Tibial vascular grooves: ambulatory physical activity and overall muscle activation

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SUMMARY

The vascular grooves on the lateral surface of the tibial diaphysis have been suggested as a qualitative indicator of mobility and physical activity. We study here the association between these grooves and an external index of cross-sectional circularity of the tibia, a biomechanical variable related to mobility. Three Iberian skeletal samples were selected for study, representing the Chalcolithic, Early Modern and Contemporary periods, a time span where a significant decrease in ambulatory activity has been documented in European samples. For each tibia, the circularity index and the presence of vascular grooves were recorded. The Chalcolithic sample presented a higher circularity index compared with the other two samples, indicating higher levels of ambulatory physical activity. It also presented a higher frequency of vascular grooves. The association between the circularity index and the presence of vascular grooves .was significant, but considerable overlapping in the index was observed between tibiae with few and several grooves. These grooves are associated to the tibialis anterior muscle, which is activated during the gait cycle but also in what has been called "active rest" postures, and possibly in other nonambulatory activities involving foot hyperdorsiflexion. The age- and sex-related changes in the vascular system could be also important in the interpretation of these grooves. These grooves might be partially related to levels of ambulatory activity, but we conclude that its presence cannot be used alone as a qualitative marker of mobility. Its use as a general indicator of overall lower limb muscle activity should be explored.

Key words: Osteology – Tibia – Physical activity – Muscle activation – Vascular

INTRODUCTION

The study of the patterns of mobility of past populations through the application of engineering principles to the diaphyses of limb bones has been a major development in the study of human skeletal remains (Larsen, 2018; Ruff, 2018). These studies are mostly based on the analysis of the cross-sectional properties of the diaphysis, although other variables of bone shape can be studied, like its longitudinal curvature (Brzobohatá et al., 2019). In addition to these well-established, quantitative techniques, it is discussed whether qualitative assessment of traits like entheseal changes can be confidently used as markers of

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physical activity (Villotte and Knusel, 2013). The relation of the size of the nutrient foramen on the diaphysis of limb bones with ontogenetic and mobility patterns has been studied in other organisms such as birds and kangaroos (Allan et al., 2014; Hu et al., 2018). In relation to the vascular system and the qualitative assessment of traits, it has been recently proposed that the vascular grooves in the human femur and tibia could be related to mobility and/or weight-bearing activity patterns (Soltysiak, 2015; Trujillo-Mederos et al., 2013). These authors observed a significant relationship between robusticity indices related to body size and mobility, and the presence of vascular grooves in the femur and tibia. A limitation of these studies was that they analyzed the intern sample variation of these variables, in Prehispanic individuals from the Canary Islands (Trujillo-Mederos et al., 2013), and in commingled remains from the Middle-East from the first half of the fourth millenium BCE (Soltysiak, 2015).

We present here the study of three Iberian skeletal samples spanning a chronological interval during which a decrease in ambulatory physical activity has been previously documented in European populations (Macintosh et al., 2014; Ruff et al., 2015). Basing our study on these previous findings, we would expect significant differences between the selected samples in the biomechanical parameters related to mobility. If these differences are observed, then the samples would be fit to test the hypothesis that the presence of vascular grooves in the tibia is a qualitative indicator of mobility, since we would expect more vascular grooves on the sample with biomechanic indices pointing to higher levels of mobility. Due to the complex nature of the variance in biological phenomena, the findings will be discussed in a broader context, considering other factors beyond levels of mobility.

MATERIAL AND METHODS

Three samples from different chronologies were selected: Carracasla and Wamba, curated at the Laboratory of Osteology, Faculty of Biological Sciences, Universidad Complutense de Madrid (UCM); and the documented collection from the Department of Legal Medicine, Psychiatry and Pathology, Faculty of Medicine, UCM. Carracasla is an archaeological collection recovered from the caves of the karstic system of Prádena de la Sierra (Province of Segovia, Spain). The radiocarbon date of one of these caves has resulted in 2460-2040 years cal BC, thus belonging to what is termed the North Plateau Chalcolithic (Carmona Ballestero, 2014). The minimum number of individuals of the Chalcolithic sample was 39 (epiphyses-fused right humeri), and the metric study of the 43 available pelvises (23 right pelvises, 21 left pelvises), indicated the presence of at least six women (right pelvises) and eight men (left pelvises) (Brůžek et al., 2017). Wamba is a collection named following its place of origin, the Church of Santa María de Wamba (Province of Valladolid, Spain), where a large secondary ossuary deposit was formed, dating from the 16^{th} to 17^{th} century, representing people affiliated with that church (López-Bueis, 1999). In this Early Modern sample, the presence of both sexes has been reported (López-Bueis, 1999), and the tibiae were selected based on visual assessment of size and robusticity with the objective of including both sexes. In these two disarticulated samples, right and left tibiae were selected for study, since each tibia probably represents one person. The documented collection is composed of skeletons of known sex and age of people who died in the city of Madrid at the end of the last century. This cemetery collection, with identification number EML-001/002, was initiated through a legal agreement between the Funeral Services of the Government of the Autonomous Community of Madrid and the Universidad Complutense de Madrid, for educational and research purposes, and complying with current legislation and personal data protection law, similar to other skeletal collections from cemeteries (Cardoso 2006; Belcastro et al., 2017).

For the present study, the three samples are named as Chalcolithic (Carracasla), Early Modern (Wamba), and Contemporary (documented). Skeletons from the Contemporary collection were divided into two age groups in the variable AGE, younger and older than 40 years. This age limit was selected due to the changes observed beyond that age in the cardiovascular system (Oxborough et al., 2014; Scuteri et al., 2014). The sex and age composition presented an overrepresentation of people older than 60 years and more women than men for younger ages. In this sample of complete skeletons, right and left tibiae were studied, but for comparison with the other two samples, the left tibiae were selected. Sample sizes are described in detail in Table 1. Only tibiae with completely fused epiphyses, without any observable pathological condition, were selected.

To illustrate the presence of vascular grooves in the tibia, we show in Fig. 1a the dissection of the leg from a body donation with code 16/99, from the body donation program of the Department of Anatomy and Radiology, Faculty of Medicine, Universidad de Valladolid. The vascular grooves are associated to the arteries arising from the anterior tibial artery, which supply the tibialis anterior muscle (Fig. 1a). Two features of each vascular groove were recorded: position (medial, lateral or posterior side), and intensity (shallow, deep). The differentiation between shallow and deep grooves was made as follows: if the groove was completely visible at plain sight with tangential natural light, the groove was classified as deep; if additional artificial tangential light was needed to observe

Table 1. Sample sizes by collection, side, sex ad age group.

Collection	Right	Left	Female	Male	20-40 years	40+ years	Total
Chalcolithic	25	20	-	-	-	-	45
Early Modern	30	34	-	-	-	-	64
Modern	78	77	50	105	55	100	155

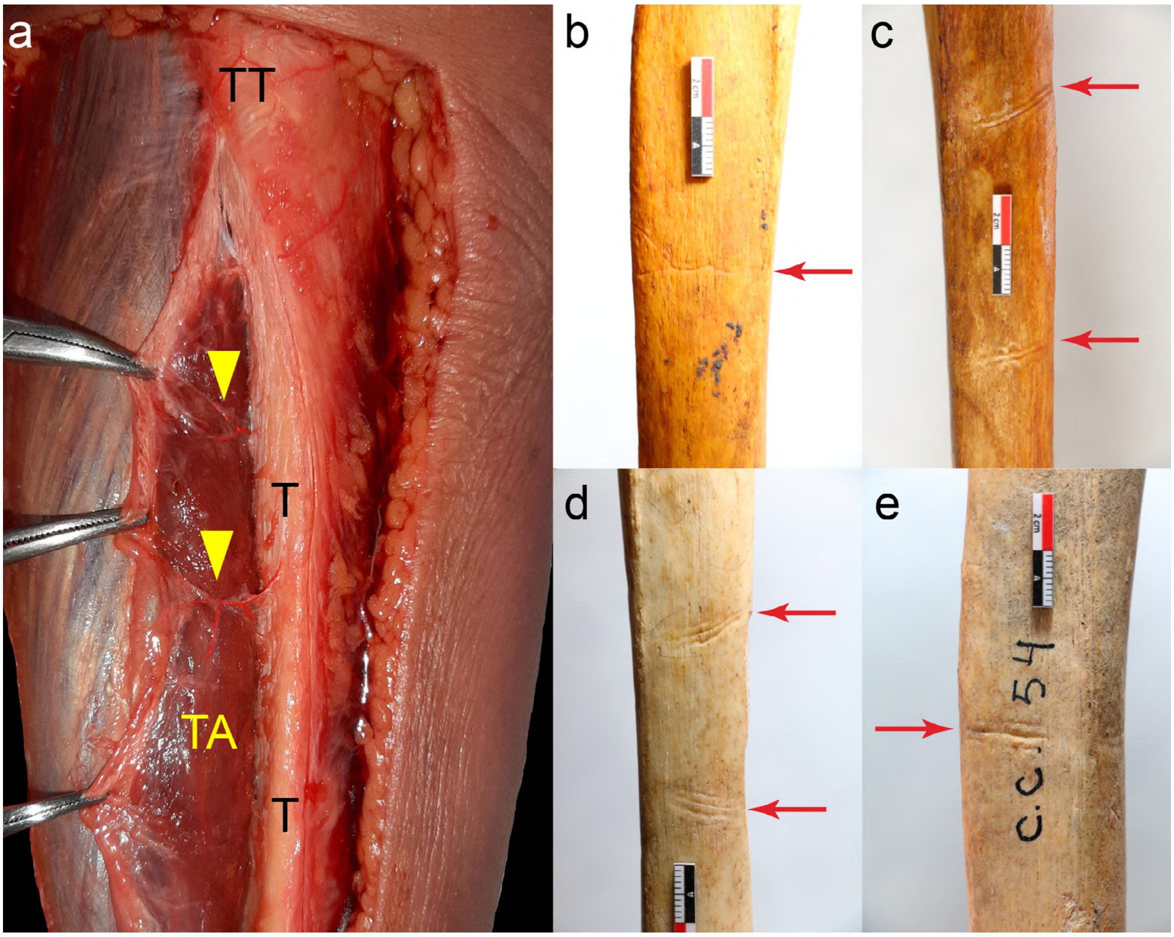

Fig. 1.- Left (**a**): Dissection undertaken at the Faculty of Medicine, Universidad de Valladolid, where the tibial tuberosity (TT) and anterior border of the tibial diaphysis (T) can be observed, as well as the tibialis anterior muscle (TA), and the transverse arteries associated to the vascular grooves of the tibial surface (yellow triangles). Right: A shallow vascular groove is shown in **b** (tibia from the Contemporary collection), while deep grooves are shown in tibia from the Contemporary (**c**), Early Modern (**d**), and Chalcolithic (**e**) samples. All vascular grooves are indicated with red arrows.

Table 2. Descriptive statistics (mean and standard deviation) of the SV (Dmax/Dmin), by collection, sex and age group.

Collection	Total		Female		Male		20-40 years		40+ years	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Chalcolithic	1.56	0.14	-	-	-	-	-	-	-	-
Early Modern	1.41	0.12	-	-	-	-	-	-	-	-
Modern	1.42	0.11	1.39	0.12	1.39	0.12	1.41	0.09	1.43	0.12

Table 3. Percentage of tibiae by total number of grooves and number of deep grooves, by collection.

	Number of grooves							
Sample	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Chalcolithic	0,0	2,6	17,9	17,9	25,6	20,5	10,3	0,0
Early Modern	7,8	18,8	26,6	25,0	12,5	3,1	3,1	3,1
Contemporary	13,0	15,6	32,5	19,5	14,3	2,6	2,6	0,0
	Number of deep grooves							
Sample	**0**	**1**	**2**	**3**	**4**			
Chalcolithic	41,0	33,3	12,8	12,8	0,0			
Early Modern	48,4	37,5	6,3	6,3	1,6			
Contemporary	61,0	22,1	9,1	3,9	3,9			

the full extent of the groove, it was classified as shallow. The aspect of the vascular grooves in four tibiae are shown in Figs. 1b-e. The total number of grooves (NG), and the number of deep grooves (DG) per tibia were recorded. Two ordinal variables were created from these data: NG2, with two categories (0-3 grooves, 4-7 grooves); DG2, with two categories (0-1 deep grooves, 2-4 deep grooves). These tresholds for NG2 and DG2 were exploratory, and based on the rationale that an increased number of vascular grooves, or deep vascular grooves, could be associated with higher levels of the index variable of shape (see below).

Cross-sectional properties of the diaphyses that take into account the cross-section (medullary or solid), are usually analyzed to obtain, among others, measurements of bone's resistance to bending and torsional loads (second moments of area, and polar second moments of area), that allow to reconstruct mobility patterns (Ruff, 2018). External measurements of the diaphyses are also useful to study mobility patterns (Laffranchi et al., 2020; Wescott, 2006), since a reasonable correspondence has been observed between indices derived from them with those calculated upon medullary or solid cross-sections of the diaphyses (Stock and Shaw, 2007). The maximum and minimum diameter (Dmax and Dmin) at the tibial midshaft were measured with a digital caliper, and the index variable of shape SV (Dmax/Dmin) was calculated, as an alternative to the shape ratio or index of cross-sectional circularity obtained from the second moments of area (Imax/Imin) from the cross-section of the diaphysis (Macintosh et al., 2014; Stock and Shaw, 2007).

Regarding statititistical methods, first, since the shape variable SV (Dmax/Dmin) is a ratio, it was log transformed for achieving a log-normal distribution for statistical analysis. A one-way ANOVA with Tukey's HSD test for multiple comparisons was used to study the variation between the three samples in the quantitative variable SV. The Kruskall-Wallis test and the pairwise comparisons with Bonferroni correction were used to study the differences between the three samples in the number of vascular grooves, an ordinal variable. The Student's t-test for independent samples was used to study the association between the SV (quantitative variable) and the presence of vascular grooves (ordinal variables). Finally, the association of sex and age with the vascular grooves was studied with the chi-square test.

RESULTS

Descriptive statistics for the SV are shown in Table 2 (mean and standard deviation). For the NG and DG variables, percetange of tibiae by number of grooves is shown in Table 3. The one-way ANOVA (F(2,181)=[24.415], *p*< .001), and Tukey's HSD test for multiple comparisons, revealed that the mean value of the log-transformed SV was significantly higher in the Chalcolithic sample in comparison with the two other samples (*p*<.001), which did not differ between them (*p*=.977) (Fig. 2a). The vascular grooves were located mostly in the lateral side (90.71%), and middle third (82.67%) of the tibiae. The Kruskall-Wallis test (H=19.237, *p*=.001), and the pairwise comparisons with Bonferroni correction revealed that the

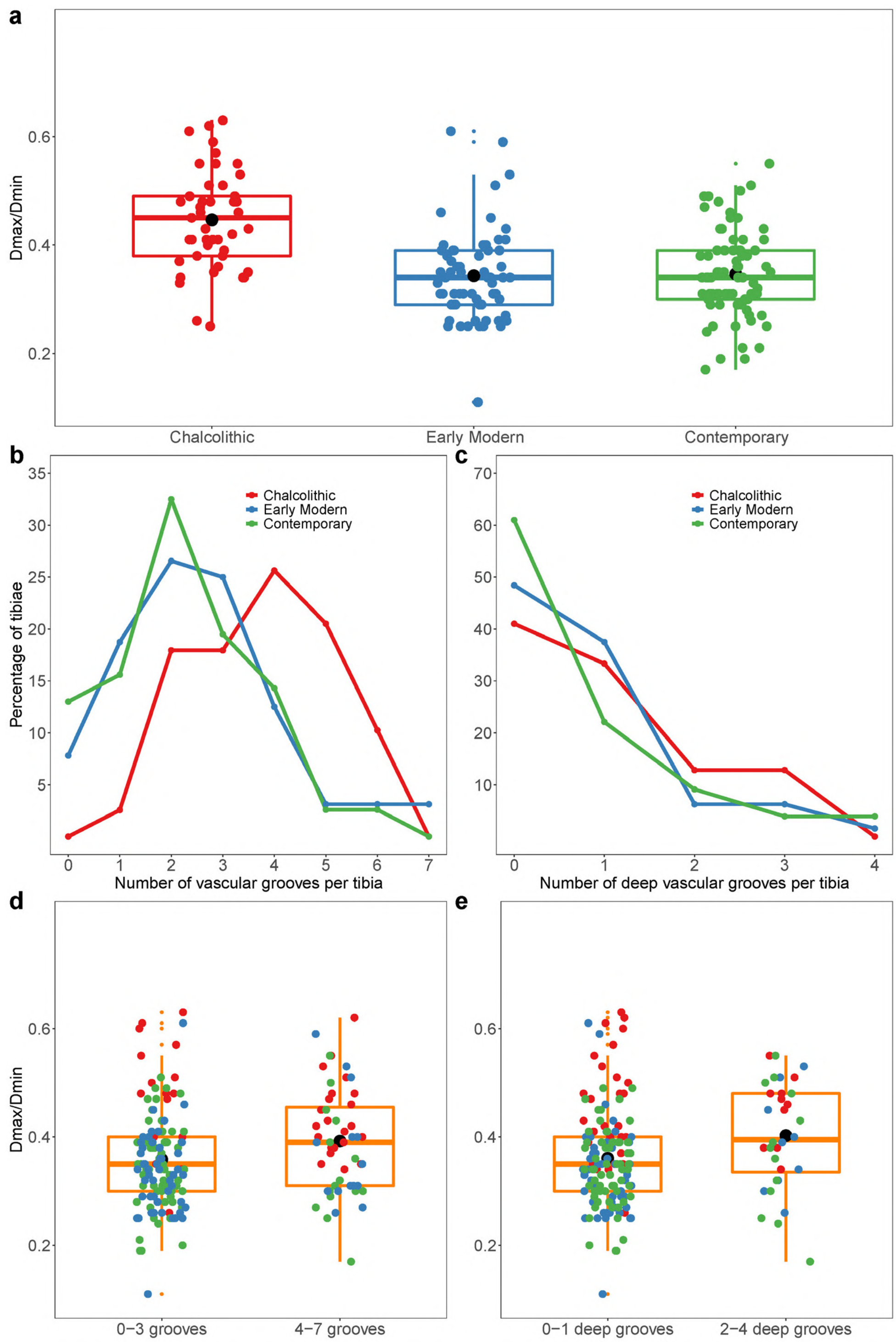

Fig. 2.- Box plot graph of the values of log-transformed SV by collection (**a**). Distribution of the tibiae by number of vascular grooves (**b**), and number of deep grooves (**c**), in percentages and by collection. Box plot graph of the values of the log-transformed SV, grouping the tibiae in two categories of total number of grooves (**d**), and number of deep grooves (**e**).

Chalcolithic sample presented a different distribution than the two other samples (p=.000, Early Modern; p=.002, Contemporary), with higher percentages of tibiae with more vascular grooves (Fig. 2b). The same test was used for the number of deep grooves (H=3.910, p=.142), and no differences were observed between the samples, although there were more tibiae with a higher number of deep grooves in the Chalcolithic sample (Fig. 2c). To study the association between the SV and the presence of vascular groups, the variables NG2 and DG2 were selected, and the Student's t-test for independent samples was used. The group of tibiae with more vascular grooves presented a significant higher value of SV for the total number of grooves or NG2 ($t(176)$=-2.272, p=.024), and

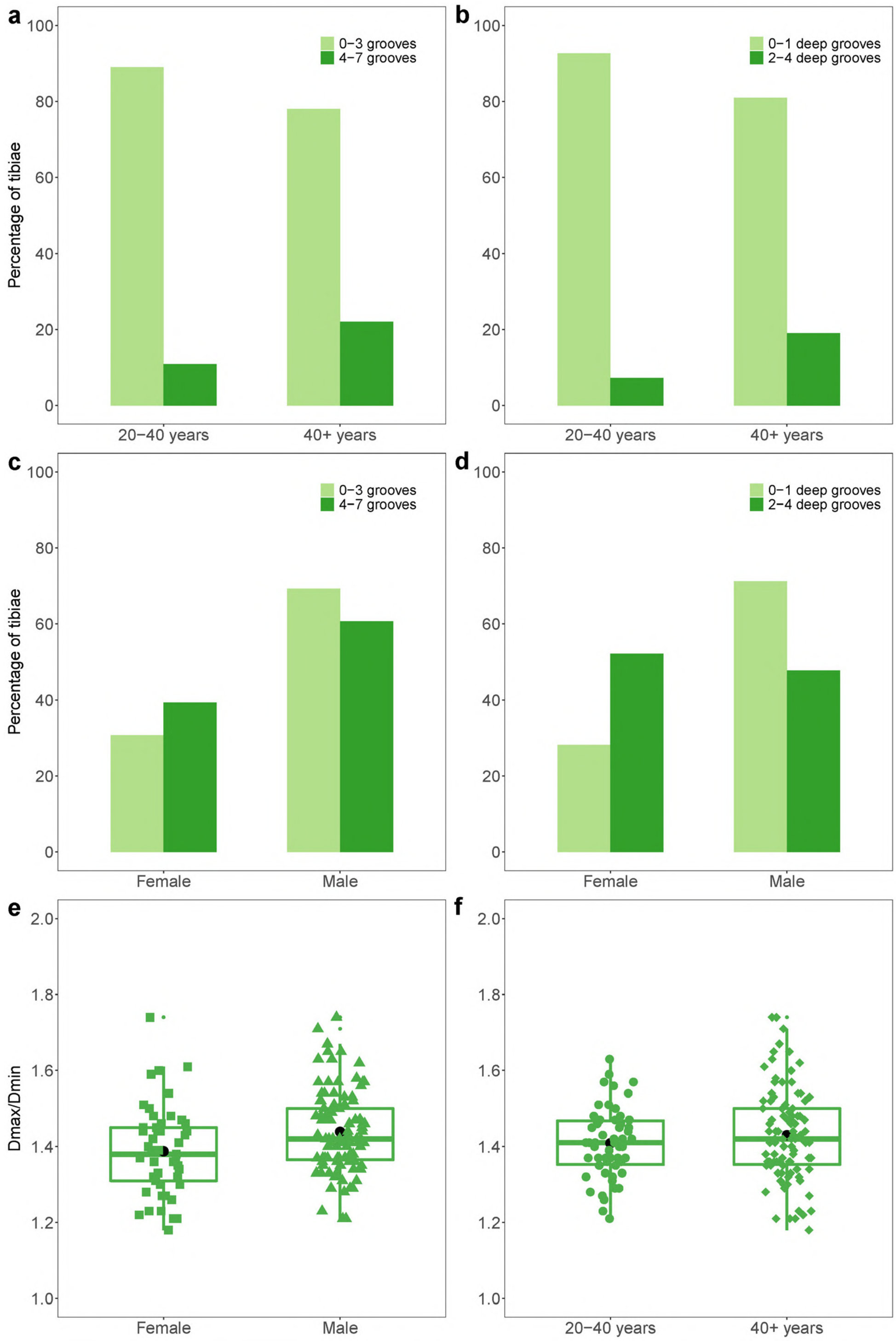

Fig. 3.- Bar graphs representing the changes associated with age in the categories of total number of groups (**a**), and deep grooves (**b**). Sexual differences in the total number of groups (**c**), and deep grooves (**d**), is also presented. Sexual differences and age changes in the values of the SV are also shown (**e** and **f**, respectively).

for the number of deep grooves or DG2 ($t(176)=-2.351$, $p=.020$) (Fig. 2d,2e).

The association of sex and age with the vascular grooves and the SV could be studied only in the Contemporary documented collection (Fig. 3). The chi-square test was used to study the relation between sex and age and the variables NG2 and DG2. The relation between sex and NG2 was significant ($p=.006$), while the relation with DG2 was not significant ($p=.077$). In both cases, women presented more tibiae with a higher number of total and deep grooves than men. The relation between the variable AGE and NG2 and DG2 was not significant (NG2, $p=.086$, continuity correction $p=.134$; DG2, $p=.049$, continuity correction $p=.084$). In both cases, tibiae in the older age group presented a higher number of total and deep grooves. With regard to the SV, the independent t-test revealed a significant difference between the sexes, with higher values for males (t(150)=-2.825, $p=.005$). No significant difference in SV was observed between the AGE groups (t(150)=-1.087, $p=.279$).

DISCUSSION

Previous biomechanical analyses have shown a temporal decrease in the values of some biomechanical properties of the cross-section of the femur and tibia in European samples from the Upper Paleolithic or Neolithic to the Early Medieval or very recent periods, associated with a decrease in ambulatory physical activity or mobility (Macintosh et al., 2014; Ruff et al., 2015). Lower circularity, or high values of the index Imax/Imin, has a strong association with high levels of terrestrial mobility, and a temporal change from lower to higher circularity of the tibia has been observed in these studies (Macintosh et al., 2014). The difference in the SV (Dmax/Dmin) between the Chalcolithic sample and the other two samples agreed with these previous results. We thus considered that the selected samples are useful to test the hypothesis of the presence of tibial vascular grooves as a qualitative marker of mobility. The Chalcolithic sample also presented a higher frequency of total number of vascular grooves, and a less marked increase in the number of deep grooves, than the two other samples, and there was a significant association between the SV and the vascular grooves. These results would support the suggestions of previous authors related to mobility (Soltysiak, 2015; Trujillo-Mederos et al., 2013), but Figs. 2D,2E indicate a more complex relation between the SV and the vascular grooves. There is a considerable overlap of values of the SV between the categories of vascular grooves, with tibias with a high value of the SV but with a lower number of total and deep grooves, and vice versa. Beyond the variation associated to the SV, the presence of vascular grooves in the diaphysis of the tibia is clearly related to other factors.

The vascular grooves studied in the present work were located mostly in the lateral side (90.7%) of the middle third of the tibia (82.67%), associated to the tibialis anterior muscle, whose most known function is foot dorsiflexion, very important in balance control and during the gait cycle (Ruiz-Munoz and Cuesta-Vargas, 2014). This well-known function of the tibialis anterior offers support to the hypothesis linking the vascular grooves with high levels of mobility, but this muscle is also involved in nonambulatory activity. Raichlen et al. (2020) examined the physical patterns of inactivity in a hunter-gatherer population, the Hadza of Tanzania, and observed that they present levels of nonambulatory time similar to those found in industrialized populations, averaging 9.9 hours of nonambulatory rest. But the Hadza often spent this time in what the authors termed “active rest” postures, which require higher levels of muscle activity than the most common posture in industrialized societies, chair sitting. One of these postures is full squatting (defined by these authors as squatting with heels in ground contact and buttocks elevated from the ground), which elicited higher levels of activity for the tibialis anterior, soleus and vastus lateralis, compared with chair sitting, as measured by electromyography (Raichlen et al., 2020). For the tibialis anterior, this activation reached almost 40% of the activation during walking. These findings are relevant from a bioarchaeological perspective, since a decline in the osteological indicators of squatting has been observed in European populations at least during the last twenty centuries (Boulle, 2001), and similar temporal changes have been observed in samples from other regions (Dlamini and Morris, 2005). As summarized by Boulle (2001), the temporal decrease in squatting could correspond to changes in interior space organization, including the increasing presence of furniture, as well as changes in some laboral activities, with less requirement of foot hyperdorsiflexion. The activation of the tibialis anterior in full squatting, and the temporal decrease of this posture, could also be associated to the variability of the frequency of vascular grooves observed in the present study. In this regard, the tibialis anterior could have been also involved in past populations in nonambulatory activities requiring foot hyperdorsiflexion. The patterns of mobility, resting posture like full squatting, and nonambulatory activities requiring foot hyperdorsiflexion, all involving the activation of the tibialis anterior, have changed through human history, and all could have a potential impact on the expression of vascular grooves on the tibia in skeletons from different periods. The difference in the SV and the distribution of the vascular grooves between the Chalcolitic sample and the other two samples would indicate a more physically active, both ambulatory and non-ambulatory, lifestyle in the former.

Other factors could be also important, like sex and age, although their effect could only be explored in the Contemporary sample. Men who lived in Madrid during the twentieth century presented higher values of the SV than women, although with a considerable overlap between sexes. Gendered division of labour has been an important factor shaping the mobility patterns in twentieth-century Western societies. Differences have been documented in work-related mobility as well as in what is termed maintenance work and mobility, associated to diverse, fundamental, non-remunerated tasks (Best and Lanzendorf, 2005). Sex also influenced the expression of vascular grooves, with women presenting a higher frequency of deep grooves than men. With regard to age, we observed an increase in the frequency of deep grooves after 40 years. Blood pressure and arterial stiffness increase with age (AlGhatrif et al., 2013; Scuteri et al., 2014), as well as muscular artery diameter, specially in women (Xu et al., 2017), and our results could be also reflecting these facts.

In conclusion, the Chalcolithic sample presented a significantly different diaphyseal shape of the tibia when compared with the Early Modern and Contemporary samples, indicating higher levels of mobility, as expected from previous works. It also presented a higher frequency of vascular grooves. But although the association between the shape of the tibia and the vascular grooves was significant, the presence of vascular grooves cannot be used to infer high levels of mobility. These vascular grooves are associated to the tibialis anterior muscle, which is activated during the gait cycle but also in what has been called “active rest” postures, and possibly in other nonambulatory activities involving foot hyperdorsiflexion. The age- and sex-related changes in the vascular system could be also important in the interpretation of these grooves. The presence of vascular grooves might be partially related to higher levels of mobility, but we conclude that it cannot be used alone as a qualitative marker of mobility in skeletal samples. Its use as a general indicator of overall lower limb muscle activity, both ambulatory and non-ambulatory, should be explored.

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