regions were similar, but the total area, medullary area, and mediolateral cortical thickness for age were significantly different (see Table 6). The children from Santarém typically had a smaller total area of the femur at the midshaft, but the children from the Algarve typically had a smaller cortical area, thinner cortical bone, and a wider medullary cavity, indicating that, overall, the Algarve children had greater appositional growth deficits.

In the Islamic Period, children from the Algarve typically had femora with a smaller total area, smaller cortical area, thinner cortical bone, and wider medullary cavity at the midshaft than those from Santarém (Table 6). In this case, only the differences in the medullary area and mediolateral cortical thickness were statistically significant (with p=0.007 and p=0.038 respectively). In the Christian Period, the children from the Algarve typically had femora with a larger total area, a wider medullary cavity, and thinner cortical bone than the children from Santarém (Table 6). Regardless, only the differences in the total area, and medullary area were statistically significant (with p=0.049 and p=0.001 respectively). Most of the differences in the appositional growth of the femur in the Christian Period were the result of greater growth deficits in the total area of the femur at the midshaft among the Santarém children, and the enlargement of the medullary area of the femur among the Algarve children.

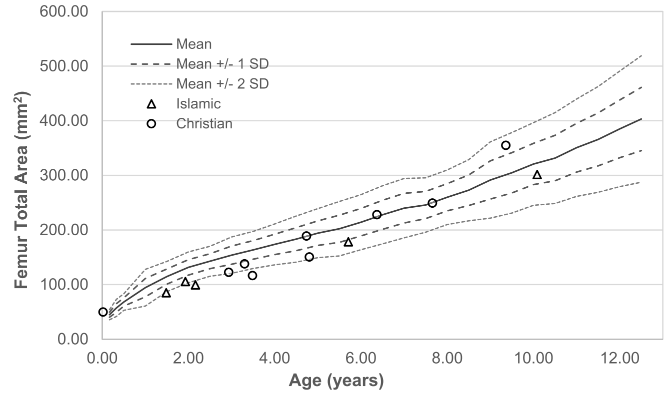

Figure 5. Scatterplot of femur total area for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

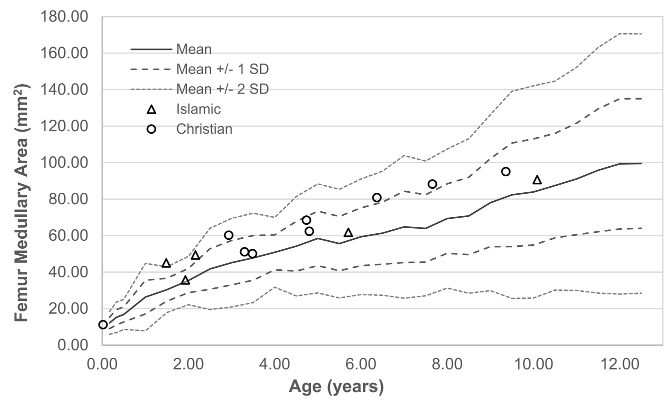

Figure 6. Scatterplot of femur medullary area for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

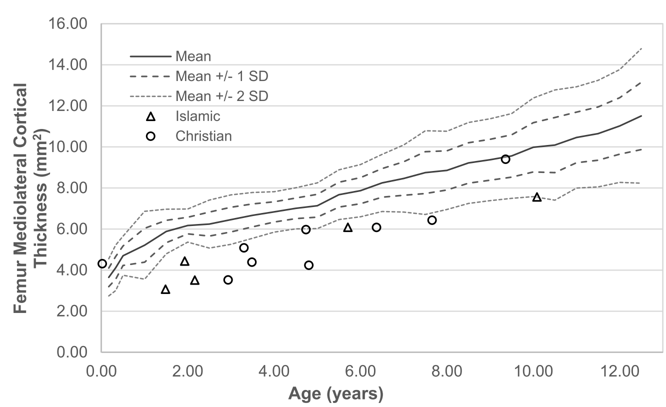

Figure 7. Scatterplot of femur mediolateral cortical thickness for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

Table 3
Sample size (n), mean (X̄), and standard deviation (SD) for femur midshaft measurement z-scores, by Period. A Mann-Whitney test compares the Islamic and Christian Periods, and was computed as a z-score (z) to facilitate interpretation. If z-score is less than -1.96 or greater than 1.96, the null hypothesis is rejected at a significance level of 0.05.

Measurement	Total			Islamic			Christian			Mann-Whitney U test	
	n	X̄	SD	n	X̄	SD	n	X̄	SD	z	p
Total Area	13	-0.81	1.28	5	-1.32	0.84	8	-0.50	1.46	-1.025	0.354
Cortical Area	13	-2.38	2.21	5	-2.75	1.80	8	-2.14	2.52	-0.439	0.724
Medullary Area	13	1.02	0.70	5	1.19	0.98	8	0.92	0.50	0.293	0.833
Mediolateral Cortical Thickness	13	-3.30	1.82	5	-3.82	1.99	8	-2.98	1.75	-0.586	0.622
Anteroposterior Cortical Thickness	13	-2.37	2.64	5	-3.43	3.25	8	-1.72	2.14	-0.878	0.435

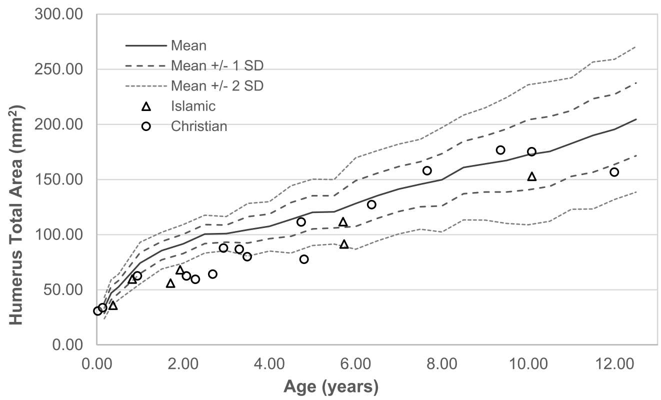

Figure 8. Scatterplot of humerus total area for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

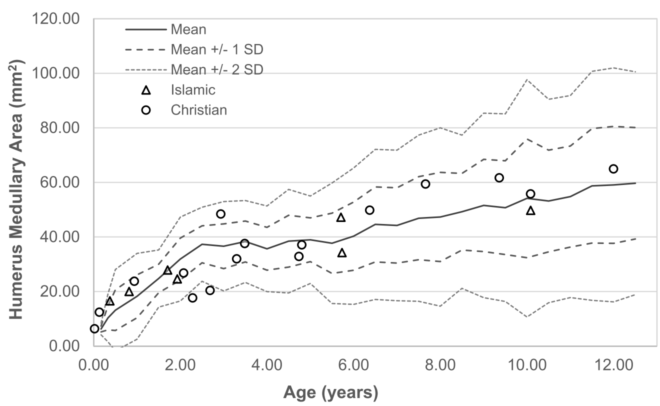

Figure 9. Scatterplot of humerus medullary area for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

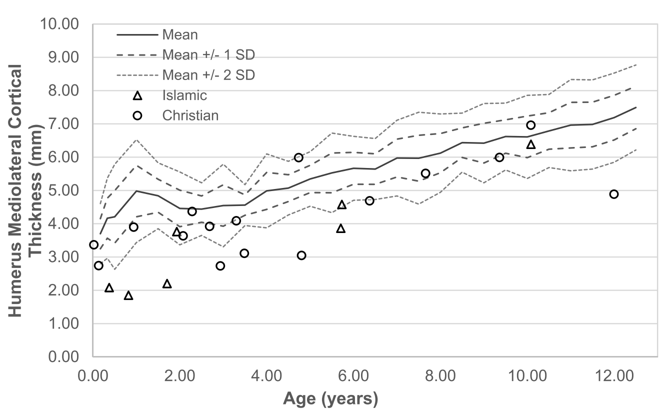

Figure 10. Scatterplot of humerus mediolateral thickness for age for the Medieval Islamic and Medieval Christian children, compared to the Denver Growth Study data.

5. Discussion

While the z-scores means for all long bone variables in both Medieval samples showed growth deficits when compared to the modern reference sample, there were no statistically significant differences in the linear growth of the long bones between the Islamic and post-Islamic Christian Medieval periods in the Algarve. Generally, the linear growth of the bones in the leg - femur, tibia, and fibula - showed greater deficits than the bones in the arm - humerus, radius, and ulna. The bones of the lower limbs are more sensitive to extrinsic factors than the growth of the upper limbs, as they must grow relatively swiftly over a longer period, so any disruptions or positive influences on growth during that time can have significant impacts on their final length (Bogin et al. 2002; Cardoso 2009; Sciulli 1994). Overall, and while the differences were not statistically significant, the Islamic Period children in the Algarve had greater linear growth deficits than their post-Islamic Christian Period counterparts. This finding suggests that the Islamic Period may have had slightly less-favourable socio-environmental conditions for growth in the Algarve. When comparing linear growth between Medieval children from the Algarve and Santarém (Gooderham et al. 2019), children from Santarém typically had greater growth deficits than those from the Algarve during both periods. However, these differences were only statistically significant for linear growth of the radii in the Christian Period.

The mean z-scores for the total sample indicate that the femoral total area in both the Islamic and post-Islamic Christian samples was slightly small, but relatively similar, to the growth of the reference sample, while their medullary area was larger, resulting in thin cortical bone. In stressful environments, the external dimensions of bones tend not to be affected, due to the strain of mechanical loading which encourages periosteal growth in the femur so that it can support the muscles (Ives and Humphrey 2020). Maintaining the external dimensions of the femur would ensure that the leg muscles would still grow normally and be capable of weightbearing (Ruff 2003; Ruff et al. 2013). Any failure to reach the expected total area for age would indicate illness or nutritional deficiencies were so severe that it slowed periosteal bone deposition, despite mechanical loading (Ives and Humphrey 2020). When nutritional deficiencies are present, but periosteal growth continues, bone is typically resorbed from the endosteal surface to recover the nutrients from the bone, resulting in the widening of the medullary cavity and a reduction in the cortical bone (Mays et al. 2009; Ruff et al. 2013).

In the case of the humerus, the mean z-scores for the total sample indicate that the total area in both the Islamic and post-Islamic Christian samples was small for age, while their medullary area was similar to the growth of the reference collection. It is possible that if the arm was not under as much biomechanical strain, it would not have been required to grow as much externally to support larger muscle attachments (Ruff 2003). Therefore, under nutritional stress, there would be a decrease in the rate of bone deposition on the periosteal surface of the humeri.

The appositional growth patterns of the femur and humerus of the Algarve children are likely tied to trade-offs resulting from their differing function in weight-bearing and activity, and the lack of nutrients available to the Medieval children. Interestingly, appositional growth was different between the Algarve and Santarém Islamic and Christian populations. Generally, in both the Medieval Islamic and Christian Periods, the children from the Algarve had wider medullary cavities and thinner cortical bone than the children from Santarém. This evidence suggests that bone was resorbed from the endosteal surface of the femora to compensate for a lack of nutrients available to them. In the Islamic Period, children from both the Algarve and Santarém tended to have a total area that was small for their age, suggesting either that nutritional deficiencies reduced periosteal growth or that they were less active. In the Christian Period, children from the Algarve tended to have a total area that was similar to the expected growth, whereas the children from Santarém tended to have a total area that was small for age. The Christian Period growth patterns could suggest that the children from the Algarve were generally more physically active than those in Santarém, thus favouring more periosteal bone growth. But it could also suggest that the children from Santarém had an environmental stressor so severe that periosteal bone growth was largely inhibited, despite mechanical loading. An analysis of the cross sectional geometric properties of the femur and humerus, using the same cross sectional data already collected to analyze appositional growth, could reveal the level of mechanical loading the bones experienced, helping us to better understand the growth due to physical activity (Bass et al. 2002; Eleazer

Table 4
Sample size (n), mean ($\bar{X}$), and standard deviation (SD) for humerus midshaft measurement z-scores, by Period. A Mann-Whitney test compares the Islamic and Christian Periods, and was computed as a z-score (z) to facilitate interpretation. If z-score is less than -1.96 or greater than 1.96, the null hypothesis is rejected at a significance level of 0.05.

Measurement	Total			Islamic			Christian			Mann-Whitney U test	
	n	$\bar{X}$	SD	n	$\bar{X}$	SD	n	$\bar{X}$	SD	z	p
Total Area	21	-1.29	1.66	7	-1.35	1.52	14	-1.25	1.78	0.261	0.799
Cortical Area	21	-2.16	1.79	7	-2.52	1.65	14	-1.98	1.89	0.448	0.689
Medullary Area	21	0.12	1.03	7	0.47	0.66	14	-0.06	1.15	-1.045	0.322
Mediolateral Cortical Thickness	21	-1.95	1.98	7	-2.67	1.56	14	-1.59	2.11	1.343	0.197
Anteroposterior Cortical Thickness	21	-2.13	1.57	7	-2.13	1.67	14	-2.13	1.59	0.067	1.000

Table 5
Sample size (n), mean ($\bar{X}$), and standard deviation (SD) for long bone length z-scores, for the total, Islamic, and Christian, Medieval samples. An unpaired t-test compares the Algarve and Santarém samples.

Long Bone	Algarve			Santarém			Unpaired t-test	
	n	$\bar{X}$	SD	n	$\bar{X}$	SD	t	p
Total								
Humerus	21	-1.07	1.59	34	-1.57	2.01	0.967	0.338
Radius	16	-1.32	0.97	30	-2.00	1.77	1.422	0.162
Ulna	19	-0.92	1.53	29	-1.84	2.02	1.691	0.098
Femur	14	-1.94	1.04	25	-2.14	2.25	0.313	0.756
Tibia	10	-1.81	1.10	27	-2.05	2.36	0.307	0.760
Fibula	6	-1.57	1.22	13	-2.13	2.77	0.469	0.645
Islamic								
Humerus	7	-0.92	1.98	22	-1.71	2.04	0.898	0.377
Radius	6	-1.93	0.84	19	-1.83	1.82	0.120	0.899
Ulna	7	-0.83	1.74	20	-1.77	1.97	1.116	0.275
Femur	5	-2.26	0.89	17	-1.95	2.15	0.310	0.760
Tibia	4	-2.01	0.87	18	-1.75	2.41	0.209	0.836
Fibula	2	-1.94	1.45	9	-2.20	3.12	0.112	0.914
Christian								
Humerus	14	-1.15	1.43	12	-1.31	2.02	0.236	0.816
Radius	10	-0.96	0.88	11	-2.30	1.73	2.201	0.040
Ulna	12	-0.98	1.47	9	-1.99	2.24	1.249	0.227
Femur	9	-1.76	1.13	8	-2.52	2.56	0.809	0.431
Tibia	6	-1.67	1.29	9	-2.64	2.28	0.939	0.365
Fibula	4	-1.38	1.28	4	-1.97	2.18	1.264	0.657

2013; Harrington and Osipov 2018; Kurki et al. 2022).

The growth of children across the Islamic and post-Islamic periods within each region indicates that there were few differences in the social and physical environment between them that would have had a differential impact on growth trajectories. The tendency for Islamic children in the Algarve to show greater growth deficits may signal that the state of near-continuous warfare in the Algarve during the Islamic Period would have been stressful; whereas, after the borders of Portugal were established during the Christian Period in 1267 A.D., there was generally much more political stability in the Algarve (Barros 2004; Garcia 2015; Oliveira 2017). There is also some historical evidence to support the idea that there were differences in infant-rearing, infant feeding practices, and maternal health (Browning and Bunge 2009; Gil'adi 1992; Haggerty and Rutstein 1999; Silveira 2009; Toso et al. 2019) that could have resulted in greater growth deficits in the Islamic Period. Despite the extensive written records relating to diet, sanitation, and medicine in the Islamic Period, it is unclear how much of it was actually reflected in the lives of the citizens. Dietary recommendations may only have been practical for those who could afford diverse foods (García Sánchez 1983). Sanitation practices, while used, were not always effective at eliminating sources of disease, and medicine was not always effective at treating the conditions it was meant to treat (Cunha et al. 2017; Knorr et al. 2019). Since a certain degree of romanticization of the past can occur when relying too heavily on written documents that describe the lives of the wealthy and can relate ideals rather than realities, one questions the extent to which "written sources reflect [the] reality for every individual" (Aceves 2019).

Because growth is a non-specific stress indicator, the growth deficits observed in this study could relate to several environmental stressors. Therefore, we cannot connect our observations to any specific stressor from the archaeological and historical evidence. The general prevalence of growth deficits among all of the Medieval samples does align with the expectation that our samples represent children who lived in a place where diseases and poor nutrition were more prevalent, and where there were frequent wars, natural disasters and other stressors.

The inability to detect differences in growth in the transition between the Medieval Islamic and Christian Periods of the Algarve may have resulted from sampling issues, as the sample sizes for both periods were small due to preservation and recovery. There is also the possibility that some of the differences detected are not real due to the low statistical power. A larger sample size would allow for greater confidence in results or may even reveal a different pattern. Unfortunately, sample

Table 6
Sample size (n), mean ($\bar{X}$), and standard deviation (SD) for femur midshaft measurement z-scores, for the total, Islamic, and Christian, Medieval samples. An unpaired t-test compares the Algarve and Santarém samples.

Femur Midshaft Z-Scores								
Midshaft Measurement	Algarve			Santarém			Unpaired t-test	
	n	$\bar{X}$	SD	n	$\bar{X}$	SD	t	p
Total								
Total Area	13	-0.81	1.28	22	-2.03	1.28	2.725	0.010
Cortical Area	13	-2.38	2.21	22	-2.02	2.10	0.481	0.634
Medullary Area	13	1.02	0.70	22	-0.93	1.30	4.979	0.000
Mediolateral Cortical Thickness	13	-3.30	1.82	22	-1.04	2.42	2.909	0.006
Islamic								
Total Area	5	-1.32	0.84	15	-0.26	7.18	0.324	0.750
Cortical Area	5	-2.75	1.80	15	-1.82	2.07	0.895	0.383
Medullary Area	5	1.19	0.98	15	-0.96	1.46	3.044	0.007
Mediolateral Cortical Thickness	5	-3.82	1.99	15	-0.83	2.73	2.241	0.038
Christian								
Total Area	8	-0.50	1.46	7	-2.19	1.56	2.167	0.049
Cortical Area	8	-2.14	2.52	7	-2.45	2.25	0.250	0.807
Medullary Area	8	0.92	0.50	7	-0.86	0.96	4.596	0.001
Mediolateral Cortical Thickness	8	-2.98	1.75	7	-1.51	1.66	1.662	0.120

sizes can only be increased by incorporating data from other archaeological sites from both periods and both regions, should further cemetery excavations be conducted. Consequently, further studies in this area are encouraged. The inclusion of remains from other towns within the Algarve that experienced a similar history of conquest, and which share many cultural elements, might strengthen the study and allow for the differences in growth between the Islamic and Christian Periods to be made more apparent. Currently, there are no other available samples which could be added to the current study. That being said, a similar pattern was seen across the different long bones, suggesting that the results are not completely biased. Some of the sample size issues may be exacerbated when comparing appositional growth because it relies on estimated rather than actual measurements of cortical bone. While these estimates are considerable reliable, we were unable to capture the real shape of the femur and humerus from CT-scans or other direct methods, and there therefore it is possible that subtle differences in shape may have been missed.

The examination of the differences in growth of children from the Visigothic/Late Antiquity Period to the Islamic Period may also allow for a means to examine the effects of the political transition to the Islamic Period. Unfortunately, as with the Gooderham et al. (2019) study for Santarém, there were no examinable skeletons from the Visigothic Period in Cacela Velha or Silves (or in the Algarve) to establish whether the social and environmental improvements, such as the introduction of agricultural technology, new foods, and the growth and expansion of cities, brought on by the Islamic Period positively affected the growth of the children.

The effect of mortality bias, and the impact of the noticeable difference between the growth of survivors and non-survivors (Saunders and Hoppa 1993; Spake et al. 2022) on the results has been considered. While all the samples consist of non-survivors, thus indicating that comparisons between samples are being made without the effects of mortality bias, recent work has suggested that may not always be the case. Spake et al. (2022), have asserted that variation in social and economic structure between samples being compared can modulate the magnitude of biological mortality bias. That is, the impact of mortality bias is dependent on the type of societies being compared. Simply assuming that comparisons are being made between samples of non-survivors may not remove the effects of mortality bias. Because the variations in social and economic conditions that biological anthropologists try to capture in growth differences are at the same time the factors that would impact the magnitude of mortality bias. Currently, this is an unresolved problem that requires further theoretical and empirical investigations to address. In this case, the authors do not find the samples to originate from societies with fundamentally distinct social and economic structures. They were coeval, shared the same geography, and were culturally and socially connected. It seems very unlikely that any mortality bias effects are being observed.

6. Conclusion

While examining child growth as a proxy for the stress experienced by the larger population, significant linear and appositional growth deficits were observed among the Medieval children from the Algarve when compared to the modern reference sample. Extrinsic stressors such as warfare, disease, malnutrition, and poor sanitation would have put a strain on children throughout the Medieval Era. It was theorized that changes in the agricultural technology, food availability, and urban and economic development brought on by the Islamic Period would have improved the quality of the living conditions of citizens during the Medieval Islamic Period, whereas living conditions would have worsened with the post-Islamic Christian Period due to their reduced dietary diversity, frequent droughts, and increased exposure to disease. However, this hypothesis is not supported by the findings of this study. Overall, Islamic Period children in the Algarve had slightly greater growth deficits than their post-Islamic Christian counterparts, suggesting that the Islamic Period children lived in a less favourable social and physical environment for growth. However, these differences in growth were statistically nonsignificant. Conversely, statistically significant differences in appositional growth were identified between the Santarém and Algarve regions. In the Islamic Period, children from the Algarve typically had femora with thinner cortical bone and wider medullary cavity at the midshaft than those from Santarém. In the post-Islamic Christian Period, the children from the Algarve typically had femora with a larger total area, and a wider medullary cavity. The patterns of appositional growth suggest that there were important differences in the disease load, diet, and activity level of children from the Algarve and children from Santarém. Ultimately, while there were fewer differences in growth from one Period to another, there were more noticeable differences between two regions within the same Period. This finding suggests that regional differences in the environment may have been more significant than the wider social, political, and economic differences between the Islamic and post-Islamic periods within each region in shaping the wellbeing of the Medieval peoples living in the modern Portuguese territory.

7. Ethics Statement

The skeletal collections were examined with permission from their heritage government agencies and from the institutions that care for the remains. No destructive analyses were conducted. The research was conducted in accordance with national (Portuguese and Canadian) and international ethical and legislative guidelines. This research was reviewed and approved by the Simon Fraser University Office of Research Ethics (protocol#: 30000968).

CRediT authorship contribution statement

Carmen Kors: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ana González-Ruiz:** Investigation, Data curation. **Maria José Gonçalves:** Supervision, Resources, Project administration. **Maria João Valente:** Writing – review & editing, Supervision, Resources, Project administration. **Cristina Garcia:** Writing – review & editing, Supervision, Resources, Project administration. **Hugo F.V. Cardoso:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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