Sex differences in diet and life conditions in a rural Medieval Islamic population from Spain (La Torrecilla, Granada): an isotopic and osteological approach to gender differentiation in al-Andalus

Running Title: Sex and gender differences in lifestyle in Medieval Islamic Spain

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Abstract

Objectives: Gender differentiation can influence the diet, physical activity, and health of human populations. Multifaceted approaches are therefore necessary when exploring the biological consequences of gender-related social norms in the past. Here, we explore the links between diet, physiological stress, physical activity and gender differentiation in the Medieval Islamic population of La Torrecilla (Granada, Spain, 13th-15th century AD), by analyzing stable isotope patterns, stature, and long bone diaphyseal measurements.

Materials and Methods: The sample includes 96 individuals (48 females, 48 males) classified as young and middle adults (20-34 and 35-50 years of age respectively). Diet was reconstructed through the analysis of $\delta^{13}C$ and $\delta^{15}N$. Stature, humeral and femoral diaphyseal shape and product of diaphyseal diameters served as proxies of physiological stress and physical activity.

Results: Isotopic ratios suggest a substantial dietary contribution of C_4 plants (e.g., sorghum, millet), a variable access to animal proteins, and no differences between the sexes. Sexual dimorphism in stature derives from a markedly low female stature. Long bone diaphyseal properties suggest that men performed various physically stressful activities, whereas women were involved in less physically demanding activities (possibly related to household work).

Discussion: Gender differentiation in La Torrecilla was expressed by a possibly differential parental investment in male *versus* female offspring and by culturally sanctioned gender differences in the performance of physical tasks. Diet was qualitatively homogenous between the sexes, although we cannot rule out quantitative differences. Our results shed new light on the effects of gender-related social norms on human development and lifestyle.

Key words: Islamic Spain; Middle Ages; sex differences; stable isotopes; long bone diaphyseal cross-sectional properties

Introduction

A traditional research focus of bioarcheology is the exploration of sex differences in physical activity, health, and relative access to food sources, studying possible links between these differences and gender-based social differentiation and inequality (Zuckerman & Crandall, 2019). Continued interest in this research topic is demonstrated by the large number of published papers examining the correlation of sex with various osteological and biogeochemical variables in different archaeological contexts. Variables used to evaluate possible sex differences in physical activity, health, and diet include skeletal and dental features related to mechanical loading and certain pathological conditions on the one hand, and stable isotope ratios (especially $\delta^{13}C$ and $\delta^{15}N$), which allow past dietary patterns to be reconstructed on the other (Berner, Sládek, Holt, Niskanen, & Ruff, 2018; Grauer & Stuart-Macadam, 1998; Hollimon, 2011; Laffranchi, Cavalieri Manasse, Salzani, & Milella, 2019; Laffranchi, Martín Flórez, Charisi, & Jiménez-Brobeil, 2016a; Ruff, 1987, 2008; Ruff & Hayes, 1983b; Slaus, 2000; Stock & Pfeiffer, 2001, 2004; Villotte & Knüsel, 2014). When considered together with available archaeological information, these data provide the opportunity to address research questions about sub-populations often neglected by historiography and contemporaneous sources (e.g., women and nonadults). This approach also allows investigation of the influence of biological (physiological) and cultural factors on the different responses of males and females to their natural and social environments. Given the composite (i.e., physiological, behavioral, psychological) and culturally contingent nature of gender and therefore gender-based distinctions (Geller, 2008; Zuckerman & Crandall, 2019), this research perspective is especially suitable for the reconstruction of gender-based lifeway differences, considering "lifeway" to refer to a mosaic of dietary, behavioral, and health variables. The use of multiple lines of evidence to test biocultural hypotheses (e.g., the physiological effects of gender-related social norms) may provide a finer-grained picture in comparison to isolated analyses of single variables. Nevertheless, only a limited number of researchers have adopted this approach to date (Arcini, Ahlström, & Tagesson, 2014; Bondioli, Nava, Rossi, & Sperduti, 2016; Laffranchi et al., 2019; Larsen et al., 2015, 2019; Osipov et al., 2020; Pfeiffer & Sealy, 2006; Suby & Guichon, 2009; Toso, Gaspar, da Silva, Garcia, & Alexander, 2019).

Various factors facilitate the bioarchaeological analysis of sex and inferred gender lifestyle differences in Medieval Islamic Spain, including: a) the presence of rich historiographic documentation, allowing for a more complete discussion of the observed skeletal data, b) the availability of large skeletal series representing both urban and rural contexts, c) the fact that women and men are traditionally characterized by distinct social roles in Islamic culture, and d) the growing amount of published bioarchaeological data on Medieval Islamic populations from Iberia (al-Oumaoui, Jiménez-Brobeil, & du Souich, 2004; Alexander, Gerrard, Gutierrez, & Millard, 2015; Alexander, Gutierrez, Millard, Richards, & Gerrard, 2019; Charisi, Laffranchi, & Jiménez-Brobeil, 2016; Guede et al., 2017; Inskip, Carroll, Waters-Rist, & López-Costas, 2018; Laffranchi et al., 2016a; Osipov et al., 2020). These populations are therefore good candidates for examining the possible effects of sex- and possibly gender-based differences in diet and physical activity on human physiology, providing an opportunity to better contextualize the results of new studies.

Bioarchaeological research on Medieval Islamic populations in Spain and Portugal has focused on paleodietary and mobility reconstructions (Alexander et al., 2015; Alexander et al., 2019; Fuller, Marquez-Grant, & Richards, 2010; Guede et al., 2017; Inskip et al., 2018; MacRoberts et al., 2020; Mundee, 2010; Osipov et al., 2020; Prevedorou et al., 2005; Salazar-García, Richards, Nehlich, & Henry, 2014; Salazar-García, Romero, García-Borja, Subirà, & Richards, 2016; Toso et al., 2019) and, to a lesser extent, on the analysis of health and physical activity patterns (e.g., al-Oumaoui et al., 2004; Inskip, 2013; Jiménez-Brobeil, Roca-Rodríguez, Al Oumaoui, & du Souich, 2012; Laffranchi et al., 2016a; Osipov et al., 2020; Pomeroy & Zakrzewski, 2009).

Intrapopulation differences suggestive of a gender differentiation in diet were found in the rural community of Tauste (Guede et al., 2017) and the São Jorge Castle of Lisbon (Toso et al., 2019). In both settings, isotopic data indicate that males consumed a larger amount of animal proteins than females, suggesting a wider variability in their diet and their potential access to external food resources. Furthermore, at São Jorge Castle, similar isotopic profiles were observed between women and children (aged >3 years), consistent with their distinct dietary habits from those of men. This may be related to the family organization of Islamic households, in which men occupy separate domestic spaces from those used by women and children (Toso et al., 2019).

Only a few studies have explored patterns of biomechanical stress among the Islamic communities of Iberia (al-Oumaoui et al., 2004; Inskip, 2013; Jiménez-Brobeil et al., 2012;

Laffranchi et al., 2016a; Osipov et al., 2020; Pomeroy & Zakrzewski, 2009). Analyses of entheseal changes, vertebral pathologies (osteoarthritis, Schmorl's nodes, and spondylolysis), and long bone size and shape have pointed to some differences in physical activity between males and females (al-Oumaoui et al., 2004; Inskip, 2013; Jiménez-Brobeil et al., 2012; Laffranchi et al., 2016a; Pomeroy & Zakrzewski, 2009). For instance, higher muscle development and greater vertebral degeneration has been observed in males than in females, and high sexual dimorphism has been found in upper and lower limb long bone size and shape. Differences between rural and urban settings have also been reported. Thus, lower muscle development and a more marked sexual dimorphism in long bones was observed among individuals from rural La Torrecilla than among those from the contemporary urban cemetery of Sahl Ben Mālik (Granada). This has been associated with the more varied activities, higher craft specialization, and more active working role of women in the urban *versus* rural setting (Charisi et al., 2016; Laffranchi et al. 2016a).

More recently, Osipov et al. (2020) published the first comparative analysis of skeletal body size proxies, diaphyseal structural properties, and stable carbon and nitrogen isotopes among Islamic populations in Ibiza, highlighting a positive correlation between body size and $\delta^{13}C$ values. The authors suggest that this relationship might reflect either improved diet quality through greater access to C_4 resources or the presence in the sample of nonlocal individuals with a different diet and larger body size.

However, only preliminary data are available on the presence of sex (and possibly gender) differences in diet and living conditions among Medieval Islamic populations in Iberia. Only two studies have addressed this research topic by combining osteological/paleopathological and isotopic data (Osipov et al., 2020; Toso et al., 2019), but no such research has been carried out in the Spanish mainland.

This study addresses these issues by exploring lifestyle differences between the sexes in La Torrecilla, a rural Medieval Islamic population from Spain. Specifically, we compare $\delta^{13}C$ and $\delta^{15}N$ ratios, stature, and long bone diaphyseal cross-sectional properties derived from external measurements, and examine any association of these variables with sex and age-at-death.

The results are then used to address the following research questions:

a. What type of diet characterized the population of La Torrecilla, and were there any sex differences in the diet?

b. What types of sex differences are observed in stature and long bone diaphyseal cross-sectional properties, and what do they reveal about sex differences in lifestyle in this population?

c. Do the stable isotope data correlate with stature, body mass, and long bone diaphyseal cross-sectional properties?

Accordingly, the objectives of this study were to determine sex differences in lifestyle in this community and to explore their association with the possible physiological effects of gender differentiation. However, it is challenging to infer gender differences from skeletal data because of the risk of conflating sex and gender (Zuckerman & Crandall, 2019). For this reason, isotopic and skeletal patterns based on biological sex are referred to as "sex differences" hereafter. The possible gender correlates of these patterns are discussed, based on the available historical and archaeological sources.

Archaeological and historical background

The cemetery of La Torrecilla (Arenas del Rey, Granada) is now part of the Bermejales swamp and almost permanently covered by water (Figure 1). The funerary area, measuring 41x 23.5 meters, was repeatedly excavated between 1968 and 1976 (Arribas & Riu, 1974; du Souich, 1979), also revealing traces of domestic structures interpreted as the remains of a small rural settlement, specifically known by the term *al-qarīa*. It was a typical rural Islamic settlement, composed of few houses and inhabited by one or several families. Unfortunately, no historical sources refer to this *al-qarīa* (Arribas & Riu, 1974; du Souich, 1979; Trillo San José, 2004). Excavation of the funerary area yielded 139 graves characterized by pits, with or without slabs as covering or external delimitation, and by the occasional use of wooden coffins. Burials are always inhumations, with individuals lying extended on their right side facing southeast and with no grave goods, in accordance with Islamic funerary customs (Chávet Lozoya, 2015; Torres Balbás, 1957). Radiocarbon dating of two individuals (graves 118 and 152) pointed to the 14th century (Charisi et al., 2016). These findings, together with the possible prolonged utilization of the area for funerary purposes (Arribas & Riu, 1974), suggest that La Torrecilla was occupied between the 13th and 15th centuries AD and therefore during the Nasrid Kingdom, the last independent Islamic state in the Iberian Peninsula (al-Andalus in Arabic*)*. The Nasrid Kingdom was spread across the southeast of the peninsula, and included the modern provinces of Malaga, Granada, and Almería (Torres Delgado, 1997), with the city of Granada as its capital.

Geographically, La Torrecilla is relatively isolated. It is not connected to the main routes crossing the region and is separated from the coast by the mountain ranges of Tejeda and Almijara. It is located at 800 m a.s.l. on Messinian limestone (IGME, Sheet 1040) and is characterized by mild winters, hot and dry summers, and moderate rainfall throughout the year. These characteristics make the area particularly suitable for dryland crops, as witnessed nowadays by the substantial cultivation of barley and of olive and almond trees. Previous paleodietary analyses of rural (Benipeixcar, 33 Bartomeu Vicent Ramon-Ibiza, Tauste-Zaragoza, Can Fonoll-Ibiza, Tossal de las Basses-Alicante, Albarracín castle-Teruel) and urban (Valencia, Écija-Sevilla, Es Soto-Ibiza, Zaragoza) Islamic sites in Spain (reported in Figure 1) suggest a mixed C_3/C_4-based economy (Alexander et al., 2015, 2019; Dury et al., 2018; Fuller et al., 2010; Guede et al., 2017; Inskip et al., 2018; Mundee, 2010; Pickard et al., 2017, Salazar-García et al., 2016). The diet may have included a large amount of C_4 plants (e.g., sorghum, millet, and sugarcane) (Alexander et al. 2019; Fuller et al. 2010; Pickard et al. 2017) and marine proteins (Alexander et al., 2015; Guede et al., 2017; Salazar-García et al., 2016), especially in certain places such as Valencia, Es Soto-Ibiza, and Can Fonoll-Ibiza. The diet could be expected to contain ample C_4 plant products in areas with climates that were less suitable for the cultivation of wheat but more favorable for the growth of plants such as sorghum, millet, and sugarcane, as on the coast of Granada (García Sánchez, 1995).

Stable isotopes of carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$)

Stable isotope ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) from bone collagen are routinely used for dietary reconstructions from ancient human and animal remains (Larsen, 2015; Schoeninger & Moore, 1992).

Stable carbon ratios ($\delta^{13}C$) in the collagen of human and animal samples reflect the proportion of plants characterized by specific photosynthetic pathways (C_3 vs.C_4 plants) in the diet (DeNiro & Epstein, 1981; Van der Merwe, 1982) and also yield information on environmental and climatic conditions (Laffranchi, Delgado Huertas, Jiménez-Brobeil, Granados Torres, & Riquelme Cantal, 2016b; Van Klinken, Richards, & Hedges, 2002). $\delta^{13}C$ ratios in collagen largely reflect the protein component of the diet, but they are also influenced by the presence of carbohydrates and lipids (Fernandes, Nadeau & Grootes, 2012; Froehle, Kellner & Schoeninger, 2010; Howland et al., 2003). δ^{15}N values indicate the trophic level of an organism, permitting an estimation of the relative amount of animal and vegetal proteins in the diet (DeNiro & Epstein, 1981; Hedges & Reynard, 2007). The combined application of δ^{13}C and δ^{15}N ratios can help to differentiate between the consumption of terrestrial and marine resources (Schoeninger & DeNiro, 1984), but other factors must be considered (Van Klinken et al., 2002). An interesting but relatively unexplored line of research investigates the relationship of bone collagen isotopic values with skeletal estimates of body size and/or long bone cross-sectional diaphyseal properties. This type of study has been carried out in a limited number of archaeological contexts, including Islamic skeletal series from Ibiza (Arcini et al. 2014; Bondioli et al. 2016; Osipov et al., 2020; Pfeiffer & Sealy, 2006; Suby & Guichon, 2009). Diet, in combination with genes, health status, and mechanical loading, influences the growth and development of the skeletal system. Given the usefulness of carbon and nitrogen isotopic ratios to assess past dietary patterns, the combined analysis of isotopic and osteological measurements appears to be a good approach for investigating the complex interactions among diet, health, and social/economic behavior in a given population (see also Osipov et al., 2020).

Stature

Skeletal growth is influenced by genetic and environmental factors (King & Ulijaszek, 1999; Silventoinen et al., 2012; Vercellotti et al., 2014). Among environmental factors, diet is known to significantly influence the growth and development of the skeletal system and, therefore, adult stature (Gunnell, Smith, Frankel, Kemp, & Peters, 1998; Steckel, 1995). Health status is also known to have a major impact on growth and final adult body size at a population level (Bozzoli, Deaton, & Quintana-Domeque, 2009; Crimmins & Finch, 2006; Larsen, 2015). Secular trends in adult stature have been shown to follow regional and temporal fluctuations in living conditions (Bertsatos & Chovalopoulou, 2018; Cardoso & Gomez, 2009; Cole, 2003; Koepke & Baten, 2005; Koepke, Floris, Pfister, Rühli, & Staub, 2018; Maat, 2005; Shin, Oh, Kim, & Hwang, 2012), while a negative correlation has been observed between income (or social) inequality and mean stature in populations (Bogin, Scheffler, & Hermanussen, 2017; Keep & Bogin, 1999). These findings explain the long-standing interest of anthropologists in stature estimates (usually obtained from long bone measurements) when testing the possible effects on the life quality of past populations exerted by socioeconomic changes and/or differences in diet and health derived from wealth inequalities (Cohen & Armelagos, 1984; Cohen & Crane-Kramer, 2007; Larsen, 2006; Mieklejohn & Babb, 2011; Mummert, Esche, Robinson, & Armelagos, 2011; Robb, Bigazzi, Lazzarini, Scarsini, & Sonego, 2001).

However, a number of confounding factors may mask the direct impact of nutritional and health status on adult stature. Peak rates of longitudinal growth in specific body parts (e.g., lower limb *versus* trunk) occur at different ages before adulthood (Bogin and Varela-Silva, 2010). Given that stress mainly affects limb growth, the main contributor to stature (Bogin and Varela-Silva, 2010), the final adult body height may be influenced by the timing and duration of stressful events rather than by stress *per se*. Catch-up growth with improved environmental conditions may also mask the negative effect of stress on growth (Steckel, 2008). Female reproductive history and selective mortality may also influence the stature of a population (Bozzoli et al, 2009; Vercellotti et al., 2014; Vercellotti & Piperata, 2012). All the above underscore the need for care in inferring past life conditions from stature.

Long bone diaphyseal cross-sectional properties

The usefulness of long bone diaphyseal morphology and structure to reconstruct past human behavior is based on the capacity of bones to optimally adapt their form to their mechanical environment throughout life by increasing/decreasing and re-distributing the amount of bone through remodeling (Ruff, 2008; Ruff, Holt & Trinkaus, 2006). Long bones are considered to behave as hollow engineering beams under loading (Huiskes, 1982; Ruff, 2008); therefore, their mechanical performance is frequently analyzed in anthropology by using engineering principles and diaphyseal properties to infer patterns of past activity (e.g. Bridges, Blitz, & Solano, 2000; Cameron, Lapham, & Shaw, 2018; Maggiano et al., 2008; May & Ruff, 2016; Miller, Agarwal, Aristizabal, & Langebaek, 2018; Nikita, Ysi Siew, Stock, Mattingly, & Mirazón Lahr, 2011; Ogilvie & Hilton, 2011; Ruff, Larsen, & Hayes, 1984; Stock & Pfeiffer, 2001, 2004; Varalli, Villotte, Dori, & Sparacello, 2020; Weiss, 2003). Long bone cross-sectional geometric properties (CSGPs) are ideal for estimating long bone strength and rigidity (Ruff, 2008; Stock & Shaw, 2007); however, estimations of shape and robusticity obtained from external shaft dimensions can be an effective alternative, as shown by the fact that the two approaches yielded similar results and inferences for major trends in activity patterns in some populations (Bridges et al., 2000; Larsen, 1981; Maggiano et al., 2008; Ruff, 1987; Ruff et al., 1984; Wanner, Sierra Sosa, Alt, and Tiesler Blos, 2007). The utilization of diaphyseal properties derived from external measurements as proxies of biomechanical stress is further supported by their high correlation with certain CSGPs (Pearson, 2000; Stock and Shaw, 2007). Hence, given the ease with which external measurements can be obtained and the limited costs involved, this method has been applied in various bioarchaeological studies (Bridges et al., 2000; Laffranchi, Charisi, Jiménez-Brobeil, & Milella, 2020; Mazza, 2019; Osipov et al., 2020; Pomeroy and Zakrzewski, 2009; Thomas, 2014; Wanner et al., 2007).

Experimental and comparative studies in animals and athletes with known activity patterns suggest that the diaphyseal shape mainly reflects directionality, while its robusticity is more indicative of the amount (intensity and repetitiveness) of applied loads and the overall diaphyseal strength (Carlson & Judex, 2007; Macinstosh & Stock, 2019; Marchi & Shaw, 2011; Rantalainen, Nikander, Heinonen, Suominen, & Sievänen, 2010; Shaw & Stock, 2009a, 2009b). Resistance of a diaphysis to bending forces increases as bone tissue is placed farther from the cross-section centroid (Ruff, 2008). When bending mainly occurs in one plane, bone apposition or redistribution increases in the direction of the applied force (Ruff & Hayes, 1983a), resulting in a less circular diaphysis, whereas greater circularity would likely result from habitual activities that involve multidirectional loading (Shaw & Stock, 2009a, 2009b). With regard to long bone strength, it has been found to vary with the intensity of activity, being greater in groups engaged in more strenuous tasks (Marchi & Shaw, 2011; Shaw & Stock, 2009a, 2009b). In summary, variations in diaphyseal shape can yield information on types of habitual activity, while the robusticity would reflect overall activity levels (Ruff, Larsen, & Hayes, 1984).

Material and methods

Sex and age-at-death

The selected sample includes 96 adults (48 males and 48 females) in two age classes (Table S1). Sex was determined according to standard anthropological protocols, based on dimorphic features of the cranium, mandible, and *Os coxae* (Ferembach, Schwidetzky, & Stloukal, 1980; Phenice, 1969; see also Buikstra & Ubelaker, 1994). Given the focus of the study on sex differences, individuals without reliable sex determination were excluded. Estimations of age-at-death were based on morphological changes in pubic symphysis, auricular surface of ilium, and sternal ends of ribs (Brooks & Suchey, 1990; Buckberry & Chamberlain, 2002; Işcan, Loth, & Wright, 1984). No individual was older than 50 years, and the sample was divided between young adults (aged 20-34 years) and middle adults (35-50 years), following Buikstra and Ubelaker (1994).

Stable isotope analyses: carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$)

Isotopic analyses were carried out on rib samples from a subset of 77 adult individuals (≥ 20 years old). Ribs were selected due to their partial fragmentation in order to minimize destruction of the skeletal remains. None of these individuals show skeletal and/or dental changes suggestive of pathological conditions that might have influenced the isotopic data (Olsen et al., 2014).

No zooarchaeological specimens are available from La Torrecilla. Therefore, the isotopic baseline for this study was estimated from eight chronologically contemporaneous animal samples (7 *Ovis aries/Capra hircus* and 1 *Oryctolagus cuniculus*) obtained from archaeological contexts in the vicinity of La Torrecilla with similar ecological and edaphological characteristics (Alhama of Granada and Arenas del Rey).

Collagen was extracted in the Stable Isotopes Laboratory of the Andalusian Institute of Earth Sciences (CSIC) following the protocol described by Bocherens et al. (1997) (see also Bocherens & Drucker, 2003). All samples were powdered in a mortar, and 300 mg of the powder were decalcified in 1 M HCl for 20 min at room temperature, eliminating phosphates, fulvic acids, and other soluble acids, and were then passed through a MF-Millipore 5 µm filter. The insoluble residue was plunged into 0.125 M NaOH for 20 h at room temperature. After rinsing with Milli-Q water, the neutralized sample was filtered (5 µm) to remove humic acids and most lipids, and the residue was immersed in a 10^{-2} M HCl (pH 2) solution within closed Pyrex tubes at 100 °C to solubilize the collagen. After centrifugation, the supernatant was lyophilized and its isotopic composition was analyzed. Around 0.7 mg of collagen was weighed within a tin capsule per duplicate and treated in a continuous flow system using an elemental analyzer (set to 1020 °C) connected to a mass spectrometer. Sample combustion was obtained in the range of 1600-1800 °C, producing a mixture of carbon and nitrogen oxides that was then reduced at 650 °C, resulting in a mixture of CO_2, N_2, and H_2O. The water was chemically removed, and CO_2 and N_2

were separated using a chromatographic column before mass spectrometry analysis. An elemental analyzer (Carlo Erba Model NA1500 NC series 2) was used for the combustion, reduction, water removal, and chromatographic separation processes. N_2 and CO_2 obtained by these procedures were introduced into a Delta Plus XL mass spectrometer for isotope analysis. The analytical error for $\delta^{15}N$ and $\delta^{13}C$ determinations was < 0.1‰. Isotope results were reported in comparison to accepted international references: V-PDB for carbon and AIR for nitrogen (Coplen, 1995). Only samples with good collagen quality were considered, i.e., with an atomic C:N ratio between 2.9 and 3.6 (DeNiro, 1985) and a collagen yield of ≥ 1% (Ambrose, 1990; Van Klinken, 1999).

In order to better contextualize the isotopic data from La Torrecilla, these were plotted alongside published data from other Islamic populations in Iberia (Alexander et al., 2015; Alexander et al., 2019; Dury et al., 2018; Fuller et al., 2010; Guede et al., 2017; Inskip et al., 2018; Mundee, 2010; Pickard et al., 2017; Salazar-García et al., 2016; Toso et al., 2019) as well as unpublished data from Talará (Granada, 13th-15th century AD) (Jiménez-Brobeil et al. in prep.), the Islamic cemetery of a small settlement (*al-qarīa*) in the Lecrín valley on the route from Granada to the coast.

Long bone cross-sectional properties and stature

Humeral and femoral midshaft diameters and femoral maximum length and superoinferior head diameter were measured according to Martin and Saller (1957) (Table 1). Metric data were only recorded when there was no apparent pathology or post-mortem deformation affecting the measurement. These data were then used to estimate the diaphyseal structural properties of humerus and femur and the body mass and stature.

First, a diaphyseal shape index was calculated for each bone as a proxy for load directionality. Maximum and minimum diameters were used to estimate the diaphyseal shape of the humerus (HMS=HDmax/HDmin), while the ratio of anteroposterior to mediolateral diameter was used for the femur (FMS=FAPD/FMLD) (Table 1). Consequently, a value of HMS or FMS close to 1 would indicate the application of equal forces to the two perpendicular planes of the diaphysis, a value >1 would indicate unidirectional strain on the humerus and greater anteroposterior strain on the femur, while a value <1 (only possible for FMS, given that HMS is the ratio of maximum to minimum diameter) would indicate greater mediolateral loading.

Next, the product of midshaft diameters was calculated for each bone (HDprod and FDprod) (Table 1) as an "area-like" measurement, broadly indicating loading levels and overall bone strength. External diaphyseal shape indices and products of diameters were chosen because they have demonstrated high correlations with certain CSGPs, i.e., I_{max}/I_{min} and I_{ap}/I_{ml}, ratios and polar second moment of area (Stock & Shaw, 2007).

For each sex, upper limb lateralization was quantified by using the formula of Auerbach and Ruff (2006) to calculate absolute bilateral asymmetry {%AA= [(maximum-minimum)/(average of maximum and minimum)]*100} for both humeral diaphyseal properties in order to test for uni-manual *versus* bi-manual activities.

Stature was estimated by means of the sex-specific equations of Ruff et al. (2012) for the femur. The right femur was used when it was present and complete and the left femur when it was not. For comparability with published data for other Islamic Iberian populations, stature was also estimated according to Mendonça (2000), frequently applied in Iberian samples. The body mass was also estimated and considered in the statistical analysis of Dprod values because of its important effect on the mechanical environment of limb bones (Ruff, 2000; 2008), using the sex-specific equations of Ruff et al. (2012) for femoral vertical head diameter. The equations were applied to both right and left femoral head diameters when present and then averaged; otherwise, body mass was estimated from measurements of the available side.

Statistical analysis

The Shapiro-Wilk test and skewness and kurtosis values were used to check the normality of data distribution. Non-parametric tests were applied when assumptions of parametric tests were not met, as specified in the respective tables.

Statistical analysis of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) values

Isotopic values were compared between the sexes, with and without subdivision by age class, and between age classes within each sex using the independent samples t test, applying the Mann-Whitney test for non-normally distributed variables (e.g., $\delta^{15}N$ values in females). Given the possible biocultural relevance of sex differences in the relative dispersion of each isotopic ratio, variances in $\delta^{13}C$ and $\delta^{15}N$ were also compared between the sexes by using Levene's test or the non-parametric Fligner-Killeen test for homogeneity of variances.

Stature, long bone cross-sectional properties, and correlation with isotopic values

Sexual dimorphism in linear measurements, long bone cross-sectional properties, stature, and body mass was first quantified as SDI (Sexual Dimorphism Index) = ln (Male mean / Female mean), following Smith (1999). Hence, positive values indicate a higher male mean and negative values a higher female mean. Because the adults were only divided between two age classes (young and middle adults), and no individual was older than 50 years of age, stature, shape indices, and Dprod were only compared between the sexes combining age groups.

All variables are normally distributed with the exception of the %AA for humeral shape and Dprod. Therefore, sex differences in long bone shape and stature were tested using the independent-samples t-test, whereas sex differences in Dprod were examined by analysis of covariance (ANCOVA), controlling for the effect of body mass.

Lateralization in humeral shape indices and Dprod values within each sex was analyzed with the paired-samples t-test and sex differences in absolute bilateral asymmetry (%AA) were examined with the Mann-Whitney test. Given that body mass, which potentially affects long bone diaphyseal morphology, remains constant within individuals, the paired-samples t-test and %AA calculations were performed with unadjusted Dprod values. Sex differences in variances of stature, body mass, diaphyseal shape and Dprod values were analyzed with Levene's test.

Correlations of isotopic values with stature, body mass, and long bone cross-sectional properties were analyzed separately for each sex using the Pearson (or non-parametric Spearman) test. For Dprod values, partial correlation analysis was applied to control for estimated body mass.

Besides p-values, appropriate measures of effect size were calculated for each comparison to estimate the strength of the relationship between the independent (e.g., sex, side) and dependent variable, using Hedges' g and Cohen's d for the t-tests, ω^2 for the ANCOVA and r for the Mann-Whitney tests and results were interpretedfollowing Cohen's criteria (Cohen, 1988) (see Tables 2-4). IBM SPSS was used for all statistical analyses, setting an alpha level of 0.05.

Results

Stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$)

Seventy-four human and eight animal samples showed sufficient collagen preservation (>1 % yield) and were therefore considered in the study. All samples met published collagen quality criteria (DeNiro, 1985; Van Klinken, 1999). Table S2 and Figures 2a and 2b report the isotopic values for the human samples from La Torrecilla and the animal samples from Alhama and Arenas del Rey. All variables are normally distributed except for $\delta^{15}N$ in the total female and young adult female samples.

Figure 2a depicts the mean values and standard deviations for urban and rural Islamic samples across Iberia (for more details see Table S3). Urban contexts include Valencia, Écija-Sevilla, São Jorge castle-Lisbon, Es Soto-Ibiza, and Zaragoza, while rural contexts include Benipeixcar, 33 Bartomeu Vicent Ramon-Ibiza, Tauste-Zaragoza, Can Fonoll-Ibiza, Tossal de las Basses-Alicante, Albarracín castle-Teruel, and Talará-Granada (see references cited above and in Table S3).

$\delta^{13}C$ values in La Torrecilla range between -19.5 ‰ and -13.1 ‰ (mean=-15.1 ± 1.3‰ V-PDB), whereas $\delta^{15}N$ values range between 8.8 ‰ and 12.6‰, (mean=10 ± 0.7‰ AIR). Mean $\delta^{13}C$ and $\delta^{15}N$ values of herbivorous mammals are − 20.8‰ ± 0.6‰ (V-PDB) and 5.8‰ ± 2 ‰ (AIR) respectively. $\delta^{13}C$ values in La Torrecilla are at the higher end of the range for rural sites (Fig. S1), whereas $\delta^{15}N$ values are at the lower end of the range for both rural and urban sites (Figures 2 and S1, Table S3). Specifically, $\delta^{13}C$ values in La Torrecilla are similar to those in Talará and higher than those in the majority of other Iberian Islamic populations. $\delta^{15}N$ values are similar to those in Écija, Zaragoza, Can Fonoll-Ibiza, and Lisbon and are lower than those in Talará, Benipeixcar, Albarracin castle, Tauste, and Tossal del las Basses (Figure 2).

In La Torrecilla, no significant sex difference was found in $\delta^{13}C$ or $\delta^{15}N$ ratios for the whole sample or for either age class (Table 2). A marked between-sex difference is observed for $\delta^{13}C$ values in Benipeixcar (rural) and for $\delta^{15}N$ values in Tauste, Talará, Tossal de las Basses (rural), Zaragoza, and Lisbon (urban). In the other sites, males and females show similar or only slightly different isotopic values.

Age class comparisons by sex reveal a significant difference between young and middle adult males alone for the $\delta^{13}C$ ratio (t=-2.8, p=0.008, Hedge's g=0.908) (Table 2), with young adult males showing higher mean $\delta^{13}C$ values (young adults: n=22, mean= -15.4 ± 1.4‰ V-PDB; middle adults: n=17, mean= -16.7 ± 1.4‰ V-PDB).

Levene`s test and the Fligner-Killeen test revealed a significant sex difference in the variance of $\delta^{13}C$ alone and only when the sample was not subdivided into age classes (Table S4), with males being characterized by a higher variance (F=5.75, p=0.019).

Stature and long bone cross-sectional properties

Table S5 displays the summary statistics and SDI values for all linear measurements, diaphyseal cross-sectional properties, stature, and body mass, while Table 3 exhibits sex comparisons in stature, long bone cross-sectional properties, and %AA.

Mean values are higher in males than females for all linear measurements, stature, and body mass, as expected (Table S5). Stature is less sexually dimorphic than linear measurements but significantly differs between the sexes, with a large effect size (t=9.675, p<0.001, Hedges' g=2.136, Table 3). Figure 3a depicts sex-specific stature estimates for La Torrecilla and other Islamic populations of the Iberian Peninsula (Barrio & Trancho, 2017; Charisi, in preparation; De Miguel-Ibáñez, 2016; Herrera, 2012; Lacalle Rodríguez & Guijo Mauri, 2006; Molero Rodrigo, 2017; Robledo Sanz, 1998; Robles Rodríguez, 1997; Roca De Togores Muñoz, 2008; Zapata Crespo, 2000). Figure 3b plots the degree of sexual dimorphism in stature at the same sites.

Statistically significant sex differences (males>females) were also found for all Dprod values after adjusting for body mass, with the right humeral Dprod showing a large effect size (ω^2=0.177), left humeral Dprod a medium-to-large effect size (ω^2=0.098), and right and left femoral Dprod values small-to-medium effect sizes (ω^2=0.057 and 0.070 respectively) (Table 3). Shape indices follow a different pattern, with males evidencing slightly higher mean values (less circular diaphyses) for the femur, although the differences were not statistically significant in t-tests. In contrast, females show higher HMS values (less circular humeri) on both sides, with statistically significant differences and large effect sizes (Table 3). HDprod values for both sides are the most sexually dimorphic of all diaphyseal properties, followed by femoral Dprod and then long bone shape indices (Table 3).

The Mann-Whitney test shows a significantly higher %AA in males for both humeral diaphyseal properties, although the effect size is only small for HMS and medium for HDprod (Table 3). Within-sex comparisons between sides using paired-samples t-tests (Table 4) reveal significant right-biased lateralization of HDprod in both sexes, with the effect size being large for males (Cohen's d=0.884) and medium for females (Cohen's d=0.564). HMS shows no statistically significant lateralization in either sex, although a higher effect size is observed in males (Table 4).

Levene's test results reveal significant sex differences in humeral and femoral Dprod for both sides and in body mass (Table S4), observing higher variances in males than in females.

Isotopic data vs. stature and long bone cross-sectional properties

Table 5 displays the results of Pearson and Spearman correlation analyses between isotopic data and other study variables for each sex. Neither $\delta^{13}C$ nor $\delta^{15}N$ correlates with stature or body mass. $\delta^{13}C$ is negatively correlated with right humeral shape in females (r= -0.39, p= 0.039), while $\delta^{15}N$ is negatively correlated with left humeral Dprod (rho= -0.42, p= 0.036) and left (rho=-0.39, p= 0.041) and right (rho= -0.46, p= 0.015) femoral Dprod values in females and is positively correlated with left (r= 0.37, p= 0.023) and right (r= 0.47, p= 0.005) femoral shape in males.

Discussion

Stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$): general dietary patterns

As reported above, zooarchaeological samples from other contexts (Alhama of Granada and Arenas del Rey) were used to estimate the isotopic baseline, given the lack of faunal specimens from La Torrecilla. This approach is supported by the shared chronology of Alhama, Arenas del Rey, and La Torrecilla and by their geographical proximity, with a large overlap in their ecological and edaphological features.

Stable carbon ratios ($\delta^{13}C$) in collagen samples from La Torrecilla show a difference of 5.7‰ in mean values between herbivores and humans, much higher than the usual range of 0-2 ‰ (Bocherens & Drucker, 2003). This suggests a differential access of humans and animals to C_3 *versus* C_4 plants. Specifically, the human isotopic values point to a diet with a marked contribution of C_4 plants, whereas the animal values indicate the exclusive consumption of C_3 plants. The difference in $\delta^{15}N$ mean values between humans and herbivores (excluding the rabbit) is 3.6 ‰, lower than the trophic level enrichment of ca. 6‰ proposed in recent studies (O'Connell, Kneale, Tasevska, & Kuhnle, 2012). The lowest $\delta^{15}N$ value (2.1‰ AIR) is for the rabbit (AL-7), which may be explained by the variability in nitrogen values that often characterizes this taxon. This likely results from an interplay between various factors, e.g., environmental (topography, soil, and vegetation) and diet, rather than from a low trophic level alone (Alagich et al. 2018; Ugan and Coltrain, 2011). The other faunal samples comprise domestic species that mostly show values higher than 6‰, probably reflecting a manure effect (Fraser et al., 2011) or the arid conditions, to which sheep and especially goats are better adapted (Van Klinken et al., 2002). These $\delta^{15}N$ values may also be linked to dietary differences between sheep and goats and/or reflect pre-weaning signals.

Human isotopic data from La Torrecilla show similarities and differences with those of other Islamic populations in Iberia. $\delta^{13}C$ values in La Torrecilla are higher than in all other sites but are similar to those in Talará (-15.4 ±1‰ V-PDB) (see Fig.2a and Tab. S3). For their part, $\delta^{15}N$ ratios are generally within the range of values (between 8.8 and 12.1‰) observed in the majority of sites (whether rural or urban), as depicted in Figure 2a, with the exception of Tauste (13.3-16.7‰ AIR). Although no clear dietary pattern is evident among the different populations, isotopic values in La Torrecilla are closer to those in other rural sites than to those in urban sites (Fig. S1).

Stable carbon ($\delta^{13}C$) values in La Torrecilla and Talará indicate the consumption of C_4 plants, which is consistent with the ecological features (climate and altitude) of the Kingdom of Granada, which were not suitable for wheat cultivation. Contemporary Andalusian authors documented the use of cereal substitutes for wheat, especially sorghum, in times of scarcity or in the diet of lower classes (García Sánchez, 1981-82; 1996; Hernández Bermejo & García Sánchez, 2008). The $\delta^{13}C$ values in La Torrecilla and Talará may be a byproduct of their use of sorghum to make bread.

An additional factor to consider is the possible consumption of sugarcane, a C_4 plant cultivated along the coast of Granada. Talará is located on an important route connecting Granada with the coast, which was used to take fish and sugarcane to the capital. La Torrecilla was geographically isolated (see above) but probably had access to sugarcane through trading activities (Espinar, 2009). Ibn al-Jatib (1984) describes several ways in which sugarcane was consumed (sucking the cane or drinking the squeezed juice). Sugar would probably not be reflected in collagen, being a pure carbohydrate (Ambrose & Norr, 1993; Tieszen & Fagre, 1993). However, the consumption of sugarcane juice may have led to partial preservation of the amino acid component of this plant (Larrahondo, 2017) and its resulting reflection in bone collagen proteins (Schwarcz, 2002).

Sex differences

Stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$)

Sex comparisons of isotopic values in La Torrecilla, with and without subdivision by age class, indicate that the females and males had access to the same type of food resources. Importantly, however, this apparent dietary homogeneity may mask quantitative differences. In this type of society, women were responsible for preparing and serving food to the men in the family, but they ate separately (Díez Jorge, 2002; García Sánchez, 2006; Toso et al., 2019). Contemporaneous Islamic sources make few references to the specific dietary customs of women, although some recommend higher caloric intakes (e.g., fats, sweets, or nuts) to increase the weight of women for esthetic or health reasons (e.g., pregnancy or wet nursing (Ibn-al Jatib 1984).

The higher $\delta^{13}C$ values in young adult males than in middle-adult males suggests their intake of a slightly different diet. One possibility is that young males were more mobile, giving them greater access to nonlocal food resources; however, additional isotopic analyses (e.g., oxygen, sulfur, strontium) would be required to test this hypothesis.

Males and females in La Torrecilla show similar $\delta^{15}N$ values, with and without subdivision by age class. Sex-specific isotopic ratios markedly vary among the different contexts, especially among urban settings, where the highest isotopic values can be observed in either females (e.g., in Zaragoza and Valencia) or males (e.g., in Écija-Sevilla and São Jorge-Lisbon). This variability may be related to differences in socio-economic conditions (urban vs. rural and rich vs. poor subsistence economies) (Alexander et al. 2019) and to geographic and environmental factors (Inskip et al. 2018; Guede et al. 2017).

The Fligner-Killeen test results show a similar variance of $\delta^{15}N$ isotopic values between the sexes, supporting the homogenous access to animal proteins of males and females in La Torrecilla. The wider dispersion of $\delta^{13}C$ values among males likely reflects the variation between young- and middle-adult males and the possible access of young adults to slightly different foods, as noted above.

Stature

La Torrecilla features a higher degree of sexual dimorphism in stature than observed in other Islamic sites (Fig. 3b), which appears to be mainly driven by the remarkably low female mean stature in comparison to other sites, with the exception of El Fontanar (Córdoba) (Fig. 3a).

Although the relationship between adult body size and life quality is not always straightforward (Steckel, 2008; Vercellotti and Piperata, 2012; Vercelotti et al., 2014), higher stature has often been associated with better living conditions in past populations (Cardoso & Gomes, 2009; Clark, Tayles, and Halcrow, 2014; Maat, 2005; Trautmann, Wißing, Días-Zorita Bonilla, Bis-Worch, & Bocherens, 2017; Weiss, Vercellotti, Boano, Girotti, & Stout, 2019; Zakrzewski, 2003). Variation in sexual stature dimorphism (henceforth SSD) has also been linked to differences in environmental conditions. Female growth is thought to be less sensitive to environmental changes (Stini, 1969; Stinson, 1985), and sexual dimorphism may decrease in populations facing adverse circumstances due to a more severe disruption of growth in boys (Bogin et al., 2017; Cámara, 2015; Nikitovic and Bogin, 2014; Vercellotti, Stout, Boano, & Sciulli, 2011; Weiss et al., 2019; Zakrzewski, 2003), although deviations from this pattern have been observed (Clark et al., 2014; Gustafsson, Werdelin, Tullberg, & Lindenfors, 2007; Shin, Oh, Kim, & Hwang, 2012).

Despite being a rural community with relatively poor living conditions, the population of La Torrecilla shows a marked sexual dimorphism. The reduced stature of females observed may therefore result from a combination of cultural and environmental factors. The patriarchal features of the Islamic society of al-Andalus and the social restrictions for women (Coope, 2013, Hirsch, 2011; Mesned Alesa, 2007) were likely more marked in rural settings (Rubiera, 1989). Coupled with poor living conditions, these may have resulted in differential parental investment (e.g., preferential allocation of resources to male offspring), as often observed in poor rural communities, which negatively affects female growth in some cases (Chen, Huq, & d' Souza, 1981; Song & Burgard, 2008). Although stable isotope findings do not suggest sex differences in the adult diet in La Torrecilla, the data on adult stature suggest that young boys may have enjoyed better overall treatment (access to foods and health care resources) in comparison to young girls. This conclusion is also supported by historical sources that highlight the persistent efforts and recommendations of physicians and jurists in favor of equality between boys and girls, as opposed to the discriminating practices of the patriarchal society of al-Andalus (Giladi, 1995; Vidal Castro, 2016).

The combined effect of social settings and environmental conditions on growth was previously described by Charisi et al (2016). In comparison to the contemporaneous urban Islamic population from the city of Granada, La Torrecilla shows a greater degree of sexual dimorphism in long bone measurements (lengths, diaphyseal circumferences, and epiphyseal widths), which may result from the stricter social norms for women and the poorer overall living conditions in this community. The hypothesis that urban populations in Medieval Islamic Spain were exposed to less stressful living conditions in comparison to rural communities is partly supported by Osipov et al. (2020) in their comparative analysis of body size proxies.

The link between SSD and socioeconomic setting is only partially confirmed by comparisons between La Torrecilla and other Islamic populations from the Iberian Peninsula (Fig. 3). The lowest SSD is observed in the rural population of Rinconada de Olivares, whereas the rural population of Xarea displays a sexual stature dimorphism closer to that of La Torrecilla. Within sex differences in stature in these last two populations may be an artifact of the different methods used for its estimation. The wide sex difference in the urban sites of El Fontanar and San Nicolás is also of interest. This apparent variability further highlights the complex nature of human growth and the need to consider both social and environmental factors when discussing patterns of sexual dimorphism.

Long bone diaphyseal shape and diameter products

Humeral midshaft shape indices (HMS) are significantly higher (less circular humeri) in females than in males (Table 3). Diaphyseal non-circularity has been shown to correspond to activities that produce unidirectional strain, whereas greater circularity may indicate torsional/multidirectional strain (Ruff & Hayes, 1983a; Shaw & Stock, 2009a, 2009b). Accordingly, the higher HMS in females in La Torrecilla may relate to their involvement in tasks that feature repetitive movements which result in unidirectional strain on arm bones (e.g., laundry, breadmaking - Mesned Alesa, 2007). However, the highest SDI among linear measurements is for the minimum diaphyseal diameter of the humerus (HDmin) (Table S5). This suggests that sex differences in humeral shape may be attributable to a greater strengthening of male humeri along both minimum and maximum axes, implying multidirectional strain. Hence, the results for diaphyseal shape may indicate a greater variety of activities for males. The higher humeral diameter products (Dprod) in males suggest that their manual activities were also associated with higher mechanical loading in comparison to females.

The higher percentage absolute asymmetry (%AA) of humeral variables in males suggests their more frequent performance of unilateral tasks (Table 3). The significant lateralization in humeral strength among females (Table 4) contrasts with the usual observations in other sedentary populations, where women are commonly involved in bimanual tasks such as craftwork or crop seed processing (Cameron, Lapham, & Shaw, 2018; Mays, 1999; Laffranchi et al., 2020; Miller, Agarwal, Aristazabal, & Langebaek, 2018; Ogilvie & Hilton, 2011; Wanner et al., 2007). Although this pattern has been found to vary among different contexts due to differences in food processing techniques (Macintosh, Pinhasi, & Stock, 2014; Sládek, Berner, Holt, Niskanen, & Ruff, 2018), the well-documented abundance of watermills for this purpose in al-Andalus (Glick, 1994; Martin Civantos, 2011) suggests that right-side lateralization in the women of La Torrecilla is not linked to specific biomechanical factors related to food processing tasks. Nevertheless, it may reflect their involvement in other habitual unimanual activities (although to a lower degree than males); however, no specific historical account is available for rural al-Andalus. Furthermore, given the low female humeral robusticity (Dprod) in our sample, it cannot be ruled out that this lateralization is simply the result of the worldwide tendency to right-biased upper limb asymmetry, even in bone measurements that are not mechanically affected (Auerbach & Ruff, 2006; Steele, 2000).

Humeral variables in La Torrecilla point to a marked sexual division of labor in this community, in line with the traditional Islamic requirement for women to stay at home and dedicate themselves to the upbringing of children (Fierro, 1989; López de la Plaza, 1992; Mesned Alesa, 2007).

Lower limb bone structure is thought to reflect terrestrial mobility, and more anteroposteriorly elongated femoral diaphyses generally correspond to increased mobility (Cameron & Pfeiffer, 2014; Cameron & Stock, 2018, 2019; Holt, 2003; May & Ruff, 2016; Ruff et al., 2015; Stock & Macintosh, 2016). A trend towards a reduction in sexual dimorphism in femoral shape with the transition from hunting-gathering to agriculture is well documented in various geographical and temporal contexts (Berner et al., 2018; Ruff, 1987; Ruff et al., 1984; Wescott, 2006), and the lack of sex differences in femoral shape in La Torrecilla is consistent with the agricultural subsistence of this population. At the same time, the greater femoral strength (Dprod) of males suggests their habitual performance of activities that produce higher mechanical loads on the lower limb.

Previous analyses of entheseal changes (al-Oumaoui et al., 2004; Laffranchi et al., 2016a) and vertebral pathologies (Jiménez-Brobeil et al., 2012) in La Torrecilla support our conclusions on the sexual division of labor in this community. A marked differentiation in male and female activities was also postulated by Pomeroy & Zakrzewski (2009) in their analysis of long bone diaphyseal shape in Medieval Islamic Écija (Spain); they mainly found sex differences in lower limbs, with males apparently characterized by greater mobility. In the present study, sex differences in diaphyseal shape are only observed in the humerus, suggesting similar mobility patterns but different types of manual activities for men and women. However, it should be noted that La Torrecilla was an agropastoral settlement, whereas Écija was an important trading center (Pomeroy & Zakrzewski, 2009). Hence, although the sexual division of labor was probably prevalent in al-Andalus, different economic strategies may have called for distinct types of gendered activity in urban and rural contexts.

Various non-mechanical variables can influence long bone diaphyseal structure. Thus, genetic factors appear to affect long bone robusticity (Agostini, Holt, & Relethford, 2018) and bone mechanosensitivity (Hamrick, Sammadar, Pennington, & McCormick, 2006; Niziolek, Warman, & Robling, 2012; Robling & Turner, 2002). Based on craniometrics and nonmetric dental data, some authors postulated the presence of a small number of individuals of North African descent in La Torrecilla (al-Oumaoui, 2009; du Souich & Ruiz, 1996). It remains unclear whether the resulting genetic heterogeneity would be sufficient to affect the present results.

Diaphyseal structure is also influenced by both sex and age, and older (especially female) individuals are characterized by increased periosteal expansion (Ahlborg, Johnell, Turner, Rannevik, and Karlsson, 2003; Feik, Thomas, Bruns, & Clement, 2000; Ruff & Hayes, 1983b; Stein, Thomas, Feik, Wark, and Clement, 1998). Our sample includes only young and middle adults, and the majority are young adults. Age-related changes in diaphyseal morphology should, therefore, be negligible in this study. However, the aforementioned possibility of quantitative dietary differences between the sexes may have played a role in the sexual dimorphism observed in diaphyseal variables. Nevertheless, given that local (mechanical) rather than systemic factors are believed to account for most of the variation in diaphyseal properties (Stock and Pfeiffer, 2001), an excessively marked division of labor still appears to be a more plausible explanation of the present results.

Correlation between isotopic and osteological data

Previous studies (Arcini et al. 2014; Bondioli et al. 2016; Osipov et al. 2020; Pfeiffer & Sealy, 2006) have described a highly variable association between isotopic values and skeletal measurements. In La Torrecilla, stable isotope values correlate with diaphyseal shape and diameter products, but the correlations widely vary according to sex, side, and anatomical region (Table 5). Before discussing these results, it should be borne in mind that isotopic values from collagen reflect the diet of individuals during the 10-30 years before their death and during a shorter time span in the case of ribs (Fahy, Deter, Pitfield, Miszkiewicz, & Mahoney, 2017; Hedges, Clement, Thomas, & O'Connell T, 2007). In contrast, adult stature is largely shaped during growth (Vercellotti et al., 2014) and is influenced by other factors (genetic, environmental, and cultural) besides diet (Vercellotti et al., 2014), potentially confounding the correlation with isotopic values. In summary, even if the diet influences both types of variable (stable isotopes and stature), their combined consideration should be approached with caution.

Females in our study show a negative correlation of $\delta^{15}N$ with left and right femoral Dprod and left humeral Dprod,and of $\delta^{13}C$ with right humeral shape (Table 5). In males, long bone strength (Dprod) is not correlated with any isotopic value. These findings may tentatively be attributed to a greater variability in the social roles of women in this community. Thus, women with lower economic or social status may have had lesser access to animal proteins, a proportionally higher consumption of plants with lower $\delta^{13}C$ values, and a greater engagement in more stressful and perhaps more diverse activities. Al-Andalus was a highly stratified society with the common presence of female servants and slaves, even in less wealthy households (Mesned Alesa, 2007). Furthermore, considering the importance placed on women as wives and mothers (Mesned Alesa, 2007), it seems reasonable to assume that women destined to give birth (young married women) or to be wet nurses would receive a better diet and be less involved in hard work. In any case, our results suggest a consistency in female patterns of diet and activity level that is not observed for males. This may be due to a general involvement of men in work related to maintenance of the community (farming, livestock care, and construction), regardless of their economic status and access to different types of food.

Males show a significant positive correlation between FMS (femoral shape) of both sides and $\delta^{15}N$ values (Table 5). Anteroposteriorly elongated femora can be linked to both greater mobility and habitual walking on rough terrain (Agostini et al., 2018; Holt & Whittey, 2019; Marchi, Sparacello, Holt, & Formicola, 2006). In La Torrecilla, the daily short-distance or seasonal long-distance driving of livestock to nearby mountainous areas (Malpica Cuello, 2012) was probably carried out by a subset of the male population. The consumption of milk and dairy products would have increased during these periods, which may explain the relationship between $\delta^{15}N$ values and femoral shape in males.

Our results contrast with those of Osipov et al. (2020), who found no significant correlations of either $\delta^{13}C$ or $\delta^{15}N$ with diaphyseal cross-sectional properties in rural Islamic Can Fonoll. This may be related to both environmental and methodological factors. La Torrecilla is a mainland context situated close to hills and mountain ranges, whereas Can Fonoll lies inland and is comparatively flatter, which may have generated differences in biomechanical stimuli between these populations (e.g., time spent on rough terrain). Furthermore, Osipov et al. (2020) did not control for sex or body mass in their analyses, which may also account for differences with the present findings.

Summing up: cultural, environmental, and socioeconomic factors and their effect on sex differences

The preceding sections discuss the biocultural implications of each variable analyzed in this study. Results are heterogeneous and their interpretation rarely straightforward, explaining our decision to follow a topic-based order up to this point. However, the main aim of our study was to explore sex differences from multiple perspectives (diet, growth, physical activity), and the following question has yet to be addressed: *"What insights into gender differences at La Torrecilla are gained from isotope analyses and osteological data, and how do these lines of evidence inform each other?* Taken together, the present findings indicate: a) a potential sex difference in parental investment during infancy and adolescence, b) no obvious sex differences in adult diet, and c) sex differences in daily activities. In general, the results of our analyses point to a combined effect of cultural, environmental, and socioeconomic factors on sex-specific biological responses.

Evidence of sex differences in daily activities at La Torrecilla is predictable, given the marked gender differentiation in traditional Islamic societies (García Sánchez, 2006).

Interestingly, in the present study, this differentiation is simultaneously supported by the long bone data, age-specific male $\delta^{13}C$ values, and the correlation of male $\delta^{15}N$ values with femoral shape. These findings offer an intriguing hint of the way in which socially-sanctioned gender roles can translate into specific biological (skeletal and isotopic) patterns within a given population. Furthermore, comparisons with the results of previous research in other Iberian Islamic populations illustrate how specific expressions of culturally imposed gender differences can be modulated by environmental and socioeconomic factors. Diet composition, especially the relative contribution of C_3 *versus* C_4 plant products, appears to have been widely diversified in Iberia (López-Costas & Alexander, 2019). As noted above, this can be largely attributed to the effects of geophysical factors on the relative viability of crop cultivations (wheat vs. millet) and/or access to specific food sources (e.g., fish and sugarcane). It is also likely that the range of locally available foods affected the expression of culturally sanctioned dietary differences between men and women and the degree and direction of isotopic differences between the sexes (Fig. 2). Comparison of isotopic and osteological data from La Torrecilla with those from other Iberian Islamic contexts suggest that socioeconomic conditions were a critical factor in population-specific sex differences. As already mentioned, rural and urban populations probably differed not only in their access to different foods but also in the types of activity performed by each sex, especially by women (Inskip, 2013; Laffranchi et al., 2016a). Other anthropological studies have highlighted the influence of environmental and socioeconomic factors on the type and degree of sexual division of labor (e.g., Maggiano et al. 2008; Havelková, Villotte, Velemínský, Poláček & Dobisíková, 2011). Although this was probably also the case for al-Andalus (Laffranchi et al., 2016a; Shatzmiller, 1997), there is a need for further studies that explicitly compare sex differences in activities between rural and urban contexts in order to test this hypothesis.

Conclusion

This study provides novel data on the biological correlates of gender differentiation in rural al-Andalus through the analysis of sex differences in diet, life quality, and physical activity in the Medieval rural Islamic population of La Torrecilla (Arenas del Rey, Granada). Results obtained depict a community with a high degree of sexual dimorphism in stature and evident sex differences in habitual physical activities. Although the isotopic ratios observed suggest that men and women enjoyed access to the same type of food, quantitative differences in favor of males cannot be ruled out, given the traditional customs of the time and the results obtained for stature. A wider variance in $\delta^{13}C$ values among males suggests that some men had access to non-local food sources, possibly due to the frequent displacements required in livestock farming. Correlations between stable isotope ratios and long bone diaphyseal properties revealed the following sex-specific patterns: lower protein intake and lower $\delta^{13}C$ ratios coinciding with higher levels and possibly more varied types of activity in females; and higher protein intake being associated with greater mobility among males.

Overall, this study indicates the presence of strongly genderized rural communities in Medieval Islamic Spain. The results demonstrate the advantage of considering multiple variables when reconstructing the lifeways of past populations and elucidating patterns of gender differentiation and social inequality among human communities.

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The late Prof. Philippe du Souich carried out the excavations and the first anthropological study of La Torrecilla skeletal remains. This work is humbly dedicated to his memory.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

No ethical committee approval was required for this study.

Figure legends:

Figure 1. a) Geographical position of La Torrecilla (green star) and other sites mentioned in the text (comparative isotopic dataset only). The image in the circle shows the local environment, including the Bermejales swamp, with the mountain range of Tejeda and Almijara in the background (photograph by S. Jiménez- Brobeil); b) plan of the cemetery of La Torrecilla, with the photograph of a burial on the right (photograph by P. Du Souich, 1975) and the two radiocarbon-dated burials highlighted in green.

Figure 2. a) δ^{13}C and δ^{15}N values of La Torrecilla compared with mean values and ranges in human and faunal samples from other Islamic sites from Spain; b) plot representing individual values and dispersion by sex of δ^{13}C and δ^{15}N in La Torrecilla.

Figure 3. Comparison between La Torrecilla and other rural and urban Islamic populations of Spain in a) mean stature and standard deviation, and b) sexual dimorphism in stature.

Figure S1. Mean δ^{13}C and δ^{15}N values of males and females in La Torrecilla compared with sex-specific ranges from urban (yellow) and rural (black) Islamic sites in Spain. Names of the sites (not indicated here for simplicity) are given in Figure 2.

Supplementary material:

Table S1. Sample distribution for each variable (sample size and percentage over total sample size) by sex and age class. YA=Young Adults, MA=Middle Adults

Table S2. Stable isotope values in bone collagen from human and animal samples. YA= young adult; MA= middle adult

Table S3. List of comparative Islamic sites (only humans) in Iberia exhibiting the relative stable isotope ranges and mean values by sex depicted in Figure 2. N: number of individuals; SD: standard deviation; min: minimum; max: maximum; NA: sex not assessable. *Es Soto-Ibiza: only means of the faunal isotopic data are shown in Figure2, due to the absence of mean values by sex in Fuller et al. (2010).

#: sex means estimated by the authors of this study.

Table S4. Results of Levene's and the Fligner-Killeen tests. Significant results are highlighted in bold.

Table S5. Descriptive statistics and sexual dimorphism index (SDI) values for linear measurements, diaphyseal variables, stature, and body mass. n: sample size, SD: standard deviation, SDI: Sexual Dimorphism Index. All linear measurements are in mm, Dprod in mm², stature in cm, and body mass in kg. See Table 1 for abbreviations.

Table 1. Linear measurements and diaphyseal cross-sectional properties included in the study

Variable	**Abbreviation**	**Formula**
Humeral maximum diameter at midshaft	HDMax	
Humeral minimum diameter at midshaft	HDMin	
Femoral maximum length	FML	
Femoral vertical head diameter	FVHD	
Femoral anteroposterior diameter at midshaft	FAPD	
Femoral mediolateral diameter at midshaft	FMLD	
Cross-sectional properties ‡		
Humeral midshaft shape	HMS	HDMax/HDMin
Femoral midshaft shape	FMS	FAPD/FMLD
Humeral product of diameters	HDprod	HDMax*HDMin
Femoral product of diameters	FDprod	FAPD*FMLD
Percent absolute bilateral asymmetry§	%AA	[(max-min)/(average max & min)]*100

† Linear measurements from Martin & Saller (1957)
‡ HMS from Mazza (2019), FMS, HDprod and FDprod from Stock and Shaw (2007)
§Auerbach & Ruff (2006)

Table 2. Summary statistics of isotopic values in the human samples by sex and age, and results of the Independent samples t test; YA= young adults; MA= middle adults; n= sample size; SD=Standard deviation.

	Males					Females							
δ^{13}C‰(V-PDB)	*n*	*Min*	*Max*	*Mean*	*SD*	*n*	*Min*	*Max*	*Mean*	*SD*	t	p	Hedges‘ g ¶
YA‡	22	-17.7	-13.1	-15.4	1.4	25	-17.8	-13.7	-15.6	1	-0.6	0.502	0.192
MA‡	17	-19.5	-14.2	-16.7	1.4	10	-17.6	-14.6	-15.9	1	1.6	0.127	0.589
Total	39	-19.5	-13.1	-16	1.5	35	-17.8	-13.7	-15.7	1	0.8	0.445	0.186
δ^{15}N‰ (AIR)	*n*	*Min*	*Max*	*M*	*SD*	*n*	*Min*	*Max*	*M*	*SD*			
YA	22	9.1	11.7	10	0.5	25	8.9	12.6	10	0.9	291†	0.741†	0.050 §
MA	17	8.8	11.1	9.9	0.6	10	8.9	10.6	9.8	0.5	-0.7	0.512	0.252
Tot	39	8.8	11.7	10	0.5	35	8.9	12.6	9.9	0.8	739.5†	0.541†	0.072 §

† Calculated with Mann-Whitney U test (U statistic is presented).

‡δ^{13}C‰(V-PDB) Males YA *vs*. MA: $t = -2.8$; $p = 0.008$, Hedge's g = 0.908

§ Effect size: r; 0.1=small, 0.3=medium, 0.5=large (Cohen, 1988)

¶ Effect size: Hedges' g; 0.2=small, 0.5=medium, 0.8=large (Cohen, 1988)

Table 3. Sex comparisons for stature, shape indices, Dprod, and humeral %AA.
n: sample size, SD: standard deviation, SE: standard error, SDI: sexual dimorphism index. Stature in cm and Dprod in mm^2.
See Table 1 for abbreviations.

	Males	Females				
				Independent samples t test		
	n / Mean / SD	n / Mean / SD	SDI	t	p	Hedges' g‡
Stature	45 / 164.81 / 6.46	37 / 152.14 / 5.14	0.080	9.675	**<0.001**	2.136
				Independent samples t test		
Shape	n / Mean / SD	n / Mean / SD	SDI	t	p	Hedges' g‡
Right HMS	43 / 1.222 / 0.089	40 / 1.301 / 0.100	-0.063	-3.819	**<0.001**	0.836
Left HMS	39 / 1.200 / 1.101	41 / 1.300 / 0.113	-0.080	-4.175	**<0.001**	1.608
Right FMS	43 / 1.074 / 0.082	44 / 1.044 / 0.088	0.028	1.623	0.108	0.353
Left FMS	43 / 1.052 / 0.078	43 / 1.030 / 0.099	0.021	1.135	0.260	0.247
				ANCOVA †		
Dprod	n / Adjusted mean / SE	n / Adjusted mean / SE	SDI §	F	p	ω^2 ‡
Right HDprod	38 / 381.2 / 8.2	31 / 292.8 / 9.3	0.264	40.158	**<0.001**	0.177
Left HDprod	36 / 343.13 / 7.97	32 / 286.47 / 8.58	0.180	18.650	**<0.001**	0.098
Right FDprod	40 / 716.01 / 14.78	36 / 624.41 / 15.82	0.137	13.936	**<0.001**	0.057
Left FDprod	41 / 738.50 / 14.75	36 / 630.59 / 16.05	0.158	18.920	**<0.001**	0.070
				Mann-Whitney U test†		
%AA	n / Mean (Median) / SD	n / Mean (Median) / SD	SDI	U	p	r‡
HMS	36 / 6.40 (5.71) / 4.68	39 / 4.23 (2.74) / 3.90	0.414	496.5	**0.029**	0.252
HDprod	36 / 10.61 (10.51) / 7.39	39 / 5.24 (4.93) / 4.32	0.706	401	**0.001**	0.369

† For Mann-Whitney U test, medians, along with means, are presented. For ANCOVA, adjusted (for body mass) means are presented

‡Effect size; Hedges' g: 0.2=small, 0.5=medium, 0.8=large (Cohen, 1988), ω^2: 0.01=small, 0.06=medium, 0.138=large (Cohen, 1988), r: 0.1=small, 0.3=medium, 0.5=large (Cohen, 1988)

§ SDI calculation for Dprod was based on adjusted means

Table 4. Statistical comparisons for humeral shape indices and unadjusted Dprod between right and left sides for each sex. n: sample size, SD: standard deviation. Dprod in mm². See Table 1 for abbreviations.

	Right			Left			Paired samples t-test		
	n	Mean	SD	n	Mean	SD	t	p	Cohen's d†
Males									
HMS	36	1.226	0.090	36	1.195	0.103	1.199	0.053	0.333
HDprod	36	400.12	54.66	36	366.27	52.33	5.307	**<0.001**	0.884
Females									
HMS	39	1.302	0.101	39	1.307	0.113	-0.335	0.740	0.054
HDprod	39	267.46	40.30	39	258.42	35.46	3.521	**0.001**	0.564

† Cohen's d: 0.2=small, 0.5=medium, 0.8=large (Cohen, 1988)

Table 5. Results of Pearson correlation analysis between isotopic values ($\delta^{13}C$ and $\delta^{15}N$) and long bone cross-sectional properties, body mass, and stature.

	$\delta^{13}C$						$\delta^{15}N$					
	Males			Females			Males			Females†		
	n	r	p	n	r	p	n	r	p	n	rho	p
Right HDprod	30	0.18	0.361	25	-0.1	0.653	30	0.04	0.837	25	-0.33	0.113
Left HDprod	30	0.15	0.432	26	-0.01	0.981	30	-0.34	0.074	**26**	**-0.42**	**0.036**
Right FDprod	32	0.32	0.082	29	-0.24	0.216	32	-0.24	0.198	**29**	**-0.46**	**0.015**
Left FDprod	35	0.26	0.135	29	-0.32	0.102	36	-0.17	0.316	**29**	**-0.39**	**0.041**
Right HMS	34	0.09	0.614	**29**	**-0.39**	**0.039**	34	-0.15	0.406	29	0.07	0.702
Left HMS	33	0.01	0.948	30	-0.16	0.414	33	0.05	0.791	30	0.26	0.167
Right FMS	34	-0.24	0.171	32	-0.04	0.819	**34**	**0.47**	**0.005**	32	-0.11	0.558
Left FMS	37	-0.11	0.505	33	-0.12	0.512	**37**	**0.37**	**0.023**	33	-0.09	0.627
Body mass	35	-0.02	0.900	29	-0.16	0.420	35	-0.09	0.622	28	-0.23	0.223
Stature	37	0.06	0.743	31	-0.01	0.963	37	0.18	0.293	34	-0.007	0.972

†: Results of Spearman correlation analysis.

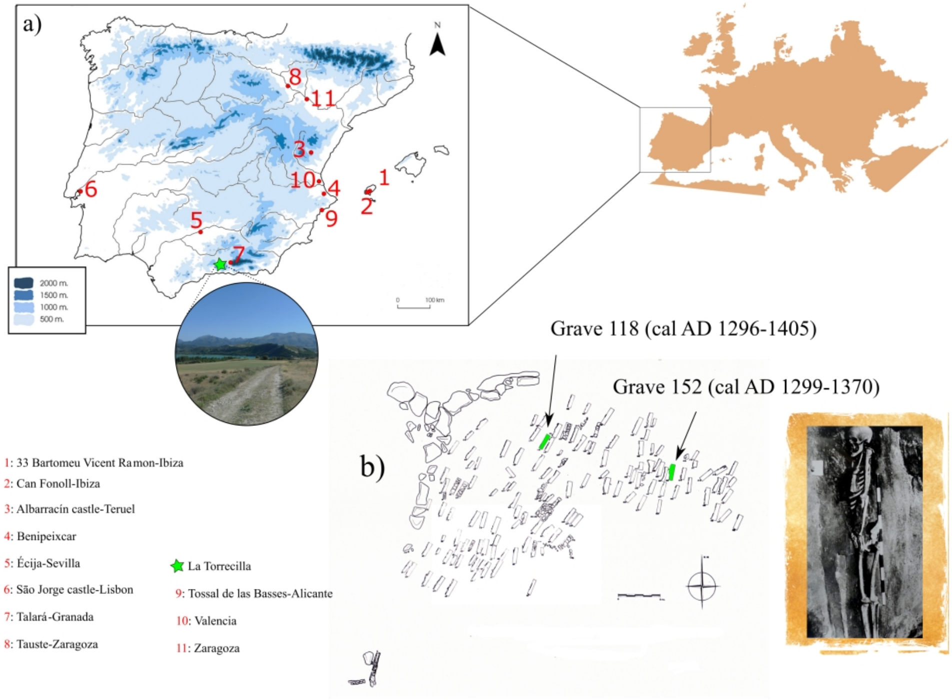


Figure 1. a) Geographical position of La Torrecilla (green star) and other sites mentioned in the text (comparative isotopic dataset only). The image in the circle shows the local environment, including the Bermejales swamp, with the mountain range of Tejeda and Almijara in the background (photograph by S. Jiménez- Brobeil); b) plan of the cemetery of La Torrecilla, with the photograph of a burial on the right (photograph by P. Du Souich, 1975) and the two radiocarbon-dated burials highlighted in green.

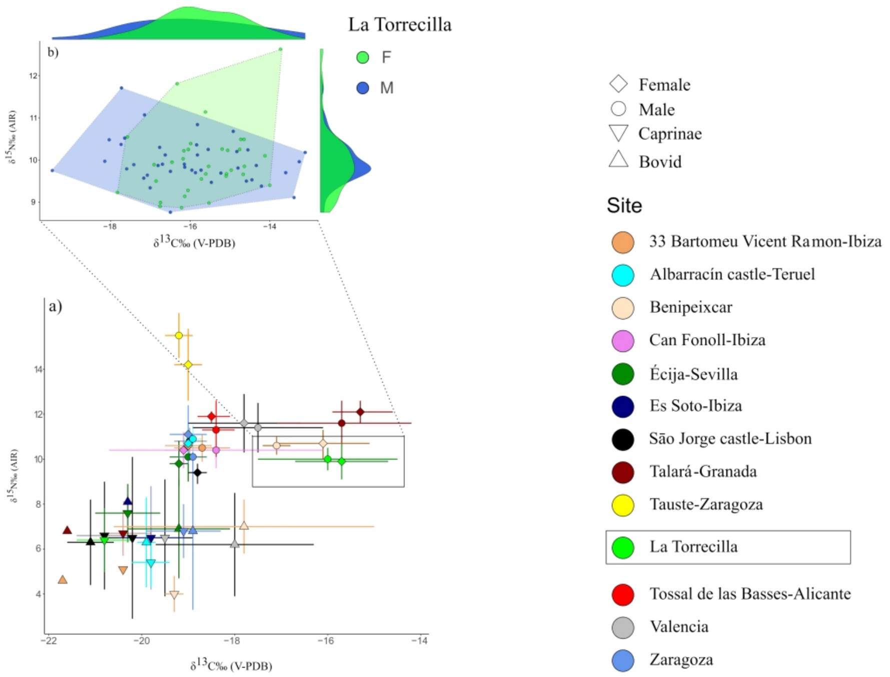
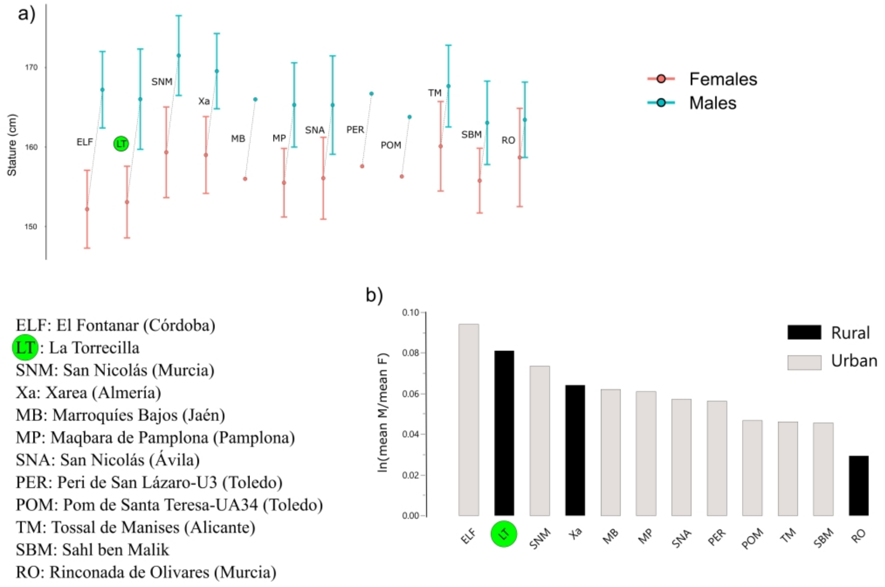


Figure 2. a) δ^{13}C and δ^{15}N values of La Torrecilla compared with mean values and ranges in human and faunal samples from other Islamic sites from Spain; b) plot representing individual values and dispersion by sex of δ^{13}C and δ^{15}N in La Torrecilla.

289x205mm (300 x 300 DPI)



ELF: El Fontanar (Córdoba)
LT: La Torrecilla
SNM: San Nicolás (Murcia)
Xa: Xarea (Almería)
MB: Marroquíes Bajos (Jaén)
MP: Maqbara de Pamplona (Pamplona)
SNA: San Nicolás (Ávila)
PER: Peri de San Lázaro-U3 (Toledo)
POM: Pom de Santa Teresa-UA34 (Toledo)
TM: Tossal de Manises (Alicante)
SBM: Sahl ben Malik
RO: Rinconada de Olivares (Murcia)

Figure 3. Comparison between La Torrecilla and other rural and urban Islamic populations of Spain in a) mean stature and standard deviation, and b) sexual dimorphism in stature.

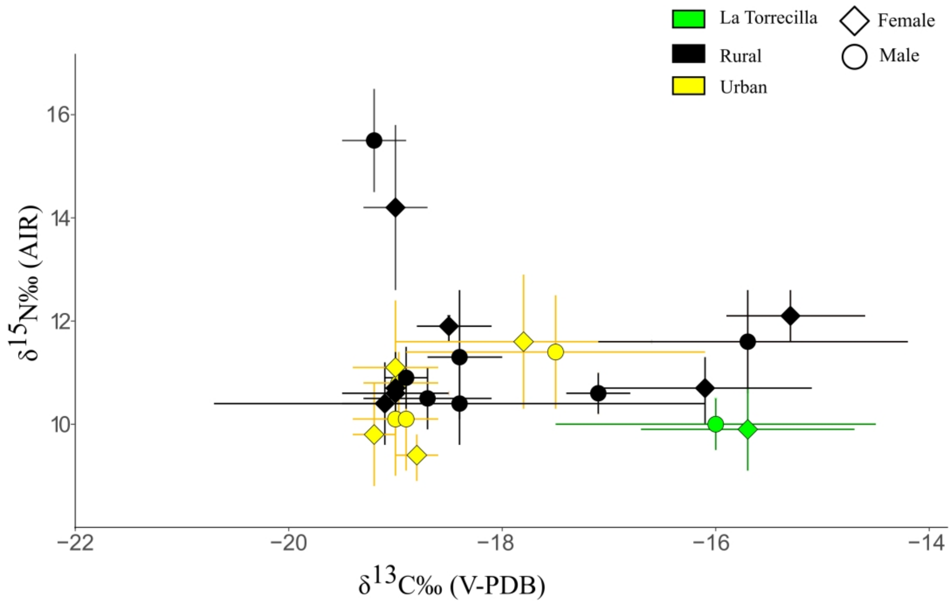


Figure S1. Mean δ^{13}C and δ^{15}N values of males and females in La Torrecilla compared with sex-specific ranges from urban (yellow) and rural (black) Islamic sites in Spain. Names of the sites (not indicated here for simplicity) are given in Figure 2.