Linear and Appositional Growth as Indicators of Social Change and Environmental Stress in the Medieval Era in the Algarve, Portugal

by

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Abstract

Growth is a sensitive indicator of children's cumulative environment and can be used as a proxy for the stress experienced by their whole population. Archaeological data and historical research suggest that the Medieval Islamic Period environment was more favourable for growth than the post-Islamic Christian Period, because of their agricultural prosperity, medical knowledge, and hygienic practices. The growth of children recovered from archaeological sites dating from Medieval Islamic and Christian Period in the Algarve were compared to determine whether the social and physical environmental changes due to the transition between the periods impacted the health of their populations. Linear and appositional bone growth deficits were found among children in all samples. Overall, Islamic Period children had slightly greater growth deficits than Christian Period children. This finding suggests that the Medieval Islamic Period was not more favourable for growth than the Medieval Christian Period in the Algarve.

Keywords: growth and development; linear growth; appositional growth; Medieval; Portugal; social environment

Dedication

To my parents for their continuous love and support.

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Chapter 1. Introduction

Through the application of life-history theory, which dictates that the energy demands of malnutrition, disease load, activity, and physical and psychological trauma, necessitate trade-offs between the energy allocated for growth, survival, and maintenance, archaeologists can assess the stress experienced by populations in the past by studying their growth and development (Agarwal 2016; Bogin et al. 2007; Pomeroy et al. 2012; Stulp and Barrett 2016). Under these circumstances, 'stress' is defined as physiological disruptions to a person, resulting from their biotic, physical, social, economic, and political environmental conditions (Goodman et al. 1988). Stressors often manifest osteologically as a reduction in linear bone growth, a reduction of 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 bone growth, and cumulative exposure to stressors (Agarwal 2016; Bogin et al. 2002; Ives and Humphrey 2020; Newman et al. 2019; Smith et al. 2003; Tanner 1987). Children are the most vulnerable sector 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). By extension, the study of differences in the growth of 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).

Through the examination of the growth of children from Medieval Islamic and Christian Period archaeological sites in Silves and Cacela Velha in the Algarve region of Southern Portugal, this study aims to examine whether the social and physical environmental changes brought on by the transition between the periods impacted the health of their populations. The Visigoths held most of the Iberian Peninsula from the 5th century until the Islamic conquest in 711 AD (Kennedy 1996). In 1249 AD the Islamic period officially ended in the Algarve, with the Conquest of Faro (David and Pizarro 1989). The Medieval Christian Period sites examined in this analysis were in use from 1249 AD until the 16th century (Casimiro et al. 2007; Garcia 2015b; Vieira 2007a; Vieira

2007c). In the context of this thesis, 'Islamic' and 'Christian' refer to the political periods rather than religious categories, since in both the Islamic and Christian Periods, the populations were composed of Muslim, Christian, and Jewish citizens (Grau-Sologestoa 2017).

The analysis found herein assumes that most of the variation in the growth of the Medieval Islamic and Christian Period children is due to differences in their environment and stressors rather than genetics. Overall, this assumption is supported by growth studies in other areas of the world wherein differences in growth were proven to be more strongly influenced by physical and social environmental factors than by genetics (Bassino 2006; Bogin et al. 2002; Smith et al. 2003). For example, within just one generation, the children of Maya immigrants in the Unites States were "on average 10.2 cm taller than the" Maya children still living in Guatemala, due to their increased access to food, clean water, and medical care (Smith et al. 2003). Given that this dramatic change in height occurred so quickly, genetics cannot be the cause. Thus, as there was no indication of genetic or hormone-related growth disorders, the growth of Islamic and Christian Period children was expected to reflect the bio-social environment in which they lived.

With the Islamic conquest of the Algarve came numerous changes in agricultural technology, the introduction of new foods, an increase in population density, an interest in medicine and sanitation, and large-scale changes in the urban layout of cities (Aceves 2019; 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 during this time (Kennedy 1996; Worman 2012). By contrast, with the Christian conquest, much of the farmlands in Portugal had been abandoned, or had been forced to grow crops unsuitable for the soil, leading to widespread erosion and frequent droughts, and diets became much less diverse (Salas-Salvadó et al. 2006; Worman 2012). Cities became densely packed, with a lack of separation between commercial and residential spaces, meaning that citizens were often exposed to vectors of disease (Hollander and Staatsen 2003; Trindade 2007). The increased exposure to these vectors would have been more noticeable in larger cities such as Silves than in very small rural areas such as Cacela Velha, where there was less crowding. However, the health of both urban and rural citizens would have been impacted during periods of conflict if forced to hide within the fortresses, thus abandoning their fields, or in times of drought when there would not have been enough food.

Considering the major changes to numerous social determinants of health – including access to medical care, sanitary conditions, proximity to vectors of disease, and access to adequate nutrition (Marmot 2005; Cumming and Cairncross 2016) – that occurred with the transition between periods, it is expected that there would have been a difference in the growth of the Medieval Islamic and Christian Period children. By examining the growth of juvenile remains (from age zero to 12.5 years) from Medieval Islamic and early post-Islamic Christian Period archaeological sites in the Algarve, and comparing these measurements for age to the expected growth based on a reference population, any growth deficits relative to the reference population in each Medieval population can then be assessed and compared, allowing for a greater understanding of the impact of the extrinsic environmental, economic, and social stress on each population's well-being.

The concept of ‘health’ is acknowledged as encompassing “a state of complete physical, mental, and social well-being and not merely the absence of disease, or infirmity” as per the World Health Oganization’s (WHO) definition (2022) but, in the context of archaeological findings, the ways people viewed their own health status, and the mental and social aspects of health are not always knowable (Reitsema and McIlvaine 2014). Therefore, the term ‘health’ used herein refers to a state of relative health and well-being, with the understanding that more exposure to extrinsic stressors would be less ‘healthy’ (Reitsema and McIlvaine 2014), in the context of the comparison of social determinants of health, extrinsic stressors, and the growth of juveniles in the Medieval Islamic and Early Medieval Christian Periods. ‘Social determinants of health’ refers to all of the “non-medical factors that influence health outcomes” (WHO 2023). There are many social determinants of health including education, child rearing practices, socio-economic status, food security, access to clean water, sanitation and hygiene, and the sociopolitical and economic environment which all impact health (Cameron and Schell 2022).

A previous bioarcheological study of juvenile remains examined growth to evaluate how the transition from the Medieval Islamic Period to the Medieval Christian Period affected population-level stress in Santarém, Portugal, a major city throughout the Medieval Era (Gooderham et al. 2019). While differences in juvenile growth were observed between the Islamic and Christian Periods, with individuals from the Christian Period typically experiencing greater growth deficits than those from the Islamic Period, these differences were not considered statistically significant. The results were limited by the small sample size of the study (Gooderham et al. 2019). To elucidate the question of whether there was a difference in the growth of children between the Late Medieval Islamic Period and the Christian Period in Portugal, relating to the transition of the social and economic environment, the current project was developed, examining juvenile skeletal remains from archaeological sites in the Algarve region. Broadly speaking, the history of Portugal is similar across all regions, in that each region had a Visigothic Period, followed by the Islamic Period, and then a Christian Period, which occurred earlier in the north and later in the south as a result of the Christian conquest (Kennedy 1996).

The methodology for data collection and data analysis in this study and the Gooderham et al. (2019) study were kept the same to ensure the comparability of the data obtained from the Algarve region and from Santarém. The growth of juvenile skeletal remains from Medieval Islamic and Christian Period archaeological sites found within Silves (an urban settlement) and Cacela Velha (a rural settlement) were examined to better understand the effects of the physical and social environmental changes from the Medieval Islamic Period to the Medieval Christian Period in the Algarve. Growth was evaluated by examining the linear growth of all six long bones, as well as the appositional growth of the humerus and femur at the midshaft.

Linear growth occurs at the growth plates between the diaphysis and the epiphyses of the long bones, leading to an increase in length (Lewis 2007). Periods of prolonged stress disrupt the expected growth rate, due to trade-offs between the energy allocated for growth and survival, impacting the final growth a child can achieve, depending on the timing of the stressor and whether their environment improved afterwards, potentially allowing for catch-up growth (Cameron and Bogin 2013; Geber 2014; Lewis 2007). Because of the relationship between long bone growth for age, and environmental stressors, the measurement of long bones as a proxy for stature, is often used by biological anthropologists to compare the effects that different social and physical environmental stressors have on growth (Cardoso and Garcia 2009; Cardoso et al. 2018; Dhavale et al. 2017; Gooderham et al. 2019; Newman et al. 2019). The comparison of child stature in order to assess the level of growth stunting in living populations, is frequently done to assess public health needs, or in order to better understand the impact of environmental conditions upon the health of children (Bogin et al. 2002; Headey et al. 2018; Hermanussen et al. 2018; Tanner 1987). Overall studies of linear growth/height are more reliable indicators of population well-being than things such as body mass index (BMI), even though both can be influenced by the same environmental factors (Smith et al. 2003). For instance, children who are short for their age are more likely to be of lower socioeconomic status while those who are tall for their age are more likely to be of higher socioeconomic status; but those with a very low or a very high BMI are both considered to be "unhealthy" and tend to be of lower socio-economic status (Bogin et al. 2002; Smith et al. 2003). Height tends to be more strongly influenced by the cumulative effects of socio-environmental improvements in nutrition, access to clean water, sanitation, lack of disease, and access to medical care, among others, while BMI is most strongly influenced by nutrition (undernutrition or the over-consumption of more affordable higher fat foods), and by activity level (Bogin et al. 2002; Smith et al. 2003) Thus, methods to measure child height or bone length are an important aspect of population health assessments in both modern and archaeological studies.

Appositional growth refers to the circumferential growth and remodelling of long bones, and it occurs throughout life (Lewis 2007). Cortical bone increases in width and thickness with age, maintaining a relative equilibrium between bone formation on the periosteal surface and bone resorption on the endosteal surface (Lewis 2007). The interruption of this balance due to malnutrition or social and physical environmental stressors can lead to thinner cortical bone via reduced periosteal deposition of new bone, and/or resorption on the endosteal surface (Himes et al. 1975; Mays et al. 2009). Poor nutrition and disease can impact the quality of cortical bone through delays in periosteal growth, reduced cortical bone mass, and the resorption of bone on the endosteal surface (Mays et al. 2009). The shape of cortical bone is also affected by activity level, and the influence of mechanical loading can be assessed through analysis of cross-sectional geometric properties (Bass et al. 2002; Eleazer 2013; Harrington and Osipov 2018). Shape analysis was not conducted for the purpose of this thesis. Increased mechanical loading prior to puberty can lead to "increased subperiosteal bone deposition…, and postpuberty, it result[s] in endosteal apposition, narrowing the medullary cavity", while a lack of physical activity can lead to a lack of cortical bone growth (Mays et al. 2009). Appositional growth has shown to be more sensitive to environmental differences than linear growth (Mays et al. 2009). Thus, the examination of the differences in growth of appositional growth variables may help to detect differences in the growth environment of group that are too subtle to be seen through linear growth differences. Through the measurement of appositional bone growth, bioarchaeologists can assess the quality of individuals' cortical bone and make interpretations about their activity level and nutritional status (Ives and Humphrey 2020; Mays et al. 2009; Schug and Goldman 2014).

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.

Chapter 2. Context

Medieval history of the Iberian Peninsula (al-Andalus) is distinct from that of most of Europe, because it was conquered and occupied by Islamic nations from roughly 711 AD to 1492 AD (the exact dates of which vary between settlements across the peninsula) (Kennedy 1996). Beginning in the 11th century, Christian forces began pushing southward from the north, re-conquering lands which had once been Christian during the previous Visigothic Period. Santarém and Lisbon were under Christian Rule by 1147 AD (Disney 2009). The Algarve region was the last part of Portugal to fall under Christian rule, owing to strong resistance from the Islamic population, ending in 1249 AD with the capture of Faro (Carvalho et al. 2017). The transition from the Islamic Period to the Christian Period was not seamless, and only occurred after a long series of sieges, treaties, wars, and recaptures of the various cities and villages throughout the region (Garcia 2015b).

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 the design of rural and urban settlements, agricultural practices, diet, hygienic practices, medical care, and the prevalence of diseases (Aceves 2019; Knorr et al. 2019; Martins 2017; Trindade 2007; Worman 2012). Thus, the Algarve presents a fascinating region to explore how the dynamics of the social and political transition impacted the health and wellbeing of citizens in the Medieval Era. The following sections describe some of the history and the social and environmental conditions of the Algarve in the Medieval Era to better understand the dynamics of the change from the Islamic Period to the Christian Period.

2.1. Medieval History of the Algarve

With the decline of the Roman Empire in the 5th century, the Visigoths held the strongest influence in Portugal (Aceves 2019; Carvalho et al. 2017; Kennedy 1996). By the end of the Visigothic Period, the larger cities from the Roman Period had become smaller, with very little long-distance trade, and very little monetary wealth in circulation (Kennedy 1996). Through a series of conquests beginning in 711 AD, large portions of the Middle East, Southeast Asia, North Africa, and the Iberian Peninsula had fallen under Islamic rule by 750 AD (Kennedy 1996). Few cities were effectively defended; some of the aristocracy thought the invaders would simply raid the cities for loot and then leave, while others realized that surrendering would allow them to maintain some autonomy and to retain their land and status by paying taxes and tributes to their new Islamic conquerors and letting them decide how the land would be divided; many even converted to Islam (Barros 2004; Garcia 2015b; Kennedy 1996). However, the property of those who fled or resisted was taken, those who resisted were killed, prisoners were often enslaved, and fewer people were left after the wars to work the fields. Gradually, the Islamic conquerors legitimized their ownership over the lands, often by marrying the daughters of Visigothic families, inheriting their estates (Kennedy 1996). Córdoba became the capital of the Caliphate in 929 AD, unifying power within Al-Andalus (Garcia 2015b; Worman 2012). Once conquered, Faro, and later Silves, became the capital of the Algarve, until a civil war broke out and Faro and Silves both became autonomous Taifa kingdoms from 1016 AD to 1052 AD, and 1013 AD to 1052/53 AD respectively (Catarino 2017). Both kingdoms were then brought under the control of the Taifa Kingdom of Seville, until the Almoravids regained control of the Empire in 1090/91 AD. In around 1143/45 AD a new period of Taifa kingdoms commenced, and were gradually reincorporated into the Empire by the Almohads beginning in 1147 AD. Under Islamic rule, Christianity and Judaism remained common, and most Christian and Jewish practices were permitted (Garcia 2015b; Kennedy 1996; Knorr et al. 2019).

Economic growth and urban development such as the fortification and expansion of large cities in the 10th century contribute to the idea of the ‘Golden Age’ of Islam; however, there was a significant degree of turnover in the governors of cities and states throughout most of the Islamic Period (Garcia 2015b; Kennedy 1996). Many governors were in power for less than a year or two, and very few lasted more than ten years. Governors were often pressured into raiding Christian territories to acquire more wealth to support their claim to power and keep their military forces satisfied, and there was regular infighting among Islamic factions over who had the best claim over the conquered lands. Revolts and uprisings were commonplace, with citizens being dissatisfied for economic or religious reasons, and Islamic military forces were regularly brought in from all over the empire to quell the conflicts. Once there, however, the military leaders often felt they deserved more power or wealth, leading them to try to take over (Garcia 2015b; Kennedy 1996).

As a result of the near-continuous state of warfare, famines were common in the Algarve during the Islamic Period (Garcia 2015b). By 1009 AD, internal conflicts were leading to the decline of the Caliphate and the rise of Taifas (small independent city states) (Catarino 2017; Worman 2012). During this time, the reinforcement of city defenses and other city works was an indicator of economic prosperity (Garcia 2015b). The fall of several major cities in the North to the Christian forces in the 11th century encouraged the formation of a unified Islamic state once again, under the Almoravid dynasty (Garcia 2015b). The struggle for power continued into the 12th century, however, and the need to prevent a revolt from one of the factions in North Africa meant that soldiers were moved out of the Algarve, allowing for the Christian forces to move in, and the power of the Almoravids decreased. A new phase of Taifa kingdoms began in 1143/45 AD (Catarino 2017; Garcia 2015b).

Christians held the northern edge of the Iberian Peninsula (namely Asturias) and successfully extended this land during the 8th century (Amaral 2021; Cuenca 1997). In the 11th century AD, 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 AD by a Leonese King, which would later become the Kingdom of Portugal under the rule of his son, Afonso Henriques (Amaral 2021; Coelho 2000). Although Henry of Burgundy fought for the independence of his land from the Kingdom of Leon, he was unsuccessful. When he came of age, Afonso Henriques then took up the mission of gaining independence and expanding his territories, having his kingdom's independence recognized by Leon in 1143 AD (Coelho 2000; Disney 2009). Recognition of his rule by the Pope, however, came later in 1179 AD, thanks to his efforts to conquer Al-Andalus which aligned with the desires of the church, foreign crusaders, and the military-monastic orders, as it was viewed as a reconquest of Christian lands from Muslim occupiers (Disney 2009; Mattoso 2001). Lisbon and Santarém fell under Christian rule permanently in 1147 AD, and significant portions of the Alentejo region fell soon after that (Disney 2009). However, the victories in the Alentejo were somewhat short-lived, as the Taifa rulers sent appeals to Islamic peoples from North Africa, requesting assistance in pushing back the Christian forces, leading to the formation of the Almohad army, who took control of the south, stalling the crusaders in 1171 AD, and retaking most of Alentejo by the 1190's (Disney 2009). The last region of Portugal to be reconquered by the Christians was the Algarve.

Cities in the Algarve typically swapped control between Islamic and Christian factions several times between the 11th and 13th centuries, sometimes by force and sometimes through treaties or surrenders, until the final push by the Christians in 1249 AD (Barros 2004; Carvalho et al. 2017; David and Pizarro 1989; Disney 2009; Oliveira 2017). Due to the in-fighting amongst the Islamic forces in the 13th century, the Christian forces did not typically meet much resistance (Garcia 2015b). Sometimes, deals were struck between the local leaders and the Christian invaders so that citizens could retain their properties and lands by paying taxes to their new Christian governors, abandoned property was distributed by the rulers among their allies, and prisoners were enslaved (Barros 2004; Garcia 2015b; Trindade 2007; Oliveira 2017). After the conquest, a large Islamic population remained in Silves and in Loulé (Barros 2016; Catarino 2017; Oliveira 2017). But often, large portions of the Islamic population who could afford to leave would abandon their homes, migrating to the eastern and southern territories still under Islamic rule, meaning that comparatively fewer Muslim people remained in the Algarve after the conquest (Barros 2004; Birmingham 2003; Gonçalves 2019; Soyer 2010). Muslim citizens who remained were often made to live in *Mouraria* on the outskirts of town, and similar Jewish quarters were made to ensure the segregation of the religious groups (Barros 2016; Catarino 2017; Garcia 2015b). Often, towns bordering Islamic territories, and thus the most at risk of invasion, were given to the military orders so that they would be protected from being retaken (Garcia 2015b). Christian colonists were encouraged to settle in the newly conquered regions to reinforce the hold on the lands (Disney 2009; Oliveira 2017).

The degree to which religious groups coexisted peacefully in the Christian Period is still under study (Barros 2004; Barros 2016; Safran 2013). Evidence of violence and non-ceremonial burials of the conquered citizens were found in Christian cemeteries dating to the time of the conquest (Vieira 2007a). In addition, after a Muslim revolt in 1264 AD, many Christian leaders still permitted Muslim citizens to remain in their cities but made them all stay in the *Mouraria* (Barros 2016; Garcia 2015b). In the 14th century, the muezzin was forbidden, and Muslim citizens were forced to rely on the church bells to inform them of the time for prayers (Barros 2016). Jewish and Muslim citizens were instructed to wear specific garments identifying themselves and laws were established to ensure the religious groups did not interact with each other. The rules of Christian holy days were enforced regardless of the citizens' religion, and a curfew was put in place preventing Muslim and Jewish citizens from going outside at night (Barros 2016). In some places this was hard to enforce as Jewish members of the community often held quite prominent roles in service of the King and his court. It was not until the 14th century and the reign of Afonso IV that these rules became more strictly enforced. However, in certain places that had a limited number of Christian citizens who could fulfil important jobs within the city such as apothecaries, physicians, or tradespeople, exceptions were made so that minorities could be granted permission to disobey these rules in the course of their duties, as long as they were deemed trustworthy (Barros 2016). In rare instances, such as in Loulé, Muslim, Jewish and Christian members participated actively in the town council, working together to solve problems that affected all of them (Barros 2004). In 1496 AD, Muslim and Jewish peoples were expelled from Portugal, or forced to convert, with few being permitted to remain (Barros 2016; Disney 2009; Soyer 2010).

2.1.1. History of Silves

The territory of Silves has been occupied since the Neolithic Era, while the foundation of the city is associated with the Islamic Period (Chanoca 2006a; Silva 2020). The soil around was relatively fertile and well suited to growing an assortment of crops (Chanoca 2006a). Silves was built on a large hill near the Arade River and was a major river port in the Medieval Era until the 16th century (Chanoca 2006a; Gonçalves 2019). Access to the town via the river meant that it was essentially a coastal city and was an important shipbuilding and trading port, conferring it considerable political power throughout the Medieval Era (Chanoca 2006a; Gonçalves 2019; Vieira 2007a). It was not until the 15th century when the river began filling up with silt that the river became less navigable by large ships, and the waters became stagnant, increasing malaria epidemics, that the city lost its prominence in favour of Faro (Carvalho et al. 2017; Gonçalves 2019).

The oldest fortifications in the city date to the 8th to 9th century with the Islamic conquest of the city. Along with the socio-economic growth of the city in the 9th to 10th centuries, the construction of the city walls resumed (Chanoca 2006a; Vieira 2007a). When Silves became part of the Umayyad Empire in 929 AD, the walls were partially dismantled (Chanoca 2006a). In other areas of the Algarve, dismantling walls was done to prevent towns from becoming too powerful and potentially rebelling against the Caliphate (Chanoca 2006a).

For a short time, early on in the 11th century, Silves became a Taifa kingdom, gaining its independence from the Caliphate of Córdoba (Gonçalves and Oliveira 2020). The walls of the city were rebuilt early in the 11th century, either to try to stop the Almoravids who were trying to reunify Islamic territories from taking over, or built after they had taken over, later in the 11th century (Chanoca 2006a). Between 1145 AD and 1151 AD, Silves became a Taifa kingdom again, until it was taken over by the Almohads, who increased the fortifications and defences of the city since Christian invasions were occurring with increasing frequency (Chanoca 2006a; Gonçalves and Oliveira 2020). In the 12th to 13th centuries, Silves changed leadership several times between Islamic and Christian factions with evidence of numerous phases of destruction and reconstruction of defensive structures (Barros 2004; Chanoca 2006a; Gonçalves and Oliveira 2020). The city was first taken by the forces of Sancho I in 1189 AD, but lost to the Almohads in 1191 AD. Not until 1248 AD did the Christian forces take the city permanently (Gonçalves and Oliveira 2020).

Silves maintained its prominence in the Christian Period and settlers were encouraged to move to Silves through tax exemptions (Gonçalves 2019). Beginning in 1361, earthquakes and plagues hit the population hard. By 1473, re-construction of the cathedral, the bridge, and many of the houses was complete, but it was noted that many of the structures were still fully or partially abandoned. Around this time, the Arade River had begun to fill with silt, and other ports became more widely used.

2.1.2. History of Cacela Velha

The fertile lands around Cacela Velha have been occupied since Prehistoric times (Garcia 2015b). The remnants of Roman Period settlements (mostly rural) have also been found in and around Cacela Velha. Being of immense strategic importance for coastal control and defence of the southern coast, the town of Cacela Velha became an important village and fortress during the Islamic Period (Catarino 2002; Garcia 2015a). Art, jewelry, and pottery found within the remains of the Islamic quarter indicate that it was well connected to other towns within the Algarve (Garcia 2015a). The earliest fortifications likely date to the first Taifa or Almoravid Periods (Garcia 2015a). In the Almohad Period, the rammed earth walls were replaced with stone.

To the east of the fortress, outside the walls of Cacela Velha are the remains of an Islamic quarter (from the Almohad Period), now called Poço Antigo, which was occupied for a very short time from the second half of the 12th century until the first half of the 13th century when the citizens packed up and abandoned it, since the area had become more dangerous as the Christian forces moved southward (Garcia 2015a; Garcia 2015b). While some citizens and military personnel remained in the fortifications and surrounding area, the Islamic quarter east of Cacela Velha had been mostly abandoned, and had filled in with sand by the time the Order of Santiago (Christian military monks who had been steadily moving south along the Guadiana River) took over Cacela Velha in 1238 AD (Garcia 2015a; Garcia and Curate 2010; Garcia et al. 2015).

The warrior monks would have been the first to settle in Cacela Velha (Garcia and Curate 2010), along with some of the villagers being allowed to remain who worked in nearby fields, and additional Christian townsfolk who would have arrived shortly after (Garcia 2015b). Upon seizing Cacela Velha, the Order of Santiago consecrated the ground at Poço Antigo, largely destroying what remained of the Islamic quarter (Garcia 2015a; Garcia and Curate 2010). A church and cemetery were put in the place of the Islamic quarter, while the fortifications at Cacela Velha were reinforced, and accommodations were built for the military monks (Garcia 2015a; Garcia 2015b). Some Moorish people remained in Cacela Velha, living in a *Mouraria*.

The rule of the Order of Santiago over Cacela Velha was made official by Sancho II in 1240 AD; the Pope Innocent IV in 1245 AD, Fernando III of Castile in 1248 AD (Garcia and Curate 2010). Cacela Velha was strategically located at the entrance of the Ria Formosa (Garcia 2015b). Throughout Medieval times, control over access to the Ria Formosa Lagoon was very important, as it allowed ships to wait until conditions were optimal for traveling up the rivers along the southern coast (Catarino 1997; Garcia 2015b; Garcia and Curate 2010; Garcia et al. 2015). The importance of this location in controlling maritime movements meant that they had considerable power, but they were also the frequent target for attacks (Catarino 2002; Garcia 2015b).

Conflicts with Castille, other Islamic nations, and pirates meant that Cacela Velha was a dangerous place (Garcia 2015a; Garcia 2015b; Garcia and Curate 2010). The town of Cacela Velha was attacked several times during the Christian Period, as indicated by a layer of charcoal, associated with a fire in 1260 AD (Garcia 2015a; Garcia and Curate 2010). Stratigraphy indicates that burials occurred in this cemetery both before and after the fire, so the town and church must have been repaired. Fractures and lesions indicative of interpersonal violence were common, especially among the male individuals exhumed from the site of Poço Antigo in Cacela Velha (Garcia 2015b; Garcia and Curate 2010; Garcia et al. 2015).

Since the capture of the Algarve had required the cooperation of numerous Christian factions in 1250 AD, the Christian kings argued over how the conquered lands should be divided, since the Algarve was strategically located for access to the Atlantic coast (Birmingham 2003; Disney 2009). The coastal access is also what contributed, in many ways, to the economic prosperity of Portugal, especially in the late 15th century onwards. The continuing connection to northern Europe and the transoceanic navigation abilities of this kingdom enabled the discovery of new trade routes, of which they were at the centre, benefiting the merchants and the Crown (Amaral 2021; Garcia 2015b).

Eventually, most of the structures, including the cemetery and church, were rebuilt within the protective walls of the fortress, and while a few houses were within the walls as well, most of the townsfolk established a village further inland where they would be safer from coastal invaders (Garcia 2015a; Garcia and Curate 2010). Not until 1267 AD were the borders between the kingdoms of Castile and Portugal officially defined (Aceves 2019; Disney 2009; Garcia 2015b).

2.2. Urban Layout, Houses, and Living Conditions

There was an important separation of residential and commercial spaces in the Islamic Period (Trindade 2007). Religious spaces, markets, crafting districts, slaughterhouses/butchers, bathhouses, cemeteries, and waste deposits all had designated spaces, and were kept separate from residential areas, allowing for a greater distance between humans and exposure to potential vectors of disease, such as decaying bodies, pests, domestic animals, and wastes (Carvalho et al. 2017; Catarino 2017; Hollander and Staatsen 2003; Macias 2018). Cemeteries were typically placed outside of the city walls by one of the major gates (García 2001; Macias 2018). This practice is seen in Silves wherein the largest Islamic Period cemetery (Rua 25 de Abril) was found outside the city gates (Chanoca 2006c). Furthermore, the use of latrines, septic pits, and wastewater drainage infrastructure during the Islamic Period also ensured that human excrement was removed from homes, and evidence of these has been found in both Cacela Velha and Silves (Garcia et al. 2015; Gonçalves and Oliveira 2020; Knorr et al. 2019; Macias 2018).

The structure of houses in the Islamic Period could also have reduced residents' exposure to vectors of disease. Patio houses were designed so that rooms faced into a central patio, to which the entrance to the street was attached, so that the house and patio were often completely enclosed, maintaining the privacy of the residents (Carvalho et al. 2017; Catarino 2017; Oliveira Marques 1971; Trindade 2007). Cooking took place in a specific room separate from the rest of the household, keeping food preparation separate from other household activities (Garcia 2015b; Worman 2012).

This organised urban layout contrasts starkly with the urban layout in the Christian Period, in which there was a significant merging and overlap of the commercial and residential spaces, problematically exposing residents to manure, wastewater, chemicals, and butchery/hide processing wastes in many Christian cities (Catarino 2017; Llave 1998). Mosques were often converted or replaced with churches in many cities, including Silves, and it was the Christian custom all over Europe to bury the dead in, or near, churches (Carvalho et al. 2017; Garcia 2015b; Instituto de Gestão do Património Arquitectónico e Arqueológico 2022; Kallio-Seppä and Tranberg 2021). Consequently, cemeteries were now being placed within the inner city, exposing citizens in the surrounding area, as well as all those visiting the churches, to the decaying bodies, associated odours, and the detrimental effects that the exposure could have had on their health (Kallio-Seppä and Tranberg 2021).

Furthermore, because of the conquest, the destruction and abandonment of rural areas, and with the arrival of Christian settlers in the cities, meant that space within the protective walls was at a premium, and the density and height of buildings within urban centres increased (Carvalho et al. 2017; Oliveira Marques 1971). Unfortunately, high density within cities, not to mention proximity to human excrement, is closely linked to the spread of infectious diseases (Hollander and Staatsen 2003; Llave 1998). 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). Houses became rectangular with entrances facing directly onto the streets and interior rooms being accessed via internal doors (Macias 2018; Trindade 2007). Additionally, the hearth was the main family room, as well as the first room entered from the street, meaning that there was food was being prepared in a room with much more exposure to outside spaces.

This layout of Christian cities coupled with the lack of adequate means of disposal of human wastes, and the reduced division between urban and commercial spaces, meant that the exposure of Christian homes to disease vectors would likely have been greater. In contrast, the separation of spaces and design of houses in the Islamic Period would have reduced the exposure of citizens to disease vectors.

2.3. Economy and Agriculture

Being at the confluence of the trade routes between the Mediterranean, West Africa, and northern Europe, cities in the Algarve had a prosperous economy during the Islamic Period (Kennedy 1996; Worman 2012). The introduction of new agricultural products and irrigation techniques by the Islamic peoples allowed for the expansion of settlements into previously uncultivable areas of Portugal, simultaneously leading to an increase in the diversity and accessibility of food (Aceves 2019; García Sánchez 2011a; Kennedy 1996; Worman 2012). Islamic agronomists experimented with growing and propagating plants imported from Asia, Africa, and the Mediterranean, as well as improving the production of local plants (García Sánchez 1992; García Sánchez 2011a). They wrote extensively about maintaining soils, plant diseases, plant propagation, fertilizers, crop rotation, and even the layouts of gardens to ensure that the spacing, shade, and temperature needs of plants would be met. Gardens typically had a variety of vegetables which were rotated seasonally so that the owners would have year-round access to vegetables (García Sánchez 1992). The environment of the Algarve is well-suited to the growth of trees (including carob, fig, olive, and citrus), as well as the growth of shrubs and vines, and to the extraction of salt; however, it is generally ill-suited to the growth of grains (Aceves 2019; García Sánchez 1992; Kennedy 1996). Grains were generally “imported from the Maghreb and northern Africa during the Islamic” Period (Toso et al. 2021).

The agricultural prosperity resulting from a variety of foods allowed for the accumulation of surpluses enabling a huge increase in population density across the landscape, and allowing cities to increase in number, size, and population (Worman 2012). The expansion of cities led to an increase in artistic tradespeople making glass, metal, and ceramic works, as well as leather goods and textiles (Kennedy 1996). Furthermore, the capacity to store foods allowed for cities under siege to survive thanks to their stored reserves and facilitated long-distance trade (Garcia 2015b; Gonçalves and Oliveira 2020; Worman 2012).

With the political instability among the Islamic factions towards the end of the Islamic Period, and the Christian conquest, many seaports changed hands, severing trade routes between Andalusia and North Africa, and the Algarve, to be replaced by trade routes to the northern and Mediterranean countries under Christian rule (Kennedy 1996; Oliveira 2017; Worman 2012). Grains were typically imported from Mértola and the Alentejo region (Aceves 2019). The threat of warfare, caused by fighting among Islamic factions and the Christian conquest, meant that agricultural lands often fell into disuse (Garcia 2015b; Worman 2012). People often emigrated away from the warfront and, at the start of the Christian Period, soils often eroded due to the over-production of crops ordered to support the military forces, such as wheat, that were ill-suited to the environment, and that had detrimental effects on the soil (Barros 2004; Birmingham 2003; Worman 2012). The lands under Christian management were not as productive as they could have been (Birmingham 2003). Soil erosion and climate change resulted in arroyos in the mid-12th century, diminishing the land's capacity for food production in many regions (Worman 2012). Adding to this lack of productivity, natural disasters were commonplace in the Christian Period, including droughts and earthquakes. "[A] minimum of twenty-two significant famines and eleven earthquakes are known to have struck Portugal between 1309 and 1404" (Disney 2009). Islamic people who stayed on their lands through the Conquest often became "enslaved or at best given a reduced status" (Birmingham 2003). Land rights were redistributed by the Crown to nobles, religious institutions, and to the people, that allowed the King to secure power over locals and colonists (Amaral 2021; Disney 2009). It was not until after the Christian conquest that contracts gave farmers greater rights to their land (Amaral 2021; Birmingham 2003).

2.4. Diet and Nutrition

It is apparent from the plethora of medical texts detailing healthy eating habits, recipe books, and religious and social customs regarding cleanliness and food preparation, that healthy food consumption was of great importance to the Islamic people, at least, conceptually (García Sánchez 2011b; Salas-Salvadó et al. 2006). Maintaining a diverse and balanced diet was important in the Islamic Period, and they adapted many of the teachings of Hippocrates and Galen when creating recipes (Aceves 2019; Salas-Salvadó et al. 2006). Recipes that encouraged a varied diet of vegetables, fruits, grains, pulses, meat, fish, dairy products, nuts, eggs, and spices, would have been beneficial for ensuring a more balanced nutritional intake in the Islamic Period (Aceves 2019; Toso et al. 2019). Medical texts, often concerned with public health and preventative medicine, included numerous details about the foods which were considered most suitable for general life, different age groups, treating aliments, as well as the quantities and timing at which food should be taken in. Along with these dietary recommendations, medical texts also encouraged relaxing exercise post-digestion, as well as the consumption of foods that eased digestion (Salas-Salvadó et al. 2006). Whether the rules and recipes from these texts were, or could be, adhered to, however, is debated (Aceves 2019).

Religious laws dictated compulsory, recommended, allowed, disliked, and forbidden acts and foods that to some degree influenced the animals and animal products consumed (Aceves 2019; Pereira 2014). However, these rules would have become laxer during times of starvation; for example, the remains of *Sus* bones found across many Islamic Period archaeological sites across Portugal indicates that boars were occasionally consumed (likely in times of need), despite being forbidden (Aceves 2019; Pereira 2014; Toso et al. 2019).

Historic documents, analysis of animal remains, and isotopic analyses indicate that mammals were typically the primary sources of meat in the Islamic Period as they were strongly favoured, with birds and fish also being consumed to a lesser degree, as well as marine invertebrates in coastal areas (Garcia et al. 2015; García Sánchez 1986; Pereira 2014; Toso et al. 2021). It is noted, however, that the bones of fish are hard to recover archaeologically, which may contribute to their comparatively lower prevalence in many zooarchaeological studies of Medieval diets (Pereira 2014). Nevertheless, isotopic studies of bone collagen seem to confirm that fewer marine resources were consumed by people in the Islamic Period than in the Christian Period (Toso et al. 2021). Goats and sheep were the most often consumed and utilised for other products such as wool and milk; cattle were used as beasts of burden, for milk, and for meat; the presence of domesticated chickens suggests that they were kept for their eggs as well as eaten; rabbits, partridges, and deer were often hunted for meat; and bears and other animals were hunted for their hides, or other parts such as feathers or shells (Garcia 2015b; Grau-Sologestoa 2017; Pereira 2014; Toso et al. 2021). The consumption of virtually all parts of the animals including their organs, heads, eyes, and feet suggests that meat was rare, forcing the lower classes to resort to eating cheap cuts of meat if they wanted protein (García Sánchez 1986). The inclusion of cheap cuts in recipe books and medical texts indicates that medical practitioners were aware that the lower classes had restricted access to meat, and still wanted to encourage them to consume what meats they could (García Sánchez 1986). Bivalve shells found at Cacela Velha indicate that they were frequently collected by the locals and consumed, although the lack of carbonization of their shells suggests they were only lightly cooked to open their shells, or eaten raw, or boiled (Garcia 2015b; García Sánchez 1986; Valente and Martins 2015). Bivalves are considered an excellent source of protein, and access to the lagoon and shore with a plethora of marine foods would have been a considerable asset for coastal cities in the Algarve.

Despite the importance placed on meat, the diet of lower-class citizens was mostly vegetarian, with grains or grain-substitutes being the most significant part of the diet (García Sánchez 1983). Most of the Algarve was ill-suited to the production of grains, meaning that they were typically imported (Garcia 2015b; García Sánchez 1983; Toso et al. 2021). Those with greater wealth were able to access preferred grains such as wheat more easily, but those who could not afford it were often forced to consume other grains such as oats, barley, and rye, or even resort to making breads and porridges from substitutes (García Sánchez 1983). Rice, lentils, chickpeas, and peas were eaten, and sometimes made into flour and mixed with grain-based flours to make bread (Aceves 2019; García Sánchez 1983). Most of these substitute flours would have been high in protein and vitamins which would have been beneficial considering they were eaten by citizens of lower social status with less access to meat (García Sánchez 1983). When even those flour substitutes were unavailable, starvation breads made in both periods were sometimes made from nuts, acorns, dried fruits, and roots, often resulting in gastric distress if the ingredients used were not entirely edible (García Sánchez 1983; Oliveira Marques 1971; Salas-Salvadó et al. 2006). If meat was not affordable, cheap cuts were sometimes used to make a soup so that the animal fats and flavours were released into the water, and then breadcrumbs were added to thicken the stew and make it more filling (García Sánchez 1983).

Vegetables and herbs such as "onion, leek, coriander, mint, thyme, marjoram, carrots, cabbages and spinach" were grown in small gardens, and "[a]lmonds, figs, carob and oranges" were either dried or eaten raw (Aceves 2019). Olives and olive oil were frequently used in cooking, as were numerous spices and herbs (Aceves 2019; García Sánchez 2011a). Sweets made from honey, sugar, and nuts were popular and often consumed.

Contrasting with the diets of the Islamic people that emphasised the consumption of vegetables and fruits, the Christian diet was far less balanced, focusing more on grains and wine and, to a lesser extent, meat, which was often scarce (Aceves 2019; Salas-Salvadó et al. 2006). Goats and sheep continued to be the most popular sources of red meat, but cattle and pigs rose in popularity during the Christian Period as well (Grau-Sologestoa 2017). Chickens were typically kept for their eggs and were a more affordable source of meat in general. Goats and sheep were also kept for their wool and milk (González 2019). Historical sources, as well as isotopic signatures from the bone collagen of skeletal remains from Christian Period sites, indicate that the consumption of fish, both marine and freshwater, also increased in frequency during the Christian Period (MacRoberts et al. 2020 ; Toso et al. 2021). Fish would have been a cheaper source of protein than other meats and was also used to supplement the diet on days when, according to Catholicism, people were meant to abstain from meat (MacRoberts et al. 2020; Toso et al. 2021). This custom and various other forms of religious fasting gained popularity in the Christian Period, both as a form of penance, and of devotion (Bynum 1985).

Grains were an important food source in the Christian Period, and most of the grains were imported (González 2019; Toso et al. 2021). Pulses were more commonly consumed, particularly by the lower classes, due to their greater abundance (González 2019). Christian gardens had far fewer varieties of vegetables (García Sánchez 1992).

Vegetables were seen as a low status food and consumed less frequently, but nuts and olives were still grown in the Christian Period and made into flour substitutes and olive oil, respectively.

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. However, the Christian faith encouraged the formation of charities for the poor, abandoned, and sick, offering food and shelter to those in need (Rodríguez-Picavea 2009; Ruano et al. 2020). Charitable institutions could have supplemented the diet and improved the wellbeing of the poor.

Concern for dietetics in the Islamic Period meant that recipes were often designed to ensure people ate a balanced diet (in a Galenic sense) of a wide array of foods that were available to them, including vegetables, grains, fruits, nuts, pulses, herbs, and spices, sugars, meats, eggs, and milk (García Sánchez 1986; García Sánchez 2011a; Salas-Salvadó et al. 2006). In the Christian Period, however, diets became much less diverse, with far fewer vegetables and fruits, and a greater emphasis on grains, meats, and fish. Thus, nutrient deficiencies owing to a lack of vegetables and fruits in the diet would be expected.

2.5. Bioarcheological Evidence of Nutritional Deficiencies

Bioarchaeological evidence from both periods suggests that nutritional deficiencies were common in both Medieval periods. The remains analyzed from all sites show a high incidence of dental caries, dental wear, and dental enamel hypoplasias despite their young age. Cribia orbitalia was common among the Islamic Period children from Silves and among the Christian Period Children from Cacela Velha, likely tied to anemia or vitamin deficiencies (Steckel et al. 2005). Some of the Islamic Period children from Silves also had prominent porotic hyperostosis and thickening of the diploe, which can be indicative of infection, anemia, or vitamin deficiencies as well (more definitive diagnostic tests have yet to be conducted). Osteological evidence from the skeletal remains at Cacela Velha suggests that dietary stress and poor diets were common among the Christian children, with many having linear enamel hypoplasias and evidence of scurvy caused by a lack of vitamin C, likely relating to a lack of raw foods and vegetables (Garcia 2015b). While the remains from all sites examined were too fragmentary to be certain if each individual's paleopathologies were recorded, their presence in a large proportion of the studied individuals does indicate nutritional deficiencies were present in both periods.

2.6. Medical Care, Sanitation, and Pediatric Care

The Islamic Period prized medical knowledge (Martins 2017; Salas-Salvadó et al. 2006). 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. Medical works built on the knowledge of Greek and Roman scholars, and described a range of topics, including: "physiology, anatomy, pathology, therapeutics, hygiene[,] medication," and diet (Salas-Salvadó et al. 2006).

In terms of pediatric medicine, childhood was a delicate time for people born throughout the Medieval Era, with high death rates of infants and small children (Gil'adi 1989). The distinct medical emphasis on pediatric care in the Islamic Period was not emphasised in Christian societies until the 15th century. Many facets of pediatric medicine are described in Islamic medical texts, including the health and sanitary conditions of the mother during pregnancy; embryology; maintaining a good diet while breastfeeding, and the dietary needs of children; the care, play, development, and diseases of children through various stages of their lives; and so on (Gil'adi 1989; Salas-Salvadó et al. 2006).

Contrasting with the empirical approach to understanding the needs of children in the Islamic Period, in the Christian Period, literature regarding the health of children tended to be much more concerned with saving them in a spiritual sense. Baptisms were often performed immediately after birth to ensure the child's soul was protected, which signifies a certainty that their lives were at great risk (Cramer 2003). The desire to protect children from their original sin (popularised by Augustine) before they died overshadowed the belief that baptisms were intended to be the result of conscious choice to repent and be forgiven for previous sins and to profess their commitment to their faith; and children cannot communicate this choice. Concern for children was also observed in that people with unwanted children were encouraged to abandon them at hospital-like institutions instead of resorting to infanticide; although infanticide did occur in both Medieval periods (Gil'adi 1989; Sá 1994).

In the Christian Period, religious orders established hospitals to care for the sick and poor as they conquered new lands (Martins 2017; Rodríguez-Picavea 2009). However, medicine, and the treatment of illness, was not the priority of these hospitals. Medical practitioners were often priests or healers, who rarely received hands-on training in medicine, and hospitals were more like charities set in place to reduce public suffering and poverty (Martins 2017; Silveira 2009). "During the 12th and 13th centuries, Christian medical education in Portugal focused on the observation of urine for the identification of diseases, astrological implications and the use of the supernatural (prayer, invocations), the teaching of pharmaceutical substances with practical application, bleeding (for hygienic and therapeutic purposes)" (Martins 2017). Even as late as the 16th century, mortality rates in hospitals were extremely high; approximately 43% of patents died within the first 10 days of their stay, and 70% within a month (Conde 1999). Patients in these hospitals often had to share their beds, the sanitation practices would have been inadequate to prevent the spread of disease, and the food provided to them would have been unsuitable for maintaining a balanced diet. Medical practitioners were more concerned with the souls of patients (Silveira 2009). Diseases were frequently attributed to a source of evil and, if a patient did not recover, their death was seen as the result of a divine punishment for their sins in life.

Individuals in the Christian Period relied heavily on prayer and folk remedies to protect themselves from plagues, 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, considering that sanitation and nutrition are important factors for maintaining strong immune functions (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).

With the Christian conquest, mass migrations and new trade routes led to a huge influx and movement of people from other regions. Diseases were easily spread, and there were over 15 epidemics between 1190 and 1497 AD (Dols 2008; Oliveira Marques 1971). By contrast, epidemics during the Islamic Period did not occur in Portugal, although they did elsewhere in the Islamic Empire, such as in the Middle East and North Africa (Dols 2008). In the Christian Period, quarantines of ships and streets, blocking of visitors to cities, and fleeing from places affected by epidemics occurred frequently in and around the 15th century, although, without the means to understand the source of diseases and the methods of their transmission, epidemics often spread regardless.

For Islamic peoples, washing of hands, the body, and clothes was an important part of life and of daily ritual (Knorr et al. 2019). Hands were washed after using latrines and before consuming food, and public baths were used frequently. In the Christian Period, however, these baths fell out of popularity due to “shifting perceptions of shame and decency,” even among remaining Islamic populations within Christian cities (Barros 2005). Furthermore, the Christian belief that filth was a form of penance meant that religiously devoted individuals often avoided bathing and washing their clothing (Oliveira Marques 1971). This difference in hygiene practices likely contributed to differences in the health of each period.

However, despite the differences in sanitation, interest in public health, and latrine/sewer usage, Knorr et al.'s (2019) findings suggest that sanitation practices during the Islamic Period were likely ineffective at eliminating fecal-oral parasites such as roundworm. Soap production, although documented, does not mean soap was used to wash hands, but may in fact have been more “cosmetic than hygienic. Ethnographic research suggests that “[r]itual handwashing likely used water exclusively, and soap was reserved for the cleaning of clothes and other odor-based cosmetic practices of the wealthier residents” (Knorr et al. 2019). Furthermore, 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 findings that, although interested in health and sanitation, Medieval Islamic populations were just as likely to contract intestinal parasites as the Christian Medieval populations means that they were also likely to experience similar patterns of physiological stress due to their presence (Knorr et al. 2019). Recognising that intestinal parasites were propagated via the use of feces and wastewater as fertilizer also means that, although un-detectable archaeologically, other bacterial and viral infections could have spread to people by the same means. Gastrointestinal infections can lead to diarrhoea or vomiting, and thus, to the malabsorption of nutrients (Cunha et al. 2017). Additionally, energy is expended fighting the infection rather than on growth. Nevertheless, the effects of infections resulting from contact with feces and wastewater may have differed depending on whether or not they were mitigated by an otherwise healthy lifestyle; that is, populations also experiencing starvation and hardships may well be more harmed by the presence of parasites than one receiving adequate nutrition, which could have provided a buffer against the negative effects of the parasites (Garcia et al. 2020). Furthermore, the diversity of parasites in both Islamic Period and Christian Period populations was likely low because of the practice of cooking meat prior to its consumption, coupled with the dry environmental conditions of the Mediterranean, which is unfavourable to most intestinal parasites (Knorr et al. 2019).

The emphasis on hygiene, and the lower frequency of disasters and epidemics in the Islamic Period is well reflected in the average lifespan of the people, which was significantly longer than in the Christian Period (Batchelor 2015; Oliveira Marques 1971). People of high socio-economic status lived for 69 to 75 years in the Islamic Period, and general citizens lived into their fifties or sixties; conversely, in the Christian Period, the average lifespan of elites was 49 years, and that of general citizens was about 35 years (noting that these numbers exclude those who died in infancy) (Batchelor 2015; Oliveira Marques 1971). In the Islamic Period, death from disease brought either martyrdom if they were faithful or was seen as a punishment from God if they were unfaithful (Dols 2008), while in the Christian Period, failure to recover from a disease was often attributed to a failure to repent from sin (Stearns 2011). In both cases, the origin of the disease was thought to be God. However, in the Islamic Period physicians were also concerned with treatments and preventative medicine in a scientific sense (Salas-Salvadó et al. 2006).

2.7. Summary of Environmental Conditions

Agricultural prosperity, diversified and nutritious diets, emphasis on sanitation and health, the layout of urban spaces, and the lower prevalence of natural disasters and epidemics, would have been beneficial for public health, as further evidenced by the comparatively long lifespan of the people from the Islamic Period (Batchelor 2015; Salas-Salvadó et al. 2006; Trindade 2007; Worman 2012). By contrast, in the Christian Period, the agricultural production of ill-suited crops to supply the war effort along with a high number of natural disasters, reduced the productivity of lands (Worman 2012). Christian diets were no longer diverse, and famines were common (Disney 2009; Salas-

Salvadó et al. 2006). The concern for sanitation was lower, and diseases and epidemics spread frequently during the Christian Period (Oliveira Marques 1971). While Catholic beliefs emphasised the importance of caring for the poor, abandoned, and sick, the care they received was often ineffective (Martins 2017; Rodríguez-Picavea 2009; Silveira 2009).

In general, studies of daily life in the Islamic Period support the belief that the social, economic, and environmental conditions of the Islamic Period were more favourable for people's well-being, while the Christian Period was less favourable. Previous research into the growth of children between the Islamic and Christian Periods by Gooderham et al. (2019) appears to generally support this belief, as children from the Christian Period typically experienced greater growth deficits. However, no statistically significant differences in growth were observed between the periods, possibly indicating that there were fewer differences in the social determinants of health than expected based on the historical accounts of the past. The historical records from the Islamic Period indicating that people had an interest in or concern for diet, medical treatments, and sanitation, may not actually equate to their success at dealing with these issues. For example, the assertion that a 'humoral imbalance' could be cured via bloodletting or the consumption of specific foods, does not suggest the existence of an accurate medical understanding or an effective treatment, even if it does indicate that they recognised a physiological problem and wanted to solve it (Cunha et al. 2017). In addition, citizens of low socioeconomic status may not have had access to diverse diets if they could not afford them (García Sánchez 1983). Furthermore, the long series of regularly occurring wars and battles between the Islamic factions and the Christians would have led to famines and times of hardship among the Islamic citizens throughout the Islamic Period, likely resulting in an unfavourable environment for child growth (Barros 2004; Carvalho et al. 2017; Catarino 2017; David and Pizarro 1989; Disney 2009; Garcia 2015b; Oliveira 2017).

Chapter 3. Materials and Methods

3.1. Samples

A total of 29 individuals were examined in this study from late Medieval Islamic Period and Medieval Christian Period archaeological sites within the Algarve, from Silves and Cacela Velha, Portugal. The Islamic Period sites examined were *Rua 25 de Abril* found to the southern side of the old city of Silves, just outside the Islamic Period city walls; and *Rua A*, located at the top of the hill, north of the Silves Cathedral, and just west of the castle (see Figure 3.1). 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 Figures 3.1 and 3.2). Excavations at these sites were either ongoing (as in the case of Poço Antigo), or the result of emergency salvage excavations due to city renewal projects (as was the case for the sites from Silves); therefore, none of the sites were completely excavated, not all skeletal remains from each site could be examined, and some of the skeletons from each collection could not be fully exhumed, due to limitations on the areas that could be excavated (Chanoca 2006a; Garcia 2015b; Ribeiro and Vieira 2007; Vieira 2007a; Vieira 2007c). Preservation of the skeletal remains was poor at all the sites examined, in large part due to their proximity to the ground surface, and subsequent human activities, such as recutting graves in the same area, farming, and urban development, leading to the fragmentation of the skeletons. Thus, not all elements were available for examination from each individual.

3.1.1. Rua 25 de Abril

Rua 25 de Abril is the site name given to an Islamic Period cemetery located outside the Porta de Loulé, one of the gates in the old city walls of Silves (see Figure 3.1) (Chanoca 2006c). The location of this cemetery is consistent with the Islamic tradition of placing cemeteries outside city walls and close to a gate (García 2001; Macias 2018). The urgent need to replace and improve infrastructure, such as the sewage, water drainage, and electrical systems beneath Rua 25 de Abril led to an archaeological survey between July and September of 2005 (Chanoca 2006a). With the discovery of archaeological structures and several burials, emergency salvage excavations took place over two additional excavation phases, between September of 2005 and July of 2006 (Chanoca 2006a; Santos et al. 2006b).

Generally, the soil was very compact, moist, and clay-like (Santos et al. 2006b). This moisture, along with disturbances such as construction work and the occurrence of floods since the deposition of the remains, meant that they were poorly preserved. Archaeological interventions only occurred in areas that would be disturbed by the construction, and thus, only those affected by the infrastructure renewal project were exhumed; the rest of the site was not excavated (Chanoca 2006a). Of a total of 87 individuals exhumed from Rua 25 de Abril, 26 were sub-adults (Santos et al. 2006b). Of those, eight juveniles had some long bones sufficiently preserved for analysis (see Table 3.1).

The bodies were positioned lying on their right sides, with their heads to the west, facing south (towards Mecca), and their feet to the east. Their arms were outstretched, with straight or semi-bent legs. Most were single occupancy, open graves without structure; however, nails and wood boards were found around a few of them, indicating the presence of a coffin, one had a tile roof, and, in one case, two individuals were buried side by side (Chanoca 2006b; Chanoca 2006c; Santos et al. 2006b). Consistent with the custom of burying the dead without any grave goods (Catarino 1997; García 2001), no grave goods were found with the remains. Overlapping graves suggest the cemetery had at least four levels of use (Chanoca 2006c). The fact that some of the graves were cut into older ones indicates that the cemetery was occupied over a long period with older burials fading from memory before new graves were dug. After its use as a cemetery, the site was used for storage and a location for temporary structures as evidenced by a silo and numerous post-holes (Chanoca 2006b).

Radiocarbon dating of Skeleton 81 indicated a date of 884-1041 AD, indicating that the cemetery was in use sometime near the start of the city's occupation in the 10^{th} to 11^{th} century (Chanoca 2006c). Estimates place the site from approximately the 9^{th} or 10^{th} century to 1249 AD (Gonçalves 2020). Due to the failure of a few of the samples sent for carbon dating to yield any results, dating of the site was mostly achieved through stratigraphic association with Islamic Period structures (Chanoca 2006c).

3.1.2. Rua A

The site named Rua A dates from the 12th century to 1249 AD (Gonçalves 2020; Ribeiro and Vieira 2007). The site was first occupied during the Islamic Period, as evidenced by the remains of housing and interfaces which were either silos or septic tanks. Around the same time as these structures fell into disuse, a cemetery was put in their place. Space was maintained between burials, and there were no signs of overlap, indicating that the cemetery was only in use during a short period of time. The late occupation of this site indicates that its use as a cemetery began at about the same time as the Christian attempts to conquer the city, which could also explain why the remains were being buried within the city walls instead of outside them (Gonçalves 2019). Citizens were not able to leave the protection of the city walls during the siege to bury their dead.

The site of Rua A is located on the street connecting the streets Largo Correia Lobo and Largo da Sé in Silves (see Figure 3.1) (Santos et al. 2006c). Originally, the site was named Rua Traseiras da Sé. A contemporary Islamic burial located one street over to the north, on Rua do Saco, indicates that the cemetery was larger than the area that has thus far been excavated and that more remains could potentially be found. However, archaeological interventions only occurred in areas that would be disturbed by the work to repair and replace the sewage, water drainage, and electrical systems underneath the street, so only the skeletons which would have been affected by the infrastructure renewal project were exhumed, and the rest of the site was not excavated (Ribeiro and Vieira 2007). Emergency salvage excavations took place between May and September of 2006. The Islamic cemetery at that location had been disturbed by both ancient structures and the modern construction of housing and infrastructure; therefore, most skeletons were fragmented and poorly preserved (Santos et al. 2006c). For instance, an old water conduit led to the destruction of parts of many of the skeletons. The soil was looser in some areas, while in others it was more compact with a mixture of debris from structures and pottery.

The individuals were buried in open graves either without structure or taking advantage of previous structures to form the sides of the graves (Ribeiro and Vieira 2007; Santos et al. 2006c). In some places, larger pits had been reused successively with multiple individuals, without the previous burials being disturbed, and a small ossuary was found as well (Ribeiro and Vieira 2007). Following the Islamic standard for burial, the individuals were placed on their right side, with their heads to the west, facing south (towards Mecca), and their feet to the east, with no associated grave goods. A total of 24 skeletons were exhumed, including 14 adults and 10 sub-adults (Santos et al. 2006c). Of these, only one was found with long bones sufficiently complete to be included in this study (see Table 3.1).

3.1.3. Largo da Sé

The site of Largo da Sé is a Christian Period cemetery located around the Silves Cathedral (see Figure 3.1) (Casimiro et al. 2007). It is likely that the cathedral was originally a mosque, converted in 1189 AD when the Christians first took the city, and then rebuilt over the course of many years, beginning when the Christians took the city permanently in 1249 AD (Instituto de Gestão do Património Arquitectónico e Arqueológico 2022). During the Islamic Period, the surrounding area contained houses, silos, and cisterns, which later fell into disuse, being partially demolished, and filled in with rubbish or soil (Vieira 2007a; Vieira 2007b). During the Christian Period, the site was then used as a cemetery from the mid-13th century to the 16th century, dated based on coins associated with the remains (Casimiro et al. 2007; Vieira 2007a). The location of the cemetery is consistent with the Medieval Christian custom of burying the dead in and around a church to protect the remains from evil (Garcia 2015b).

Most of the bodies were found along the north side of the cathedral, while excavations at the front of the cathedral revealed silos from the Islamic Period (Santos et al. 2006a). Many were buried in graves without structure, but some were buried in anthropomorphic graves (Santos et al. 2006a; Vieira 2007a). The walls from the Islamic Period structures were sometimes used to form the sides or floor of a burial, and stones would sometimes be moved and placed around the body (Casimiro et al. 2007; Vieira 2007a; Vieira 2007b). In one case, a male body was deposited in a small silo, and another silo was used as a repository for the secondary burial of a female and child (Santos et al. 2006a; Vieira 2007a). Due to the placement of the male body in the silo, and the fact that it was bent into position to fit in the small space rather than laid out in a typical canonical way, it is assumed that these silo burials were a non-ritualized means of burying the body of a person defeated during the conquest of the city (Vieira 2007a).

Surveys and emergency salvage excavations took place at Largo da Sé between October of 2004 and December of 2005 (Santos et al. 2006a; Vieira 2007a). A total of 81 skeletons were exhumed, consisting of 65 adults, and 16 sub-adults, but few among them were complete (Santos et al. 2006a). Of the juveniles, four had long bones complete enough to be measured (see Table 3.1).

The excavations were limited to the areas where there were plans to update the sewage, electrical, and telecommunication lines, and to place trees along the road. Surveying and excavation of the whole site was not possible due to its location in a high traffic area (Vieira 2007b). Preservation was negatively affected by the shallowness of the graves, resulting in the fragmentation of the remains due to several factors, including rainwater leeching chemicals from the surface, the pressure exerted by cars travelling over the roads, the construction of more recent structures, pipes, roads, the parking lot, and a garden (Santos et al. 2006a; Vieira 2007b).

Typically, the bodies were buried with their heads to the west and feet to the east, in a supine position, legs parallel, with most of having their arms flexed over their pelvis or chest (Santos et al. 2006a; Vieira 2007a). Stratigraphically, there was a lot of overlap of the graves, with many ossuaries, scattered bones, and bones which ended up in other burials due to the reuse of the site over the Christian Period (Santos et al. 2006a; Vieira 2007a).

Pins associated with some of the burials indicate that they were likely buried in shrouds; however, coins, adornments, and clothing remnants were also present in many burials, indicating that religious edicts dictating that the remains be buried with only a shroud were not always followed (Casimiro et al. 2007). Some had coins, earrings, beads of amber or filigree, and one had a metal box (which presumably once had something inside). The coins associated with the remains likely indicate a continuation of the Roman belief that the dead would need to pay for safe passage into the afterlife.

3.1.4. Largo da Sé - Cisterna

Largo da Sé – Cisterna is another phase of salvage excavations at the cemetery surrounding the Silves Cathedral (see Figure 3.1), which dates from the mid-13th century after the conquest, when the cathedral was built, to the 16th century, as indicated by the association of the remains with chronologically specific structures and pottery (Vieira 2007c). Prior to carrying out city works in the area, excavations took place to the north side of the cathedral extending to the roads, excavating only part of the total cemetery (Vieira 2007c). Largo da Sé – Cisterna was excavated between September 2005 and 2006 (Silva and Ramos 2006). It had been partially excavated several years earlier, when some of the silos and cisterns were dismantled to make room for plumbing and electrical pipes, leaving many of the burials only partially exhumed. These new excavations were intended to focus on exhuming rest of the skeletal remains (Silva and Ramos 2006; Vieira 2007c). Unfortunately, the previous excavations had had a negative effect on the preservation of the site, and the original site records were largely inaccessible to the subsequent archaeologists, thus information about the contents of the surface layers were largely lost. As with Largo da Sé, digging from the previous archeological works, construction, the weight of cars above, and gardening in the area all contributed to the fragmentation of the remains (Silva and Ramos 2006; Vieira 2007c). The soil was compact, clay-like, and slightly humid, with debris and plant roots throughout.

While not all graves were excavated, 177 graves (three of which held multiple individuals) were identified (Silva and Ramos 2006). Few skeletons were well preserved, and most were incomplete. Disassociated remains such as scattered bones and ossuaries were relatively common, but it was harder to extract information from them because they were decontextualized from their original burials (Silva and Ramos 2006). Of the 174 individual graves, 141 were adults and 33 were sub-adults (Silva and Ramos 2006). Among the juvenile individuals exhumed, eight had long bones sufficiently preserved for analysis (see Table 3.1).

Most graves were without structure, although the presence of nails near some of the skeletons may indicate they originally had coffins. Some graves made use of pre-existing structures from the Islamic Period to form the edges of the burials, some had rocks placed around the sides, and a few were anthropomorphic graves (Silva and Ramos 2006). They were buried in a supine position with their heads to the west and feet to the east, with their arms over their abdomen or chest, and the legs either parallel or slightly flexed (Silva and Ramos 2006). Some grave goods were detected including a flower, a small box made of metal, some earrings, and coins (Silva and Ramos 2006).

3.1.5. Poço Antigo

Poço Antigo is the site name given to a Christian Period cemetery which dates to the second half of the 13th to the 14th century, on the basis of radiocarbon dating, which also coincides with the establishment of the church in 1240 (Garcia and Curate 2010; Rodrigues 2022). Historical documents indicate that the church and cemetery were used until the 16th century when a new church was built within the walls (Garcia 2015b). It is located to the east of the fortress in Cacela Velha (see Figure 3.1), near the cliffs of the coastline, directly adjacent to the entrance from the ocean to the Ria Formosa lagoon.

The site of Poço Antigo was discovered during in 1997 and, in 1998, a formal archeological excavation revealed the Christian cemetery and the foundations of the Islamic quarter from the Almohad Period (Garcia and Curate 2010). Excavations at Poço Antigo are ongoing, beginning in 2001, uncovering 57 graves, including 41 adult and 16 sub-adults, as well as numerous ossuaries and individual bones (Garcia 2015b; Garcia and Curate 2010). Excavations at Poço Antigo were resumed in 2018-2019, and in 2022, bringing the total number of skeletons exhumed to 85 (Rodrigues 2022). The 2022 excavations also confirmed that there was another cemetery from the Islamic Period (and possibly the Roman Period) a bit further inland (Rodrigues 2022). Of the juveniles' remains found between 1998 and 2019, only eight had long bones complete enough to be measured (see Table 3.1).

Preservation of the remains at Poço Antigo was generally good (Curate 2008; Garcia 2015a; Garcia et al. 2015). However, agricultural activities such as plowing have been taking place over the site since the 18th century, resulting in the churning of the top layers of the soil and damaging some of the remains close to the surface (Garcia 2015b; Garcia and Curate 2010). Additionally, some damage caused by plant roots were noticed and, due to the natural processes of erosion and sedimentation, parts of the site were exposed to the environment, with sand subsequently being deposited over the remains by the wind (Garcia and Curate 2010). The soil was generally compact and sandy, with rocks, fragments of walls, tile roofs, and pottery pieces from the previous Islamic quarter. The alkaline pH and generally dry soil made it suitable for the protection of bones, even if it was less suitable for the preservation of organic materials, and the soil was generally well suited for water drainage (Garcia 2015b; Garcia and Curate 2010). The practice of reusing graves and the creation of ossuaries affected the preservation of the remains as well as the ability to associate bones with specific individuals. The earthquake in 1755 likely also contributed to the poor preservation of some stratigraphic layers at the site (Garcia and Curate 2010).

Most graves were simple pits, with very little distinction between them and the surrounding soil (Garcia and Curate 2010). Historical records state that the remains were buried near a small church (although the remains of the church have not yet been found). It was customary to bury individuals in and around churches in the Christian Period to protect their bodies from evil (Garcia 2015b). All exhumed skeletons were in a supine position, with their head to the west and feet to the east, and their arms crossed over their chest or abdomen (Garcia 2015a; Garcia and Curate 2010). Many of the graves made use of the ruins of the old walls, and rubble of the Islamic dwellings, to form the sides of the graves, and stones were often placed at the ends, around the head, or under it as a sort of pillow (Garcia 2015b; Garcia and Curate 2010). Most would have been buried in shrouds (as evidenced by one with a shroud pin), but some of the graves show evidence of coffins as indicated by nails; and, in one case, an iron handle and bolt; and, in another, decorative metal elements. In rare instances, jewellery and clothing were found on certain skeletons including an earring, a metal scallop shell shaped pendant (a souvenir of a pilgrimage often imposed as a penance for pilgrims of Santiago de Compostela at the end of the 12th century), a bronze pendant, copper needles, a copper pin, a bead, and a belt (Garcia 2015b; Garcia and Curate 2010).

Figure 3.1 Map of Silves. City walls are shaded in brown, sites are shaded in beige and numbered. (2) is Largo da Sé and Largo da Sé - Cisterna, (4) is Rua 25 de Abril, (5) is Rua A. Map adapted by Carlos Oliveira for the Museu Muncipal de Arqueologia de Silves (2023). Reproduced with permission from the Museu Muncipal de Arqueologia de Silves.

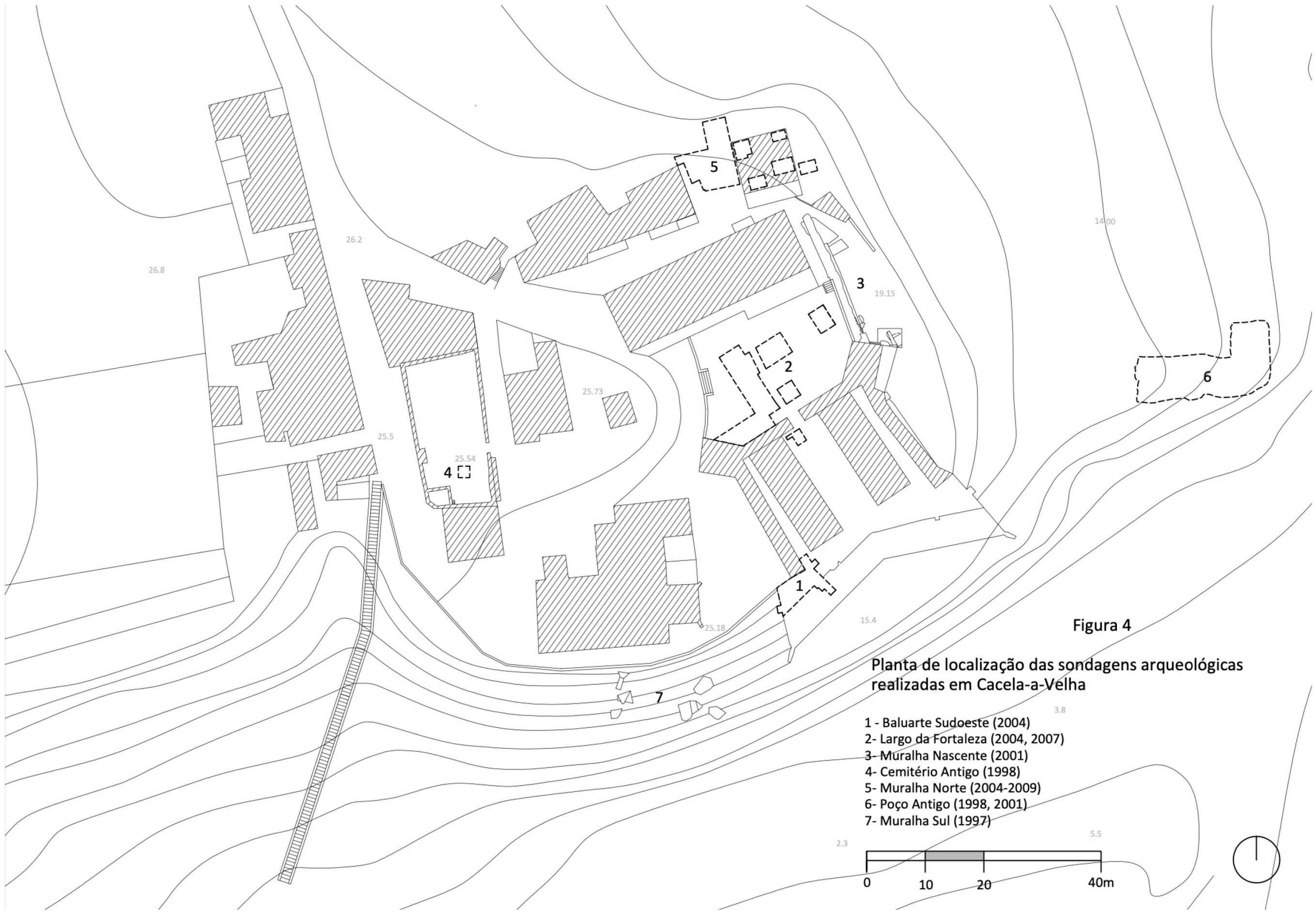

Figure 3.2 Map of Cacela Velha. Sites are represented by dashed lines and numbered. (6) is Poço Antigo, located to the east of the town's fortifications. Map reproduced with permission from Garcia (2015b). Location plan of archaeological surveys carried out in Cacela-a-Velha, 1 - Southwest Bulwark (2004), 2 – Fortress Square (2004, 2007), 3 – Rising Wall (2001), 4 – Old Cemetery (1998), 5 – North Wall (2004-2009), 6 – Old Well (1998, 2001) 7 – South Wall (1997).

Table 3.1 Sample size distribution by site, Medieval Period, number of individuals, age group, and skeletal elements.

Site Name	Time Range	Medieval Period	n	Age<2	Age>2	Humerus	Radius	Ulna	Femur	Tibia	Fibula	Femur Midshaft	Humerus Midshaft
Rua 25 de Abril	9th century – mid 13th century	Medieval Islamic	8	5	3	6	5	6	5	4	2	5	6
Rua A	12th century – mid 13th century	Medieval Islamic	1	0	1	1	1	1	0	0	0	0	1
Largo da Sé – 1 Fase	13th century – mid 16th century	Medieval Christian	4	0	4	4	2	1	3	2	0	2	4
Largo da Sé Cisterna	13th century – mid 16th century	Medieval Christian	8	0	8	6	5	5	3	2	3	3	6
Cacela Velha Poço Antigo	Mid 13th century – 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

3.2. Methods

To assess their linear and appositional growth, all available juvenile skeletons, with at least one unworn incompletely-formed mandibular tooth, and at least one complete long bone with unfused epiphyses were examined from all the sites. Age was estimated based on the tooth length of the incompletely-formed mandibular teeth. Only individuals between the ages of zero and 12.5 years were included in the study, as the reference collection for the expected growth of juveniles only has individuals of up to 12 years of age for linear growth, and of up to 12.5 years of age for appositional growth. While there were many individuals below the age of 12.5 years, most were poorly preserved, either missing all their teeth, or having long bones that were too fragmented to be measured for growth analysis. Only 29 individuals were complete enough to be suitable for this study; nine from the Islamic Period, and twenty from the Christian Period (see Table 3.1).

3.2.1. Bone Measurements

To measure linear growth, the maximum diaphyseal length of each available complete long bone, with unfused epiphyses, was measured and recorded, as per the recording standards in set out in Buikstra and Ubelaker (1994). When available, the bones of the left side were measured; when absent or incomplete, the bones from the right side were substituted. The bones were measured to the nearest millimetre when using an osteometric board, or to the nearest tenth of a millimetre when using sliding digital calipers.

Appositional growth was examined 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 measure their true cross sections (O'Neil and Ruff 2004). All radiographs were scaled to account for radiographic magnification and distortion. Bones from the left side were radiographed, unless absent or incomplete, in which case, the bones from the right side were examined. To scale the radiographs and ensure that each was measured at the correct location, a 10 mm radio-opaque scale bar was placed at the 41% mark of the humerus' midshaft and at the 45.5% mark of the femur's midshaft (measured from the distal end using sliding digital calipers), as per the protocols outlined in O'Neil and Ruff (2004), and Ruff (2003). The 41% mark from the distal end of the humeral diaphysis and the 45.5% mark from the distal end of the femoral diaphysis accounted for the difference from the midpoint due to the lack of epiphyses in juvenile individuals (Ruff 2000; Ruff 2003). The 41% mark also allowed for the deltoid tuberosity of the humerus to be avoided, since it would not give a clear picture of appositional growth using elliptical formulae. Although humeri and femora are not perfectly elliptical, total area, cortical area, and medullary area were calculated using elliptical formulae, as per the protocols of O'Neill and Ruff (2004). Using the elliptical formulae simplified the analysis and was consistent with the methodology of the previously collected data from Gooderham et al. (2019) as well as the unpublished Denver Growth Study data (used in this study as a reference collection for standard growth) for appositional growth, provided by Dr. Christopher Ruff, which also used elliptical formulae to calculate long bone cortical dimensions from two-dimensional radiographs.

The Denver Growth Study data was selected as a reference collection because of its well established and widespread use in bioarchaeological studies as a reference population for standard growth, and because it has reference data for all the growth variables examined in this study (Cardoso 2005; Gooderham et al. 2019; Ives and Humphrey 2020; Newman and Gowland 2017; Spake and Cardoso 2021). The Denver Growth Study data was collected by Maresh between 1915 and 1967 by making radiographs of the long bones of living children, at regular intervals, over the course of their childhood, so that their growth over time could be observed; the original data has since been corrected to account for radiographic magnification and distortion (Feldesman 1992; Ruff 2007).

Because the humerus and femur have the most elliptical shape of the long bones, particularly at the 45.5% and 41% marks of the midshaft of juvenile diaphysis, using elliptical formulae gives relatively accurate cross-sectional measurements (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 calculated.

3.2.2. Age Estimation

To determine if long bone measurements were stunted for their age, the age at death was estimated. 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. The maximum length of each available unworn and incompletely-formed, deciduous and permanent mandibular tooth was measured to the nearest tenth of a millimetre. Tooth measurements were made "parallel to the long axis, and the length … defined as the distance from the mid-incisal edge, cusp tip, or mesiobuccal cusp tip to the inferior anterior edge of the developing cusp or root, recording the maximum length of each tooth" (Cardoso et al. 2016). Mandibular teeth from the left side were measured, unless missing or incomplete, in which case the teeth from the right side of the mandible were substituted. If a tooth was not socketed, then its maximum length was measured with a sliding digital caliper; if the teeth remained socketed, they were measured from a scaled periapical radiograph (Cardoso et al. 2019).

Radiographs were made with a portable digital radiograph machine, in the lingual-buccal plane, with a 10 mm radio-opaque scale bar placed above the centre of the cusps. ImageJ software was then used to measure each tooth. Because the Cardoso et al. (2016) and Cardoso et al. (2019) age estimation formulae were developed from the mandibular teeth, they were not as accurate when applied to maxillary teeth. Therefore, only mandibular teeth were used to estimate age. 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 2007a).

Dental aging methods for sexes combined (Cardoso et al. 2016) were selected, because biological sex was unidentifiable since the children had not yet reached puberty. As previously observed, since they had not reached puberty, there were unlikely to be significant differences in their growth "even if one sex outnumbers the other[s]" (Cardoso and Garcia 2009). The accuracy of methods which claim to be able to distinguish between the sexes are still questionable when applied to pre-pubertal skeletons, since sexual dimorphism often varies depending on their age and biosocial environment (Corron et al. 2021). For the most part, significant differences between male and female stature come into play after the adolescent growth-spurt (Feldesman 1992). In any event, short of genetic testing, which was expensive and not feasible, sex estimation of the children was not possible, as is common with archaeological studies (Cardoso et al. 2016). Therefore, age was estimated using a method for the sexes combined (Cardoso et al. 2019; Cardoso et al. 2016).

Using the measurement of teeth to estimate the age of juveniles in archaeological contexts, when no written record of their age at death is available, is the most accurate and reliable method of age estimation. Dental development is much less sensitive to environmental influences and, thus, it is a better reflection of actual age at death than skeletal development, even among individuals of exposed to greater social and environmental stressors (Cardoso 2007b; Conceição and Cardoso 2011). Furthermore, measuring the teeth is a more objective and quantitative way to age the individuals, which can provide an age on a continuous scale, rather than relying on the identification of a categorical age based on tooth formation stage methods (Cardoso et al. 2016).

3.2.3. Skeletal Growth Profiles, Z-Score Analysis, and Statistical Testing

Once age was estimated, skeletal growth profiles (SGP) were made for each of 16 growth variables (the length of the humerus, radius, ulna, femur, tibia, and fibula, and the total area, cortical area, medullary area, and mediolateral and anteroposterior cortical thickness, at the midshaft of the humerus and femur). Each SGP included the age-specific reference data from the Denver Growth Study. The reference data for males and females from the Denver Growth Study data was pooled for the calculation of the means and standard deviations for each age group (Cardoso 2005).

All the variables were then examined using Z-scores, to standardize individual measurements so that they accounted for differences in size due to age and allow comparisons to be made for the samples, despite any unequal distribution in ages. Using Z-scores, growth deficits in each of the samples are identified by reference to a modern growth standard (Gooderham et al. 2019; Spake and Cardoso 2021). Z-scores described how many standard deviations above or below the mean growth of the reference collection each measurement was. A positive Z-score indicated that the growth of the individual was greater than the mean growth of the reference collection, while a negative Z-score indicated that it was smaller than the mean growth of the reference collection. A Z-score of <-2 (or >+2 in the case of the medullary cavity), means that the measurement for that individual is considered stunted compared to the reference collection (WHO 1995). A Z-score of <-3 (or >+3 in the case of the medullary cavity), means that the measurement for that individual is severely stunted.

The Z-scores for each variable were calculated by "subtracting the age-specific mean from the individual value and dividing by the standard deviation" (Gooderham et al. 2019). The age-specific mean and standard deviation for 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 (as per Gooderham et al. 2019). The Denver Growth Study data was used to calculate Z-scores for the six linear and ten appositional growth measurements. Since the Denver Growth Study data only has reference data beginning at two months of age, two individuals below that age could not be included. Only those between two months and 12.5 years of age could be included.

Long bone lengths were also analysed by calculating Z-scores from the higher-resolution reference data from Spake and Cardoso (2021) that was interpolated from the Maresh data. The Spake and Cardoso (2021) dataset provides reference values for the mean and standard deviations of the expected growth of all the long bones at one-month intervals, starting at age zero until age twelve. In assigning individuals to age groups at one-month intervals instead of half-year intervals (as in the original Maresh data), they were assigned to an age category which more precisely reflected their estimated age, and more accurately reflected their growth deficits for age, relative to the healthy standard (Spake and Cardoso 2021). For example, using the original Maresh dataset, an individual with a femur length of 122mm at an age of 0.94 years would be categorized as 0.50 years of age for their Z-score calculations following the Gooderham (2018) protocols, since it would be the preceding age category; consequently, that individual would be assigned a Z-score for their femur length of 2.81, which is a much larger Z-score than they should have because the score would assume they were almost half a year younger than they actually were (Spake and Cardoso 2021). Thus Z-scores calculated using the Maresh data would have made individuals at the upper end of each age category appear larger for their age than they were. In contrast, using the interpolated Maresh data for long bone lengths, the same individual would be assigned a much more appropriate Z-score for femur length of -1.30 and be categorized as 11 months old, or 0.92 years of age, which is the nearest preceding age category using the interpolated data, and is much closer to the estimated age at death of the individual.

Given how dramatically the Z-scores for long bone length can change depending on which age group they are assigned to using the interpolated and non-interpolated data, it was decided that Z-scores for all six long bones should be calculated using both datasets. Using both datasets was done in order to test whether using the more age-appropriate reference data versus the original data would still identify the same variables as being similar or different from one another. Ideally, the interpolated data would be used over the original data for all 16 growth variables as it does assign more age-appropriate Z-scores to each individual (Spake and Cardoso 2021), but the interpolated reference data only exists for the linear growth variables and has not been calculated for the appositional growth variables yet. Furthermore, the interpolated data has not been widely employed by other growth studies (such as Gooderham 2018) who used the non-interpolated reference data for the calculation of their Z-scores. The growth of children from different populations is only comparable using Z-scores if those Z-scores were calculated using the same reference data for long bone growth. Therefore, to make the data comparable to other populations, Z-scores were calculated for all 16 growth variables using the non-interpolated data.

A one sample t-test was run for each of the 16 growth variables using GraphPad Software LLC. (2022) to identify whether there was a statistical difference between the mean Z-scores of the long bone growth variable for the Medieval samples, and zero. Zero is the Z-score that represents the mean of the modern growth reference population, and that the sample is on par with the reference sample, being neither delayed nor advanced in size for age (World Health Organization 1995).

Mann-Whitney U tests and unpaired T-tests were run comparing the Z-scores of all 16 growth variables between the Islamic and Christian Period children from the Algarve to assess any differences in growth between the periods. Additional testing was done dividing each population by age group to see if there were statistically significant differences in growth, related to the differential growth velocity, nutrition, and care of infants (those under two years of age), and of children (those at and above two years of age). The growth velocity of infants and children tends to be different (Cameron and Bogin 2013). Furthermore, infants who are not yet weaned tend to have very different exposures to stressors than children who have been weaned, and weaning typically occurred at around two years of age in both Medieval periods (Gil'adi 1992; Katzenberg et al. 1996; Newman et al. 2019). Differences in the growth of the age-groups between periods might indicate differences in cultural practices regarding infant/child care and feeding. Furthermore, if there were age-group related differences in growth, subdividing the sample by age allows for the growth of each group to be compared between the periods despite any unequal distributions in age-groups within the samples from each period.

Lastly, the Algarve growth data from this study was compared to the growth data from Santarém, Portugal (a very large urban centre throughout the Medieval Era, in central Portugal) (Gooderham 2018) so that the regional differences in growth for age between Santarém and the Algarve during the Medieval Islamic and Christian Periods could be observed. Santarém was a very large urban centre throughout the Medieval Era. T-tests were used to compare the Z-score means for all six long bone length measurements, and femur total area, cortical area, medullary area, and mediolateral cortical width (as published in Gooderham 2018), between the Santarém and Algarve populations for the total sample, the Islamic Period, and the Christian Period. This comparison allowed for the testing of whether there were any statistically significant differences between growth in the Algarve and Santarém across time, to see if juvenile growth was affected by regional differences in their social and physical environment.

Due to the small total sample size for every growth variable, and because only two groups were examined in each test, Mann Whitney U Tests and unpaired t-tests were chosen to determine whether there were any significant differences in Z-score means/medians of all 16 growth variables between the two groups. All Mann-Whitney U tests were done in SPSS, and all t-tests were done in GraphPad Software LLC. (2022), provided they met the criteria for minimum sample sizes per group for the tests to be able to return a statistically significant value. A Mann-Whitney U test must have at least eight samples in total, because any fewer will always result in a *p*-value above the cut-off of 0.05 for statistical significance, even if they are different. Similarly, a t-test must have at least two samples per category to prove statistical significance. Having more samples, of course, improves the statistical strength of the tests. An alpha level of 0.05 was chosen for all statistical tests.

Chapter 4. Results

4.1. Linear Growth Analysed with High-Resolution Reference Data

As seen in Table 4.1, the mean Z-scores for the humerus, radius, ulna, femur, tibia, and fibula diaphyseal length using the interpolated Maresh data were significantly smaller for age than their expected growth based on the reference collection. One sample t-tests confirmed that the mean Z-scores for the total sample for all long bone growth variables were statistically different from zero, and thus, statistically different from the mean growth of the reference population (humerus: t=3.698, p=0.001; radius: t=5.049, p=0.000; ulna: t=4.363, p=0.000; femur: t=5.591, p=0.000; tibia: t=6.720, p=0.000; fibula: t=4.340, p=0.007). While, on average, all the long bones experienced a growth deficit, the mean Z-scores for the femur, tibia, and fibula of the total sample had mean Z-scores of less than -2, indicating they experienced growth stunting. In general, the femur, tibia, and fibula, were more stunted than the humerus, radius, and ulna (see Table 4.1).

Overall, there were greater growth deficits in long bone length for age in the Islamic Period (as seen in Table 4.1), however, based on the Mann-Whitney U and unpaired t-tests these differences did not reach statistical significance, except in the case of the radius.

The difference in radius growth between the periods was mainly the result of the differences in growth between of the juveniles below age two from each period. The t-test results presented in Table 4.2 indicate that there were statistically significant differences in the mean Z-scores for radius diaphyseal length between the Islamic and Christian Periods for the individuals below age two, but not for the individuals at and above age two (see Table 4.2).

While there were few samples available, on average, the children below the age of two from the Islamic Period had much lower mean Z-scores for long bone length than the children below the age of two from the Christian Period (see Table 4.2). Comparatively, the children at and over age two, had relatively similar Z-scores for long bone length between periods.

For these and all subsequent tables, dashes are shown where there were insufficient samples to run the Mann-Whitney U test and/or the t-test, and where there were too few samples to calculate a mean or standard deviation.

Table 4.1 Sample size (n), mean (x), and standard deviation (SD) for long bone length Z-scores, by time period. A Mann-Whitney U test and an unpaired t-test compare the Islamic and Christian Periods.

Long Bone Length Z-scores with Interpolated Denver Growth Study Data													
Long Bone	Total			Islamic			Christian			Mann-Whitney U test		Unpaired t-test	
	n	x	SD	n	x	SD	n	x	SD	z	p	t	p
Humerus	23	-1.28	1.66	7	-1.57	1.83	16	-1.16	1.63	0.267	0.820	0.536	0.598
Radius	18	-1.44	1.21	6	-2.31	0.73	12	-1.00	1.19	2.341	0.018	2.454	0.026
Ulna	21	-1.39	1.46	7	-1.44	1.57	14	-1.36	1.46	-0.149	0.913	0.116	0.909
Femur	15	-2.05	1.42	5	-2.66	0.29	10	-1.75	1.67	1.225	0.254	1.188	0.256
Tibia	10	-2.21	1.04	4	-2.51	0.59	6	-2.01	1.28	0.426	0.762	0.721	0.492
Fibula	6	-2.02	1.14	2	-2.62	0.02	4	-1.72	1.34	-	-	0.896	0.421

Table 4.2 **Sample size (n), mean (x), and standard deviation (SD) for all long bone length Z-scores, by time period. An unpaired t-test compares the age groups.**

Long Bone Length Z-scores with Interpolated Denver Growth Study Data											
Long Bone and Age Group	Total			Islamic			Christian			Unpaired t-test	
	n	x	SD	n	x	SD	n	x	SD	t	p
Age <2											
Humerus	7	-0.33	2.58	4	-1.63	2.48	3	1.41	1.71	1.806	0.131
Radius	6	-0.83	1.90	3	-2.42	0.80	3	0.77	0.88	4.646	0.010
Ulna	9	-0.69	1.86	4	-1.37	2.11	5	-0.16	1.66	0.967	0.366
Femur	3	-1.16	2.67	2	-2.70	0.11	1	1.92	0.00	-	-
Tibia	2	-2.59	0.30	2	-2.59	0.30	0	-	-	-	-
Fibula	2	-2.62	0.02	2	-2.62	0.02	0	-	-	-	-
Age ≥2											
Humerus	16	-1.70	0.88	3	-1.49	0.91	13	-1.75	0.91	0.446	0.662
Radius	12	-1.75	0.57	3	-2.20	0.80	9	-1.59	0.43	1.742	0.112
Ulna	12	-1.90	0.82	3	-1.53	0.83	9	-2.03	0.82	0.912	0.383
Femur	12	-2.28	1.00	3	-2.64	0.40	9	-2.16	1.13	0.699	0.502
Tibia	8	-2.11	1.16	2	-2.43	0.96	6	-2.01	1.28	0.417	0.691
Fibula	4	-1.72	1.34	0	-	-	4	-1.72	1.34	-	-

4.2. Linear and Appositional Growth Analysed with Lower-Resolution Data

4.2.1. Linear Growth Analysis

As seen in Tables 4.1 and 4.3, t-tests which used the interpolated and non-interpolated data to calculate Z-scores for long bone length still identified the same groups as being or not being statistically significant. This similarity offers some validity to the use of the non-interpolated data since it is still capable of identifying differences in growth between the two populations despite calculating Z-scores for long bone lengths with less age-appropriate categories.

The mean Z-scores for the humerus, radius, ulna, femur, tibia, and fibula diaphyseal length for the total sample, using the Maresh data, were significantly smaller for age, than the expected growth of the reference collection. One sample t-tests confirmed that the mean Z-scores of the total sample for all long bone growth variables were statistically different from zero, and thus, statistically different from the mean growth of the reference population (humerus: t=3.084, p=0.006; radius: t=5.443, p=0.000; ulna: t=2.621, p=0.017; femur: t=6.980, p=0.000; tibia: t=5.203, p=0.001; fibula: t=3.152, p=0.0253). On average, all the long bones experienced a growth deficit, but the bones of the lower limb typically had greater growth deficits than those of the upper limb, in both Medieval periods (as seen in Figures 4.1 through 4.6).

When using the non-interpolated reference data for long bone growth, the only mean Z-scores for long bone growth to show a statistically significant difference in growth between the Islamic and Christian Medieval Periods were those of the radius, where there were greater growth deficits during the Islamic Period than in the Christian Period (see Table 4.3). According to the t-test results (t=2.169, p=0.048), there were significantly greater growth deficits of the radius among the individuals from the Islamic Period than from the Christian Period; and this difference was very near significance for the Mann-Whitney U test as well (z=-1.952, p=0.056) (see Table 4.3). Given the previous interpolated data (Table 4.1) the t-test likely bears more weight in terms of identifying the presence of a statistically significant difference between the Z-scores for growth, since when the Z-scores were assigned using more appropriate age groups for each individual, the comparison of the Z-scores for radius length yielded p-values of well under 0.05 for both the Mann Whitney U test and t-test. The difference in growth can be seen in the SGP for radius length (Figure 4.2) in which the measurements of the radius from the Islamic Period were typically smaller for age than those of the Christian Period.

That being said, Figures 4.1 and 4.2 reveal that the differences observed between periods for radius length were due to the sampling. As seen in Figure 4.1, there were two Islamic Period individuals below the age of two whose growth was very similar to the expected growth of the reference collection, such that the Z-scores for humerus length appeared to be similar across the periods. These two individuals did not have radii and so they were not included in the calculations for the radius length Z-scores, leaving only individuals from the Islamic Period with lower Z-scores for radius length. Because the radius Z-score calculations were missing the radii for the two Islamic Period individuals with the highest Z-scores for long bone length, the comparison of their growth across the periods identified a difference between the Islamic and Christian Periods, when it is likely that there would not have been a difference had those individuals been included in the calculations.

Generally, the other bones also showed greater growth deficits in the Islamic Period, compared to the Christian Period; however, these differences did not reach statistical significance (see Table 4.3). The SGP for the humerus, ulna, femur, tibia, and fibula do not show a clear difference in long bone growth between the periods (see Figures 4.1, 4.3, 4.4, 4.5, and 4.6).

While there were generally too few samples available to establish whether there were statistically significant differences in growth between periods when the samples were subdivided by age group, there were typically greater growth deficits among juveniles below the age of two from the Islamic Period, than from the Christian Period (see Table 4.4). In fact, Christian Period children below the age of two tended to have positive Z-scores for long bone length, indicating they experienced greater growth than expected based on the reference collection, while those from the Islamic Period tended to have negative Z-scores for long bone length indicating that they had growth deficits. At and above the age of two, the Z-scores for long bone length from both periods indicated that they experienced growth deficits, with those from the Islamic Period typically experiencing greater growth deficits than the individuals from the Christian

Period (see Table 4.4). However, the differences in growth between the children at and above age two from each period did not reach statistical significance.

Table 4.3 **Sample size (n), mean (x), and standard deviation (SD) for long bone length Z-scores, by time period. A Mann-Whitney U test and an unpaired t-test compare the Islamic and Christian Periods.**

Long Bone Length Z-scores with Denver Growth Study Data													
Long Bone	Total			Islamic			Christian			Mann-Whitney U test		Unpaired t-test	
	n	x	SD	n	x	SD	n	x	SD	z	p	t	p
Humerus	21	-1.07	1.59	7	-0.92	1.98	14	-1.15	1.43	-0.671	0.535	0.306	0.763
Radius	16	-1.32	0.97	6	-1.93	0.84	10	-0.96	0.88	-1.952	0.056	2.169	0.048
Ulna	19	-0.92	1.53	7	-0.83	1.74	12	-0.98	1.47	-0.507	0.650	0.201	0.843
Femur	14	-1.94	1.04	5	-2.26	0.89	9	-1.76	1.13	-1.267	0.240	0.849	0.413
Tibia	10	-1.81	1.10	4	-2.01	0.87	6	-1.67	1.29	-0.213	1.000	0.458	0.659
Fibula	6	-1.57	1.22	2	-1.94	1.45	4	-1.38	1.28	-	-	0.488	0.651

Table 4.4 Sample size (n), mean (x), and standard deviation (SD) for humerus length Z-scores, by time period. An unpaired t-test compares the age groups.

Long Bone Length Z-scores with Denver Growth Study Data											
	Total			Islamic			Christian			Unpaired t-test	
Long Bone	n	x	SD	n	x	SD	n	x	SD	t	p
Age <2											
Humerus	5	0.01	2.70	4	-0.62	2.65	1	2.55	0.00	-	-
Radius	4	-1.19	1.74	3	-1.95	1.02	1	1.10	0.00	-	-
Ulna	7	0.18	1.81	4	-0.46	2.29	3	1.04	0.24	1.103	0.320
Femur	2	-2.01	1.68	2	-2.01	1.68	0	-	-	-	-
Tibia	2	-1.90	1.14	2	-1.90	1.14	0	-	-	-	-
Fibula	2	-1.94	1.45	2	-1.94	1.45	0	-	-	-	-
Age ≥2											
Humerus	16	-1.41	0.95	3	-1.33	0.90	13	-1.43	0.99	0.160	0.875
Radius	12	-1.36	0.67	3	-1.90	0.85	9	-1.19	0.53	1.753	0.110
Ulna	12	-1.56	0.89	3	-1.31	0.75	9	-1.65	0.96	0.553	0.592
Femur	12	-1.93	1.01	3	-2.43	0.26	9	-1.76	1.13	0.988	0.347
Tibia	8	-1.78	1.17	2	-2.12	0.97	6	-1.67	1.29	0.444	0.673
Fibula	4	-1.38	1.28	0	-	-	4	-1.38	1.28	-	-

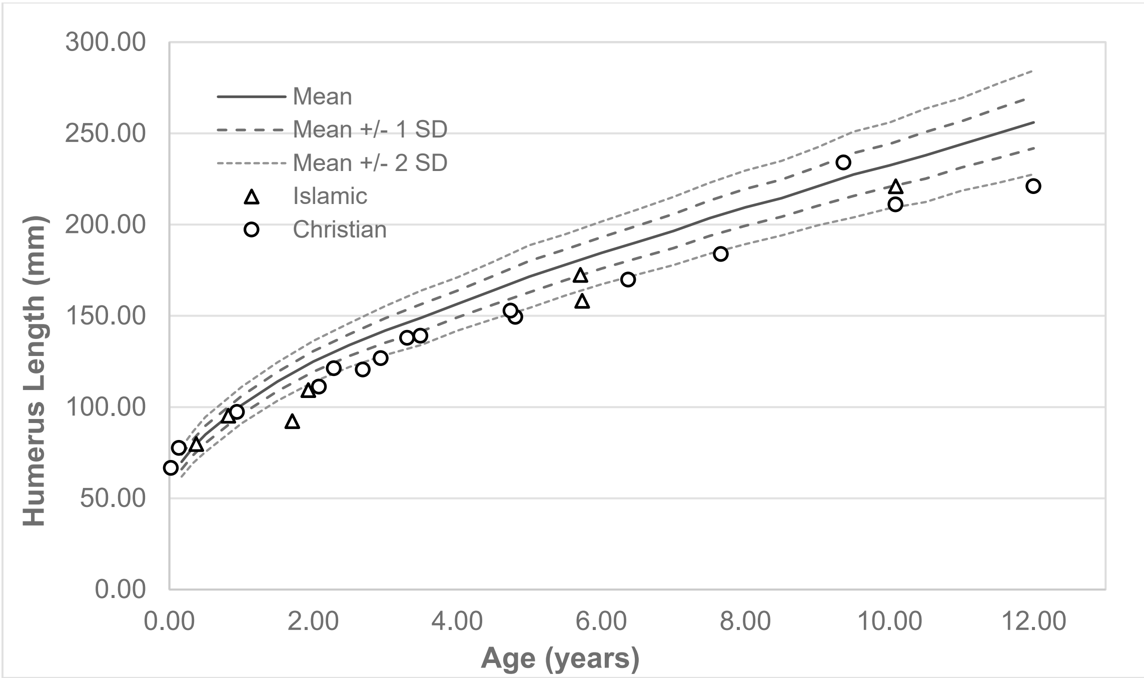

Figure 4.1 **Scatterplot of the humerus length for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

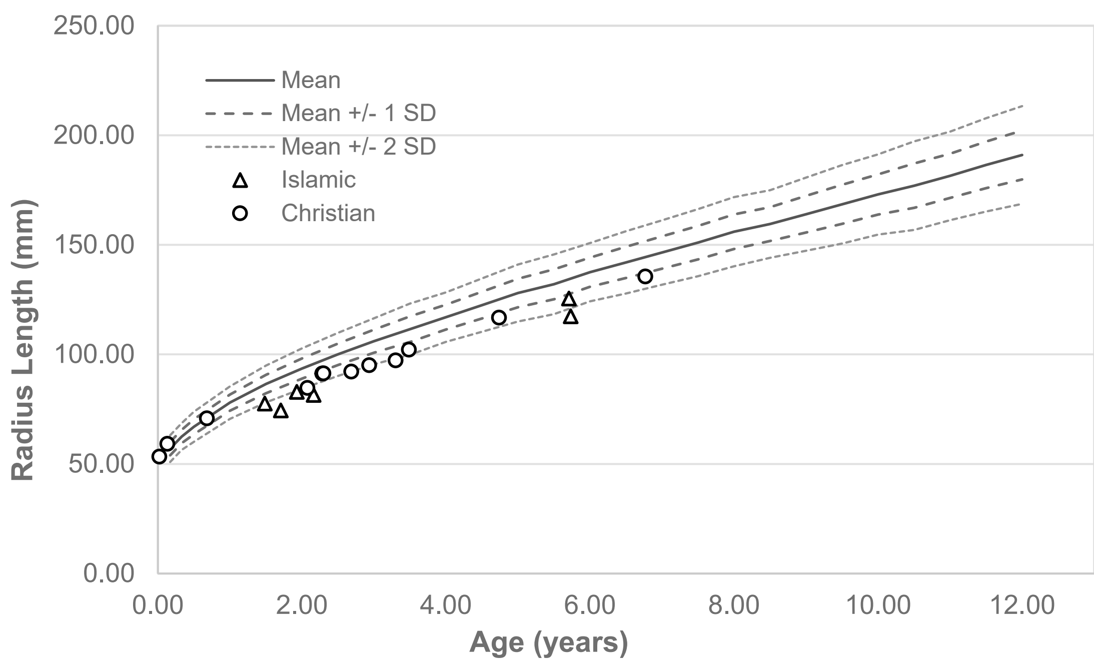

Figure 4.2 **Scatterplot of the radius length for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

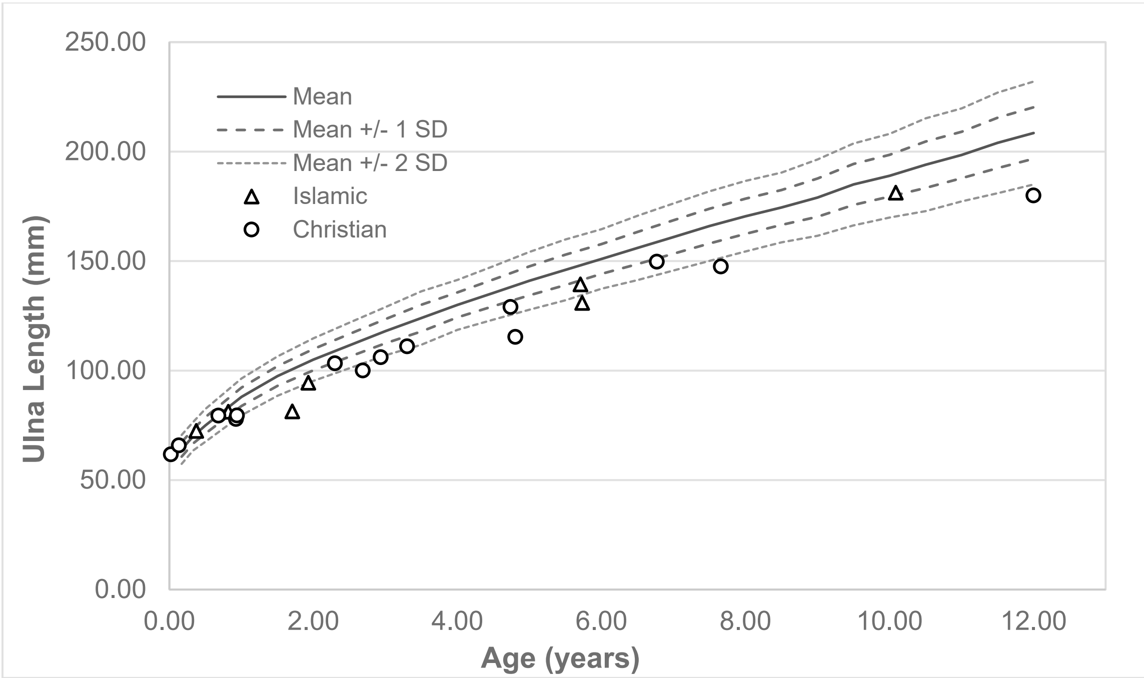

Figure 4.3 Scatterplot of the ulna length for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

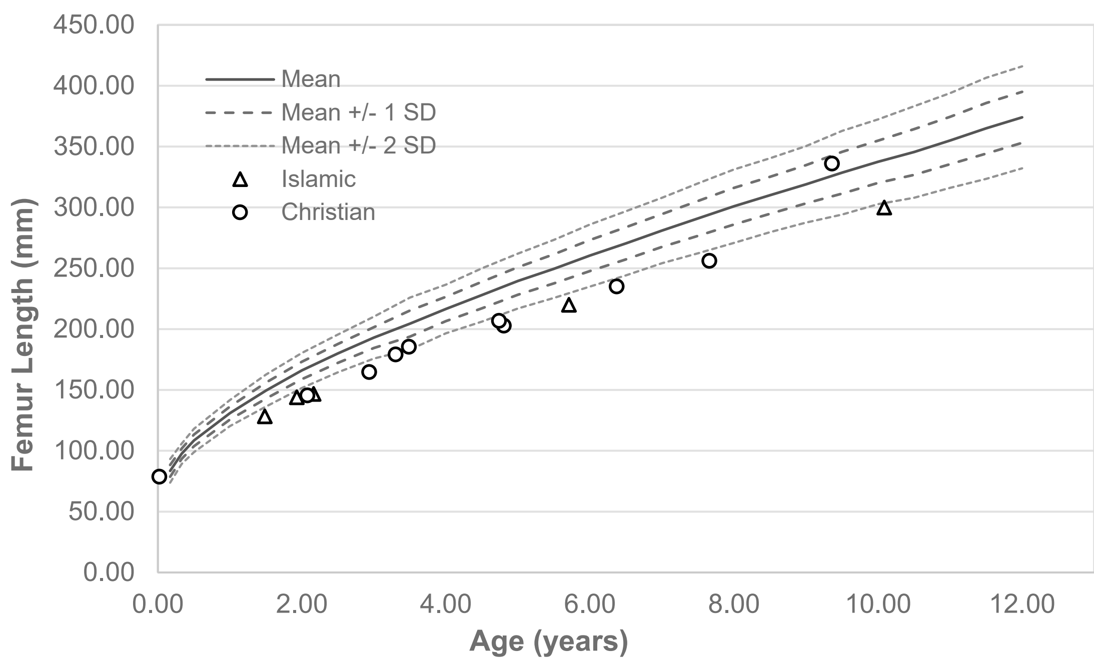

Figure 4.4 Scatterplot of the femur length for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

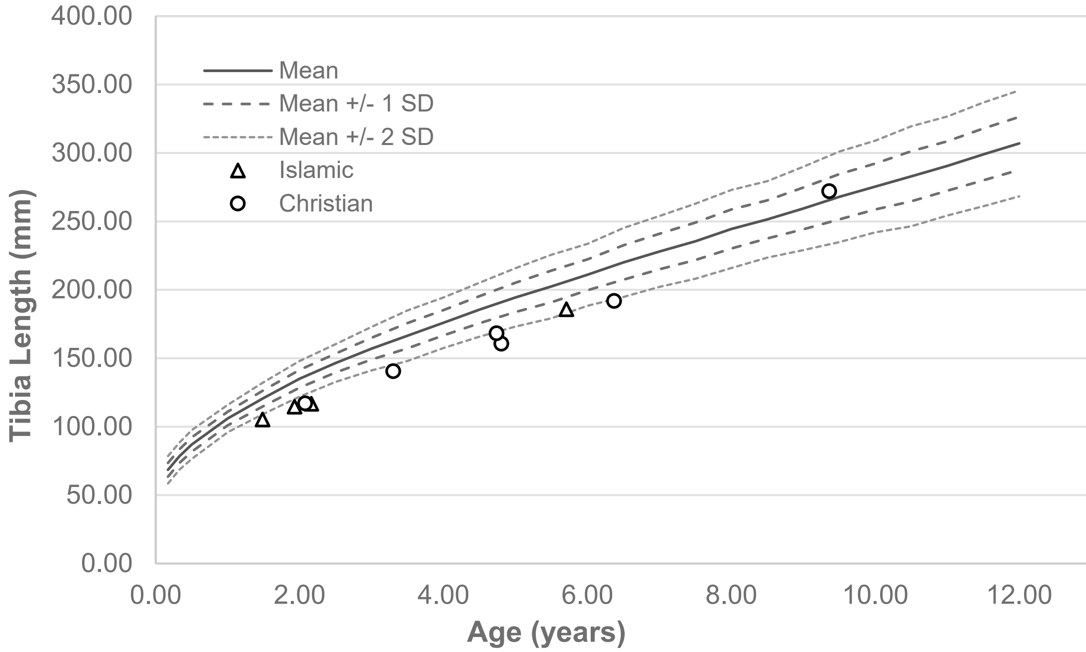

Figure 4.5 Scatterplot of the tibia length for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

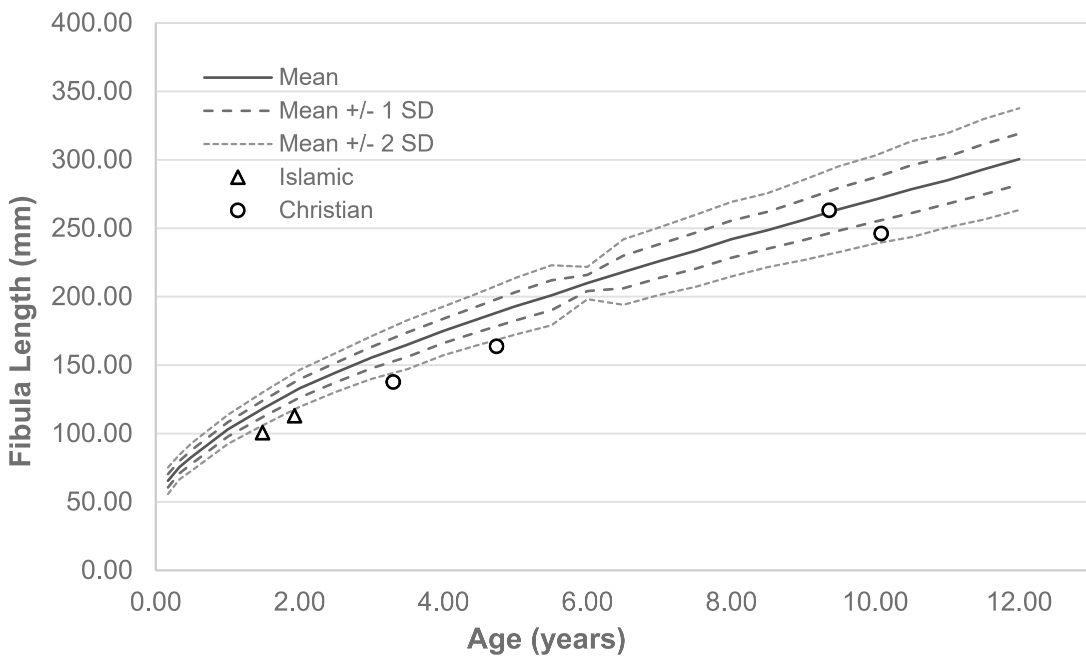

Figure 4.6 Scatterplot of the fibula length for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

4.2.2. Femur Appositional Growth Analysis

The mean Z-score for the total area of the femur at the midshaft for the total sample indicated that, despite being smaller than the expected growth, the total area measurements of the femur were typically within one standard deviation of the mean expected growth of the reference collection (x=-0.81). By contrast, the mean Z-score for the medullary area of the femur at the midshaft for the total (x=1.02) indicated that, on average, the medullary cavities of all medieval children were wider for age than the expected growth of the reference collection. Since cortical area is calculated from total area minus medullary area, cortical area and cortical thickness in the mediolateral and anteroposterior directions for the total sample were much smaller for age than expected (see Table 4.5). Overall, the mean Z-scores for the total sample for cortical area (x=-2.38), mediolateral cortical thickness (x=-3.30), and anteroposterior cortical thickness (x=-2.37) all had a Z-score of less than -2, indicative of stunting. One sample t-tests confirmed that the mean Z-scores for the total area, cortical area, medullary area, mediolateral cortical thickness, and anteroposterior cortical thickness of the total sample, were statistically different from zero, and thus, statistically different from the mean growth of the reference population (total area: t=2.282, p=0.042; cortical area: t=3.883, p=0.002; medullary area: t=5.254, p=0.000; mediolateral cortical thickness: t=6.538, p=0.000; anteroposterior cortical thickness: t=3.237, p=0.007). These patterns are also seen in the SGP, wherein most individuals had a total area, cortical area, mediolateral cortical thickness, and anteroposterior cortical thickness measurement below the mean growth of the reference collection (see Figures 4.7, 4.9, 4.10, and 4.11), and a medullary area above the mean growth of the reference collection (see Figure 4.8).

The mean Z-scores for appositional growth of the femur indicate that there were greater growth deficits in the appositional growth of the femur among children from the Islamic Period than among children from the Christian Period; although, based on the Mann-Whitney U and unpaired t-test results, these differences did not reach statistical significance (see Table 4.5). While children from both periods experienced appositional growth deficits of their femora, in the Islamic Period, the cortical bone was typically thinner for age than in the Christian Period, because the total area of their femora were generally smaller for age, and the medullary area of their femora were generally larger for age (see Table 4.5).

Due to the small sample sizes, it was not possible to subdivide the sample by age group into those at and above age two, and those below age two. However, a slight trend can be seen in the SGP wherein there were greater growth deficits among the children below age six for both Medieval populations (see Figures 4.7 to 4.11). Above age six, the measurements were typically much closer to the mean expected growth of the reference population (see Figures 4.7 to 4.11).

Table 4.5 Sample size (n), mean (x), and standard deviation (SD) for femur midshaft Z-scores, by time period. A Mann-Whitney U test and an unpaired t-test compare the Islamic and Christian Periods.

Femur Midshaft Z-scores with Denver Growth Study Data													
Femur Cortical Measurement	Total			Islamic			Christian			Mann-Whitney U test		Unpaired t-test	
	n	x	SD	n	x	SD	n	x	SD	z	p	t	p
Total Area	13	-0.81	1.28	5	-1.32	0.84	8	-0.50	1.46	-1.025	0.354	1.133	0.282
Cortical Area	13	-2.38	2.21	5	-2.75	1.80	8	-2.14	2.52	-0.439	0.724	0.468	0.649
Medullary Area	13	1.02	0.70	5	1.19	0.98	8	0.92	0.50	0.293	0.833	0.664	0.520
Mediolateral Cortical Thickness	13	-3.30	1.82	5	-3.82	1.99	8	-2.98	1.75	-0.586	0.622	0.800	0.440
Anteroposterior Cortical Thickness	13	-2.37	2.64	5	-3.43	3.25	8	-1.72	2.14	-0.878	0.435	1.154	0.273

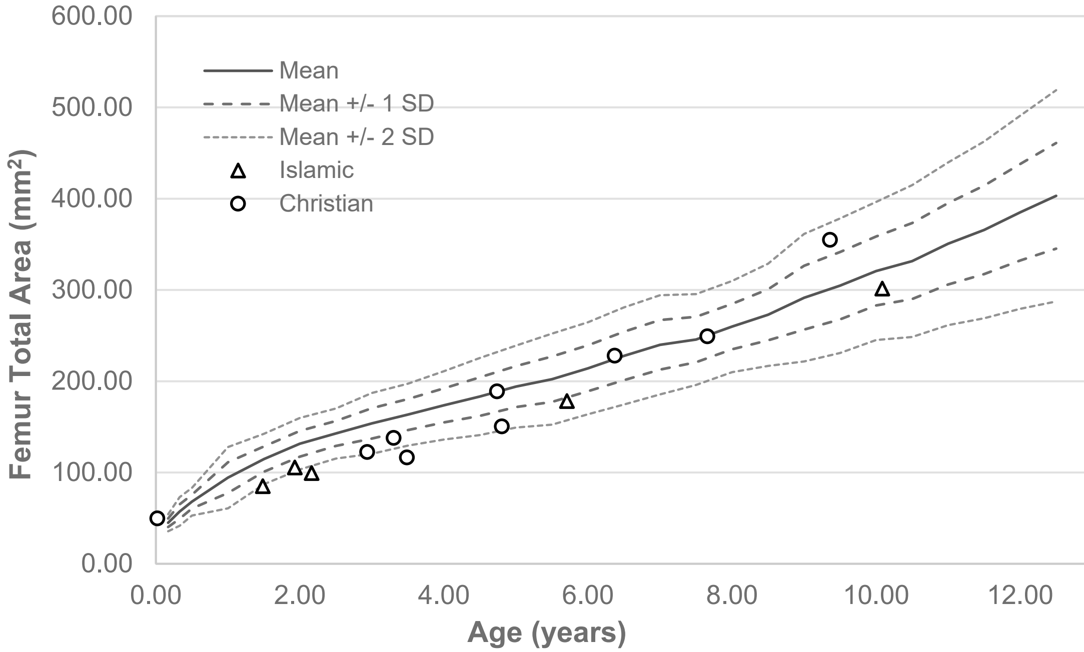

Figure 4.7 **Scatterplot of the total area of the femur for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

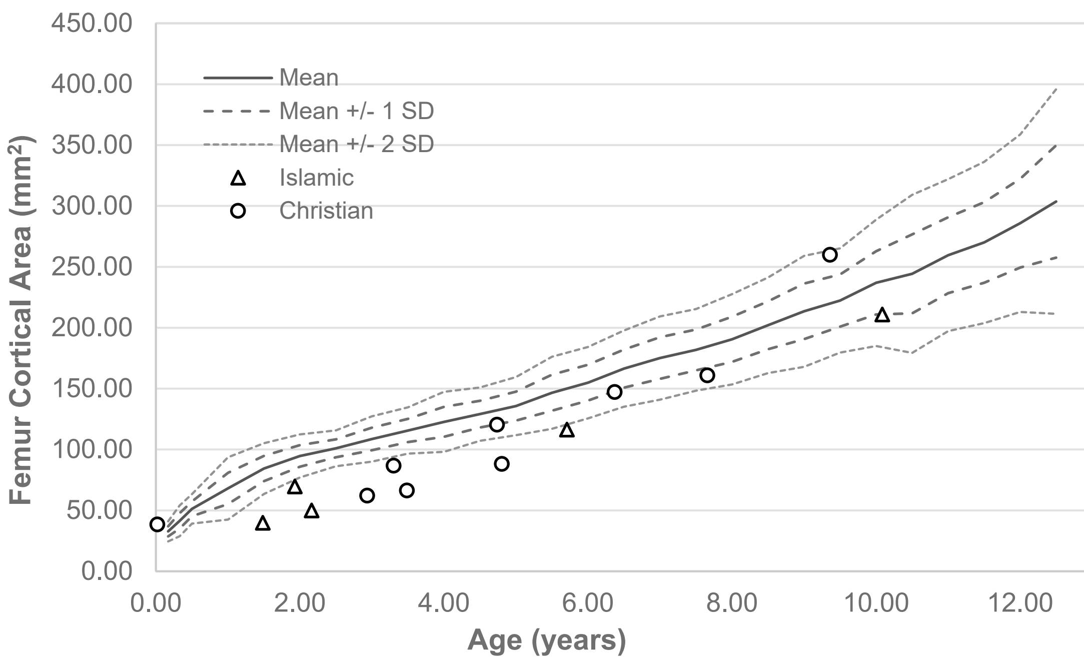

Figure 4.8 **Scatterplot of the cortical area of the femur for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

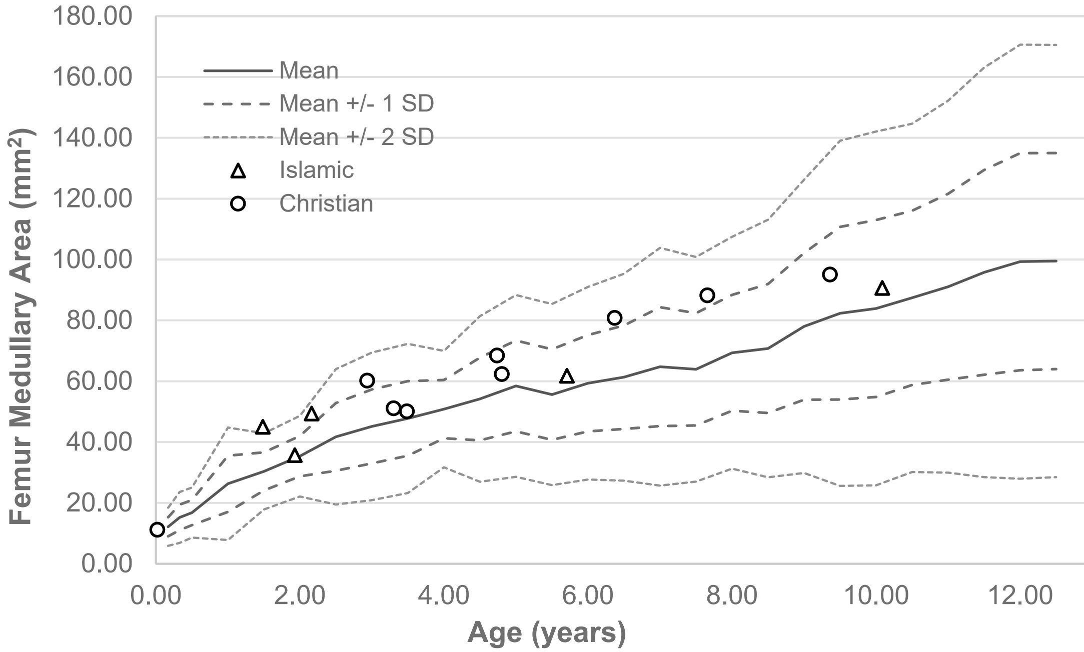

Figure 4.9 **Scatterplot of the medullary area of the femur for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

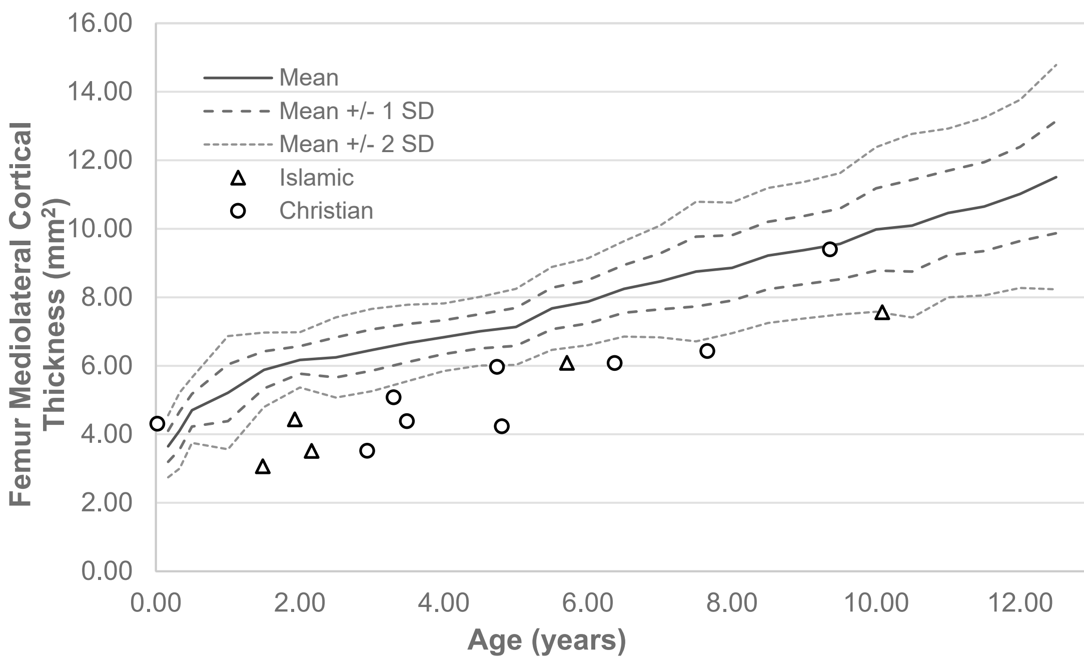

Figure 4.10 **Scatterplot of mediolateral cortical thickness of the femur for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

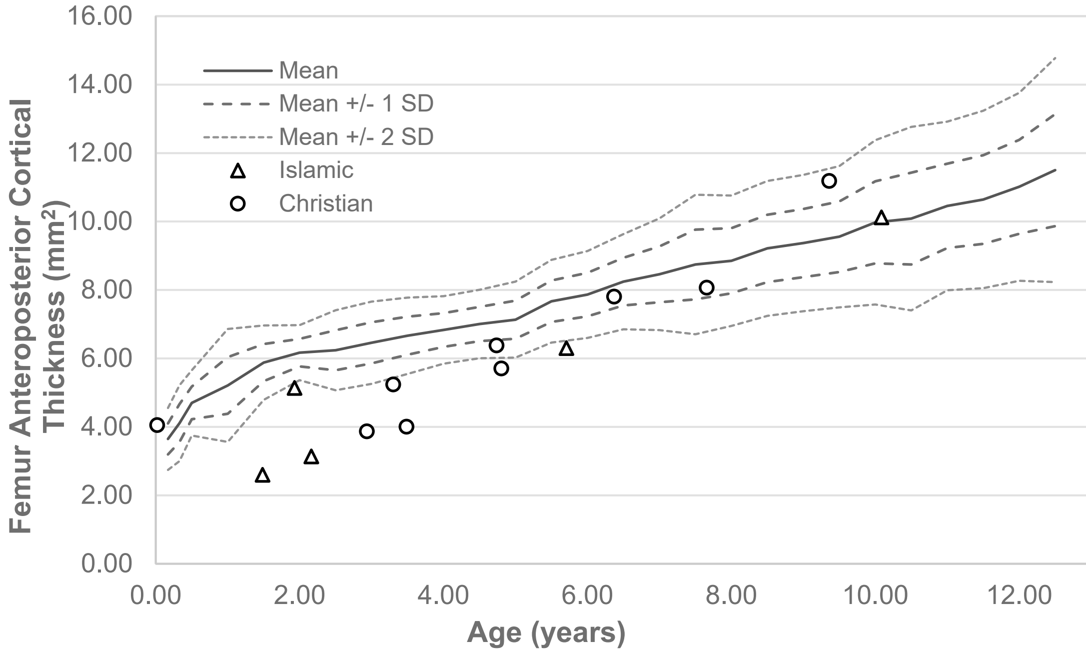

Figure 4.11 Scatterplot of anteroposterior cortical thickness of the femur for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

4.2.3. Humerus Appositional Growth Analysis

The Z-score means of the total area, cortical area, mediolateral cortical thickness, and anteroposterior cortical thickness of the midshaft of the humerus for the total sample were typically small for age when compared to the mean expected growth (see Table 4.6). Overall, the mean Z-scores for the cortical area (x=-2.16), and the anteroposterior cortical thickness (x=-2.13) for the total sample had a Z-score of less than -2, indicative of stunting. As seen in the SGP (Figures 4.12, 4.13, 4.15, and 4.16), the total area, cortical area, mediolateral cortical thickness, and anteroposterior cortical thickness at the midshaft of the humerus were smaller for age for most individuals when compared to the mean growth of the reference population. The mean Z-score for the medullary area of the humerus, for the total sample (x=0.12), was within one standard deviation of the mean expected growth of the reference collection. The growth of the medullary area of the Medieval humeri was similar to the growth of the medullary area of the reference collection. In the SGP for the medullary area (Figure 4.14), most individuals from both periods were within one standard deviation of the mean expected growth. The medullary area for age was the only growth variable for the total sample that was not statistically different from zero when a one-sample t-test was conducted (t=0.534, p=0.599). For the remaining appositional growth variables of the humerus, one sample t-tests confirmed that the mean Z-scores for total area, cortical area, mediolateral cortical thickness, and anteroposterior cortical thickness of the total sample were statistically different from zero and, thus, statistically different from the mean growth of the reference population (total area: t=3.561, p=0.002; cortical area: t=5.530, p=0.000; mediolateral cortical thickness: t=4.513, p=0.000; anteroposterior cortical thickness: t=6.217, p=0.000).

In general, there were greater growth deficits in the appositional growth of the humerus in the Islamic Period than in the Christian Period (see Table 4.6). Overall, the mean Z-scores for the appositional growth of the humerus indicate that the children from the children from both periods had humeri with a similar total area at the midshaft, but the Islamic Period children had slightly wider medullary cavities, and thinner cortical bone than the children from the Christian Period. Based on the Mann-Whitney U and unpaired t-test results, the differences in the medullary area and cortical bone thickness had not reached statistical significance (See Table 4.6).

Due to the small sample sizes, it was not possible to subdivide the sample by age group into those at and above age two, and those below age two.

Table 4.6 Sample size (n), mean (x), and standard deviation (SD) for humerus midshaft Z-scores, by time period. A Mann-Whitney U test and an unpaired t-test compare the Islamic and Christian Periods.

Humerus Midshaft Z-scores with Denver Growth Study Data													
Humerus Cortical Measurement	Total			Islamic			Christian			Mann-Whitney U test		Unpaired t-test	
	n	x	SD	n	x	SD	n	x	SD	z	p	t	p
Total Area	21	-1.29	1.66	7	-1.35	1.52	14	-1.25	1.78	0.261	0.799	0.127	0.900
Cortical Area	21	-2.16	1.79	7	-2.52	1.65	14	-1.98	1.89	0.448	0.689	0.642	0.529
Medullary Area	21	0.12	1.03	7	0.47	0.66	14	-0.06	1.15	-1.045	0.322	1.121	0.276
Mediolateral Cortical Thickness	21	-1.95	1.98	7	-2.67	1.56	14	-1.59	2.11	1.343	0.197	1.195	0.247
Anteroposterior Cortical Thickness	21	-2.13	1.57	7	-2.13	1.67	14	-2.13	1.59	0.067	1.000	0.076	0.941

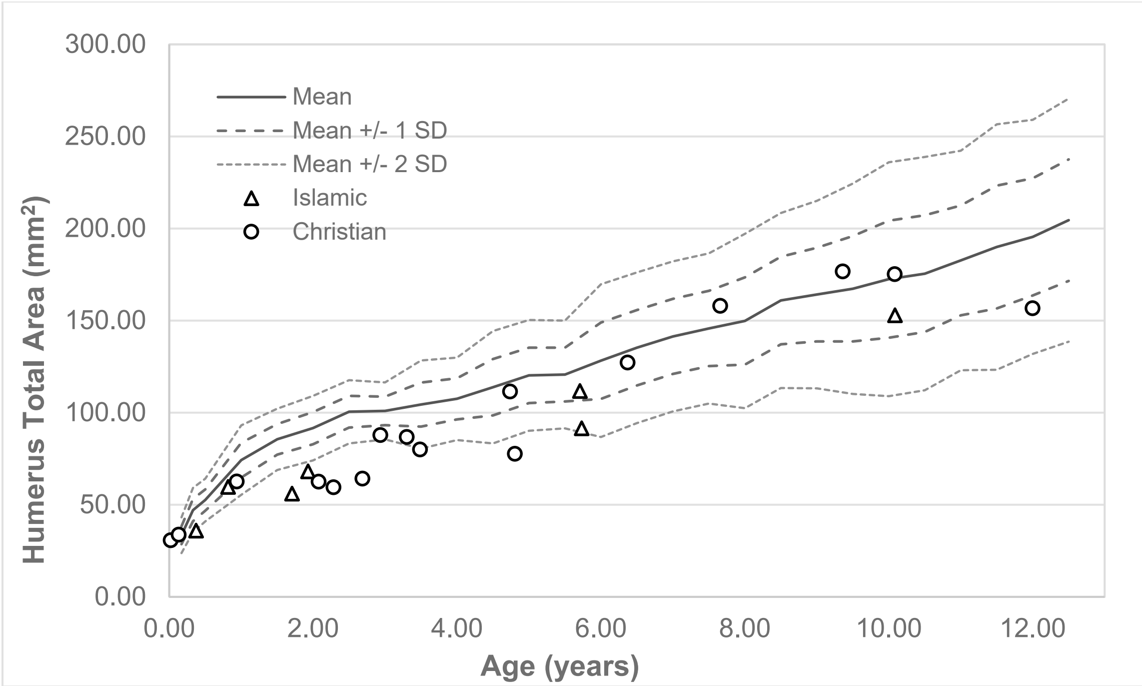

Figure 4.12 **Scatterplot of the total area of the humerus for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

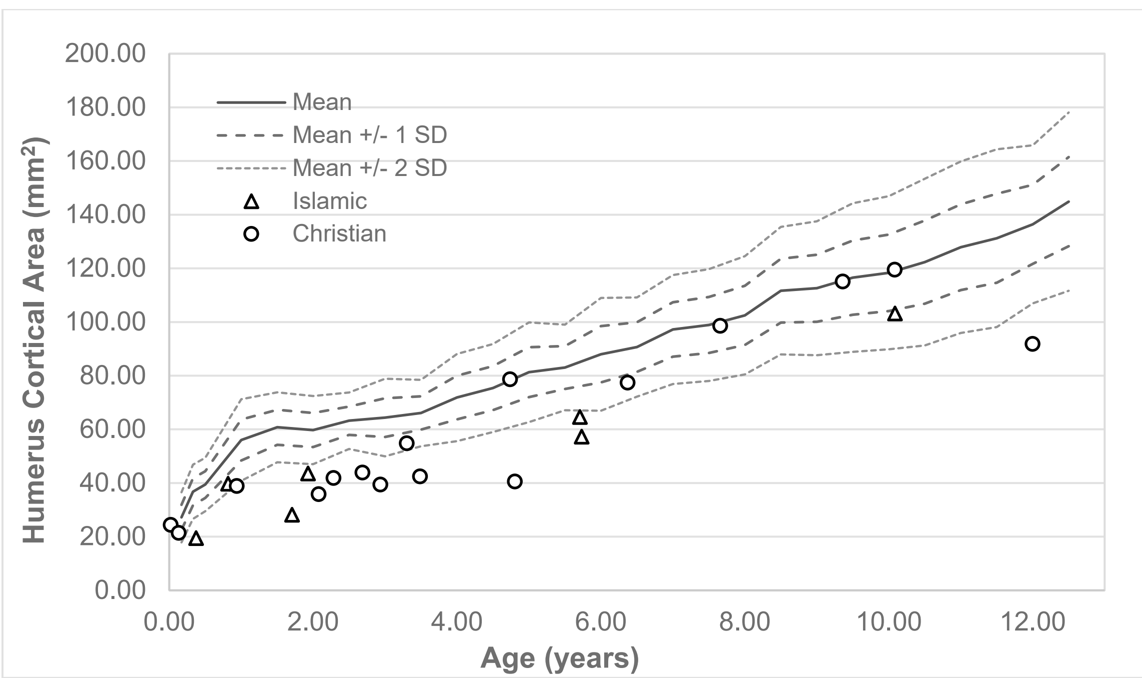

Figure 4.13 **Scatterplot of the cortical area of the humerus for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.**

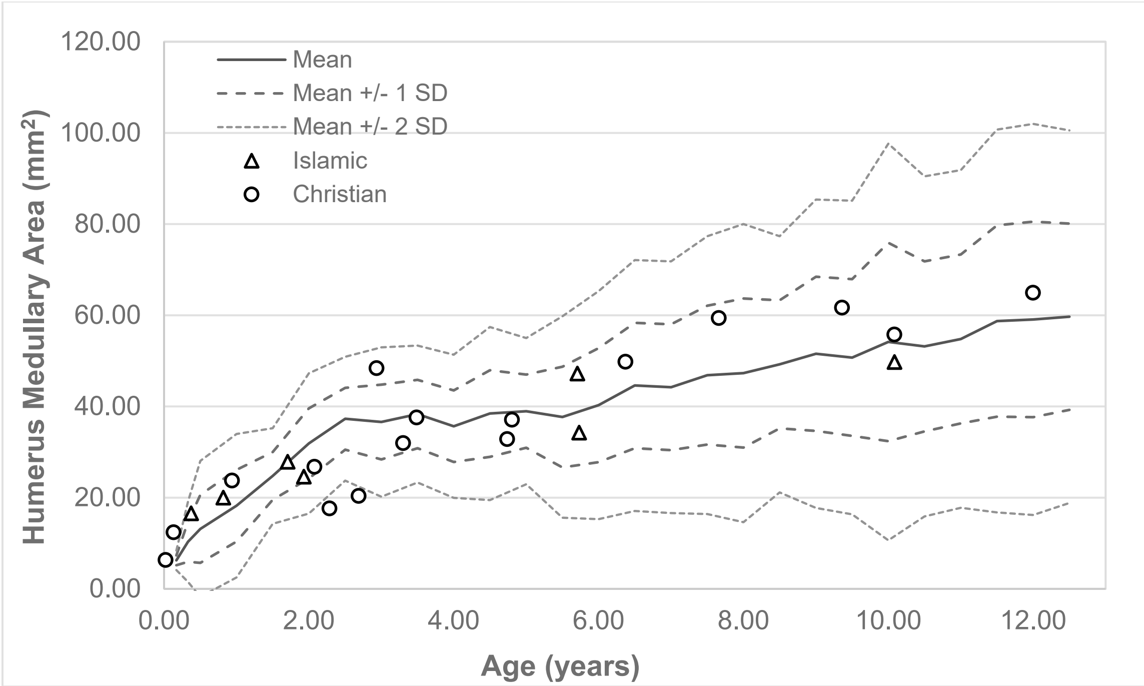

Figure 4.14 Scatterplot of the medullary area of the humerus for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

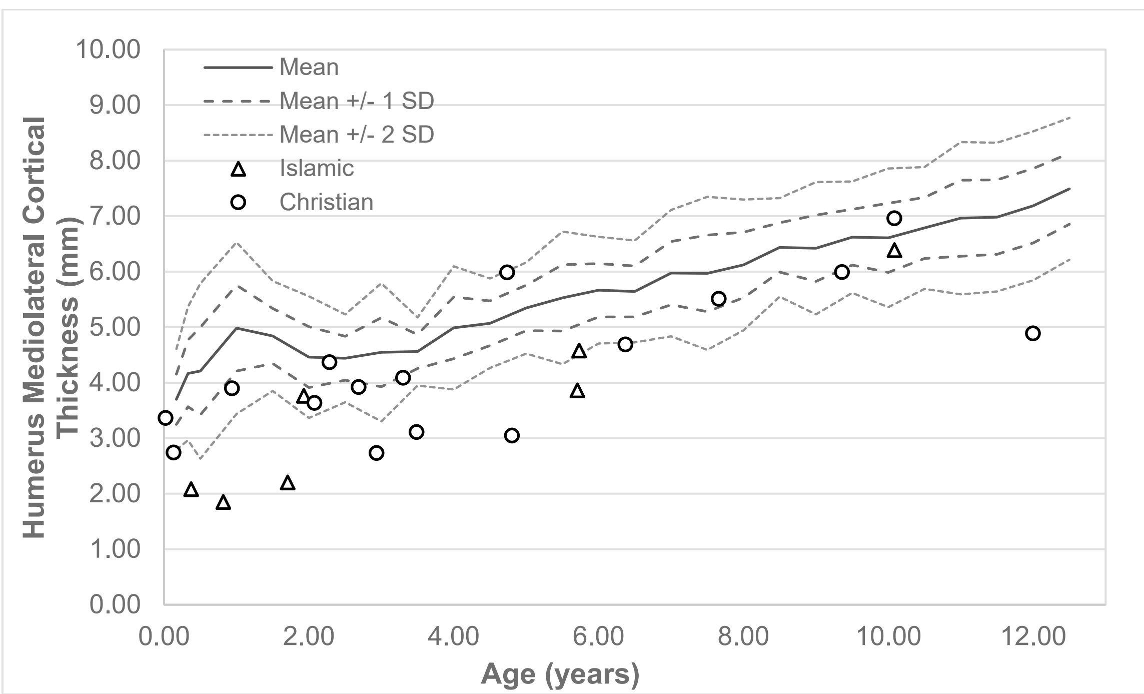

Figure 4.15 Scatterplot of the mediolateral cortical thickness of the humerus for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

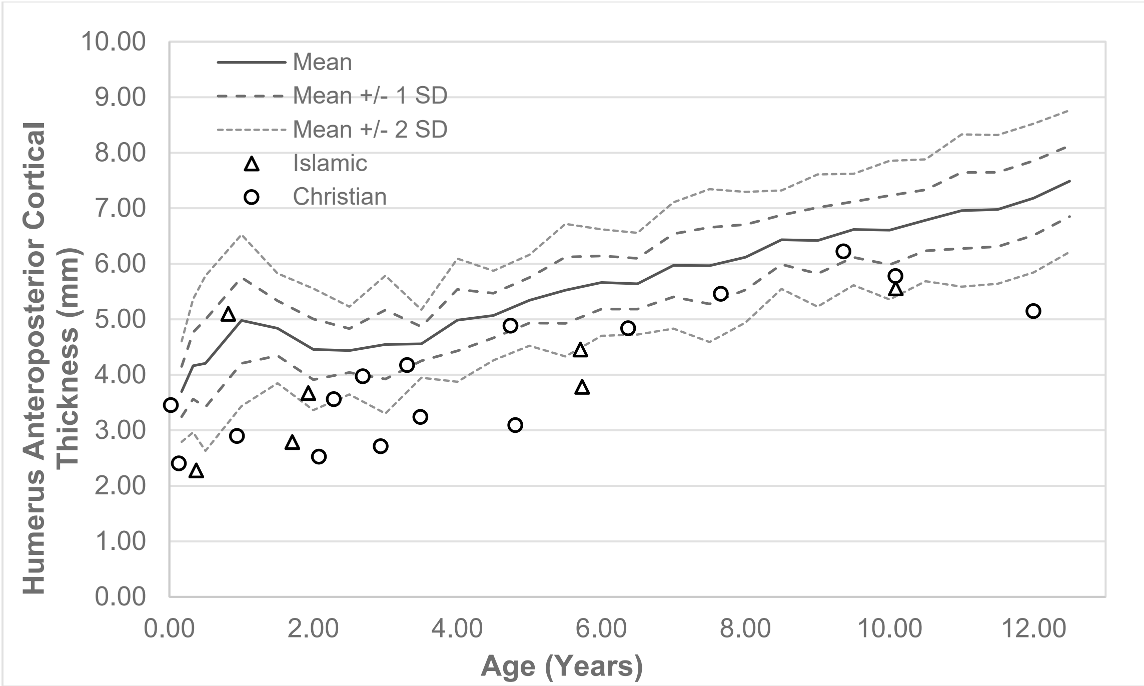

Figure 4.16 Scatterplot of the anteroposterior cortical thickness of the humerus for age of the Medieval Islamic children and Medieval Christian children, compared to the Denver Growth Study.

4.3. Comparison of Linear Growth and Femur Appositional Growth Between the Medieval Algarve and Santarém Populations

4.3.1. Comparison of Linear Growth Between the Algarve and Santarém

In general, the Islamic Period children in the Algarve had greater growth deficits than the Christian Period children, while in Santarém, the Christian Period children tended to have greater growth deficits for age than the Islamic Period ones. However, these differences were only statistically significant for radius length in the Algarve, otherwise, there were no statistically significant differences in the linear growth of the long bones between the periods within each region.

Overall, there were greater growth deficits for the linear growth variables for the total sample from Santarém (growth data obtained from Gooderham 2018) than for the total sample from the Algarve (see Table 4.7). However, based on the results of unpaired t-tests, the differences in growth between each region for the total sample did not reach statistical significance.

When subdivided by period, greater growth deficits were generally observed in the Islamic Period children from Santarém than among the Islamic Period children from the Algarve (see Table 4.7). Overall, the unpaired t-tests results indicate that the differences in growth between the Islamic Period populations of each region did not reach statistical significance (see Table 4.7).

Greater growth deficits were generally observed among the children from the Christian Period in Santarém than among the Christian Period Children from the Algarve (see Table 4.7). However, the only growth variable to show a statistically significant difference in Z-scores for long bone length between regions in the Christian Period children was the radius. The unpaired t-tests for the other long bones indicated that the differences in growth between the Christian Period populations of each region did not reach statistical significance. The mean Z-scores for long bone length in the Santarém children were below -2 for the radius (x=-2.30), femur (x=-2.52), and tibia (x=-2.64), indicating they experienced growth stunting (see Table 4.7). In contrast, none of the mean Z-scores for the long bone length of the Algarve children was below -2, though they were smaller for age than the mean expected growth of the reference collection (see Table 4.7).

Table 4.7 Sample size (n), mean (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 Length Z-Scores								
Long Bone	Algarve			Santarém			Unpaired t-test	
	n	x	SD	n	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

4.3.2. Comparison of Femur Appositional Growth Between the Algarve and Santarém

In the Algarve, the Islamic Period children tended to have greater appositional growth deficits but, in Santarém, Christian Period children tended to have greater growth deficits. However, the differences between the growth of the children between periods within each region was not statistically significant.

There was a similarity in the cortical area for age between regions, but differences in total area and medullary area for age between regions, indicating that the medieval children from each region experienced different environmental stressors leading to differences in their appositional growth patterns. Based on the unpaired t-tests, the differences in growth between regions for the total area, medullary area, and mediolateral cortical thickness for the total sample were statistically significant, but differences in the growth of the cortical area for age did not reach statistical significance (see Table 4.8). The children from Santarém typically had a smaller total area of the femur at the midshaft than the children from the Algarve (see Table 4.8). However, the children from the Algarve typically had a smaller cortical area, thinner cortical bone, and a wider medullary cavity for age than the children from Santarém, indicating that, overall, the Algarve children had greater appositional growth deficits.

When subdivided by period, 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 the Islamic Period children from Santarém (see Table 4.8). Based on the unpaired t-tests, the differences in the total area and cortical area of the femora between regions did not reach statistical significance; however, the differences in the medullary area and mediolateral cortical thickness did (see Table 4.8). This finding indicates that most of the differences in the appositional growth of the femur in the Islamic Period between regions were because of the enlargement of the medullary area of the femur among the children from the Algarve.

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 (see Table 4.8). Based on the unpaired t-tests, the differences in cortical area, and mediolateral cortical thickness did not reach statistical significance; however, the differences in the total area, and medullary area did (see Table 4.8). This finding indicates that 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 for age of the medullary area of the femur at the midshaft among the Algarve children.

Table 4.8 **Sample size (n), mean (x), and standard deviation (SD) for femur midshaft Z-scores, for the total, Islamic, and Christian, Medieval samples. An unpaired t-test compares the Algarve and Santarém samples.**

Femur Midshaft Z-Scores								
	Algarve			Santarém			Unpaired t-test	
Midshaft Measurement	n	x	SD	n	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

Chapter 5. Discussion

5.1. Growth Trends and Interpretation

Overall, the comparison of the linear and appositional growth variables indicates that the growth of Medieval children from the Algarve was similar between the Islamic and Christian Periods. This finding is consistent with the Gooderham (2018) growth study which also found a similarity in the growth of the Medieval children between the periods, suggesting that similar studies in additional regions will likely reveal similarities in the growth of the Medieval children between the periods as well. This finding indicates that there were few differences in the social and physical environment that would have had a differential impact on the growth trajectories of the children from different periods.

Though the differences in the growth of children from one period to the next were not found to be statistically significant, in Gooderham (2018), it was concluded that the children from the Christian Period in Santarém had slightly more stressful socio-environmental conditions, as their growth was slightly more delayed than those from the Islamic Period, suggesting that the Islamic Period was slightly more favourable environment for the growth of children. In the current study, slightly greater growth deficits were observed among the children from the Islamic Period (although these differences were only statistically significant for the radii), contradicting the idea that the socio-environmental conditions of the Islamic Period were more favourable for the growth of children. The finding that the appositional growth of the Medieval children within each period was statistically different between the Algarve and Santarém samples, while there were no statistically significant differences in the appositional growth of the Medieval children between the periods within each region, suggests that regional differences in the bio-social environment had a more significant impact on child growth than the differences associated with the political transition between the periods.

5.1.1. Linear Growth Trends in the Algarve

The Z-score means for the Medieval Islamic and Christian Period populations for all the linear growth variables were statistically smaller than the expected growth for age of the reference collection. The small size of the Medieval juveniles' long bones suggests that there were more extrinsic sources of biological stress throughout the

Medieval Era than there were among the children from the Denver Growth Study. Understandably, many of the social determinants of health – such as adequate nutrition, the availability of clean water, the sanitation of living spaces, medical care, and a lack of mass-migrations – would likely have been easier to manage for the middle- to upper-class children from Denver in 1915 to 1967, than they would have been in the Medieval Era. Throughout the Medieval Era, medical science lacked a fundamental understanding of nutrition, the mechanisms of the propagation and transmission of diseases, and sanitation; and water sources were often contaminated (Cunha et al. 2017; Knorr et al. 2019; Salas-Salvadó et al. 2006; Silveira 2009). Furthermore, invasions and migrations occurred frequently (Garcia 2015b; Kennedy 1996).

While all long bone Z-score means from the Medieval Populations were small for age, reflecting the extrinsic sources of stress in the Medieval Era, the femur, tibia, and fibula showed greater growth deficits than the humerus, radius, and ulna. This finding is consistent with previous research suggesting that, under harsh environmental conditions, the growth of the bones of the lower limbs are more sensitive to extrinsic factors than the growth of the upper limbs (Bogin et al. 2002; Cardoso 2005; Cardoso 2009; Gooderham et al. 2019; Sciulli 1994). The bones of the lower limbs must grow relatively swiftly over a longer period of time, 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).

When the linear growth of the long bones of the Medieval Islamic and Christian Period children was compared, there were no statistically significant differences in their growth (except in the case of the radius due to the sampling issues discussed in section 4.2); however, the Islamic Period children tended to have slightly smaller Z-scores for long bone length. This finding would seem to contradict the hypothesis that there were greater extrinsic sources of stress in the Christian Period than in the Islamic Period, since the Islamic Period children had greater growth deficits. However, it is worth noting that the sample size of this study was quite small, and that no statistically significant differences between the Z-score means for long bone length of the Islamic Period and Christian Period were identified for the linear growth variables, except the radius, where the Z-score mean was significantly smaller in the Islamic Period than in the Christian Period.

A few hypotheses might explain the lack of significant differences in long bone growth between the periods. There may have been fewer differences in the social determinants of health between the Islamic and Christian Periods than expected based on the review of the historical and archeological literature and, thus, few statistically significant differences in growth between the periods. Or the impact of the differences in the social determinants of health between periods may be obscured when the Z-scores for long bone length of children of all age groups (those below age two and those at and above age two) are pooled, because environmental differences may have impacted one age group more than the other.

When subdivided by age group (despite the small sample sizes), children below the age of two from the Islamic Period typically had greater growth deficits than the children below the age of two from the Christian Period. On average, the Z-score means for the long bone lengths of children from the Christian Period children was above the mean expected growth, while the Z-score means for the long bone length of the Islamic Period children were typically below -2, indicating stunting (although due to the small sample sizes, these differences were not statistically significant except in the case of the radius). When at the age of two or above, the Z-score means for long bone length became more similar between periods, including those for the length of the radius, indicating that most of the differences in growth observed between the periods were related to differences in the growth of children below the age of two. However, these differences may also simply reflect the sampling biases since there was only often only a couple of individuals to compare for each long bone growth variables below the age of two, and those from the Christian Period were nearer to age zero while some of those from the Islamic Period were closer to age two. The certainty of being able to draw age-related conclusions is therefore low. Increased sampling and examination of those below the age of two from additional sites within the Algarve may help to elucidate whether there is growth differences between the periods among those below the age of two, as there is some historical evidence to support the idea that there were differences in infant-rearing and maternal health or resulting in growth differences between the periods (Gil'adi 1992; Silveira 2009; Toso et al. 2019). However, despite the differences in growth observed, it is well established that infancy was a fragile time across the Medieval world, and infant mortality was high (Gil'adi 1992; Silveira 2009).

Growth differences in infants between the periods may have been influenced by differences in diet and nutrition. Typically, throughout most of the Medieval Era, infants were fed whenever they cried and wanted food, which, based on modern medical literature, is typically eight to ten feedings per 24-hour cycle, allowing infants to maintain an appropriate weight for their age (Browning and Bunge 2009; Haggerty and Rutstein 1999). However, in the Islamic Period, it was believed that children's digestion would be aided by never quite being full after a meal, and parents were advised to only feed their infants two or three times a day so as not to overfeed them (Browning and Bunge 2009; Gil'adi 1992). If these feeding practices were followed, the difference in the amount of milk received by infants during each period could very well account for the lesser growth of infants during the Islamic Period and the greater growth of infants during the Christian Period, as the Christian Period infants would have received more food.

It is also possible that the Christian Period infants may have had longer bones than Islamic Period infants due to differences in maternal nutritional status; women in the Islamic Period may have had less access to protein-rich food than women in the Christian Period. Toso et al.'s (2019) isotopic study of diet in the Islamic Period does suggest that women ate less meat than men, and higher protein intake by mothers during pregnancy has been shown to result in larger infants (Bogin et al. 2007). Adverse environmental conditions and malnutrition during pregnancy and early in the life of a child can lead to reduced bone mineralization and skeletal muscle mass, greater stress response, impaired immune function, low birth weight, and reduced growth, among other growth and developmental outcomes (Bogin et al. 2007; Lewis 2007). If the environmental conditions remained adverse, the growth and developmental stress responses would have worsened (Bogin et al. 2007). Thus, the appearance of undergrown infants could reflect their mother's health (Gowland 2015). Mothers must devote nutrients such as calcium to their fetus and to forming milk after the child is born; if they lack the nutrients and are unable to consume them or to resorb nutrients from their own bones, the child will not be able to receive the nutrients they need (Gowland 2015; O'Brien et al. 2021).

The seeming decline in growth among the Christian Period children at and above the age of two may be explained by the onset of weaning at that age. Prior to weaning, Medieval infants would have received antibodies transmitted through breastmilk, which would have offered them some protection from pathogens (Katzenberg et al. 1996;

Silveira 2009). Furthermore, they would have been exposed to fewer food-borne pathogens (Katzenberg et al. 1996). Once weaning began, however, they would have been exposed to many more food-borne pathogens. For instance, contaminated animal milk can contain bacteria and viruses, which can cause many diseases including brucellosis, cholera, diphtheria, enteroviruses, hepatitis, scarlet fever, tuberculosis, and typhoid fever, among others (Atkins 1992). Exposures to diarrhoeal infections have a known impact on growth as they result in the malabsorption of nutrients (Cameron and Schell 2021). Due to the generally unsanitary conditions and the lack of medical knowledge in the Christian Period, it is reasonable to assume that exposure to new pathogens after weaning could have resulted in growth deficits once weaned. A similarity in exposure to pathogens after weaning might also explain why there were similarities in the growth of juveniles at and above age two between the Medieval Islamic and Christian Periods.

5.1.2. Appositional Growth Trends in the Algarve

Overall, the children from the Medieval Islamic Period experienced greater appositional growth deficits than the children from the Christian Period. However, the Z-score means for all appositional growth variables were not significantly different between periods. The Z-score means for the appositional growth variables indicate that, relative to the reference collection, there were significant appositional growth deficits of the femur and humerus among the children from the Medieval Islamic and Christian Periods in the Algarve. The growth of the medullary area of the humerus was the only exception, having a mean Z-score indicating that the growth of the medullary area was not different from the reference collection. Generally, the Medieval juveniles' femora and humeri had thinner cortical bone for age, resulting from reduced periosteal deposition and, in the case of the femora, increased endosteal absorption.

Prior to puberty, there is periosteal growth and endosteal reabsorption of cortical bone (Bass et al. 2002; Frisancho et al. 1970; U.S. Department of Health and Human Services 2004). During childhood, periosteal deposition is affected by both activity level and nutrient availability, but endosteal remodeling is affected mostly by nutrient availability (Mays et al. 2009; Ruff et al. 2013). Increased activity can lead to reduced endosteal resorption, but new bone is not deposited on the endosteal surface (Kurki et al. 2022; Ruff et al. 1994). Post-puberty, bone is deposited on the endosteal surface

(Bass et al. 2002; Frisancho et al. 1970; U.S. Department of Health and Human Services 2004). Therefore, the endosteal deposition of bone due to increased activity levels to only occurs post-puberty (Kurki et al. 2022; Mays et al. 2009; Ruff et al. 1994). Therefore, any bone loss from the endosteal surface due to harsh environmental conditions during childhood will not be recovered until adolescence. Thus, the severity of bone loss from the endosteal surface is cumulative and not subject to catch-up growth during childhood, unlike linear growth and periosteal growth, even if their environmental conditions have improved (Mays et al. 2009). Periosteal deposition in juveniles tends to be strongly influenced by the need to maintain muscle mass and bone strength and support motor functions (Ives and Humphrey 2020; Ruff et al. 2013). Illness and a lack of nutrients (such as protein, calcium, phosphate, iron, and vitamins C and D) can disrupt both the ability to exercise, and the periosteal apposition of bone, because the body will use its limited energy and resources on survival rather than growth (Bonjour et al. 2012; Brickley et al. 2020; Ives and Humphrey 2020). Furthermore, numerous metabolic diseases resulting from a lack of nutrients, such as vitamin C and iron, can increase the porosity of the bones (Brickley et al. 2020). Depending on the differences in bone apposition, remodeling, and shape as viewed through the cross-sectional geometric properties of the femur and humerus, it is possible to make some assertions about the ways different stressors could have affected the dimensions of the Medieval juveniles' bones based on their activity levels and access to nutrients (Bass et al. 2002; Eleazer 2013; Harrington and Osipov 2018; Ruff et al. 2013).

The mean Z-scores for the appositional growth of the femur indicate that, overall, the growth of the total area of the femur for the total sample at the midshaft was slightly smaller, but relatively similar, to the growth of the reference collection, while their medullary area was larger for age, resulting in thin cortical bone for age. In stressful environments, the external dimensions of bones tend not to be affected, while bone is typically resorbed from the endosteal surface resulting in a reduction in the cortical bone (Mays et al. 2009; Ruff et al. 2013). Bones are a repository for a significant amount of nutrients such as vitamin D, protein, calcium, and phosphate (Ives and Humphrey 2020; Ross et al. 2011). In times of stress, these nutrients are resorbed from the endosteal surface so that they can be used by other systems in the body, causing the medullary cavity to widen. Maintaining the external dimensions of the femur would ensure that muscle attachments were still able to grow normally, and the legs would still be capable of bearing the weight of the individual (Ruff 2003; Ruff et al. 2013). In juveniles, normal mechanical loading due to locomotor development typically encourages a standard pattern of periosteal growth in the femur for age (Ives and Humphrey 2020). Any failure to reach the expected total area for age would indicate illness or nutritional deficiencies (such as a lack of protein, phosphate, calcium, or vitamins) so severe that it slowed periosteal bone deposition, despite growth that should have occurred due to mechanical loading (Ives and Humphrey 2020). Growth deficits in the total area of the femur have been observed in previous studies where juveniles were under nutritional and environmental stress, preventing the deposition of periosteal bone (Gooderham et al. 2019; Ives and Humphrey 2020).

The mean Z-scores for the appositional growth of the humerus indicated that the growth of the total area of the humerus at the midshaft was smaller for age than the reference collection, while the growth of the medullary area was similar to the growth of the reference collection, showing a very different pattern from the appositional growth of the femur. It is possible that the arms were not under as much biomechanical strain in day-to day life as the legs since they do not have to bear the weight of the whole body, so they would not have been required to grow as much externally to support larger muscle attachments (Ruff 2003). Therefore, when under nutritional stress, there may have been a decrease in the rate of bone deposition on the periosteal surface of the humeri, diverting what little nutrients they had away from non-essential structures, and into the growth and maintenance of more crucial bones such as the femur.

The differences in the periosteal growth and endosteal resorption trends of the humerus and femur 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. Generally, the width of the femur increases more than the humerus during childhood due to its role in weightbearing, and the growth rate of the total area of both the femur and humerus is slower than their linear growth (Sumner and Andricchi 1996). Growth deficits in the total area of the humerus and slight growth deficits in the femur indicate that, overall, Medieval children would have been under significant physiological stress disrupting the deposition of periosteal bone. The effects of the delays to periosteal deposition could have been mitigated in the femora due to their role in supporting the weight of the body and increased activity level by comparison to the humerus, encouraging periosteal growth so that muscle attachments and bone strength could be maintained. The need for nutrients to support the femoral periosteal growth likely came at the expense of the endosteal bone of the femur, leading to resorption in the medullary cavity. The humeri would not have been under as much mechanical pressure to grow to support muscle mass if the arms were not as active. Thus, their periosteal growth was not prioritized, given the lack of resources for growth, giving them a smaller total area for age in cross-section.

5.1.3. Growth Trends in the Algarve Compared to Santarém

The Algarve and Santarém were both conquered by Islamic peoples in the early 6th century, later being taken by the Christian forces: Santarém in 1147 AD, and the Algarve region being taken about a century later, between 1240 AD and 1249 AD (Disney 2009; Garcia 2015b). Although Santarém was never a capital of a region, unlike Silves, it was a still a major city with considerable autonomy and wealth due to their placement along the Tagus River and their agricultural prosperity (Gooderham 2018). The Gooderham (2018) growth study of Medieval Islamic and Christian Period children from Santarém, Portugal, found that there were no statistically significant differences in their growth between the periods; a finding very similar to that of this study. However, the overall growth trends of each period were different between regions. Despite overall similarities in the administrative policies, religious beliefs and customs, and child-rearing practices within periods, the differences in growth between the Medieval Santarém and Algarve children are likely reflective of differences in their history of conflicts and conquests, activities, and food resources.

In terms of linear growth, the Medieval children from Santarém typically had greater growth deficits than those from the Algarve during both the Islamic and Christian Periods. Notably, these differences were only statistically significant when the Z-scores for the linear growth of the radii in the Christian Period were compared. For all other long bones, no statistically significant differences in linear growth between the regions was identified.

When the appositional growth of the femur at the midshaft was examined, numerous variables had statistically significant differences in growth between the regions. The finding of more statistically significant differences in growth between the populations for appositional growth than for linear growth is consistent with the observation that appositional growth tends to be much more sensitive to environmental differences than linear growth (Mays et al. 2009). Given that statistically significant differences in appositional growth were found between the regions but not between the periods within each region it suggests that there were few differences in the growth environment of the children before and after the transition within each region.

In both the Medieval Islamic and Christian Periods, the children from the Algarve generally had wider medullary cavities and thinner cortical bone than the children from Santarém. The children from the Algarve tended to have bone resorption from the endosteal surface, while those from Santarém tended not to. During the Islamic Period, children from the Algarve and Santarém both generally had a total area at the midshaft of their femora that were small for their age, but the children from the Algarve had a smaller cortical area at the midshaft of their femora than the Santarém children, although this difference was not statistically significant. In the Christian Period, children from the Algarve tended to have a total area at the midshaft of their femora that was similar to their expected growth, but the children from Santarém tended to have a total area that was stunted for age. Numerous interacting factors could account for the different appositional growth deficit patterns observed between these two populations. Appositional growth is affected by nutrition, activity level, illness, and injuries (Ives and Humphrey 2020; Mays et al. 2009; Ruff et al. 2013). It can be very difficult to tease apart these factors when examining growth, especially in Medieval populations for which dietary, medical, and environmental information is incomplete or unknown.

Generally, mechanical loading encourages periosteal growth of bone in juveniles prior to puberty, and nutritional deficiencies lead to endosteal reabsorption, but illnesses or a lack of nutrients may also lead to delays in periosteal deposition (Himes et al. 1975; Ives and Humphrey 2020; Mays et al. 2009). Therefore, the findings of this study and of the Santarém growth study could suggest that the children from the Algarve were generally more physically active than those in Santarém, thus encouraging 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. Analysis of the cross-sectional geometric properties of the femur and humerus, using the same cross-sectional data already collected to analyse appositional growth, could reveal the level of mechanical loading the bones experienced, helping us to better understand the growth due to activity (Bass et al. 2002; Eleazer 2013; Harrington and Osipov 2018; Kurki et al. 2022).

Periods of starvation were common throughout the Medieval Era in both regions (Garcia 2015b; Gooderham 2018; Worman 2012). Because the remains examined are thought to represent the lower classes, these would also have been the people under the most nutritional stress during hard times. Depending on which nutrients they were lacking – and how severely they lacked those nutrients – it could have led to periosteal growth stunting, or the resorption of bone from the endosteal surface (Himes et al. 1975; Huss-Ashmore 1981; Ives and Humphrey 2020; Mays et al. 2009; Ruff et al. 2013). Some individuals suffering from chronic protein-calorie malnutrition have been shown to have reduced periosteal bone growth, despite normal mechanical loading activities (Himes et al. 1975; Ives and Humphrey 2020). In other cases, environmental pressures to grow despite malnutrition can result in bones which, externally, attempt to meet expected growth values, but which have had bone resorbed from the endosteal surface to compensate for the nutrients they need to support periosteal growth (Ives and Humphrey 2020; Mays et al. 2009; Ruff et al. 2013). Thus, dietary differences between the Santarém and Algarve populations could have led to the differences observed in the appositional growth patterns. The wider medullary cavities and thinner cortical bone for age among the Algarve children suggests that bone was resorbed from the endosteal surface of the femora to compensate for a lack of nutrients available to them. In Gooderham et al. (2019) it is suggested that "stress caused a significant disruption to the normal rate … of periosteal deposition" in the bones of the Medieval children from Santarém. Similar to the environmental factors preventing the lack of linear bone growth, there was a lack of energy and resources available to the Medieval Santarém children to devote to periosteal growth (Gooderham et al. 2019).

Regional and cultural dietary differences in protein intake could account for the some of the differences in the periosteal growth patterns observed. Some isotopic dietary studies have already been conducted in the Algarve and in Santarém (Aceves 2019; González 2019; Leite 2019). A comprehensive study and comparison of the results of these dietary studies may reveal whether there were significant differences in the protein consumption of these populations that could account for the patterns of periosteal growth observed. In the Islamic Period, fish were not considered to be a nutritious meat and were therefore unpopular (except among the lower-classes in coastal areas) (Aceves 2019; García Sánchez 1986; García Sánchez 2011b; Salas-Salvadó et al. 2006). Simultaneously, meat was generally a high-status food, and those of the lower social classes would have consumed less of it than those of the higher social classes (Salas-Salvadó et al. 2006). Thus, the Islamic Period samples from both Santarém and the Algarve may have had a smaller total area at the midshaft of their femora due to having less protein. However, in the Christian Period, fish increased in popularity due to its use as a substitute for meat during times of religious fasting (González 2019; MacRoberts et al. 2020). Being close to the shore and a major shipping route, the people of Cacela and Silves likely benefited from the easy access to sources of marine protein, regardless of class; by contrast, those from Santarém would have had more difficult access to fish and mollusks (although they would have had access to some species from the river), and possibly consumed less protein as a result (Garcia 2015b; Leite 2019). The easier access to more protein might explain why the Christian Period children from the Algarve had wider femora than the other populations.

The regional differences in growth stunting and the lack of significant differences in growth between the Medieval Islamic and Christian Periods within each region highlight the need to better understand the effects of differences in the biosocial environment between the periods and the regions of Medieval Portugal. Overall, growth appears to be related to regional variation in environmental stressors, rather than to the period they were from.

5.2. Limitations and Future Areas of Research

Of over 200 juvenile skeletons examined in Silves and Cacela Velha, only 29 individuals from five of the Medieval Archaeological sites were complete enough to be suitable for this study. Most of the remains were only partially preserved, affecting the overall distribution of age groups per period and site. Therefore, Z-scores of the growth variables were employed to standardise the growth measurements between samples despite the unequal age distributions, by comparing the measurements to the expected mean growth.

Due to the limited sample sizes and the relatively long span of use of the larger sites, particularly Rua 25 de Abril, Largo da Sé, and Largo da Sé – Cisterna, which had burials spanning multiple centuries, it was not possible to subdivide the total sample to see growth trends within the periods themselves in terms of older and younger individuals, or in terms of the early and late Islamic and Christian Periods. It was only possible to observe the larger growth trends from the Islamic Period to the Christian Period. The inclusion of remains from other towns within the Algarve which experienced a similar history of conquest and which shared many cultural elements might have strengthened the study and allowed for the differences in growth between the Islamic and Christian Periods to be made more apparent.

Methodological or sampling difficulties may also be responsible for the finding that there was generally a greater growth deficit among the Islamic Period children (which was only statistically significant for the linear growth of the radius (due to the sampling issues discussed in section 4.2) as the sample populations were small, although there is some historical evidence to support the idea that the Islamic Period would have been more stressful. 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 in 1267, there was generally much more political stability in Portugal (Barros 2004; Garcia 2015b; Oliveira 2017). Furthermore, 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 possible to follow for those who could afford diverse foods, sanitation practices while practiced 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; García Sánchez 1983; Knorr et al. 2019). A certain degree of romanticisation of the past can occur when relying too heavily on written documents that reflect ideals rather than realities, archaeological evidence is often required to corroborate the extent to which "written sources reflect [the] reality for every individual" (Aceves 2019).

An alternative way to examine whether the changes brought on by the Islamic Period were beneficial for society might have been to examine the differences in growth of children from the Visigothic Period to the Islamic Period (Gooderham 2018). Unfortunately, as with the Gooderham (2018) study, there were no examinable skeletons from the Visigothic Period in Cacela Velha or Silves 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 discovery and examination of juvenile remains dating to the Visigothic Period in the Algarve could improve our understanding of how the social and environmental changes of the Islamic Period affected the citizens.

In each period, and across regions, the Medieval Islamic and Christian Period faced considerable socio-environmental stressors. Differences in the growth of Medieval children may not have been observed between periods within each region, but statistically significant differences were observed in the growth of Medieval children between the Algarve and Santarém. This suggests that most of the differences in growth were related to regional differences in the biosocial environment of the children rather than temporal differences between periods. Differences in the size and resources of each town/region may well account for the differences observed. Santarém was a very large urban centre, and Silves was also a relatively large urban centre while Cacela Velha was more rural. Depending on whether children in the city and rural areas were expected to work or what type of physical activities they performed and how strenuous these activities were, their cortical bone growth patterns could be different. Cacela Velha and Silves are also much more coastal than Santarém likely impacting the type of trade goods they received via boat and land, and the types of crops their soils could grow. Some of the samples for the Algarve for the Christian Period were from Cacela Velha, where the remains are expected to be those of rural settlers, while all those from the Islamic Period were urban settlers from Silves. The rural children from Cacela Velha may have had different environment related stressors than the children from Silves, potentially obscuring the results of the comparison between the periods and regions. Further research should investigate the cross-sectional geometric properties of the long bones between the regions to identify any differences in the activity level and nutritional status of children from each location.

Another potentially confounding element in the comparison of the growth of the Santarém and the Algarve children is that the cemeteries of each region's Islamic and Christian Periods did span different centuries. In the Algarve, the Islamic Period sites date from the 9th century to 1249 AD, while in Santarém, the Islamic Period sites date from 714 AD to 1147 AD; Christian Period sites from the Algarve date from 1249 AD to the 16th century, while in Santarém, they date from 1147 AD to 1640 AD (Chanoca 2006c; Gonçalves 2020; Ribeiro and Vieira 2007; Gooderham et al. 2019). Thus, while the periods of each region represent the same religious administrative forces, they do not align perfectly in a temporal sense. Each period took place over hundreds of years, and large-scale events such as invasions, sieges, food shortages, epidemics, and droughts would have occurred at different times between regions. The total sample size of this project and of the Gooderham (2018) study are small and may not be uniformly representative of all the environmental conditions spanning all of the centuries of each period. If more of the juvenile remains happened to come from a time of warfare or famine in one region, versus a time of relative peace and prosperity in the other, it is likely that we would see a difference in their growth between regions.

A lack of statistically significant differences in growth between periods may also be observed if the composition of the population was not radically different from one period to the next. During the conquest, some cities were taken by force, while others were taken through treaties or alliances, leaving the majority of the population in place provided they obeyed and paid tributes to their new governors (Garcia 2015b; Kennedy 1996; Oliveira 2017). Some cities in the Algarve, such as Loulé and likely Silves, maintained a very large Islamic population after the Christian conquest, with many of their religious and cultural traditions being allowed to continue (Barros 2004; Oliveira 2017). Under those circumstances, differences in their growth due to the change in leadership would be minimal. Without the aid of DNA testing, it is difficult to confirm whether the transition from the Islamic Period to the Christian Period resulted in the expulsion of the Muslims and their replacement with Christian Peoples, or whether the population's composition remained largely the same in both periods. If the composition of the population did remain the same, population-related changes in growth may not have been significantly different from one period to the next, simply because there would have been few changes to their diet and behaviours. Over time, Christian influences would have increased, due to pressures from the Christian leaders and an increase in Christian migrants, and converts would have gradually adopted Christian customs and diets. At that stage, differences between the periods may have been more noticeable.

The assumption that the Islamic Period children would have had a more diverse diet might also be incorrect, as the lower classes would not have had access to as many foodstuffs and would have suffered more in times of hardship (Salas-Salvadó et al. 2006). For instance, recipes exist in both the Islamic and Christian Periods for flours made from sources such as roots and acorns, many of which were mildly toxic (García Sánchez 1983; Oliveira Marques 1971; Salas-Salvadó et al. 2006). Because the lower classes from both periods were examined, they would all have been people with less access to food, possibly explaining the lack of significant differences in growth between the periods within each region. The juveniles studied would all have had greater exposure to disease vectors and less access to food, regardless of the period they lived in. Regional differences in growth might be more reflective of how easy it was to forage for food in different regions.

The bioanthropological evidence collected thus far indicates that there was a great deal of similarity in the environmental conditions of the Islamic and Christian Periods within the Algarve, which is not in accordance with a lot of the historical evidence. Having more information about living conditions, epidemics, waste management, diet, funerary details, cause of death, and paleopathology specific to the remains examined would have been useful in interpreting the findings of this study. Many of the information sources about the Medieval living conditions, medicine, and diet of the people buried at these sites were based on other towns in Portugal and Spain that also experienced a transition from the Islamic Period to the Christian Period. Isotopic studies could indicate the source of their diet and whether it was mainly plant-based, meat-based, or marine-based (Aceves 2019; González 2019; Leite 2019). Caries, tooth wear, and dental calculus could indicate the types of foods they consumed (Jiménez-Brobeil et al. 2021; Mitchell and Brickley 2017; Steckel et al. 2005). Paleopathological examination and analyses, including the sampling of soil associated with the remains, could indicate nutrient deficiencies, diseases, parasites, or trauma, which could point directly to sources of environmental stress they were exposed to (Mitchell and Brickley 2017; Steckel et al. 2005). Ancient DNA analysis could indicate whether the remains were male or female, which, in conjunction with stress markers, paleopathology and growth analysis, may shed light on whether there was differential treatment of juveniles based on sex; and whether one sex or another was overrepresented in either population compared to the other. Ancient DNA analysis could also be used to better understand the migration of peoples throughout the Islamic and Christian Empires and to see who settled in the Algarve, and whether the Islamic and Christian Peoples merged with each conquest or were replaced. Each of these might provide additional insights into the reasons for the growth patterns observed between the Islamic and Christian Period children.

Chapter 6. Conclusion

While examining child growth as a proxy for the stress experienced by their whole population, significant linear and appositional growth deficits were observed among the Medieval children from the Algarve when compared to the modern reference collection. Extrinsic stressors such as warfare, disease, malnutrition, and poor sanitation would have put a strain on children throughout the Medieval Era. It was hypothesised 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, and that living conditions would have worsened with the Christian Period due to their reduced dietary diversity, frequent droughts, and increased exposure to disease.

However, this hypothesis was not supported by the findings of this study. Overall, Islamic Period children had slightly greater growth deficits than the Christian Period children, indicating that the Islamic Period children lived in a less favourable social and physical environment for growth. However, this difference in the growth of the Medieval Islamic and Christian Period children was only found to be statistically significant for the linear growth of the radius.

When the growth of the Medieval children from the Algarve was compared to the growth of Medieval children from Santarém, there were no statistically significant differences in linear growth, but many statistically significant differences in appositional growth. 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, the most interesting finding was that there were fewer statistically significant of differences from one time period to another than there were between two regions within the same time period. This finding suggests that regional differences in the environment were more significant than the social, political, and economic differences between periods within each region in shaping the wellbeing of Medieval people.

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