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Structural Trends in the Aging Femoral Neck and Proximal Shaft: Analysis of the Third National Health and Nutrition Examination Survey Dual-Energy X-Ray Absorptiometry Data*

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ABSTRACT

Hip scans of U.S. adults aged 20–99 years acquired in the Third National Health and Nutrition Examination Survey (NHANES III) using dual-energy X-ray absorptiometry (DXA) were analyzed with a structural analysis program. The program analyzes narrow (3 mm wide) regions at specific locations across the proximal femur to measure bone mineral density (BMD) as well as cross-sectional areas (CSAs), cross-sectional moments of inertia (CSMI), section moduli, subperiosteal widths, and estimated mean cortical thickness. Measurements are reported here on a non-Hispanic white subgroup of 2719 men and 2904 women for a cortical region across the proximal shaft 2 cm distal to the lesser trochanter and a mixed cortical/trabecular region across the narrowest point of the femoral neck. Apparent age trends in BMD and section modulus were studied for both regions by sex after correction for body weight. The BMD decline with age in the narrow neck was similar to that seen in the Hologic neck region; BMD in the shaft also declined, although at a slower rate. A different pattern was seen for section modulus; furthermore, this pattern depended on sex. Specifically, the section modulus at both the narrow neck and the shaft regions remains nearly constant until the fifth decade in females and then declined at a slower rate than BMD. In males, the narrow neck section modulus declined modestly until the fifth decade and then remained nearly constant whereas the shaft section modulus was static until the fifth decade and then increased steadily. The apparent mechanism for the discord between BMD and section modulus is a linear expansion in subperiosteal diameter in both sexes and in both regions, which tends to mechanically offset net loss of medullary bone mass. These results suggest that aging loss of bone mass in the hip does not necessarily mean reduced mechanical strength. Femoral neck section moduli in the elderly are on the average within 14% of young values in females and within 6% in males. (J Bone Miner Res 2000;15:2297–2304)

Key words: hip structural geometry, age trends, subperiosteal expansion, section modulus, bone mass

INTRODUCTION

THE PATTERN of declining hip bone mineral density (BMD) with age is well recognized, as is the accompanying increase in hip fracture risk. As BMD declines, fracture becomes more likely, but the details of the progression toward that endpoint are not well understood. In particular, discrepancies have been observed between changes in dual-energy X-ray absorptiometry (DXA) derived BMD, and risk of fracture, both with age[1] and with antiresorptive treatment.[2,3] For example, Hui et al. found that the risk of fracture varied by a factor of 8–10 between ages <45 years and ≥ 80 years for the same BMD level.[1] The non-BMD factors that explain this discrepancy are unknown at present,

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but change in risk factors for falling down and alterations in bone remodeling have been proposed.[4–6] The changes underlying decline of BMD with aging include thinning cortices and reduced trabecular density. Conceptually, one should be able to model the mechanical effects of these changes using structural details and engineering principles. Such modeling is fairly straightforward in long bones such as the femur, where structural strength at a particular location is largely determined by the shape and dimensions of the cross-section. However, conventional BMD regions of interest (ROIs), that is, the femoral neck, trochanter, or Ward's triangle, enclose bone volumes that cannot be modeled easily as a cross-section.

The earliest bone mineral scanners based on single photon absorptiometry (SPA) measured bone mineral mass in narrow paths extending across the bone axis, effectively defining ROIs corresponding to thin cross-sectional slabs observed from the edge. Using SPA, Martin and Burr[7] showed that the distribution of the mass across the bone in such "cross-sectional" ROIs could yield not only the BMD but also mechanically interpretable structural parameters such as subperiosteal width, cross-sectional area (CSA), cross-sectional moment of inertia (CSMI), and the section modulus. Furthermore, using appropriate assumptions, one can estimate endocortical width and the cortical thickness.[8] Thus, using narrow cross-sectional analysis regions, changes in BMD can be complemented with simultaneous structural geometry measurements to provide insight into the apparent mechanical consequences of altered bone mass.

We have previously developed software to perform this type of structural analysis on hip bone mass images and have used earlier versions to investigate sex differences in femoral neck geometry in an aging population[9] and differences in pre- and postmenopausal hip geometry in females.[10] In the present study, we used a more refined software version that provides structural and BMD measurements for several femur regions. Here, we compare age trends measured at a purely cortical and uncommonly fractured site—the proximal shaft—with a common fracture site at the femoral neck that incorporates both trabecular and cortical bone. Addition of the shaft site permits comparison of age-related structural changes that are thought to differ between the neck and shaft, for example, subperiosteal expansion is known to accompany aging in the shafts of long bones,[11–14] but some believe that lack of conventional periosteum prevents the process from occurring in the femoral neck.[15] Data were taken from hip scans acquired in the Third National Health and Nutrition Examination Survey (NHANES III, 1988–1994). We sought to determine whether structural measurements at these sites can provide mechanically relevant insights into aging patterns of bone mass. Furthermore, we intended to investigate whether these insights offer alternative factors besides propensity to falls and altered bone turnover to explain the discrepancies between the observed changes in BMD and fracture risk with age.

MATERIALS AND METHODS

Data source

Bone mineral data were acquired in this study as a part of the NHANES III. The NHANES is conducted periodically by the National Center for Health Statistics, Centers for Disease Control and Prevention, to assess the health and nutritional status of the civilian noninstitutionalized population of the United States. The survey collected data via household interviews and by direct standardized physical examinations conducted in specially equipped mobile examination centers. NHANES III was conducted in 1988–1994. The survey used a stratified, multistage probability design to select the sample and has been described in detail elsewhere.[16]

All men and nonpregnant women aged 20 years and older who received the physical examination in the mobile centers were eligible for bone densitometry unless they had fractured both hips previously. Acceptable bone mineral measurements were obtained on 14,646 men and women aged 20 years and older. The left hip was scanned unless there was a history of previous fracture or surgery; only 1% received a scan of the right femur. Because their inclusion did not alter estimates, those who received a scan of the right femur were included in the analyses.

NHANES III was designed to provide estimates for three major race/ethnic groups in the United States: non-Hispanic whites, non-Hispanic blacks, and Mexican-Americans.[16] The present study was restricted to whites not of Hispanic origin, leaving ethnic comparisons for future study.

Bone densitometry

Measurements were obtained with three Hologic QDR 1000 DXA scanners (Hologic, Inc., Waltham, MA, U.S.A.), located in mobile examination centers. A rigorous quality control (QC) program, including use of anthropomorphic phantoms and review of each QC and respondent scan at a central site, was used throughout the study to ensure data quality. QC results for the first phase of NHANES III have been published elsewhere.[17] QC results from the second phase were similar to those for phase 1. All scans that were rejected for quality reasons during the conventional BMD processing ($n = 321$) also were excluded from structural analysis leaving a total of 14,646 scans. An additional 1031 scans (7% of remaining scans) were excluded in cases in which structural analysis was not possible. Reasons for exclusion from structural analysis were obscured femoral neck margins, incomplete (cut-off) scans, osteoarthritic growths, metal artifacts, prosthetics or calcifications, and excessive anteversion. The total number of scans providing structural measurements was 13,615, which represents 59% of the eligible selected sample, 72% of the eligible interviewed sample, and 82% of the eligible examined sample. In this article, we report the analysis of a subset of non-Hispanic white participants including 2719 men and 2904 women.

Extraction of bone mass and structural properties

Before analysis, DXA scan files were first converted into bone mass images in which pixel values represent bone

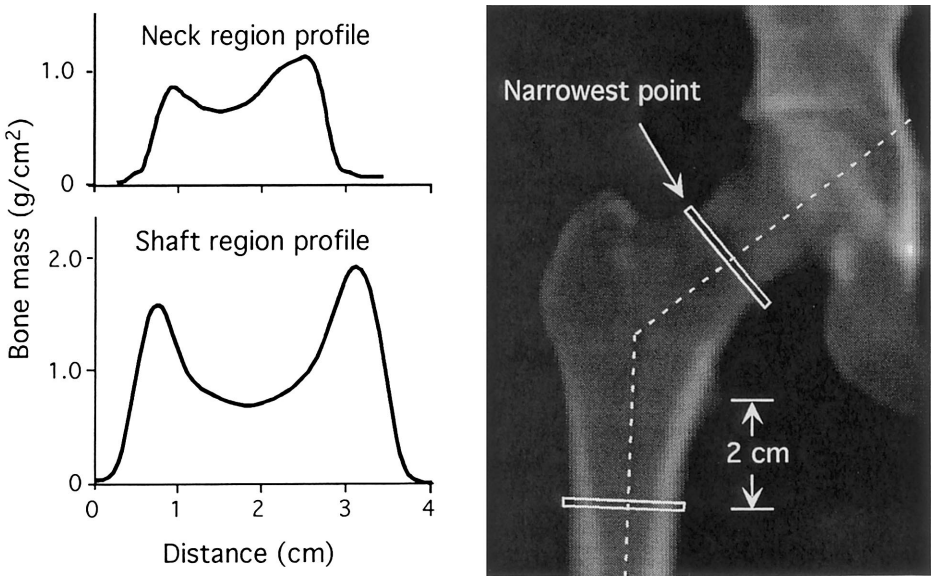

FIG. 1. Hip image from Hologic DXA scanner showing positions of narrow analysis regions across the narrowest region of the femoral neck and across the shaft at a point 2 cm distal to the lesser trochanter. Left side shows typical bone mass profiles corresponding to the two analysis regions. Mass profiles are used directly in measurements of geometric properties.

mass in grams per square centimeter; this was done with an automated program developed in our laboratory with assistance from Hologic, Inc. Structural analysis was then done in image files by two technicians at two workstations using a special interactive computer program. The analysis is based on a structural model of the hip described elsewhere.[18] Analysis begins with the user manually defining the limits of the femoral neck with cursors. The algorithm then automatically places the linear axes of the femoral neck and shaft, as well as the cross-sectional analysis regions. Three narrow, 3-mm-wide regions were analyzed in each scan; to avoid excessive complexity, only results from the two regions depicted in Fig. 1 are reported here. The region locations were defined as narrow neck, traversing the narrowest width of the femoral neck, and shaft, along a line 2 cm distal to the user located midpoint of the lesser trochanter, measured along the shaft axis. Results from a third intertrochanteric region (located along the bisector of the neck-shaft angle) will be reported in the future.

BMD is calculated in the conventional manner although the cross-sectional ROIs used here do not correspond to familiar BMD analysis locations. There are no conventional counterparts to the cross-sectional region in the shaft, but the narrow neck region either overlaps or is proximal to the conventional Hologic femoral neck region, depending on femoral neck length.

Using an algorithm described previously,[7,19] profiles of pixel bone mass values across each region (Fig. 1) are used to derive a large number of structural variables at analysis locations. Measurements include CSA, CSMI, inner and outer cortical diameters, cortical thicknesses, and section moduli as well as other variables not discussed here. To show the clearest picture of aging patterns in hip geometry, we have restricted the variables presented in this study to BMD, inner and outer cortical diameters, cortical thicknesses, and section moduli. The section modulus, computed as the ratio of CSMI to half of the subperiosteal width, is a measure of bending and torsional strength.[20] The other structural parameters are included to better characterize age-related patterns of modeling/remodeling.

Endocortical diameters and cortical thicknesses were estimated by combining the measured dimensions into a simple model of the cross-section. The model assumes that cortices are circular and symmetric with outer diameters equal to the measured subperiosteal width. To account for trabecular bone in the neck region, it is assumed that 60% of the measured mass is cortical. This approximation is based on values measured in vitro by Kuiper et al. and Bell et al.[21,22] Endocortical diameter (d_e) was computed for these sections as

$$d_e = 2 \times \sqrt{\left(\frac{d_p}{2}\right)^2 - f_c \frac{A}{\pi}}, \quad (1)$$

where d_p is the measured subperiosteal bone width, A is the measured cortical equivalent CSA, and f_c is the assumed cortical mass fraction (0.6 for the neck and 1 for the shaft). Mean cortical thicknesses were calculated as the difference between subperiosteal and endocortical radii.

Data analysis

Sampling weights were used to calculate means and to account for oversampling and nonresponse to the household interview and physical examination (see Discussion). All analyses were performed using SUDAAN (Research Triangle Institute, Research Triangle Park, NC, U.S.A.),[23] a family of statistical procedures for analysis of data from complex sample surveys.

RESULTS

For the purpose of interpretation, means by decade for each parameter were tabulated by sex beginning at the ages of 20–29 years for the youngest groups and with all subjects

TABLE 1. MEANS AND SDS OF BMD, CORTICAL DIMENSIONS, AND SECTION MODULI FOR NARROW NECK REGION IN NON-HISPANIC WHITE MALES

Age group (years)	*Narrow neck BMD (g/cm^2)*	*Hologic neck BMD (g/cm^2)*[a]	*Subperiosteal width (cm)*	*Endocortical width (cm)*	*Mean cortical thickness (cm)*	*Section modulus (cm^3)*
20–29	1.06 ± 0.16	0.934 ± 0.14	3.41 ± 0.26	3.00 ± 0.26	0.205 ± 0.034	1.97 ± 0.44
30–39	1.02 ± 0.16	0.886 ± 0.14	3.47 ± 0.25	3.08 ± 0.27	0.196 ± 0.033	1.97 ± 0.40
40–49	0.960 ± 0.15	0.836 ± 0.12	3.54 ± 0.26	3.17 ± 0.27	0.185 ± 0.031	1.95 ± 0.40
50–59	0.932 ± 0.15	0.812 ± 0.13	3.64 ± 0.26	3.29 ± 0.27	0.179 ± 0.031	1.99 ± 0.43
60–69	0.902 ± 0.16	0.793 ± 0.13	3.64 ± 0.27	3.29 ± 0.29	0.173 ± 0.033	1.92 ± 0.40
70–79	0.843 ± 0.15	0.751 ± 0.13	3.67 ± 0.27	3.35 ± 0.29	0.161 ± 0.030	1.88 ± 0.40
80+	0.789 ± 0.16	0.707 ± 0.14	3.71 ± 0.26	3.41 ± 0.28	0.150 ± 0.031	1.81 ± 0.43

[a] BMDs for the conventional Hologic region are shown for comparison with that from the narrow region.

TABLE 2. MEANS AND SDS OF BMD, CORTICAL DIMENSIONS, AND SECTION MODULI FOR NARROW NECK REGION IN NON-HISPANIC WHITE FEMALES

Age group (years)	*Narrow neck BMD (g/cm^2)*	*Hologic neck BMD (g/cm^2)*[a]	*Subperiosteal width (cm)*	*Endocortical width (cm)*	*Mean cortical thickness (cm)*	*Section modulus (cm^3)*
20–29	0.983 ± 0.15	0.860 ± 0.12	2.90 ± 0.24	2.51 ± 0.24	0.192 ± 0.031	1.35 ± 0.29
30–39	0.952 ± 0.15	0.826 ± 0.12	3.00 ± 0.25	2.63 ± 0.24	0.185 ± 0.031	1.41 ± 0.31
40–49	0.922 ± 0.15	0.796 ± 0.12	3.05 ± 0.25	2.68 ± 0.25	0.179 ± 0.032	1.39 ± 0.31
50–59	0.854 ± 0.15	0.736 ± 0.12	3.11 ± 0.26	2.77 ± 0.26	0.164 ± 0.031	1.35 ± 0.33
60–69	0.787 ± 0.14	0.688 ± 0.12	3.14 ± 0.26	2.84 ± 0.26	0.151 ± 0.029	1.29 ± 0.29
70–79	0.710 ± 0.12	0.629 ± 0.12	3.19 ± 0.26	2.91 ± 0.26	0.135 ± 0.024	1.19 ± 0.28
80+	0.662 ± 0.12	0.591 ± 0.12	3.26 ± 0.26	3.01 ± 0.26	0.125 ± 0.025	1.17 ± 0.24

[a] BMDs for the conventional Hologic region are shown for comparison with that from the narrow region.

TABLE 3. MEANS AND SDS OF BMD, CORTICAL DIMENSIONS, AND SECTION MODULI FOR SHAFT REGION IN NON-HISPANIC WHITE MALES

Age group (years)	*BMD (g/cm^2)*	*Subperiosteal width (cm)*	*Endocortical width (cm)*	*Mean cortical thickness (cm)*	*Section modulus (cm^3)*
20–29	1.54 ± 0.23	3.35 ± 0.28	2.22 ± 0.40	0.567 ± 0.114	3.15 ± 0.64
30–39	1.52 ± 0.23	3.44 ± 0.30	2.33 ± 0.42	0.556 ± 0.111	3.32 ± 0.68
40–49	1.49 ± 0.23	3.50 ± 0.28	2.42 ± 0.39	0.537 ± 0.107	3.40 ± 0.68
50–59	1.48 ± 0.25	3.57 ± 0.31	2.50 ± 0.43	0.533 ± 0.113	3.54 ± 0.73
60–69	1.44 ± 0.27	3.60 ± 0.31	2.56 ± 0.47	0.516 ± 0.121	3.53 ± 0.67
70–79	1.36 ± 0.24	3.62 ± 0.31	2.66 ± 0.42	0.480 ± 0.102	3.43 ± 0.67
80+	1.26 ± 0.25	3.65 ± 0.32	2.78 ± 0.43	0.438 ± 0.104	3.29 ± 0.65

over 80 years included in the oldest groups. Sample sizes in each age/sex category ranged from 319 to 487. Average values for BMD and geometric properties at the narrow neck and shaft regions are listed by decade in Tables 1 and 3 for males and 2 and 4 for females, respectively. Mean values of BMD from the narrow neck region are on the average about 14% higher in both sexes than the conventional Hologic neck ROI values (Tables 1 and 2) on the same subjects, although age trends are similar. Differences are likely to be caused by variation in shapes of enclosed bone volumes and to differences in the edge finding algorithms. Despite these differences, clear declines in BMD with age are evident in all regions and in both sexes (Tables 1–4). For clarity, hereafter, all references to neck BMD refer to the narrow neck ROI rather than the standard Hologic neck ROI.

To further examine apparent age trends, we corrected values of BMD and section modulus for body weight and then expressed means relative to those of the third decade (20–29 years). In the NHANES data, weight accounted for 11–13% of the variance (i.e., R^2) in BMD and 27–28% of the variance in section modulus at the narrow neck region for both sexes. In the shaft region weight accounted for a more substantial 20–22% of the variance in BMD and 45–47% of the variance in section modulus. Relative trends in BMD are compared with those of section moduli at both regions for males in Fig. 2 and for females in Fig. 3. As has been shown before,[24,25] rates of BMD loss are greater in cancellous-containing sites like the femoral neck than in the purely cortical shaft. BMD appears to decline more slowly before the age of 50 years at both regions in females and more linearly with age in males.

Measured on the same subjects, apparent trends in section moduli are quite discordant with those in BMD. Compared with young adult values, shaft section moduli in males appear to remain static until the fifth decade and then

TABLE 4. MEANS AND SDS OF BMD, CORTICAL DIMENSIONS, AND SECTION MODULI FOR SHAFT REGION IN NON-HISPANIC WHITE FEMALES

Age group (years)	*BMD (g/cm^2)*	*Subperiosteal width (cm)*	*Endocortical width (cm)*	*Mean cortical thickness (cm)*	*Section modulus (cm^3)*
20–29	1.36 ± 0.18	2.94 ± 0.24	1.94 ± 0.32	0.502 ± 0.086	2.17 ± 0.45
30–39	1.37 ± 0.20	3.02 ± 0.23	2.01 ± 0.33	0.501 ± 0.098	2.30 ± 0.47
40–49	1.36 ± 0.21	3.02 ± 0.25	2.02 ± 0.35	0.500 ± 0.102	2.30 ± 0.46
50–59	1.30 ± 0.22	3.12 ± 0.27	2.19 ± 0.38	0.470 ± 0.102	2.40 ± 0.51
60–69	1.20 ± 0.23	3.16 ± 0.26	2.31 ± 0.37	0.425 ± 0.100	2.30 ± 0.47
70–79	1.09 ± 0.21	3.20 ± 0.27	2.45 ± 0.37	0.377 ± 0.087	2.19 ± 0.45
80+	1.01 ± 0.22	3.24 ± 0.27	2.55 ± 0.38	0.345 ± 0.090	2.10 ± 0.41

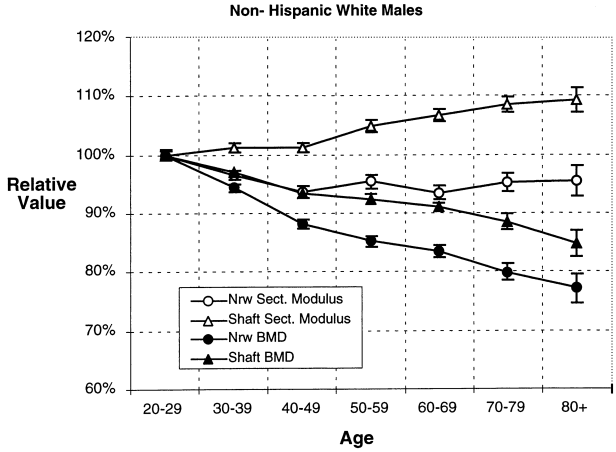

FIG. 2. Weight-corrected age trends in BMD and section moduli in non-Hispanic white males. Adjusted values were measured at the narrow neck and shaft regions and expressed relative to those of the young (20–29 years old) male cohort. Error bars represent the SEM.

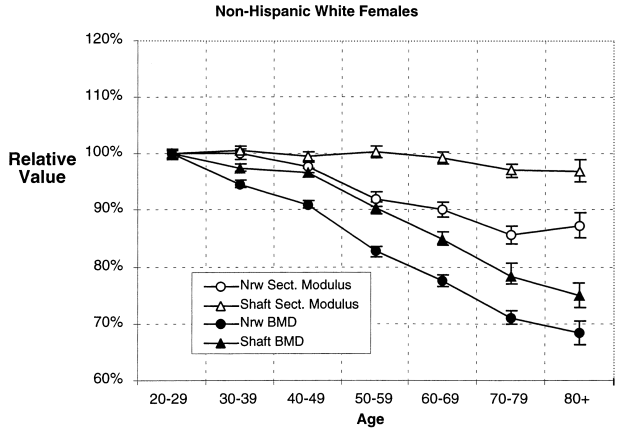

FIG. 3. Weight-corrected age trends in BMD and section moduli in non-Hispanic white females. Adjusted values were measured at the narrow neck and shaft regions and expressed relative to those of the young (20–29 years old) female cohort. Error bars represent the SEM.

increase linearly thereafter, whereas in females, shaft section moduli remain fairly static through life. In this uncommon fracture location, section moduli in those over 80 years old when compared with those at the age of 20–29 years are 9% higher in males and only 3% lower in females. In the more commonly fractured femoral neck, there are greater reductions in section moduli with age in both sexes, but the pattern differs; essentially, the entire decline in neck section modulus occurs after the age of 40–49 years in females and paradoxically before this age in males. Although neck BMD in the oldest female cohort averages 32% less than young females, the corresponding section moduli are only 13% less. In males, the neck BMD is 22% lower in the oldest group, whereas the average neck section modulus is only 4.5% below young values.

DISCUSSION

When weight-corrected age patterns in BMD and section moduli are compared (Figs. 2–3), our results suggest that although decline in bone mass is nearly universal, reduction in bone strength as reflected by the section modulus may not be so ubiquitous. The details of the process are evident in the cortical dimensions. Both subperiosteal and estimated endocortical diameters in the present sample are consistently larger in each successive decade in both sexes at both measurement locations. Mathematically, the section modulus is more strongly dependent on periosteal diameter than endocortical diameter, such that net loss of mass from the endosteal surface can be compensated by a small increase in periosteal diameter. Consider, for example, a simple 3-cm-diameter tubular bone with a 2-cm endocortical diameter. Expanding endocortical diameter by 10% (2 mm) would reduce BMD by about 16%. To maintain a constant section modulus, only a 0.83-mm increase in the subperiosteal diameter would be required. Because less material is added to the subperiosteal surface than removed from the endocortical surface, there remains a net loss of 9% in BMD but no real change in bending or torsional strength.

It is likely that the stimuli for observed changes in hip cortical dimensions are mechanically regulated by normal weight-bearing physical activities coupled with normal bone turnover and net loss from endocortical and trabecular surfaces.[26] In terms of magnitude, muscle forces produce greater loads on bones than do gravitational forces because of body weight[27] and in long bones the dominant bending

and torsional stresses are highest on the subperiosteal surface. Subperiosteal expansion with age is thought to be a direct response to increases in peak strains on that surface, combined with net loss of bone from the endocortical surface.[28] Our observations here are remarkably consistent with a semiempirical theoretical model of this process proposed by van der Meulen and colleagues.[29] The model assumed that throughout adulthood, the mechanical stimulus (torsional moment) and strain-modulated apposition rates on the endocortical and subperiosteal surfaces were constant, with no resorption permitted from the subperiosteal surface. This results in net loss of material from the endocortical surface and consistent increases in the subperiosteal diameter that leads to a relatively constant section modulus throughout adulthood. These authors also observed that section moduli in animals and humans were related more strongly to body weight than to age during development.[30,31] The patterns we observe in section modulus through adulthood appear to be related to body weight changes, because body weight in the NHANES III sample peaks in middle age.[32] Note, for example, that there is some corresponding peaking in uncorrected shaft section moduli in both sexes (Tables 2 and 4), which is removed by weight correction (Figs. 2–3).

The incidence of hip fracture in white men and women increases exponentially with age after the age of 50 years in both sexes, but it does so more rapidly in females.[33] These minimal trauma fractures are at least in part a consequence of diminished bone strength. Studies have established strong statistical links between low BMD and bone fragility in vitro[34,35] as well as fracture risk in vivo.[36] Our results in a cross-sectional sample of U.S. non-Hispanic whites show that although BMD declines with age in both sexes, the measured sites in the hip on average, do not appear to get much weaker with age based on the section modulus corrected for body weight.

Although loss of BMD is nearly universal with aging, most people will not suffer hip fractures; thus, the pattern in the section modulus may be entirely consistent with the epidemiological evidence. Depression of the average value of a strength-related measure should nevertheless reflect the proportion of a population with weaker bones; here we see a greater age decline in femoral neck section modulus in women than in men, consistent with the greater hip fracture rates among women. One might argue that those who do not fracture either do not fall or their BMD, although lower, is still sufficient to withstand any force it might receive, for example, mechanics of the fall or other extenuating circumstances such as musculature or fat padding, may dissipate enough force to prevent fracture. We would suggest an alternative position, that reduction of bone mass does not necessarily mean loss of bone strength. However, we cannot resolve this issue with the current NHANES III data set because it is a cross-sectional study and the individuals who will suffer hip fractures cannot be identified with certainty beforehand. The number of whites who reported a hip fracture caused by moderate or minimal trauma before their NHANES III examination and who also had valid structural data were too small to permit analysis ($n = 41$). In addition, analyses of prevalent cases must be interpreted cautiously because it is possible that physiological or lifestyle changes after hip fracture may influence structural properties. To address this issue adequately, it will be necessary to compare baseline hip structural geometries and bone densities between hip fracture cases and noncases using a prospective study design.

Here, we observe an age-related pattern of subtle subperiosteal expansion compensating for net bone loss from the endosteal surface apparently to maintain homeostasis with respect to the dominant bending and torsional forces on the hip. Note that although this process may maintain bone strength appropriate for the skeletal loading conditions through life, it does so with progressively thinner cortices. It may be that progression to fragility in the very old involves loss of a relatively small fraction of the available bone mass compared with that of younger individuals. Frost speculates that osteoporotic fragility is basically a disuse phenomenon in which bones adapt to reduced skeletal loads associated with physical wasting, weight loss, and diminished physical activity.[26] Under these conditions, the elderly femoral neck begins with an already large diameter and a relatively thin cortex. Adaptation to a diminished load would mean accelerated endocortical expansion. Note that the alternative adaptation, subperiosteal narrowing, is not known to occur. The resulting changes might cause the cortex to become critically thin. It is worth noting that Bell et al. observed that the main difference between femoral neck fracture biopsy specimens and elderly cadaveric controls was thinner cortices.[22] Resolving the precise details of progression toward femoral neck fragility will require theoretical modeling and analyses of longitudinal data including specific details of how femoral neck geometry is altered in the process.

Study limitations

DXA scanners were not designed to measure bone geometry; our ability to delineate subtle dimensional and geometric differences was clearly aided by the statistical power of the large NHANES sample. It is nevertheless reasonable to question whether the observations are in fact artifactual, in particular the apparent subperiosteal expansion with age, crucial to explaining the apparent trends in the section modulus. However, the apparent change in subperiosteal width is quite modest; shafts and femoral necks of the oldest cohorts are only 3 mm wider on average than those in the third decade (Tables 1–4). The trend in breadth, although linear with age ($R^2 \geq 0.93$ for linear regressions on age, represents an increase of only 0.5 mm per decade. Such small dimensional differences are easily buried by individual variability in most cross-sectional studies with less than a few hundred subjects. Although periosteal expansion with aging in adults has been less frequently reported in the femoral neck,[9,10,25] there is ample evidence to show that it occurs in the femoral shaft[12–14,25,37–39] and in other long bones.[11,25] We found no significant differences between slopes of regressions on age for subperiosteal widths of the femoral neck and shaft in either sex. It would not seem logical that the underlying mechanism would be absent in the neck and present in the shaft, particularly because both sites are subjected to bending and torsional stress stimuli in vivo.[40,41] Although the osteogenic potential of the subperiosteal surface of the femoral neck has been questioned,[42] others have shown that subperiosteal deposition of bone in

the femoral neck is possible in adults.[43,44] Finally, using the same scan data, the conventional Hologic femoral neck results are fully in line with the present analysis based on narrow ROIs. A crude estimate of mean neck width can be obtained by dividing the Hologic neck region area by its axial length (1.5 cm). Results (data not shown) indicate a significant ($p < 0.0001$, linear regression) increase with age in both sexes.

Other limitations of this work are the simple models of the femoral neck and shaft cross-sections used with measured dimensions to estimate endocortical widths and mean cortical thickness. Actual cross-sections of the femoral neck and shaft are not perfectly modeled by the assumed circular annuli. Also, we do not know whether the proportions of trabecular and cortical mass in the femoral neck change through life, though from the work of Bell et al. it does not appear that the proportion of cortical versus trabecular bone differs between fracture cases and elderly controls.[22] The purpose of these models was not to attempt accurate measures of real cortical dimensions but to provide reasonable estimates consistent with both the measured BMD data and the geometry measured from the mass distribution across the bone.

Our study sample is limited by the exclusion of institutionalized people from the NHANES III sample frame and by potential nonresponse bias in those with data suitable for structural analysis. Institutionalized persons are excluded from the NHANES III sample by design[16]; these individuals may have lower bone mass[47] and potentially different geometries because of the presence of other illnesses or prolonged bed rest. To examine nonresponse bias, we compared characteristics between examinees with and without structural analysis data and found differences for the same variables as found previously between examinees with and without BMD data.[48–51] Characteristics of respondents with structural data differed by 2% or less when compared with the examined sample for all variables, which suggest that there were no major biases because of nonresponse.

In this study we have looked at apparent age trends in bone mass from narrow cross-sectional regions traversing the narrowest part of the femoral neck and the proximal shaft in hip DXA scans from non-Hispanic white participants in the NHANES III. We also have used the distribution of that mass across the bone axis to compute the cross-sectional properties and have used simple models of the cross-sectional shapes at these locations to estimate endocortical dimensions and mean cortical thickness. These geometric measurements and modeled cortical dimensions were used to provide structural insights into patterns of loss in bone mass. We have observed the usual apparent decline in BMD with age, occurring at a faster rate in the cancellous neck compared with the purely cortical shaft. We also have noted that aging is accompanied by a small, but highly significant, linear increase in subperiosteal expansion at both regions in both sexes. It appears that this subtle increase largely compensates the net loss of mass with age by largely maintaining the section modulus, an index of bending or torsional strength. These results suggest that aging loss of bone mass in the hip does not necessarily mean reduced mechanical strength.

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