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Forensic Anthropology Population Data

Body mass estimation from the skeleton: An evaluation of 11 methods

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A B S T R A C T

Estimating an individual body mass (BM) from the skeleton is a challenge for forensic anthropology. However, identifying someone's BMI (Body Mass Index) category, i.e. underweight, normal, overweight or obese, could contribute to identification. Individual BM is also known to influence the age-at-death estimation from the skeleton. Several methods are regularly used by both archaeologists and forensic practitioners to estimate individual BM. The most commonly used methods are based on femoral head breadth, or stature and bi-iliac breadth. However, those methods have been created from mean population BMs and are therefore meant to estimate the average BM of a population. Being that they are based on individual BM data and estimated femoral cortical areas, the newest published methods are supposed to be more accurate. We evaluated the accuracy and reliability of the most commonly used and most recent BM estimation methods (n = 11) on a sample of 64 individuals. Both sexes and all BMI categories are represented, as well as a wide range of BM. Ages in this sample range from 20 to 87 years of age. Absolute and real differences between actual BM and estimated BM were assessed; they determined the accuracy for individual BM estimation and for average BM estimation of a population, respectively. The proportion of the sample whose estimated BM falls within ±10% and ±20% of their actual BM determines the reliability of the methods in our sample for, respectively, individual BM estimation and average BM of a population. The tested methods result in an absolute difference of 11 kg–26 kg ± 10 kg with regards to prediction of individuals actual BM. The real differences are very variable from method to method, ranging from −14 kg to 25 kg. None of the tested methods is able to estimate BM of half of the sample within ±10% of their actual BM but most of them can estimate BM of more than half of the sample within ±20% of their actual BM. The errors increase with increasing BM, demonstrating a bias in all the methods. No bone variable tested correlated with BM. BMI categories were correctly predicted for less than 50% of the sample in most cases. In conclusion, our study demonstrates that the 11 methods tested are not suited for estimating individual BM or for predicting BMI categories. However, they are accurate and reliable enough for estimating the average BM of a population.

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1. Introduction

The individual body mass (BM) can be a feature of the biological profile that directly contributes to identification in forensic anthropology [1–5]. However, the prediction of BMI (Body Mass Index) categories from estimated BMs and statures (i.e. distinguishing underweight, normal, overweight, and obese individuals) from the skeleton, has proven difficult [3,6]. BM is also one of the most confounding factors in age estimation from the skeleton. Knowing one's BM would therefore help improving the reliability of identification procedures [7–9] and could directly participate to identification [1–5].

Three sets of methods exist to estimate BM from the skeleton; they are based on: (1) femoral head breadth (FHB) [10–13]; (2) stature (St) and maximum breadth of the body (measured from the living bi-iliac breadth, LBIB) [14,15]; and (3) estimated cortical area

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(CA) measured at different locations along the femoral diaphysis [16]. The former and the latter assume the existence of a "biomechanical" relationship between BM and the skeleton, i.e. the femoral head breadth and the cortical area would remodel according to the constrains imposed on the bone, including BM. Cortical area, particularly, is supposed to be more sensitive than articular breadths (especially more than the femoral head breadth that is constrained by the size of the acetabulum in adulthood) and to continuously remodel along the life course (e.g. Ref. [10]). In contrast, the equations based on a "cylindrical" model of the human body, where its length is the stature and its breadth is the living bi-iliac breadth, are often referred as the "morphometrical" approach because the body increases its volume and relative mass following the evolution in general size [14].

With the exception of the estimated CA-based formulae, all the other methods have been developed to avoid variation of BM linked to soft tissues apposition or deletion. In other words, they are not supposed to take into account soft tissue changes. Therefore, we hypothesized that they should only be applicable and reliable for the estimation of an inter-specific BM (population level) or average BM but not for the estimation of an intra-specific BM, namely the actual BM of an individual.

Nevertheless, the equations based on external dimensions (femoral head breadth, stature and bi-iliac breadth) are frequently applied or tested in bioarchaeology to estimate the body mass of a single individual (e.g. refs. [17–19]). Those formulae have recently been discussed as a way to estimate individual BM in forensic anthropology contexts [3,20,21]. Despite their wide use, their accuracy has mostly been tested on individuals of unknown BM through the evaluation of agreement between their results [3,18,22–24], which, in fact, only shows whether or not they produce similar results, not how accurate or reliable they are. More recently, a few research projects endeavored to test the actual reliability and accuracy of some of the equations in samples made of individuals of known body masses, representative of all age classes [17,25], and in one sample exclusively composed of elderly individuals [21]. As for the equations based on estimated CA, they have been developed recently and are supposed to be able to predict BM with more accuracy, but they have not been validated on an independent sample.

This paper aims to test the accuracy and reliability of the newest as well as the most used BM estimation methods on an independent sample of known and widely distributed age, stature and body mass. The evaluation is twofold: (1) testing the accuracy and reliability of the methods for the estimation of one individual's BM; and (2) assessing the accuracy and reliability of the methods for estimating average BM of a population.

2. Material and methods

We evaluated the accuracy and reliability of the six most used methods [10–15] along with the five newest published equations [16] for estimating body mass using CT scans of 64 Danish adults. The scans were performed on cadavers at the Department of Forensic Medicine, University of Copenhagen, Denmark [26]. Bodies were scanned within three days after death and exhibited very limited or no sign of decomposition. No formal ethical consent is needed from Danish ethical committees to work with CT images of deceased humans. Autopsies are mandated by the police and CT scans are part of the routine investigation at the Department of Forensic Medicine (University of Copenhagen). The Department of Forensic Medicine adheres to Danish accreditation standards regarding data security. All personal data are removed from the images; only age, sex, weight and height data were retained.

The sample is composed of 36 males and 28 females for whom body mass and stature are known and encompass a wide range of variation (Table 1 and Fig. 1). Bodies have been weighed on an electronic scale with clothes removed prior to autopsy. Light devices such as intra-uterine devices and tubes from operations were left in place. The stature was measured using a metal ruler from the sole of the foot to the top of the head on corpses that were lying in a horizontal, supine position. Following the World Health Organization BMI classification [27], five females are considered underweight (Body Mass Index $< 18.5\ kg/m^2$), eight are considered as being of normal weight ($18.5 \leq BMI \leq 24.99$), eleven are classified overweight ($25 \leq BMI \leq 29.99$) and four are categorized as obese ($BMI \geq 30$). As for males, two are classified underweight, nineteen are considered of normal BM, fourteen are considered overweight and one is classified obese.

Males have been scanned using a Siemens Sensation 4 scanner with the following settings: 120 kV, 112.50 mAs, 2 or 3 mm slice thickness, 2 or 3 mm increment and either smooth (B30f or B31f) or sharp (B60f) reconstruction algorithms. Female scans were scanned using a Siemens Somatom Definition CT scanner with the following settings: 120 kV, 190 mAs, 3 mm slice thickness, 3 mm increment and a smooth reconstruction algorithm (B30f).

Only the left femurs were used for analysis. All of the external dimensions were derived from distances between 3D landmarks taken on axial slices in ImageJ [28,29]. This measure is independent of the orientation of the innominate during the scanning procedure as it is calculated from the position of the landmarks, the slice thickness and the pixel size of the scan. Data for estimating cortical area have been extracted from re-oriented femoral diaphyses with a recently paper published September 15th custom-built software [30].

The tested methods are described in Table 2. As for Elliott et al. [16], we tested the equations based on estimated CA at five different levels of the femoral diaphysis: 20, 35, 50, 65 and 80% of the maximum femoral length; 20% being the most distal of the five. CA has been estimated as $\pi/4 \times (D^2 - d^2)$, where D and d refer to the outer (subperiosteal) and the inner (medullar) diameters of the cross-section, respectively [10,16].

We evaluated the accuracy of each method based on the differences between estimated BM and actual BM [25]. The research aims are different between studies that estimate an average BM (mostly for population comparisons or estimates in palaeoanthropology and bioarchaeology) and an individual BM (mostly for individual assessment in forensic anthropology and bioarchaeology). Therefore, the criteria to evaluate the accuracy and reliability of the BM estimation methods are different whether

Table 1
Sample's averaged characteristics.

	♀ (n = 28)			♂ (n = 36)			♀ + ♂(n = 64)		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Age (years)	57	14	23–82	53	14	20–87	55	14	20–87
BM (kg)	66	15	38–90	70	13	46–98	69	14	38–98
Stature (cm)	163	6	156–182	173	7	161–88	169	8.5	156–188
BMI (kg/m^2)	24.8	5.8	15.5–36.5	23.6	3.6	14.9–30.9	24.1	4.7	14.5–36.6

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