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ORIGINAL ARTICLE

Age-related changes in cortical bone thickness of ancient Egyptians

Moushira Erfan Zaki *, **Ayman A. Azab**, **Walaa Yousef**

Biological Anthropology Department, Medical Research Division, National Research Centre, Egypt

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KEYWORDS

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Abstract *Background:* Cross-sectional properties are affected by intrinsic factors such as age and levels of sex hormones. The aim of the present study was to assess age related changes in long bone cortical bone measurements in ancient Egyptian males and females.

Material and methods: The material of the present study consisted of 245 skeletons. Measurements of cross-sectional properties from CT images were taken from humerus, femur, and tibia. Cross-sectional images were obtained in the transverse plane of each bone, perpendicular to both coronal and sagittal planes.

Results: The results of the present study revealed that the cortical area showed a consistent decrease after age 50 years in all bones for both sexes; this reduction was significant in the tibia of males and in the humerus and femur of females. The present study demonstrated an increase in endosteal diameter of long bones, with an associated decrease in thickness of compact cortical bone which is more obvious in ancient Egyptian females than in males.

Conclusions: The present results highlight important sex-specific differences in patterns of age-related bone loss. These findings are comparable to those from other human populations and represent a valid resource for clinical application and for comparisons with contemporary subjects.

1. Introduction

In general, bone is deposited at the periosteal envelope prior to mid-adolescence and at the endosteal envelope after that (1–5). Other age-related changes include expanded medullary cavities, thinner cortices and the net loss of trabecular bone (6,2,7–9,5).

Ruff and Hayes (10) concluded that, age progress resulted in notable changes in bone properties, through increased bone resorption by increasing the age, especially in females after the menopause. In the human females, after menopause, bone resorption increases due to estrogen reduction. On the other hand, in males bone loss is about 30% less than in females. Once the reduction in bone amount and/or density has become clinically significant, the individual is diagnosed as an osteoporotic patient. Therefore, after menopause, the females become more susceptible to osteoporosis (11).

Bone density increases by age till getting the greatest bone density (peak bone amount) at about the age of 30 years in

* Corresponding author.

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the majority of people, and then after this age, the amount of bone resorption exceeds the amount of bone deposition. Thus, bone mass starts to decrease at a rate of 0.5–1.0% per year (12,13). Feik et al. (14) studied the effect of age on bone remodeling of the femoral midshaft and the related-difference between the two sexes. They found distinctive sex differences in cortical bone remodeling along the duration of adulthood. In adults, till the seventh decade, males showed a quite consistent increase in subperiosteal area (total cross-sectional area), polar moment of inertia, and medullary area. In old age, sex differences decreased and both sexes showed a decrease in periosteal apposition and an increase in endosteal resorption. The aim of the present study was to assess age related changes in long bone cortical bone measurements in ancient Egyptian males and females.

2. Materials and methods

The study skeletons were kept in a storeroom at Giza and belong to the Old Kingdom period (2700–2190 B.C.), which is known as the period of pyramid builders (15). They were excavated from the Giza necropolis. The materials of the present study consisted of 245 adult skeletons of ancient Egyptians, with no gross pathological changes or fractures that may affect the bone's biomechanical properties. They were classified according to sex: 128 males and 117 females.

Determination of the sex of the skeletons was done using the descriptive methods of both pelvises (16) and skull (17) when available.

When both pelvis and skull were absent, sexing depended on the long bones. The maximum length and head diameter of humerus and femur and bone length of tibia were measured according to the definitions, landmarks and the techniques described by Buikestra and Ubelaker (18).

Age at death was estimated using the metamorphosis of the auricular surface (19) depending on the chronological changes in the auricular surface of the ilium.

Biomechanical length of humerus, femur and tibia was obtained according to Ruff and Hayes (10). The biomechanical bone lengths, and the maximum bone lengths, were measured and the bone midpoint was obtained. The biomechanical bone lengths were used to mark the bone points at which the cross-sectional images were obtained in the transverse plane of each bone, i.e., perpendicular to both coronal and sagittal planes, at the mid-shaft point of femur and tibia, and at the 40% from the distal end of the humerus (to avoid the deltoid tuberosity), using a Toshiba CT somatom scanner. Bone lengths were measured parallel to the longitudinal axis of each bone, defined by the intersection of the coronal and sagittal planes. Antero-posterior and mid-lateral breadths of both subperiosteal and endosteal areas were measured at the two planes from M–L axis counterclockwise to major axis. In addition, cortical bone thickness at anterior, posterior, medial, and lateral parts of the bone section was measured.

Body size standardization is a very important process to avoid the effect of the difference between individuals or samples in their body size on bone geometric properties. Body size standardization was done, using the following equations: For cross-sectional areas: (area/long bone length^3) * 10^8. The geometrical properties generated from the CT image included the following: Total subperiosteal are (TA); Medullary area (MA); cortical area (CA). Percent cortical area (%CA) was calculated as (CA/TA) * 100 (18).

3. Results

Table 1 shows the frequency distribution of the age at death for males and females. The material was classified into four age groups: 20–30y, 30–40y, 40–50y, and above 50 years.

Table 2 shows means and standard deviations of the standardized cross-sectional areas "total sub periosteal area (TA); medullary area (MA); cortical area (CA); and percent cortical area (CA %)" of humerus, femur, and tibia for males and females of the four age groups. These data indicate that the alterations of the total cross-sectional area (TA) with age, either by the increase or by the decrease, in all bones for males and females, are non-significant except for the significant decrease after age 50 years of female humerus. The medullary area (MA) of the femur and tibia was significantly increased at the fourth age group of the females, while in males this increase was significant in the femur. The cortical area (CA) shows consistent decrease after the age 50 years in all bones for both sexes. This decrease is significant in the tibia of males and the humerus and femur of females. The highest values of cortical area (CA) were in the first and third age groups ((20–30) and (40–50) years) for all bones of males and for humerus and tibia of females, while the lowest was in the fourth age group (50 + years), in all bones of both sexes. The cortical area percent (CA%) showed a significant decrease at age 50 + in the femur and tibia of both males and in the humerus, femur and tibia of females. CA% of male humerus shows an increase by age till 50 years and then decreases, while male femur shows an increase till age 40 years followed by a significant decrease. The cortical area percent (CA%) of both the femur and tibia in females shows a consistent decrease by age. In males, the highest significant differences between age groups were noticed in the anterior cortical thickness of the femur, medial and lateral of the tibia followed by the posterior and lateral thicknesses of the femur and then by the anterior and posterior thicknesses of the tibia. In females the significant differences between age groups were noticed in the medial thickness of the humerus and the medial and lateral thicknesses of the tibia followed by the posterior and lateral thicknesses of the humerus. The significant decrease in the cortical thicknesses of the humerus of the females was at the third age group (40–50 years) for the anterior, posterior and lateral thicknesses, and this decrease was earlier at the second age group (30–40 years). The medial (M) and lateral (L) cortical thicknesses of the tibia were more affected by the age as they showed a significant decrease at the old age when compared with the anterior and posterior thicknesses, particularly in females. In males, the humeral (A & P), femoral (A, P & L)

Table 1 Age distribution of workers and high officials males and females.

Age/years	Males %	Females %
20–30	25.5	38.3
30–40	81.1	53.1
40–50	60.7	52.2
50 +	32.6	46.4
Mean age	39.35 years	40.24 years

Table 2 Standardized mean cross-sectional areas of humerus, femur, and tibia of males and females in different age groups.

	Bone		*N*	TA		MA		CA		CA%	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD
Males	Humerus	20–30	10	1033	157	270	163	763	93	75	12
		30–40	33	971	183	230	127	741	174	76	12
		40–50	29	993	159	222	95	771	133	78	8
		50+	14	980	113	267	89	713	101	73	8
	Femur	20–30	12	782	91	161^{c*}	41	620	107	79^{c*}	7
		30–40	30	777	116	161^{e*}	58	617	95	80^{e*}	6
		40–50	21	799	102	170^{f*}	36	629	105	78^{f*}	5
		50+	16	825	135	208	48	617	136	74	7
	Tibia	20–30	12	1097	172	195	71	903^{c*}	189	82^{c*}	7
		30–40	37	1074	146	213	81	861^{e*}	148	80^{e*}	8
		40–50	26	1066	155	202	61	865^{f*}	144	81^{f*}	5
		50+	15	1009	203	248	70	761	177	75	7
Females	Humerus	20–30	9	1035^{f*}	174	187^{b*}	60	849^{a*}	143	82^{b*}	4
		30–40	15	966	105	238	91	728^{c*}	100	76^{c*}	8
		40–50	20	1060	136	306	119	753	157	71	10
		50+	20	921	164	244	127	678	115	74	11
	Femur	20–30	17	749	74	165^{a*}	36	584^{e*}	78	78^{c*}	5
		30–40	21	800	135	202^{c*}	69	598^{f*}	120	75	7
		40–50	14	808	96	205	51	603	100	74	6
		50+	15	750	65	217	65	533	71	71	8
	Tibia	20–30	13	998	136	179^{b*}	50	819	99	82^{a*}	3
		30–40	17	1055	218	239^{c*}	81	816	205	77^{b*}	8
		40–50	16	1088	211	261^{e*}	82	827	201	76^{c*}	7
		50+	16	1107	244	307	111	800	189	73	8

(TA) total area; (MA) medullary area; (CA) cortical area; and (CA %) percent cortical area.
$^{d*}p < 0.05$ for age (30–40) vs (40–50).
^{a*} $p < 0.05$ for age (20–30) vs (30–40).
^{b*} $p < 0.05$ for age (20–30) vs (40–50).
^{c*} $p < 0.05$ for age (20–30) vs (50+).
^{e*} $p < 0.05$ for age (30–40) vs (50+).
^{f*} $p < 0.05$ for age (40–50) vs (50+).

and tibial (A, P, M & L) cortical thicknesses of the older males of age group (50+ years) showed significant decreases when compared to the younger groups. In female, the humeral (P, M & L) and tibial (M & L) cortical thicknesses of the older females of age group (50+ years) showed significant decreases when compared to the younger group, thus indicating the significant loss in bone cortical thickness by age.

The change in bone cortical bone thicknesses for the humerus, femur and tibia in males and females is represented. The cross-sectional thicknesses of the studied bones; the humerus, the femur and the tibia had different trends of change with respect to age till age 50 years. Above this age, most cross-sectional thicknesses of the three bones showed significant decreases in both males and females, except for the humerus of the females.

Figs. 1 and 2 show photographs of mid-shaft cross-sectional measurements of a femur and Figs. 3 and 4 show photographs of the mid-shaft cross-sectional measurements of a humerus taken by the CT-image tool.

4. Discussion

The present study shows the effect of age on long bone cross-sectional geometric properties. Individual's age is an important factor that can affect bone density and robusticity in both

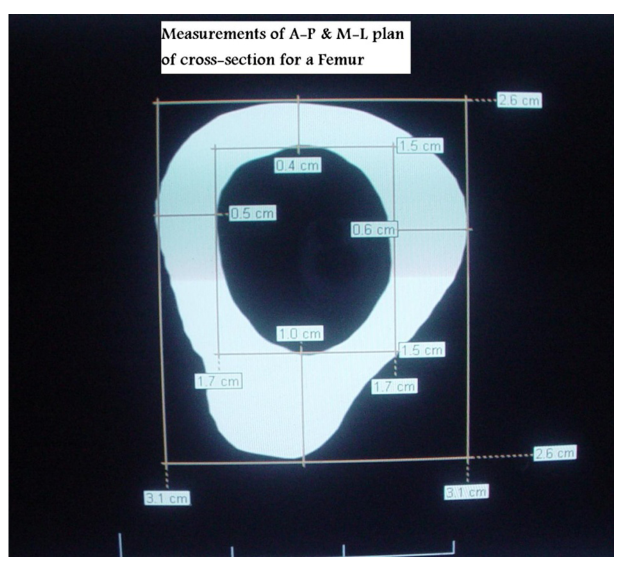

Fig. 1 Mid-shaft cross-sectional measurements of a femur taken by the CT-image tool. The dimensions of outer rectangle represent the antero-posterior and medio-lateral subperiosteal widths, and the dimensions of the inner rectangle represent the antero-posterior and medio-lateral medullary widths.

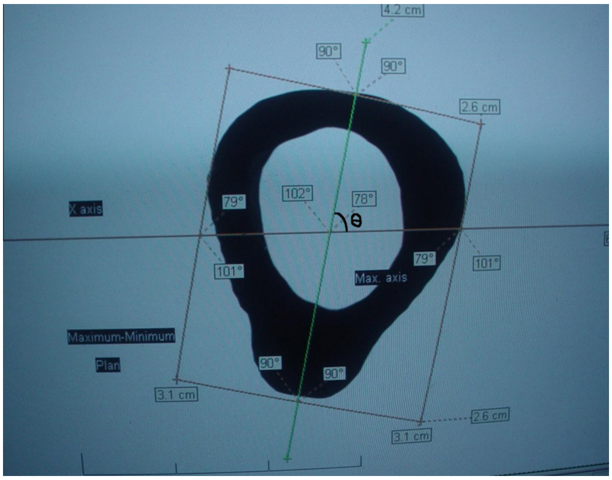

Fig. 2 Mid-shaft cross-sectional measurements of a femur taken by the CT-image tool. The maximal plan is determined by the angle (θ).

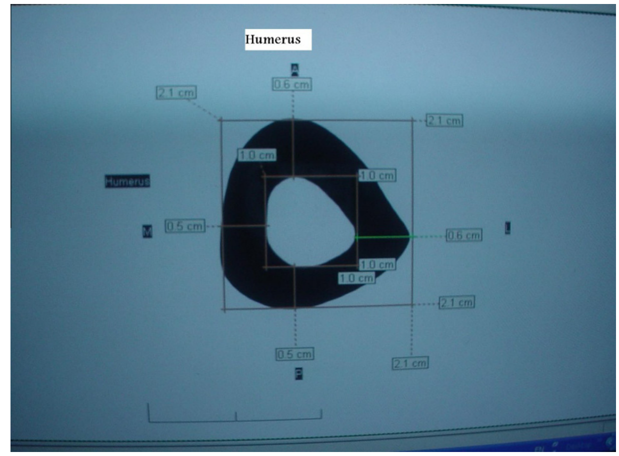

Fig. 4 A mid-shaft cross-sectional measurements of a humerus taken by the CT-image tool. The dimensions of outer rectangle represent the antero-posterior and medio-lateral subperiosteal widths, and the dimensions of the inner rectangle represent the antero-posterior and medio-lateral medullary widths.

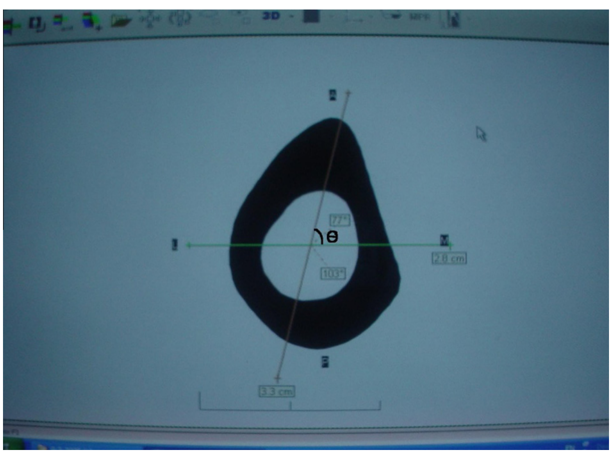

Fig. 3 Mid-shaft cross section of a tibia, the angle (θ) which determines the maximal plane.

males and females due to various factors such as hormonal changes and decreased body activities which accompany the progress of age (20,21). The changes in long bone anterior (A), posterior (P), medial (M) and posterior (P) cortical thicknesses by age are indicators of the change not only in the cortical bone amount, but also in its distribution throughout the bone cross section i.e. the cross-sectional shape. In males, the highest significant differences between age groups were noticed in the anterior cortical thickness of the femur, medial and lateral of the tibia followed by the posterior and lateral thicknesses of the femur and then by the anterior and posterior thicknesses of the tibia. In females the significant differences between age groups were noticed in the medial thickness of the humerus and the medial and lateral thicknesses of the tibia followed by the posterior and lateral thicknesses of the humerus. The cross-sectional thicknesses of the studied bones; the humerus, the femur and the tibia had different trends of change with respect to age till age 50 years. Above this age most cross-sectional thicknesses of the three bones showed significant decreases in both males and females, except for the humerus of the females. The significant decrease in the cortical thicknesses of the humerus of the females was at the third age group (40–50 years) for the anterior, posterior and lateral thicknesses, and this decrease was earlier at the second age group (30–40 years). The medial (M) and lateral (L) cortical thicknesses of the tibia were more affected by the age as they showed a significant decrease at the old age when compared with the anterior and posterior thicknesses, particularly in females. In males, the humeral (A & P), femoral (A, P & L) and tibial (A, P, M & L) cortical thicknesses of the older males of age group (50+ years) showed significant decreases when compared to the younger groups. In female, the humeral (P, M & L) and tibial (M & L) cortical thicknesses of the older females of age group (50+ years) showed significant decreases when compared to the younger group, thus indicating the significant loss in bone cortical thickness by age. This finding can be interpreted as a result of the increased bone resorption or decreased physical activities that accompany the older ages. Such increased bone loss in old ages was found in several modern and archaeological populations (22,23). Carlson et al. (23) interpreted the bone loss in old aged individuals as a result of bone turnover during the individual's life, as well as, the increased bone resorption in old age, which is higher in its intensity and speed in females than in males, particularly following the age of the menopause.

Our results revealed that, the medullary area (MA) increases by age in most bones of both sexes and this increase is significant in the femur of males and in the humerus, femur and tibia of females (Table 2). These findings agree with those of Ruff and Jones (24) and Ruff and Hayes (25). Feik et al. (26) studied femoral cross sections of modern Australian cadavers aged from 1 to 90 years old (n = 180) to assess the age-related changes in their cortical bone. They found an age-related cortical bone loss and an increased medullary area in both sexes, but they were greater in females than in males. It is worth mentioning that our findings agree with their findings. They also found an increase in the periosteal diameter till the age of seventy years old to compensate for the greater bone loss at the endosteum.

Many radiographic studies have been focused on the effect of age on the cortical bone geometry (27,28). In these studies, an increase in endosteal diameter and subsequently the medullary area of long bones were found to be associated with a decrease in their compact cortical thickness after the age of 40 years, and more marked in females than in males. On the other hand, other studies reported a consequent increase with age in subperiosteal dimensions (total cross-sectional area) in both sexes (24,25). This increase in the outer (subperiosteal) dimensions is due to the fact that, the outer (subperiosteal) surface of bone is exposed to the largest bending and torsional forces. In older females, the greater increase in bone the medullary area leads to a greater loss of compact cortical bone area.

Ruff and Hayes (25) and Stein et al. (29) reported the effect of age on bone size and bone biomechanics, as they found age-related thin cortices and wider diaphysis of the long bones. On the other hand, Martin and Atkinson (30) did not find such wider diaphyses in older individuals.

The results of the present study revealed that the cortical area (CA) showed a consistent decrease after age 50 years (the fourth age group) in all bones for both sexes; this reduction was significant in the tibia of males and in the humerus and femur of females. This result indicates that the individuals' long bones had resisting ability to axial tension or compression till the fifth decade of their life and this may be due to continuous activities which induce bone formation till that age; after which the reduced physical activity accompanying the old-aged individuals caused a decrease in the cortical area of long bones.

Age-related trends in our sample were similar to those age-related changes reported in other population studies (6,2,7,4).

In the females of Pecos population, Ruff and Hayes (31) found an increase in the cross-sectional cortical area (CA) through the fourth decade (40 years), followed by a decrease. They also found a slight decrease in MA in the third and fourth decades, followed by an increase after the age 35 or 40 years. There is a consistent increase in the total area (TA) throughout adulthood in both sexes. Endosteal resorption is greater than subperiosteal expansion after about 40 years of age. Ruff (32) reported that, the main reason for the increase in the total cross-sectional area (subperiosteal area) of active individuals by age is to increase bone strength which is an adapting process to compensate for bone loss due to the increased endosteal resorption and increased medullary area in old ages.

In our study, the cortical area percent (CA%) of male humerus showed an increase by age till 50 years and then decreased, while male femur showed an increase till age 40 years and then followed by a significant decrease. Male tibia showed some kind of stability till age of 50 years and then followed by a significant decrease. On the contrary, female humerus showed a significant decrease till age 50 years and then followed by an increase. The cortical area percent (CA %) of both the femur and tibia in females showed a consistent decrease with age, which may be due to bone turnover that is more in its intensity and rate in females than in males, especially after the age of the menopause. In ancient Egyptians, the delay in the bone loss till the age after 50 years may be due to their physical activity when compared with other populations that showed a marked bone loss after age 40 years (24,25,31).

Cortical bone changes with age, in its morphology (bone geometry) as well as in its density. The greater porosity in older bone and marked variation in porosity for any given age are interpreted by Stein et al. (33) as a result of greater pore size rather than a larger number of pores. However, Bertelsen et al. (34) attributed the greater porosity with age to the increase in both number and size of the pores in the cortical bone. Osteoporosis, which is characterized by marked bone loss and bone tissue micro-structural deterioration, consequently increases bone fragility and elevates the risk of bone fracture. Osteoporosis is affected by age and is more frequent in postmenopausal women. Sex hormones have great effect on both bone development (during puberty) and bone preservation (in older aged-individuals), which is more notable in females. Wang et al. (35) found positive correlations between female sex hormones and the bone geometric properties, as well as, bone mineral density in Finnish girls during early pubertal period ($N = 248$). Estrogen deficiency, in postmenopausal females, causes an increase in bone resorption on the endo-cortical surface due to the increase in bone turnover. The decrease in estrogen levels that accompany the postmenopausal age is assumed to cause a greater loss of muscle strength. Since muscle contractions exert the greatest forces to bones (resulting in an induced bone formation), the loss of muscle strength accelerates the loss in bone amount.

El-Banna (36) studied osteoporosis (on the same sample of "Giza- Old Kingdom") and reported that there was an age-related bone loss, indicating the primary type of osteoporosis (physiological). She concluded that females were more affected with osteoporosis than in males, also females had less bone mineral density than in males and this may be due to age-related hormonal changes in females. This can be attributed to the less physical activity of females, since osteoporosis is affected by the prolonged life style and body activity thus supporting the results of the present work.

Males of the present material showed a relative stability (i.e. no significant changes) with age, in antero-posterior, mid-lateral, and polar second moments (their bending and torsional rigidities) of the humerus, femur and tibia, while females showed a relative stability in the second moments in both femur and tibia. These findings suggest the continuous activities of the lower limbs in both sexes which may reflect their life style (continuous walking activity), their environmental conditions e.g. walking on sandy ground or sloping ways constructed for pyramid building. This finding is supported by the fact that males' sectional moduli (measures of bending and torsional strength of the bones) of both upper and lower limb bones are stable by age, while females' sectional moduli stability is confined to those of femora and tibiae.

In conclusion the present study demonstrated increase in endosteal diameter of long bones associated with a decrease in thickness of compact cortical bone beyond the age of 50 years that is much more marked in females than in males. Our findings are comparable to those from other human populations and represent a valid resource for clinical application and for comparisons with contemporary subjects.

Conflict of interest

The authors declared that there is no conflict of interest.

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