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Bending and torsional strengths of the tibia *vs.* simple anthropometric variables among the prehispanic population of El Hierro (Canary Islands)

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SUMMARY

Assessment of skeletal robusticity is an important tool for the archaeologist and anthropologist, since it may be related to the intensity and type of activity performed by ancient population groups. Development of computed tomography (CT) allows determination of biomechanical properties of long bones. However, CT technology may not be easily available and is a relatively expensive procedure. Therefore, it is pertinent to estimate whether any of the parameters which can be easily measured in bare bones by simple anthropometry are useful to assess the torsional strength and bending strength of these bones. We included twenty one well preserved tibiae corresponding to prehispanic adult individuals (13 men) from El Hierro island. These bones were anthropometrically measured following classical methods, and also subjected to CT analysis, and further calculation of minimum and maximum second moments and polar second moment of area, both at midshaft and at the nutrient foramen levels, using the software (www.hopkinsmedicine.org/FAE/mmacro.htm). The diaphyseal robusticity index showed a close relationship with minimum second moment of area at the nutrient foramen ($r=0.824$, $p<0.001$) and polar second moment of area at the nutrient foramen ($r=0.824$, $p<0.001$), whereas correlations with the epiphyseal robusticity index were weaker ($r=0.628$, $p=0.005$, and $r=0.618$, $p=0.007$, respectively). The variable which allows the best estimation of the torsional strength is the perimeter at the nutrient foramen, by the formula Polar second moment of area (in mm^3) = -700.30 + 11.77 * perimeter at the nutrient foramen (in mm) for the whole population (standard error of the estimation=56.91; absolute range from-114.26 to 140.29), or Polar second moment of area (in mm^3) = -897.93 + 13.74 * perimeter at the nutrient foramen (in mm) when only men were analyzed, with a standard error of the estimation of 32.17 (absolute range= from -44.53 to 50.32 mm^3).

Key words: Polar second moment of area – Bone strength –Bone cross sectional geometry – Prehispanic population of the Canary Islands

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Therefore, anthropometric parameters may serve to roughly estimate torsional strength in this prehispanic sample of El Hierro, but this correlation is not strong enough to allow an accurate estimation of the torsional strength based on the values of bone perimeter at this level.

INTRODUCTION

A relationship exists between mechanical loading and functional adaptation in the skeleton (Stock and Shaw, 2007). Recent research has led to the discovery of the importance of the so called canonical Wnt-catenin pathway in this process: robust muscle contraction, such as that derived from repetitive activity and training, activates bone synthesis by stimulation of the canonical Wnt pathway (Liu et al., 2008). Osteocytes play an outstanding role in this pathway, because they are able to translate mechanical loading –sensed by a network of cell prolongations – into biochemical signals which modulate bone synthesis or resorption in response to these stimuli (Bonewald and Johnson, 2008). Undoubtedly, this biological system has an effect on bone shape. On this basis, several robusticity indices which relate transverse measurements to longitudinal ones were developed (Martin and Saller, 1957). However, cross sectional geometry of the bones, with calculation of the minimum and maximum second moments of area and the polar second moment of area allows a more precise estimation of bending and torsional strength (Ruff et al., 1993). Direct assessment of cross sectional biomechanical parameters of long bones is a destructive process, but development of computed tomography has overcome this handicap (Jungers and Minns, 1979).

Assessment of skeletal robusticity is an important tool for the archaeologist and anthropologist, since it may be related to the intensity and type of activity performed by ancient population groups. In this sense, studies on skeletal robusticity have been performed on Australian aborigines and other populations, such as Southern Africa Late Stone Age individuals and individuals of the Andaman Islands, assessing maximum and minimum second moments of area and polar second moments of area (Carlson et al., 2007; Stock and Pfeiffer, 2001), looking for a relation with mobility and physical activity. Other authors have also assessed robusticity using metric parameters (Pearson and Millones, 2005) in populations exposed during many generations to a cold environment, since a cold climate also leads to increased robusticity (Pearson, 2000).

Computed tomography may be not universally available and is a relatively expensive procedure. Therefore, it is pertinent to estimate whether any of the parameters which can be easily measured in bare bones by simple anthropometry are useful to assess the torsional strength and bending strength of these bones. This is the aim of this study, in which we analyze the relationship between anthropometrically calculated robusticity indices with CT-assessed torsional strength and bending strength on a sample of 21 individuals

Table 1. Tibial measurements of left and right tibiae

	Left tibiae	n	Right tibiae	N	T; p
Spino-malleolar length	350.29 ± 23.80	7	347.08 ± 21.35	12	Z=0.68; NS
Tibial length	343.86 ± 23.26	7	339.75 ± 20.13	12	Z=0.55; NS
Tibial articular length	312.56 ± 6.91	9	312.09 ± 9.73	11	Z=0.19; NS
Proximal epiphyseal breadth	68.86 ± 8.17	7	70.58 ± 5.50	12	Z=0.47; NS
Distal epiphyseal breadth	49.43 ± 6.63	7	46.50 ± 5.33	12	Z=1.10; NS
Minimum shaft circumference	79.44 ± 7.25	9	78.75 ± 9.05	12	Z=0.14; NS
Transverse (medial-lateral) diameter (midshaft)	20.67 ± 1.87	9	20.67 ± 2.06	12	Z=0.18; NS
Circumference at nutrient foramen	92.33 ± 9.23	9	91.00 ± 8.53	12	Z=0.36; NS
Anteroposterior diameter (foramen)	33.78 ± 4.71	9	33.58 ± 3.92	12	Z=0.14; NS
Transverse (medial-lateral) diameter (foramen)	22.67 ± 1.87	9	22.58 ± 1.50	12	Z=0.07; NS
Anteroposterior diameter (midshaft)	29.22 ± 3.90	9	28.00 ± 4.00	12	Z=0.50; NS

Results given in mm, as mean ± standard deviation; “n” means number of cases. In the last column we show the value of Mann Whithney´s U test (Z), followed by NS, which means p>0.5 (in this table).

belonging to the prehispanic population of El Hierro, in the Canary Islands.

MATERIALS AND METHODS

Twenty one well preserved tibiae (12 right, 9 left) were analyzed in this study. They belong to adult prehispanic individuals of El Hierro, one of the islands of the Canary Archipelago, and yield an antiquity of 1000-1500 years BP (Velasco-Vázquez et al., 2005). These individuals were buried in a volcanic cave in Punta Azul, one of the most important prehispanic burial caves in El Hierro, containing skeletal remains of more than 100 individuals. The cave had already been plundered when excavated by members of the Department of Prehistory of the University of La Laguna (Tenerife, Canary Islands) about 18 years ago (Velasco-Vázquez et al., 2005). It contained about 100 corpses, which were deposited on stony or vegetal layers, but not interred, a burial procedure which undoubtedly favoured preservation of the bones, especially in an arid environment such as that of the southern slopes of El Hierro. The island El Hierro was colonized about 2500 years ago by people of North African origin. They were mainly goatherds and shell-fishers; huge shell middens have been found in certain areas of the island, not at the seashore but about at 200 m altitude. Preliminary inspection of the skeletal remains shows that the population was robust, something probably related to the style of life, considering the marked slopes of the island, the mentioned shell middens located relatively far away from the seashore, and the activity as goat- and sheepherders. Tibiae were well-preserved and allowed accurate measurement of nearly all anthropometric variables besides some few exceptions (Table 1). Right and left bones belong to different individuals, as inferred by macroscopic examination. However Mann Whitney's U-test indicates the homogeneity of the sample when the side of the bone is taken into account (Table 1). No gross pathological changes were observed which can affect the analysis. Bones are currently preserved at the Dpto. de Prehistoria, Arqueología, Antropología e Historia Antigua of the University of La Laguna (Tenerife, Canary Islands, Spain). Tibiae were chosen because of their abundance and good preservation.

Sex was assessed by genetic methods, as described elsewhere (Arnay-de-la-Rosa et al., 2007). This was successfully performed in 14 cases; for the remaining tibiae we utilised the discriminant functions described some years ago by ourselves (González-Reimers et al., 2000). Combining both methods, 13 samples belong to men, (7 left, 6 right) and 8 (2 left, 6 right), to women.

Anthropometric measurements

Anthropometric parameters which describe the morphology of tibiae were measured following standard criteria (Martin, 1914; Martin and Saller, 1957; Olivier, 1960). Measurements were independently performed by two of us, repeating the measurements jointly if there were differences in the measurements performed separately. The parameters recorded were:

1.- Tibial length, from the medial malleolus to the lateral condyle

2.- Tibial articular length, from the medial condyle to the center of the distal articular surface.

3.-Tibial spino-malleolar length, from the tip of the intercondyloid eminence to the tip of the medial malleolus

4.- Circumference at the nutrient foramen level, with a plastic-covered tape.

5.- Minimum shaft circumference, usually located near the distal end of the tibia, with a plastic covered tape.

6.- Anteroposterior and transverse (medial-lateral) diameters at the nutrient foramen level.

7.- Proximal epiphyseal breadth, as the maximum distance between the condyles.

8.- Distal epiphyseal breadth, as the distance between the medial malleolus and the center of the fibular notch. These last three variables were obtained with a sliding calliper.

9.- Midshaft medial-lateral (transverse) diameter, as maximum transverse distance between both ends of the tibial cortex of the shaft of the tibia at its midpoint.

10.- Midshaft anteroposterior diameter, as maximum anteroposterior distance between both ends of the tibial cortex of the shaft of the tibia at its midpoint.

The three tibial-length measurements were obtained with an osteometric board. The last five variables were measured with a sliding calliper.

In accordance with other studies, we calculated the following indices:

1.- Diaphyseal robusticity index, as (midshaft anteroposterior diameter + midshaft medio-lateral diameter)/articular length (Pearson 2000).

2.- Epiphyseal robusticity index, as maximal proximal epiphyseal breadth / tibial articular length (Pearson 2000).

3.- Residual robusticity index, as (midshaft posteroanterior diameter + midshaft medio lateral diameter)/ proximal epiphyseal breadth (Pearson & Millones, 2005).

4.- Robusticity index, as minimum shaft circumference/tibial spino-malleolar length (Wood, 1920).

As commented, these indices, which usually relate breadth measurements with longitudinal ones, are usually utilized to compare robusticity among populations, and were therefore chosen for comparison with data related with bending and torsional strength (see below).

Calculation of maximum, minimum and polar second moments of area

Cross-sectional properties of these tibiae were recorded both at the midshaft of the maximum length of the tibiae and at the nutrient foramen by computed tomography (CT). CT images were taken with the aid of a TOSHIBA ASTEION^{TM} VP, which allows high resolution images 0.8 mm slice thickness. With the aid of an image J and moment macro (www.hopkinsmedicine.org/FAE/mmacro.htm) the parameters calculated were (Table 2): the cortical area, the percent cortical area in relation to the total area of the section, the maximum and minimum second moment of area, which estimate the maximum and minimum bending strengths, respectively, and the polar second moment of area, which estimates the torsional strength (Stock and Shaw, 2007). All these data were obtained both at midshaft and nutrient foramen. In order to assess skeletal robusticity and avoid the problems of the allometry the maximum and minimum second moment of area and the polar second moment of area were standardized to maximal (spino-malleolar) length (Ruff, 2000).

Statistics

The Kolmogorov-Smirnov test was used to test normality of the quantitative variables. Although variables were normally distributed, because of the small size of the analyzed sample the Mann-Whitney's U-test was used to compare the variables between the two sexual series and between right and left tibiae. In order to test if there was an association among two quantitative variables (as, for instance, second polar moment at the nutrient foramen and robusticity index) we used Spearmann's correlation analyses. This was done for men, for women and for all the whole sample (men and women together).We also performed stepwise multivariate linear regression analysis, introducing those variables which showed a significant relationship with the moments of area, in order to test the ability of simple anthropometric parameters in the estimation of torsional strength and bending strength.

RESULTS

Table 2. Tibial measurements in men and women

	Men	N	Women	N	T; p
Spino-malleolar length	356.75 ± 21.73	12	333.71 ± 12.37	7	Z=2.20; p=0.028 *
Tibial length	349.25 ± 20.81	12	327.57 ± 12.49	7	Z=2.29; p=0.022 *
Tibial articular length	315.92 ± 8.00	12	306.88 ± 5.77	8	Z=2.44; p=0.012 *
Proximal epiphyseal breadth	72.25 ± 6.73	12	66.00 ± 3.56	7	Z=2.12; p=0.034 *
Distal epiphyseal breadth	50.25 ± 5.72	12	43.00 ± 1.91	7	Z=2.72; p=0.007 *
Minimum shaft circumference	82.69 ± 7.26	13	73.13 ± 5.82	8	Z=2.86; p=0.004 *
Transverse (medial-lateral) diameter (midshaft)	21.46 ± 1.90	13	19.38 ± 1.18	8	Z=2.47; p=0.014 *
Circumference at nutrient foramen	95.85 ± 8.09	13	84.63 ± 3.42	8	Z=2.87; p=0.004 *
Anteroposterior diameter (foramen)	35.38 ± 4.13	13	30.88 ± 2.42	8	Z=2.41; p=0.016 *
Transverse (medial-lateral) diameter (foramen)	23.08 ± 1.75	13	21.88 ± 1.13	8	Z=1.86; p=0.064
Anteroposterior diameter (midshaft)	29.69 ± 4.40	13	26.63 ± 1.92	8	Z=1.79; p=0.074
Robusticity index	24.24 ± 1.19	12	23.04 ± 1.15	7	Z=1.82; p=0.069
Diaphyseal robusticity index	18.53 ± 1.54	12	17.19 ± 0.79	7	Z=2.43; p=0.015 *
Residual robusticity index	7.08 ± 0.57	12	6.96 ± 0.29	7	Z=0.97; NS
Epiphyseal robusticity index	22.81 ± 2.06	11	21.51 ± 1.17	7	Z=1.59; NS

Results of the single anthropometric parameters are given in mm, as mean ± standard deviation; "n" means number of cases. In the last column we show the value of Mann Whithney´s U test (Z) together with significance (p). NS means p>0.1 and * means p<0.05

The results on the metric and biomechanical tibial measurements, and the correlation coefficients of the multiple linear regression analyses between both kinds of variables are shown in Tables 2-4. There are marked sexual differences, statistically significant in all the anthropometric measurements of tibia, excluding medial-lateral and anteroposterior diameters at midshaft. These differences seem more important in some variables related with bone breadth, such as epiphyseal breadth or shaft circumference, as shown in Table 2. Interestingly, regarding minimum second moment of area and polar second moment of area, maximal differences among men and women were observed at the nutrition foramen. As shown in Table 3, there are indeed significant differ-

Table 3. Cortical areas, second moments of area, and polar moments of area both at the midshaft and at the cnemic foramen, among male and female tibiae

	Men (n=13)	Women (n=8)	T; p
Cortical area at midshaft (% in relation to total area)	77.04 ± 7.28	70.09 ± 9.86	Z=1.74; p=0.082
Cortical area at nutrition foramen (% in relation to total area)	51.58 ± 7.47	49.01 ± 7.12	Z=0.70; NS
Minimum second moment of area at midshaft/ maximal length (mm^3) (Imin)	71.65 ± 22.33	70.37 ± 21.85	Z=0.17; NS
Maximum second moment of area at midshaft /maximal length (mm^3) (Imax)	180.07 ± 74.65	173.01 ± 64.06	Z=0.09; NS
Minimum second moment at nutrition foramen /maximal length (mm^3) (Imincn)	119.18 ± 36.28	77.90 ± 15.93	Z=2.79; p=0.005 *
Maximum second moment at nutrition foramen / maximal length (mm^3) (Imaxcn)	295.88 ± 100.08	192.16 ± 8.70	Z=1.78; P=0.076
Polar second moment of area at nutrition foramen/maximal length (mm^3)	433.11 ± 118.29	290.47 ± 49.32	Z=2.28; p=0.022 *
Polar second moment of area at midshaft /maximal length (mm^3)	252.74 ± 94.38	244.45 ± 86.35	Z=0.09; NS

In the last column we show the value of Mann Whithney´s U test (Z) together with significance (p). NS means p>0.1.

Table 4a. Significant relationships obtained among men between the moments of area at the nutrient foramen and those anthropometric variables with which the cross-sectional parameters showed the closest correlations

	Diaphyseal robusticity index	Epiphyseal robusticity index	Transverse diameter at the nutrient foramen	Perimeter at the nutrient foramen
Second Polar moment	R^2= 0.821; p<0.001			R^2= 0.940; p<0.001
Minimum second moment		R^2= 0.541 p=0.01	R^2= 0.587; p=0.006	
Maximum second moment				R^2= 0.452; P=0.023

Table 4b. Significant relationships in the whole sample between the moments of area at the nutrient foramen and those anthropometric variables with which the cross-sectional parameters showed the closest correlations

	Diaphyseal robusticity index	Perimeter at the nutrient foramen	Transverse diameter at the nutrient foramen
Second Polar moment	R^2= 0.642; p<0.001	R^2= 0.787; p<0.001	
Minimum second moment	R^2= 0.491; p=0.001		R^2= 0.617; p<0.001
Maximum second moment	R^2= 0.332; p=0.012	R^2= 0.562; p<0.001	

ences among men and women regarding polar second moment (i.e., torsional strength) and minimum second moment of area (i.e., bending strength).

As expected, significant correlations (assessed by Spearman´s correlation) were observed between some robusticity indices and torsional or bending strength. Despite significant sexual differences observed in the analyzed anthropometrical variables and in order to increase the sample and observe behaviour of the variables of the present study, the correlation between the anthropometrical variables and biomechanical variables was calculated considering the men, women and the whole sample (men and women together).

When only men were considered, correlation between diaphyseal robusticity index and polar second moment of area at the nutrient foramen was highly significant ($r=0.945$, $p<0.001$). Also, significant correlations were observed between epiphyseal robusticity index and minimum second moment of area at the nutrient foramen ($r=0.818$, $p=0.002$) and polar second moment of area ($r=0.736$, $p=0.01$).

When only women were considered, any correlation was observed, possibly due to the smaller number of cases.

When the whole sample was considered the diaphyseal robusticity index showed a close relationship with the minimum second moment of area at the nutrient foramen ($r=0.824$, $p<0.001$) and the polar second moment of area ($r=0.824$, $p<0.001$), whereas correlations of these variables with the epiphyseal robusticity index were less narrow ($r=0.628$, $p=0.005$ and ($r=0.618$, $p=0.007$, respectively).

We performed stepwise multiple linear regression analysis, in order to test the ability of indices and/or single variables to estimate the polar second moment or the maximum and minimum second moments of area. Significant relationships are shown in Tables 4a and 4b. The variable which allows the best estimation of the torsional strength is the perimeter at the nutrient foramen, by the formula, among the whole population:

Second polar moment (in mm^3) = -700.30 + 11.77 * perimeter at the nutrient foramen (in mm), with a standard error of the estimation of 56.91 (absolute range= from -114.26 to +140.30 mm^3).

When only men were included a similar formula was obtained:

Second polar moment (in mm^3) = -897.93 + 13.74 * perimeter at the nutrient foramen (in mm), with a standard error of the estimation of 32.17 (absolute range= from -44.53 to +50.32 mm^3).

DISCUSSION

Our results show that, in parallel with the mere anthropometric parameters, those derived from cross-sectional analysis showed a marked sexual dimorphism, but only at the nutrient foramen. The lack of differences among men and women regarding the biomechanical parameters is somewhat surprising, as well as maximum and minimum second moments of area and polar second moment of area at the midshaft of the tibiae. Although there is not a clear explanation for these results, it is important to note that differences were also absent when anteroposterior diameter at midshaft was compared between men and women, or even when robusticity indices were considered. The only robusticity index which was significantly different among sexes was the diaphyseal robusticity index, and even in this case, differences were subtle. When, years ago, we performed a discriminant analysis for sexing tibiae (González-Reimers et al., 2000), using as gold standard the tibiae of 59 complete prehispanic skeletons from Gran Canaria, we observed that transverse parameters were markedly different among male and female bones among the population of Gran Canaria. But these differences were by far less marked among the population of El Hierro, so that the accuracy of the discriminant functions obtained was lower when applied to the population of El Hierro. This is probably in relation with a more marked robusticity of the population of El Hierro. If we compare our data with others reported for other population groups (Martínez Flores, 2010), we found that women from El Hierro showed the second highest values of the epiphyseal robusticity, after the Sami population, but the highest diaphyseal robusticity indices of all the nine population groups analyzed (yielding values approximately 10-20% higher than those of other women). This result was confirmed – robusticity was even more marked – when only women with genetically assessed sex were considered (mean= 17.62 ± 2.78 in 18 women from El Hierro). Also, when minimum shaft perimeter was compared between women from El Hierro and those from Gran Canaria, those from El Hierro showed thicker diaphyses despite smaller stature.

This increased robusticity, especially among women, may explain the lack of differences in some of the indices and variables assessing bending and torsional strengths between sexes. Indeed, polar and maximum and minimum second moments of area are standardized to tibial length, and female sample show shorter tibial length values than male ones. Therefore, the existing differences in breadth parameters (Table 1) become "diluted" when divided by length parameters. However, the increased female robusticity does not explain the lack of correlation between the biomechanical parameters assessed by the mentioned software program, and the transverse and anteroposterior diameters measured by anthropometry. Considering that the software which allows a precise calculation of the second moments of area takes up the radiological image from the scanner and the area to be measured is defined on a colour scale, errors are possible, given the dense, thick cortical area at the tibial midshaft and the presence of a crest, which may show variations among individuals . This possibility has been also argued by other authors, who also obtained relatively poor correlation coefficients between polar second moment of area and shaft perimeter or the product of maximum and minimum shaft diameters. In this sense, Stock and Shaw (2007) report a poor correlation (R^2= 0.138) between the second polar moment of area and the product of maximum and minimum diaphyseal diameters, but at the nutrition foramen. They explain the poor correlation observed on the basis of variations in the morphology of the anterior border and interosseous crest of the lateral side of the tibial shaft crest at the nutrient foramen. In any case, ideally, estimation of skeletal robusticity requires standardization of both the external and biomechanical parameters both to body size – estimated by bone length, as we did here – and by body mass (Ruff, 2000) –estimated by femoral head diameter, which requires the analysis of femurs, something not afforded in this study.

In contrast with the results at the tibial midshaft, results obtained at the nutrient foramen are quite good. Differences between sexes are highly significant – despite the short number of cases, and correlations with the robusticity indices were also highly significant. In some cases, even higher correlation coefficients were observed between bending and/or torsional strength and anthropometric variables such as transverse diameter or perimeter at the nutrient foramen. Indeed, this last parameter was that one which showed the closest correlation with the second polar moment of area, with a R^2 of 0.787 among the whole population and 0.94 when only men were considered. Although this result allows a rough estimation of the torsional strength, the error in the estimation, as shown in the results' section, is high enough to preclude the precise calculation of the polar moment on the basis of single anthropometric variables. As shown in Table 4, results regarding the other moments of area are even poorer. Possibly the relative short number of cases analyzed may play a role in these results, as well as the morphological features of this population, especially those of the female sample. Indeed, results are slightly better when only men were considered, but standard error and absolute range of differences between estimated values of the polar second moment of area and calculated ones with the aid of the moment macro program are high enough to preclude an accurate estimation.

Thus, we conclude that simple anthropometric parameters may serve to roughly estimate torsional strength in this prehispanic sample of El Hierro, in the Canary Islands, especially at the nutrient foramen. Indeed, polar second moment of area at this level is related to the perimeter at the nutrient foramen level with a R^2 value of 0.787 (r=0.89; R^2=0.94, r=0.97 if only men were analyzed). However, this correlation is not strong enough to allow an accurate estimation of the torsional strength based on the values of bone perimeter at this level. Given the commented marked robustness of the population analyzed, especially among women, it would be of interest to test this hypothesis in other population groups. In any case, even a rough estimation of torsional and bending strengths, easy to perform at the moment of excavation of a burial site, may be of great value for the archaeologist and/or anthropologist.

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