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RESEARCH ARTICLE

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Body mass prediction from femoral volume and sixteen other femoral variables in the elderly: BMI and adipose tissue effects

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Abstract

Objectives: The frequently used prediction equations of body mass do not seem appropriate for elderly individuals. Here, we establish the relationship between femoral dimensions and known body mass in elderly individuals in order to develop prediction formulas and identify the factors affecting their accuracy.

Materials and Methods: The body mass linear least-squares regression is based on 17 femoral dimensions, including femoral volume, and 66 individuals. Body proportion and composition effects on accuracy are analyzed by means of the body mass index (BMI) and on a subset sample ($n = 25$), by means of the masses of adipose, bone and muscle tissues.

Results: Most variables significantly reflect body mass. Among them, six dimensions (e.g., biepicondylar breadth, femoral volume, and head femoral diameter) present percent standard errors of estimate ranging from 9.5 to 11% ($r = 0.72–0.81$) in normal BMI samples. Correlations are clearly lower in samples with normal and abnormal BMI [$r = 0.38–0.58$; % of standard error of estimate (SEE) = 17.3–19.6%] and not significantly correlated in females (femoral volume) who present high proportions of abnormal BMI and adipose tissue. In the subset, femoral volume is well correlated with bone mass ($r = 0.88$; %SEE = 7.9%) and lean body mass ($r = 0.67$; %SEE = 17.2%).

Discussion: Our body mass estimation equations for elderly individuals are relevant since relatively low correlations are recurrent in studies using younger individuals of known body mass. However, age, sex, lifestyle, and skeleton considerations of studied populations can provide information about the relevance of the body mass estimation, which is dependent on the BMI classification and the proportion of adipose tissue. Our general considerations can be used for studies of younger individuals.

KEYWORDS
body composition, body weight, elderly, femur

1 | INTRODUCTION

Reference to body size (i.e., body mass and stature) in overviews of ancient or recent human evolution is unavoidable (e.g., Antón, Richard, & Aiello, 2014; Chevalier, 2011; McHenry, 1992; Pomeroy & Stock, 2012; Ruff, 2002). Such data can contribute to enhancing discrimination among different human groups (e.g., Arsuaga et al., 2014; McHenry, 1992; Ruff, Trinkaus, & Holliday, 1997; Ruff, 2010; Trinkaus & Ruff, 2012) and present close links with the adaptive and behavioral aptitude of species (e.g., Froehle & Churchill, 2009; Holliday, 1997a,b; Ruff, 1994, 2002; Steudel-Numbers & Tilkens, 2004; Trinkaus, 1981). In addition, the estimation of body mass is important for evaluating, for example, the relative size of the masticatory system, the degree of encephalization and the structural properties of bone to consider the pattern and level of activity of a human group (Carlson & Marchi, 2014; McHenry, 1992; Ruff, 2002; Ruff et al., 1997; Trinkaus & Ruff, 2012). In forensic science, the estimation of body mass also adds supplementary information to the overall description related to the

identification of a cadaver (Chevalier, Lefèvre, Clarys, & Beauthier, 2016; Lorkiewicz-Muszyńska et al., 2013).

Although the equations for estimating body mass from McHenry (1992), Grine, Jungers, Tobias, and Pearson (1995) and Ruff, Scott, and Liu (1991) have met with widespread success and have been applied to many human fossil specimens, recently, new proposals have been advanced to improve predictions (e.g., Grabowski, Hatala, Jungers, & Richmond 2015; Squyres & Ruff, 2015; Will & Stock, 2015). In two recent studies, the reliability of the three commonly used formulas was tested on measurements taken from individuals with known body mass (Chevalier et al., 2016; Lorkiewicz-Muszyńska et al., 2013). In Lorkiewicz-Muszyńska et al. (2013), taking into account individuals of any age, and in Chevalier et al. (2016), taking into account elderly individuals, the authors sometimes noted very high prediction errors (PEs) of body mass. They highlight a relationship between the error of estimation of body mass and body proportions as reflected by the body mass index (BMI). In Chevalier et al. (2016), the best percent PE of the sample mean body mass is low (4.8%), whereas the mean percent PE (% PE) of individual body mass is high (16.7%). With only individuals with normal BMI, the % PE of the sample mean body mass (5.7%) is almost equal to that obtained with the total sample, whereas the mean % PE for individual body mass falls below 10%, well below that obtained with the total sample. These results show the relatively good reliability of body mass prediction under certain conditions with individuals aged between 55 and 98 years, but also some high errors. As predicted by Chevalier et al. (2016), the formula used was not specifically appropriate for the elderly sample. Age effect on body mass and body composition (and also fat distribution) are well known (e.g., Borkan, Hults, Gerzof, & Robbins, 1985; Borkan, Hults, Gerzof, Robbins, & Silbert, 1983; Burmaster & Crouch, 1997; Delmonico et al., 2009; Doherty, 2003; Gallagher et al., 1997; Tanguy, Zeghnoun, & Dor, 2007; see also Squyres & Ruff, 2015). As a matter of fact, body mass can increase, muscle mass decrease and adipose mass increase relatively, whereas the external articular dimensions become stable in adulthood (Ruff et al., 1991). This could explain some cases of high individual body mass PEs when Chevalier et al. (2016) test the classical prediction formula (i.e., better correlations are obtained with individuals with normal BMI). However, the error could come from the femoral variables used as well as differences between the reference sample used to establish the formulas and the sample to which they were applied (e.g., geographic and cultural origins; average biological age).

This information incited us to study body mass prediction in elderly individuals based on a homogeneous sample and new variables in order to discuss how BMI and the proportion of adipose tissue affect the accuracy of body mass predictions. This kind of analysis should bring valuable information for studies of body mass prediction in a broad spectrum (i.e., unfocused in elderly).

The use of data from elderly individuals to establish equations to predict body mass has been identified as a problem in various studies (Ruff et al., 1991; Squyres & Ruff, 2015). Fundamentally, the estimation of body mass, unlike stature, appears to be conducive to greater PEs (for body mass, see Grabowski et al., 2015; Ruff et al., 1991; Squyres & Ruff, 2015; Uhl, Rainwater, & Konigsberg, 2013; for stature, see Olivier, 1963). The fact that body mass changes throughout life, even over very short periods, is a fundamental difference with respect to stature. The stabilization of external joint dimensions at the end of growth (Lieberman, Devlin, & Pearson, 2001; Ruff et al., 1991) is detrimental to the estimation of body mass in old adults. In contrast, the diaphyseal structure is likely to change during adult life (Ruff & Hayes, 1983). Nevertheless, the effect of age on the shaft could also be considered as a factor affecting the quality of the analysis (Ruff, 1990). As a result, some studies included the youngest known body mass for an adult and not, or not only, body mass at the time of bone measurement (Ruff et al., 1991; Squyres & Ruff, 2015). However, to develop prediction formulas for old individuals, we need this kind of sample and it is this risk factor that we wish to test in our study. We want to observe the limits of the body mass prediction method by answering the question: Do the elderly show a significant relationship between femoral dimensions and body mass despite the age-effect? And develop the debate by asking: What factors affect the degree of correlation, the PE and the standard error of estimation, and to what extent?

To answer these questions, we chose an elderly sample from Belgium with known body mass ($n = 66$) and we established the relationship between individuals of known body mass and 17 femoral variables with special interest in femoral volume, and the effect of BMI and body composition (e.g., adipose tissue) on PE. Our study presents several advantages:

Firstly, taking measurements directly from bones and CT-scans (e.g., Lorkiewicz-Muszyńska et al., 2013) offers some advantages compared to radiographic values (e.g., Ruff et al., 1991; Squyres & Ruff, 2015). Radiographic data require an adjustment to correct the magnification (Ruff et al., 1991; Squyres & Ruff, 2015) and the parallax effects, and limit the types of measurements used or the capacity to acquire them. Conversely, the measurements taken from fresh/dry bones and CT-scans can encompass a multitude of variables, and in the case of fresh/dry bones can incorporate the same procedure used to estimate the body mass of an individual from part of the skeleton, like in an archaeological context.

Secondly, the fact that the body mass of the individuals included in this study is known represents valuable information (here, age, sex, and stature are also known). The relationships between bone size and body mass are in the best case initiated from a regression based on the knowledge of individual data (i.e., both known body mass and bone measurements for each individual; Grabowski et al., 2015; Ruff et al., 1991; Squyres & Ruff, 2015; Uhl et al., 2013). However, in other studies this relationship is established using mean body mass from distinct samples, and not individual known body mass (Grine et al., 1995; McHenry, 1992). Furthermore, it can be established indirectly from previously estimated body masses. For example, the body mass prediction formulas proposed by McHenry (1992) are initially based on body mass estimated from stature (using long bone lengths). In other words, body mass is estimated by deriving body mass from stature, then a new regression is established with the body mass estimated and the variable of interest (e.g., femoral head). The Grine et al. (1995) and McHenry (1992) methods are useful in the absence of knowledge of real individual body mass. Unfortunately, it generally produces

extremely high correlations but the estimate of error can also sometimes be very high. These high correlations between bone variables and body mass are overestimated compared with results published by Grabowski et al. (2015), Squyres and Ruff (2015), and Uhl et al. (2013) for which the known body mass of individuals was used.

Thirdly, previous studies show that the dimensions of the femur correlate well with body mass in immature and adult individuals (Grine et al., 1995; McHenry, 1992; Robbins, Sciulli & Blatt, 2010; Ruff, 2007, Ruff et al., 1991), and thus they are traditionally used, particularly in fossils (e.g., Trinkaus & Ruff, 2012). While some of our 17 variables present a high degree of correlation, the presentation of the results obtained with many femoral variables provides an opportunity for future studies to choose the appropriate femoral variable depending on bone preservation. Moreover, we hope to determine if articular or diaphyseal variables can be preferentially used to predict body mass given the distinct modification of their external dimensions during life (Lieberman et al., 2001; Ruff & Hayes, 1983; Ruff et al., 1991; Russo et al., 2006). However, a crucial element of this study is the use, for the first time, of the femoral volume ($n = 64$) as a predictive variable. The comparison of the results obtained with this volumetric variable with linear dimensions will extend the scope of application of this study to all research interested in the estimation of the body mass, more especially as the body mass is itself distributed within a volume. The femur is the longest, the largest and heaviest bone, it supports a large part of the body weight, which overhangs it, and it has the best relation with total skeletal mass (Clarys, Scafoglieri, Provyn, & Bautmans, 2010) and directly supports a large mass constituted by the thighs. Thus, we explore the appropriateness of using the volume of this bone to estimate body mass compared with other femoral variables (usually used or not).

Fourthly, we have access to the real body composition of 25 individuals from our sample, previously published in Clarys, Martin, & Drinkwater (1984). The masses of distinct biological tissues were obtained after the dissection session. These data will contribute with the BMI to determining the factors that affect PE (only for femoral volume). How muscle mass, adipose mass, bone mass, and lean body mass are related to the femoral volume is of general interest to identify what lies behind predicted total body mass.

Finally, our result [i.e., correlation and % standard error of estimate (SEE)] will be discussed in the light of previous studies integrating the known body mass of younger individuals. Following these comparisons, we will evaluate the quality of our formulas (i.e., can we reasonably use them?), but also those established on younger individuals.

In sum, we propose in this new study to test the significance of the relationship between known body mass and femoral volumetric and linear dimensions directly from the femurs of elderly individuals. Seventeen different variables are used here (i.e., femoral volume and maximal length, joint and diaphyseal variables) to highlight the most relevant variables for body mass prediction and to propose variate formulas applicable to fragmentary femurs in future studies. In addition, the influence of the BMI and body composition on both the PE and the correlation is evaluated, respectively, for each variable and for the femoral volume. A first application is proposed from eight linear regressions developed in this study and applied to seven elderly Belgian individuals of known body mass. While we focus primarily on elderly samples, the integration of femoral volume, the discussion about limiting factors in body mass prediction (e.g., adipose tissue) and the relatively good results obtained with elderly individuals in relation to previous studies with younger individuals expand the interest of this study beyond the case of the elderly.

2 | MATERIALS AND METHODS

2.1 | The sample

The sample is comprised of 66 individuals (Table 1) from human anatomy laboratories of two Belgian universities (Vrije Universiteit Brussel, VUB, and Université Libre de Bruxelles, ULB). It includes as many men as women, with an average age of 79 years (ranging from 55 to 98 years), for whom body mass, stature, sexual determination, and age are known. Thus, the sample consists of both the ULB sample and the VUB sample. In some analyses, only the ULB sample or the VUB sample is used because some data are not available in either sample (Table 2). This sample can be divided into a normal BMI sample (from 18.5 to 24.9) and an abnormal BMI sample. When a sample comprises all the available individuals (i.e., it is composed of a sample with mixed BMI), it is referred to as a total sample.

In the VUB sample ($n = 25$), only the femoral volume is available (previously archived). In the ULB sample ($n = 41$), 17 variables are measured for this study (femoral volume, maximal length and six articular variables and nine diaphyseal variables). Thus, the femoral volume is available for 64 specimens; 31 women and 33 men, whereas the other measurements are available in 37–40 specimens. When we restrict the sample to individuals with normal BMI, the number of individuals with measured femoral volume is 36. This number varies between 21 and 23 for the other femoral dimensions. Depending on bone preservation, it was not always possible to integrate all the femurs from the ULB sample, which explains the very slight differences between the total sample and the sample used (see Tables 3 and 4 for details).

In the ULB sample, the BMIs are on average 22.6 (range of variation: 15.0–31.3), with a standard deviation of 4.2 with four specimens over 30.0. The maximal BMI is 31.3 (i.e., in the inferior part of obese class I). In the VUB sample, the BMIs are on average 23.6 (range of variation: 16.5–31.3), with a standard deviation of 3.9. No individual is above 30.0 (i.e., no obese individuals).

An additional sample of seven individuals from VUB is used to apply eight formulas to individuals that were not previously used in this study. Like the individuals in the other sample, these are white elderly Belgian individuals. Other details are presented in Table 5.

2.2 | Method

For this study, we benefited from a set of data previously recorded during an earlier research program in ULB and VUB: body mass, sex, age and stature, and the femoral volume for the VUB sample (Table 2). These two distinct projects present some differences in their protocols.

TABLE 1 Sample statistics

			Age			Body mass			Stature		
Sample	Sex	*N*	Mean	Min-Max	SD	Mean	Min-Max	SD	Mean	Min-Max	SD
VUB	F	13	79.7	68–94	7.4	61.0	44.3–74.3	9.9	158.6	148.3–172.3	6.9
	M	12	71.7	55–83	8.5	64.7	46.4–88.9	13.5	168.0	156.2–186.5	8.2
ULB	F	20	83.8	55–98	10.2	53.2	35.0–74.0	10.4	155.0	139.8–168.1	7.2
	M	21	79.5	58–91	8.0	64.3	40.0–81.0	12.4	168.3	153.0–180.0	8.2
VUB/ULB	F	33	82.2	55–98	9.3	56.3	35.0–74.3.0	10.8	156.4	139.8–175.3	7.2
	M	33	76.6	55–91	8.9	64.5	40.0–88.9	12.6	168.2	153.0–186.5	8.0

VUB: Vrije Universiteit Brussel; ULB: Université Libre de Bruxelles; F: female; M: male; S.D.: standard deviation.

In ULB and VUB, the body mass is measured in cadaveric condition (as in Grabowski et al., 2015), respectively, during the first 48 and 72 hr after death at reception at the leg service with a dynamometric balance (using straps and hooks). It is very difficult to estimate the loss of body mass during this lapse of time. Based on the personal experience of one of the co-authors (JPC from VUB), a delay inferior to 72 hr could cause a weight loss of 3 kg, and at most, of 5 kg. Given that most of the cadavers probably arrive around 48 hr after death in VUB and ULB, it seems reasonable to propose a mean weight loss of ~3 kg. However, as is ethically understandable, it is not possible to weigh a person just before death and then upon arrival at the leg service. Furthermore, body mass and body composition probably contribute, to varying degrees, to the extent of weight loss in each individual. Thus, it is preferable not to use a corrective factor for each individual. For the VUB sample, constituted during the 1980s, we know almost all the conditions of death (see in Clarys et al., 1984) and no individuals with severe emaciation, physical abnormalities, or deterioration were used. For the recent ULB sample, no information is known about the cause of death or pathology due to deontological and ethical rules. Individuals with osteosynthesis equipment were eliminated. No intraobserver or interobserver errors are recorded for the body mass of the cadaver.

In VUB, the stature is measured four times (twice with the elongated body and twice in suspension with an orthopedic splint), and the mean of these four measurements corresponds to the recorded measurement. In ULB, the stature was measured in decubitus dorsal using the anthropometric gauge. The feet are positioned in dorsal flexion (at 90°).

Analyses incorporating the BMI (Body mass/stature^2) are based on the known body mass and stature at death. The BMI is used like an index of body proportion for the classification into abnormal-BMI and normal-BMI in order to evaluate how the general body proportion affects the relationship between femoral variables and body mass. The sample of individuals with a normal BMI is comprised of a subset of our total sample. Our goal is not to classify each individual with absolute certainty to one or to the other category in reference to stature and body mass during life. Effectively, the stature and body mass recorded in our study are slightly different to these data during the lifetime of the individual, but that is not a problem here. The BMI index is used as a benchmark to highlight an observed trend (i.e., we find that a good correlation between femoral variables and body mass depends on a certain relationship between body mass and stature). In this study, the normal BMI (from 18.5 to 24.9) takes into account World Health Organization data (WHO, 1995).

The 17 variables taken into account in this study are listed in Tables 3 and 4. The measurements refer to Martin and Saller (1959) for maximum length (M1), head anteroposterior diameter (M19), mid-diaphysis perimeter (M8), mid-diaphysis mediolateral diameter (M7), mid-diaphysis anteroposterior diameter (M6), and biepicondylar breadth (M21); and McHenry & Corruccini (1978) for superoinferior diameter of the neck (#2), anteroposterior diameter of the neck (#3), subtrochanteric mediolateral diameter (#4), subtrochanteric anteroposterior diameter (#5), lateral condyle height (#16). The neck perimeter is taken at the same level as the neck superoinferior diameter. The subtrochanteric perimeter is taken at the same level as the subtrochanteric

TABLE 2 Sample description

	Sample	Known body mass, stature, sex, and age	Known body composition from dissection[a]	Volume previously measured by immersion	Volume measured by CT-scan in this study	Sixteen femoral variables measured in this study
ULB	41	41	0	0	39	38–40
VUB	25	25	25	25	0	0

Following analysis and data, the sample is used as a total sample (i.e., mixed BMI) or normal BMI sample, and as ULB sample or VUB sample.
All data are taken from cadavers.
Abbreviations [ULB = Université Libre de Bruxelles (Belgium); VUB = Vrije Universiteit Brussels (Belgium)].
[a]Published in Clarys et al. (1984).

TABLE 3 Accuracy of body mass prediction from 17 femoral variables with the total sample

Total sample-Regression 1	*N*	*r*	Slope	Intercepts	PEabs (kg) Total sample N-BMI/AB-BMI	%PEabs Total sample N-BMI/AB-BMI	SEE	%SEE
Volume	64	0.434***	5.3713E-05	33.360	9.0	15.0	11.1	18.2
					5.8/13.3	9.4/22.0		
Volume (VUB sample)	25	0,365	–	–	–	–	–	–
Volume (ULB sample)	39	0,449**	5.7405E-05	31.206	9.0	15.2	11.3	19.0
					4.9/14.8	8/25.5		
Volume (males)	33	0.426*	6.1320E-05	29.527	9.4	14.9	11.6	18.0
Volume (females)	31	0.162	–	–	–	–	–	–
Maximum length	37	0.442*	0.179	−21.106	9.5	16.5	11.6	19.3
					5.4/14.8	8.8/26.8		
Head anteroposterior diameter	39	0.380*	1.186	5.298	9.4	15.9	11.7	19.6
					5.5/15.1	9.0/26.2		
Neck perimeter	40	0.474**	0.881	−28.455	9.1	15.3	11.1	18.7
					5.7/13.9	9.5/24.1		
Neck superoinferior diameter	39	0.417**	1.528	8.151	9.6	16.2	11.6	19.5
					6.7/14.0	11.0/24.2		
Neck anteroposterior diameter	39	0.448**	2.079	2.695	9.3	15.7	11.4	19.2
					6.1/13.9	10.1/24.1		
Subtrochanteric perimeter	39	0.460**	0.896	−29.996	9.3	15.6	11.2	18.8
					6.1/13.9	10.0/24.1		
Subtrochanteric mediolateral diameter	39	0.164	–	–	–	–	–	–
Subtrochanteric anteroposterior diameter	39	0.474**	2.788	−23.196	9.0	15.2	11.2	18.9
					6.5/12.6	10.9/21.8		
Mid-diaphysis perimeter	38	0.372*	0.698	−3.575	9.6	16.2	11.7	19.7
					6.8/13.9	11.2/24.0		
Mid-diaphysis mediolateral diameter	40	0.216	–	–	–	–	–	–
Mid-diaphysis anteroposterior diameter	40	0.484**	2.384	−10.707	8.6	14.5	11.0	18.5
					5.6/13.2	9.2/22.8		
Lateral condyle height	39	0.471**	1.094	−10.219	8.9	14.9	11.2	18.8
					4.9/14.6	8.0/25.2		
Lateral condyle breadth	39	0.294	–	–	–	–	–	–
Patellar surface breadth	40	0.544***	1.828	−8.328	8.7	15.0	10.6	17.8
					6.2/12.5	10.3/21.6		
Bicondylar breadth	39	0.582***	1.238	−32.881	8.4	14.1	10.3	17.3
					5.1/13.1	8.4/22.6		
Biepicondylar breadth	38	0.569***	1.053	−27.105	8.0	13.6	10.1	17.2
					4.6/13.3	7.5/23.7		

[a]Abbreviations [r = the linear correlation; PEabs = absolute prediction error (kg); PEs are listed when r is statistically significant: * $p < .05$; ** $p < .01$; *** $p < .001$; SEE = Standard error of estimate; Slope and intercepts are, respectively, (a) and (b) in linear regression: $y = ax + b$ with (x) for femoral variables (mm and mm^3) and (y) for body mass (kg); N-BMI = Normal BMI sample; AB-BMI = Abnormal BMI sample].
PEabs is decomposed into two parts (N-BMI/AB-BMI) to show the average contribution of individuals with normal and abnormal BMI to the global PE.

TABLE 4 Accuracy of body mass prediction from 17 femoral variables with a selected sample from individuals with normal BMI

Individual with normal BMI-Regression 2	*N*	*r*	Slope	Intercepts	PEabs (kg)	%PEabs	SEE	%SEE
Volume	36	0.750***	7.4129E-05	21.393	5.2	8.5	6.7	11.0
Volume (VUB sample)	13	0.750**	9.8677E-05	5.573	6.0	9.7	8.0	13.0
Volume (ULB sample)	23	0.802***	7.0266E-05	24.465	5.9	9.8	5.8	9.5
Maximum length	21	0.740***	0.262	−58.992	5.2	8.5	6.6	10.8
Head anteroposterior diameter	23	0.717***	1.594	−13.466	5.0	8.2	6.7	10.9
Neck perimeter	24	0.704***	0.926	−32.859	5.9	9.8	6.9	11.4
Neck superoinferior diameter	22	0.547**	1.361	14.215	6.8	11.2	8.3	13.7
Neck anteroposterior diameter	23	0.684***	2.525	−7.999	5.8	9.7	7.2	12.0
Subtrochanteric perimeter	23	0.682***	9.612	−36.503	6.1	9.9	7.0	11.5
Subtrochanteric mediolateral diameter	22	0.347	–	–	–	–	–	–
Subtrochanteric anteroposterior diameter	22	0.517*	2.282	−8.208	6.8	11.2	8.5	14.3
Mid-diaphysis perimeter	23	0.491**	6.952	−2.741	7.0	11.3	8.6	14.2
Mid-diaphysis mediolateral diameter	23	0.443*	1.474	20.536	6.8	11.1	8.8	14.5
Mid-diaphysis anteroposterior diameter	23	0.645***	2.844	−24.407	5.7	9.4	7.3	12.0
Lateral condyle height	22	0.760***	1.223	−17.769	4.6	7.5	6.2	10.1
Lateral condyle breadth	22	0.699***	1.838	6.145	5.4	8.9	6.8	11.1
Patellar surface breadth	23	0.611**	1.725	−4.382	6.1	10.1	7.6	12.4
Bicondylar breadth	22	0.757***	1.202	−30.331	5.2	8.5	6.2	10.2
Biepicondylar breadth	22	0.808***	1.131	−33.090	4.8	8.1	5.6	9.5

[a]Abbreviations [r = the linear correlation; PEabs = absolute prediction error (kg); PEs are listed when r is statistically significant: * $p < .05$; ** $p < .01$; *** $p < .001$; SEE = standard error of estimate; Slope and intercepts are, respectively, (a) and (b) in linear regression: $y = ax + b$ with (x) for femoral variables (mm and mm^3) and (y) for body mass (kg)].

anteroposterior diameter. For subtrochanteric measurements, it is recommended to avoid the distal bulge just below the lesser trochanter. The lateral condyle breadth is taken at mid-height of the intercondylar notch in inferior view. The patellar surface breadth corresponds to the distance between the two anterior extremities of the femoral condyle at the border of the patellar surface. The bicondylar breadth corresponds to the maximal transverse diameter taken between the lateral border of the lateral condyle and the medial border of the medial condyle. Sixteen variables (all except the femoral volume) were measured directly on dry bones with a sliding caliper, a flexible cloth tape, and an osteometric board.

The volumes of the VUB specimens were measured by immersing the fresh bone suspended in water. This consists in weighing the femur in air and in water for volume determination according to the principle

TABLE 5 Sample description from seven independent individuals.

	I	II	III	IV	V	VI	VII	Mean	Mean without VII
Sex	M	M	F	M	F	F	M		
Body mass	43.6	66.3	50.9	80.1	49.0	55.8	97.2	63.3	57.6
Normal BMI[a]	No	Yes	Yes	No	Yes	Yes	No		
BMI estimated	15.0	24.9	23.3	26.4	21.5	19.7	28.9		
Maximum femoral length	475.0	450.0	400.0	488.0	411.0	468.0	518.0	458.6	448.7
Subtrochanteric perimeter	102.0	96.0	87.0	93.0	81.0	88.0	98.0	92.1	91.2
Mid-diaphyseal perimeter	95.0	96.0	81.0	92.0	81.0	90.0	99.0	90.6	89.2
Biepicondylar breadth	90.6	80.8	77.0	94.0	78.0	81.0	88.9	84.3	83.6

[a]BMI taking into account femoral length and body mass. More details in Method.
Biometric data in mm.

of Archimedes (i.e., by calculating its hydrostatic weight, hydrostatic weighing in water is a direct measure and accurate to 0.01 g). This method was used in the 1980s and today we are using these data for our study. It is not our personal choice. It is thus a method used by default. For example, the same method was also used by Kim et al. (2004).

The femoral volumes of the ULB specimens were measured from CT-scan data from dry femurs (picture matrix: 512 × 512, field of view: 50 mm, slice thickness: 1 mm). The ULB femurs were scanned with CT-scans as this technology was easily available at the time of dissection. This should not be seen as a particular recommendation for this method. A surface scan may suffice. Using the Avizo software, we select the entire scanned femur as a specific material with a semiautomatic method (by means of the module "Image segmentation" and "Edit new label field") and we generate a 3D surface to produce a 3D model. Then, we can measure the volume of one piece from this model automatically. Contrary to the previous method for measuring volume, CT volume determination is based on a model-related calculation (i.e., this indirect approach will have a higher error impact because of the associated bounding identification).

It is not possible to compare the two methodologies for measuring femoral volume (immersion vs. CT-scan). Currently, we do not have permission to immerge, the ULB femur in a liquid, or prepare the femurs for this, to avoid the risk of altering the bones. And we do not have the material necessary to reproduce the method based on the principle of Archimedes (see VUB method used in the 1980s). Moreover, the VUB femurs were returned to the families, so it is impossible to scan them. As a precaution due to the different protocols for volume measurements at VUB and ULB, we also present the results separately (Table 3). Finally, while data in the ULB sample is based on dry bone and data in the VUB sample is from fresh bone, Kim et al. (2004) showed the absence of significant differences between fresh and dry femoral volume.

For 16 linear measurements, intraobserver error was evaluated by remeasuring five individuals with at least two weeks between each session, and interobserver error was evaluated by measuring four individuals by three distinct observers. The intraobserver and interobserver errors are, respectively, 0.7 and 1.2%, on average, with a maximum of 1.4 and 2.1%. The femoral volume intraobserver error obtained from CT-scan data was evaluated by remeasuring three individuals and the interobserver error was evaluated by measuring three individuals by two distinct observers. The intraobserver and interobserver errors are, respectively, 0.7 and 1.3%, on average, with a maximum of 1.3 and 2.0%. No data are available for intraobserver and interobserver error for the volume measured by immersion.

Regression equations are based on linear least-squares regression, which is advantageous for minimizing PE, here, for body mass (i.e., dependent variable). The PE is equal to [observed BM-predicted BM]. The % PE is equal to [(observed BM-predicted BM)/predicted BM] multiplied by 100.

As a first application of our formulas (i.e., regression equations), we use seven independent specimens from VUB (not incorporated in the previous sample). Only four variables are used (see Table 5). Measurements of the four variables for the new VUB specimens have been previously recorded and archived. It is not possible to access this femur for new measurements. Thus, we applied eight formulas to these new individuals: four formulas obtained from the total sample (i.e., mixed BMI) and four formulas obtained from the normal BMI sample. All known data (e.g., body mass) are obtained with the same protocol described before. This is an additional sample that we could not include in our main study because we did not have all the necessary data (e.g., known stature). To estimate the category of BMI (normal BMI vs. abnormal BMI) of these seven new individuals, we could not directly use the traditional formula based on stature and body mass. In the absence of known stature, first, we chose to consider the "maximum length of the femur/body mass" ratio as an alternative to BMI. Thus, we observed this ratio for the individuals with normal BMI in our sample ($N = 21$). For 21 individuals with normal BMI from the ULB sample, this ratio is between 0.113 and 0.162. Thus, we estimated that four of the seven individuals from the independent sample have a normal BMI (Table 5). Secondly, we estimate the stature from the ULB sample ($n = 37$) by linear least-squares regression: stature = 0.3027*Maximal FemoralLength + 26.593), $r^2 = 0.81$, SEE = 4.6, %SEE = 2.9%. Then, we calculate the BMI. The classification is exactly the same as that obtained with the previous method. Here, PE is converted into an absolute value (PEabs) to calculate the PE mean and the percent PE mean (% PEabs) for each variable. When testing the prediction formula of body mass with the seven new individuals, the PE mean reported the prediction error for the estimation of the sample mean body mass while the PEabs mean reported the mean prediction error for individual body mass (i.e., the expected error).

Body mass is often considered as a whole, but mass of tissues (bone, muscle, adipose) or lean body mass are potentially differently correlated to bone size, and notably for elderly specimens if we consider the age effect on body composition and body mass (e.g., Borkan et al., 1983, 1985; Burmaster & Crouch, 1997; Delmonico et al., 2009; Doherty, 2003; Gallagher et al., 1997; Tanguy, Zeghnoun, & Dor, 2007; see also Squyres & Ruff, 2015). Thus, body composition can affect (and therefore explain) the error of prediction. Consequently, an additional analysis, using the 25 individuals of the VUB sample (previously presented in Tables 1 and 2), studies the relationship between the femoral volume and adipose tissue, bone tissue and muscle tissue, and also between the femoral volume and lean body mass (i.e., adipose-tissue-free weight, see in Clarys et al., 1984). Data relative to the distinct masses of tissues were previously presented in Clarys et al. (1984), but with no analysis of their relationship with the femoral volume. The protocol of dissection is detailed in this latter publication. There is therefore no particular interest in repeating it here. However, some information should be specified. The dissection of fresh cadavers is influenced by several factors, for example, postmortem timing, unanticipated deterioration of the internal tissues and dehydration during dissection. Some researchers (Clarys et al., 1984; Clarys, Provyn, & Marfell-Jones, 2005; Todd & Lindala, 1928) argued that the embalming process restored the dehydrated cadavers to a more representative morphology of the living state. Clarys et al. (1984) made a full all-in body composition dissection of 13 unembalmed (6 male, 7 female) and

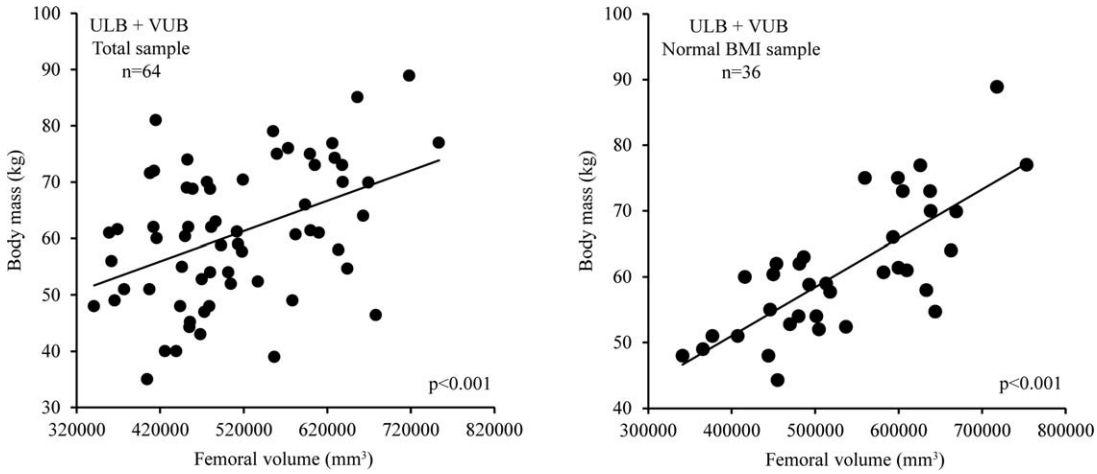

FIGURE 1 Femoral volume and body mass: ULB and VUB sample

12 embalmed (6 male, 6 female) corpses. The external morphology was indeed restored but the distribution of the embalming fluid mixed with body fluids was variable, however the experimental treatment of embalmed and unembalmed cadavers remained essentially the same. Later, in 2006, a comparative study of age-matched cadavers and living subjects did not produce significant anthropometric differences (Clarys, Marfell-Jones, & Van Roy, 2006). Fresh material is relative since dissection started between 48 and 96 hr after death. A full dissection with a pro sector team of 16 or 17 persons took between 12 and 15 hr (Clarys et al., 1984). During each dissection, an approximate weight loss of 2 kg was observed. This was determined from the difference between the total body weight measured at the beginning of dissection and the summation of all tissue and fluid weights at the end of dissection. Since tissue losses were negligible, the weight loss was assumed to be evaporative loss from the large areas of moist tissues exposed during dissection. The measured tissue weights have, therefore, been augmented by an amount equal to the total evaporative loss multiplied by the ratio of the tissue weight to the total body weight. All tissues (bone, muscle, viscera, skin, and adipose tissue) were weighted in air and in water for volume determination. Fascia, nerves, and blood vessels were attributed to the main tissue they belong to. Each dissected particle was collected under cling film and kept in color-labeled, continuously covered plastic containers of known weight to minimize or eliminate evaporation. Full container mass was measured during dissection by the same two researchers using a Mettler-Toledo digital scale (Excellence XS precision balance model 40025; Mettler-Toledo GmBH, Greifensee, Switzerland) accurate to 0.01 g.

For all analyses, correlations, linear least-squares regressions, SEE, PE, and graphics are obtained using Statistica 10, Microsoft Excel 2010 and PAST 2.14 software.

3 | RESULTS

3.1 | Femoral size and body mass

The femoral volume correlates significantly ($r = 0.43$; $p < 0.001$) with the known body mass of individuals from the total sample (Regression 1, $N = 64$; Figure 1). It is associated with a PEabs of 15% and a SEE of 18.2%. This result is similar to that obtained with only the ULB sample ($N = 39$). The smaller VUB sample ($N = 25$) shows no significant correlation. Given the former analysis ($N = 64$), the coefficient of correlation and the two kinds of PEs are relatively similar to those of each significant correlation identified among the 16 other variables analyzed here (Table 3). Note that femoral volume is more reliable than the femoral head and less reliable than some variables measured on the distal epiphysis. Within this regression 1, individuals with normal BMI (mean PE = 9.4%) contribute less to PE than individuals with abnormal BMI (mean PE = 22%). Figure 2 clearly illustrates this result. The individuals with the lowest PE percentages (<15) have a BMI of between ~18.5 and 24.9 (i.e., normal BMI). Inversely, the individuals with the highest PE percentages (>15) generally have a BMI inferior to 18.5 and superior to 24.9 (i.e., abnormal BMI).

By restricting individual data to individuals with normal BMI (Regression 2), we observed a significant increase in the correlation (0.75, $p < 0.001$; Table 4 and Figure 1). In this context, the reliability of femoral volume to predict body mass is close to both the diameter of the femoral head and maximum length, but inferior to biepicondylar width and lateral condyle height.

Due to the relatively large number of individuals with known femoral volume, body mass regression on femoral volume is also developed in

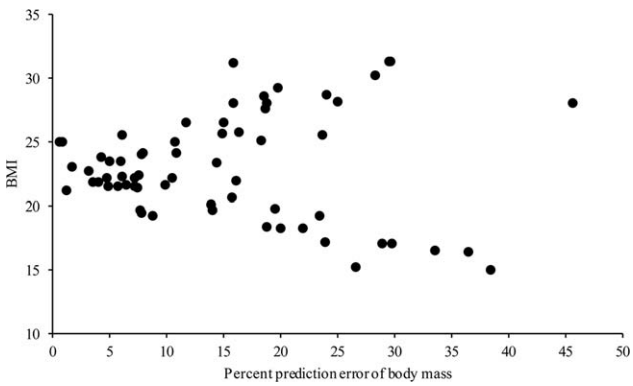

FIGURE 2 BMI and PE of body mass (%) from femoral volume

accordance with sexual affiliation. We found that the femoral volume was not significantly correlated with body mass in women ($r = 0.16$; $p = 0.387$; $n = 31$), unlike in men ($r = 0.426$; $p = 0.014$, $n = 33$), for whom the correlation is almost identical to that of the total sample. This sex-specific analysis was not conducted with the sample composed only of normal BMI individuals since a sex-based sample would be too small.

More generally, we note that 14 variables showed significant correlations with known body mass when considering the total sample (Table 3). The three variables not showing significant correlations are the subtrochanteric mediolateral diameter, mid-diaphyseal mediolateral diameter, and lateral condyle width. Considering the sample restriction to individuals with normal BMI, only one variable has no significant correlation with known individual body mass (i.e., subtrochanteric mediolateral diameter).

In view of regression 1, the individual with normal BMI contributes less than the abnormal individual to the PEabs. The PEabs of the individuals with normal BMI vary between 4.6 and 6.8 kg (7.5–11.2%), although the PEabs of the individual with abnormal BMI vary between 12.5 and 15.1 kg (21.6–26.8%). In the light of Tables 3 and 4, it is clear that all correlations between femoral dimensions and known body mass are higher with the normal BMI sample (between 0.347 and 0.808) compared with the total sample (between 0.164 and 0.582).

The three best correlations with the total sample range between 0.54 and 0.58 and are associated with the value of standard error of estimate ranging from 17.2 to 17.8%. They correspond to the distal epiphysis variables (i.e., patellar surface width, bicondylar width, biepicondylar width). All the other significant correlations are >0.4 and <0.5, except for the femoral head diameter (0.38). These correlations are associated with percent standard error of estimate $>18\%$ and $\leq 19.6\%$. The latter %SEE is obtained with the femoral head diameter. Indeed, the correlations and prediction errors (PE and SEE) are best using four of the six diaphyseal variables comparatively to the femoral head diameter.

The best correlation with the normal BMI sample is 0.8 (i.e., biepicondylar width). Five other correlations are above 0.7 (i.e., femoral volume, maximum length, head diameter, lateral condyle height, and bicondylar width). For these variables, the SEE ranges from 10.1%, with the lateral condyle height, to 11%. The diameter of the femoral head is associated with a %SEE of 10.9%, almost equivalent to the %SEE in relation to femoral volume (i.e., 11%). Five other variables show higher correlations than 0.6 and <0.7 for %SEEs ranging from 11.1 to 12.4%. Considering this selection of individuals, the diaphyseal variables are less reliable than the femoral head diameter.

Thus, with a sample restricted to individuals with normal BMI, for which the estimate of the body mass from femoral size is the most accurate (with reference to the coefficient of correlation), the most reliable femoral variables are also femoral volume, maximum length, as well as some variables of the proximal and distal epiphysis and some diaphyseal variables.

3.2 | Body mass prediction formulas tested with an additional sample: A first application

Here, we observe the prediction of the body mass from a new sample of seven individuals of known body mass for which four femoral variables were measured independently of this study (i.e., maximum length, subtrochanteric perimeter, midshaft perimeter, and biepicondylar width). The eight formulas used to predict body mass correspond to four formulas obtained from the total sample and four formulas from the normal BMI sample. These formulas result in linear least-squares regressions. Slope and intercepts are shown in Tables 3 and 4.

According to the four variables and two formulas for each of them (i.e., one from the ULB total sample and the other from the ULB normal BMI sample), the mean of the PEabs is always clearly higher than the mean of the raw PEs. In other words, the prediction of individual body mass is still significantly less accurate than the prediction of the mean body mass of the sample (Table 6).

For the distinct variables, the PE of the mean body mass of the sample differs little between the formula derived from the total sample and the formula derived from the individuals with normal BMI, except for the midshaft diameter. For the latter, the %PE decreased from 29.1 to 4.3%. Whatever sample is used to develop prediction formulas, predicting the mean body mass of the sample is more reliable with biepicondylar width (%PE between 1.2 and 2.1%), and maximum femoral length (%PE between 3.1 and 3.6%).

Similarly, the PE of individual body mass is generally not improved with the formulas established from individuals with normal BMI (16.2–30.1%), compared with those derived from the total sample (17.1–33.3%). Again, the difference between the two formulas is only clear for the midshaft perimeter, it decreases from 33.3 to 19%. Taking the first two individuals (I and II) as an example and the independent "femoral maximum length" variable, we note for individual I that errors are equal to -19.9 and -21.9 kg using the formula established respectively from the total sample and the normal BMI sample. For individual II, the errors are equal to 7.3 and 7.4 kg. Finally, with respect to this small independent sample ($N = 7$), formulas based on total sample and normal BMI sample give approximately the same results (i.e., error of prediction) when we apply them to individuals with normal BMI (e.g., individual II) and when we apply them to individuals with abnormal BMI (e.g., individual I).

However, substantial PEs occur for the three individuals with abnormal BMI. For these three individuals, the PEs ranged from 7.7 kg (15%) to 43.5 kg (81.1%). These PE are often close to, or above 20 kg. Considering the four individuals with normal BMI, the PE is between 0.3 kg (0.6%) and 14.4 kg (27.8%), and often <10 kg.

We note that individual VII tends to show very high PEs in some cases. Therefore, it can strongly affect mean PE. It is important to note that this individual presents high body mass in relation to the initial reference sample used to establish the formulas. By removing it from the sample, the absolute mean PE for individual body mass is between 13.7 and 14.4%, based on maximum femur length and biepicondylar width (as opposed to 16.2 and 18.4% with individual VII).

3.3 | Femoral volume, estimation of body mass, and body composition

The present analysis is based on 25 individuals from the VUB collection (included in previous analyses in this study) for which the

TABLE 6 Predicted body mass and PE for seven independent individuals (I–VII) with four femoral variables and two kinds of formula based on total and normal BMI samples

		I	II	III	IV	V	VI	VII	Mean	Mean[b]
Maximum femoral length									$N = 7$	$N = 6$[b]
Total sample[a]	BMpred	63.5	59.0	50.1	65.8	52.1	62.2	71.1	60.5	58.8
	PE	−19.9	7.3	0.8	14.3	−3.1	−6.5	26.1	2.7	−1.2
	%PE	−31.3	12.4	1.6	21.8	−5.9	−10.4	36.7	3.6	−2.0
	PEabs	19.9	7.3	0.8	14.3	3.1	6.5	26.1	11.1	8.6
	%PEabs	31.3	12.4	1.6	21.8	5.9	10.4	36.7	17.1	13.9
Normal BMI sample[a]	BMpred	65.5	58.9	45.8	68.9	48.7	63.6	76.7	61.2	58.6
	PE	−21.9	7.4	5.1	11.2	0.3	−7.9	20.5	2.1	−1.0
	%PE	−33.4	12.5	11.1	16.3	0.6	−12.4	26.7	3.1	−0.9
	PEabs	21.9	7.4	5.1	11.2	0.3	7.9	20.5	10.6	9.0
	%PEabs	33.4	12.5	11.1	16.3	0.6	12.4	26.7	16.2	14.4
Subtrochanteric perimeter										
Total sample[a]	BMpred	61.4	56.1	48.0	53.4	42.6	48.9	57.8	52.6	51.7
	PE	−17.8	10.2	2.9	26.7	6.4	6.9	39.4	10.7	5.9
	%PE	−29.0	18.3	6.1	50.1	15.0	14.0	68.0	20.4	12.4
	PEabs	17.8	10.2	2.9	26.7	6.4	6.9	39.4	15.8	11.8
	%PEabs	29.0	18.3	6.1	50.1	15.0	14.0	68.0	28.7	22.1
Normal BMI sample[a]	BMpred	61.5	55.8	47.1	52.9	41.4	48.1	57.7	52.1	51.1
	PE	−17.9	10.5	3.8	27.2	7.6	7.7	39.5	11.2	6.5
	%PE	−29.2	18.9	8.0	51.4	18.5	15.9	68.5	21.7	13.9
	PEabs	17.9	10.5	3.8	27.2	7.6	7.7	39.5	16.3	12.5
	%PEabs	29.2	18.9	8.0	51.4	18.5	15.9	68.5	30.1	23.7
Mid-diaphyseal perimeter										
Total sample[a]	BMpred	51.3	51.9	43.0	49.5	43.0	48.3	53.7	48.7	47.8
	PE	−7.7	14.4	7.9	30.6	6.0	7.4	43.5	14.6	9.8
	%PE	−15.0	27.8	18.4	61.8	14.0	15.4	81.1	29.1	20.4
	PEabs	7.7	14.4	7.9	30.6	6.0	7.4	43.5	16.8	12.3
	%PEabs	15.0	27.8	18.4	61.8	14.0	15.4	81.1	33.3	25.4
Normal BMI sample[a]	BMpred	63.3	64.0	53.6	61.2	53.6	59.8	66.1	60.2	59.2
	PE	−19.7	2.3	−2.7	18.9	−4.6	−4.1	31.1	3.1	−1.6
	%PE	−31.1	3.6	−5.0	30.9	−8.5	−6.8	47.1	4.3	−2.8
	PEabs	19.7	2.3	2.7	18.9	4.6	4.1	31.1	11.9	8.7
	%PEabs	31.1	3.6	5.0	30.9	8.5	6.8	47.1	19.0	14.3
Biepicondylar width										
Total sample[a]	BMpred	68.3	58.0	54.0	71.9	55.0	58.2	66.5	61.7	60.9
	PE	−24.7	8.3	−3.1	8.2	−6.0	−2.4	30.7	1.6	−3.3
	%PE	−36.2	14.3	−5.7	11.4	−11.0	−4.2	46.1	2.1	−5.2

(Continues)

TABLE 6 (Continued)

		I	II	III	IV	V	VI	VII	Mean	Mean[b]
	PEabs	24.7	8.3	3.1	8.2	6.0	2.4	30.7	11.9	8.8
	%PEabs	36.2	14.3	5.7	11.4	11.0	4.2	46.1	18.4	13.8
Normal BMI sample[a]	BMpred	69.4	58.3	54.0	73.2	55.1	58.5	67.5	62.3	61.4
	PE	−25.8	8.0	−3.1	6.9	−6.1	−2.8	29.7	1.0	−3.8
	%PE	−37.2	13.7	−5.8	9.4	−11.1	−4.8	44.1	1.2	−6.0
	PEabs	25.8	8.0	3.1	6.9	6.1	2.8	29.7	11.8	8.8
	%PEabs	37.2	13.7	5.8	9.4	11.1	4.8	44.1	18.0	13.7

The seven individuals are numbered I–VII and their number is underlined when they have abnormal BMI.
[a]Two equations are used to estimate the body mass from the femoral variables. The first was conducted from the total ULB sample (total sample), the second from ULB individuals with normal BMI (normal BMI sample).
[b]This mean takes into account the independent sample without individual VII.

femoral volume, body mass, lean body mass, adipose mass, muscle mass, and bone mass are known. The femoral volume does not present significant correlation with body mass. However, the masses of the distinct biological tissues are significantly correlated with the femoral volume (Table 7), except for the adipose tissue if we keep one specific individual (see footnote, Table 7). Muscle mass is positively correlated and the adipose tissue mass is negatively correlated with the femoral volume. This result is consistent with the significant and negative correlation between the proportions of adipose tissue and muscle tissue. Muscle tissue is itself positively and significantly correlated with the proportions of bone mass (Table 8). The relationship between femoral volume and bone mass is the most reliable with a %SEE of 7.9%. The other two tissues have a %SEE of 27.1 and 26.1%.

The same sample restricted to individuals with normal BMI ($N = 13$) showed a significant correlation between body mass and femoral volume whereas body mass is not correlated significantly with adipose tissue. The muscle mass and bone mass, significantly correlated with femoral volume, present, respectively, a %PE of 14 and 6.4%, and a %SEE of 18.3 and 8.3%. Thus, the PE is clearly lower for muscle mass and not for bone mass. The estimation of bone mass is the most reliable in both cases.

In the last result, the PE (PEabs) is not correlated with any of the proportions of body tissues considered (Table 8).

By referring only to lean body mass ($n = 25$), a significant correlation is observed with the femoral volume, contrary to the relationship taking into account the (whole) body mass. The results are slightly better for correlation (0.67 vs. 0.77) and %SEE (17.2 vs. 14.7%) when we only use individuals with normal BMI (Table 7).

4 | DISCUSSION

Our analyses offer the possibility to discuss how femoral dimensions reflect body mass in the elderly despite the age-effect in body mass, muscle and adipose masses and also periosteal and endosteal bone modifications (e.g., Borkan et al., 1983, 1985; Burmaster & Crouch,

TABLE 7 Accuracy of tissue mass prediction from femoral volume

	N	*r*	PEabs (kg)	%PE	SEE (kg)	%SEE
Total sample						
Body mass	25	0.36	–	–	–	–
Lean body mass (ATFM[b])	25	0.67***	5.53	12.90	7.20	17.20
Adipose mass[c]	24	−0.47*	4.71	22.09	5.84	27.10
Muscle mass	25	0.58**	4.23	19.38	5.53	26.07
Bone mass	25	0.88***	0.55	6.49	0.67	7.88
Normal BMI sample						
Body mass	13	0.75**	5.98	9.70	8.00	13.00
Lean body mass (ATFM)	13	0.77**	4.51	9.54	6.59	14.7
Adipose mass	13	−0.33	–	–	–	–
Muscle mass	13	0.83***	3.27	13.98	4.11	18.30
Bone mass	13	0.90***	0.59	6.44	0.73	8.25

[a]Significant correlation: * $p < .05$; ** $p < .01$; *** $p < .001$.
Abbreviations (PEabs = absolute prediction error; % PE = percent prediction error; SEE = standard error of estimate)
[b]ATFM: noted as Adipose-Tissue-Free Mass in Clarys et al. (1984).
[c]Body adipose mass does not take into account one individual with exceptional adipose mass (40.1 kg) compared with other individuals in the study sample. If this individual is included in the analyzed sample, then the correlation between adipose mass and femoral volume is not significant.

TABLE 8 PE of (known) body mass from femoral volume compared with body composition (known percent of adipose, muscle, and bone tissues)

n = 25	PEabs	%Adipose	%Muscle	%Bone
PEabs	0	0.11	0.27	0.52
%Adipose	−0.33	0	0.002	0.60
%Muscle	0.23	−0.60	0	0.04
%Bone	−0.13	−0.11	0.42	0

Correlations are located below the "0" line, significance is indicated above the "0" line.

1997; Delmonico et al., 2009; Doherty, 2003; Gabet & Bab, 2011; Gallagher et al., 1997; Lambert, Zaidi, & Mechanick, 2011; Rigg et al., 2004; Tanguy et al., 2007; see also Squyres & Ruff, 2015). The results bring new information of broader interest and can be integrated in future studies of body mass prediction in younger samples. We discuss the impact of body proportions (i.e., BMI) and body composition on the relationship between femoral measurements and body mass. In addition, we consider the contribution of femoral volume to more traditional procedures based on linear measurements.

4.1 | Accuracy of femoral variables in predicting body mass in elderly individuals

Femoral volume presents a relatively reliable SEE of body mass in comparison with the other variables analyzed with the total sample and the sample of individuals with normal BMI. It is more reliable for the total sample than the femoral head diameter and equivalent when we take into account the normal BMI sample. Finally, neither femoral volume nor the femoral head diameter were found to be the best predictors of body mass. The best standard errors of estimate are obtained with the distal epiphysis variables for both kinds of samples (total sample and normal BMI sample). According to our study, the usual focus on the femoral head diameter versus other femoral variables does not seem to be methodologically justified although it contributes to the femoral articular joint between the leg and pelvis. However, the frequent presence of this element among the human fossil material fully justifies its use. Femoral volume does not prove to be the best variable although initially we had reason to believe that this variable could be a better estimator than the other. Nonetheless, it is important to recall that these two variables (femoral head diameter and femoral volume) are among the best predictors of body mass.

More generally, almost all of the variables present significant correlation with the known body mass of individuals. The slight difference between the SEE values for many variables captures our attention. For example, six variables have a %SEE between 10 and 11% following the analysis with the normal BMI sample. These differences may be due to our specific sample or related to an error of measurement, and are probably not due to real biological differences in recording body mass in bone size. Thus, multiple dimensions are considered to have similar relationships to body mass. In addition, our results clearly highlight both the best correlations between the femoral dimensions and known body mass in individuals with normal BMI (vs. total sample) and the low contribution to PE of individuals with normal BMI (vs. individuals with abnormal BMI) to the global PE when the total sample is analyzed (Regression 1). Nevertheless, we note a relatively low reliability of femoral dimensions to estimate the body mass in elderly individuals, even for individuals with normal BMI. That is, even if the coefficient of correlation increases more by only integrating individuals with normal BMI, it remains inferior or equal to 0.8. Unfortunately, we cannot compare the SEEs related to the total sample and the BMI normal sample because regression 2 included a subsample of the total sample used in the regression 1. In fact, it is statistically logical that the SEEs associated with regression 2 are inferior to the SEEs associated with regression 1, because inevitably the subsample is less variable.

Among the 17 variables included in this study, we observe the best SEE among the variables least affected by bone modeling (e.g., external joint dimensions, Ruff et al., 1991; Lieberman, Devlin, & Pearson, 2001). Thus, the diaphyseal variables, which could present a more tenuous relationship with the body mass of individuals due to their sensitivity to mechanical stimuli (Ruff & Hayes, 1983), and which are therefore regarded as particularly interesting variables in the case study of elderly individuals (because they could change during the lifespan in relation to body mass changes), prove less reliable than some epiphyseal variables and femoral length, which present stabilized dimensions at the end of growth. In other words, we find a low correlation because the diaphysis does not change much to adapt to body mass change, while it has the aptitude to change size during the adult lifespan (Ruff & Hayes, 1983). The much lower levels of activity in elderly people is one parameter that can explain this result.

Finally, the incorporation of another sample for a first application of the formula derived here is a first step towards evaluating our previous consideration. For this new sample, body mass and four femoral variables are known. The results are partly consistent with our expectations. In other words, it clearly appears to be less reliable to estimate the body mass of individuals with abnormal BMI than individuals with normal BMI (while obviously in a blind study it is impossible to know the BMI when we do not know body mass). This result confirms our previous study (Chevalier et al., 2016). However, the predictions for the seven individuals do not seem best with formulas established from an undifferentiated sample compared to those from a sample of individuals with normal BMI. This may appear surprising in light of the correlation associated with the prediction formulas presented in Tables 2 and 3. Only the results obtained with the midshaft perimeter contradict this finding. In the latter case, PE are very low for individuals with normal BMI. The best predictions for both individual body mass and sample mean body mass are obtained with the maximum femoral length and biepicondylar width, two biometrically stable variables in adulthood. However, diaphyseal variables likely to change their outer diameter in adulthood (potentially related to change in body mass) generally have much higher PE. By eliminating the individual with the strongest influence on the mean (individual VII) and keeping the top two variables, the % PE for individual body mass is close to 14% and thus about 4% higher than the %SEE associated with the prediction formulas. In contrast, the PE for the estimation of the mean body mass of the

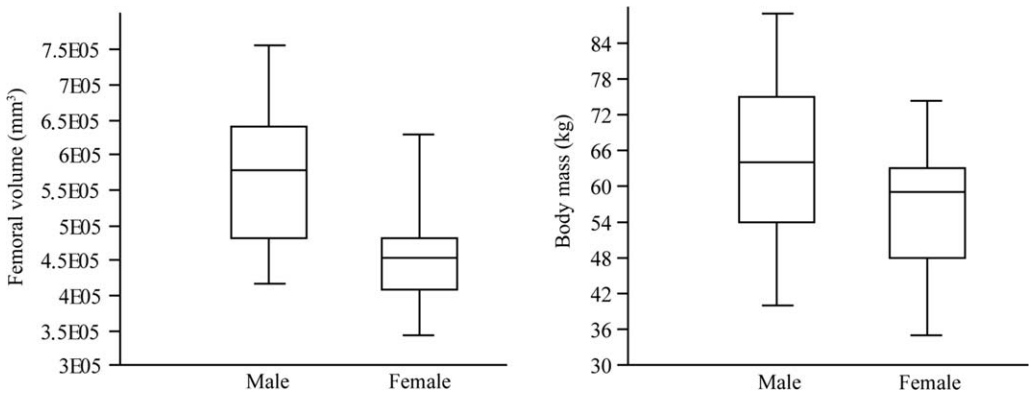

FIGURE 3 Femoral volume and body mass in males ($n = 33$) and females ($n = 31$): VUB and ULB sample

sample is remarkably low and remains the most reliable measurement. While this first application of our formula is informative, it is necessary to envisage a future study, when samples will be available, to test our formulas more rigorously with a larger and ultimately, a more variable sample.

4.2 | Adipose tissue, sex, and prediction of body mass

For femoral volume only, it is possible to produce a sex-specific analysis with a sample of more than 20 individuals for each sex. Surprisingly, the linear relationship between body mass and femoral volume showed no significant correlation in females ($n = 31$), unlike in males ($n = 33$). It is interesting to note that 41.9% of the women have a normal BMI in this sample as opposed to 69.7% for men. In addition, the clear distinction between the femoral volumes of male and female specimens ($p<0.001$) is less obvious than that obtained with body mass ($p<0.05$; Figure 3). Indeed, female femoral volume represents 79% of male femoral volume while their body mass is 88.4% of male body mass. Thus, the lack of significant correlation in females could be related to a high proportion of adipose tissue (Clarys et al., 1984; see the following paragraph) and excess weight relative to femoral volume. In addition, these distinct results between females and males are not surprising given the distinct age-effect in bone between the two sexes (e.g., see Ferrucci et al., 2014), notably in periosteal apposition, and also in the widening of the medullar cavity (Gabet & Bab, 2011; Lambert et al., 2011; Rigg et al., 2004).

To develop our interpretation, we observed the role of adipose tissue more closely. Only a subsample (i.e., VUB sample) of our total sample (ULB + VUB sample) could be used to analyze the relationship between femoral volume and body composition. Unlike the total sample ($n = 64$), this sample ($n = 25$) shows no significant correlation between femoral volume and body mass. This lack of significant correlation can be attributed primarily to the high proportion of individuals with abnormal BMI, ~50% in this sample. As we know the decomposed body masses of these individuals, we can search in our case for the biological tissue primarily responsible for the lack of significant correlation. We note that the mass of adipose tissue is significantly correlated with volume ($n = 25$) (under one condition, see Table 7), but not in the normal BMI sample ($n = 13$), while we observe the opposite between the body mass and the femoral volume. Thus, when the mass of the adipose tissue is less related to the femoral volume, the body mass is more so. Adipose tissue represents on average 34.6% of body mass in this sample, as opposed to 30.4% in the normal BMI sample and 39.1% in the abnormal BMI sample consisting mainly of females (9/12; see data in Clarys et al., 1984). Interestingly, males have 37.4% of muscle tissue and 28.1% of adipose tissue while females have 28.6% of muscle tissue and 40.5% of adipose tissue (see data in Clarys et al., 1984). Here, the fact that females are associated with higher adipose mass tissue relative to males tend to produce less reliable relationships between femoral volume and body mass.

Consequently, femoral volume indicates body mass more precisely in males compared to females, due to the fact that the former proportionately contain less adipose tissue. Additional analysis from lean body mass shows that the best result is obtained by partly removing the presence of the adipose tissue, that is, the effect of the adipose tissue. We can thus assume that elderly females and adipose tissue had an impact on the study of our larger (total) sample, composed by the ULB and VUB sample. Finally, femoral volume is more reliable for estimating the total bone mass (which represents on average 13.4% of the body mass), than the total muscle mass (which represents on average 32.9% of the body mass; see data in Clarys et al., 1984). It is probable that the masses that change least since the beginning of the adulthood stage are the most accurate for estimates from metric bone variables.

4.3 | Correlation between femoral dimensions and known body mass: Comparison with previous studies

The relatively low correlation between femoral dimensions and known body mass in the elderly can be considered as a disappointing result indicative of the difficulties involved in estimating the body mass of elderly individuals (i.e., high PE). However, given that body mass prediction in elderly specimens is primarily obscured at the adulthood stage by the distinct history between body mass and bone size, this accuracy can be considered as a satisfactory result with a relatively low error of estimate. To objectively assess the relevance of our new body mass estimation equations derived from femoral measurements in a modern elderly sample, the correlations obtained in this study need to be

TABLE 9 Comparative coefficient of correlation for BM prediction from femoral dimensions

	This study		Grabowski et al. (2015)	Ruff et al. (1991) Current	Squyres & Ruff (2015)
	Total sample	Normal BMI sample			
Head anteroposterior diameter[a]	0.380	0.717	0.424	0.486	
Neck superoinferior diameter	0.417	0.517	0.318	0.533	
Neck anteroposterior diameter	0.448	0.678	0.277		
Subtrochanteric mediolateral diameter	0.164	0.347	0.380	0.603	
Subtrochanteric anteroposterior diameter	0.474	0.517	0.240		
Mid-diaphysis mediolateral diameter	0.216	0.443	0.355		
Mid-diaphysis anteroposterior diameter	0.484	0.645	0.200		
Bicondylar breadth	0.582	0.757			0.680
Biepicondylar breadth[b]	0.569	0.808	0.399		0.720

[a]Our correlation for the head anteroposterior diameter is compared to the correlation for the superoinferior head diameter in Ruff et al. (1991).
[b]Here, the bicondylar breadth of Grabowski et al. (2015) is the biepicondylar breadth.

compared to three interesting previously published studies (Table 9). One of them presents the advantage of taking into account a large number of individuals ($N = 220$; biological age not mentioned), for which body mass was taken on cadavers, as in our study (Grabowski al., 2015). Another study included 80 living people with a mean age of 52.3 years (24–81), with known body mass and data taken from radiography (Ruff et al., 1991), and for whom interestingly current body mass and the "memorized" body mass at 18 were integrated. The sample is composed by as many males as females and more white (about two-thirds) than black individuals. The latest study presents the advantage of reducing the age-effect on the relationship between body mass and bone size by integrating the earliest known body mass recorded, referred to as the "young adult body mass" (Squyres & Ruff, 2015). In the latter sample, Euro-American individuals are dominant, but various ethnicities are included, and approximately as many females as males.

The comparative analysis of correlation with Grabowski et al. (2015), using eight similar variables to our study, shows the existence in both studies of roughly equivalent low correlations if our total sample is considered [correlations Grabowski et al. (2015): 0.200–0.424; correlation in this study: 0.164–0.582]. The correlations presented in our study are clearly higher (0.347–0.757) if our sample is restricted to individuals with normal BMI. More precisely, in this case, seven of the eight variables were better correlated than the best correlation in Grabowski et al. (2015). In both cases (total sample or normal BMI sample), their variables are less correlated than the femoral volume used in our study.

In our analysis, two variables (superoinferior diameter of the neck, subtrochanteric diaphyseal width) are considered to be identical to those used by Ruff et al. (1991). Although we have taken into account the anteroposterior diameter of the femoral head and Ruff et al. (1991) consider the superoinferior diameter, these data are included in our comparison because of strong correlations between these two types of diameters. The correlations of Ruff et al. (1991) range from 0.486 to 0.603 (%SEE: 18.5–20.3%). Ours are clearly lower for the total sample (from 0.164 to 0.417, %SEE: 19.5% for the latter). With the normal BMI sample (0.347–0.717), only our correlation obtained with the femoral head diameter is higher (0.717; %SEE: 10.9%) than the Ruff et al. (1991) correlations. The correlation obtained from the neck presents nearly the same value (0.517 vs. 0.533). However, in both cases (i.e., total sample and normal BMI sample), our sample shows no significant correlation between the subtrochanteric mediolateral diameter and body mass. This could be due to the difficulty in reproducing the measurement and not only to the difficulty to predict body mass with the subtrochanteric region while intraobserver and interobserver errors of measurement are relatively low (respectively, 0.38 and 1.27%). Indeed, the anteroposterior diameter and the perimeter of the subtrochanteric region are significantly correlated to body mass (with the total sample: 0.474 and 0.460; with normal BMI sample: 0.517 and 0.682). Finally, in the same manner as Ruff et al. (1991), some diaphyseal variables (with our total sample) show a better correlation than the femoral head. However, the correlation with the femoral head is higher when we consider the normal BMI sample. These data would indicate that the ability of the shaft to model involves the more accurate estimation of body mass with diaphyseal variables compared with joint variables, such as the femoral head diameter, if the normal and abnormal BMI sample is taken into account. However, this finding cannot be generalized to the joint variables of the distal epiphysis. Thus, we cannot confirm that the diaphysis is a better representative of body mass in adults because of possible external bone modeling, unlike in articular regions for which external measurements would be constant at the end of growth. This proposal was approved by Ruff et al. (1991) by considering only the femoral proximal portion.

Finally, the importance of the BMI in predicting body mass (i.e., to develop and apply prediction equations) is particularly evident with respect to Squyres & Ruff (2015), although the influence of BMI is not directly addressed in their study. They advocate the use of the youngest known body mass of an adult rather than the known body mass of the adult at the time of taking measurements on the knee. Their

argument is based on the fact that bone dimensions are primarily a reflection of body mass at early adulthood (Ruff et al., 1991). Therefore, they use what they call "young adult body mass." Their methodological preference is supported by the differences between current and former individual body mass. The current body mass of their individuals is higher on average by 8.5 kg (Squyres & Ruff, 2015), compared with the youngest body mass recorded. If we consider our total sample and their analysis based on "current body mass", biepicondylar width and bicondylar breadth have a correlation ranging from 0.39 to 0.45 (this variation also incorporates a correlation concerning the breadth of the tibial plateau) in Squyres & Ruff (2015) and 0.58 and 0.57 in our study. If we take into account their restriction to "young adult body mass" and individuals with normal BMI in our study, they obtain a correlation between 0.72 and 0.68, associated with a SEE of 11.48 and 12.22%, and we obtain a correlation between 0.76 and 0.81, associated with a SEE of 10.2 and 9.5%. Thus, their results are close to ours. Although biological age has an impact on the relationship between bone measurements and individual body mass, their results (more or less high correlations) may partly reflect the influence of BMI on the relationship between body mass and bone size. The impact of age on the prediction of body mass due to the variation in body mass (and body composition) during adulthood and the influence of BMI (i.e. change in body proportion) should be differentiated. The error in body mass prediction must reflect both the BMI and age. Moreover, the influence of BMI is not only active for very high BMI values (obesity BMI$>$ 30), because in our study the maximum BMI is 31.3 ($N = 4/64$ with BMI > 30). Consequently, studies focusing on the estimation of body mass should take age into account (Ruff, 1990; Squyres & Ruff, 2015), as well as the BMI when such information is available. We mean by this that (1) when we develop prediction formulas, the age and BMI of individuals will probably influence the relationship between bone measurements and body mass; (2) when we apply prediction formulas to new samples, a specific formula can produce reasonable results depending on, for example, age, sex and origins, but it seems that no good results can be expected with abnormal BMI individuals (while obviously it is impossible to know this data, only indirect information can help us, except in a medico-legal context).

To conclude, in agreement with our previous study (Chevalier et al., 2016), here also, we think that some recommendations about body mass prediction of elderly individuals are valid for younger individuals. The prediction of the sample mean body mass is a result that could be used with confidence in an evolutionary framework while the prediction of individual body mass must be discussed in accordance with the geological period or cultural affiliation associated with the studied specimens as its reliability can vary according to body proportions and composition. Any knowledge about lifestyle and the apparent robusticity of the skeleton can help us to evaluate the relevance of our estimate, i.e., if the individual/population has a normal BMI or/and a low proportion of adipose tissue. For example, in a paleoanthropological context, we can reasonably expect that early modern humans during the Middle and Upper Paleolithic probably generally have a normal BMI, taking into account their stature, lifestyle (hunter-gatherer, high mobility), pelvis breadth and articular size (see data and information in Carlson & Marchi, 2014; Trinkaus & Ruff, 2012). Furthermore, it is interesting to include additional information about climatic conditions, given the strong effect of climate on body shape and size, and robusticity (e.g., Ruff, 1994; Ruff & Larsen, 2014; Stock, 2006).

For future studies, it will be interesting to extend our investigation to observe the impact of low and high abnormal BMI on the prediction of body mass, to apply our formulas to large samples and to investigate the accuracy of other long bone volumes (and associations of multiple elements) to predict body mass among young and old individuals.

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