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Lifestyle, Occupation, and Whole Bone Morphology of the Pre-Hispanic Maya Coastal Population from Xcambó, Yucatan, Mexico

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ABSTRACT The present bioarchaeological study examines the external diaphyseal geometric properties of humeri, radii, femora and tibiae of the Classic period skeletal population of Xcambó, Yucatan, Mexico. The diaphysial proportions are evaluated using a biomechanical approach together with data from the material context and other osteological information. Our intent is to provide new answers to questions concerning lifestyle, domestic labour division and subsistence strategies of this coastal Maya settlement that was inhabited from the Late and Terminal Preclassic (300 BC–350 AD) to the Postclassic Period (900–1500 AD).

Our results provide evidence for a marked sexual division of labour when compared with values from contemporaneous inland populations. The overall male and female loading patterns differ remarkably in terms of form and in bilateral comparison. A high directional asymmetry in the upper limbs is evident among males, a condition related to maritime transportation and trading activities. On the other hand, female upper limbs are characterized by very low side differences. Forces on the arms of women were probably dominated by food processing, in particular the grinding of grains or seeds. In the lower limbs, males show significantly higher anteroposterior bending strengths, which can be explained by greater engagement in transportation tasks and carrying heavy loads. In the course of the Classic period (350–900 AD), diachronic changes affect the male sample only, which suggests a shift of occupational pattern and physical demands. This shift, in turn, reflects Xcambó's changing role as the centre of a densifying settlement area and its place in the trading activities of northern Yucatan. Other topics of discussion relate to general regional trends and local prehispanic subsistence strategies. Our conclusions emphasize the value of geometric long bone analysis in the reconstruction of activity patterns and lifestyles in ancient coastal settlements. Copyright © 2007 John Wiley & Sons, Ltd.

Key words: biomechanics; whole bone measurements; activity patterns; anthropometrics; bioarchaeology; Maya

Introduction

The biocultural study of biomechanical long-bone properties has come a long way since the seminal

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efforts by Angel (1946, 1960). Over the past two decades, new approaches to biomechanical analysis using histomorphology and moments of area, aided by computerized geometric analysis and non-invasive CT, have led to new insights into specific lifestyle patterns of past populations. Despite remaining methodological limitations, these approaches have established promising correlations between diaphysial properties – both cross-sectional and external – and factors such as environmental effects, subsistence strategies, and specific occupational activities. Such correlations, for example, have been documented by the changes of diaphysial geometric properties during the prehistoric adoption of *maize* agriculture in eastern North America (Bridges, 1989; Ruff & Larsen, 1990; Fresia *et al.*, 1990; Bridges, 1991; Larsen & Ruff, 1991; Ruff, 1994; Bridges *et al.*, 2000; Ruff & Larsen, 2001).

Biomechanical investigation of human remains and indeed bioarchaeological investigation in general has only recently become a part of Maya research, partly due to the poor preservation of skeletal material, dispersed interment patterns, and a research tradition that has centered heavily around cultural heritage (Tiesler Blos, 1996; see Buikstra, 1997). This trend has definitely changed in recent years. New powerful analytical tools and new comprehensive frames of reference have made bioarchaeological approaches increasingly applicable in Maya investigation (Whittington & Reed, 1997; White, 1999; Tiesler Blos, 2001b). In this light, the present joint investigation, through the study of context, biographical data, and diaphysial form in the adult population of Classic period Xcambó (Yucatan, Mexico), attempts to provide new answers to questions concerning lifestyle, domestic labour division and subsistence strategies at this ancient coastal Maya settlement (Figure 1).

Figure 1. Plaza Prinzipal, Xcambó. This figure is available in colour online at www.interscience.wiley.com/journal/oa.

Whole bone measurements as behavioural indicators

Long bones must resist various kinds of stresses such as compression, bending and torsion. These forces are resisted by biomechanical characteristics, e.g. material properties, mineralization, porosity, and by the way the cortical bone is distributed along the shaft. In living organisms, bone is able to respond to mechanical loads (body weight and/or applied muscle forces) by functional remodelling through the activity of *basic multicellular units* (Frost, 1966; Lanyon *et al.*, 1979; Currey, 1984; Carter & Beaupre, 2001). According to Frost's original description, bending forces on a bone's shaft result in compression on one bone surface of the shaft and tension on the opposite faced surface. Concave diaphysial surfaces (surfaces where compression occurs) stimulate higher appositional reactions, whereas a convex surface (tension) will cause higher osteoclastic activity. Today we know that Frost's explanation simplifies the intricate processes involved in mechanical bone adaptation. More recent theories discuss interstitial fluid flow or micro fractures as localized stimulators of bone turn over (Martin, 1989; Turner & Pavalko, 1998). So far, there has been no consensus concerning the mechanisms of mechanically regulated remodelling. However, the dependence of bone geometry on activity is evident (Jones *et al.*, 1977; Pfeiffer, 1980; Ruff & Hayes, 1983a). Geometric properties of a diaphysis therefore provide a record of the demands that were made upon it during the lifetime of the individual and allow, under certain circumstances, a reconstruction of occupational activities on a population level (Ruff & Hayes, 1983b; Larsen, 1987; Bridges *et al.*, 2000; Ruff, 2000a; Schmitt *et al.*, 2003). Along with changes due to biomechanical demands, geometrical properties of a diaphysis can be affected

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by non-mechanical influences such as age-related modifications, hormonal or nutritional effects, pathologies, and even taphonomic processes, which should all be taken into consideration in the analysis of ancient bone morphometry. The fact that the majority of these conditions are at most approximately assessable in the skeletal record imposes limitations on attendant biocultural interpretations (Jurmain, 1999; Knüsel, 2000).

Despite its shortcomings, the investigation of cross-sectional properties has found numerous applications in bioarchaeological research, as demonstrated by recent studies in gender related activity patterns. In men, upper limb properties are interpreted in terms of weapon use (Stirland, 1993; Schmitt *et al.*, 2003) whereas upper limb properties of women have been studied under the theme of food processing activities (Bridges, 1989; Fresia *et al.*, 1990; Bridges, 1991; Bridges *et al.*, 2000).

Geometrical properties of the bony legs primarily reflect the physical demands imposed by locomotion. Forces arising from the hip joints are oriented mediolaterally and decrease towards the distal end of the femur (Burr, 1980; VanBuskirk, 1989). Conversely, forces generated by gait are above all anteroposteriorly oriented, are most intense close to the knee joints, and vary with different kinds of locomotion (Lovejoy *et al.*, 1976; Ruff & Hayes, 1983a; Duncan *et al.*, 2002), ground conditions (Ruff, 2000a), and body weight (Ruff, 2000b). In these terms, high anteroposterior expansion of the shaft is explained by high mobility, rough physical terrain or habitual heavy loads (Trinkaus, 1976; Ruff & Hayes, 1983b; Cole, 1994; Trinkaus & Ruff, 1999; Ruff, 2000a). In turn, sedentary populations, and more so modern industrialized societies, display more circular cross-sections, which can be explained by decreased mobility and a diminished physical work load (Ruff, 1987). Many investigations evaluate changes of diaphysial properties over time as expressed by the degree of sexual dimorphism. These changes are attributed to gender roles, lifestyle patterns and domestic organization, and have been demonstrated for the adoption of *maize* agriculture and for conditions that arose under colonialism in the case of North American populations (Bridges, 1989; Ruff & Larsen, 1990; Fresia *et al.*, 1990; Bridges, 1991; Larsen & Ruff, 1991).

The site

The Maya coastal port of Xcambó is located in the midst of natural *ciénagas* (marshlands) that border the chain of estuaries off the Peninsula's northern Gulf Coast (Figure 1). The site, which is only 700 m long and 150 m wide, was constructed on top of an artificially elevated, single large platform emerging from the swampy marshland. In ancient times, the settlement area sat on the inland edge of an estuary formation (Garza *et al.*, 1980; Sierra Sosa, 2004). Canals and trails connected Xcambó with both the outer barrier beaches and the inland areas. The small size of the site and the characteristics of the natural environment seemed to have limited the expansion of its monumental religious and administrative centre and its associated domestic areas.

According to the archaeological evidence, Xcambó was populated continuously from the Terminal Preclassic (AD 100–350) to the Classic period; during the Postclassic period (AD 900–1500), it was visited only sporadically (Sierra Sosa, 2004). Especially during its Classic period occupation (AD 350–700), Xcambó played a strategic role in the administration of local salt production and was engaged in long-distance trade. While its economy was thriving, the port's population was growing at a constant rate, a condition that led to an outward migration during the Late Classic period, as witnessed by the increase in settlement area around the site (Tiesler Blos *et al.*, 2004). Towards the end of its occupational history, around AD 700, its population decreased dramatically, apparently in response to general changes in the regional trading network of the northern Yucatan Peninsula. Postclassic artifacts are related to ceremonial activities, at a time when the city stayed only sparsely inhabited (Sierra Sosa, 1999a, 1999b).

Recently, the ancient site was extensively excavated by the Instituto Nacional de Antropología e Historia (INAH), Yucatan (Figure 2). The explorations brought to light a representative sample of more than 580 skeletons from burials in

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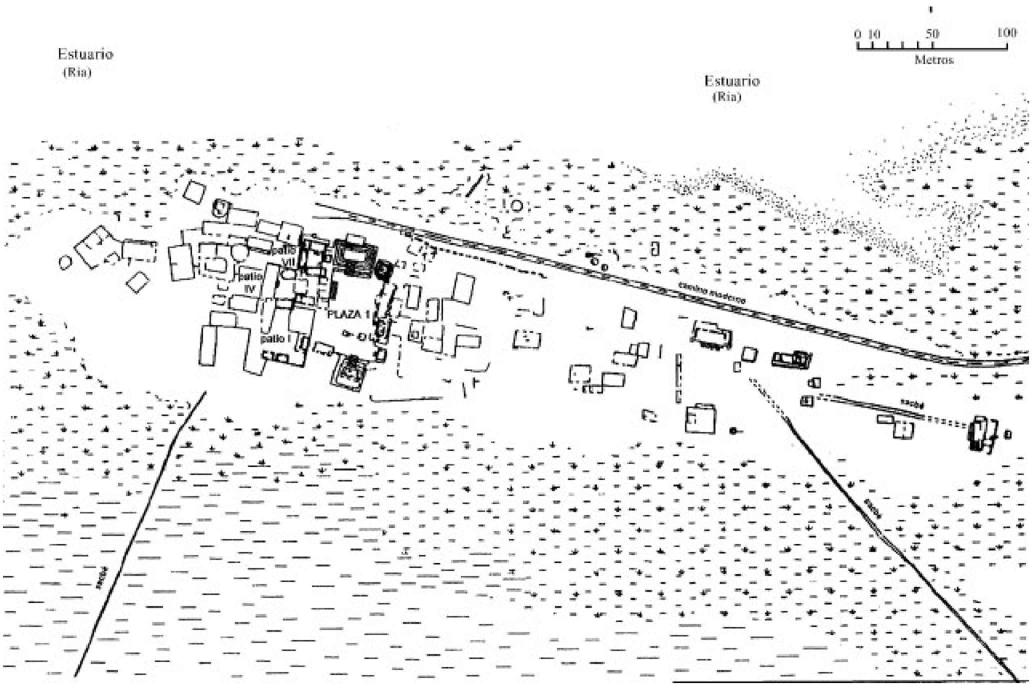

Figure 2. Site map, Xcambó, Yucatán.

the settlement's residential areas and its central ceremonial precinct. The sample dates to the early and late Classic period (AD 350–550/AD 550–700, respectively) and constitutes one of the largest pre-Hispanic Maya burial populations. The good state of preservation of the skeletal material is probably due to the water-logged cienaga environment and soil chemistry (Figure 3, Medrano Chan, 2005).

Previous analysis of Xcambo's skeletal sample and mortuary record suggest that Xcambó's steadily growing population enjoyed a balanced diet that was relatively high in marine protein with low rates of both non-specific deficiency diseases and low rates of marks of growth arrest (Tiesler Blos *et al.*, 2002; Cetina & Sierra Sosa, 2003; Cucina *et al.*, 2003a, 2003b). Xcambo's dead received similar treatment in both the residential compounds and the central structures (Medrano Chan, 2005). When compared to other sites, the distribution of funerary objects associated with the skeletal remains denotes a homogeneous abundance (Sierra Sosa, 1999a). This, along with the port's architectural characteristics and homogeneous biological profile, points to a local population with low external admixture (Cucina *et al.*, 2003b). The findings on the site's internal composition are surprising, considering its far reaching trade network, which extended to Belize, southward into the central Petén areas of Campeche and Guatemala, stretching to its west towards Tabasco and southern Veracruz (Sierra Sosa & Lizarraga, 2001).

From the material evidence and strategic location, we infer that its population must have been actively involved in trading, along with the exploitation of salt and marine resources, in addition to various other daily tasks such as carrying water, collecting firewood, construction, handicrafts and, of course, food production (e.g. gardening and *milpa* cultivation) and processing (Tiesler Blos *et al.*, 2002).

Materials and methods

Xcambó's exceptionally well preserved, large, adult population, which presumably shared a common

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Figure 3. Burial compound, Structure 18.

lifestyle, offers satisfactory conditions for the purpose of this investigation. From the overall sample, 321 individuals were considered for our osteometric analysis. These correspond to Xcambó's adult population over 20 years and under 50 years of age-at-death. Along with individuals with pathologically deformed long bone segments, the skeletons of individuals that fall over the 50 year threshold were excluded in order to avoid biases related to age-related osteoporosis. Macroscopic parameters were employed for age and sex assignment. Sex was determined based on the macroscopic dimorphic features of the pelvis and skull (Buikstra & Ubelaker, 1994), whereas age-at-death was estimated mainly from morphological changes in the pelvis (Todd, 1921; Lovejoy *et al.*, 1985; Brooks & Suchey, 1990) along with general degenerative patterns of the skeleton (Buikstra & Ubelaker, 1994). Geometric properties were assessed from a series of whole bone measurements only, for reasons of large sample size and – more important – legal restrictions on transporting or sectioning the bones.

Whole bone geometric values were scored in 0.01 mm intervals for humeri, radii, femora and tibias, using an osteometric board and a digital caliper. When possible, 21 measurements were taken on each side of the body, depending on skeletal condition. For diaphysial shape analysis, breadth ratios of humeral midshaft, radial midshaft, femoral subtrochanteric region (platymeric index) and midshaft (pilasteric index), tibial area of nutrient foramen (cnemic index) and midshaft were calculated (Martin & Saller, 1957). Measurements and formulas are listed in Tables 1 and 2. Besides breadth ratios, whole bone diameters and shaft circumferences were investigated, because these measurements have been shown to correlate strongly with cross-sectional geometry (Burr, 1980; Borgognini Tarli & Repetto, 1986b). Circumferences were employed as indicators of general robustness for the study of sexual dimorphism. Since this bone property is strongly size-related, we standardized measurements by whole bone length to receive comparable indices for the sex groups that crystallize dimorphism apart from physiological sex differences (Borgognini Tarli & Repetto, 1986a).

The sample was then divided into sex and age groups to investigate directional asymmetry and sexual dimorphism. The Early Classic sample (AD 350–550) was then compared to that dated to the Late Classic period (AD 550–700). To determine whether groups were significantly different from each other, a t-test was employed (SPSS 11.0).

Results

Upper limbs

When comparing the different age groups (individuals from 20 to 34 and from 35 to 50), no marked age-dependent difference of bone properties was observed (Table 3). The data for analysis of directional asymmetry of the upper limbs are shown in Tables 4 and 5. Among males, there is a

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Table 1. Measurements*

Abbreviation	Description
H1	Maximum length of the humerus
H6	Minimum diameter of the humeral midshaft
H5	Maximum diameter of the humeral midshaft
H7a	Circumference of the humeral midshaft
R1	Maximum length of the radius
RS**	Maximum diameter of the radial midshaft
RT**	Minimum diameter of the radial midshaft
R3	Minimum circumference of the radius
F2	Physiological length of the femur
F10	Subtrochanteric anteroposterior diameter of the femoral shaft
F9	Subtrochanteric mediolateral diameter of the femoral shaft
F6	Anteroposterior diameter of the femoral midshaft
F7	Mediolateral diameter of the femoral midshaft
F8	Circumference of the femoral midshaft
T1a	Maximum length of the tibia
T8a	Anteroposterior diameter of the tibial shaft, at the level of the nutrient foramen
T9a	Mediolateral diameter of the tibial shaft, at the level of the nutrient foramen
T8	Anteroposterior diameter of the tibial midshaft
T9	Mediolateral diameter of the tibial midshaft
T10a	Circumference of the tibial shaft, at the level of the nutrient foramen
T10	Circumference of the tibial midshaft

* Standard measurements and abbreviations are based on those of Martin (1957).
** Defined by Bridges *et al.* (2000).

significant side difference in the diaphysial shape of the humerus with $p \leq 0.001$ ($t = -3.33$) (Table 4). The right humerus is characterized by a higher degree of anteroposterior bending strength expressed by a lower arithmetic mean in the breadth ratio ($M_{right} = 73.3$, $M_{left} = 75.3$). At the same time, there is no significant side difference observable in the diaphysial geometric properties of the radius ($t = 1.48$, $p = 0.144$). In the female sample, the properties are remarkably symmetrical. The degree of bending strength on both sides of the body is nearly equivalent in the humerus ($M_{right} = 73.1$, $M_{left} = 73.9$, $t = -1.38$, $p = 0.175$), as well as in the radius ($M_{right} = 82.0$, $M_{left} = 81.9$, $t = 0.08$, $p = 0.934$). Still, proportional sexual dimorphism of the humeral and radial breadth ratio is low (Table 6). Values of the humeral diaphysial index lay between 0.39% (Early Classic) and 1.96% (Late Classic). Sexual dimorphism as indicated by the radial index is higher, with values between 2.33% (Late Classic) and 3.95% (Early Classic). T-tests for sexual dimorphism of humeral robusticity emphasize a sex-dependent difference of the general load ($t = 2.686$, $p = 0.013$) (Table 7).

Table 2. Formulas of breadth ratio indices*

	Index	Formula	No
Humerus	Midshaft shape index	H6 × 100/H5	1
Radius	Midshaft shape index**	RT × 100/RS	2
Femur	Platymeric index	F10 × 100/F9	3
	Pilastric index	F6 × 100/F7	4
Tibia	Cnemic index	T9a × 100/T8a	5
	Midshaft shape index	T9 × 100/T8	6

* Based on Martin (1957).
** Defined by Bridges (1989).

Lower limbs

In the lower limb, the data reveal significant side differences for the platymeric index among males ($t = 4.07$, $p \leq 0.001$) and females ($t = 4.43$, $p \leq 0.001$) (Table 4). At the same time, the cnemic index displays directional asymmetries in the male sample only ($t = 3.59$, $p \leq 0.001$) (see also Table 5 for comparison of external bone diameters). As for the upper limb, in total, males show a higher asymmetric pattern then females. Moreover, there is a high degree of sexual dimorphism in the subtrochanteric region of the femur (4.70%), the femur midshaft (9.58%) and the cnemic index (3.96%) (Table 6). According to the mean values of all investigated parameters, males resisted significantly higher bending forces then females (platymeric index of the femur: $t = 3.13$, $p = 0.002$; pilastric index: $t = 5.11$, $p \leq 0.001$; cnemic index: $t = -2.41$, $p = 0.018$). Those areas that are most adaptive to different degrees of physical activity, the distal femur and the proximal tibia, indicate proportionally stronger anteroposteriorly extended diaphyses among males, whereas the sex difference at the tibial midshaft is comparatively low at 1.45% ($t = -0.84$, $p = 0.401$). There is a marked dimorphism in the general robustness of the tibia, both in the area of the nutrient foramen ($t = 3.82$, $p \leq 0.001$) as well as the midshaft ($t = 2.95$, $p \leq 0.009$) (Table 7).

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Table 3. Comparison of breadth-ratios of two different age groups (t-test)

No	n	M 20–34	SD 20–34	n	M 35–50	SD 35–50	t	p
				Males				
1	25	75.21	4.53	32	73.12	4.11	1.82	0.074
2	25	84.72	6.18	21	85.70	6.56	−0.65	0.518
3	24	84.28	7.87	29	82.94	4.71	0.77	0.445
4	25	108.65	12.31	31	107.72	8.86	0.33	0.745
5	18	66.79	5.72	24	67.44	4.96	−0.39	0.698
6	21	66.79	5.49	28	67.85	5.75	−0.52	0.604
				Females				
1	16	73.90	4.19	21	73.19	4.29	0.51	0.617
2	16	82.31	4.18	16	81.22	7.82	0.49	0.627
3	15	78.32	5.02	22	80.17	4.79	−1.13	0.265
4	15	97.82	8.75	24	96.77	9.19	0.36	0.723
5	15	69.59	3.73	17	69.37	5.60	0.13	0.899
6	16	67.63	4.52	18	68.89	6.68	−0.64	0.529

Nos of breadth ratio indices are defined in Table 2, n: sample size, M: arithmetic mean, SD: standard deviation, t: test value, p: probability (one-sample t-test).

Diachronic changes

Diachronic changes of activity pattern from the Early to the Late Classic period were of special interest in our investigation. According to our results, a clear transformation of physical demands took place for the males of Xcambó. Particularly, in the upper limb, the bending strength of the left humerus decreases from 73.6 in the Early Classic sample to 76.1 in the Late Classic sample (Table 4). A considerable directional asymmetry in the humeral diaphysial

Table 4. Directional asymmetry of breadth ratio indices (t-test)

No	Sex	n	M right	SD right	M left	SD left	t	p
				Whole sample				
1	Male	68	73.7	4.80	75.3	5.12	−3.33	$\leq 0.001^{***}$
	Female	46	73.1	4.91	73.9	5.24	−1.38	0.175
2	Male	50	85.9	7.63	84.4	6.59	1.48	0.144
	Female	39	82.0	7.47	81.9	7.48	0.08	0.934
3	Male	59	85.1	7.26	82.5	6.09	4.07	$\leq 0.001^{***}$
	Female	41	81.5	5.68	78.5	6.10	4.43	$\leq 0.001^{***}$
4	Male	66	108.4	11.11	107.2	11.50	1.43	0.157
	Female	51	98.5	8.88	98.1	8.89	0.66	0.510
5	Male	48	68.0	5.32	66.4	5.33	3.59	$\leq 0.001^{***}$
	Female	39	69.9	4.95	69.6	4.98	0.77	0.445
6	Male	55	67.8	5.75	67.5	7.05	0.39	0.698
	Female	42	68.4	5.95	68.8	5.84	−0.81	0.423
				Early Classic Period				
1	Male	15	74.1	4.05	73.6	4.99	−3.89	0.616
	Female	7	74.2	6.29	74.0	5.62	0.18	0.861
2	Male	14	86.4	6.69	85.6	8.54	0.41	0.691
	Female	3	85.2	3.69	80.2	5.60	2.15	0.165
				Late Classic Period				
1	Male	44	73.8	5.23	76.1	5.29	−3.89	$\leq 0.001^{***}$
	Female	33	73.2	4.91	74.1	5.32	−1.24	0.226
2	Male	29	85.2	6.51	84.6	5.23	0.61	0.548
	Female	29	82.8	7.86	83.2	7.57	−0.35	0.728

Nos of breadth ratio indices are defined in Table 2, n: sample size, M: arithmetic mean, SD: standard deviation, t: test value, p: probability (***:$p \leq 0.001$) (one-sample t-test).

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Table 5. Directional asymmetry of external shaft diameters (t-test)

	Sex	n	M right	SD right	M left	SD left	t	p
H6	Male	69	16.7	1.36	16.5	1.31	2.60	0.011*
	Female	46	14.0	1.12	14.1	1.16	5.44	0.986
H5	Male	69	22.8	1.97	21.9	1.85	6.84	≤0.001***
	Female	46	19.3	1.39	19.0	1.42	1.87	0.068
RS	Male	50	14.6	1.46	14.5	1.25	1.55	0.499
	Female	39	12.8	1.24	12.8	1.39	0.12	0.621
RT	Male	51	12.5	1.14	12.2	1.05	3.60	≤0.001***
	Female	39	10.5	0.83	10.4	0.77	0.88	0.387
F10	Male	60	25.8	1.49	25.8	1.68	0.08	0.938
	Female	41	23.0	1.48	22.8	1.58	1.64	0.110
F9	Male	60	30.4	2.16	31.3	1.97	−4.76	≤0.001***
	Female	43	28.3	1.88	29.1	2.09	−3.70	≤0.001***
F6	Male	67	28.2	2.71	28.4	2.89	−1.44	0.154
	Female	51	24.4	2.20	24.4	2.00	−0.24	0.810
F7	Male	67	26.2	2.15	26.7	2.37	−4.04	≤0.001***
	Female	53	24.8	2.14	24.9	2.10	−0.86	0.397
T8a	Male	49	34.0	2.28	34.1	2.28	−0.67	0.509
	Female	40	28.8	2.44	28.9	2.61	0.01	0.992
T9a	Male	53	23.1	1.69	22.7	1.85	2.78	0.008**
	Female	39	20.1	1.83	19.9	1.83	0.69	0.497
T8	Male	56	30.4	1.89	30.3	2.28	0.28	0.779
	Female	42	26.3	2.42	26.3	2.42	−0.14	0.890
T9	Male	55	20.5	1.58	20.4	1.64	1.30	0.201
	Female	42	17.9	1.59	18.0	1.52	−1.14	0.262

Measurements are defined in Table 2, n: sample size, M: arithmetic mean, SD: standard deviation, t: test value, p: probability (*: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$) (one-sample t-test).

Table 6. Sexual dimorphism of the indices (t-test)

No	n	M male	SD male	n	M female	SD female	t	p	M male – M females/M female × 100
					Whole sample				
1	68	74.5	4.56	46	73.5	4.62	1.17	0.246	1.15
2	50	85.1	6.11	39	81.9	6.87	2.33	0.022*	3.91
3	59	83.7	6.19	41	79.9	5.47	3.13	0.002*	4.70
4	66	107.7	10.78	51	98.3	8.61	5.11	≤0.001***	9.58
5	48	67.2	5.11	39	69.7	4.74	−2.41	0.018*	−3.69
6	55	67.6	5.80	42	68.6	5.72	−0.84	0.401	−1.45
					Early Classic Period				
1	15	73.8	4.31	7	74.1	5.76	−0.13	0.897	−0.39
2	14	85.9	6.65	3	82.6	4.28	0.80	0.434	3.95
3	15	86.0	5.54	6	83.1	7.22	0.98	0.338	3.44
4	17	113.4	8.32	7	101.6	10.66	2.91	0.008**	11.60
5	14	66.9	4.77	5	69.8	2.82	−1.26	0.224	−4.13
6	15	67.2	3.45	5	68.4	3.91	−0.61	0.548	−1.65
					Late Classic Period				
1	44	74.9	4.91	33	73.6	4.70	1.12	0.265	1.69
2	29	84.8	5.45	29	82.9	7.06	1.17	0.248	2.33
3	34	82.5	6.24	30	79.8	5.27	1.84	0.070	3.36
4	40	104.8	10.52	36	98.5	8.20	2.89	0.005*	6.41
5	28	67.4	4.91	26	69.9	4.64	−1.91	0.062	−3.55
6	34	67.8	6.16	30	69.0	5.76	−0.81	0.419	−1.76

Measurement nos 1–6 are defined in Table 1, n: sample size, M: arithmetic mean, SD: standard deviation, t: test value, p: probability (*: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$) (t-test for independent samples).

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Table 7. Sexual dimorphism of standardized robustness indices (t-test)

	n	M male	SD male	n	M female	SD female	t	*p*
Humerus	11	0.214	0.02	15	0.196	0.02	2.69	0.013*
Ulna	11	0.141	0.01	9	1.140	0.01	0.27	0.791
Radius	11	0.172	0.01	10	0.157	0.01	3.41	0.003**
Femur	11	0.201	0.01	8	0.194	0.01	1.31	0.206
Tibia (proximal)	10	0.249	0.01	9	0.228	0.01	3.82	$\leq$0.001***
Tibia (midshaft)	10	0.224	0.01	9	0.207	0.01	2.95	0.009**

n: sample size, M: arithmetic mean, SD: standard deviation, t: test value, p: probability (*: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$) (t-test for independent samples).

index appears exclusively in the later period ($t = -3.89$, $p \leq 0.001$). At the same time, there are no changes in upper limb properties in the female sample. Furthermore, the sexual dimorphism of the upper limb shaft indices does not alter remarkably (Humerus: 0.39% (Early Classic), 1.69% (Late Classic); Radius: 3.95% (Early Classic), 2.33% (Late Classic)) (Table 6). In the lower limb, diachronic changes are evident for the indices of the area around the knee (pilastric and cnemic indices), where incoming forces are most variable in conjunction with different kinds of activities (Lovejoy *et al.*, 1976; Ruff & Hayes, 1983a; Duncan *et al.*, 2002). Most remarkable is a lessening of the sex difference of the pilastric index, which decreases from 11.6% in the earlier period to 6.41% in the later period (Table 6). This is predominantly caused by a reduction of anteroposterior bending strength among males, which decreases from 113.4 to 104.8. In contrast, female values only change from 101.6 to 98.5. At the same time, the sex difference of the cnemic index declines from 4.13% to 3.55%, again most evident through a decline of anteroposterior bending strength among males. Diachronic changes in the tibial midshaft are insignificant (changing from 1.65% (Early Classic) to 1.76% (Late Classic)) as well as the modifications of the platymeric index (changing from 3.44% (Early Classic) to 3.36% (Late Classic)).

Discussion

The results on upper and lower limb bone geometry strongly support a sexual division of labour among the Maya of Xcambó. A comparison of the two age groups, individuals of 20–34 years and 35–50 years at the time of death, according to age determination, does not reveal any marked differences. Previous experimental studies on animals (Lanyon *et al.*, 1979; Woo *et al.*, 1981; Matsuda *et al.*, 1986; Umemura *et al.*, 1997) as well as clinical examinations (e.g. observations of bed rest patients, astronauts, sportsmen, etc.) (Jones *et al.*, 1977; Ashizawa *et al.*, 1999; Duncan *et al.*, 2002) have shown that biomechanical stress is, in healthy individuals, the most important factor determining geometric bone properties. The impact of activity-related remodelling on bone geometry is higher than bone alterations occurring in conjunction with age, nutrition or other influences (Pfeiffer, 1980; Trinkaus *et al.*, 1994). In our sample, there are no significant age differences in the geometric properties of the long bones. This could either indicate that all age groups between 20 and 50 were similarly involved in the working sphere, or, more probably, that the age range under study was too restricted to permit any comparisons of age-related bone adaptations. Previous studies including broader age ranges have shown distinct functional trends in remodelling within age groups, which reflect behavioural variations (Pfeiffer, 1980; Ruff & Jones, 1981).

For the reconstruction of behavioural features through bone properties of the upper limb, handedness has to be taken into account. Among humans, there is a consistent tendency for right-handedness (Annett, 1972). Side differences in humeral whole bone length are already observable in the foetus, which strongly indicates a congenital determination (Schultz, 1937; Ingelmark, 1946; Steele & Mays, 1995; Steele, 2000). In turn, directional asymmetries in shaft dimensions appear as the result of different mechanical

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demands on the dominant and the non-dominant arm, as shown for example by the striking bilateral differences in tennis players (Jones *et al.*, 1977; Ashizawa *et al.*, 1999). In bioarchaeology, male upper limb bone dimensions have been interpreted predominantly as the result of weapon use (Ruff & Larsen, 1990; Fresia *et al.*, 1990; Ruff, 1992; Stirland, 1993; Schmitt *et al.*, 2003). However, the scholarly community has expressed doubts as to the actual relevance of specific activities such as spear throwing or handling bows and arrows, in view of the general bulk of loads occurring through the whole spectrum of possible occupations (Trinkaus & Churchill, 1999; Jurmain, 1999; Bridges *et al.*, 2000). For the Maya of Xcambó, weapon use was probably diminished. We consider that meat was acquired for nutritional supplementation or ceremonial purposes, mainly. Maritime resources were more intensively exploited (Tiesler Blos *et al.*, 2002); however, fishing and collecting were carried out predominantly with nets rather than by spearing. Various other occupational activities connected to salt exploitation, fishing, storing, transporting, gardening, the construction of houses, and especially canoeing, to name only some, must have placed high physical stresses on the arms. Taken together, our results indicate that everyday life confronted Xcambó's men with a range of physically demanding activities, resulting in a high degree of bending strength and robustness and, due to the consistent dominance of right-handedness, their right arms were consistently subjected to higher loads. Conditions among females can be accounted for more specifically. As in other societies, the remarkably low bilateral asymmetry is consistent with food processing activities, involving the stone grinding of *maize* or other seeds – with mortars and pestles, and more so with *manos* and *metates*. This time-consuming and strenuous activity – in which the *mano* has to be held firmly with both hands – places much biomechanical stress on both arms, and it has been shown in numerous bioarchaeological investigations of past populations that it does manifest itself on the bone (Fresia *et al.*, 1990; Bridges *et al.*, 2000). The notable symmetry of bone properties in our sample suggests that grinding put a strong physical demand on women. Our results are consistent with female geometric properties observed in other coastal Maya sites, as well as in the skeletal samples of inland Copán, Honduras, which support the present assertions, and at the same time point towards a homogeneous behavioural pattern among adult women in ancient Maya societies (Tiesler Blos, 1999, 2001a).

Regarding sexual dimorphism, there was a significant difference in the degree of physical demands between males and females, especially in the upper extremity, indicating that males resisted greater forces. In the femur, dimorphism of general robustness is low ($t = 1.31$, $p = 0.206$). One of the authors (Tiesler Blos, 2001a) has observed a lower sexual dimorphism in upper extremity properties for coastal Maya sites (5.8%), when compared to inland Copán (7.4%). Together with the present investigation, general regional differences in male physical demands and subsistence-dependent behavioural diversity are emphasized. Regional production activities certainly varied between the coastal areas and Copán, where agricultural tasks clearly dominated daily life. At this moment it would be risky to attempt to pinpoint more specific activities in the context of regional trends among Maya populations; however, as more sites are investigated, these will hopefully be identified.

On the lower limb, we again observed a higher asymmetric pattern among males in comparison to females. While both sex groups show marked side differences in the subtrochanteric region of the femur (platymeric index), evidence for a directional asymmetry of the cnemic index appears exclusively among males. Previous studies mention a constant constitutional variability of the hip joints as a possible factor causing a bilateral asymmetry of the femur (Ruff & Hayes, 1983b; Macho, 1991). Directional side differences of the tibia, on the other hand, have been related to behavioural implications in the literature, e.g. males using their left leg more often to push off from the ground during certain activities (Ruff & Hayes, 1983b). For the interpretation of the sexual dimorphism of the platymeric, the pilastric and the cnemic index, it is important to consider the fact that the subtrochanteric region of the femur (platymeric index) is dominated by forces depending on the constitution of the pelvis and the hip joints,

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which show constant and high sexually dimorphic patterns in all humans (Ruff & Hayes, 1983b). Therefore, a concomitant sex difference in this property was to be expected. In contrast, as mentioned before, loads in the area closer to the knee (pilastric and cnemic index) have been shown to correlate more with the type of activity (Burr, 1980; Ruff & Hayes, 1983a; VanBuskirk, 1989). For example, running causes much higher bending forces on the lower limb than walking. Walking with loads carried on the body or locomotion on uneven terrain also leads to a substantial increase in biomechanical stress (Lovejoy *et al.*, 1976; Ruff & Hayes, 1983a). In ancient Maya society, the aspect of load-bearing has a different meaning from the Old World, as the Maya did not use wheels. Goods had to be transported by canoe, in baskets or nets, or carried on the back or on the head. Accordingly, in our sample, there is a high anteroposterior bending strength and a high robustness among males, who were strongly engaged in trading activities and, therefore, occupationally bore high loads. Moreover, ground properties need to be considered. Xcambó is situated in a part of Yucatan that its present inhabitants call *tzekel*, which means "land very stony and poor for sowing" (Folan *et al.*, 1983). It is characterized by porous limestone bedrock that certainly causes greater forces on the lower limb bones than locomotion tasks on leached zonal soils that can be found in the southern Lowlands and the Highlands of the Maya area. Interesting in this context are regional differences shown by one of us (Tiesler Blos, 2001a) that reveal greater sexual dimorphism of the cnemic index resulting from greater bending forces among men of Yucatan's coastal populations, again in comparison to Copán. Likewise, we found a very high anteroposterior bending strength in the present evaluation, which is particularly observable in the pilastric index. Thus, higher demands among coastal inhabitants might be partly due to differences in geological settings. Whereas some authors have designated the pilastric index as the 'mobility index' (Ruff, 1992, 1994; Larsen, 1997), and have correlated its proportional sexual dimorphism with different subsistence strategies (Ruff, 1987), in our regional context the pilastric index is more related to the principal impacts of water or land transportation, i.e. load bearing, and ground conditions.

For any explanation of diachronic changes, we have to keep in mind the increase in local population, which took place at Xcambó towards its later occupational phase during the Classic. It is of special interest to investigate whether demographic growth was accompanied by a noticeable change in lifestyle and activity patterns more so as previous analyses of trace elements, skeletal stress markers and oral pathology have revealed diachronic changes (Tiesler Blos *et al.*, 2002). Besides, alterations of architecture and storage beds have been observed in Xcambó's settlement area (Sierra Sosa, 1999b). A simultaneous shift in occupation is therefore quite conceivable. Our results point to diachronic changes in geometric properties in the male sample, whereas the female cohort manifests continuity. Particularly regarding the upper limb, there is a reduction of bending strength of the left humerus in males. Together with the observed asymmetric pattern of the lower limbs, this possibly points to a decline of maritime transportation activities, most importantly canoeing. Except for the platymeric index, all lower limb bone properties show diachronic changes. The nature of forces on the subtrochanteric region of the femur is, as mentioned above, more independent from the type of activity and predominantly determined by the constitution of the hip and its joints (Ruff & Hayes, 1983a; VanBuskirk, 1989). These joints are placed more laterally from the centre of the body in females, indicating that the distribution of forces is sexually determined. Since within the same population, physiological sexual dimorphism can be expected to be relatively constant, only global influences should be held responsible for the diachronic changes in this area. As the subtrochanteric index stays unchanged, alterations of other segments of the lower extremity will thus be the result of non-systemic influences, above all mechanical loading (Ruff, 1987). For the Maya of Xcambó, there is, as mentioned, a continuity of sexual dimorphism of the platymeric index, whereas remarkable diachronic changes are evident for the indices of the area closer to the knee (pilastric and cnemic index). Again, incoming forces are more variable and probably activity-related in

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this area of the legs (Lovejoy *et al.*, 1976; Ruff & Hayes, 1983b; Kimura & Amtmann, 1984). The reduction of the sexual dimorphism of the pilastric index is striking; it decreases from 11.6% in the earlier period to only 6.41% in the later period. A clear decrease of anteroposterior forces in the male sample is observable, which is also seen in the alterations of the cnemic index. Apparently, in the Late Classic period, Xcambó's men lived a less physically demanding lifestyle than before. Transportation and storage tasks were apparently taken over by people living in the surrounding areas, while Xcambó became a site with more administrative functions. Interestingly, the lack of changes in the female sample, in the upper as well as in the lower limb, reveals that only minimal changes, if any, occurred in their mechanical loading patterns, implying that women probably did not benefit from the improvements in lifestyle of their male counterparts.

Conclusions

With the present evaluation we achieved key goals regarding the organization of labour and economic processes of the Classic coastal Maya population of Xcambó (Yucatan, Mexico). Our results indicate a sexual division of labour, as male and female occupational patterns differ remarkably. In the upper limb, directional asymmetry is high among men, which might be related to physical demands during maritime transportation, whereas the robust upper limbs of Xcambó's women are remarkably symmetric and, rather than a lack of mechanical loading, very likely can be accounted for by the activity of grinding grain and seeds. When the sexual dimorphism of the lower limbs is compared to inland sites, Xcambó's males resisted markedly greater loads than females, and most notably in the Early Classic period, as evident in the anteroposterior plane. Higher levels of engagement in trading tasks (transporting, storing, etc., implying more load bearing), the exploration of marine resources (possibly including salt exploitation itself) as well as ground conditions can, taken together, appropriately explain the marked sex differences observed. Changes over time that are evident among the male sample strongly support the inference of economic transformations, more precisely, the extension of Xcambó's trade network and changes of function and status of the site during the Late Classic period. With such changes the port's male population was freed from the harsh physical labour witnessed during the Early Classic. Xcambó was now holding a more administrative function as trading activities in the whole area became more centralized. Over the course of this study, it became clear that multiple characteristics of each site (size, location, function, geology) are critical in determining the physical demands on its inhabitants. Altogether, our results draw attention to new aspects of interior labour divisions related to gender roles, subsistence patterns, and economic changes.

Despite the vast amount of information compiled in the course of this research, all patterns cannot be quantified until the nature of biomechanical responses of bone and the role of all non-mechanical influences (nutrition, hormones, disease, genetics, age) are fully understood. So far, it is not known which biomechanical factor (stress magnitude, stress rate, stress interval, etc.) actually stimulates remodelling reactions, or how biomechanical stresses are then transferred from the level of the whole bone to that of individual cells. Experimental animal studies (Lanyon *et al.*, 1979; Woo *et al.*, 1981; Matsuda *et al.*, 1986) as well as clinical investigations of sportsmen or immobilized persons (Jones *et al.*, 1977; Meade, 1989; Ashizawa *et al.*, 1999) confirm the existence of a general activity-related functional adaptability of bone. Still, our knowledge of bone responses to physical loads within the "normal" range of activities is not at all elucidated by the aforementioned studies, since they all apply physical demands that are incomparable with regular day-in, day-out activities (Jurmain, 1999). Besides, the range of physical demands within which bone remains unresponsive is unclear (Carter, 1984), which implies a major limitation of the present methodological approach. With these constraints in mind, as well as the acknowledgement that our knowledge of lifestyle features of past populations is limited, our most important lesson was that bioarchaeological

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approaches can only provide us with general pictures of ancient and biocultural contexts integrated into an interdisciplinary frame of reference. Osteological analysis alone will not establish indisputable links with behavioural patterns, and attempting to do so runs the risk of over-simplifying the complex physiological and biocultural dynamics involved (Knüsel, 2000).

For the present sample, application of modern measurement techniques (e.g. histological thin sections, computed tomographic scanning, multiple plane radiography, bone mineral absorptiometric scans) is desirable in future research, since linear external measurements and breadth ratios offer only a partial reflection of the geometric distribution of bone tissue. Despite shortcomings, we feel that biomechanical analyses such as the present investigation can expand our knowledge of past populations by providing new insights into past behavioural diversity and, in turn, social organization. Like intracortical biomechanics, external geometric bone properties hold much promise as a tool for the reconstruction of activity patterns and lifestyles of past populations, such as the changing lifestyles of the ancient coastal Maya, as we have intended to demonstrate.

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