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The Effect of Diet and Sociopolitical Change on Physiological Stress and Behavior in Late Roman-Early Byzantine (300-700 AD) and Islamic (902-1235 AD) Populations from Ibiza, Spain

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Abstract

Objectives
This study evaluated chronological changes in physiological stress and levels of habitual loading of Ibizan populations from the Late Roman-Early Byzantine (LREB) to the Islamic period (300-1235 AD) using measures of body size and bone cross-sectional properties to compare Urban LREB, Urban Medieval Islamic, and Rural Medieval Islamic groups. It also explored the effect of diet, modeled using stable isotopes, on physiological stress levels and behavior.

Materials and Methods

The sample comprised individuals from three archaeological populations: Urban Late Roman- Early Byzantine (LREB) (300-700 AD), Medieval Urban Islamic (902-1235 AD), and Medieval Rural Islamic. Bone lengths, femoral head dimensions, and cross-sectional properties, diaphyseal products and circumferences, were compared to assess differences in body size and habitual loading in 222 adult individuals. Ordinary least squares regression evaluated the correlations between these measures and carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope ratios in 115 individuals for whom both isotope values and osteological measures are available.

Results

The Medieval Rural Islamic group had shorter stature and reduced lower limb cross-sectional properties compared to the two urban groups. Limb shape differs between Urban LREB and Urban Medieval Islamic groups. Measures of body size length were positively correlated with $\delta^{13}C$ values in all individuals and separately in the Urban LREB and Rural Medieval Islamic groups. $\delta^{15}N$ showed a positive correlation with left humerus shape in the Urban LREB sample.

Conclusions

The low stature and cross-sectional properties of the Medieval Rural Islamic group may be an indicator of greater physiological stress, potentially due to poorer diet. Positive correlations between measures of body size and $\delta^{13}C$ values further suggest that greater access to C_4 resources improved diet quality. Alternatively, this relationship could indicate greater body size among migrants from areas where individuals consumed more C_4 resources.

Keywords: Stable Isotopes; Bone Functional Adaptation; Behavior; Mediterranean; Dietary Reconstruction, Ibiza

1. Introduction

1.1 Archaeological and Historical Background

The Spanish island of Ibiza, part of the Balearic Islands, is located in the Western Mediterranean. The island has a surface area between 541-570 km^2, and the terrain is rugged (Naval Intelligence Division, 1941; Vallès, 2000 a,b,c). Its location, along major maritime Mediterranean trade routes, made it an important hub for trade and migration since the 8th Century BC (Ruiz de Arbulo, 1991, Aubet 1993, 1995, Moreno, 2003; Garrigós et al., 2004; Albero Santacreu et al., 2019; Zavagno, 2019). The Phoenician period was followed by the Carthaginian or Punic period, which from the 6th century onwards involved deep demographic, economic, religious and cultural transformations to the island (Costa, 2019a). From the 2nd century BC and in particular from the 1st century AD onwards, Ibiza came under the control of Rome (Costa, 2019b). During the Late Antiquity-Early Byzantine period (4th-8th centuries AD), Roman political control collapsed, Vandals conquered the island from c. 455 AD until 535 AD, and subsequently

the Byzantine Empire asserted control until approximately 700 AD (O'Callaghan, 1983; Collins, 1995; Kulikowski, 2004; Costa, 2019c). Changes came with the arrival of Islam in Iberia in 711 AD, with Islamic influence or exploration extended to Ibiza in the 8th and 9th centuries and a final colonization of Ibiza in 902 AD (O'Callaghan, 1983; Collins, 1995; Garrigós et al., 2004; Ferrer Abárzuza, 2019a; Zavagno, 2019). This colonization of the Balearic Islands in 902 AD as evidenced in historical texts, appears to have been quick by migration from the Iberian Peninsula or in a small and less likely scale, by an influx from North Africa (Ferrer Abárzuza, 2019a). Islamic rule ended in 1235 AD with the conquest of the island by Christian troops from the Crown of Aragon (Ferrer Abárzuza, 2019b).

Some attention has been given to the effect of the socio-political changes that occurred during these periods on behavior and levels of physiological stress (e.g. diet quality, disease load) (see Márquez-Grant, 1999, 2006) but this still largely remains poorly understood. This study focuses on the relationship between diet, stress, and behavior. Previous isotopic studies of diet have demonstrated diachronic change and inter-individual variability in diet throughout the Late Roman-Early Byzantine (LREB) and the Medieval Islamic period (Alexander et al. 2019; Alaica et al., 2019; Dury et al., 201; Fuller et al., 2010; Márquez-Grant et al., 2003; Nehlich et al., 2012; Pickard et al., 2017). Other lines of evidence also suggest political, economic, and cultural change across these periods (Costa, 2019c; Ferrer Abárzuza, 2019a; Gurrea and Martín, 2000; Ramon, 1986). As on mainland Spain, a number of rural settlements in the Balearic Islands were abandoned in the Late Roman period due to either population decline or relocation to more defensible sites (Florit and Ontiveros, 2011). This is also potentially linked to a decrease in the export of wine and oil (Ramon, 1995). These changes in settlements and in the economy, resulting in a reorganization of the rural landscape, have also been observed especially in the 3rd century AD onwards in a number of sites in Ibiza (Ramón, 1995; González and Pachecho, 2002, Costa, 2019c). Alternatively, a general period of aridity and drought appears to have occurred in the Mediterranean between AD 300-400 and AD 800 (Lamb, 1982). Whether consequent crop failure contributed to change in settlement patterns remains unclear, but some reoccupation of rural settlements began in Byzantine times (Ramon 1995; González and Pacheco, 2002). Islamic migrants from Spain in particular, as well as North Africa contributed to the reoccupation of rural areas and introduced new technologies and crops amongst other innovations; there was also considerable diversity in farming methods (Kirchner, 2009; Heiss et al., 2014; Ferrer Abárzuza, 2019a).

Despite these considerable social, political, and behavioral transformations, published studies on disease and behavior from skeletal remains in this latter period are lacking with some exceptions (Kyriakou et al., 2012), and data is primarily encountered in dissertations or unpublished reports (e.g. Márquez-Grant,

1999; Camarós i Pérez et al., n,d,; Valli, 2012; Gundersen, 2019; Tonks, n.d.). One notable study has compared Medieval Rural Islamic skeletal material to LREB populations and mainland Spanish medieval samples (Kyriakou et al., 2012). Rural Islamic individuals exhibited lower stature than earlier Ibiza populations and medieval Islamic and Christian groups from mainland Spain. However, the Rural Islamic group also showed lower frequencies of cribra orbitalia, an indicator of anemia or other non-specific stress (Cole and Waldron, 2019). This study explores how health, workloads, and behavior varied across approximately 1000 years in Ibiza's history by comparing the Late Roman-Early Byzantine (300-700 AD) to the Islamic period (902-1235 AD) using measures of body size and cross-sectional properties. These measures are used because they provide direct evidence of differences in body size and habitual behavior. It also evaluates the relationship between diet, physiological stress, and behavior. This will allow new insights into the history of the Balearic Islands and complement prior archaeological studies.

1.2 Skeletal Studies of Body Size, Physiological Stress, and Behavior

Analysis of body size and bone robusticity provides insight into levels of physiological stress and behavior of past populations. Growth perturbations, such as disease and malnutrition during childhood, stunt appositional growth and accrual of body mass. If deficits are severe or sustained enough to prevent catch-up growth, they result in reduced adult stature, long bone length, and body mass (Saunders, 2008; Mays et al., 2009). Variation in stature and bone length has been used extensively to evaluate differences in longitudinal growth reflective of difference in growth stress between populations (Maat, 2005; Saunders, 2008; Mays et al., 2009; Ruff et al., 2013; Lukacs et al., 2014; Temple et al., 2014; Hughes-Morey, 2016; Mays, 2016). Joint surface dimensions allow reconstruction of body mass, as they undergo functional adaptation to the mechanical load imposed by body mass (Trinkaus et al., 1994; Lieberman et al., 2001; Auerbach and Ruff, 2004). As is the case with long bone length, temporal and chronological changes in body mass have been considered indicative of differences in disease load and diet during development (Pfeiffer and Sealy, 2006; Stock et al., 2010, 2011; Auerbach, 2011). Importantly, articular surface dimensions may most closely correspond to body weight at the end of development and not closely track body mass changes in adulthood. In a study of modern individuals, femoral head dimensions exhibited a higher correlation with body weight at the age of 18 years than body weight at the time of the study (Ruff et al., 1991). Thus, both long bone length and joint dimensions primarily provide information about levels of developmental stress from birth to young adulthood.

Analyzing diaphyseal cross-sectional properties, reinforcement of skeletal elements in a transverse plane to the long axis, allows reconstruction of both the habitual behavior and body size of past populations (Ruff et al., 2006a; Ruff, 2008; Ruff and Larsen, 2014). While joint surfaces primarily adapt to the

mechanical loads imposed by body weight, cross-sectional dimensions adapt to withstand habitual loads imposed by both body size and activity (Ruff, 2000; Lieberman et al., 2004). Most studies have used diaphyseal cross-sectional properties to reconstruct behavior (Bridges, 1989; Holt, 2003; Stock and Pfeiffer, 2004; Marchi et al., 2006; Sparacello and Marchi, 2008; Larsen and Ruff, 2011; Lieverse et al., 2011; Stock et al., 2011; Macintosh et al., 2014, 2017; Ruff and Larsen, 2014; May and Ruff, 2016). Lower limb shape and strength have primarily been used to identify differences in levels of terrestrial mobility, because bipedal locomotion creates greater loads in the anteroposterior than the mediolateral plane (Holt, 2003; Stock and Pfeiffer, 2004; Marchi et al., 2006; Sparacello and Marchi, 2008; Shaw and Stock, 2009, 2013; Lieverse et al., 2011). Variation in upper limb shape and strength has been linked to the practice of different subsistence modes and the employment of different technology (Haapsalo et al, 1996; Stock and Pfeiffer, 2004; Macintosh et al., 2014; Shackelford, 2014; Cameron et al., 2018). In archaeological studies, increased humeral strength corresponds to evidence for greater habitual loading due to employment of watercraft or intensified resource processing (Stock and Pfeiffer, 2004; Macintosh et al., 2017; Cameron and Stock, 2018). Similarly, the use of different tools alters the habitual range of motion, producing differences in bone shape (Stock and Pfeiffer, 2004; Cameron et al., 2018). For instance, repetitive scraping stimulates uniaxial bone hypertrophy, resulting in less circular humeral diaphyses in indigenous North American females involved in the colonial fur trade (Cameron et al., 2018).

Furthermore, combining estimates of body mass from diaphyseal cross-sectional properties and joint dimensions may provide a unique perspective on changes in weight throughout life (Pomeroy et al., 2018). Although the greatest changes in both diaphyseal cross-sectional properties and joint dimensions occur during the growth period, diaphyseal cross-sections continue to respond to changes in mechanical loading into later adulthood, albeit at a reduced rate compared to the juvenile period (Ruff et al., 1991; Lieberman et al., 2001). Therefore, it is reasonable to postulate that joint dimension comparisons shed light on body mass differences established by young adulthood, whereas diaphyseal cross-sectional properties may prove more indicative of body mass at time of death (Pomeroy et al., 2018). A small number of studies have used bone robusticity to analyze differences in body mass in both juveniles and adults of past and current populations (Ruff et al., 1991; Cowgill, 2010, 2017; Robbins et al., 2010; Pomeroy et al., 2018). However, since diaphyseal dimensions also adapt to activity induced loading, it has proven difficult to parcel out the extent to which differences in cross-sectional properties between past populations reflect variation in activity level or body mass (Cowgill, 2017).

Lastly, variation in body size and cross-sectional properties can reflect genetic differences between populations. Some proportion of bone cross-sectional properties and bone length is heritable, though the extent of genetic control remains poorly understood (Holliday, 1997; Peacock et al., 2005; Ruff et al., 2006a; Duren et al., 2013; Adams and Ackert-Bicknell, 2015; Roseman and Auerbach, 2015). Joint surfaces and bone length "grow ahead" of body mass, suggesting growth towards genetically canalized endpoint, which may vary between populations being compared (Frisancho et al., 1980; Ruff, 2007; Saunders, 2008; Ruff et al., 2013; Roseman and Auerbach, 2015). Similarly, studies have repeatedly demonstrated that population structure explains a substantial portion of variation in body size between populations (Allen, 1877; Holliday, 1997; Cowgill et al., 2012; Ruff et al., 2012; Roseman and Auerbach, 2015). As Ibiza has been repeatedly colonized throughout its history, the contribution of migration to Ibiza's genetic history makes this an especially important consideration. The origin of migrants to Ibiza and the extent of their genetic contribution to contemporary Ibiza remain much debated, and a full consideration falls beyond the scope of this analysis (Tomàs et al., 2006; Zalloua et al., 2018; Biagini et al., 2019). Craniometrics may give support to some migration from North and Sub-Saharan Africa since at least the Punic colonization (6th century BC onwards) (Márquez-Grant, 2005, 2006) and genetic discontinuity through time is also supported by recent DNA studies (Biagini et al. 2019). Migration, whether primarily from mainland Spain as well as North and Sub-Saharan Africa seems to be the scenario for most of Ibiza's archaeological past, as documented not only through biology but also material culture (Kaufman, 2000; Márquez-Grant, 2006; Ferrer, 2019). Overall, our critical analysis of skeletal cross-sectional properties and body size can shed necessary light on chronological variation in the levels of physiological stress, behavior, and genetics of Ibizan populations.

1.3 The Relationship between Diet, Physiological Stress, and Behavior

Stable isotope analysis and historical sources permit dietary reconstruction, facilitating nuanced interpretations of chronological variations in body size and behavior. The stable carbon isotope ratio, $^{13}C/^{12}C$ ($\delta^{13}C$), and stable nitrogen isotope ratio, $^{15}N/^{14}N$ ($\delta^{15}N$), of bone collagen indicate the sources of dietary protein (Chisholm et al., 1982; Sealy, 2001; Katzenberg, 2008; Salazar-García et al., 2014; Pickard et al., 2017). When individuals primarily depend on the terrestrial food web, variation in $\delta^{13}C$ between individuals or populations may reflect differences in the proportion of C_3 and C_4 crops in diet, as C_4 crops and animals eating these plants are typically enriched in ^{13}C relative to the C_3 food web. Alternatively, enrichment in $\delta^{13}C$ can result from consumption of marine foods, due to the relative ^{13}C enrichment of inorganic carbon in ocean water in comparison to atmospheric CO_2 (Schoeninger and DeNiro, 1984). Variability in $\delta^{15}N$ arises due to soil values, method of fixing atmospheric N_2, and trophic level fractionation effects. Within a single food chain, organisms occupying a higher trophic level have

higher $\delta^{15}N$ (Schoeninger and DeNiro, 1984; Katzenberg, 2008). As aquatic food chains are generally longer than terrestrial ones, $\delta^{15}N$ comparisons have been used to distinguish individuals that include marine or freshwater resources in their diet from those that do not (Kusaka et al., 2010).

A central ambiguity in reconstructing diet from bone collagen is that it remains unclear how accurately carbon isotope values reflect dietary energy sources (i.e. lipids and carbohydrates). It has been well established that collagen is, in protein adequate diets, predominantly synthesized from dietary protein (Ambrose and Norr, 1992; Jim et al., 2004, 2006; Katzenberg, 2008; cf. Fernandes et al., 2012). As C_4 crops tend to be high in carbohydrates, collagen carbon values would underestimate their contribution to diet. However, Roman-Medieval/Islamic period Spanish diets were likely dominated by cereals (predominantly wheat and barley) and low in protein (Pickard et al., 2017). In this case, nutrient scrambling may occur, resulting in an increased contribution of carbohydrate carbon atoms to the synthesis of non-essential amino acids. Conversely, nitrogen will still derive from dietary protein (Jim et al., 2006; Pickard et al., 2017). This potential scenario must be taken into account when interpreting stable isotope signatures of Ibizan populations. However, variation in nitrogen isotope ratios may also reflect differences in levels of physiological or dietary stress (Katzenberg, 2008; Waters-Rist et al., 2011; Trochine et al., 2019).

Evaluating correlations between skeletal dimensions and stable isotope ratios of bone collagen can improve understanding of the relationship between subsistence strategies, body size, behavior, and physiological stress levels. This approach has been previously employed in only a handful of studies (Larsen et al., 2001; Pfeiffer and Sealy, 2006; Suby and Guichón, 2009). These detected correlations between stable isotope signatures, body mass, and bone cross-sectional properties, indicating that such analysis has the potential to provide new insights into the interactions between diet, stress levels, and behavior. When stable isotopes serve as a proxy for diet, correlations between stable isotope signatures, joint dimensions, and diaphyseal cross-sectional properties may reflect several scenarios: **1.)** Individuals with different diets may consume a different number of calories or have a heterogeneous risk of malnutrition. In this case, differences in joint dimensions and bone cross-sectional properties will reflect variation due to body mass. **2.)** Correlations between diaphyseal cross-sectional properties, shape, and stable isotope signatures can arise from different subsistence behaviors involving different levels of habitual loading, terrestrial mobility, and the use of different technologies.

1.4 Previous Studies on Dietary Reconstruction in Late Roman- Early Byzantine and Islamic Spain (300-1235 AD)

Recent years have seen an increase in the number of isotope studies of archaeological populations in Spain for both dietary reconstruction and provenance. It is in fact, Ibiza that yielded one of the first Spanish studies in isotope analysis to reconstruct diet (Márquez-Grant et al., 2003), with previous studies particularly focusing on trace element analysis (e.g. Subirà and Malgosa, 1992; García and Subirà, 2001). Prior studies of Ibizan diet based on $\delta^{13}C$ and $\delta^{15}N$ stable isotopes of bone collagen indicate that, from the Roman to the Islamic period, Ibizan diet predominantly consisted of C_3 cereal crops (e.g. wheat, barley, and, in the Islamic period, rice) (Fuller et al., 2010; Nehlich et al., 2012; Alaica et al., 2019). Supporting this interpretation, historical sources, archaeological remains (e.g. ploughs, mills, terraced lands) and archaeobotany identify cereal crops such as wheat and barley as main dietary staples from the Late Roman to the Islamic period (Watson, 1983; Garnsey, 1999, García-Sánchez, 2002; Adamson, 2004; Alonso Martínez, 2005; Salas-Salvadó et al., 2006; Dalby and Granger, 2012; Peña-Chocarro et al., 2019). Oil, nuts, fruit, pulses and legumes supplemented the predominantly cereal-based diet. Both isotopic data and historic accounts further indicate that upper class individuals consumed more meat than lower class individuals (Jiménez-Brobeil et al., 2016; Alexander et al., 2019). The type and quantity of meat consumed also likely varied diachronically. The importance of pork to Roman diet is well known, whereas mainland Medieval Iberian Islamic sites show a greater proportion of sheep and goat remains (King, 2001; Grau-Sologestoa, 2015, 2017). In all time periods, cattle may have predominantly been used for traction rather than food (Grau-Sologestoa, 2015). Cultural prohibitions likely also shaped meat consumption. Islamic law prohibited the consumption of pork and shellfish (Adamson, 2004; Constable, 2013). Poultry, milk, and eggs were also common sources of protein in all archaeological periods.

Although C_3 cereals were dietary mainstays from the Roman to Islamic periods, the potential importance of C_4 crops should not be overlooked. Although considered less desirable than wheat, millet was consumed, particularly by the poor and during times of scarcity in the Roman period (Killgrove and Tykot, 2013; Murphy, 2016). Islamic migration is associated with greater consumption of C_4 crops such as millet, sorghum, and sugarcane (Butzer et al., 1985; Adamson, 2004; Glick, 2005; Peña-Chocarro et al., 2019). Isotopic studies confirm greater consumption of C_4 crops in Islamic Ibizan populations (Fuller et al., 2010; Nehlich et al., 2012; Pickard et al., 2017; Alaica et al., 2019; Dury et al., 2018; Peña-Chocarro et al., 2019). However, the greater isotopic diversity of Islamic individuals may also reflect migration, because isotopic signatures of certain individuals may reflect migration from locations where cultivation of C_4 crops was more extensive (Fuller et al., 2010; Pickard et al., 2017; Dury et al., 2018; Alexander et al., 2019). Thus, it remains unclear whether higher $\delta^{13}C$ values of Islamic populations reflect increased cultivation of C_4 crops, an increase in the number of migrants, or both. Differences in rural and urban diet have not been systematically studied, but it has been previously noted that rural Islamic groups

have lower $\delta^{15}N$ signatures than urban groups, a pattern suggesting increased consumption of plant foods (Pickard et al., 2017; Dury et al., 2018).

Recently, a new study has raised the possibility that the calorie contribution of C_4 crops to the Ibizan/ Spanish diet has been overlooked. Dury et al. (2018) examined isotopic signatures of enamel apatite as well as bone collagen from a single Islamic period urban cemetery. Apatite's chemical composition reflects the combined isotopic values of carbohydrates, protein, and lipids (Jim et al., 2004; Katzenberg, 2008; Dury et al., 2018). While collagen samples indicated primarily C_3 protein sources, the apatite $\delta^{13}C$ was consistent with C_4 crops comprising up to 25-40% of whole diet. Thus, C_4 crops such as millets or sorghum may have been more important dietary supplements for Ibizan populations than previously appreciated, but their low protein content masks their contribution in collagen analysis (Dury et al., 2018). While these findings are intriguing, their significance remains ambiguous. Apatite isotopes have not been analyzed in other Ibizan samples and sample size (n=6) was small. The analysis may have predominantly sampled migrants. Furthermore, estimates of carbohydrate intake from conventional (i.e. non-Bayesian) mixing models are generally speculative. Therefore, the relative importance of C_4 and C_3 resources in Ibiza diets remains unclear.

Given the terrestrial isotope signatures of Ibiza populations, seafood appears to have been a minor component of Ibizan diet (Fuller et al., 2010; Pickard et al., 2017; Alaica et al., 2019; Dury et al., 2018). Still, given the proximity of the ocean, individuals likely consumed some fish, which may have influenced habitual loading patterns. Consistent with this, fishing implements and some icthyofauna have been recovered from archaeological sites, and auditory exostoses, potentially indicators of habitual swimming, have been documented in skeletal remains (Ramon 1995; Márquez-Grant, 2006). Regular use of watercraft or fishing gear (e.g. nets and lines) has been associated with increased upper limb loading, though watercraft use may have a greater effect on upper limb cross-sectional properties than shoreline fishing (Stock and Pfeiffer, 2001; Weiss, 2003; Osipov et al., 2016). Many Roman sources depict fish as the food of the destitute, suggesting cultural mores against habitual consumption (Purcell, 1994; Donahue, 2015). On the other hand, upper class individuals did not embrace this stigma, and garum, a fish sauce, was ubiquitously consumed (Purcell, 1994; Prowse et al., 2004). Likewise, Christian individuals may have consumed more fish than Islamic people due to fasting rules prohibiting meat, but whether such dietary practices would affect bulk collagen analysis remains unclear (Adamson, 2004; Constable, 2013; Pickard et al., 2017).

Although this study focuses on Ibiza, comparing dietary trends to those seen in mainland archaeological populations places Ibizan dietary patterning into a larger context. The most noticeable similarity between the mainland and Ibiza is the association between Islamic rule and greater reliance on C_4 foods (Salazar-García et al., 2014; Alexander et al., 2015, 2019). As hypothesized for Ibizan populations, C_4 signatures may reflect the cultivation of new crops, a greater proportion of migrants from areas in which these crops were more extensively cultivated, or some combination of these factors. In addition, greater reliance on C_4 crops may reflect lower socioeconomic status, as higher status medieval individuals tend to have C_3 based diets that also contain a higher proportion of animal products (Alexander et al., 2015; Pickard et al., 2017). While consumption of C_4 crops likely increased during the Islamic period, their importance prior to this should not be understated. Notably, in the Northwest Iberian peninsula, the decline of Roman political control corresponds to a growing dependence on C_4 cereals such as millet, and similar patterning is seen in Italian sites (Iacumin et al., 2014; López-Costas and Müldner, 2016). It remains unclear whether altered agricultural practices reflect worsening economic conditions, changing climate, or influx of new populations with different dietary habits are responsible for increased dependence on C_4 crops in Late/ post-Roman contexts. Similarly, analysis of Late Roman/ Early Byzantine populations from Ibiza tentatively suggests a small but significant consumption of C_4 cereals (Alaica et al., 2019). Thus, taken together, studies of other Iberian and Mediterranean populations suggest that Ibizan diachronic trends in diet generally follow those seen on mainland Spain. Diets were predominantly based on C_3 crops. Individuals also consumed C_4 crops, and isotopic signatures indicating greater consumption of C_4 crops may reflect migration or differences in social status. Overall, variation in the behavior and physiological stress levels of Ibizan populations from the Roman to Islamic period has not been well-explored. The extent to which dietary variation related to differences in behavior, body size, and physiological stress levels in Ibiza population from the Roman to Medieval Islamic Period has not been addressed in previous studies. Exploring this topic would improve understanding of past populations of the Balearic Islands and the Iberian Peninsula.

1.5 Research Goals

The analysis explores the following questions:

1. Did body size and bone cross-sectional properties vary in urban and rural populations dating to the LREB and Islamic periods (300-1235 AD)? If significant differences are detected, what does this reveal about chronological and geographic variation in physiological stress levels and behavior?

2. How does variation in body mass, diaphyseal length, and bone cross-sectional properties correlate with variation in stable isotope signatures? If correlations exist, what do they reveal about the effect of diet on levels of physiological stress and behavior in the specific historical and environmental context?

2. Materials and Methods

2.1 Sample Description

A total of 222 individuals from eight cemetery sites provided data for analyses of body size, bone length, and bone diaphyseal products and circumferences (cross-sectional properties). Stable isotope data was available for 115 individuals. Sample sizes by cemetery are reported in Table 1. For analysis of correlations between stable isotope values and aforementioned bone properties, sample size ranged from 86 to 20 individuals, depending on the measure employed. All individuals were fully mature adults, as determined by the lack of open epiphyses and mature dentition. Due to poor preservation of the sample, many individuals lack measurements for one or more variables, and it was not possible to reliably estimate sex for a majority of the individuals under study. Pubic symphysis or cranial morphology was rarely assessable. Previously sex estimates for several individuals were made using discriminant function analysis of long bone length based on modern Spanish standards or examination of the sciatic notch alone (Màrquez-Grant, 2006; Kyriakou et al., 2012). Sex estimates based on modern standards and sciatic notch alone were considered unreliable, since the accuracy of these methods for the populations studied has not been ascertained. Nevertheless, osteometric data from as many excavated sites as possible has been obtained in order to undertake this study and the number of individuals is indeed a reflection of the practical limitations regarding poor preservation, bone condition, and completeness.

Here we present a brief description of cemetery sites. For more in-depth description, please refer to cited sources. Late Roman Early Byzantine individuals come from four urban or semi-urban cemeteries all located in or around Ibiza town (Via Púnica 33, Joan Planells, Carrer Arragó 33, S'Hort des Llimoners). Twenty-eight individuals come from the cemetery of Via Púnica, dating to 300-400 AD (Llinas and Casanova, 2009). Most burials were in cist graves, and grave goods were typical for pre-Christian Roman funerary traditions. Twenty-one individuals come from the cemetery located in the street of Joan Planells (300-700 AD). This site was also located just outside the old city wall, and the majority of these individuals were interred in cist burials with few grave goods (Esquembre et al., 2005; Girdwood et al., 2011). S'Hort des Llimoners is also located just outside the city wall and the cemetery was used between 300-700 AD, though the bulk of burials date from between 300-500 AD (Ramon et al, 2005). Graves surround two funerary structures on either side of a main Roman road. This analysis includes 11

individuals from this cemetery (Marquez-Grant, 2006). Individuals buried at Carrer Aragó 33 were interred between 300-600 AD, but most burials date to the 500-600 AD (Torres, 1995; Marquez-Grant, 2006). In the laboratory, the remains were analyzed as a commingled assemblage, though in some cases commingling was limited such that paired elements could be identified. From a total minimum of 28 individuals from this assemblage, a total of 21 femora, 24 tibiae, and 9 left humeri as well as 3 right humeri recovered paired with left humeri were employed. If commingling was limited such that pairs could be identified with a high degree of confidence at time of measurement, left, right, and average values were recorded as described below.

The Medieval Islamic period sample consists of individuals from four urban cemeteries in Ibiza town (Es Soto, Carrer Major, Avenida de España, and Puig des Molins) and one rural cemetery (Can Fonoll) all dating according to their funerary rite to between 902 and 1235 AD. Burials are typical of the Islamic style: individuals lying on their right side with heads to the SW and face facing SE towards Mecca. Except for Carrer Major, all the other cemeteries are located beyond the city walls. Although traditionally considered contemporaneous with Islamic rule, it has been proposed that some burials from Es Soto are of Islamic slaves from the subsequent period of Christian control (1235-1500 AD) (Ferrer Arbázurza, 2015). Eight individuals are from the site of Es Soto, which was uncovered during two separate rescue excavations (Màrquez-Grant, 1999). One individual is from Carrer Major, the only Islamic cemetery known within the city walls of Ibiza town (Martín Parrilla and Graziani Echávarri, 2008). Nineteen individuals are from Avenida de España, which dates to 902-1235 AD (Gurrea and Ramon n.d.). The site of Puig des Molins, located outside the city walls, was used as a cemetery from the Punic to the Islamic periods (Bellard, 1989). Islamic burials were all interred in earth cut graves. Finally, the Islamic site of Can Fonoll is the only rural site in the analysis. Ninety-six individuals were uncovered during excavation several kilometers from Ibiza town and 83 individuals are included in the analysis (Castro, 2009; Kyriakou et al., 2012; Pickard et al., 2017).

2.2 Body Size and Bone Cross-sectional properties

Where complete diaphyses were available, the maximum length of the femur and humerus, and tibia were measured using an osteometric board. Femoral head diameter, as well as maximum and minimum diameters of bone diaphyses, were measured with sliding calipers. Circumferences were taken with measuring tape. Diaphyseal diameters and circumferences were taken at three locations: humerus midshaft, femur midshaft, and tibia nutrient foramen. In most individuals, diaphyseal length could not be measured due to poor preservation. On fragmented remains, midshaft locations were estimated visually. To reduce measurement error, midshaft measures were taken three times and averaged. The bones that

were able to be measured did not present any evidence of infection such as periostitis or any joint disease such as osteoarthritis, which may have affected the measurements. To ensure that taphonomy did not affect measurement of periosteal diameters, we excluded any elements with noticeable flaking or erosion of periosteal bone at the point of measurement or visible deformation of the diaphysis.

Femoral head diameter serves as a proxy for body mass, as it is the best-preserved joint dimension, and it is also the most commonly used measure for body mass estimation (McHenry, 1992; Grine et al., 1995; Ruff et al., 2012). In this study bone cross-sectional properties provide a proxy for bone strength. Following Stock and Shaw (2007), cross-sectional properties were calculated from external dimensions. We calculated the diaphyseal product (calculated as maximum * minimum diameter) and circumference measurements at set locations of the midshaft humerus, femur midshaft, and tibia nutrient foramen. These locations are commonly used in biomechanical analysis, because they provide good proxies for upper and lower limb loading levels (Ruff, 2008). As it remains unclear whether the femur or tibia provide the best proxy for loading levels, we analyze both elements to quantify lower limb cross-sectional properties (Ruff et al., 2006b; Stock, 2006; Nadell and Shaw, 2016). Diaphyseal shape was calculated as the ratio of maximum to minimum diaphyseal diameters. Maximum and minimum diameters were used instead of anteroposterior and mediolateral diameters, because this avoids the error introduced by misalignment of anatomical axes. Also, especially in the upper limb, the axis of maximum loading may deviate significantly from the anteroposterior or mediolateral axis. Following the approach taken by several analyses of fragmented remains, femur and tibia measures were taken on the side sufficiently preserved to allow measurement (Shaw and Stock, 2013; May and Ruff, 2016). In the minority of individuals in which both sides could be measured, values were averaged. Averaging bilateral lower limb measures in the minority of individuals with bilateral preservation was done, because there is no bias in the number of left and right elements in individuals with only one side preserved. Averaging is further not likely to bias analysis, because lower limb dimensions have limited asymmetry (Auerbach and Ruff, 2006). Given the potential for asymmetric loading due to handedness, left and right humeral diaphyseal products and circumference were analyzed separately, though comparisons of average values are also reported (Auerbach and Ruff, 2006; Sládek et al., 2016). Results from average values agreed with patterns seen in left and right elements. As poor preservation prevented measurement of both left and right humeral length for most individuals, length was reported with lefts and rights combined or averaged in individuals were both could be measured. Lack of side specific comparison is unlikely to bias analysis, because asymmetric loading primarily effects cross-sectional size but not bone length (1-2% asymmetry in humerus length in modern and archaeological populations) (Trinkaus et al., 1994; Auerbach and Ruff, 2006).

Due to a lack of diaphyseal lengths and articular surfaces, it was not possible to control for differences in body size for most individuals. Measures of bone length and joint dimensions are commonly used to standardize diaphyseal products and circumferences for body size (Ruff, 2000; Stock and Shaw, 2007). However, few individuals have fully preserved long bones or femoral head dimensions. Also poor preservation of cranial and pelvic remains prevented sex estimation in a majority of individuals. Therefore, differences between samples in body size, stature, and diaphyseal products and circumferences could reflect unequal sex distributions. Following May and Ruff's (2016) previous analysis of poorly preserved samples, size-unstandardized diaphyseal products and circumferences were used to compare samples with no division by sex. Comparisons of the smaller number of femoral head and bone length measurements allowed a critical evaluation of differences in body size on bone cross-sectional properties. The potential effects of body size and a lack of sex estimates are explicitly addressed in the discussion. We also report the coefficient of variation to evaluate potential differences in sexual dimorphism between samples (Villmoare et al, 2019). Furthermore, it should be noted that given their relationship to body size, analysis of cross-sectional properties can directly provide new insight into variation in body size (Pomeroy et al., 2018).

Lastly, diaphyseal products and circumferences do not quantify diaphyseal strength and shape as accurately as cross-sectional geometry calculated from combined periosteal and endosteal contours (Stock and Shaw, 2007; Sparacello and Pearson, 2010; Davies et al., 2012). However, obtaining this data requires CT scans or a combination of periosteal molds and biplanar radiographs, which were unavailable when measurements were collected. Stock and Shaw (2007) found strong correlations between measures of bone strength and shape derived from true periosteal contours and estimates of endosteal contours and bone diameters/circumferences. Average standard estimates of the error for measures of bending rigidity derived from diaphyseal products or circumferences ranged between 20-23 percent, though individual errors may be substantially higher or lower. Overall, prior investigations have concluded that diaphyseal products and circumferences provide a reasonable approximation of group differences in cross-sectional properties when sample sizes are sufficiently large. Therefore, the use of external dimensions should provide an accurate picture of biomechanical differences between the populations examined.

2.3 Stable Isotope Analysis

The methodology for extracting bone collagen and stable isotope analysis has been previously described in Pickard et al. (2017), Alaica et al. (2019), and Fuller et al. (2010). Briefly, bone samples were cleaned, demineralized, and gelatinized before mass-spectrometry. Isolation of well-preserved collagen was

indicated by C:N ratios between 2.9 and 3.6. Five individuals with C:N ratios outside this range were excluded from analysis.

2.4 Sample Comparisons and Statistical Analysis

The Urban LREB, Urban Medieval Islamic and Rural Medieval Islamic samples were compared to each other. Data was analyzed with the R statistical package. Outliers were defined as values above or below 3 standard deviations from the mean, and removed prior to testing. A Shapiro-Wilks test was carried out to test for normal distribution. If variables were normally distributed, i.e. bone length, body mass, and diaphyseal cross-sectional properties, the three samples were then compared using a one-way ANOVA with Tukey HSD post-hoc comparisons. For non-normally distributed variables, non-parametric Kruskal-Wallis tests with the Dunn post-hoc comparison were carried out. All post-hoc tests were adjusted for multiple comparisons. Following Rosenthal and DiMatteo (2001) and Lakens (2013) effect sizes were calculated using the r family of product moment correlations. These indices calculate the proportion of variance in dependent variable explained by the independent variable (Cohen, 1988; Lakens, 2013; Tomczak and Tomczak, 2014). We reported omega-squared for ANOVA and eta-squared for Kruskal-Wallis tests, as these are the commonly reported effect size statistics for these tests. Correlations between osteological measures and $\delta^{13}C$ and $\delta^{15}N$ were evaluated by regressing relevant bone dimension on isotope ratio values using Ordinary Least Squares regression (OLS). Correlations were assessed both for the combined sample and separately for LREB and Islamic samples. Due to the small number of Urban Islamic individuals with both osteometric and stable isotope data, the Islamic sample was analyzed with urban and rural components both combined and separated.

3. Results

3.1 Body Size, Diaphyseal Length, and Diaphyseal Cross-sectional properties

Descriptive statistics for all variables by group are given in Table 2. Boxplots with sample sizes are presented in Figure 1 for femur head maximum breadth and bone lengths. For all variables, coefficients of variation are similar for bone lengths, femur head diameter, and shape ratios (Table 2). The Medieval Urban Islamic group exhibits a slightly higher coefficient than other groups for lower limb diaphyseal products and circumferences. P-values and effect sizes for statistical comparisons are presented in Table 3. Post-hoc effect sizes are reported in Supplemental Table 1. Femoral head breadth does not differ significantly between groups, though the Rural Islamic group produces the lowest range for this variable. The Rural Islamic group has significantly shorter humeri than Urban Islamic and Urban LREB individuals (Tables 2 and 3). The Rural Islamic group also has shorter femora than the other groups, but the ANOVA comparison does not reach statistical significance (p=0.07).

Table 2
Figure 1
Table 3

Boxplots for diaphyseal products and circumferences by cemetery are given in Figures 2 and 3. The smaller diaphyseal products and circumferences of the Rural Islamic population are clearly apparent. Statistical comparisons in Table 3 demonstrate that Rural Islamic individuals have significantly smaller upper and lower limb diaphyseal products and circumferences than Urban LREB individuals, but comparisons of Rural to Urban Islamic individuals are only significant for the lower limb. Urban LREB and the Urban Islamic group do not show significant differences in diaphyseal circumference or products. Boxplots for shape ratios are given in Figure 4 and descriptive statistics in Table 2. Humerus and tibia shape differs significantly between groups. Specifically, Urban Islamic individuals have significantly higher humerus midshaft shape ratios (left humerus p= 0.03, right humerus p=0.08) and lower tibia nutrient foramen shape ratios than the Urban LREB group. In other words, the Urban Islamic group has less circular humeri and more circular tibiae than the Urban LREB group.

Figure 2
Figure 3
Figure 4

3.2 Correlations between Stable Isotope Signatures and Osteometric Variables

R-squared values are provided in Table 4 for OLS regressions of femur head breadth, bone length, and diaphyseal products, circumferences, and shape on $\delta^{13}C$ and $\delta^{15}N$. Statistically significant regressions are marked. Exact p-values for each regression are provided in Supplemental Table 2. Regressions were carried out for the combined sample and separately for the Urban LREB and Rural Islamic groups. Prior studies did not sample the majority of Urban Islamic individuals for which osteometrics are available for stable isotopes analyses. For this reason, sample size for this group is five individuals for the femoral head and one individual for other variables. To address this issue, correlations are reported for all individuals combined and separately for the Urban LREB, and Rural Islamic samples. Pooling the Urban Islamic individuals with either the LREB Urban group or the Rural Islamic group did not change the results. Visual analysis assesses if Urban Islamic individuals depart markedly from significant correlations seen in other groups.

Table 4

A significant positive correlation exists between $\delta^{13}C$ and femur head diameter for the combined sample and for the Urban LREB group, as $\delta^{13}C$ increases femoral head diameter also increases (Table 4). A scatterplot of femoral head breadth plotted against $\delta^{13}C$, given in **Figure 5**, shows that a lack of correlation in the Islamic Rural group results from one individual with a high $\delta^{13}C$ value but low femoral head diameter. Prior research has concluded this individual is non-local to the island and almost certainly a migrant from Africa (Pickard et al., 2017). If this individual is excluded, the regression becomes significant. While the Urban Islamic correlation does not reach statistical significance, the five individuals do exhibit a positive trend, and the regression remains significant in the combined Urban Islamic and Rural Islamic sample. This group also contains an outlier with an even more positive isotopic value than the Rural Islamic outlier. In the combined sample, $\delta^{13}C$ also correlates positively with humerus length (Table 4). Femur length correlates positively with $\delta^{13}C$ in the Urban LREB sample. Initially, the relationship is not significant in the combined and Rural Islamic samples, but exclusion of one Rural Islamic individual with an extremely low femur length results in a significant correlation for the combined sample, and a positive trend in the Rural Islamic group, though the latter is not statistically significant (p=0.09). The plot for femur length is given in **Figure 6** with regression lines shown by group, and the Rural Islamic outlier marked. Thus, higher $\delta^{13}C$ appears to correlate positively with body size and bone length in LREB and Rural Islamic samples.

Figure 5
Figure 6

Regressions of combined sample diaphyseal products and circumferences on $\delta^{13}C$ are significant for all locations, though correlation coefficients are very low ($R^2<.1$) (Table 4). A scatterplot of femoral circumference regressed on $\delta^{13}C$ is provided as an example in Figure 7. Individuals with higher carbon isotope values have more robust bones. Further analysis by group only found a significant positive relationship between $\delta^{13}C$ and right humerus diaphyseal product and circumference in the Urban LREB group. Regressions of shape ratios on $\delta^{13}C$ are not significant.

Figure 7

Nitrogen isotope ratios show no significant correlations with skeletal measures in the combined sample. However, for the Urban LREB period left humerus shape ratio shows a significant positive correlation

with $\delta^{15}N$ ($R^2 = 0.17$) (Table 4). As seen in the bivariate plot of left humerus shape on $\delta^{15}N$ in Figure 8, individuals with higher $\delta^{15}N$ have less circular humeri.

Figure 8

4. Discussion

4.1 Summary of Results

The goal of this study was to determine if there were differences in physiological stress levels and behavior between Ibizan populations dating from the LREB-Islamic periods. We also investigated if differences in behavior and physiological stress correlate with differences in diet. The Rural Islamic sample has significantly shorter humeral diaphyses than the Urban LREB and Urban Islamic populations (Figure 1; Table 3). Comparisons further highlight the low cross-sectional properties of Rural Islamic individuals (Figures 2 and 3; Table 3). The Urban Islamic group has less circular humeri and more circular tibiae than the Urban LREB group (Table 3). Femoral head breadth and length correlate positively with $\delta^{13}C$ values in the entire sample, and separately in the Urban LREB and Rural Islamic groups (Table 4; Figure 5). Diaphyseal products and circumferences also show a positive correlation with $\delta^{13}C$ in the combined sample, though the correlations are weaker than for femoral head diameter (Figure 7; Table 4). Left humerus shape exhibits a positive correlation with $\delta^{15}N$ in the LREB Urban group (Figure 8).

4.2 Limitations

This study has several limitations. First, sex could not be reliably estimated. Due to sexual dimorphism in body size and musculature, males would have longer limbs, greater body mass, and more robust diaphyses than females. Additionally, testosterone increases the sensitivity of the periosteum to loading, further contributing to greater male cross-sectional properties (Frisancho et al., 1970; Orwoll, 2003; Schoenau, 2006; Högler et al., 2008; Gabel et al., 2017). Consequently, males may appear more robust even if habitual loading levels relative to body size did not differ between the sexes (Stock and Macintosh, 2016). Culturally mediated variation in behavior, diet, and social status are also important sources of sexual differences in body size and cross-sectional properties. Thus, one cannot exclude the possibility that some of the differences detected between populations may reflect uneven sex distributions combined with varying levels of dimorphism. Coefficients of variation for bone length and femur head diameter are equivalent across groups compared, suggesting that populations are equally heterogeneous in terms of body size (Table 2). The Urban Islamic group exhibits a higher coefficient than other groups for diaphyseal products and circumferences. A potential explanation for this might be higher levels of sexual

dimorphism in levels of loading. On the other hand, variability in load levels between Urban Islamic and Rural Islamic groups may also reflect a greater diversity of behaviors in an urban population compared to a rural population. The Urban Islamic coefficient is higher than that of the Urban LREB sample, and the reasons for this are unclear, and whether this reflects a more heterogeneous behavioral repertoire is unclear.

The reduced accuracy of estimates of cross-sectional properties calculated from external dimensions compared to those based on "true" periosteal and endosteal contours has been noted in the methods section. However, lack of radiographic imaging limited analysis to external dimensions. Still, Stock and Shaw (2007) noted that diaphyseal products and circumferences showed strong correlations with cross-sectional properties calculated using direct imaging of cross-sections and mean values are meaningful representations of group differences. Thus, this is the best method currently available for biomechanical analysis, and it should reliably capture differences between groups. Also, diaphyseal cross-sectional properties could not be standardized for differences in body mass and length, the two determinants of load related to body size, complicating behavioral reconstruction (Ruff, 2000). Some prior studies have size-standardized diaphyseal products by femoral head diameter alone or a body mass estimate derived from this measure (Wescott, 2006). However, this would dramatically decrease sample size. Furthermore, Stock and Shaw (2007) found that diaphyseal products standardized by femoral head size showed weak correlations with size-standardized measures of bending/torsional rigidity derived using cross-sectional geometry. Correlations improved if products of bone length and body mass were used, which is not practical given the poor preservation of Ibiza skeletal material. The potential effect of body size and diaphyseal length on comparisons of bone cross-sectional properties is discussed in greater detail below.

In our study we compare LREB and Medieval Islamic Urban groups to a Medieval Islamic Rural group. Problematically, due to variable preservation and isotopic sampling, combined isotope values and osteometric measurements were not available for most Urban Islamic individuals (n= 5 for femur head diameter and 0 or 1 for other variables). As a result, this study primarily describes relationships between isotopic values, body size, and diaphyseal measures in the other two samples. Analysis of the Urban Islamic individuals only evaluated if the data available is consistent with that seen for the femur head correlations in other samples. For comparisons of body size proxies and diaphyseal products and circumferences, sample size for the Urban Islamic group is enough for comparison to the LREB Urban and Rural Islamic groups. The lack of a Rural LREB group further means that we cannot fully evaluate how rural-urban differences changed through time. Thus, we cannot exclude that differences between LREB Urban and Islamic Rural groups may reflect some general diachronic change in skeletal phenotype.

Lastly, it should be noted that cemeteries cover centuries of occupation and dating has not been undertaken on each individual. Therefore, the results essentially represent "averages" for the periods compared, and they are do not account for changes within archaeological periods

4.3 Chronological Variation in Body Size and Habitual Behavior

Rural Islamic mean values for humerus length are significantly lower than in the Urban LREB and Islamic samples (Table 3). Rural Islamic individuals also have significantly smaller lower limb diaphyseal products and circumferences than the Urban LREB and Urban Islamic groups (Tables 2 and 3). Upper limb patterning is more complex. The Urban LREB group has significantly greater products and diameters significantly from the Rural Islamic group but the Urban Islamic group does not. Reduced humerus length in the Rural Islamic sample may contribute to this patterning, because reduction in moment arm decreases mechanical strain. However, this would not account for a lack of differentiation from the Urban Islamic group.

The lower cross-sectional properties (diaphyseal products and circumferences) of the Rural Islamic group prove unexpected. Given the intense habitual loading involved in agricultural labor, one would expect greater cross-sectional properties than in urban groups. If these findings do reflect activity differences, lower habitual workloads among the Rural Islamic group could potentially reflect technological innovations in farming and manufacture. Following Islamic settlement, irrigation improved, and watermills were constructed for grinding grain, potentially reducing the strenuousness of agricultural labor (Butzer et al., 1985; Kirchner, 2009). The greater robusticity of the urban samples would conversely suggest habitual engagement in more strenuous labor than the Rural Islamic group. Some prior biomechanical studies have suggested that greater lower limb strength arises due to traversal of more rugged terrain (Marchi et al., 2006; Ruff et al., 2006b). However, the topography of Ibiza is fairly uniform, and if anything, one would expect more rugged terrain in rural areas.

One also cannot exclude genetic change due to increased migration as a contributing factor to the distinctive skeletal phenotype of Rural Islamic individuals. Studies of settlement patterns suggest abandonment of rural sites outside of urban nuclei in the Balearic Islands at the beginning of the LREB (Florit and Ontiveros, 2011). This may have led to the repopulation of rural spaces by a genetically distinct group in the Islamic period, though repopulation appears to have already begun in the Early Byzantine period (Ramon 1995; González and Pacheco, 2002). Still significant migration took place during the Islamic period, as evidenced by the distinct craniometrics and non-metric trait frequencies of Islamic Ibiza populations, as well as the frequency of non-local isotopic signatures in Islamic populations

and land rents with names of Arabic-Berber derivation, which suggest a North African and/or sub-Saharan origin (Kirchner, 2009; Fuller et al., 2010; Girdwood, 2012; Nehlich et al., 2012; Kranioti et al., 2015; Pickard et al., 2017). Consequently, reduced body size may reflect genetic differences between Rural Islamic and other groups. In turn, the lower loads engendered by a smaller body or a genetic difference in bone cross-sectional size could theoretically account for low cross-sectional properties in this group. More diachronic stability in skeletal phenotype among urban groups may indicate that either the genetic contribution of migrants was subsumed within a larger population or that urban and rural migrants had different origins. However, it remains unclear if genetically encoded differences in diaphyseal robusticity and bone length can be so large as to overshadow the effect of mechanical loading, diet, and disease load on bone dimensions (Frisancho et al., 1980; Adams and Ackert-Bicknell, 2015).

As it seems improbable that rural individuals performed markedly less strenuous labor than urban groups or that genetic differences could completely account for differences in skeletal phenotype, reduced body size offers the most convincing explanation for the gracility of the Rural Islamic sample. Studies of relationships between body size and skeletal dimensions have noted stronger correlations between diaphyseal strength and body size than joint dimensions or bone length (Lieberman et al., 2001, 2004; Ruff, 2007; Cowgill, 2010, 2017). Also, while femoral head size does not differ significantly between groups, the Rural Islamic sample produces the lowest range, and humeral length is significantly lower than in urban groups (Figure 1).

Prior studies provide contradictory evidence for greater physiological stress in the Rural Islamic population. Kyriakou et al. (2012) found that Rural Islamic individuals exhibit a similar prevalence of skeletal lesions, cribra orbitalia and linear enamel hypoplasia, indicative of malnutrition and illness, as other Ibizan populations. On the other hand, Kyirakou et al. (2012) also found that Rural Islamic individuals had smaller stature and diaphyseal length than LREB Ibizan populations or contemporaneous mainland Spanish Islamic and Christian populations, though small sample size makes these conclusions tentative. Nevertheless, our findings are consistent with reduced body size in the Rural Islamic sample, emphasizing the uniqueness of the population compared to other Ibiza groups and Medieval populations from the Spanish mainland. A recent study demonstrated a greater prevalence of caries in rural Islamic populations, supporting dietary differences between the rural and urban groups (Márquez-Grant and Busom, n.d.). Also, lower δ^{15}N in Rural Islamic individuals compared to Urban Islamic samples may indicate reduced meat consumption (Dury et al., 2018). Therefore, differences in body size may reflect reduced diet quality in the Rural Islamic group. It is possible, for instance, that populations of the port city had greater access to or the financial means to purchase imported food.

The current study can only directly support rural-urban differences in body size and diaphyseal biomechanics in the Medieval Islamic period. Importantly, as stated in the limitations section, a lack of LREB Rural individuals makes it unclear if the magnitude of rural-urban differences varied over time and exploring this question further would require the excavation of more skeletal remains. Thus, we cannot exclude that differences between LREB Urban and Islamic Rural groups may reflect some general diachronic change in skeletal phenotype. However, it should be noted that neither limb lengths or lower limb diaphyseal products and circumferences differ significantly between LREB and Medieval Islamic Urban groups, suggesting similarity in body size and workloads of urban populations across time.

Although body size and lower limb cross-sectional properties are similar in urban groups, the LREB and Medieval Islamic Urban samples did exhibit several differences. Interestingly, while LREB Urban individuals had a significantly more robust upper limb than the Rural Islamic group, the Islamic Urban group did not differ significantly from either the LREB Urban or Islamic Rural group. This difference may reflect several scenarios. Urban Islamic individuals may have practiced a wider repertoire of tasks, obscuring differences with other groups. This is consistent with higher coefficients of variation for upper limb diaphyseal products and circumferences in this group (Table 2). Alternatively, it is possible that some of the individuals buried in Islamic Urban cemeteries lived or worked in rural areas for some part of their lives. Distinguishing between these scenarios requires further research.

Limb shape also differentiated the two urban groups. While femur midshaft shape did not differ between Urban LREB and Islamic groups, the Urban Islamic group has a more circular tibia nutrient foramen section than the Urban LREB group (Figure 4; Table 3). In the upper limb, significant differences in humeral shape between Urban LREB and Islamic groups suggest a difference in the habitual range of motion (Figure 4; Table 3). The Islamic Rural group exhibits an intermediate range of values for humerus shape and does not differ significantly from either urban group. The contradictory femur and tibia results are difficult to reconcile, but prior studies have noted that femur midshaft shape shows a closer linkage to inferred habitual mobility than the tibia, arguing against a difference in habitual mobility, the total distance traveled (Stock, 2006). However, lower limb shape can also vary due to genetically encoded differences in body shape as well as *in-vivo* adaptation to terrain ruggedness and the linearity of movement (Ruff et al., 2006b; Shaw and Stock, 2009; Wescott, 2014). For instance, body breadth and rugged terrain alter the ratio of mediolateral to anteroposterior strains engendered by locomotion (Shaw and Stock, 2009). Also, athletes engaged in frequent non-linear movement (such as soccer) have more circular tibiae than long distance runners. Thus, given the previously discussed importance of migration,

genetic differences in the tibia shape of Ibiza populations cannot be excluded. Diachronic differences in tibia shape of the urban groups may also reflect differences in habitual behavior other than mobility (e.g. plowing, horseback riding, spear throwing) (Wescott, 2014). In addition, while both urban groups likely traversed similar terrain in the city, perhaps one group may have spent more time outside it, where terrain engendered different strain patterns.

The less circular humeri of Urban Islamic compared to Urban LREB individuals may further indicate chronological changes in the types of manual labor performed by urban groups (Wescott, 2014; Cameron et al., 2018). Given the wide range of trades practiced within an urban environment, identifying the specific activity responsible for shape differences is not possible. Still, Islamic expansion into the Balearic Islands brought technological and economic change (Florit and Ontiveros, 2011; Heiss et al., 2014). Therefore, it is not unreasonable to suggest that the types of activities practiced in economic centers such as the port city of Ibiza town changed diachronically.

4.4 The Effect of Diet on Body Size and Cross-sectional properties

Analysis of correlations between stable isotope signatures and skeletal dimensions showed that $\delta^{13}C$ correlated positively with femoral head diameter in all individuals and in the Urban LREB and Islamic Rural sample (Table 4; Figures 5 and 6). While the relationship does not reach statistical significance, the Urban Islamic sample shows a positive trend between femur head diameter and $\delta^{13}C$ (Figure 5). The correlation of $\delta^{13}C$ to femur length was also significant in all individuals from all time periods and the Urban LREB group. The Rural Islamic group showed a positive, but insignificant association between these variables (p=0.09), and the humerus length- $\delta^{13}C$ regression was only significant in the combined sample of all individuals from all time periods (Table 4). In the combined sample of all individuals, diaphyseal cross-sectional properties correlate positively with $\delta^{13}C$ values, but the correlation is notably weaker than for femoral head breadth (Figure 7).

The consumption of C_4 resources elevates $\delta^{13}C$ relative to a diet based exclusively on C_3 resources. Consequently, the positive correlation between femoral head, femur length, humerus length, and carbon isotope ratios suggests that greater access to C_4 crops or animals consuming those crops was associated with higher body mass and stature in both the LREB Urban and Islamic Rural populations. (Figure 5). On the basis of past studies, the relationship between C_4 foods and body size proves surprising, because it has been thought that C_4 resources constituted a minor part of local Ibizan diet, especially in the LREB period (Fuller et al., 2010; Pickard et al., 2017; Alaica et al., 2018). However, a recent study based on enamel apatite suggests that collagen analysis underestimates the contribution of C_4 resources to the Ibiza diet

during the Islamic period (Dury et al., 2018). The same issue may have led to an underestimation of the amount of C_4 resources in LREB diet, and future studies may address this problem via modeling of dietary signatures from collagen and apatite to create more nuanced dietary reconstructions. Greater access to C_4 crops could have increased body size in two ways. First, it may have improved regular caloric intake. Second, in times of shortfall, locally raised or imported millet and sorghum, which are resistant to drought and have shorter growing seasons than major C_3 crops, may have been fallback foods, ensuring the consumption of sufficient calories and nutrients. López-Costas and Müldner's (2016) suggested a similar scenario in a study of post-Roman diet in Northwest Spain. Based on isotopic data, they theorized that millet may have been particularly important when "a hard winter or other event ruined crops with longer growing seasons" (p. 149).

The positive correlation between access to C_4 foods and body size could further indicate differences in food access due to socioeconomic status or social connections in both LREB Urban and Islamic Rural populations. For instance, Islamic settlement of the island appears to have been organized on the basis of clans, which may have had variable access to imported C_4 foods or farmed different crops (Kirchner, 2009; Dury et al., 2018). Familial or class differences in financial resources or subsistence strategies may similarly explain variation in access to C_4 foods during the LREB period. Also, absent better biological data on sex, one cannot exclude the possibility that the positive correlation also reflect greater consumption of C_4 resources by men, because their higher body mass would lead to the appearance of a positive correlation.

Correlations between diaphyseal cross-sectional properties and $\delta^{13}C$ are also significant, but R^2 values are markedly lower than for the femoral head and humerus/femur length (Table 4; Figure 7). The weakness of the correlations may reflect that both body mass and activity generated loads affect cross-sectional properties. Individuals consuming more C_4 resources have higher body mass, but the additional variation introduced by activity related loading largely jumbles this signal. Thus, habitual loading levels may not have differed markedly between individuals with different diets, thereby accounting for low correlations between $\delta^{13}C$ and diaphyseal products and circumferences. However, confirming this will require analyzing the effects of body mass and bone length on the correlation between cross-sectional properties and $\delta^{13}C$ using a larger sample in which body size can be controlled for.

Alternatively, bone cross-sectional properties and femoral head/ length may provide information about the relationship between body mass and diet at different points in the life course. Cross-sectional properties track changes in body mass throughout life to a greater extent than articular dimensions, which

show the closest correspondence to late adolescent body size (Ruff et al., 1991; Lieberman et al., 2004; Ruff, 2007; Pomeroy et al., 2018). Therefore, the stronger correlation of femoral head diameter than cross-sectional properties to δ^{13}C might reflect that diet had an especially strong impact on body size during growth. Diet can change throughout life, and it has been generally estimated that bone collagen may take 10-30 years to fully turnover (Libby et al., 1964; Hedges et al., 2007). More recently, studies have shown that stable isotope signatures of midshaft cortical bone essentially become fixed in adolescence (Matsubayashi and Tayasu, 2019). While preservation issues complicate age assessment, the majority of individuals analyzed are young or middle-aged adults. In this age-range, cortical bone would predominantly reflect adolescent diet even if one uses the most precocious estimates of bone turnover. Although diet can shift throughout life, prior analyses of Islamic and LREB populations from Ibiza did not show age-related differences in stable isotope signatures (Pickard et al., 2017; Alaica et al., 2019). Therefore, results tentatively suggest the intriguing possibility that access to C_4 resources may have been especially important for developmental health. However, it remains unclear if C_4 foods were consumed as fallback foods or regularly. Sporadic consumption of C_4 fallback foods would not likely affect bulk collagen samples. For instance, studies combining isotopic analysis of bulk collagen and dentine have shown that bulk collagen does not record sporadic dietary changes whereas dentine, which is laid down serially, does (Montgomery et al., 2013). Thus, it may be most parsimonious to assume that the correlation between body size and carbon isotope signatures reflects lifelong differences in diet rather than the use of fallback foods during growth.

A positive correlation between δ^{13}C, femur head diameter, and bone cross-sectional properties may not entirely reflect variation in local diet. It is also possible that it indicates greater body size among migrants. Individuals raised outside of Ibiza, in areas more dependent on C_4 resources, may have had higher body mass due to either the positive effect of C_4 resources on diet quality/health or genetic differences. Exploring this possibility would require further studies that employed sulfur, strontium, and oxygen isotope ratio analysis to explicitly identify migrants in these cemeteries. The Islamic period rural and urban individuals with markedly high δ^{13}C values and low femoral head values marked in Figure 5 provide another example of potential heterogeneity in diet and body size due to migration. Including these individuals in the analysis makes the linear correlation between femoral head and δ^{13}C non-significant. Pickard et al. (2017) hypothesized that the rural individual was a migrant from Africa, who spent a significant portion of their life in an area where individuals depended to a greater extent on the C_4 food web. As a result, a different set of "dietary rules" potentially applied, with greater access to C_4 resources not correlating with increased dietary quality or body size. The same may be true of the urban individual. Prior analysis of medieval diet on mainland Spain has also linked differences in the consumption of C_4

resources to social status or migration (Alexander et al., 2015, 2019). However, it remains unknown if $\delta^{13}C$ also correlates with phenotypic variation in mainland groups.

Lastly, femoral head size and bone cross-sectional properties did not correlate significantly with nitrogen isotope ratios (Table 4). This suggests that higher consumption of marine or terrestrial fauna did not correlate with higher body size or habitual loading. Given the overwhelmingly cereal based terrestrial diet indicated by isotopic data and historical sources, this finding is somewhat unsurprising, though *a priori* one might have expected some socioeconomic patterning (Purcell, 1994; Donahue, 2015; Pickard et al., 2017; Alaica et al., 2019; Dury et al., 2018). However, greater meat consumption may be linked to habitual use of the upper limb for different types of activities. Left humerus shape shows a significant positive correlation to $\delta^{15}N$ in Roman/LREB individuals, indicating that the difference between maximum and minimum diameters increases as $\delta^{15}N$ increases (Table 4; Figure 8). As previously stated, the complex mechanical environment of the upper limb and hand dominance complicates behavioral interpretations. One potential explanation for this positive correlation is differential use of the upper limb by individuals acquiring marine resources, since such foods would especially raise $\delta^{15}N$ values. Evidence of fishing (tools, icthyofauna) have been recovered from archaeological sites (Ramon 1995; Márquez-Grant, 2006). Interestingly, Alaica et al.'s (2019) analysis of LREB individuals from Joan Planells found two individuals with relatively high $\delta^{15}N$ values, a pattern consistent with intra-group variation in marine resource consumption. Using fishing gear and piloting watercraft might lead to less circular humeri due to repetitive unidirectional loading (e.g. rowing, line hauling, swimming). As boat-use is often associated with bimanual loading due to the use of oars, it is unexpected that correlations would be significant for only the left humerus (Table 5) (Weiss, 2003). However, fishing and sailing also involve other activities such as gutting, throwing, and hauling lines that may place significantly higher strains on one arm. Also, as Alaica et al. (2019) only found two Joan Planells individuals with outlying high $\delta^{15}N$ values consistent with marine resource consumption, small sample size may explain the lack of significance in right and average values. There are also potential explanations for the correlation between $\delta^{15}N$ and humerus shape other than fishing. For instance, individuals with higher $\delta^{15}N$ may represent higher status individuals with the resources to purchase meat and fish. In this case, the correlation would not directly stem from subsistence behavior but a difference in the types of behaviors engaged in by individuals of different socioeconomic status.

5. Conclusion

The current analysis improves understanding of chronological variation in physiological stress, behavior, and diet among Ibizan populations from the Late Roman/Early Byzantine to the Medieval Islamic period.

Urban populations from the LREB to the Islamic period show equivalence in body size and loading levels, whereas Rural Islamic groups exhibit evidence of reduced body size and habitual loading compared to both urban groups. The differentiation of Islamic Rural from urban populations might reflect differences in workload or genetic differences. However, a more convincing explanation is increased physiological stress among rural populations due to poorer diet, either reflecting reduced access to high protein foods or more frequent food scarcity. However, confirming this hypothesis would require additional isotopic data for Islamic Urban individuals or comparisons of pathological markers for poor diet between Islamic Urban and Rural individuals. Only limb shape differentiates the Urban LREB and Islamic groups, which may reflect a diachronic change in the type of activities but not the strenuousness of workloads. Analysis of the effect of diet on skeletal dimensions identified a relationship between $\delta^{13}C$ and body size. One explanation for this pattern is that greater access to C_4 resources improved diet quality or allowed for supplementation of the diet during periods of nutritional shortfall. Alternatively, non-locals from regions that depended more on the C_4 food web tended to be larger than individuals born on Ibiza due to dietary or genetic differences. Additional work would help clarify the relationship between body size, physiological stress, activity, diet, and place of origin in Ibizan and other Mediterranean populations. Future research can apply the techniques employed here to mainland Spain or around the Mediterranean. It could also use non-invasive imaging to assess changes in trabecular and cortical bone quantity due to diet and behavior. Increased sampling of enamel apatite will add further nuance to the understanding of Mediterranean diet. Also, further sulfur, strontium and oxygen isotope studies need to be carried out to identify non-local individuals, and this will clarify differences in behavior and health between locals and non-locals. Overall, this investigation advances understanding of variability in behavior and physiological stress in Ibiza and Mediterranean populations from 300-1235 AD. More broadly, it demonstrates the utility of combining stable isotope analysis with measures of body size and cross-sectional properties. This approach represents a valuable addition to the toolkit for studying biological and cultural change in past populations.

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Conflicts of Interest

The authors have no conflicts of interest.

Ethical Statement and Informed Consent

Analysis and data collection carried out for this study followed standard ethical guidelines for the analysis of archaeological human remains.

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Figure Legends

Figure 1: Boxplots of femur head diameter and bone lengths with overlaid raw data

Figure 2: Boxplots of diaphyseal products with overlaid raw data

Figure 3: Boxplots of diaphyseal circumferences with overlaid raw data

Figure 4: Boxplots of diaphyseal shape ratios with overlaid raw data

Figure 5: Scatterplot of femur head diameter regressed on δ13C with group specific regression lines (Outliers marked with arrows)

Figure 6: Scatterplot of femur length regressed on δ13C with group specific regression lines

Figure 7: Scatterplot of femoral circumference regressed on δ13C. Only whole sample regression line shown, as archaeological period specific regressions non-significant

Figure 8: Scatterplot of left humerus maximum/minimum diameter ratio regressed on δ15N with Late Roman/ Early Byzantine period regression line.