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Age at death estimation using bone densitometry: Testing the Fernández Castillo and López Ruiz method in two documented skeletal samples from Portugal

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ABSTRACT

This study aims to evaluate the accuracy, precision and bias of a method for age at death estimation based in bone mineral density values assessed by dual X-ray absorptiometry at Ward's area (proximal femur). Estimated age at death was contrasted with documented age at death in two Portuguese reference samples (Coimbra Identified Skeletal Collection – CISC, and Identified Skeletal Collection of the 21st Century – Santarém XXI). Mean absolute error (accuracy) varies between 10.5 years (females) and 11.6 years (males) in the CISC sample; and between 11.9 years (males) and 12.7 years (females) in the Santarém XXI study base. The precision of the method varies between 13.0 years (females) and 14.5 years (males), in the CISC sample, and between 8.4 years (females) and 9.5 years (males), in the Santarém XXI sample. Mean error values (bias) suggest that this method tends to overestimate age in younger individuals, and to underestimate it in older individuals, regardless of sex or sample. Nonetheless, the method seems to perform as well as, or better than, other widely tested age estimation techniques, making it a suitable option when more accurate tests are not feasible in any given situation.

1. Introduction

Establishing an accurate age at death on the basis of skeletal remains is a prerequisite to determine a comprehensive biological profile, and a pivotal step for the identification of individual skeletal remains [1,2]. Unfortunately, biological aging shows great variation, both within and between populations [3–5]; and the assessment of age at death in adult skeletal remains usually renders mediocre to poor estimates of both biological and chronological age [2,3,6]. Hence, it is appropriate to consider as many techniques as possible to assess age at death in adult skeletons, although recognizing that the available aging methodologies are not equivalent, with different accomplishments in the issues of reliability and validity [2,5,7].

Dual X-ray absorptiometry (DXA) has seldom been applied in the forensic sciences [e.g., 8–10] but it is widely acknowledged as the gold-standard methodology to assess bone mineral density (BMD) and to diagnose osteoporosis in clinical and epidemiological settings [11]. DXA calculates the quantity of hydroxyapatite in bone, conveying it in grams of mineral per unit of area. The technology uses radiation from two X-ray beams with different energy levels. The radioactive beams are collimated and directed into a radiation detector, located opposite to the mensuration area, where the X-ray attenuation by bones and soft tissues is used to define the bone mineral content (BMC). Bone mineral density is then computed as the ratio between BMC and the measured area. Fundamentally, DXA produces a linear measurement of BMC (in g) that is subsequently converted into an area of bone density (g/cm^2) [8,11,12].

BMD declines with age in all populations, especially in females [12,13]. Hence, theoretically BMD can be a useful indicator of biological age in skeletal remains. Following this assumption, Fernández Castillo and López Ruiz [14] developed an aging method based on BMD measurements at the Ward's triangle area. The authors found a very high correlation between BMD values measured at the Ward's area region of interest (ROI) of the proximal femur and documented age in a Spanish hospital population. As such, they proposed two regression formulae (for men and women) to infer chronological age based on BMD values at the ROI "Ward's area".

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In forensic anthropology, the continuous re-testing of existing age at death estimation methods in adult skeletons perseveres as the superlativetrial to ascertain their reliability [5]. Such validation trials are also intended to test the uniformity of biological aging patterns, clarifying which aging methods can be validated across populations [15]. In this study we aimed to test the accuracy, precision and bias of the Fernández Castillo and López Ruiz method [14] for age at death estimation, by applying it in two documented samples from Portugal. Our specific purposes were to determine if this new aging technique could be endorsed across populations, and applied to skeletonized bodies, both in forensic and archeological contexts.

2. Materials and methods

The "Coimbra Identified Skeletal Collection" (CISC) was assembled between 1915 and 1942 and comprises individuals born between 1822 and 1921, and dead between 1904 and 1936. The collection of 505 skeletons with known sex and age at death (among other biographical information) consists mainly of Portuguese nationals, mostly manual workers with low socioeconomic status. Individuals exhumed from shallow graves in the Municipal Cemetery of Conchada (Coimbra, Portugal) compose the bulk of the collection ($N = 198$). These individuals were buried for at least five years – after that it was common to perform the exhumation of the bodies [16].The "Identified Skeletal Collection of the 21st Century" (Santarém XXI) is the latest Portuguese osteological reference collection. It includes 77 identified individuals, of Portuguese nationality, born between 1905 and 1968, and dead between 1995 and 2001. All individuals from the Santarém XXI skeletal collection were recovered from the Municipal Cemetery of Capuchos (Santarém, Portugal), where they were interred from five to seven years.

The testing samples consist of 100 individuals (50♀; 50♂) from the CISC and 40 individuals (20♀; 20♂) from the Santarém XXI, randomly chosen from the two identified skeletal assemblages. The CISC sample included individuals born between 1831 and 1914; and dead between 1910 and 1936. Recorded ages at death varied between 20 and 95 years (mean = 54.6; SD = 18.2; 95%CI: 51.0–58.2). The sampled Santarém XXI individuals were born between 1906 and 1968 and died between 1995 and 2001. The youngest individual of this sample died at 33 years, the oldest at 96 years (mean = 75.2; SD = 14.8; 95%CI: 71.0–80.2).

BMD at ROI "Ward's area" was measured in the left femur of each individual with a Hologic QDR 4500C densitometer. Femurs were placed anteroposteriorly, with the diaphysis parallel to the central axis of the scanner, in a low-density paper box with dry rice (10 cm depth) standing for a soft-tissue proxy [17,18].

Age at death was estimated following the regression equations proposed by Fernández Castillo and López Ruiz [14]:

$$\text{Men}: \text{Age} = 100.558 - 79.124\ (\text{BMD Ward's area}) \pm 4.149$$
$$\text{Women}: \text{Age} = 94.488 - 66.391\ (\text{BMD Ward's area}) \pm 4.855$$

Linear Pearson correlation was used to associate documented age at death with estimated age at death. The mean difference between estimated ages at death and documented ages at death was evaluated with a paired sample *t*-test (the normal distribution of the variables was evaluated with a Kolmogorov–Smirnov test and the homogeneity of variances with a Levene test). Accuracy was expressed as the mean absolute error (MAE) [19], as follows:

$$\text{MAE} = \frac{\sum |\text{estimated age} - \text{documented age}|}{n}$$

The precision of the method was measured as the standard deviation (SD) of the mean difference between estimated age and documented age. Bias (i.e., systematic error) was computed using the mean error (ME) [19]:

$$\text{ME} = \frac{\sum \text{estimated age} - \text{documented age}}{n}$$

All statistical analyses were performed with IBM®SPSS® (version 19.0.0), and Microsoft®Excel® (version 14.2.1).

3. Results

There was a strong positive linear dependency between documented age at death and estimated age at death in both samples and sexes. In the CISC sample, females showed a higher Pearson product-moment correlation coefficient (Pearson's $r = 0.732$; $p \leq 0.001$) when compared to males (Pearson's $r = 0.574$; $p \leq 0.001$). On the contrary, in the Santarém XXI study base, the estimated correlation coefficient in men (Pearson's $r = 0.803$; $p \leq 0.001$) exceeded that of the women (Pearson's $r = 0.704$; $p \leq 0.001$).

The paired sample *t*-tests showed a significant difference between the means of documented versus estimated ages in the CISC women ($t = -2.860$, df = 49, $p = 0.006$), the Santarém XXI women ($t = 6{,}145$; df = 19; $p \leq 0.001$), and the Santarém XXI men ($t = 4.821$; df = 19; $p \leq 0.001$). There was no significant difference between estimated and documented values in the CISC male group ($t = -1{,}172$; df = 49; $p = 0.247$).

Mean absolute error (expressing the accuracy of the method) in the CISC sample varied between 11.1 years in the female group and 12.9 years in the male group. In both sexes there was a decrease of mean inaccuracy in older age categories. In the younger age category (20–39 years), MAE values ranged between 14.8 (males) and 17.1 (females). In the intermediate age group (40–59 years), MAE was 11.4 in men and 10.5 in women, whilst in the older age category (60+ years); the mean absolute error was 9.8 in men and 8.2 in women. In the males group, across all age categories, 28% of age estimates were within ±5 years of documented age; 52% within ±10 years of documented age; and 76% within ±15 years of documented age. In the female set, across all age groups, 30% of age estimates fell within ±5 years of documented age; 60% within ±10 years of documented age; and 78% within ±15 years of documented age (Table 1).

Accuracy in the Santarém XXI sample ranged from 11.9 years in men and 12.7 years in women. Overall, in women, 20% of age estimates were within ±5 years of known age; 35% within ±10 years of documented age; and 55% within ±15 years of documented age. In the men's group, across all age categories, 35% of age estimates fell within ±5 years of acknowledged age; 45% within ±10 years of documented age; and 65% within ±15 years of documented age (Table 1).

Table 1
Mean absolute error (accuracy) in the younger, middle, older age categories and all ages (CISC and Santarém XXI).

Accuracy	MAE (males/females)	
Age groups		
20–39	CISC	14.8/17.1
	Santarém XXI	–
40–59	CISC	11.4/10.5
	Santarém XXI	–
60+	CISC	9.8/8.2
	Santarém XXI	–
All ages	CISC	12.9/11.1
	Santarém XXI	11.9/12.7