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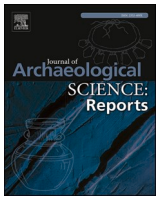

Health and well-being in Medieval Estremoz, Portugal: Uncovering the diet and longevity of a distinct and thriving community

Ana Curto [a,b,c,*], Vanessa Navarrete [a,b,d], Anne-France Maurer [a,b], Cristina Barrocas Dias [a,b,e], Teresa Fernandes [c,f]

[a] HERCULES Laboratory, Paácio do Vimioso, Largo Marquês de Marialva, University of Évora, 7000-809 Évora, Portugal
[b] IN2PAST, Associate Laboratory for Research and Innovation in Heritage, Arts, Sustainability and Territory, 7000-809 Évora, Portugal
[c] Department of Biology, Pólo da Mitra, University of Évora, 7002-554 Évora, Portugal
[d] Consejo Superior de Investigaciones Científicas. Institución Milà y Fontanals de investigación en Humanidades. Arqueologia de les Dinàmiques Socials. Carrer de les Egipcíaques, 15. 08001 Barcelona, Spain
[e] Department of Chemistry and Biochemistry, School of Sciences and Technology, University of Évora, 7000-671 Évora, Portugal
[f] Research Centre for Anthropology and Health, Department of Life Sciences, University of Coimbra, 3000-456 Coimbra, Portugal

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ABSTRACT

The intersection of socioeconomic policies and health in archaeological contexts highlights how ancient societies' structures, practices, and regulations influenced their people's health and well-being. This study investigates the diet and health of a 13th to 15th-century Portuguese town, Estremoz, known for having royal privileges. By analysing human remains for physiological stress indicators and employing stable isotopic analysis to estimate adult diet, the research provides insights into the life of this medieval population. Human remains (141 skeletons: 72 under 15 years old; 69 over 15 years old) from Rossio Marquês de Pombal (13th – 15th centuries) were analysed and faunal remains (N = 171) and bone collagen (N = 13 faunal remains; N = 37 human ribs: 14 females, 18 males, 5 undetermined) were examined to estimate adult diet using stable isotopic composition ($\delta^{15}N$ and $\delta^{13}C$). Skeletal indicators of physiological stress (*cribra orbitalia, cribra cranii*, periosteal lesions, stature and body mass) were assessed to infer overall health. The diet was relatively uniform ($\delta^{13}C\ \bar{x} = -18.3 \pm 0.46$ ‰; $\delta^{15}N\ \bar{x} = 10.9 \pm 0.77$ ‰) with some outliers, mostly male, suggesting that there might have been outsiders in Estremoz attracted by the privileges given to its inhabitants. The low and non-severe frequency of physiological stress, particularly in females, indicates a good quality of life without major nutritional deficits. These findings illustrate how bioarchaeological studies can reveal the impact of social dynamics and cultural influences on past health.

1. Introduction

The intersection of socioeconomic policies and health highlights the importance of a holistic approach to policy-making. Research consistently shows that comprehensive and inclusive socioeconomic policies are essential for reducing health disparities and fostering a healthier society (e.g. Barakat & Konstantinidis, 2023; Marmot, 2005). While the effects of these policies on health are well-documented in contemporary settings, studying their impacts on past populations presents unique challenges. In archaeological contexts, this involves investigating how ancient societies' structures and practices influenced their people's health and well-being. This study aims to explore the diet, health, and well-being of a thriving medieval community in Estremoz, Portugal (13th–15th centuries), known for its royal privileges and distinct social structure. By analysing human remains for physiological stress indicators and using stable isotopic analysis to estimate adult diet, we aimed to understand how socioeconomic privileges shaped well-being. We also examined broader implications of these findings for understanding the interplay between social dynamics and health.

Health is a dynamic state of well-being characterised by a balance in physical, mental, and social domains, where an individual can adapt to changes, manage stress, maintain relationships, and function effectively in daily life (e.g. Huber et al., 2011). Applying this complex term to past populations requires careful interpretation of skeletal indicators that

* Corresponding author.
E-mail address: ana.curto@uevora.pt (A. Curto).

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provide insights into people's lives, activities, and environments. Physiological stress affects the physical remodelling and molecular signalling of bone homeostasis (Pappalardo et al., 2023). Skeletal indicators of physiological stress can reveal the frailty of individuals or populations. Frailty reflects a physiological vulnerability encompassing the cumulative challenges faced throughout life, potentially increasing susceptibility to diseases and premature mortality (e.g., DeWitte, 2010).

Several skeletal indicators can be used to understand health and physiological stress in archaeological populations. *Cribra orbitalia* and *cribra cranii* may indicate anaemia, nutritional deficits and unsanitary conditions (Walker et al., 2009) and can even be regarded as indicators of social and economic inequalities (e.g. Biehler-Gomez et al., 2023). These lesions usually appear in childhood and might not persist in adulthood (Papathanasiou et al. 2018). Inadequate nutrition can indirectly impede physical activity through conditions like anaemia, characterised by symptoms such as weakness, fatigue, and difficulty concentrating (Steckel & Kjellström, 2018). Healed periosteal lesions might offer survival advantages in contrast to individuals with active lesions and those without lesions (e.g. DeWitte, 2014). Numerous studies have shown a link between growth impairment and adverse health outcomes in adulthood (e.g. McGovern, 2014) for contemporary living populations and skeletal samples (e.g. Dewitte & Hughes-Morey, 2012; Kemkes-Grottenthaler, 2005). Some studies observed that short stature within the same population may elevate the risk of mortality during epidemics (Dewitte & Hughes-Morey, 2012). However, an inverse relationship between stature and age at death has also been suggested, with odds of survival beyond 40 years old having been registered to improve approximately 16 % per one standard deviation in bone length (Kemkes-Grottenthaler, 2005). The presence of indicators of physiological stress may also be a sign of good general health as it suggests that, besides having episodes of physiological stress, the individual was able to survive them (e.g. DeWitte & Wood, 2008; Wood et al., 1992; Dewitte & Hughes-Morey, 2012; Curto et al., 2019).

A well-balanced diet is essential for strengthening the immune system's ability to fight off pathogens (e.g., Calder, 2013). In contrast, malnutrition during early life can result in persistent immune deficiencies (e.g., Reitsema et al., 2016) and stress related to the weaning process primarily becomes evident in the post-weaning phase, after breastfeeding has fully stopped (Velte et al., 2023). This highlights the importance of food choices. Underweight and undernutrition are significant contributors to an elevated risk of mortality and low body mass can be used as an indicator of growth deficiencies (Fried et al., 1998). The intricate connection between nutrition and immunity in the context of pathogen response has garnered significant attention in contemporary populations. However, in historic pre-antibiotic societies, this association has been relatively overlooked. Archaeological skeletal collections may hold important lessons at a time when the continued supply of effective antibiotics and vaccines is under threat, as well as the redistribution of pathogens due to climate change. Therefore, bioarchaeological collections are a good model for studying diet and health without the confounding factors of modern medicine.

Stable isotope ratios are frequently used to estimate diet in archaeological populations. Stable isotope analyses also have the potential to aid in studying health in the past (see Reitsema, 2013; Jaouen & Pons, 2016) for an in-depth review of the potential of isotopes beyond diet estimations and mobility), but their potential link to paleopathology is still not well explored. Physiological stress can increase $\delta^{15}N$ in human bone tissue (e.g. Katzenberg & Lovell, 1999; Olsen et al., 2014; Curto et al., 2020) and a higher risk of mortality has been associated with higher $\delta^{15}N$ and lower $\delta^{13}C$ (Redfern et al., 2019), probably representing protein-stressed individuals. Other researchers reported that individuals who had diets based on lower trophic levels died before reaching adulthood (e.g. Kinaston & Buckley, 2017; Dent, 2017). Individuals with signs of generalised infections have shown lower $\delta^{15}N$ values than those without lesions (Curto et al., 2019). This discrepancy may be linked to a diet characterised by reduced animal protein intake, potentially reflecting lower socioeconomic status (Curto et al., 2019). These studies illustrate the complexity of the relationship between stable isotope ratios and health in archaeological skeletal remains.

This study aims to investigate how socioeconomic benefits from royal privileges impacted the diet and health of Estremoz, Portugal's inhabitants during the 13th to 15th centuries. By analysing human remains for indicators of physiological stress and estimating the adult diet using stable isotopic analysis.

2. Geographical and historical context

Estremoz, a town with a medieval foundation near the Spanish border, holds significant historical and strategic importance in Portugal. The urban and architectural study of Estremoz reveals the royal interest in occupying and populating a high, strategic point with vast visual control over the surrounding territory (Liberato, 2012). This royal intervention is evident in the town's planning and substantial growth, even compared to other cities in the region such as Évora and Elvas, situated equidistantly from Estremoz (Fig. 1).

The first written mention of the territory dates to 1211, and the settlement, initially a small cluster with a single church, is noted in 1250 (Silveira, 1797). Estremoz's position relative to the border places it in the second line of defence, serving as an immediate protection point for Lisbon in case Elvas would be taken. This strategic context drew royal attention to the settlement, leading to Estremoz receiving a royal charter in 1258 (Silveira, 1797). Since then, Estremoz experienced exponential growth throughout the late 13th century. Initially, the town occupied the castle area, fortified by 1261. The settlement then expanded significantly with the construction of the Santiago residential quarter, whose parish church was documented in 1279 (Liberato, 2012). In less than two decades, Estremoz became one of the most important urban centres of southern Portugal. The town's strategic importance stems from its location on the Lisbon-Mérida route and at the confluence of several other crucial pathways in southern Portugal (Fig. 1), including direct connections to Santarém and Évora (Liberato, 2012).

Estremoz's development exemplifies the convergence of strategic military planning and urban expansion, highlighting the significant influence of medieval royal priorities on the town's growth. The town's historical architecture and urban layout reflect its pivotal role in regional defence and administrative networks. As a possession of the Crown, Estremoz enjoyed a strong relationship with the monarchs, who granted the town numerous privileges in recognition of its loyalty and services to the Kingdom (Silveira, 1797). Notable privileges included the representation of Estremoz by two delegates in the kingdom's courts and

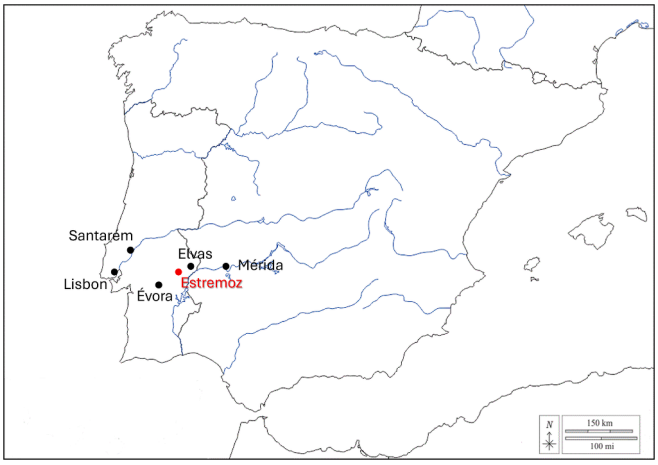

Fig. 1. Map of Iberian Peninsula indicating the location of Estremoz and other cities in the Lisbon-Mérida route.
Adapted from https://d-maps.com/.

exemptions from certain taxes for its inhabitants (Silveira, 1797). Another example was granting privileges to crossbowmen, the construction of the Santiago neighbourhood, providing work and houses for new settlers, and protection from the King against the pressure of other nobles or military orders (Liberato, 2012). However, it is important to note that such privileges may not have been distributed equally, as certain social groups or families with lower status could have had less access to these benefits. Furthermore, monarchs frequently resided in Estremoz, directly overseeing judicial matters, underscoring the town's importance in royal governance during the Middle Ages (Gomes, 1995). In 1478, King *Afonso V* informed the Duke of Bragança about the burning of a man as punishment in Estremoz, the only known case of such punishment in 15th century Portugal (Duarte, 1999). This event indicates the king brought a criminal to Estremoz for a dramatic penalty and temporarily revoked the House of Bragança's judicial privileges (Cunha, 1990). Additionally to this historical record, three skeletons with both hands and feet amputated were found in Rossio Marquês de Pombal (Fernandes et al., 2017). Early medieval chronicles (Lopes, 1970) and recent studies (Duarte, 1999) indicate that hand and foot amputations were inflicted on some supporters of *D. Afonso* who opposed *D. Dinis* during the early 14th century civil war (Lopes, 1970).

Coelho's (2023) research revealed that vineyards and olive groves frequently suffered damage from grazing animals, underscoring the challenges of integrating these agricultural practices. References to orchards, gardens, and grain fields indicate a diverse production of fruits, legumes, and vegetables (Coelho, 2023). In 1797, Silveira (1797) noted the quality and abundance of local food resources sufficient for both consumption and commerce. These included wine, olive oil, honey, vegetables (beans, cabbages, turnips, carrots, radishes, beets), grains (wheat, barley, rye, millet), fruits (grapes, oranges, lemons, cherries, peaches, apricots, pears, apples, pomegranates, quinces), and meat from domestic and wild animals (cattle, pigs, sheep, boar, rabbit, hare, and various birds). Despite being distant from the sea, some river fish were also consumed (Silveira, 1797). Estremoz processed its local resources, as evidenced by grain storage pits, millers, and ovens, confirming bread production in the area (Coelho, 2023). Livestock farming provided numerous resources, primarily for food. Common people primarily consumed pork, while the wealthy had access to beef. Livestock were raised on common lands and collective fields, with pigs often raised freely (Coelho, 2023).

Mobility in Estremoz was expected to be high, driven by trade and military activities. Beyond meat consumption, animals provided raw materials like wool and leather for clothing and writing, enhancing their economic value (Silveira, 1797). Estremoz's white marble, renowned since Roman times, along with its clay and wool, were highly prized commodities (Silveira, 1797). Additionally, records indicate that gold was traded with local goldsmiths (Silveira, 1797). Silveira (1797) documents several significant military movements to Estremoz, such as in 1336, when soldiers from across the kingdom gathered in the town to join King Afonso IV for a campaign into the Kingdom of Castile. In 1382, English soldiers allied with the Portuguese to defend against Castilian forces. By 1384, Dom Nuno Álvares Pereira, leading the campaign against Castile, arrived in Estremoz with over a thousand soldiers (Silveira, 1797).

3. Materials and methods

3.1. Sample

The osteological collection from Rossio Marquês de Pombal in Estremoz (Portugal), comprises 141 individuals from 84 graves. The excavation was an archaeological intervention conducted during construction work in 2001, so the graveyard was not fully excavated, leaving its exact extent unknown. Additionally, our understanding of this archaeological site is limited by the absence of a comprehensive excavation report, with only the graves' drawings available. These individuals, who died between the 13th and 15th centuries (according to radiocarbon dating, see Fernandes & Costa, 2007), were buried with Christian rituals. The predominant burial method involved anthropomorphic graves carved into the rock, with the majority devoid of accompanying grave goods. Some graves were reused, with at least 17 having more than one individual, varying between two and nine individuals in the same grave. These might have been family graves, as most contained adults and non-adults. For example, grave number 51 had the skeleton of an adult male in anatomical connection, the bones of an adult female and seven non-adults between six months and ten years of age.

Faunal remains (n = 171) from Rua de Santo André were analysed to understand the baseline diet better. Rua de Santo André is located less than 50 m from the graveyard at Rossio Marquês de Pombal and is from the same chronology as the necropolis. For the stable isotope analysis, 37 humans and 13 faunal remains (herbivores and carnivores) were selected (Supplement A).

3.2. Biological profile

Age at death was estimated using various methods depending on the individual's age and available anatomical areas (AlQahtani et al., 2010; Scheuer & Black, 2004; Brooks & Suchey, 1990; Buckberry & Chamberlain, 2002). Only individuals with an estimated age at death of 15 years or older were included in this study. Sex was estimated (Bruzek, 2002) only for individuals older than 18 years.

3.3. Diet estimation

3.3.1. Faunal remains

To better understand the baseline diet of the humans, the archaeozoological analysis focused on taxonomic and anatomical representation frequencies, age estimation, and palaeopathology analysis. We quantitatively assessed assemblages using the Number of Identified Specimens (NISP) and Minimum Number of Individuals (MNI), calculated based on the estimated age of specimens, anatomy, and laterality of bones(Lyman, 1994). Age estimation relied on postcranial epiphyseal fusion(Barone, 1999; Silver, 1969). Taxonomic variability was determined by the relative frequency and presence/absence of taxa. The anatomical variability for each taxon was based on the presence/absence of skeletal elements grouped into the anatomical parts of the head, trunk, forelimb, hindlimb, and distal extremity. The location and orientation of each butchering mark were recorded, differentiating between carcass processing marks, to identify the different culinary processes and techniques (Gifford-Gonzalez, 2018). The works of Bartosiewicz et al. (1997) and De Cupere et al. (2000) were used to identify paleopathological lesions.

3.3.2. Stable isotopes

Approximately 1–2 g of human (N = 37) and faunal (N = 13) bone samples were collected with a rotary DREMEL® drill and cleaned to remove debris. For humans, only ribs were sampled by cutting them longitudinally and removing all trabecular bone and superficial residuals. Different bones were selected for the faunal remains from different archaeological levels, each sample from a different adult individual, and only compact bone was sampled (Supplement A).

Collagen extraction was performed using a modified (Longin, 1971) method (Brown et al., 1988); Richards & Hedges, 1999). Approximately 300 to 500 mg of bone demineralised in 10 ml of 0.5 M HCl at 4 °C for about 14 days. The acid solution was changed after one week. Next, the demineralised samples were rinsed with ultrapure water until they reached neutrality and then soaked in 0.125 M NaOH for 20 h at room temperature. Afterwards, the samples were rinsed again to neutrality and gelatinised in 0.01 M HCl at 70 °C for 48 h. To remove impurities, the liquid fraction was filtered using Ezee-Filter™ separators (Elkay Laboratory Products). The solubilised collagen was then lyophilised for

48 h. Subsequently, 0.3 to 0.4 mg of sample was weighed into tin capsules and combusted into CO_2 and N_2 using a Thermo Flash 1112 elemental analyser (EA) coupled to a Thermo Delta V Advantage isotope ratio mass spectrometer (IRMS) with a Conflo III interface, at the Institute of Environmental Science and Technology (ICTA) in Autonomous University of Barcelona (Spain). A two-point calibration was used to quantify bone collagen $\delta^{13}C$ and $\delta^{15}N$, based on 1806-C ($\delta^{13}C$: −14.97 ‰; $\delta^{15}N$: +13.52 ‰) and IAEA600 ($\delta^{13}C$: −27.771 ‰; $\delta^{15}N$: +1‰), while the NIST1577C ($\delta^{13}C$: −17.52 ‰; $\delta^{15}N$: +8.21 ‰; Szpak et al. 2017) was used as a check standard. Precision was 0.06 ‰ for $\delta^{13}C$ and 0.24 ‰ for $\delta^{15}N$, while accuracy was 0.10 ‰ for $\delta^{13}C$ and 0.34 ‰ for $\delta^{15}N$. The total analytical uncertainty was determined to be 0.12 ‰ for $\delta^{13}C$ and 0.42 ‰ for $\delta^{15}N$. Precision, accuracy and analytical uncertainty were calculated according to Szpak et al. (2017).

3.4. Physiological stress

Growth delay in non-adults was assessed by comparing dental age-at-death estimations (AlQahtani et al., 2010) with metric skeletal age estimations (Cardoso, 2005). Dental age is considered more stable, whereas skeletal age is more sensitive to environmental influences (e.g., Lewis, 2006; Liversidge & Molleson, 2004). For each individual, the mean age from the intervals obtained using both methods was calculated. The difference between the dental and skeletal age estimates was then converted into months to facilitate interpretation.

The frequencies of the presence of lesions were calculated for each age group and sex. Periosteal lesions in the tibiae were considered if signs of *periosteum* inflammation were observed, at least markedly accentuated longitudinal striations (score equal or higher than 2; Steckel et al. 2006). These lesions were also differentiated between active and healed (DeWitte, 2014). The presence of woven bone was considered an indicator of an active lesion, while only compact lamellar new bone was classified as a healed lesion. *Cribra orbitalia* and *cribra cranii* were considered present if there were at least small, scattered holes on the bone's surface were observed (score equal to or higher than 1; Rinaldo et al., 2019).

The maximum diameter of the femoral head was used as a proxy for body mass (Zedda et al., 2021), but only in individuals with femora where the epiphyses were fully fused and therefore older than. The tibial length (Bass, 1987) was considered a proxy for stature. We used the tibial length directly as a proxy for stature, avoiding any biases related to the stature estimation equations. The tibia was chosen instead of the femur because it is more sensitive to environmental and nutritional stresses and is associated with lifelong health risks (e.g. Jantz & Jantz, 1999; Bogin & Varela-Silva, 2010).

3.5. Statistical analysis

Descriptive statistics, such as frequency, mean and standard deviations were performed whenever appropriate. Pearson's correlation was used for metric variables and non-parametric tests were used for comparisons between sexes (Mann-Whitney *U* test) and age groups (Kruskal-Wallis rank sum test). Fisher's exact test was used for comparing the proportion of categories (sex and age group) in contingency tables. All statistics were computed in RStudio (R. C Team, 2013; R. Team, 2019) for Windows and $p \leq 0.05$ was considered statistically significant. Graphics were created using the packages ggstatsplot (Patil, 2021), ggplot2 (Wickham et al., 2016) and GGally (Schloerke et al., 2021).

4. Results

4.1. Biological profile

Out of the 141 skeletons examined, 72 were younger than 15 years old, while 69 were 15 years or older, however, it was not possible to estimate an age group for all of them. The age group (Fig. 2) with the highest representation consisted of individuals older than 44 years (N = 31), followed by the 0- to 4-year-olds (N = 26), and those between 5 and 9 years old (N = 20). To address the limited sample size within certain age brackets, individuals older than 15 were grouped into three age categories for stable isotope analysis: 15——30, 31——45, and over 45 years.

4.2. Diet estimation

4.2.1. Fauna remains from Rua de Santo André (Estremoz, Portugal)

Among domesticates intended for consumption, cattle have the greatest quantitative importance, followed by caprines and pigs.

An examination of anatomical frequencies reveals a predominance of skeletal elements from the distal extremities of cattle and caprines. These portions with lower meat content, as well as the heads, were probably discarded during primary butchery practices. Butchering-related modifications were observed in cattle (40 % of remains) and sheep (5 % of remains), indicative of limb separation. These slaughtering patterns suggest the targeting of adult individuals aged over 18–24 months across all analysed animal species. In the case of cattle, the slaughter of individuals older than 24 months old was documented.

Several lesions were noted in cattle remains, specifically in metapodials (n = 2) and phalanges (n = 20). These lesions consist mainly of bone deformations, such as broadening of the medial trochlea and lipping, and the formation of exostoses of varying degrees.

4.2.2. Stable isotope analysis

Raw data from the stable isotope analysis can be found in Supplement A.

All samples in the current study exhibited satisfactory C:N ratios according to DeNiro ((DeNiro, 1985) ranging from 2.9 to 3.6 and Van Klinken (1999) for preserved collagen: C% and N% ranged from 26 % to 44 % and 11 % to 16 %, respectively. Collagen yield ranged from 3.4 % to 19.9 %, with lower values for the fauna (3.4 % to 12.2 %) than the humans (9.8 % to 19.9 %).

For domestic herbivores (N = 9: 3 cattle, 4 caprines; 1 rabbit, 1 equid) the mean $\delta^{13}C$ value is −20.8 ± 0.28 ‰ and the mean $\delta^{15}N$ value is 6.5 ± 0.68 ‰ (Fig. 3). The $\delta^{13}C$ values ($\bar{x}$ = −20.6 ± 0.14 ‰) of the pigs (N = 2) are also relatively close to that of the caprines ($\bar{x}$ = −20.7 ± 0.21) while their $\delta^{15}N$ values ($\bar{x}$ = 7.7 ± 0.35 ‰) are slightly higher (caprines $\delta^{15}N$ = 6.9 ± 0.44 ‰). The carnivores (N = 2; cat and dog)

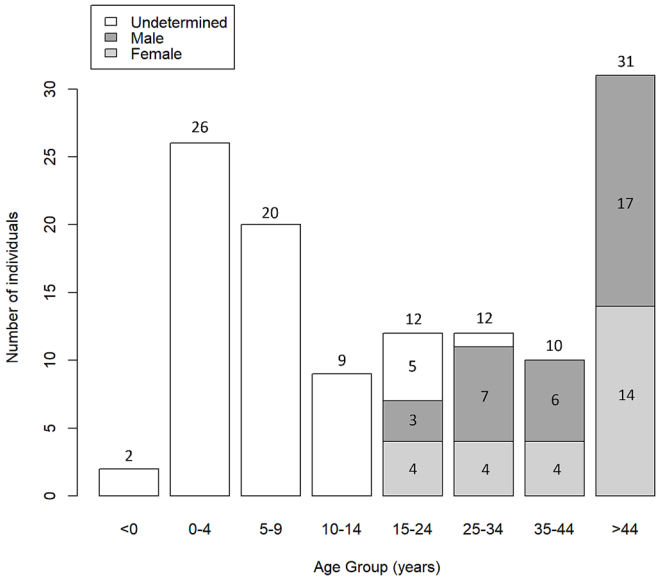

Fig. 2. Number of individuals from Estremoz's collection by age group and sex.

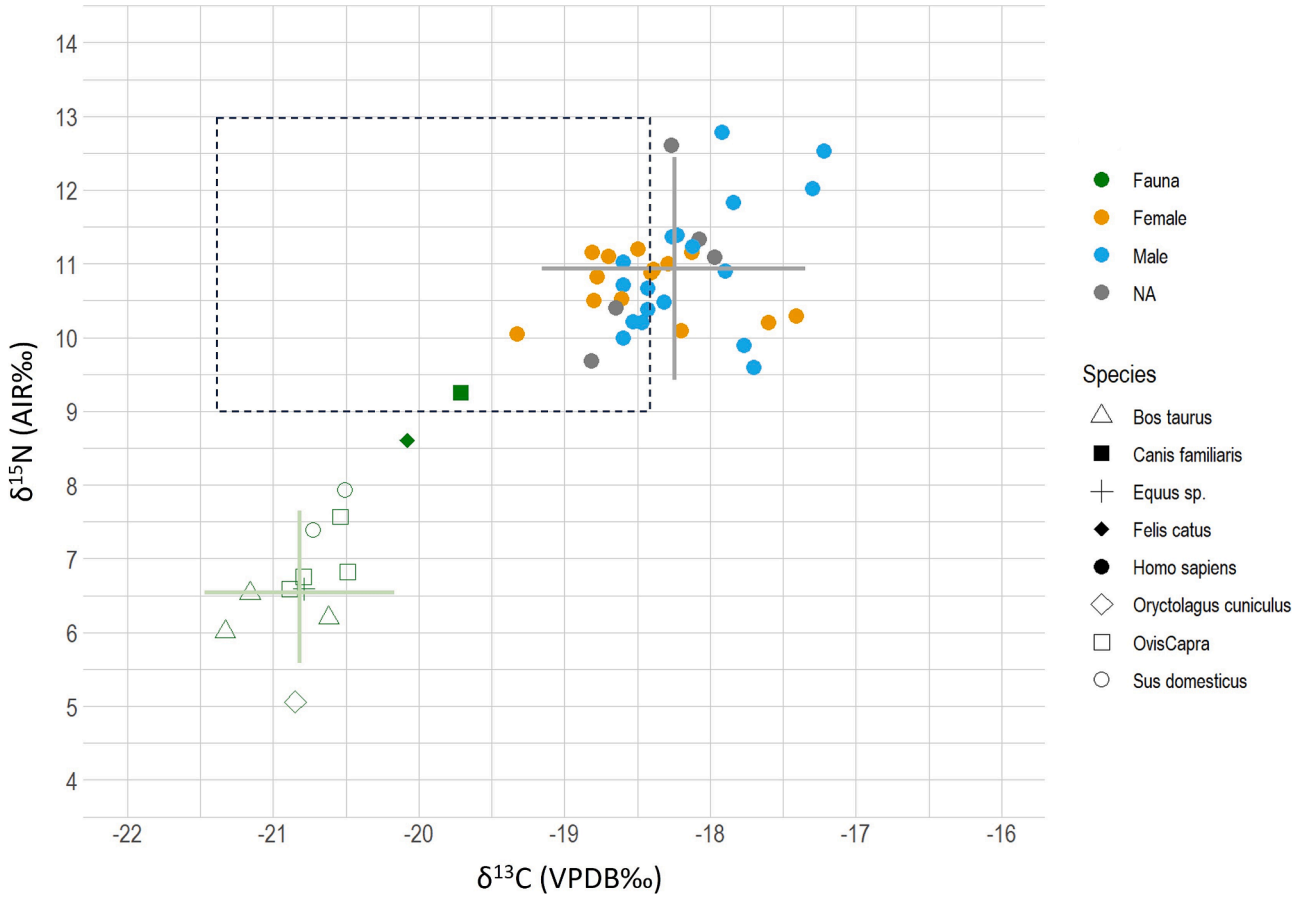

Fig. 3. Stable isotope values of fauna and human bone collagen. Lines indicate the mean and two standard deviations (μ ± 2σ) for humans in grey ($\delta^{13}C = -18.3 \pm 0.46$ ‰; $\delta^{15}N = 10.9 \pm 0.76$ ‰) and herbivores in green ($\delta^{13}C = -20.8 \pm 0.28$ ‰; $\delta^{15}N = 6.47 \pm 0.68$ ‰). The dashed rectangular area indicates expected values for the trophic level increases from the maximum and minimum values of the analysed fauna (except the carnivores). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

yield the highest $\delta^{13}C$ (−20.1 ‰ to −19.7 ‰) and $\delta^{15}N$ (8.6 ‰ to 9.3 ‰) values.

In humans, the mean $\delta^{13}C$ is -18.3 ± 0.46 ‰ (N = 37), ranging from −19.3 ‰ to −17.2 ‰ and the mean $\delta^{15}N$ is 10.9 ± 0.77 ‰ (N = 37) with values from 9.6 ‰ to 12.8 ‰. Most humans have similar stable isotope ratios, apart from a few having higher $\delta^{13}C$ and variable $\delta^{15}N$ (Fig. 3). Females have a mean $\delta^{13}C$ of -18.4 ± 0.50 ‰ (N = 14) and a mean $\delta^{15}N$ of 10.7 ± 0.42 ‰ (N = 14). For males, the mean $\delta^{13}C$ is -18.1 ± 0.43 ‰ (N = 18) and the mean $\delta^{15}N$ is 11.0 ± 0.90 ‰ (N = 18). There are no statistically significant differences between males and females, however, males tend to have higher $\delta^{13}C$ and a wider range of $\delta^{15}N$ (Fig. 4), while females have a wider range of $\delta^{13}C$. The $\delta^{13}C$ and $\delta^{15}N$ values or the three adult age groups are similar (15–30 years: $\delta^{13}C$: $\bar{x} = -18.2 \pm 0.55$ ‰; $\delta^{15}N$: $\bar{x} = 11.2 \pm 1.03$ ‰; N = 12; 31–45 years: ($\delta^{13}C$: $\bar{x} = -18.4 \pm 0.33$ ‰; $\delta^{15}N$: $\bar{x} = 10.3 \pm 0.42$ ‰; N = 6; 45 + years: $\delta^{13}C$: $\bar{x} = -18.3$ ‰ ± 0.48; $\delta^{15}N$: $\bar{x} = 10.9$ ‰ ± 0.63; N = 16). The youngest adults have the most isotopic variation (especially in $\delta^{15}N$) and the middle-aged adults have the least (Fig. 5).

4.3. Physiological stress

Individuals younger than 4 years exhibited a mean growth delay of approximately 4 months ($\bar{x} = -4.2 \pm 6.25$). Those aged 5 to 9 years had a mean growth delay of 15 months ($\bar{x} = -15.0 \pm 12.53$), while individuals aged 10 to 14 years experienced a mean growth delay of 24 months ($\bar{x} = -15.0 \pm 12.53$). Outliers were observed notably in the age group between 5 and 9 years old showing a growth delay of 42 months (Fig. 6).

Cribra orbitalia (Table 1) was present in 35 % (N = 26/74) of the observable skeletons and was more frequent in individuals aged 5 to14 years (age group 5—9: 71 %, N = 10/14; age group 10—14: 75 %, N = 3/4). An increase in the frequency of *cribra orbitalia* is observed from individuals younger than 4 years old (50 %, N = 4/8) to those aged 5 to 14 years (72 %, N = 13/18). This frequency decreases in adults, with individuals older than 34 exhibiting a low prevalence of these lesions (18 %, N = 5/28). Among the adults, *cribra orbitalia* was observed in 19 % (N = 9/47) of the analysed individuals, with a higher frequency in males (24 %, N = 6/25) compared to females (16 %, N = 3/19). More severe *cribra orbitalia*, characterised by more than small scattered holes, was identified in only four adults (9 %, N = 4/47), all older than 30 years, and in nine non-adults (38 %, N = 9/27) aged between 5 and 11 years.

Cribra cranii was observed in only two skeletons, one approximately 5 months old and the other approximately 10 months old, accounting for 17 % of the skeletons aged between 0 and 4 years old (N = 2/12). Additionally, *cribra cranii* was identified in one male aged 25 to 30, representing 2 % (N = 1/58) of the adult skeletons with at least 75 % observable crania (Table 1). Only the one approximately 10 months old showed marked development of the trabecular part of the bone surface, the remaining ones only had small scattered holes.

Active periosteal lesions in long bones (Table 1) were only detected in two non-adults (one approximately three years old and another approximately 13 years old) and in one adult male (2 %, N = 1/57) diagnosed as having madura foot, a fungal infection in the foot (Curto & Fernandes, 2016). Healed periosteal lesions (Table 1) were present in three males (5 %, N = 3/25; females: N = 0/27).

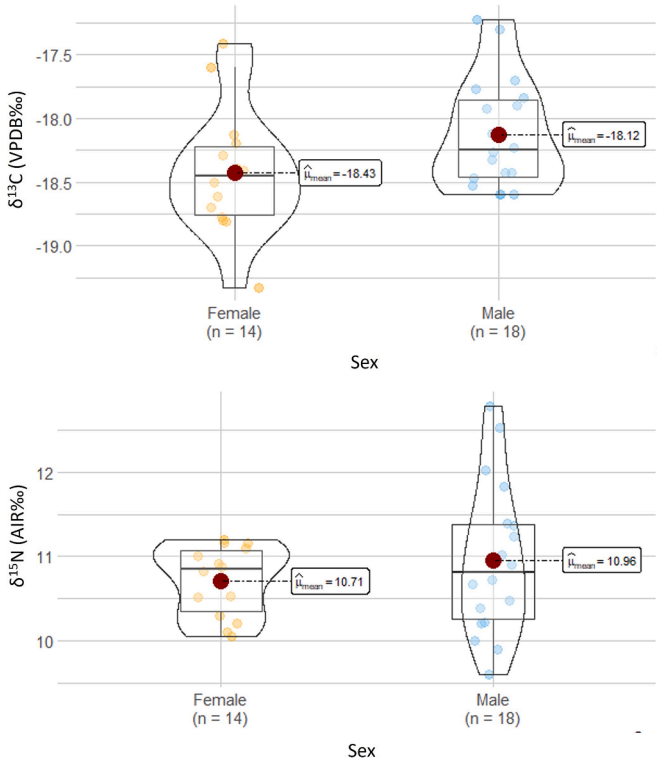

Fig. 4. Violin graphics illustrating stable isotope values ($\delta^{13}C$ and $\delta^{15}N$) by sex.

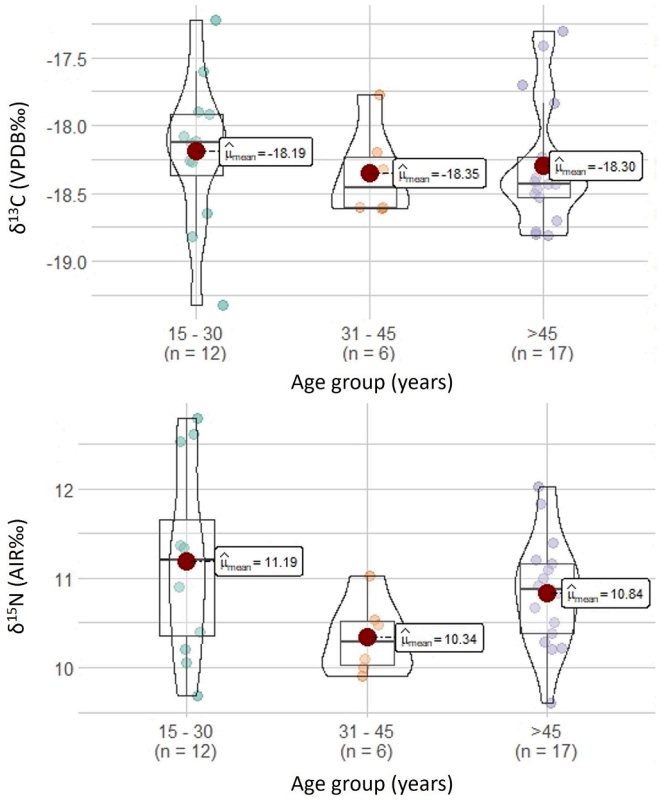

Fig. 5. Violin graphics illustrating stable isotope values ($\delta^{13}C$ and $\delta^{15}N$) by age group.

There are no significant differences between the tibia length (W = 188, *p-value* = 0.76) or the femur head diameter (Table 2) between age groups (W = 142, *p-value* = 0.99) and only the femur head is significantly different between sexes (W = 50, *p-value* = 5.2e-5). There is also no correlation between $\delta^{15}N$ or $\delta^{13}C$ values, with the tibia length or femur head diameter.

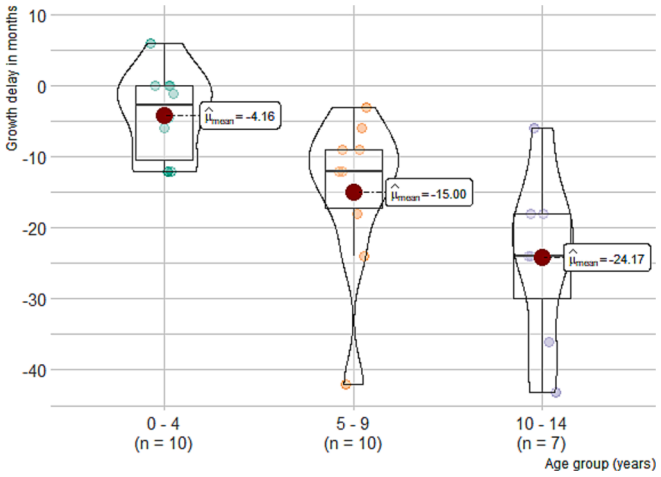

Fig. 6. Violin graphics illustrating growth delay (in months) in non-adults by age group.

5. Discussion

The archaeozoological analysis reveals that cut marks, particularly on cattle and caprines, are indicative of human consumption practices. The high percentage of butchering modifications observed in cattle suggests their significant role in the diet and economy of the Estremoz site during the 13th to 15th centuries. Cattle were more frequently consumed by individuals of higher social status, and the concentration of faunal remains in this specific area implies the presence of a butcher rather than common households, which predominantly raised pigs (Coelho, 2023). The emphasis on limb separation indicates that limbs were being processed and consumed, possibly reflecting trade or storage practices where certain cuts held greater value or practicality for transport.

Most of the animals were slaughtered at an age older than 18–24 months, suggesting that they were kept until reaching an optimal age for meat production or served a dual-purpose role. This is corroborated by lesions found on the cattle's metapodials, indicative of traction work, pointing to an integrated and multifunctional approach to animal husbandry within this medieval community. In the 18th century, Silveira (1797) noted that the oxen from this region, although less corpulent than those in the north, were tougher and more resilient for work. These findings collectively suggest a mixed-use strategy for livestock, wherein animals were raised not only for meat but also for labour, particularly in the case of cattle.

In terms of stable isotope enrichment which occurs along the trophic levels, it is typically expected to be around 1 ‰ for $\delta^{13}C$ (Minagawa & Wada, 1984; Schoeninger & DeNiro, 1984; Schoeninger et al., 1983) and around 3 ‰ for $\delta^{15}N$ (Ambrose & Norr, 1993; van der Merwe & Vogel, 1978). However, it is noteworthy that most of the human samples exhibit a higher level of enrichment (N = 24, Fig. 3), particularly in the case of $\delta^{13}C$. This suggests a dietary intake that may include aquatic protein sources (Chisholm et al., 1983; Chisholm et al., 1982; Tauber, 1981) and/or C_4 plants (Vogel, 1978). Considering Estremoz's geographical distance from the sea (over 130 km in a straight line) and the absence of nearby rivers, a dietary intake of C_4 plants (e.g. millet) appears to be the most plausible explanation for the observed stable isotope ratios, but we cannot exclude the possibility of aquatic protein arriving by trade, especially dry or salted fish. The population of Estremoz shows very similar $\delta^{13}C$ values (−18.3 ± 0.46 ‰) to the contemporaneous late medieval (13th-15th centuries) adults in Beja

Table 1
Frequency of individuals with skeletal indicators of physiological stress by age group and by sex. Statistic tests were applied whenever relevant. N – number of observable individuals; n – number of individuals with the skeletal indicator of physiological stress.

		Cribra orbitalia		Cribra cranii		Active periosteal lesions		Healed periosteal lesions	
		n/N	Frequency	n/N	Frequency	n/N	Frequency	n/N	Frequency
Age Group	<0	–		–		–		–	
	0—4	4/8	0.50	2/12	0.17	1/4	0.25	0/4	0.00
	5—9	10/14	0.71	0/15	0.00	0/10	0.00	0/10	0.00
	10—14	3/4	0.75	0/5	0.00	1/3	0.33	0/3	0.00
	15—24	1/6	0.17	0/9	0.00	0/6	0.00	1/6	0.17
	25—34	3/9	0.33	1/11	0.09	0/10	0.00	0/10	0.00
	35—44	0/6	0.00	0/7	0.00	1/5	0.20	2/5	0.40
	> 44	5/22	0.23	2/25	0.00	0/24	0.00	2/24	0.08
	<4	4/8	0.50	2/12	0.17	1/4	0.25	0/4	0.00
	5—14	13/18	0.72	0/20	0.00	1/13	0.08	0/13	0.00
	15—34	4/15	0.48	1/20	0.05	0/16	0.00	1/16	0.06
	>34	5/28	0.18	0/32	0.00	0/29	0.00	4/29	0.14
	Fisher's exact test	$\chi2 = 15.12$	*p-value* = 1.71E-03	$\chi2 = 8.02$	*p-value* = 0.046	–		$\chi2 = 2.47$	*p-value* = 0.48
	Non-adult	17/27	0.63	2/34	0.06	2/27	0.07	0/27	0.00
	Adult	9/47	0.19	1/58	0.02	1/57	0.02	3/57	0.05
	$\chi2$ test	$\chi2 = 12.586$	*p-value* = 3.89E-04	–		–		–	
	Total all ages	26/74	0.35	3/92	0.03	3/84	0.04	3/84	0.04
Sex	Female	3/19	0.16	0/22	0.00	0/20	0.00	0/20	0.00
	Male	6/25	0.24	1/31	0.03	1/25	0.04	3/25	0.12
	Fisher's exact test	$\chi2 = 0.09$	*p-value* = 0.77	–		–		–	

Table 2
Descriptive statistics of the tibia length (proxy for stature) and femoral head diameter (proxy for body mass) by age group and sex. N – number of observable individuals; SD – standard deviation; 1stQ – first quartile.

			Tibia length					Femoral head diameter				
			N	Mean	SD	Median	1stQ	N	Mean	SD	Median	1stQ
Age group	15—34	F	3	352.3	17.0	353	344.0	3	41.9	2.67	41.1	40.4
		M	8	361.0	25.3	358.5	348.5	12	42.4	2.1	41.9	43.7
	>34	F	9	345.1	16.8	345	338.0	8	46.0	3.8	45.0	41.09
		M	11	359.5	21.9	365	350.5	14	46.8	2.21	46.5	45.6
	Wilcoxon rank sum test		W = 188		*p-value* = 0.76			W = 142		*p-value* = 0.99		
Sex	Female		12	346.9	16.4	349	337.3	16	42.4	2.1	41.9	41
	Male		20	359.4	22.3	361.5	347.3	23	46.3	2.98	46.2	44.3
	Wilcoxon rank sum test		W = 79.5		*p-value* = 0.12			W = 50		*p-value* = 5.185e-05		

(−18.5 ± 0.5 ‰, Toso et al., 2021) located inland about 100 km south. However, their $\delta^{15}N$ values (11.6 ± 0.9 ‰) are slightly higher than those at Estremoz (10.9 ± 0.8 ‰) and marine protein, up to 10 %, may have contributed to the diet of Beja population (Toso et al., 2021). Approximately 10 km from Beja, the late Antiquity population of Monte da Cegonha (Saragoça et al., 2016) also shows similar $\delta^{13}C$ values (−18.4 ± 0.26 ‰). While the $\delta^{15}N$ values of the adults (10.3 ± 0.65 ‰) are lower than those of Estremoz and Beja, Saragoça et al. (2016) did not exclude the consumption of low trophic level fish or fish sauce. It is worth noting that only fauna from Monte da Cegonha was analysed (not fauna from Beja) and the herbivores $\delta^{15}N$ (6.9 ± 0.7 ‰) values are very similar to those at Estremoz.

Most of the individuals analysed in this study exhibit comparable stable isotope ratios, except for a few showing elevated $\delta^{13}C$ (N = 3; $\delta^{13}C$ > −17.5 ‰) and $\delta^{15}N$ (N = 3; $\delta^{15}N$ > 12.5 ‰) values (Fig. 3). This suggests different access to food sources or that these individuals may not be native to Estremoz, considering its historical significance as a crucial thoroughfare connecting Portugal and Castille (Spain) (Liberato, 2008). Males exhibit a broader spectrum of $\delta^{15}N$ values (Fig. 4). Though these differences between sexes are not statistically significant, it is important to consider the context and detailed analysis instead of purely statistical significance, particularly in small sample sizes. These data can still provide important insights into patterns within the population and guiding future research. The broader range of $\delta^{15}N$ values among males might indicate greater variability in their consumption of protein sources, possibly reflecting a mix of higher trophic-level foods (e.g., meat, fish) and lower trophic-level foods. These values may reflect differences in social status, occupation (e.g., soldiers having different diets than civilians), or access to hunting and fishing resources. These stable isotope values ($\delta^{15}N$) might suggest potential sex differences in access to various food sources or, for example, a greater impact of social status on male diets, assuming that higher animal protein intake is linked with socioeconomic status. The outliers with the highest and the lowest $\delta^{15}N$ are males, which might also suggest either a more variable diet for males or the presence of foreign males in Estremoz due to the town's military presence and trade, which likely attracted more male than female outsiders. Estremoz also shows less sexual dimorphism in long bone length than other contemporary Portuguese collections (Curto et al., 2024). The age of menarche, driven by oestrogens, leads to an earlier cessation of growth, contributing to a shorter female stature (Dunsworth, 2020). Consequently, the earlier menarche occurs, the greater the difference in size between the sexes. A lower degree of sexual dimorphism in bone length has been associated with factors such as improved food security and higher female status (Gleeson & Kushnick, 2018). In the case of Estremoz, this reduced dimorphism could also be influenced by the presence of foreign males, which may have altered the average male body size, thus affecting the overall sexual dimorphism observed in the population.

The analysis revealed no significant differences in stable isotope ratios across age groups (Fig. 6). However, the youngest (15–30 years old) and the oldest (>45 years old) individuals exhibit the greatest variability in $\delta^{13}C$ and $\delta^{15}N$ values. The high variability in $\delta^{13}C$ and $\delta^{15}N$ values among the youngest individuals suggests a more diverse diet. This variability is notably influenced by sex, as the three younger

outliers with the highest $\delta^{15}N$ values are males. This pattern supports the hypothesis that young male outsiders were present in Estremoz. The elevated $\delta^{15}N$ values among young males imply greater consumption of protein-rich foods, pointing to potential migration or movement of these into Estremoz, likely associated with military service, trade or attracted to the low taxes. There were several strategies to increase the population at Estremoz, as (Liberato, 2012) discussed. One of them was that all inhabitants of Estremoz would not need to pay taxes. This initiative promoted the migration of people ready to clear up spaces left uncultivated, safe in the knowledge that their work would correspond to extra productivity since it would not be necessary to allocate resources to pay for that benefit (Liberato, 2012). Another example was granting privileges to crossbowmen, who were generally mobilised in towns and cities. A local militia was formed and the Santiago neighbourhood was built, providing work and houses for new settlers (Liberato, 2012). The inhabitants of Estremoz also had protection from the King against the pressure of other nobles or military orders, which may have led to people moving from neighbouring towns. Estremoz's strategic importance and military presence likely attracted young men from various regions, introducing dietary diversity reflective of different geographical and social backgrounds. Strontium stable isotope analysis would help to better understand migration patterns at Estremoz.

Overall, individuals from Estremoz exhibit low frequencies of physiological stress indicators, with most cases showing low severity. It is also interesting to note that the age group with the largest number of individuals was the one over 44 years old (n = 31/122; Fig. 2), even though this is the group that has the largest age range. The age distribution in Estremoz osteological assemblage is unusual, as most archaeological sites from similar chronology show a lower frequency of individuals over 44 years old compared to the preceding age groups (e.g. Curto, 2019; Mangas-Carrasco & López-Costas, 2021). The larger number of older adults suggests that this population might have been relatively healthy, supported by the low frequency of other skeletal indicators of health and frailty. Interestingly, historical records from the 18th century also mention that the people of Estremoz were very healthy with many individuals living to over 80 or even 100 years old (Silveira, 1797).

Growth delay is a cumulative process, where the evidence of disruption increases as exposure to the stressor continues (Hodson & Gowland, 2020). Chronic growth disruption and pathological lesions are well-documented in low-status cemetery samples (e.g., Gowland, 2018). In this study, non-adults displayed little low growth delay (Fig. 6), suggesting that most were not subjected to chronic physiological stress, despite their early deaths. However, it is important to note the ambiguity in defining what constitutes a growth delay, especially when comparing different age groups (e.g., a delay of 6 months versus 6 years) and without knowing the sex of the individuals. Additionally, the methodologies used for age estimation (both dental and skeletal methods) were developed from non-Portuguese collections and different chronological contexts. This discrepancy may partially explain the differences in age estimation based on dental development and long bone length. Chronological age estimation using dental development is generally more accurate for younger infants and children (AlQahtani et al., 2010). Consequently, inaccuracies in age estimations could contribute to errors in assessing growth delays and physiological stress.

Porotic lesions (e.g. *cribra orbitalia* and *cribra cranii*) are considered childhood lesions that might be preserved into adulthood (Aufderheide et al., 1998) and stem primarily from nutritional demands unique to non-adult individuals or anaemia (e.g. Lewis, 2018), malaria (e.g. Gowland & Western, 2012), dietary iron deficiency (e.g. Oxenham & Cavill, 2010), possible parasitic infections (e.g. Djuric et al., 2008; Mangas-Carrasco & López-Costas, 2021), and folate deficiency and rickets (Ortner & Mays, 1998). Despite the ongoing discussion about the aetiology of both *cribra orbitalia* and *cribra cranii,* these lesions are indicators of nonhealthy conditions (e.g. Papathanasiou et al., 2018).

In this study, *cribra orbitalia* (Table 1) was less frequently registered in non-adults (63 %, N = 17/27) than in other skeletal assemblages from the Medieval Iberian Peninsula in NW Spain (79 %, N = 11/14, Mangas-Carrasco and López-Costas, 2021). These lesions are more frequent in the age groups between 5 and 9 years old (71 %, N = 10/4) and 10 to 14 years (75 %, N = 3/4), while Mangas-Carrasco and López-Costas (2021) observed a higher frequency in 13 to 19-year-olds (86 %, N = 6/7) followed by 1 to 12-year-olds (71 %, N = 5/7). The low frequency of porotic lesions (Table 1) in non-adults from Estremoz is even more noticeable in the presence of *cribra cranii* (6 %, N = 2/34), that only affected 2 individuals between 5 months to 1 year old. Mangas-Carrasco and López-Costas (2021) registered *cribra cranii* in 36 % (N = 9/25) of the non-adults, mainly in adolescents (13—–19 years old, 58 %, N = 7/12). These low values of porotic lesions, with more severe cases being even rarer, suggest that the non-adults at Estremoz might not have been exposed to chronic dietary deficiencies (e.g. Lewis, 2018; Oxenham & Cavill, 2010). Poverty is known to severely affect the growth and health of infants (Hodson & Gowland, 2020), so the low physiological stress that the non-adults exhibit supports the hypothesis of an overall good quality of life at medieval Estremoz.

The low frequency of these porotic lesions (Table 1) in individuals older than 15 years, also suggests that the population had sufficient access to a well-balanced diet with adequate iron and other nutrients necessary for healthy bone development and low pathogen pressure. Other collections in the Iberian Peninsula, as in Medieval NW Spain (Mangas-Carrasco and López-Costas, 2021) registered frequencies of *cribra orbitalia* in adults between 54 % to 100 % and *cribra cranii* in 32 % to 51 % of the individuals, while Estremoz registered 20 % and 2 % respectively.

Wang et al. (2023) suggest that adults aged 15 years and older who do not exhibit *cribra orbitalia* tend to have a longer median survival compared to those individuals who do display this lesion. McFadden and Oxenham (2020) suggest that the investigation of *cribra orbitalia* in adults can establish whether childhood health challenges resulting in these lesions are correlated with either frailty or resilience (McFadden & Oxenham, 2020). While the infrequent occurrence of porous lesions may be associated with a good quality of life, it is also plausible that the absence of these markers is linked to diminished survivability among individuals who experienced childhood stress (DeWitte & Wood, 2008; Wood et al., 1992). While this seems to be the case in Estremoz for *cribra orbitalia* (high frequencies in those younger than 15), the same pattern is not observed for *cribra cranii*, which is practically absent across all age groups (Table 1).

Often porotic lesions are more common in females than males (e.g. Mangas-Carrasco and López-Costas, 2021). However, even though the differences are not significant, the opposite was registered in Estremoz. Females appeared to experience lower levels of physiological stress during their developmental years compared to males. This pattern raises two potential interpretations. Firstly, it is possible that females genuinely faced less physiological stress during childhood. Infections and immunity show sex differences in several ways. In general, men tend to experience infections more frequently, while women usually have stronger immune responses and clear infections more quickly. Additionally, pathogens often have greater virulence in men, leading to more severe outcomes (e.g. Fink et al. (2018); Mitchell et al., 2022). Alternatively, the data could suggest that males had a higher survival rate to stress than females. Assuming that females did indeed experience less stress during their early years, this discrepancy may point to differences in the living conditions between the sexes. Such differences could imply that the males grew up under harsher conditions, supporting the hypothesis that they were possibly outsiders to the community. This outsider status could have subjected them to environments or situations that contributed to higher stress levels or different survival pressures during their formative years.

Periosteal lesions are non-specific stress indicators associated with repetitive biomechanical stress (e.g. Franklyn & Oakes, 2015), vitamin deficiencies (e.g. Weston, 2011) and pathogen infections (e.g. see Klaus,

2014). Therefore, periosteal lesions, particularly active ones, can be a general indicator of disease, chronic or acute infection, or physiological stress. However, while active periosteal lesions are associated with frailty, healed lesions may indicate low frailty by representing those who survived the stressor (Wood et al., 1992; DeWitte, 2014). In this study, only three individuals exhibited active periosteal lesions. The only adult with these lesions had a fungal infection (madura foot), likely causing the periosteal reaction (Curto & Fernandes, 2016). The frequency of healed periosteal lesions was also low (males: 5 %, N = 3/25; females: 0 %, N = 0/27), suggesting low physiological stress among adults.

In adults, there are no significant differences in tibia length (a proxy for stature) and femoral head diameter (a proxy for body mass) between age groups, despite evidence that shorter stature may be linked to increased mortality risk (McGovern, 2014; Kemkes-Grottenthaler, 2005). Additionally, the lack of correlation between stable isotope analysis ($\delta^{15}N$ and $\delta^{13}C$) and tibia length or femoral head diameter suggests that body size and its determinants (such as activity levels and low physiological stress) are not related to adult diet. Although it might be expected that larger individuals would consume more animal protein, the data indicate that the diet at Estremoz was quite uniform.

6. Conclusion

Most individuals studied exhibit similar stable isotope ratios, with the exception of a few who show elevated $\delta^{13}C$ and $\delta^{15}N$ values, which might suggest either different access to food sources or that these individuals may not be native to Estremoz, given its historical importance as a key route connecting Portugal and Castille (Spain). Overall, the population of Estremoz exhibited low frequencies of physiological stress indicators, with most cases showing only mild severity, minimal signs of growth delay and a large number of individuals older than 44 years of age. The low frequency of skeletal stress indicators and a relatively uniform diet in medieval Estremoz may be attributed to low population density, social dynamics, and protective strategies against famine and pathogens. The presence of young male outliers with high $\delta^{15}N$ values suggests possible migration or movement into Estremoz, whereas the absence of similar outliers among females and other age groups indicates more stable, localised dietary patterns. This stability implies a stronger reliance on domestic or agricultural food sources and less mobility for these groups.

CRediT authorship contribution statement

Ana Curto: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vanessa Navarrete:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Anne-France Maurer:** . **Cristina Barrocas Dias:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation. **Teresa Fernandes:** Writing – review & editing, Visualization, Resources, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105011.

Data availability

Data will be made available on request.

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