AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 127:000–000 (2005)

Trauma-Induced Changes in Diaphyseal Cross-Sectional Geometry in Two Elites From Copan, Honduras

Kenneth C. Nystrom* and Jane E. Buikstra

Department of Anthropology, University of New Mexico, Albuquerque, New Mexico 87131

KEY WORDS biplanar radiographs; Copan; paleoradiography

ABSTRACT This research utilized biplanar radiographs to estimate cross-sectional biomechanical properties for the skeletal remains of two elite individuals from the Early Classic period (ca. AD 400–600) of Copan, Honduras: K'inich Yax K'uk' Mo' (Hunal Burial 95-2), founder of the Early Classic Dynasty at Copan, and the primary female interment (Burial 37-8) from the Motmot tomb. Both individuals survived severe blunt-force insults to the right forearm. Gross skeletal examination and evaluation of the radiographs for K'inich Yax K'uk' Mo' suggest that these traumas resulted from, at least in part, disuse atrophy of the affected forearm skeletal elements. Gross and radiologic evaluation of the Motmot remains countered the possibility that she suffered from a metabolic bone disease, and confirmed the presence of a well-healed parry fracture of the right ulna. The degree of asymmetry in cross-sectional biomechanical properties reported here for K'inich Yax K'uk' Mo' is likely the secondary result of the described blunt-force trauma. The results obtained for the principal Motmot interment are not as dramatic, but suggest subtle changes to humeral cross-sectional geometry subsequent to trauma. Am J Phys Anthropol 127:000–000, 2005.

Bone is a plastic organ, reflecting behavioral decisions and their biomechanical consequences, and numerous studies examined the biomechanical responses of long bones to shifts in subsistence patterns, foreign conquest (Larsen and Ruff, 1994; Larsen et al., 1990, 1995; Ruff and Larsen, 2001), activity patterns (Stirland, 1993), and evolutionary forces (Ruff, 2000a; Trinkaus et al., 1994, 1998, Trinkaus and Churchill, 1999). Broadly this research contributes to the literature concerning behavioral and biomechanical responses to trauma and stress (Bridges, 1989; Bridges et al., 2000; Churchill and Formicola, 1997; Ruff, 1999; Stirland, 1993). The specific aim of the current project is to more completely understand the physiological and structural response of the humeri to blunt-force trauma of the forearms, as seen in the skeletal remains of two individuals from the Early Classic Period of Copan, Honduras: K'inich Yax K'uk' Mo' and the primary interment from the Motmot tomb. Both suffered significant trauma to the forearm, and as such it was reasonable to expect that posttraumatic disuse of the injured limb would have affected humeral cross-sectional geometric properties.

While this study focuses on only two remains, it is significant in that it forms part of a larger inquiry into the lives of Copan's early elite. K'inich Yax K'uk' Mo', for example, was the founder of Copan's Classic Dynasty, and the physical sequelae of the blunt forces that fractured his upper body are important in evaluating his life and contributions to Maya history. The Motmot interment, while not historically identified, is presently interpreted as an elite, ritual specialist. Her life, too, as an elite woman who died during young adulthood, is an important part of the rich historical fabric of the ancient Maya world.

Copan is located near the southeastern limit of the Maya region in modern-day Honduras (Fig. 1). The Principal Group at Copan represents the remains of the Classic Maya polity capital, and consists of plazas to the north and a complex of superimposed structures to the south. A ballcourt and Structure 10L-26 (Temple of the Hieroglyphic Stairway) demark these north and south components. An elevated Acropolis is divided into two enclosed courts by Structure 10L-25 (the Dance Platform) and Structure 10L-16. The latter is the highest point in the Principal Group, and represents a pivotal period in the history of the Acropolis (Canuto et al., 2004).

Grant sponsor: National Geographic Society; Grant sponsor: National Science Foundation; Grant sponsor: Texas A&M University; Grant sponsor: FAMSI; Grant sponsor: Ahau Foundation.

*Correspondence to: Kenneth C. Nystrom, Department of Anthropology, University of New Mexico, Albuquerque, NM 87131.
E-mail: knystrom@unm.edu

Received 13 February 2004; accepted 4 October 2004.

DOI 10.1002/ajpa.20210
Published online in Wiley InterScience (www.interscience.wiley.com).

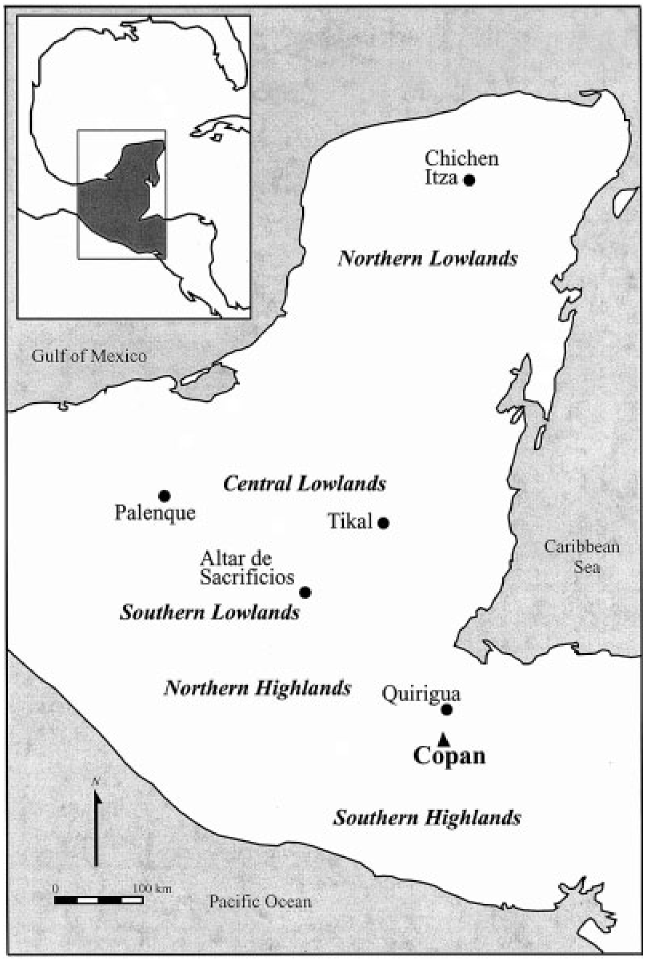


Fig. 1. Copan and its regional context.

The male skeletal remains (Buikstra et al., 2004) that are attributed to K'inich Yax K'uk' Mo', founder of the Early Classic Dynasty of Copan, were recovered from the Hunal Tomb (Burial 95-2). The Hunal Tomb is located in the earliest levels of the Acropolis (Structure 10L-16), and dates to ca. AD 400–450 (Bell et al., 2004). While the tomb and its remains were disturbed by human activity, seismic events, and water infiltration, the remains appear to have initially rested upon a fine reed mat, and were accompanied by a number of shell and jade ornaments, bone implements, and ceramics (Bell et al., 2004).

Aspects of K'inich Yax K'uk' Mo's life are available to us, based on archaeological evidence. K'inich Yax K'uk' Mo' is said to have arrived and consolidated political power within the Copan Valley in AD 426 (Schele, 1986; Sharer et al., 1999; Stuart and Schele, 1986). Architectural and hieroglyphic evidence link K'inich Yax K'uk' Mo' with other Mesoamerican regions, including central Petén, the Valley of Guatemala, the Valley of Mexico, and Tikal (Buikstra et al., 2004).

K'inich Yax K'uk' Mo' suffered from a wide range of grossly and radiographically visible traumatic and degenerative afflictions (Buikstra et al., 2004; Nystrom et al., 2005). K'inich Yax K'uk' Mo' suffered a "parry" fracture of the right radius and ulna (Figs. 2, 3). The radius healed in gross misalignment, yet cortical bone density is normal. The ulnar fragments never fully reunited, and the cortical bone was thin due to disuse atrophy (Nystrom et al., 2005). Further evidence of trauma involves a significant restructuring of the left shoulder (Fig. 4). The superior third of the glenoid fossa and the coracoid process were separated from the body of the scapula, and likely significantly affected normal functioning of the arm. Pronounced arthritic development and eburnation are grossly visible at the shoulder joint (Buikstra et al., 2004). There is also moderate arthritic development in the elbow, wrist, and hand. Both areas of arthritic reactive bone suggest that K'inich Yax K'uk' Mo' retained some mobility in the limb. Other indications of trauma include rib fractures, dislocation, and the subsequent development of new articular facets on the medial aspect of the clavicles, as well as altered articulation between the manubrium and body of the sternum (Buikstra et al., 2004). All of the above-described traumas were not active at time of death (Buikstra et al., 2004). There were no indications of epiphyseal growth plate disruption, and the humeri were identical in length, indicating that the injuries were sustained during adulthood.

Isotopic analyses revealed that K'inich Yax K'uk' Mo' was originally from the north rather than the Valley of Oaxaca (Buikstra et al., 2004). It is not unrealistic to assume that the above injuries were directly related to his journey to, and eventual domination of, Copan.

Other Early Classic Period burials, including the Motmot Tomb, were found below Structure 10L-26 (Fash et al., 2004). The principal interment in the Motmot tomb (Burial 37-8) was a seated young female. The tomb was capped with a circular marker inscribed with iconography that suggests it was constructed during the reign of Ruler 2, the son and successor of Yax K'uk' Mo' (Fash et al., 2004). The tomb was reopened, and there is evidence for the use of fire and the inclusion of at least two more skulls (Fash et al., 2004). Based on the material found in association with the remains, the young woman may have been a day-keeper, an individual associated with divination and curing (Fash et al., 2004).

Gross evaluation of the skeletal remains indicates that the principal Motmot interment was gracile, with skeletal elements generally lacking strong indications of muscle markings (Buikstra et al., 2004). Radiographically, cortical bone thickness is normal, and there is no indication of deossification, which might account for the slight nature of her skeletal elements (Nystrom et al., 2005).

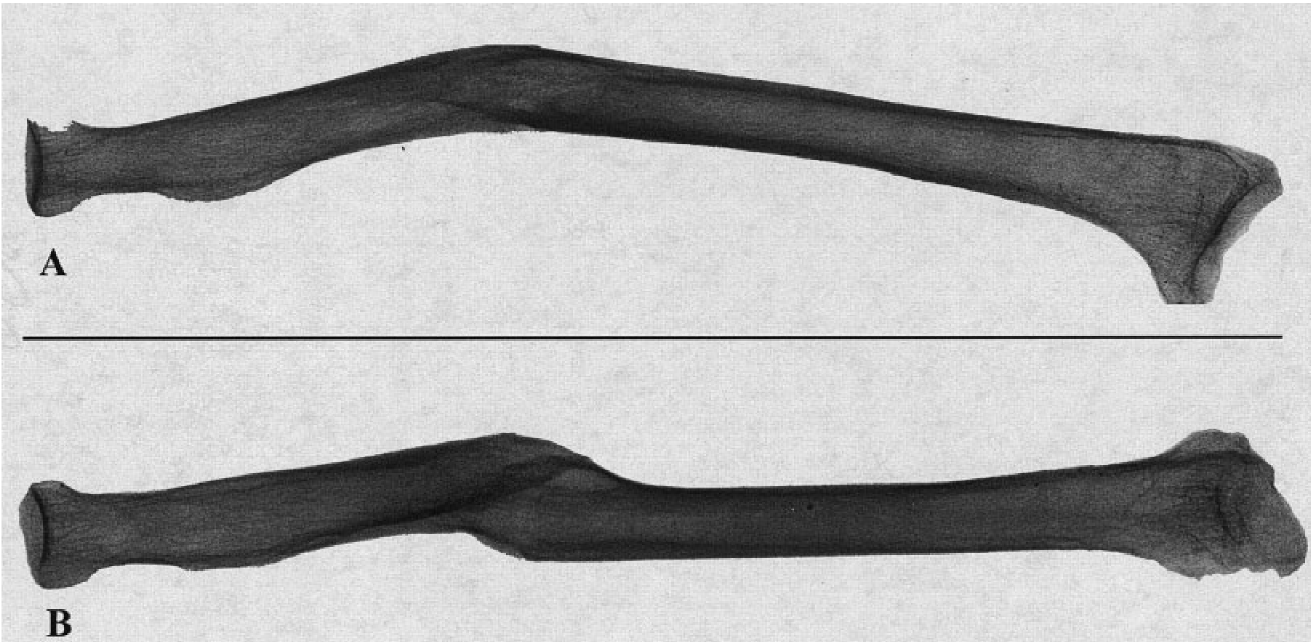


Fig. 2. Anterior-posterior (**A**) and medial-lateral (**B**) radiographs of K'inich Yax K'uk' Mo's right radius.

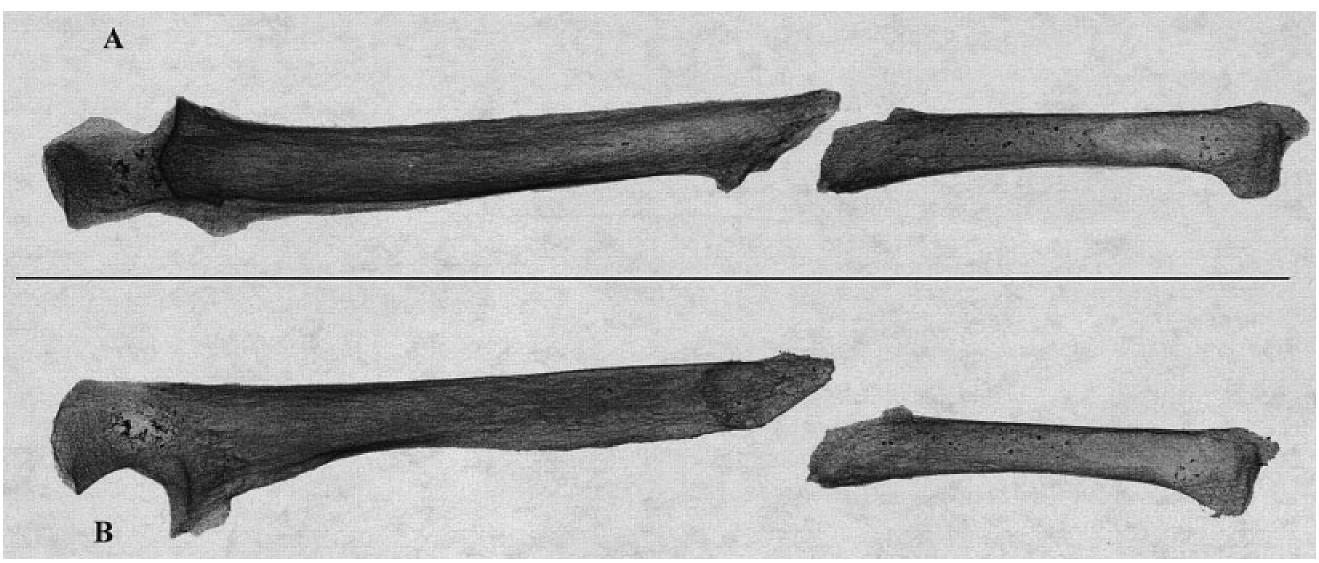


Fig. 3. Anterior-posterior (**A**) and medial-lateral (**B**) radiographs of K'inich Yax K'uk' Mo's right ulna.

The only notable pathology was a well-healed mid-shaft fracture of the right ulna (Fig. 5). Isotopic analyses also revealed that the Motmot individual appears to have spent her childhood in the Petén region of Mesoamerica (Buikstra et al., 2004).

We can further our understanding of these individuals' life histories by examining the biomechanical consequences of the above-described skeletal traumas. Humeral cross-sectional geometries were calculated for both K'inich Yax K'uk' Mo' and the Motmot interment, as they may provide clues concerning possible behavioral changes and adaptations.

METHODS

Radiography

Radiographs were taken using a portable veterinary x-ray unit (Soyee Products, Inc.). Instead of conventional radiographic film, 800 ISO Polaroid Polapan 803 8″ × 10″ black-and-white photographic film was used. Polaroid film has a number of advantages over conventional radiographic film when dealing with field conditions (Conlogue and Nelson, 1999), not the least of which is instant assessment of element exposure and positioning. Disadvantages, however, include the limited size of

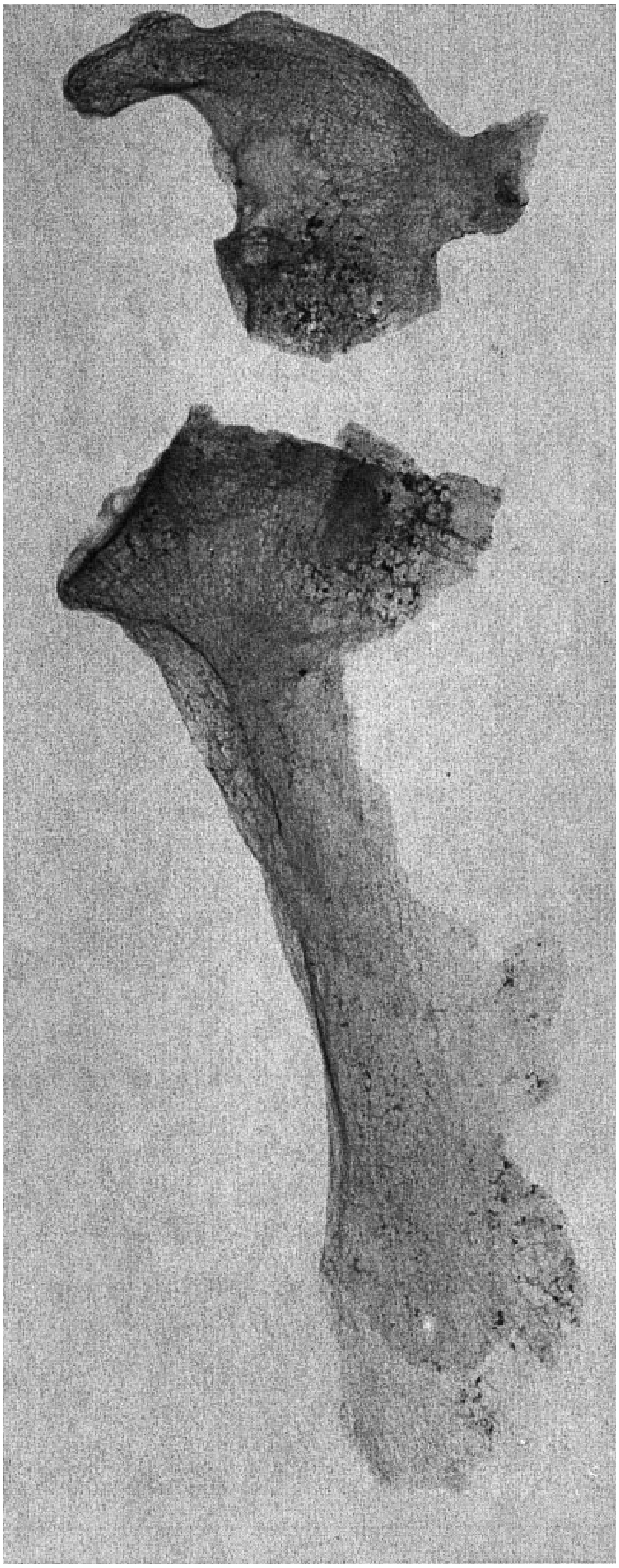


Fig. 4. Anterior-posterior radiograph of K'inich Yax K'uk' Mo's left scapula, demonstrating separation of superior portion of glenoid fossa and coracoid process.

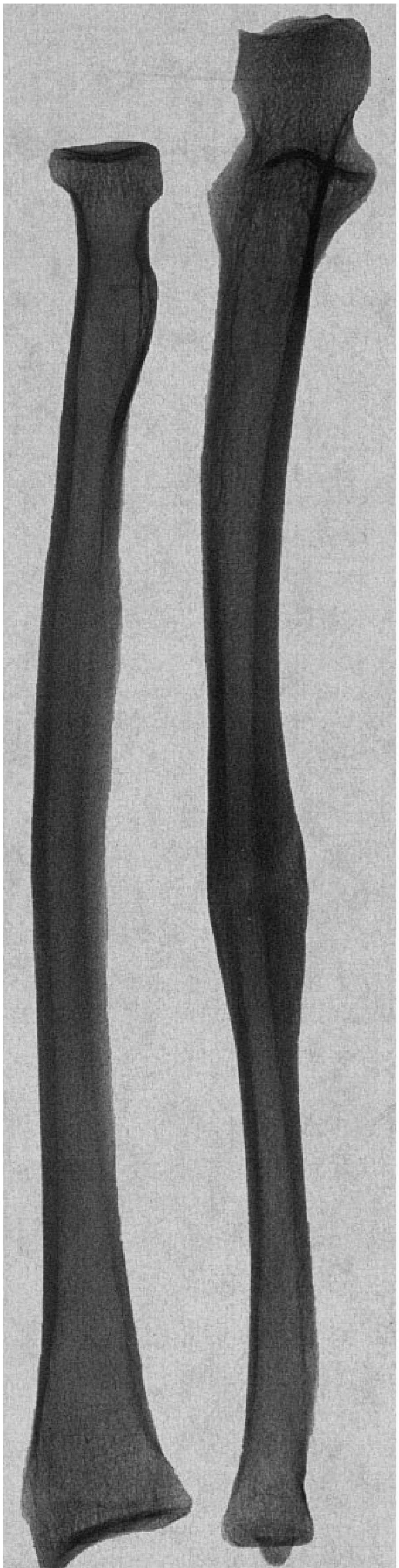
the film, which at times necessitated multiple exposures to record long bones. Exposures were generally set at 80 kV/15 mA, and the focal film distance was 40 inches (100 cm). Power fluctuations at both locations made it difficult to maintain these levels, requiring increased exposure time.

To accurately measure diaphyseal dimensions from radiographs, we must control for any potential radiographic magnification and distortion, which are dependent on source-image distance and object-image distance. While increasing the source-image distance reduces magnification (Carlton and Adler, 2001), it was not possible in this instance to raise the x-ray unit. The amount of magnification and distortion will also depend on the nature of the elements being radiographed. The object-image distance for elements such as teeth, which rest directly on the film, would be essentially zero, and therefore there would be no magnification. For curved elements such as the humerus, magnification error will change, dependent on which area of the bone is under investigation. For this project, 1 inch (2.54 cm) was taken as the object-image distance, which produces a magnification factor of 3%. All measurements taken directly from radiographs were adjusted by this factor before calculating cross-sectional properties (Table 1 and Table 2).

Measurement

Radiographs of the humeri were taken from standardized anterior-posterior and medial-lateral positions (Ben-Itzhak et al., 1988; Ruff and Jones, 1981). When necessary, humeri were stabilized with foam in order to maintain position, such that the plane of interest (anterior-posterior or medial-lateral) was parallel to the film. A portable osteometric board was used to determine maximum bone length, while biomechanical length (Ruff, 2000b) was measured directly from radiographs. Periosteal and endosteal dimensions were measured from the original radiographs at 35% (mid-distal), 50% (midshaft), and 65% (midproximal) of humeral biomechanical length. The illustrations in this paper were produced by combining the original radiographs in Adobe Photoshop, utilizing the previously recorded maximum bone lengths to aid in positioning.

Periosteal and endosteal diameters were measured to the nearest 0.01 mm, using Mitutoyo digital calipers. The average of three trials was used to calculate cross-sectional properties. Measurement error throughout all three trials ranged from 0.01–0.57 mm. Error rates tended to be larger when measuring the endosteal area, which is not unexpected, given the generally more variable nature of the endosteal surface (Ruff and Jones, 1981). While measurement errors could affect the derivation of biomechanical properties, they are small, and the averaging of trials should reduce any introduced error. Additionally, since such mea-



surement errors will affect both sides equally, right-left comparisons should remain robust.

Calculation of cross-sectional properties

The use of biplanar radiographs to estimate cross-sectional biomechanical properties is an appropriate methodology in circumstances when a bone cannot be sectioned or CT equipment is unavailable (Ben-Itzhak et al., 1988; Biknevicius and Ruff, 1992; Runestad et al., 1993). The geometric properties used to address the questions raised above include: cortical area and the second moments of area, J, and I_X and I_Y. These properties are derived by utilizing a beam model of diaphyseal bone distribution (Ruff et al., 1993). Under this model, the cross-sectional area of a bone is proportional to axial compressive forces, while the second moments of area are proportional to bending and torsional forces (Ruff et al., 1993).

Cortical area (CA) is a measure of bone axial strength and measures resistance to compressive or tensile loadings and is calculated with the following equation:

$$CA = \pi \times ((ML \times AP) - (ml \times ap))/4 \qquad (1)$$

where ML and AP refer to medial-lateral and anterior-posterior periosteal diaphyseal diameter, respectively, and ml and ap refer to medial-lateral and anterior-posterior endosteal diaphyseal diameter, respectively. Medullary area (MA) and total area (TA) were also calculated:

$$MA = \pi(ml * ap) \qquad (2)$$

$$TA = \pi(ML * AP) \qquad (3)$$

Given that we are only using biplanar radiographs, estimating maximum and minimum second moments of area (I_{max}, I_{min}) is not possible (Runestad et al., 1993). Second moments of area in radiographic planes, however, may be estimated. I_X and I_Y measure anterior-posterior and medial-lateral bending rigidity, respectively, and are calculated from the following equations:

$$I_X = \pi \times ((ML \times AP^3) - (ml \times ap^3))/64 \qquad (4)$$

$$I_Y = \pi \times ((AP \times ML^3) - (ap \times ml^3))/64 \qquad (5)$$

Low second moment of area values indicate that bone is distributed close to the central or neutral axis of the cross section. High values, on the other hand, indicate that the bone is distributed farther from the central axis and reflects greater strength and ability to resist bending and torsional forces

Fig. 5. Anterior-posterior radiograph of Motmot's right forearm.

TABLE 1. Raw periosteal and endosteal dimensions for K'inich Yax K'uk' Mo' taken at middistal (35%), midshaft (50%), and midproximal (65%) after being adjusted for magnification

Right humerus, raw[1]						
	Middistal (35%)		Midshaft (50%)		Midproximal (65%)	
	Periosteal	Endosteal	Periosteal	Endosteal	Periosteal	Endosteal
AP	21.00	16.87	20.53	16.63	21.39	17.47
ML	18.90	13.73	20.46	16.74	19.47	15.83

[1] Maximum length, 313 mm. Biomechanical length, 308 mm.

Left humerus, raw[2]						
	Middistal (35%)		Midshaft (50%)		Midproximal (65%)	
	Periosteal	Endosteal	Periosteal	Endosteal	Periosteal	Endosteal
AP	19.56	14.33	19.21	14.72	23.39	19.12
ML	17.77	12.75	19.93	15.98	19.66	16.16

[2] Maximum length, 313 mm. Biomechanical length, 308 mm.

TABLE 2. Raw periosteal and endosteal dimensions for Motmot after being adjusted for magnification

Right humerus, raw[1]						
	Middistal (35%)		Midshaft (50%)		Midproximal (65%)	
	Periosteal	Endosteal	Periosteal	Endosteal	Periosteal	Endosteal
AP	16.39	9.08	17.68	10.41	16.82	9.24
ML	15.67	8.51	16.82	9.42	16.64	10.14

[1] Maximum length, 281 mm. Biomechanical length, 278 mm.

Left humerus, raw[2]						
	Middistal (35%)		Midshaft (50%)		Midproximal (65%)	
	Periosteal	Endosteal	Periosteal	Endosteal	Periosteal	Endosteal
AP	17.46	10.03	18.29	11.41	16.85	9.83
ML	15.50	8.67	15.85	7.87	16.84	10.19

[2] Maximum length, 284 mm. Biomechanical length, 281 mm.

(Ruff, 1995). The ratio of I_X and I_Y can also be used to assess the cross-sectional "shape" of long bones. Ratios close to 1.0 reflect a nearly circular distribution of bone, while deviations reflect a more ovoid shape (Larsen, 1997).

J is a measure of torsional rigidity, and is calculated from the equation:

$$J = I_X + I_Y \quad (6)$$

Given that we were interested in assessing changes in long bone structure due to trauma and the possible effects of disuse atrophy, the calculation of bilateral asymmetry was incorporated (Churchill and Formicola, 1997; Trinkaus et al., 1994):

$$((\max - \min)/\min) * 100 \quad (7)$$

For comparisons with other samples, all measures of area (CA, MA, TA, and %CA) were standardized over biomechanical length^3 (Churchill, 1995; Trinkaus et al., 1998; Trinkaus and Churchill, 1999). The second moments of area (I_X, I_Y, and J) were standardized over both biomechanical length$^{5.33}$ and biomechanical length^4 (Trinkaus et al., 1994). Comparative Amerindian humeral samples at 35% of bone length were obtained from the literature (Ruff and Larsen, 2001; Ruff, 1999, and personal communication). For analyses of bilateral asymmetry, results were compared with those of Trinkaus et al. (1994) and Churchill and Formicola (1997).

RESULTS

Yax K'uk Mo'

At the middistal humerus, size-standardized CA values for both humeri (Table 3) fall well below the mean and outside one standard deviation as reported for male Amerindians (Ruff and Larsen, 2001; Ruff, 1999, and personal communication) (Table 5). Conversely, MA values in both humeri (Table 3), in particular the right humerus, are well above the comparative means and outside one standard deviation (Table 5). Values for TA, while above the comparative means (Table 5), fall within one standard deviation. All second moments of area, regardless of size-standardization technique, are below the mean values reported in Table 5, but fall within one standard deviation. The I_X/I_Y ratio at the middistal humerus (Table 3) is above the mean value (Table 5).

TABLE 3. Body-size standardized cortical areas, second moments of area, and I_X/I_Y ratio for K'inich Yax K'uk' Mo' at middistal (35%), midshaft (50%), and midproximal (65%)

	Left humerus			Right humerus		
Property	35%	50%	65%	35%	50%	65%
CA[1]	44.32	39.73	40.55	44.49	38.15	37.59
MA[1]	49.11	63.23	83.05	62.24	74.82	74.34
TA[1]	93.43	102.96	123.60	106.72	112.98	111.93
%CA[1]	16.23	13.21	11.22	14.27	11.56	11.49
I_X[2]	255.17	241.72	370.37	291.93	268.06	283.56
I_Y[2]	213.99	246.33	259.49	262.71	262.05	236.58
J[2]	469.16	488.05	629.86	554.64	530.11	520.13
I_X[3]	520.72	493.27	755.81	595.74	547.03	578.65
I_Y[3]	436.67	502.69	529.53	536.10	534.75	482.77
J[3]	957.39	995.95	1,285.33	1,131.83	1,081.78	1,061.42
I_X/I_Y[3]	1.19	0.98	1.43	1.11	1.02	1.20

[1] Cortical areas were standardized over humeral biomechanical length^3.
[2] Second moments of area were standardized over humeral biomechanical length$^{5.33}$.
[3] Second moments of area were standardized over humeral biomechanical length^4.

TABLE 4. Body-size standardized cortical areas, second moments of area, and I_X/I_Y ratio for Motmot at middistal (35%), midshaft (50%), and midproximal (65%)

	Left humerus			Right humerus		
Property	35%	50%	65%	35%	50%	65%
CA[1]	65.04	70.94	62.83	65.67	72.82	68.06
MA[1]	30.82	31.76	35.46	28.27	35.91	34.29
TA[1]	95.85	102.70	98.29	93.93	108.73	102.34
%CA[1]	30.58	31.13	28.81	32.54	31.17	30.95
I_X[2]	321.97	372.35	286.56	289.29	380.05	328.57
I_Y[2]	255.06	293.88	298.21	265.53	348.05	313.44
J[2]	577.03	666.23	584.78	554.82	728.10	642.02
I_X[3]	581.57	672.56	517.61	515.13	676.73	585.07
I_Y[3]	460.70	530.83	538.65	472.81	619.77	558.14
J[3]	1,042.27	1,203.39	1,056.26	987.94	1,296.50	1,143.22
I_X/I_Y[3]	1.26	1.27	0.96	1.09	1.09	1.05

[1] Cortical areas were standardized over humeral biomechanical length^3.
[2] Second moments of area were standardized over humeral biomechanical length$^{5.33}$.
[3] Second moments of area were standardized over humeral biomechanical length^4.

At the middistal humerus, asymmetry values (Table 6) for CA fall below the mean values reported for all four comparative Amerindian population (Table 7), while asymmetry values for MA and J are above the mean. The MA and J asymmetry values most closely approximate the values reported by Trinkaus et al. (1994) for California Amerindians.

At the midproximal humerus (Table 6), CA asymmetry values fall between the mean values reported for Aleuts and Late Pueblo populations (Churchill and Formicola, 1997). The MA value at the midproximal humerus is well below the mean reported for the Aleut and Late Pueblo populations. The midproximal J value (Table 6) is nearly identical to the J asymmetry value for the Aleut population (Table 7). Noteworthy levels of asymmetry can be seen in a number of cross-sectional cortical areas, including the middistal MA (26.72), the middistal I_Y (22.77), and the middistal (18.22). While noteworthy, none of these values is greater or lesser than the total range of values reported for the comparative, presumably nonpathological, samples (Churchill and Formicola, 1997). Further, high levels of asymmetry can be seen at midproximal I_X (30.62) and midproximal J (21.10) (Table 6).

Examining intrahumeral values, we can see that CA values decrease proximally, while MA values increase proximally in both humeri. Percent cortical area (%CA) decreases proximally in both humeri (Table 3). Values of J in the left humerus increase proximally, while in the right humerus, J decreases proximally. The J values in the right humerus, except at the midproximal location, are greater than those in the left humerus.

The I_X/I_Y ratios value the same pattern in both humeri (Table 3). Ratios begin greater than 1.0 at the middistal humerus, decrease to near 1.0 at midshaft, and then increase substantially at the midproximal humerus. In particular, the I_X/I_Y ratio at the midproximal location of the left humerus is notably high (Table 3).

Motmot

The middistal humeral cortical areas and second moments of area (Table 4) are all, except for MA

TABLE 5. Body-size standardized mean values for cortical areas, second moments of area, and I_X/I_Y ratio from comparative Native America populations (Ruff and Larsen, 2001; Ruff, 1999; personal communication) at mid-distal (35%) with right and left sides averaged

Property	Male (n = 111), 35% (±STD)	Female (n = 109), 35% (±STD)
CA[1]	64.41 (11.86)	55.29 (11.55)
MA[1]	28.66 (10.92)	29.03 (11.49)
TA[1]	93.07 (14.2)	84.32 (12.8)
I_X[2]	307.25 (82.77)	239.84 (67.19)
I_Y[2]	298.01 (88.49)	221.68 (67.65)
J[2]	605.26 (167.09)	461.52 (131.54)
I_X[3]	641.66 (150.59)	461.43 (110.89)
I_Y[3]	621.93 (161.86)	425.74 (110.09)
J[3]	1,263.59 (302.79)	877.17 (213.66)
I_X/I_Y[3]	1.044 (0.132)	1.096 (0.131)

[1] Cortical areas were standardized over humeral biomechanical length^3.
[2] Second moments of area were standardized over humeral biomechanical length$^{5.33}$.
[3] Second moments of area were standardized over humeral biomechanical length^4.

on the right side, above the mean values, but within one standard deviation of the figures reported in Table 5 for female Amerindians. The middistal MA value in the right humerus is below the comparative mean, but is within one standard deviation (Table 5). The I_X/I_Y ratio at the middistal humerus is slightly above the comparative mean plus one standard deviation (Table 5).

At the middistal humerus, CA asymmetry values (Table 6) are below the mean values reported for the comparative Amerindian populations (Table 7), while asymmetry values for MA and J are above the mean. The MA and J asymmetry values most closely approximate the values reported by Trinkaus et al. (1994) for California Amerindians.

Looking at intrahumeral differences, CA values increase proximally from middistal to midshaft, and then decrease at midproximal in both humeri (Table 4). Medullary area in the left humerus increases proximally. MA values follow this pattern in the right humerus, but drop slightly at the midproximal position. In both humeri, TA values increase proximally from middistal to midshaft, and then decrease at the midproximal position.

Percent cortical area (%CA) in the left humerus increases slightly from middistal to midshaft, and then decreases at midproximal (Table 4). In the right humerus, %CA decreases proximally. Differences between humeri in %CA are slight but do increase proximally.

DISCUSSION

Interpreting biomechanical changes due to the trauma observed in Yax K'uk Mo' is complicated. He suffered from a high-impact injury that disrupted the left shoulder girdle, separating a portion of the glenoid fossa and the coracoid process. Further, both the right radius and ulna were fractured. Given such trauma, we expect significant cortical bone tissue redistribution resulting from altered function.

The most obvious conclusion is that while it appears Yax K'uk Mo' may have had normal cortical bone density (Nystrom et al., 2005), the total amount of cortical bone is low when compared to other groups. Size-standardized CA middistal values (Table 3) are well below the mean and standard deviation of the comparative groups (Table 5). Low %CA values evident in Yax K'uk Mo' suggest that in general, his bones may not have been strongly resistant to axial loading, though %CA by itself is not a reliable indicator of functional and mechanical demands (Larsen, 1997, p. 201).

MA values reported for Yax K'uk Mo' are considerably larger than seen in comparative samples, again suggesting the redistribution of cortical bone. Given the proposed advanced age (>50 years) of Yax K'uk Mo' (Buikstra et al., 2004), we must consider age-progressive loss of CA coupled with increases in TA and MA in order to maintain bone strength (Ruff and Hayes, 1982, 1983). After 40 years of age, the rate of bone loss on the endosteal surface exceeds subperiosteal bone deposition, resulting not only in overall bone loss with age (Ruff, 1995; Ruff and Jones, 1981), but also with bone redistribution in order to maintain a bone's resistance to mechanical forces (Bridges, 1989; Ruff, 2000a).

Despite low values for %CA, the second moments of area values reported for Yax K'uk Mo' suggest that cortical bone was distributed far from the neutral axis of the humerus, indicative of substantial resistance to bending and torsional loadings (Larsen, 1997). While both middistal I_X and I_Y values are below the comparative means, they are within one standard deviation. The middistal values calculated for J, as a measure of bone strength, are also below the means reported for Amerindian populations, but again are within one standard deviation (Table 5). While measures of CA and MA are substantially different from the comparative populations, the cortical bone of the humeri, as reflected in the second moments of area, was redistributed to compensate for this loss.

Interestingly, there are very high values for I_X at the left midproximal humerus, the region most intimately associated with the fracture of the coracoid process and glenoid fossa. Given that the primary functioning of the muscles that originate on the coracoid process involves movement in the anteroposterior plane, the high I_X value at this location, which suggests increased resistance to anteroposterior loadings, is a somewhat anomalous result. This high I_X value may be due to a pathological process, being the result of bone deposition following trauma (Fig. 5). The J asymmetry values most closely approximate those reported for California Amerindians (Trinkaus et al., 1994) and Aleut populations (Churchill and Formicola, 1997).

TABLE 6. Bilateral asymmetry values at middistal (35%), midshaft (50%), and midproximal (65%), based on raw humeral diaphyseal dimensions for K'inich Yax K'uk Mo and Motmot after being corrected for magnification

	Yax K'uk Mo'				Motmot		
Property	35%	50%	65%	Property	35%	50%	65%
CA	0.36	4.13	7.88	CA	2.28	0.60	4.89
MA	26.72	18.33	11.72	MA	12.59	9.46	6.80
TA	14.22	9.73	10.43	TA	5.38	2.51	0.83
% CA	13.84	14.26	2.36	% CA	3.03	3.13	4.03
I_X	14.41	10.90	30.62	I_X	17.85	3.74	8.28
I_Y	22.77	6.38	9.69	I_Y	1.71	11.85	0.74
J	18.22	8.62	21.10	J	10.12	3.21	3.68
I_X/I_Y	7.31	4.25	19.08	I_X/I_Y	15.87	16.04	9.08

TABLE 7. Comparative median asymmetry values of humeral diaphyseal cross-sectional properties at middistal (35%) and mid-proximal (65%) from Amerindian populations, with quartile ranges for Aleut and Late Pueblo populations in parentheses

	Georgia coast[1]		California[1]		Aleuts[2]		Late Pueblo[2]	
Property	35%	65%	35%	65%	35%	65%	35%	65%
CA								
Male	4.92		8.27		9.5 (2.6–15.3)	13.0 (5.9–17.1)	5.4 (3.1–8.7)	9.5 (1.6–16.0)
Female	4.97		5.83					
MA								
Male	10.47		24.27		13.2 (3.2–11.6)	12.5 (5.0–23.7)	13.7 (7.1–24.4)	21.7 (4.2–30.0)
Female	4.17		7.08					
J								
Male	9.90		19.46		16.4 (6.4–21.8)	21.0 (9.3–27.3)	13.0 (8.5–22.9)	16.2 (8.1–23.7)
Female	4.94		8.41					

[1] Trinkaus et al., 1994.
[2] Churchill and Formicola, 1997.

Further, there are some interesting differences when we compare the right and left humeri. Except at the midproximal shaft, measures of MA and TA are larger in the right humerus, indicating a relatively expanded medullary space and total subperiosteal area. It is possible that with trauma-induced disuse atrophy of the right forearm, that loss of cortical area was accelerated in the right relative to the left humerus. There is also a large degree of asymmetry in %CA between humeri, averaging larger on the left side, with values as large 14% (Table 7). Asymmetry values of CA (Table 7) fall between the medians reported for Late Pueblo and Aleut Amerindian populations (Churchill and Formicola, 1997).

With I_X/I_Y ratios greater than 1, both humeri show preferential bone distribution to accommodate stress in the anterior-posterior plane (Table 3). The left humerus, except at midshaft, is relatively elongated in the anteroposterior plane compared to the right humerus. The relatively low ratios calculated for the right humerus, when compared to the left humerus, may be due to reduced functioning of the right forearm subsequent to trauma, or may also reflect dominance of the left arm.

It is interesting to compare the asymmetry values calculated for K'inich Yax K'uk' Mo' to values reported by Churchill and Formicola (1997) based on pathological humeri. The middistal and midproximal MA, CA, and J asymmetry values calculated for K'inich Yax K'uk' Mo' are lower than those calculated for Oberkassel 1, Dolni Vestonice 15, and Neanderthal 1 (Table 6 in Churchill and Formicola, 1997). The only asymmetry value derived from K'inich Yax K'uk' Mo' that approaches the values of the pathological specimens is the middistal MA value of 26.72, most closely approximating the 29.3% asymmetry found in Neanderthal 1 (Churchill and Formicola, 1997).

For Motmot, the differences between the humeri are smaller. Medullary area in the right humerus, except at midshaft, is generally smaller than in the left. Asymmetry values of TA range from <1–5%, with the right humerus exhibiting a slightly greater total subperiosteal area at the midshaft and midproximal locations. Asymmetry values of MA range from 6–12%, the latter value occurring at midshaft, demonstrating that the right humerus has an expanded medullary cavity at this location relative to the left humerus. The middistal and midshaft I_X/I_Y ratios for the left humerus suggest a cross section that is slightly stronger in the anterior-posterior plane (Table 4). The cross sections at middistal and midshaft on the left humerus are anteroposteriorly elongated relative to the corresponding sections on the right humerus. Cross sections in the right humerus are consistently roughly circular in shape and slightly stronger in the anterior-posterior plane.

CONCLUSIONS

Based on the visual evaluation of the skeletal material and the radiographs of Yax K'uk Mo' and the Motmot principal interment, it was possible to document the presence of a number of injuries due to blunt-force trauma (Buikstra et al., 2004, Nystrom et al., 2005). Further, it was possible to conjecture on subsequent physiological changes, such as disuse atrophy, due to these injuries. The current paper adds the derivation of cross-sectional geometric properties from biplanar radiographs to quantify these bony changes.

The right forearm fractures sustained by Yax K'uk Mo' clearly affected the cross-sectional geometric properties of the corresponding humerus. As detailed by Nystrom et al. (2005), the injury to the right ulna and radius significantly affected diaphyseal density, particularly in the ulna. This injury also appears to have affected the distribution of cortical bone in the right humerus. While the low %CA values reported here for Yax K'uk Mo' may in part be explained by his advanced age, the values calculated for the right humerus are generally lower than those reported for the left humerus. The reported asymmetry in %CA, by as much as 14%, also supports the conclusion that the right humerus suffered significantly from the injury to the right forearm. In addition, the larger values for medullary area in the right humerus, except at the midproximal location, indicate an expanded medullary space, when compared to the left. Further, while both humeri show preferential bone distribution to accommodate stress in the anterior-posterior plane, as indicated by I_X/I_Y ratios greater than 1, the relatively lower ratios calculated for the right humerus may be due to reduced functioning of the right forearm subsequent to trauma. Alternatively, this difference in I_X/I_Y ratios may indicate that Yax K'uk Mo' was left-handed.

The restructuring of the left shoulder girdle does not appear to have had a significant effect on cortical bone distribution in the midproximal left humerus. The coracobrachialis and the short head of the biceps brachii are the two major upper limb muscles that originate on the coracoid process. The former is responsible for flexion and adduction of humerus, while the latter is a prime mover in forearm flexion. Separation of the coracoid process seems to have affected the proper functioning of these muscles. The high I_X value at the midproximal shaft of the left humerus, which suggests an increased resistance to anterior-posterior loadings, is interesting. Physiologically, this may indicate normal activity levels at this joint, perhaps coupled with additional bony buttressing of the proximal humerus, despite the separation of bony elements. Lieberman et al. (2004) noted from their in vivo strain tests that while the interindividual patterning of cross-sectional properties may be useful, the same properties do not necessarily provide an accurate description of the orientation of loads to which these bones were subjected. Therefore, according to Lieberman et al. (2004), while we may reliably discuss the relative redistribution of cortical bone in Yax K'uk Mo' and Motmot following trauma, we will not be able to accurately determine that nature of the loadings.

The only insult of note evident for the Motmot principal interment was a complete parry fracture of the right ulna. The insult was completely healed at time of death. There was no discernible difference between the right and left radius and ulna in terms of cortical thickness or density (Nystrom et al., 2005). Derivation of cross-sectional geometric properties, however, allowed us to document a slight asymmetry in humeral medullary area, suggesting a relatively expanded medullary area at the midshaft of the right humerus. In contrast to Yax K'uk Mo', there is only a slight asymmetry in %CA between Motmot's right and left humeri. Further, %CA values for Motmot are more comparable with other populations (Larsen et al., 1995). In sum, the right forearm fracture does not appear to have significantly impaired the functioning of the right humerus in the Motmot principal interment.

Rich archaeological and osteological evidence provided us with insights into the lives of these two individuals. While examination of the archaeological record is often dominated by a concern for the lifestyles of the elite, this study is unique in that the personal identity of these individuals can be fairly well-established.

Archaeological evidence suggests that the primary Motmot interment was involved with divination. Osteological analyses suggest that while she did not lead an active life, she did suffer from a fracture of the right ulna. Isotopic evidence reveals that she was also foreign to Copan, having spent her childhood in Petén.

Architectural and hieroglyphic evidence associated with K'inich Yax K'uk' Mo' connects him with a number of regions in Mesoamerica. Isotopic analyses of his skeletal remains, however, establish that he spent his childhood years in the northern region of Petén (Buikstra et al., 2004). Traces of his life and his journey to Copan remain visible on his skeleton. K'inich Yax K'uk' Mo' suffered from a broken right radius and ulna, separation of the superior third of the glenoid fossa and the coracoid process from the body of the left scapula, rib fractures, dislocation, and subsequent development of new articular facets on the medial aspect of the clavicles, and moderate arthritic development in the elbow, wrist, and hand.

Radiographic evaluation of the skeletal remains provided us with the opportunity to examine in more detail the traumas discussed above. Specifically, derivation of biomechanical properties for these individuals allowed the documentation of intraindividual changes in humeri cross-sectional properties due to altered physiological functioning. The differences in cross-sectional properties described above may be slight, but an inclusive evaluation of the evidence suggests a subtle physiological adaptation subsequent to trauma. Gross evaluation of the skeletal remains and radiographs, in particular those of K'inich Yax K'uk' Mo', clearly indicates significant physiological alterations due to blunt-force injuries. The cross-sectional geometric properties reported here provide supporting evidence, while also expanding our interpretive capabilities.

ACKNOWLEDGMENTS

Permission for study was granted by Oscar Cruz and the Instituto de Hondureño de Antropología y Historia, and by Robert Sharer and William and Barbara Fash of the Copan Acropolis Project. The assistance of Ellen Bell, Marcello Canuto, Lynn Grant, Christopher Powell, David Sedat, and Loa Traxler was essential to the success of the project. The radiographic portion of the research was made possible by funding from FAMSI and the Ahau Foundation. Special thanks go to Christopher Ruff, who unselfishly shared his time, effort, and comparative data set to improve this paper. We thank the anonymous reviewers and Clark Spencer Larsen, whose comments and suggestions were also extremely helpful. Finally, we thank Osborn Pearson and Michael Schillaci for reading earlier versions of this article. Figures 2, 3, 5, and 6 were reprinted from "Field Paleoradiography of Skeletal Material From the Early Classic Period of Copan, Honduras," Can Assoc Radiol J 55: 246–253, by permission of publisher. © 2004 Canadian Medical Association.

LITERATURE CITED

Bell EE, Sharer RJ, Traxler LP, Sedat DW, Carrelli CW, Grant LA. 2004. Tombs and burials in the Early Classic Acropolis at Copan. In: Bell EE, Marcello AC, Sharer RJ, editors. Understanding Early Classic Copan. Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology. p 131–157.

Ben-Itzhak S, Smith P, Bloom RA. 1988. Radiographic study of the humerus in Neandertals and *Homo sapiens sapiens*. Am J Phys Anthropol 77:231–242.

Biknevicius AR, Ruff CB. 1992. Use of biplanar radiographs for estimating cross-sectional geometric properties of mandibles. Anat Rec 232:157–163.

Bridges PS. 1989. Changes in activities with the shift to agriculture in the southeastern United States. Curr Anthropol 30:385–394.

Bridges PS, Blitz JH, Solano MC. 2000. Changes in long bone diaphyseal strength with horticultural intensification in west-central Illinois. Am J Phys Anthropol 112:217–238.

Buikstra JE, Price TD, Burton JH, Wright LE. 2004. Tombs from Copan's Acropolis: a life history approach. In: Bell EE, Marcello AC, Sharer RJ, editors. Understanding Early Classic Copan. Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology. p 191–212.

Canuto MA, Bell EE, Sharer RJ. 2004. Understanding Early Classic Copan: a Classic Maya center and its investigation. In: Bell EE, Marcello AC, Sharer RJ, editors. Understanding Early Classic Copan. Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology. p 1–14.

Carlton R, Adler AM. 2001. Principles of radiographic imaging: an art and a science, 3rd ed. Columbia: Delmar Thomson Learning.

Churchill SE. 1995. Humeral strength to bone length scaling relationships in recent humans. Am J Phys Anthropol [Suppl]20:76–77 [abstract].

Churchill SE, Formicola V. 1997. A case of marked bilateral asymmetry in the upper limbs of an Upper Palaeolithic male from Barma Grande (Liguria), Italy. Int J Osteoarch 7: 18–38.

Conlogue G, Nelson A. 1999. Polaroid imaging at an archaeological site in Peru. Radiol Technol 70:244–250.

Fash WL, Fash BW, Davis-Salazar KL. 2004. Setting the stage: origins of the Hieroglyphic Stairway Plaza on the great period ending. In: Bell EE, Marcello AC, Sharer RJ, editors. Understanding Early Classic Copan. Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology. p 65–83.

Larsen CS. 1997. Bioarchaeology: interpreting behavior from the human skeleton. Cambridge: Cambridge University Press.

Larsen CS, Ruff CB. 1994. The stresses of conquest in Spanish Florida: structural adaptation and change before and after contact. In: Larsen CS, Milner GR, editors. In the wake of contact: biological responses to conquest. New York: Wiley-Liss. p 21–33.

Larsen CS, Schoeninger MJ, Hutchinson DL, Russell KF, Ruff CB. 1990. Beyond demographic collapse: biological adaptation and change in native populations of La Florida. In: Thomas DH, editor. Columbian consequences. Volume 2: archaeological and historical perspectives on the Spanish borderlands east. Washington, DC: Smithsonian Institution Press. p 409–428

Larsen CS, Ruff CB, Kelly RL. 1995. Structural analysis of the Stillwater postcranial human remains: behavioral implications of articular joint pathology and long bone diaphyseal morphology. In: Larsen CS, Kelly RL, editors. Bioarchaeology of Stillwater Marsh: prehistoric human adaptation in the western Great Basin. Anthropological Papers of the American Museum of Natural History. New York: American Museum of Natural History. no. 77. p 107–133.

Lieberman DE, Polk JD, Demes B. 2004. Predicting long bone loading from cross-sectional geometry. Am J Phys Anthropol 123:156–171.

Nystrom KC, Buikstra JE, Braunstein E. 2005. Radiographic evaluation of Early Classic elites from Copan, Honduras. Int J Osteoarch 15: (in press).

Ruff CB. 1995. Biomechanics of the hip and birth in early *Homo*. Am J Phys Anthropol 98:527–574.

Ruff CB. 1999. Skeletal structure and behavioral patterns of prehistoric Great Basin populations. In: Hemphill BE, Larsen CS, editors. Prehistoric lifeways in the Great Basin wetlands: bioarchaeological reconstruction and interpretation. Salt Lake City: University of Utah Press. p 290–320.

Ruff CB. 2000a. Biomechanical analyses of archaeological human skeletons. In: Katzenberg MA, Saunders SR, editors. Biological anthropology of the human skeleton. New York: Wiley-Liss. p 71–102.

Ruff CB. 2000b. Body size, body shape, and long bone strength in modern humans. J Hum Evol 38:269–290.

Ruff CB, Hayes WC. 1982. Subperiosteal expansion and cortical remodeling of the human femur and tibia with aging. Science 217:945–948.

Ruff CB, Hayes WC. 1983. Cross-sectional geometry of Pecos Pueblo femora and tibiae—a biomechanical investigation: II. Sex, age, and side differences. Am J Phys Anthropol 60:383–400.

Ruff CB, Jones HH. 1981. Bilateral asymmetry in cortical bone of the humerus and tibia—sex and age factors. Hum Biol 53:69–86.

Ruff CB, Larsen CS. 2001. Reconstructing behavior in Spanish Florida: the biomechanical evidence. In: Larsen CS, editor. Bioarchaeology of Spanish Florida: the impact of colonialism. Gainseville: University Press of Florida. p 113–145.

Ruff CB, Trinkaus E, Holliday TW. 1993. Postcranial robusticity in *Homo*, I: temporal trends and mechanical interpretation. Am J Phys Anthropol 91:21–53.

Runestad JA, Ruff CB, Nieh JC, Thorington RW, Teaford MR. 1993. Radiographic estimation of long bone cross-sectional geometric properties. Am J Phys Anthropol 90:207–213.

Schele L. 1986. The founders of lineages at Copan and other Maya sites. Copan note 8. Report prepared for the Instituto Hondureno de Antropología e Historia, Teguicigalpa and the Copan Acropolis Project, Austin TX.

Sharer RJ, Traxler LP, Sedat DW, Bell EE, Canuto MA, Powell C. 1999. Early classic architecture beneath the Copan Acropolis. In: Ancient Mesoamerica 10. New York: Cambridge University Press. p 3–23.

Stirland AJ. 1993. Asymmetry and activity-related change in the male humerus. Int J Osteoarch 3:105–113.

Stuart D, Schele L. 1986. Interim report on the hieroglyphic stair of Structure 26. Copan note 17. Copan, Honduras: Copan Mosaics Project and the Instituto Hondureno de Antropología e Historia.

Trinkaus E, Churchill SE. 1999. Diaphyseal cross-sectional geometry of Near Eastern Middle Paleolithic humans: the humerus. J Archaeol Sci 26:173–184.

Trinkaus E, Churchill SE, Ruff CB. 1994. Postcranial robusticity in *Homo*. II: humeral bilateral asymmetry and bone plasticity. Am J Phys Anthropol 93:1–34.

Trinkaus E, Ruff CB, Churchill SE. 1998. Upper limb versus lower limb loading patterns among Near Eastern Middle Paleolithic hominids. In: Akazawa T, Aoki K, Bar-Yosef O, editors. Neandertals and modern humans in western Asia. New York: Plenum Press. p 391–404.