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CORRELATION BETWEEN COMPRESSION OF THE PROXIMAL TIBIA AND GROSS EXTERNAL INDICATORS OF JOINT DEGENERATION

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ABSTRACT. Previous research conducted on the dynamics of trabecular bone suggests that changes in the dimensions of the proximal metaphysis of the tibia would be consistent with joint degeneration of a mechanical etiology. Data on the circumference of the proximal metaphysis were collected from 44 tibiae exhibiting various degrees of degeneration of the proximal surfaces. Statistical analysis indicates that the broadness of the proximal metaphysis is positively correlated with the degree of observable joint degeneration as scored by Jurmain's (1975) method. Circumference to length ratios in the metaphysis are higher in specimens with a greater degree of observable joint degeneration, and correlation between bone length and circumference is less.

Keywords: Mechanical joint degeneration, osteoarthrosis, tibia, trabecular bone

Recent anthropological studies of activity patterns in human skeletal populations have generally focused on either cortical bone dynamics (e.g., Ruff 1987; Ruff & Hayes 1983) or joint degeneration (e.g., Bassett 1982; Bridges 1989, 1991, 1994; Jurmain 1977, 1980, 1990; Ortner 1968). While research on the dynamics of cortical bone is increasing in sophistication, little emphasis has been placed on refining the study of joint degeneration in skeletal populations. This imbalance may be due in part to an ignorance of and disinterest in trabecular bone dynamics among physical anthropologists. Experimental and clinical evidence (e.g., Radin & Rose 1986; Radin et al. 1973) suggests that trabecular bone in the metaphyses plays an integral role in the initiation and progression of joint degeneration of a mechanical etiology.

The role that trabecular bone plays in the initiation and progression of joint degeneration suggests that mechanical stresses can cause observable and quantifiable internal and external remodeling of joints prior to significant or total cartilage loss and the subsequent appearance of more conspicuous bony changes. The term "joint degeneration" is used here to refer to a suite of bony changes observable in joints as the result of mechanical stress and/or other conditions. It is not meant to refer exclusively to osteoarthrosis, osteoarthritis, or any other specifically defined medical condition, diagnosis of the severity of which requires the presence of soft tissue.

Gross changes of the joint surface, such as pitting, eburnation, and marginal lipping, are commonly used to identify and characterize joint degeneration in skeletal populations. These changes occur subsequent to significant or total deterioration of the articular cartilage (Ortner & Putschar 1985). In archaeological studies, the degree of joint degeneration is often scored using an ordinal scale. Such studies have generally interpreted observed differences in the distribution of degenerative joint disease as the result of particular activities: the use of tumplines (Bridges 1994), atlatls (Angel 1966), and grinding stones (Miller 1985), for example, have been suggested as "causes" of joint degeneration. These studies often cite "general wear-and-tear" (e.g., Bridges 1991; Jurmain 1977, 1990) as the primary cause of joint degeneration, and fail to discuss the specifics of activity-related joint stress that might be of use in more clearly defining the behavioral implications of joint degeneration (see Miller 1985 for an exception).

Some of the shortcomings of the current approach to joint degeneration in skeletal populations can be addressed by recognizing "non-pathological" changes in the proximal tibia that are related to joint degeneration of a mechanical etiology. Specifically, the basic dimensions of the proximal tibia are examined in relation to Jurmain's (1975) method of scoring the degree of joint degeneration in skeletal remains.

MECHANICAL STRESS AND JOINT DEGENERATION

All bone is generally classified as either cortical bone or trabecular bone. The two kinds of bone are differentiated on the basis of their porosity: cortical (compact) bone porosity varies from 5–30%; trabecular (spongy) bone porosity varies from 30% to over 90% (Carter & Hayes 1977). Cortical bone is the dense bone that forms the outer shell of most bones and makes up the diaphyses of long bones. Trabecular bone is a "three-dimensional lattice composed of plates and columns" (Carter & Hayes 1977) that is found in the medullary cavity of most bones. In the long bones, trabecular bone is concentrated in the metaphyses and epiphyses.

The distribution of cortical and trabecular bone in the long bones is determined by biomechanical stresses, and contributes to the overall strength of the bone. Trabeculae are generally oriented along lines of stress (i.e., Wolff's Law). While the formation and mechanics of trabecular architecture are complex (e.g., Carter et al. 1989; Fyhrie & Carter 1986; Heřt 1994), it is widely agreed that metaphyseal trabecular bone is most sensitive to forces transmitted in the direction of the long axis of the bone (axial forces). Interestingly, Ruff & Hayes (1983) note that resistance to axial loading (compression) is the least critical determinant of diaphyseal shape in lower limb bones. The shape of long bone diaphyses is influenced by bending (shear) and torsional loads (Ruff 1987), and the thickness of diaphyseal cortex in the axial plane forms a structure that is virtually impervious to fracture by a compressive load under normal circumstances (Cowin 1995). As trabecular structures are much more elastic than the denser cortical bone, the concentration of trabecular bone in a long bone metaphysis functions as a "bumper" to absorb forces transmitted across the joint.

Because the elasticity of trabecular bone plays an integral role in joint mechanics, changes in the elasticity of trabecular bone are of consequence to the normal functioning of a synovial joint. Many studies have suggested that the compressive strength and elasticity of trabecular bone is related to its density (e.g., Bartley et al. 1966; Bell et al. 1967; Carter & Hayes 1977; Weaver & Chalmers 1966). If trabecular bone becomes too dense (too strong in the axial plane), it becomes inelastic and cannot function as a shock absorber. If trabecular bone is not dense enough (too weak in the axial plane), it cannot absorb normal forces and is in danger of fracture (hence the occasionally mentioned mutual exclusion of osteoarthrosis and osteoporosis [e.g., Burr et al. 1983]). Research conducted since the 1960s has investigated a number of other relationships between the density, contiguity, strength, organization, and number of trabeculae (e.g., Carter & Hayes 1977; Carter et al. 1989; Goulet et al. 1994; Parfitt et al. 1983; Pugh et al. 1973a, b; Pugh et al. 1974; Radin & Rose 1986; Radin et al. 1973).

Radin & Rose (1986) and Radin et al. (1973) suggest that the initiation and progression of mechanical joint degeneration (osteoarthrosis) is intimately related to the dynamics of metaphyseal trabecular bone. There is evidence that the deterioration of articular cartilage is preceded, and even caused, by changes in the subchondral bone and trabeculae which underlie it. Using live rabbits, Radin et al. (1973) demonstrated that repeated axial loading of knee joints produced fractures of individual trabeculae. These fractures subsequently healed, with a resulting increased stiffness of the subchondral bone. By studying the timing of changes in both cartilage and subchondral bone, Radin et al. (1973) showed that stiffening of the subchondral bone preceded degenerative changes in the articular cartilage. The compressive strength of normal trabecular bone is related to its density: the more bone present per unit of volume, the stiffer the bone. As the trabeculae fracture and heal, bone is added and the trabecular structure loses elasticity (Radin & Rose 1986). Thus the loss of elasticity brought about by the stiffening of the subchondral bone can cause the cartilage to degenerate as it is exposed to forces normally absorbed by the underlying trabecular bone.

Additional studies have supported the contention that trabecular micro-fracturing and healing can cause an increase in the stiffness of subchondral bone and lead to the deterioration of articular cartilage. Pugh et al. (1974) found a significant difference in the contiguity (interconnectedness) and relative stiffness of trabecular bone underlying "normal" and "abnormal" (deteriorating) cartilage. Guo et al. (1994) suggest that the strength of trabecular bone "may be highly sensitive to fractures of individual trabeculae" (see also Goulet et al. 1994). The disorganization and thickening of subchondral trabeculae subsequent to compressive fracture is well-documented (Pugh et al. 1974; Pugh et al. 1973b; Radin et al. 1973). This thickening is plainly visible in radiographs as relatively discrete areas of increased density in arthrotic knees (e.g., see Maquet 1976, 1985). Thus, the relationship between the density and axial compression strength of trabecular bone (Bartley et al. 1966; Bell et al. 1967; Carter & Hayes 1977; Goulet et al. 1994; Weaver & Chalmers 1966) is probably a combined function of the thickness of individual trabeculae, the number of trabeculae, and the organization of a trabecular structure.

Taken together, available evidence strongly suggests that an increase in the density of subchondral trabecular bone is a key factor in joint degeneration of a mechanical etiology. This view of joint degeneration raises specific expectations concerning changes in the internal and external architecture of the joint in relation to mechanical stress. Axial "compression" of the proximal tibia would be consistent with the progression of mechanical joint degeneration as described above. Repeated fracturing and healing of subchondral trabeculae and trabeculae deeper into the metaphysis could result in a "compression" of the metaphyseal shell in the axial plane. There is presently no direct evidence for trabecular fractures occurring deep into the metaphysis. There is good evidence to suggest that axial forces are transmitted to this depth, however, and that these forces result in increased density and stiffness of trabecular bone through some mechanism. Finlay et al. (1989) studied the stiffness of trabecular bone underlying healthy and osteoarthrotic plateaus, and suggested that the trabecular bone below the plateaus of arthrotic tibiae showed an increased stiffness at unspecified depths (less than 30 mm). Areas of increased trabecular density below affected plateaus are visible in radiographs of living subjects (Maquet 1976), and plainly extend beyond the subchondral bone. Goldstein et al. (1983) observed patterns of increased stiffness in trabecular bone at a depth of 40–50 mm below the plateaus.

In vivo, the metaphyseal cortical shell is flexible. In a study of fresh femora from autopsy specimens, for example, Hirsch & Frankel (1961) noted that "strains in various parts of the cortical shell could be seen" as forces were applied. As both cortical and trabecular bone are viscoelastic and exhibit a variety of attributes which allow them to deform and "flow" (Bowman et al. 1994), it is reasonable to suspect that the shape of the cortical metaphyseal shell of the proximal tibia may vary in conjunction with the state of the underlying trabecular structure and the shape of the articular surfaces. If the cortical shell of the proximal tibia tends to be compressed in conjunction with mechanical joint degeneration, the circumference of the tibia immediately inferior to the plateau would be expected to be greater relative to bone length in specimens exhibiting grossly observable signs of joint degeneration.

METHODS

Measurement and observational data were collected from 44 tibiae from the University of Chicago collection housed at Southern Illinois University at Carbondale, Illinois. Although information concerning the origin of the collection is imprecise, it is generally thought to be composed of cadavers collected by the University of Chicago dissecting laboratories in the first half of the 20th century (White 1999). As it is a medical sample, it is in fair condition, with joint surfaces, metaphyseal cortical shell, and trabeculae generally intact. The collection contains at least 180 tibiae, representing at least 92 adult individuals. The collection includes individuals that exhibit various degrees of gross degeneration of the joint surfaces, as well as a large number of individuals who display no such involvement.

The sample requirements for this study were quite basic. For the most part, the sample needed only to consist of relatively well-preserved tibiae. Although the sample did not need to represent a "population" in the usual sense, it had to contain specimens which displayed a suitable range of degenerative involvement. Most of the individuals in the collection lack pelves and crania, and sex could not be reliably estimated for most of the collection.

Table 1.—Jurmain's (1975) scale for scoring degeneration of the proximal tibia.

Location	Score	Morphology
Lateral condylar tubercle	0	Rounded
	1	Pointed (definite build-up)
	2	Obliterated by eburnation
Medial condylar tubercle	0	Rounded
	1	Pointed (definite build-up)
	2	Obliterated by eburnation
Insertion of posterior cruciate ligament	0	Smooth contour
	1	Some excavation with lipping; spicules (<50% intercondylar space)
	2	Deep excavation with significant pointed spicules (>50% of intercondylar space)
Lateral marginal lipping	0	None
	1	Moderate (>50% of circumference)
	2	Pronounced (vertical build-up)
Medial marginal lipping	0	None
	1	Moderated (>50% of circumference)
	2	Pronounced (extends horizontally)
Lateral articular surface	0	Smooth
	1	Small bony accretion(s)
	2	Pitted and/or eburnated
	3	Pitted and/or eburnated >25% of surface area
Medial articular surface	0	Smooth
	1	Small bony accretion(s)
	2	Pitted and/or eburnated
	3	Pitted and/or eburnated >25% of surface area
Facet for head of fibula	0	Smooth and flat
	1	Marginal lipping present >50% of circumference (or sharp anywhere)
	2	Projected (sharp); lipping >25% of circumference
	3	Fibula fused to tibia

The sample was chosen based both on condition (White 1999) and the degree of observable joint degeneration as scored using Jurmain's (1975) method. Jurmain's (1975) method uses an ordinal scale, scoring the morphology of eight locations on the proximal tibia (Table 1). The scores from all locations are added together to arrive at a final "degeneration score." A tibia with no external signs of joint degeneration would have a score of 0. The most severely affected tibia would have a score of 19. Tibiae chosen for this study have scores ranging from 0–13. It should be noted that some components of Jurmain's (1975) scale are not diagnostic of osteoarthrosis in a clinical or medical sense. In its use here, Jurmain's (1975) scale should be considered a general measure of the condition of the proximal tibia, reflecting a broad amalgam of gross bony degenerative changes rather than accurately characterizing the severity of a disease condition that can be effectively measured only when soft tissue is present.

To simply characterize the size of the metaphyseal cortical shell at equivalent points, a proportional scale was established on each specimen. The condyle-malleolus length (CML) of the tibia (the distance from the most distal point of the medial malleolus to the superior surface of the lateral plateau) was measured using an osteometric board (as in Bass 1987). Points were then established on the tibia by dividing the condyle-malleolus length by 20 and measuring the resulting distance down the shaft with an osteometric board, proceeding distally from the plateau (Fig. 1). Point A, for example, was located inferior to the lateral plateau at a distance of $\frac{1}{20}$ of the condyle-malleolus length. Subsequent points were likewise located, each point $\frac{1}{20}$ of the condyle-malleolus length from the previous proximal point. Circumference was determined at each

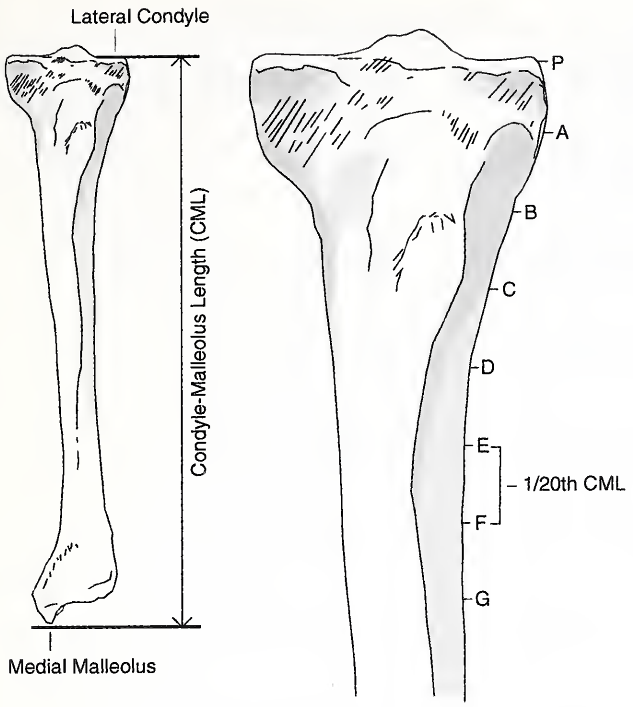

Figure 1.—Measurement of condyle-malleolus length of tibia (left) and establishment of points for measuring metaphyseal circumference (right).

of these points using a cloth tape. Measurements were taken from the plateau to point G. Point G was located distal to the portion of the metaphysis that contained significant amounts of trabecular bone, and was considered suitably distal to the plateau.

Among tibiae that exhibit no gross signs of joint degeneration (or where such signs are mild), a stronger relationship between bone length and circumferences is expected. Among tibiae that exhibit more pronounced gross signs of joint degeneration, a weaker relationship between bone length and circumference would be expected if the metaphysis has experienced disproportionate compression. Such expectations can be tested by calculating correlation coefficients between condyle-malleolus length and circumference measurements, examining differences in the ratio of circumference to condyle-malleolus length, and examining correlation between the degeneration score and the amount of metaphyseal compression proportionate to condyle-malleolus length.

RESULTS

In tibiae with a degeneration score of 0, 1, or 2 (n = 29), correlation between circumference and condyle-malleolus length is high at all measured points, with r_s ranging from 0.59 at A to 0.82 at F (Fig. 2). All of these correlations are statistically significant at the P = 0.05 level ($r_{s\,crit}$ = 0.37, t_{crit} = 2.052, df = 27). In tibiae with a degeneration score greater than 2 (n = 15), correlation between condyle-malleolus length and circumference is lower, ranging from 0.08–0.51 (Fig. 2). Correlations at P through G are not significant at the P = 0.05 level ($r_{s\,crit}$ = 0.52, t_{crit} = 2.160, df = 13). Spearman's rank-order statistic (r_s) was used rather than parametric correlation because the condyle-malleolus length measurements exhibit a non-normal distribution.

The relationship between circumference and condyle-malleolus length in the proximal fifth of the tibia is weaker in tibiae with a higher degeneration score. By dividing each of the circumference measurements by the condyle-malleolus length, it is possible to characterize the circumference of the proximal tibia in relation to bone length. Mean ratios of circumference to condyle-malleolus length at P through G are shown in Fig. 3. The mean ratio of circumference to condyle-malleolus length is consistently greater in tibiae with a degeneration score greater than 2, indicating that the proximal portions of tibiae in this group are, on average, broader in proportion to their total length. This difference is greatest at P through D. The t-test and Wilcoxon statistics return similar results about the statistical significance of these differences. Both agree that the ratio of circumference to condyle-malleolus length is significantly higher at the P = 0.05 level (t_{crit} = 2.018; z_{crit} = 1.96) at B, C, D, and E. The t-test also returns a significant result at P and A. The Wilcoxon statistic returns an additional significant result at F.

These probabilities are two-tailed. If the statistical results are corrected for the Bonferroni effect by dividing the critical alpha (0.05) by the number of tests (8), a probability of 0.006 would be required for statistical significance (t_{crit} = 2.895; z_{crit} = 2.748). At this level, statistical significance is limited to B, C, D, and E. There is justification for phrasing the statistical hypothesis directionally, as it is theoretically expected that "affected" specimens would exhibit greater circumference in proportion to length. If the hypothesis is phrased directionally, several more results are significant at the P = 0.006 level (t_{crit} = 2.626; z_{crit} = 2.512).

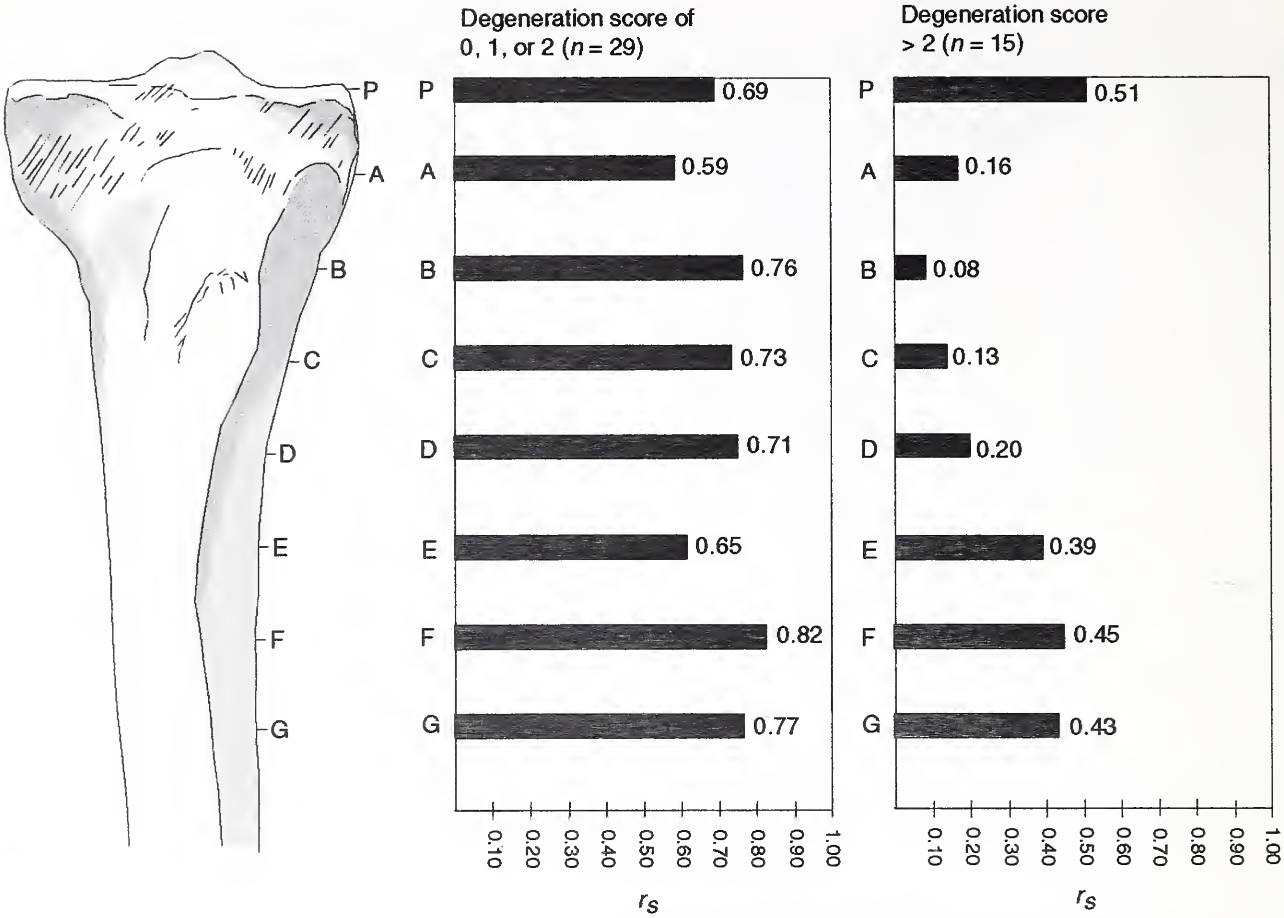

Figure 2.—Rank-order correlation (r_s) between condyle-malleolus length and circumference at points P through G in "unaffected" (degeneration score of 0, 1, or 2) and "affected" (degeneration score > 2) specimens. Degeneration score is calculated by combining the ordinal scores of eight locations on the proximal tibia using Jurmain's (1975) method (see Table 1).

Circumference data from each specimen can be combined into a single, size-adjusted measurement of metaphyseal circumference. This can be done by using the circumference measurement at G as a "standard" for each specimen. The circumference at G was chosen as a "standard" because is situated well into the diaphysis and shows little indication of involvement in metaphyseal broadening (i.e., circumference at G is relatively highly correlated with condyle-malleolus length in both "affected" and "unaffected" groups, and the ratio of circumference at G to condyle-malleolus length is not significantly different between these groups). By subtracting the circumference at G from the circumference at each of the other locations on the metaphysis superior to G (with the exception of the plateau), a relative measure of the broadness of the metaphysis (MB) is derived:

$$MB = (CA\text{-}CG) + (CB\text{-}CG) + (CC\text{-}CG) + (CD\text{-}CG) + (CE\text{-}CG) + (CF\text{-}CG)$$

where CA is the circumference at A, CB is the circumference at B, etc.

A plot of this measurement against degeneration score is presented in Fig. 4. There is a positive correlation between the two variables. This correlation is significant at the $P = 0.001$ level using Spearman's rank-order statistic ($r_s = 0.57$, $t = 4.461$, df = 42), indicating that tibiae with higher degeneration scores tend to be broader in the proximal portions of the bone relative to bone size. Metaphyseal broadness is positively correlated with condyle-malleolus length to some degree ($r_s = 0.21$, $P = 0.176$, $t = 1.378$, df = 42) in the combined sample ($n = 44$). Degeneration score is also positively correlated with condyle-malleolus length ($r_s = 0.11$, $P = 0.474$, $t = 0.723$, df = 42). Neither of these correlations is statistically significant.

DISCUSSION AND CONCLUSIONS

The data presented here suggest that increases in the circumference of the metaphy-

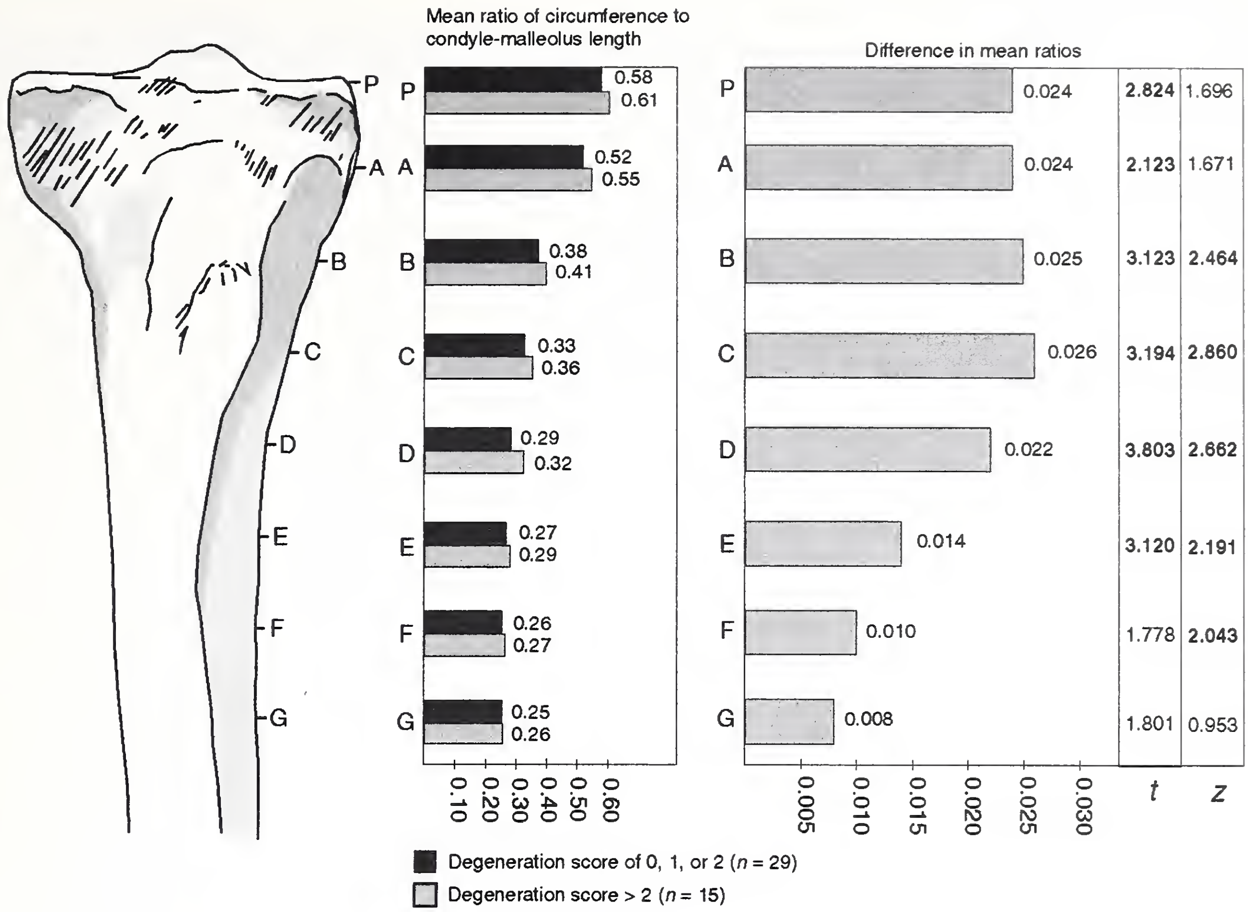

Figure 3.—Ratio of circumference to condyle-malleolus length at points P through G in "unaffected" (degeneration score of 0, 1, or 2) and "affected" (degeneration score > 2) specimens. The difference in mean ratios was evaluated using the Wilcoxon statistic (z) and the t-test (t). Results significant at the $P < 0.05$ level are in bold. Degeneration score is calculated by combining the ordinal scores of eight locations on the proximal tibia using Jurmain's (1975) method (see Table 1).

seal cortical shell of the proximal tibia are correlated with the grossly observable external indicators of joint degeneration commonly used by physical anthropologists. Difference in the mean ratio of circumference to condyle-malleolus length in "unaffected" (degeneration score of 0, 1, or 2) and "affected" (degeneration score > 2) specimens is greatest at points P through D. Correlation between condyle-malleolus length and circumference is at its lowest in "affected" specimens at A through D. The increase in the circumference at point P is accompanied by an antero-posterior broadening of the lateral plateau, a flattening of the medial plateau, and a decrease in the angle between the plateaus (White 1999). These findings are consistent with research that suggests that the trabeculae-filled metaphysis of the proximal tibia functions to absorb the forces transmitted across the knee joint, and that such forces may cause a compression of the metaphysis in the axial plane.

The mechanisms responsible for these changes in the circumference are undetermined. Looking only at the proximal portion of the tibia, the patterning of correlations suggests that the greatest changes in circumference occur within the proximal fifth of the shaft. In the present sample, this corresponds to a depth of approximately 61–87 mm below the plateaus. Patterned differences in the properties of trabecular bone (presumably associated with forces transmitted across the knee joint) have been recognized through the upper portions of this depth range. Goldstein et al. (1983) documented patterns of increased trabecular stiffness at a depth of 40–50 mm below the plateaus, and suggested that these patterns become more peripheral (i.e., oriented towards the outside of the shaft) as they progress distally, perhaps transmitting loads to the cortex. It is possible that trabecular fracturing and/or some other mechanism of restructuring are operating inferior to the sub-

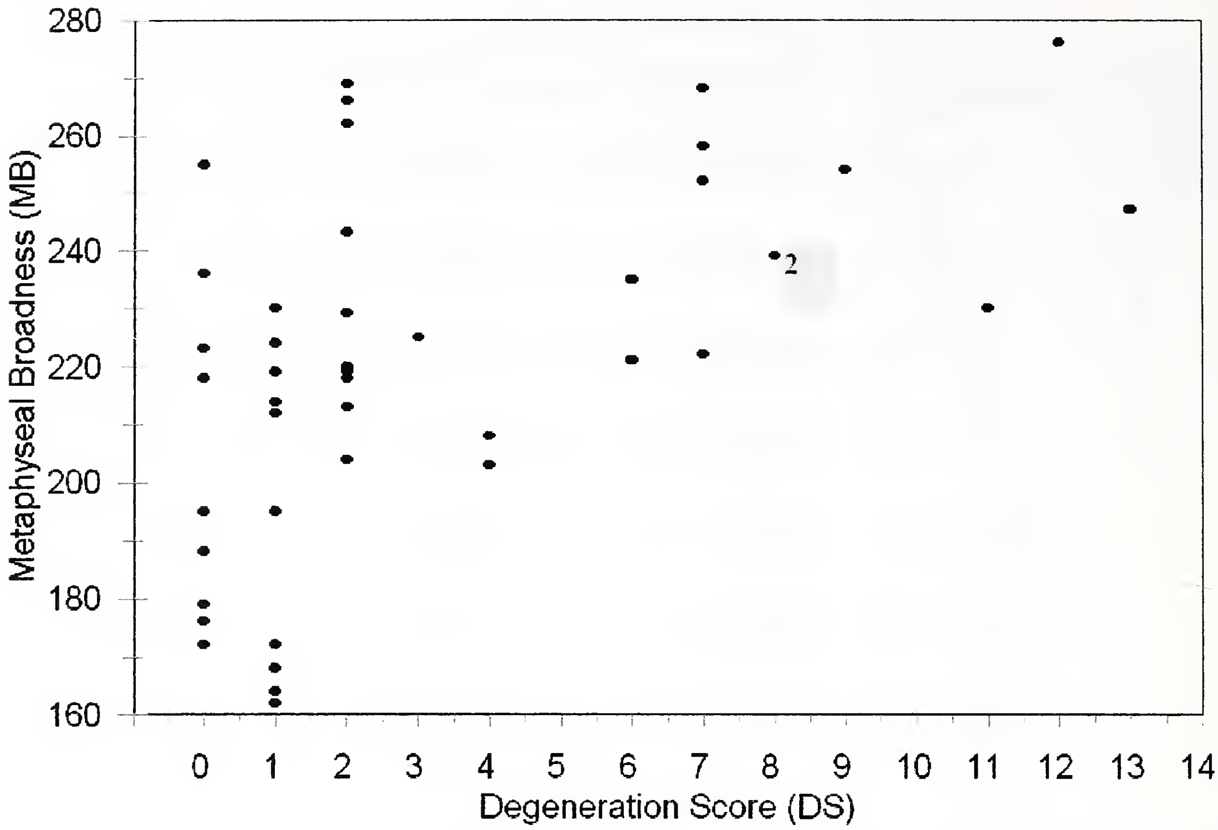

Figure 4.—Metaphyseal broadness (MB) plotted against degeneration score. Metaphyseal broadness is calculated using the formula MB = (CA-CG) + (CB-CG) + (CC-CG) + (CD-CG) + (CE-CG) + (CF-CG), where CA is the circumference at point A ($\frac{1}{20}$ of condyle-malleolus length distal to the plateaus), CB is the circumference at point B ($\frac{2}{20}$ of condyle-malleolus length distal to the plateaus), etc. Degeneration score is calculated by combining the ordinal scores of eight locations on the proximal tibia using Jurmain's (1975) method (see Table 1).

chondral bone in reaction to mechanical forces. It remains to be demonstrated that the increases in circumference described here are directly related to the mechanisms of joint degeneration and/or the history of mechanical loading. Given the nature of the sample used in this study, it was not possible to control for the age-at-death of the individuals examined. It is possible that the observed changes in the ratios of proximal tibial circumference to metaphysis length are related to a variety of factors, including cumulative mechanical loading over the life of the individual.

Internal and external pre-pathological changes of the proximal tibia are complex (White 1999). Much further research will be needed to elaborate, refine, and integrate their study. Relationships between the architecture of the trabecular bone underlying the subchondral bone of the proximal tibia and metaphyseal shape changes as measured here are unknown. There is a wider range of variation in the metaphyseal broadness measurements of "unaffected" specimens than "affected" specimens (Fig. 4). It seems plausible that the metaphyseal cortical shell of the proximal tibia may undergo stress-related changes in shape and/or size prior to the appearance of any of Jurmain's (1975) indicators. Such changes may be more apparent when finer resolution data are collected (i.e., circumference measured at a closer interval), a larger sample (controlled for age and sex) is used, more sophisticated methods of characterizing size and shape are employed, and data on internal structure and bone cross-section are incorporated. Study of the entire tibia rather than just the proximal metaphysis, as well as study of the other bones involved in the knee joint, may yield additional information.

LITERATURE CITED

Angel, J.L. 1966. Early skeletons from Tranquility, California. Smithsonian Contributions to Anthropology 2:1–19.

Bartley, M.H., Jr., J.S. Arnold, R.K. Haslam & W.S.S. Jee. 1966. The relationship of bone strength and bone quantity in health, disease, and aging. Journal of Gerontology 21:517–521.

Bass, W.R. 1987. Human Osteology. 3rd ed. Special Publication No. 2 of the Missouri Archaeological Society, Columbia, Missouri.

Bassett, E.J. 1982. Osteological analysis of Carrier Mills burials. Pp. 1027–1085, *In* The Carrier Mills Archaeological Project (R.W. Jefferies & B.M. Butler, eds.). Research Paper No. 33. Center for Archaeological Investigations, Southern Illinois University, Carbondale.

Bell, G.H., O. Dunbar, J.S. Beck & A. Gibb. 1967. Variations in strength of vertebrae with age and their relation to osteoporosis. Calcified Tissue Research 1:75–86.

Bowman, S.M., T.M. Keaveny, L.J. Gibson, W.C. Hayes & T.A. McMahon. 1994. Compressive creep behavior of bovine trabecular bone. Journal of Biomechanics 21:301–310.

Bridges, P.S. 1989. Changes in activities with the shift to agriculture in the southeastern United States. Current Anthropology 30:385–394.

Bridges, P.S. 1991. Degenerative joint disease in hunter-gatherers and agriculturalists from the southeastern United States. American Journal of Physical Anthropology 85:379–391.

Bridges, P.S. 1994. Vertebral arthritis and physical activities in the prehistoric southeastern United States. American Journal of Physical Anthropology 93:83–93.

Burr, D.B., R.B. Martin, M.B. Schaffler, R.D. Jurmain, E.J. Harner & E.L. Radin. 1983. Osteoarthrosis: Sex-specific relationship to osteoporosis. American Journal of Physical Anthropology 61:299–303.

Carter, D.R. & W.C. Hayes. 1977. The compressive behavior of bone as a two-phase porous structure. Journal of Bone and Joint Surgery 59A:954–962.

Carter, D.R., T.E. Orr & D.P. Fyhrie. 1989. Relationships between loading history and femoral cancellous bone architecture. Journal of Biomechanics 22:231–244.

Cowin, S.C. 1995. On the minimization and maximization of the strain energy density in cortical bone tissue. Journal of Biomechanics 28:445–447.

Finlay, J.B., R.B. Bourne, W.J. Kraemer, T.K. Moroz & C.H. Rorabeck. 1989. Stiffness of bone underlying the tibial plateau of osteoarthritic and normal knees. Clinical Orthopaedics and Related Research 247:193–201.

Fyhrie, D.P. & D.R. Carter. 1986. A unifying principle relating stress to trabecular bone morphology. Journal of Orthopaedic Research 4:304–317.

Goldstein, S.A., D.L. Wilson, D.A. Sonstegard & L.S. Matthews. 1983. The mechanical properties of human tibial trabecular bone as a function of metaphyseal location. Journal of Biomechanics 16:965–969.

Goulet, R.W., S.A. Goldstein, M.J. Ciarelli, J.L. Kuhn, M.B. Brown & L.A. Feldkamp. 1994. The relationship between the structural and orthogonal compressive properties of trabecular bone. Journal of Biomechanics 27:375–389.

Guo, X.E., T.A. McMahon, T.M. Keaveny, W.C. Hayes & L.J. Gibson. 1994. Finite element modeling of damage accumulation in trabecular bone under cyclic loading. Journal of Biomechanics 27:145–155.

Heřt, J. 1994. A new attempt at the interpretation of the functional architecture of the cancellous bone. Journal of Biomechanics 27:239–242.

Hirsch, C. & V.H. Frankel. 1961. The reaction of the proximal end of the femur to mechanical forces. Pp. 68–80, *In* Biomechanical Studies of the Musculo-skeletal System (G.F. Evans, ed.). Charles C. Thomas, Springfield, Illinois.

Jurmain, R.D. 1975. Distribution of Degenerative Joint Disease in Skeletal Populations. Unpublished Ph.D. Thesis, Harvard University.

Jurmain, R.D. 1977. Stress and the etiology of osteoarthritis. American Journal of Physical Anthropology 46:353–366.

Jurmain, R.D. 1980. The pattern of involvement of appendicular degenerative joint disease. American Journal of Physical Anthropology 53:143–150.

Jurmain, R.D. 1990. Paleoepidemiology of a central California prehistoric population from CA-ALA-329: II. Degenerative disease. American Journal of Physical Anthropology 83:83–94.

Maquet, P.G.J. 1976. Biomechanics of the Knee. Springer-Verlag, Heidelberg.

Maquet, P.G.J. 1985. The treatment of choice in osteoarthritis of the knee. Clinical Orthopaedics 192:108–112.

Miller, R.J. 1985. Lateral epicondylitis in a prehistoric central Arizona Indian population from Nuvakwewtaqa (Chavez Pass). Pp. 391–400, *In* Health and Disease in the Prehistoric Southwest (C.F. Merbs & R.J. Miller, eds.). Arizona State University Anthropological Research Papers No. 34.

Ortner, D.J. 1968. Description and classification of degenerative bone changes in the distal joint surfaces of the humerus. American Journal of Physical Anthropology 28:139–156.

Ortner, D.J & W.G.J. Putschar. 1985. Identification Of Pathological Conditions In Human Skeletal Remains. Smithsonian Contributions to Anthropology, No. 26. Smithsonian Institution Press, Washington, D.C.

Parfitt, A.M., C.H.E. Mathews, A.R. Villanueva, M. Kleerekoper, B. Frame & D.S. Rao. 1983. Relationships between surface, volume, and thickness of iliac trabecular bone in aging and osteoporosis. Journal of Clinical Investigation 72: 1396–1409.

Pugh, J.W., E.L. Radin & R.M. Rose. 1974. Quantitative studies of human subchondral cancellous bone. Journal of Bone and Joint Surgery 56A: 313–321.

Pugh, J.W., R.M. Rose & E.L. Radin. 1973a. A structural model for the mechanical behavior of trabecular bone. Journal of Biomechanics 6:657–670.

Pugh, J.W., R.M. Rose & E.L. Radin. 1973b. Elastic and viscoelastic properties of trabecular bone: Dependence on structure. Journal of Biomechanics 6:475–485.

Radin, E.L., H.G. Parker, J.W. Pugh, R.S. Steinberg, I.L. Paul & R.M. Rose. 1973. Response of joints to impact loading-III: Relationship between trabecular microfractures and cartilage degeneration. Journal of Biomechanics 6:51–57.

Radin, E.L. & R.M. Rose. 1986. Role of subchondral bone in the initiation and progression of cartilage damage. Clinical Orthopaedics 213:34–40.

Ruff, C.B. 1987. Sexual dimorphism in human lower limb bone structure: Relationship to subsistence strategy and sexual division of labor. Journal of Human Evolution 16:391–416.

Ruff, C.B. & W.C. Hayes. 1983. Cross-sectional geometry of Pecos Peublo femora and tibiae—a biomechanical investigation: I. Method and general patterns of variation. American Journal of Physical Anthropology 60:359–381.

Weaver, J.K. & J. Chalmers. 1966. Cancellous bone: Its strength and changes with aging and an evaluation of some methods for measuring its mineral content. I. Age changes in cancellous bone. Journal of Bone and Joint Surgery 48A: 289–299.

White, A.A. 1999. Correspondence Between Internal and External Variables of the Proximal Tibia in Relation to Joint Degeneration. Unpublished M.A. Thesis, Southern Illinois University at Carbondale, Carbondale, Illinois.

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