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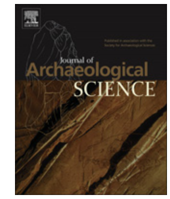

Highlights

► Two age-estimation methods have been tested in a documented collection from Madrid. ► The two age-methods analysed were based on pubic symphysis and auricular surface. ► Suchey–Brooks is more appropriate for populations with a majority of youth. ► Buckberry–Chamberlain method works better in the 60–70 years age range. ► Both methods provide different mortality profiles and lead to different conclusions.

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A test of Suchey–Brooks (pubic symphysis) and Buckberry–Chamberlain (auricular surface) methods on an identified Spanish sample: paleodemographic implications

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ABSTRACT

Forensic Anthropology and Bioarchaeology studies depend critically on the accuracy and reliability of age-estimation techniques. In this study we have evaluated two age-estimation methods for adults based on the pubic symphysis (Suchey–Brooks) and the auricular surface (Buckberry–Chamberlain) in a current sample of 139 individuals (67 women and 72 men) from Madrid in order to verify the accuracy of both methods applied to a sample of innominate bones from the central Iberian Peninsula. Based on the overall results of this study, the Buckberry–Chamberlain method seems to be the method that provides better estimates in terms of accuracy (percentage of hits) and absolute difference to the chronological age taking into account the total sample. The percentage of hits and mean absolute difference of the Buckberry–Chamberlain and Suchey–Brooks methods are 97.3% and 11.24 years, and 85.7% and 14.38 years, respectively. However, this apparently greater applicability of the Buckberry–Chamberlain method is mainly due to the broad age ranges provided. Results indicated that Suchey–Brooks method is more appropriate for populations with a majority of young individuals, whereas Buckberry–Chamberlain method is recommended for populations with a higher percentage of individuals in the range 60–70 years. These different age estimation methodologies significantly influence the resulting demographic profile, consequently affecting the biological characteristics reconstruction of the samples in which they are applied.

1. Introduction

The main objective when studying any archaeological sample is to reconstruct the life of the population studied as far as possible. Paleodemographic studies have the potential to provide important information regarding past population dynamics (Hoppa and Vaupel, 2002). Although a diagnosis of the age and sex are vital in this respect, paleodemographic analysis of osteological remains suffers from a number of limitations, especially when we consider it at a population level (Bocquel-Appel and Masset, 1982, 1985; Hoppa and Vaupel, 2002; Konigsberg and Frankenberg, 1992; Milner and Boldsen, 2012; Milner et al., 2008; Wood et al., 1992). One of the most important of those limitations is the validity of age estimation techniques, which has been largely questioned (Bocquel-Appel and Masset, 1982, 1985; Hoppa and Vaupel, 2002; Konigsberg and Frankenberg, 1992). Thus, despite the fact that determination of the age of sub-adult individuals has been fairly well resolved (Cox, 2001), this is one of the complex steps for adult individuals. Variations in the rate of age-related morphological changes in the various adult age markers on which the various methods are based depend on a complex interaction between three factors (genes, culture and environment) that affect the entire life history of the individual concerned. As a result, errors in this preliminary step consequently affect the subsequent biological and cultural interpretation (Schmitt, 2004). Furthermore, the variability observed in the age markers increases with age and continues to increase throughout a person's life, which is a well known characteristic of the ageing process called Trajectory Effect (Nawrocki, 2010), and it is the reason why the age-estimation error is lower in sub-adult individuals than in adults. The key to the success of any particular method of age estimation lies in an understanding of whether the method is accurate (correct), precise (refined) and repeatable from an intra- and inter-observer stand point when applied to unknown individuals outside of the original reference sample. However, the reference collections used to develop the majority of methods for estimating the age of adult skeletal remains

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are some of the few documented collections (known age, sex and biological origin) that exist, the majority of which are from the USA. Although documented human skeletal collections in museums, anatomical institutes and universities have increased in number since the 19th century, they tend to be rare outside the USA and are not generally sufficiently large to be used as a reference sample or for testing the different methods. Despite this, the error committed during age estimation can only be tested and quantified when applied to a documented or contextualised collection. A contextualised collection includes known demographic data (sex, age, year of birth, geographical area) as well as the socioeconomic and temporal context in which the individuals lived (Rissech and Steadman, 2010).

The pubic symphysis and the auricular surface are two of the most common markers for adult age estimation. The first standards for estimating age based on the pubic symphysis were developed by Todd (1920), who based his work on a sample of white males from the Hamann-Todd osteological collection. Todd subsequently expanded his methodology to white females and black males and females (Todd, 1921a,b,c). More recently, Katz and Suchey (1986) refined the Todd phase method using a sample of modern autopsied remains from the Los Angeles County Coroner's Office. These authors concluded that the sex-and population-based differences had a marked impact on the reliability of the method. However, for American samples, the resulting Suchey–Brooks method (Brooks and Suchey, 1990) is commonly considered to be the best age estimation method, and is widely used in Forensic Anthropology and Bio-archaeological contexts (Garvin and Passalacqua, 2012; Garvin et al., 2012; Hens et al., 2008). The Suchey–Brooks reference sample was based on a large multiracial sample of individuals of diverse socio-economic backgrounds; although the individuals died and were autopsied in Los Angeles, they were born throughout the North American continent with a minority born in Europe, South America and Asia. However, despite its popularity, application of this method outside the USA on current samples from autopsied French individuals (Baccino et al., 1999), Canadian colonists (Saunders et al., 1992), Portuguese and Italians from current cemetery-based skeletal collections (Hens et al., 2008; Santos, 1996) and populations from the Balkans (Djurić et al., 2007) demonstrated biased age estimates and difficulty in determining the age of individuals over 40 years. Furthermore, Sinha and Gupta (1995) observed differences in the timing of age-progressive pubic changes between USA and Indian samples; Hoppa (2000) and Kimmerle et al. (2008) observed similar differences between females from USA and England and between females from USA and Balkans, respectively. In fact, these results are not surprising because Brooks and Suchey's original work (1990) pointed out a wide range of variability, especially in phases III to VI. For this reason, they recommended employing multiple age indicators whenever possible. To try to solve these limitations in the Suchey–Brooks method, some authors (Berg, 2008; Hartnett, 2010) have proposed modifications by adding a new phase, the seventh.

As far as the auricular surface is concerned, Lovejoy was the first to develop a standard method for estimating adult age on the basis of this anatomical region (Lovejoy et al., 1985). This method was based on a collection of early 20th century American cadavers (Hamann-Todd collection), archaeological samples (Libben collection) and forensic cases from the Cuyahoga County Coroner's Office. The auricular surface has the advantage that it is normally more resistant to post-depositional processes than the pubic symphysis and that the morphological changes observed in it continue after the sixth decade of life. However, the Lovejoy method is more difficult to apply than the Suchey–Brooks method, and validation studies have shown it to suffer from repeatability problems (Falys et al., 2006; Murray and Murray, 1991). Thus, in the Belleville Canadian sample, Saunders et al. (1992) found that the reliability decreased after the age of 45 years. Similar results to those found by Murray and Murray (1991) and Falys et al. (2006) were found in Portuguese (Santos, 1996) and Italians (Hens et al., 2008). Q2

Likewise, upon applying the Lovejoy and Suchey–Brooks methods to a Thai collection, Schmitt (2004) reached the conclusion that these methods should not be applied to Asian samples.

On the basis of the above findings, Buckberry and Chamberlain (2002) proposed to refine the Lovejoy method using a sample of 180 individuals from the Spitalfields collection (London). This method is based on the morphological characteristics of the auricular surface described by Lovejoy et al. but accepts that each of them changes independently of the others. As a result, each characteristic is evaluated individually and subsequently combined with the others to give a single value, which the authors term the "Composite Score", that is related to an age range given by the method based on the "Composite Score" obtained. Although this method is the most recent, and some authors have tested (Nagaoka and Hirata, 2008) or proposed modifications to it (Falys et al., 2006), it has seldom been evaluated using documented osteological collections (Hens and Belcastro, 2012; Mulhern and Jones, 2005; Rissech et al., 2012).

Rissech et al. (2012) applied the Suchey–Brooks and Buckberry–Chamberlain methods to a sample originating from the north-western Iberian Peninsula (Valladolid) and concluded that the application of the two methods to a Spanish sample may be problematic and further studies would be required before they could be applied systematically in Spanish forensic and archaeological contexts.

Information regarding the applicability of the different age-estimation methods to samples from different populations and knowledge of population variation in ageing processes are therefore key to obtaining a successful adult age estimation. Despite this, very few studies have evaluated such differences when applying these methods to different populations. Generally speaking, these methods have been developed or tested in current skeletal samples from the UK, USA, Italy, Portugal (Brooks, 1955; Brooks and Suchey, 1990; Gilbert and McKern, 1973; Nemeskéri et al., 1960; Murray and Murray, 1991; Santos, 1996) and, as noted above, a sample from the north-western Iberian Peninsula (Rissech et al., 2012). However, they have never been tested in a documented skeletal sample from the central Iberian Peninsula. The present study was therefore designed to analyse the reliability and accuracy of the two methods proposed, one based on the pubic symphysis (Brooks and Suchey, 1990) and the other on the auricular surface (Buckberry and Chamberlain, 2002), in a 20th century documented skeletal sample from Madrid. Specifically, this work was intended to provide information regarding the performance of the ~~Brooks and Suchey (1990)~~ and ~~Buckberry and Chamberlain (2002)~~ age-estimation methods in a modern population from the central Iberian Peninsula (Madrid) as a continuation of the studies initiated by Rissech et al. (2012) in the north-western Iberian Peninsula (Valladolid) and to gain a more in-depth understanding of the morphological changes to adult age markers during the ageing process in these populations. The ~~Brooks and Suchey~~ method ~~(1990)~~ was selected due to its popularity in forensic and bio-archaeological Spanish contexts, which is highly recommended in Spanish anthropological manuals (Campillo and Subirà, 2004; Márquez-Grant et al., 2010). The ~~Buckberry and Chamberlain~~ method ~~(2002)~~ was also selected because it recently has increased its popularity in Spain (Rissech et al., 2012).

2. Materials and methods

Data were collected from the modern documented skeletal collection housed in the School of Legal Medicine at the Faculty of

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Medicine of the Complutense University of Madrid (Madrid, Spain). This twentieth century collection includes 195 individuals (80♀, 115♂) ranging from 3 to 97 years of age. Demographic information, including age-at-death, was derived from obituary records (Rissech and Steadman, 2010; San Millán, 2011; Ruiz et al., 2012). Like most modern collections, the Madrid collection contains a high proportion of older individuals, reflecting increased life expectancy, lower birth rates and the marked improvement in general health (Rissech and Steadman, 2010). From this collection, the individuals with the three elements of the innominate fused were selected. Individuals displaying innominate pathologies were excluded from the study, while individuals with non-inflammatory osteoarthritis or diffuse idiopathic skeletal hyperostosis were included as these conditions are commonly related to age. A total of 139 individuals (67♀ and 72♂) from 20 to 97 years old were selected. As differences between the right and left pubis (Hens et al., 2008) and the right and left auricular surface (Buckberry and Chamberlain, 2002; Falys et al., 2006) are negligible, only the left side was scored. Fig. 1 depicts the chronological distribution of females and males examined during the course of the analysis. T tests show that the differences in mean ages-at-death for females (69.1 years) and males (57.8 years) are statistically significant ($t = 3.727$, $p = 0.000^*$). The female subsample is slightly older and more evenly distributed than the male subsample. During the laboratory component of the study, the innominates were separated from the rest of the skeleton to prevent subjective information from affecting the results. Thus, the age was calculated without knowing the chronological age of the individuals analysed as no additional information that could affect the study (except for the individual's code) is available where the material is stored. The methods were applied independently and separated by a period of one month.

2.1. Statistical analysis

The success in the performance of an ageing method can be defined as the proximity of an age estimate to an individual's actual chronological age (Hartnett, 2007). We analysed the success in the performance of the Suchey–Brooks, and Buckberry–Chamberlain ageing methods in two ways: 1) by scoring the accuracy; that is, whether or not the chronological age of each individual was included in the age ranges provided for each method; and 2) by evaluating the bias and the absolute difference between estimated age and chronological age for each method, with the estimated age being defined as the average age provided by each method for each age range category. Both bias and absolute difference are good indicators of a method's inaccuracy. Bias is the statistical measure that identifies the direction of the difference between the estimated age and the chronological age (Hens et al., 2008; Martrille et al., 2007; Murray and Murray, 1991; Sinha and Gupta, 1995) – whether the estimated age is over- or under-estimated. If the estimated age is older than the chronological age then the bias is positive. If the estimated age is younger than the chronological age then the bias is negative. Bias was calculated as the average difference between estimated age and chronological age using each method (Σ (estimated age − chronological age)/n).

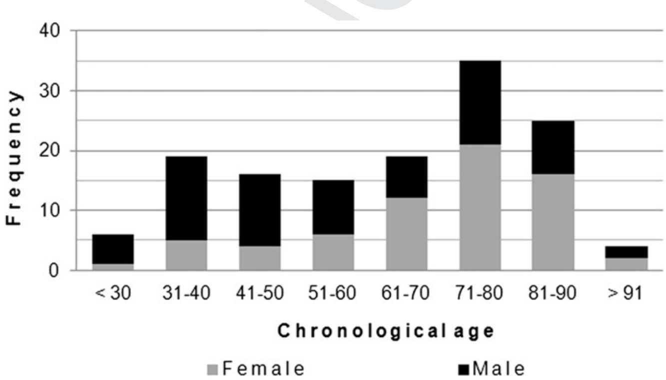

Fig. 1. Age distribution by sex of the 139 individuals sampled from the Madrid collection.

Absolute difference is the statistical measure that evaluates the degree of the method's inaccuracy. Absolute difference was calculated as the average absolute difference between estimated age and chronological age using each method (Σ|estimated age − chronological age|/n). It does not take into account the sign (positive or negative) of the difference between estimated age and chronological age.

Differences in the number of correctly and incorrectly classified individuals (accuracy) between methods and sexes were evaluated with Chi-square tests of independence. Differences in the value of bias and absolute difference between methods were analysed by paired Student's t-test applied in the sample as a whole and in each sex series separately. The sex-based differences in bias and absolute difference for each method were analysed using Student's t-test. The Mann–Whitney U-test was used to evaluate the existence of sex-based differences in bias and absolute difference within each age group. The relationship between age and bias/absolute difference was checked for the 107 individuals (53 females and 54 males) to whom both methodologies could be applied. This relationship was quantified using the Pearson correlation in all cases except those for which one or more of the variables did not fit a normal distribution, in which case the Spearman correlation was applied.

3. Results

For clarity, the results of accuracy will be presented first, followed by the results of bias and absolute difference.

3.1. Accuracy

For the purposes of this analysis, accuracy is defined as whether or not the chronological age of each individual was included in the age ranges provided for each method. The total number of hits obtained using each method for the sample as a whole, and taking the sex into account, can be found in Table 1. This table shows that the Buckberry–Chamberlain method provides a higher accuracy percentage than the Suchey–Brooks method for both the sample as a whole and when considering each sex separately. However, the X^2 test indicates that these differences are only significant for the female series and the sample as a whole (total: $X^2 = 4.105$, $p = 0.043^*$; females: $X^2 = 6.139$; $p = 0.013^*$; males: $X^2 = 0.414$, $p = 0.520$).

An evaluation of the sex-based differences in accuracy when using the same method shows that a higher accuracy percentage in

Table 1
Number of individuals whose chronological age falls within the age intervals estimated using each method (accuracy) for all individuals and when considering each sex separately.

	Female	Male	Total
Suchey–Brooks			
Accuracy	47 (87%)	50 (84.7%)	97 (85.8%)
Inaccuracy	7 (13%)	9 (15.3%)	16 (14.2%)
n	54	59	113
Buckberry–Chamberlain			
Accuracy	64 (98.5%)	55 (88.7%)	119 (93.7%)
Inaccuracy	1 (1.5%)	7 (11.3%)	8 (6.3%)
n	65	62	127

females than in males in all cases and irrespective of the method analysed (Table 1). However, these differences were only significant for the Buckberry–Chamberlain method (Buckberry–Chamberlain: $X^2 = 5.113$, gl = 1, $p = 0.024^*$; Suchey–Brooks $X^2 = 0.122$, gl = 1, $p = 0.727$).

The accuracy obtained when applying Buckberry–Chamberlain and Suchey–Brooks methods in relation to age using 10 year intervals is shown in Fig. 2. For the Suchey–Brooks method, it can be seen that the highest accuracy is retained from 30 years of age until 70 years; from this age, it gradually descends. In contrast, the highest accuracy for the Buckberry–Chamberlain method is found between the ages of 31 and 90 years, descending in the extremes of life (before 31 years and after 90 years). The behaviour of these two methods appears to be the opposite at the extremes of these age groups. Thus, the Suchey–Brooks method seems to provide a greater accuracy than the Buckberry–Chamberlain method for individuals aged less than 40 years, whereas the latter provides a greater accuracy for those aged more than 70 years. However, it is necessary to say that both methods display a marked accuracy decrease in individuals over 90 years old. This is probably due to the upper age limit of the last age stage in both methods. In the Suchey–Brooks method it is 87 years in females and 86 years in males, and in the Buckberry–Chamberlain method it is 92 years for both sexes. This indicates that people over 87 years for Suchey–Brooks method and over 92 years for Buckberry–Chamberlain method would never be well classified.

3.2. Bias and absolute distance

Table 2 provides the mean bias and absolute difference associated with the two ageing methods, considering the entire sample and each sex. The Buckberry–Chamberlain method performed comparatively well with regards to bias in both considering the entire sample and sexual series. When considering the entire sample, the mean bias for Buckberry–Chamberlain method is close to zero and the mean bias for Suchey–Brooks method is negative (underestimation). In fact, in the Suchey–Brooks method the mean bias is also negative when considering sexes separately and in contrast for Buckberry–Chamberlain method the mean bias oscillates between a negative bias (underestimation) in the feminine series and positive bias in the masculine series (overestimation). Student't t-test shows that these differences between Suchey–Brooks and Buckberry–Chamberlain methods are significant in both cases, when the whole of the sample ($t = -15.603$, $p = 0.000^*$) and sexual series are considered (females: $t = -10.633$, $p = 0.000^*$; males: $t = -11.815$, $p = 0.000^*$). With regard to the sexual

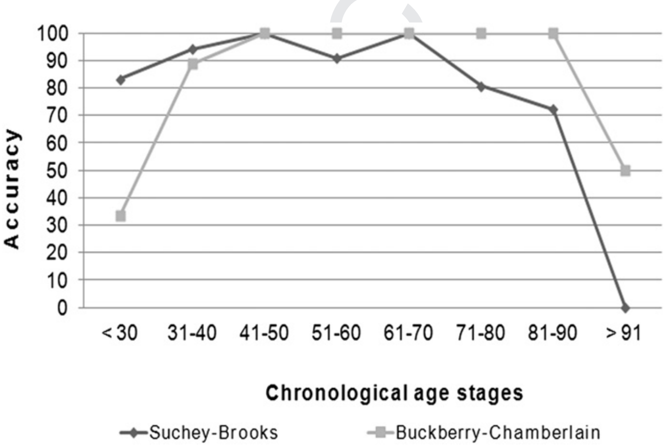

Fig. 2. Number of successes (reliability) for the two methods studied in relation to age using 10 year age intervals.

Table 2
Mean bias and absolute difference values for the Suchey–Brooks and Buckberry–Chamberlain methods for the sample as a whole and for each individual series.

	Female	Male	Total
Suchey–Brooks			
Bias	−15.17	−10.52	−12.74
Absolute difference	16.04	12.87	14.38
n	*54*	*59*	*113*
Buckberry–Chamberlain			
Bias	−4.09	5.13	0.41
Absolute difference	9.45	13.12	11.24
n	*65*	*62*	*127*

differences observed in the performance of each method, Student's t-test shows that the underestimation obtained when applying Suchey–Brooks and Buckberry–Chamberlain methods is significantly higher for females than for males in both methods (Suchey–Brooks: $t = -2.110$, $p = 0.037^*$; Buckberry–Chamberlain: $t = -3.936$, $p = 0.000^*$).

As far as the absolute difference is concerned, it can be seen from Table 2 that the degree of the difference obtained when applying the Buckberry–Chamberlain method to the sample as a whole is significantly lower than that obtained when applying the Suchey–Brooks method ($t = 2.392$; gl = 106; $p = 0.019^*$). Both methods provide the same absolute difference for the male series ($t = -0.286$; gl = 53; $p = 0.776$) but not for the female series, where the absolute difference for the Buckberry–Chamberlain method is significantly lower than for the Suchey–Brooks method ($t = 4.792$; gl = 52; $p = 0.000^*$). Analysis of the possible sex-based differences in absolute difference for each method showed that these differences are only significant for the Buckberry–Chamberlain method (Buckberry–Chamberlain: $t = -2.625$, gl = 114.632, $p = 0.010^*$; Suchey–Brooks: $t = 1.725$, gl = 111, $p = 0.087$).

In order to perform a more in-depth analysis of the bias (Table 3) and absolute difference (Table 4) for each of the methods studied herein, the sex-based dimorphism of both variables for the different age ranges was determined. The results indicated a lack of sex-based differences in the bias or absolute difference for either of these methods in any age range, except for bias in the ranges 20–40 and 41–60 years when using the Suchey–Brooks method (Table 3).

To determine the relationship between bias and absolute difference with chronological age more specifically, those individuals in which both Suchey–Brooks and Buckberry–Chamberlain methods could be applied were analysed. Figs. 3 and 4 show the

Table 3
Descriptive statistics for the bias in terms of method, sex and age group. Mann–Whitney U-test to evaluate the sex-based differences. Such–Br: Suchey–Brooks method. Buck–Cham: Buckberry–Chamberlain method.

Age	Method	Sex	*n*	Mean	DS	Mean rank	*U*	*p*
20–40 years	Such–Br	F	6	−5.517	2.34	6.25	16.5	0.013*
~~años~~		M	17	1.518	8.27	14.03		
	Buck–Cham	F	6	15.403	11.46	9.92	38.5	0.310
		M	18	~~20.31~~	10.03	13.36		
41–60 years	Such–Br	F	7	~~1.80~~	5.54	19.57	17.0	0.004*
~~años~~		M	18	−7.567	6.04	10.44		
	Buck–Cham	F	10	5.428	7.44	12.30	68.0	0.228
		M	19	8.726	9.47	16.42		
61–80 years	Such–Br	F	27	−15.444	6.70	24.19	184.0	0.272
		M	17	−19.106	8.26	19.82		
	Buck–Cham	F	32	−5.292	5.92	23.88	236.0	0.661
		M	16	−5.141	6.99	25.75		
>81 years	Such–Br	F	14	−27.271	6.83	10.79	46.0	0.856
		M	7	−26.457	5.41	11.43		
	Buck–Cham	F	17	−14.316	5.10	13.82	71.0	0.792
		M	9	−14.588	4.28	12.89		

Table 4
Descriptive statistics for the absolute difference in terms of method, sex and age group. Mann–Whitney *U*-test to evaluate the sex-based differences. Such–Br: Suchey–Brooks method. Buck–Cham: Buckberry–Chamberlain method.

Age	Method	Sex	*n*	Mean	DS	Mean rank	*U*	*p*
20–40 years ~~años~~	Such–Br	F	6	5.517	2.34	13.33	43.5	0.575
		M	17	6.035	5.66	11.53		
	Buck–Cham	F	6	~~16.96~~	8.41	10.25	40.5	0.378
		M	18	20.607	9.37	13.25		
41–60 years ~~años~~	Such–Br	F	7	4.857	2.63	9.57	39.0	0.158
		M	18	8.144	5.18	14.33		
	Buck–Cham	F	10	7.574	4.93	11.90	64.0	0.164
		M	19	11.028	6.46	16.63		
61–80 years	Such–Br	F	27	15.444	6.70	20.81	184.0	0.272
		M	17	19.106	8.26	25.18		
	Buck–Cham	F	32	6.040	5.12	24.34	251.0	0.913
		M	16	6.371	5.81	24.81		
>81 years	Such–Br	F	14	27.271	6.83	11.21	46.0	0.856
		M	7	26.457	5.41	10.57		
	Buck–Cham	F	17	14.316	5.10	13.18	71.0	0.792
		M	9	14.588	4.28	14.11		

plot of the bias and absolute difference with chronological age segregated by sex. Results indicate that both methods behaved very differently as regards both bias and absolute difference. Thus, for the bias (Fig. 3), the Suchey–Brooks method tended to underestimate the age of both male and female individuals, with this underestimation increasing with age, thereby leading to a significantly negative correlation for both sexes (females: $r_s = -0.855$, $n = 54$, $p = 0.000^*$; males: $r = -0.807$, $n = 59$, $p = 0.000^*$); the best age estimates were therefore obtained for younger individuals. In contrast, the Buckberry–Chamberlain method (Fig. 3) overestimated the age of both male and female individuals up to the age of approximately 60 years but underestimated it for subsequent age ranges. The best age estimations using this method were obtained for the 60–70 years age range and the worst for the youngest (greater positive bias) and oldest individuals (greater negative bias). As for the previous method, this leads to a negative correlation for both sexes (females: $r_s = -0.878$, $n = 65$, $p = 0.000^*$; males: $r = -0.835$, $n = 62$, $p = 0.000^*$).

The absolute difference (Fig. 4) was found to behave in a similar manner for both sexes in each method. The Suchey–Brooks method appears to follow a rising trend, with the best estimates being found for the youngest age group and the largest differences for the oldest individuals (females: $r_s = 0.858$, $n = 54$, $p = 0.000^*$; males: $r = 0.764$, $n = 59$, $p = 0.000^*$). In contrast, the Buckberry–Chamberlain method follows a "U-shaped" trend, with the highest differences being found for the youngest and oldest individuals and the best estimations occurring around 68 years of age: the female series shows a quadratic correlation with age ($r = 0.669$, $n = 65$, $p = 0.000^*$) and the male series, a cubic correlation ($r = 0.669$; $n = 62$; $p = 0.000^*$). A comparison of the two methods shows that better results are obtained using the Suchey–Brooks method at younger ages whereas use of the Buckberry–Chamberlain method is recommended in the 60–70 years age range.

4. Discussion

In general terms, our findings indicate a broader applicability of the Buckberry–Chamberlain method with respect to the Suchey–Brooks method, as can be seen from the higher accuracy percentage (93.7% vs. 85.7%) and lower absolute difference (11.24 vs. 14.38 years) for the sample as a whole, and are thus in accordance with those of Rissech et al. (2012) for a collection from Valladolid (NW Spain). It should be noted that the accuracy percentages obtained herein using the Suchey–Brooks method are higher than those obtained by Rissech et al. (2012) and Santos (1996) for their samples from the Iberian Peninsula and Djurić

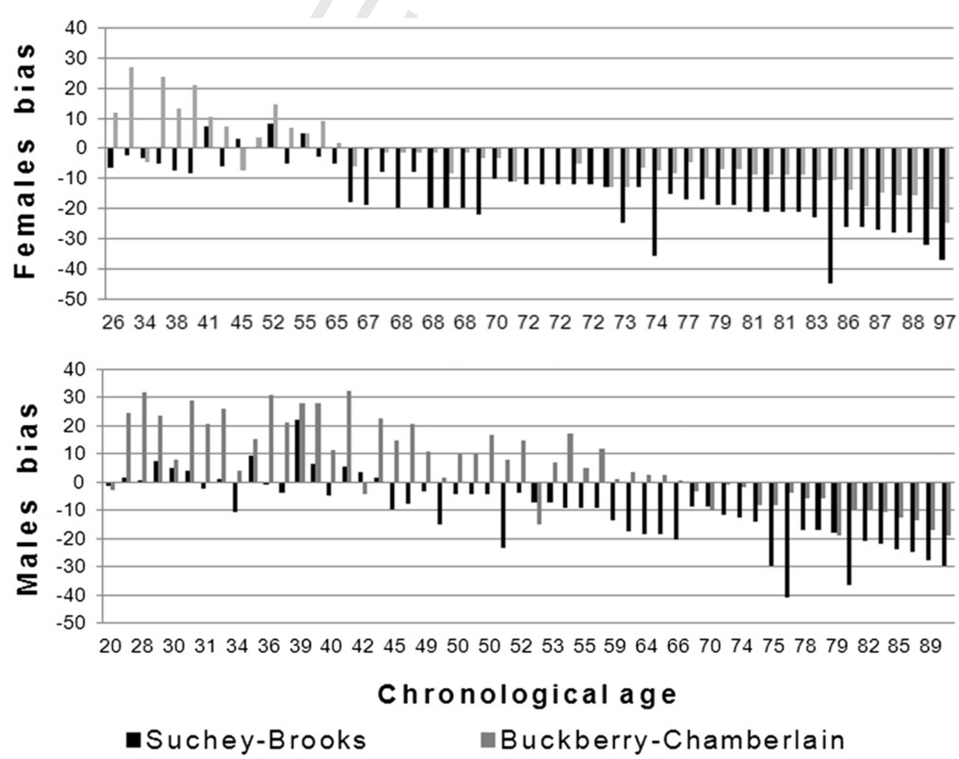

Fig. 3. Difference between chronological and estimated age-at-death (bias) for each female (top) and male (bottom) obtained upon application of the Suchey–Brooks and Buckberry–Chamberlain methods.

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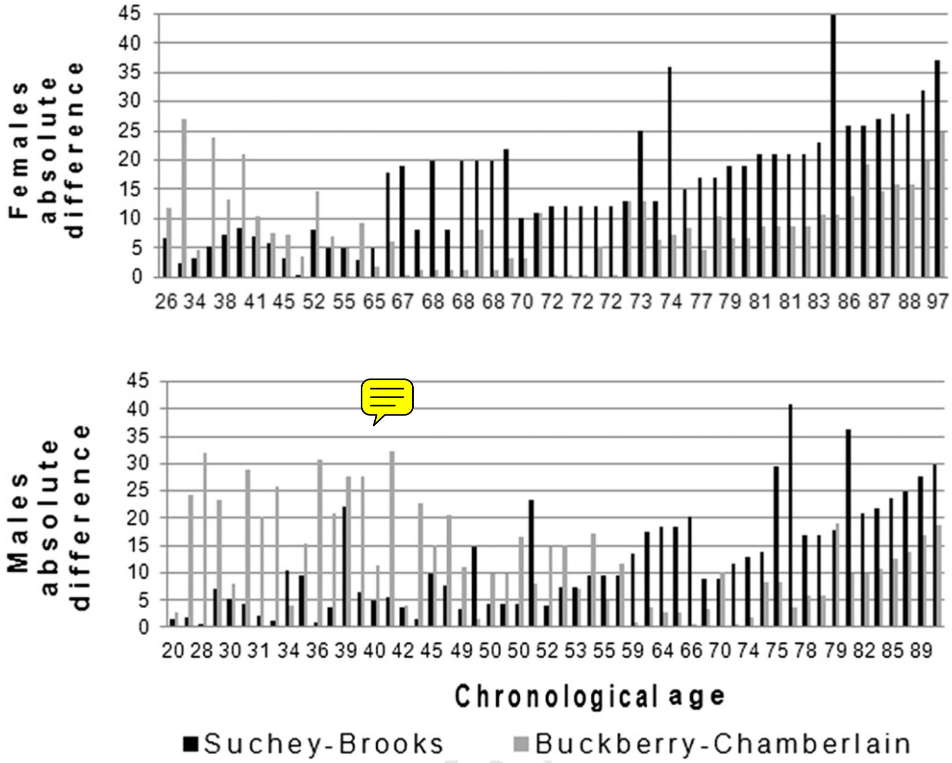

Fig. 4. Absolute difference between chronological and estimated age-at-death for each female (top) and male (bottom) obtained upon application of the Suchey–Brooks and Buckberry–Chamberlain methods.

et al. (2007) based on a population from the Balkans. We have also obtained better results in terms of accuracy percentage when using the Buckberry–Chamberlain method than those obtained by Rissech et al. (2012), except for the male sample, for which the latter obtained a higher percentage. As far as the sex-based dimorphism is concerned, the Buckberry–Chamberlain method showed significant sexual differences, while results of the Suchey–Brooks method was comparable between males and females in accordance with the findings of Djurić et al. (2007) and Rissech et al. (2012). However, in the present study, the best results were found in females, whereas in Djurić et al. (2007) and Rissech et al. (2012) they were found in males. These results, in conjunction with significant sexual differences found in bias and absolute difference averages in the present study and the sexual differences of score distribution observed by Hens and Belcastro (2012), suggest that in further analysis when using the Buckberry–Chamberlain method, the sexes should not be combined. In fact, these results are not surprising because Igarashi et al. (2005) demonstrated that the mode of chronological change in the auricular surface differs between males and females.

The mean absolute difference obtained herein when applying the Suchey–Brooks method is higher than that reported by Martrille et al. (2007) in a North American sample and Hens et al. (2008) in a documented Italian collection and lower than the results of Schmitt (2004) in a Thai skeletal collection. The mean absolute difference obtained when using the Buckberry–Chamberlain method is higher than that obtained by the original authors (Buckberry and Chamberlain, 2002) and by Falys et al. (2006) in two English samples, but lower than that reported by Mulhern and Jones (2005) in their American collection and Hens and Belcastro (2012) in their Italian collection.

Although the bias and absolute difference values obtained suggest that the Buckberry–Chamberlain method has a broader applicability than the Suchey–Brooks method when considering the sample as a whole, a more in-depth analysis highlights the wide range of the original age intervals defined by the former. Indeed, although both methods provide wide estimated age intervals (Tables 5 and 6), those obtained using the Buckberry–Chamberlain method are wider than those obtained using the Suchey–Brooks method after phase III (see Tables 5 and 6), which are the phases most used in this study due to the high proportion of elderly individuals in the sample analysed. For example, when using the Buckberry–Chamberlain method, phases IV (29–81 years) and V (29–88 years) have an amplitude of 52 and 59 years, respectively,

Table 5
Descriptive statistics for each phase given by the original study of the Suchey–Brooks pubic age determination system (Brooks and Suchey, 1990).

Phase	Females				Males			
	Mean age	Standard deviation	95% range	Amplitude range	Mean age	Standard deviation	95% range	Amplitude range
I	19.4	2.6	15–24	9	18.5	2.1	15–23	8
II	25.0	4.9	19–40	21	23.4	3.6	19–34	15
III	30.7	8.1	21–53	32	28.7	6.5	21–46	25
IV	38.2	10.9	26–70	44	35.2	9.4	23–57	34
V	48.1	14.6	25–83	58	45.6	10.4	27–66	39
VI	60.0	12.4	42–87	45	61.2	12.2	34–86	52

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Table 6
Descriptive statistics for each phase by the original study of the Buckberry–Chamberlain auricular surface age estimation system (Buckberry and Chamberlain, 2002).

Phase	*n*	Average age	Standard deviation	Median age	Range	Amplitude range
I	3	17.33	1.53	17	16–19	3
II	6	29.33	6.71	27	21–38	17
III	22	37.86	13.08	37	16–65	49
IV	32	51.41	14.47	52	29–81	52
V	64	59.94	12.95	62	29–88	59
VI	41	66.71	11.88	66	39–91	52
VII	12	72.25	12.73	73	53–92	39

thus covering the entire adult life of the individual. This apparently broader applicability of the Buckberry–Chamberlain method with respect to the Suchey–Brooks method is also probably related to the mean age of the sample studied here (63.24 years) and the low proportion of individuals younger than 60 years (40.3% of the sample), for whom, according to our findings, the Suchey–Brooks method is more appropriate.

Generally speaking, and as was the case for the Suchey–Brooks method in this study (see Fig. 4), the estimation error produced upon applying a specific method is expected to increase with age (Nawrocki, 2010), as described previously by numerous authors when applying different age-estimation methods (Hens et al., 2008; Katz and Suchey, 1986; Martrille et al., 2007; Mulhern and Jones, 2005; Rissech et al., 2007; Sakaue, 2006; Schmitt, 2004). However, this was not found to be the case for the results obtained using the Buckberry–Chamberlain method, probably due to the mean age and range structure estimated by the method itself. Indeed, this method presents a "U-shaped" pattern and thus has a greater applicability for the 60–70 years age range, in agreement with the findings of the authors of this method (Buckberry and Chamberlain, 2002) and those of Mulhern and Jones (2005) and Hens and Belcastro (2012). This greater applicability of the Buckberry–Chamberlain method to individuals aged between 60 and 70 years is probably due to the fact that the mean ages for the final four of the seven original phases of which this method consists are higher than 50 years (see Table 6). The estimated age intervals and their average ages given by the original methods, which are determined by the phases of the method, are higher for the Buckberry–Chamberlain method than for the Suchey–Brooks method (see Tables 5 and 6 and Fig. 5). It should also be noted that five of the six original phases determined using the Suchey–Brooks method have a mean estimated age of less than 50 years. As such, given that the maximum mean age estimated using this method is 60 years for females and 61.2 years for males, the Suchey–Brooks method is likely to be more suitable for detecting younger individuals. Indeed, the Suchey–Brooks method is based on morphological changes that occur upon formation of the distal pubic epiphysis (located in the pubic symphysis region), which complete their maturation process in the fourth decade of life (Scheuer and Black, 2000; Schmitt and Broqua, 2000), whereas the age-related morphological changes in the auricular surface are degenerative, occur at an early stage and continue up until around 60 years of age (Bedford et al., 1993; Lovejoy et al., 1985; Sashin, 1930).

Apart from determining the sex of the individual, age is one of the most important criteria for excluding large parts of the population for identification purposes (Modi, 1988). Accuracy is therefore vital for identifying remains in such cases, and the results of this study show that neither of the methods analysed is sufficiently accurate. It would therefore be desirable to reduce the error intervals for both methods in order to be able to use them effectively in Forensic Anthropology and Bioarchaeology.

4.1. *Implications for the mortality profiles*

In order to approximate the mortality profile of the sample studied on the basis of the two methods used, a graph of the percentage of individuals in each age group depending on the method was constructed (Fig. 6). This graph clearly shows that the profile can change drastically depending on the method applied. The difference is perhaps clearest for the 41–50 and 71–80 years age groups, in which more than 30% of the sample was placed by one of the methods used whereas the other did not classify any individual in these groups. On the other hand, the Suchey–Brooks method does not assign individuals with an average age of more than 70 years, and the Buckberry–Chamberlain method more than 80 years, thus meaning that a large proportion of the sample could be incorrectly classified, as a result of age underestimation, when applied to osteological series mainly containing elderly individuals, such as the current Spanish population. Physical anthropologists have long been confronted with the problem of ageing older individuals, particularly those over 50 years of age. This is due to the great variability expressed by the age markers during the ageing process, specifically in older ages. In sub-adult individuals these changes occurs more predictably but once the skeletal development has ended, maturation of the skeleton occurs with less of an age specific chronology (Cox, 2000; Maples, 1989). There no set rates for the maintenance of the adult skeleton (Brooks and Suchey, 1990; İşcan and Loth, 1989) and for this reason, the observed variability in age markers increases and the accuracy of the ageing methods decreases with age. Many researches in Physical Anthropology have proposed that it may be nearly impossible to determine age in elderly skeletons (Meindl and Lovejoy, 1989; Suchey et al., 1986). Recently and regarding the Suchey–Brooks method, Komar (2003) determined that only 20% of the individuals greater than 50 years old were aged accurately in a Bosnian forensic

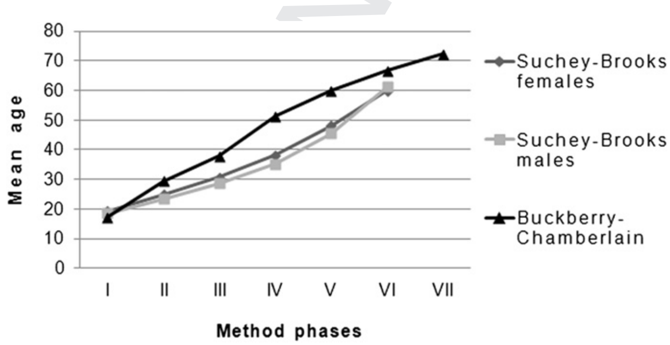

Fig. 5. Mean age (Y-axis) for each phase (X-axis) given by the original studies of the Suchey–Brooks and Buckberry–Chamberlain methods.

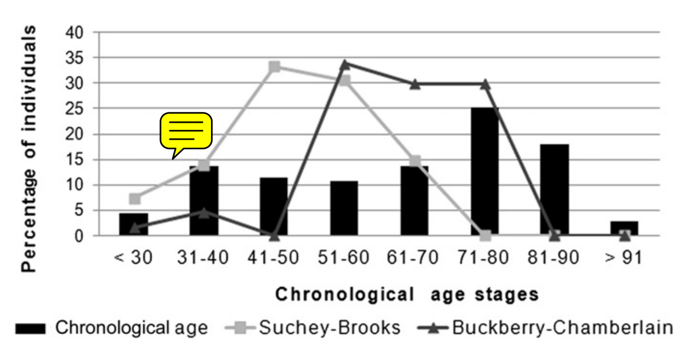

Fig. 6. Different mortality profiles depending on the method selected. Percentage of individuals (Y-axis) vs. age groups in years (X-axis).

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population. In this direction, some authors (Berg, 2008; Hartnett, 2010) have presented some reviews of this issue that could be a good alternative to original ageing method based on the pubic symphysis reducing the age ranges associated with the age phases and increasing the accuracy and precision, especially in older individuals with the creation of a seventh phase. The inclusion of a phase VII into future analyses will hopefully rectify this problem.

However, in light of the fact that the life expectancy of earlier populations was much lower, and the population group therefore consisted of much younger individuals than at present, the Suchey–Brooks method may be more appropriate for archaeological samples than the Buckberry–Chamberlain method. For forensic samples, however, both methods could be useful applied to Spanish populations, although it would be important to consider the different accuracies of them along with the lifespan of the individuals to minimise errors.

In any case, age diagnosis in forensic cases requires a level of accuracy that neither of these methods is currently able to achieve as both minimise the errors by broadening the variation ranges and place greater importance on accuracy than on precision. A further interesting aspect can be deduced from Fig. 6, namely that there appears to be a time lapse of around 10 years between the two methods as, if the mortality profiles of the two methods were superimposed on the graph, they would broadly overlap to give very similar profiles. Such considerations are important when it comes to choosing an age-estimation method in order to minimise the error produced during the estimation. It should also be noted that, although the differences between the estimated and chronological ages may be small at an individual level, their impact at a population level may be much greater, and even significant, when the mortality profiles for the samples collected are analysed.

The different behaviour of these two methods in terms of bias and absolute difference obtained during age determination highlights the need to evaluate all current methodologies before applying them indiscriminately to a sample as this may lead to different mortality profiles and therefore different conclusions. The importance of precision in forensic cases, the main objective of which is personal identification, has already been noted. In this sense, the current study shows the need to develop new and more precise methods for estimating adult age that lead to a reduction in the age intervals and greater flexibility in the sense of being able to vary the reference sample according to the characteristics of the sample to be studied. The emphasis is finding statistical methods that will have correct "coverage" (Konigsberg et al., 2008). "Coverage" means if a method has a stated coverage of 50%, then approximately 50% of the individuals in a particular stage of a method should have ages that are between the stages age limits, and that approximately 25% should be below the bottom age limit and 25% above the top age limit (Konigsberg et al., 2008). In a number of applications it is shown that if an appropriate prior age-at-death distribution is used, then the method will provide accurate "coverages". Recent work in this field points to Bayesian inference-based methods, the utility and efficacy of which have already been demonstrated (Godde and Hens, 2012; Lucy et al., 1996; Rissech et al., 2006, 2007; Storey, 2007).

5. Conclusions

The present study has evaluated two adult age-estimation methods based on the pubic symphysis (Suchey–Brooks) and auricular surface (Buckberry–Chamberlain) in a sample from Madrid on the basis of their accuracy, bias and absolute difference between estimated age and chronological age. The results highlight the lack of precision of both methods, as seen from their broad age ranges, which do not well represent the skeletal ageing process. When considering the age of the individuals, and as a result of the bias and absolute difference distributions, the Suchey–Brooks method appears to more suitable for samples containing a majority of individuals younger than 60 years of age, such as archaeological samples, whereas the Buckberry–Chamberlain method appears to be more suited to samples containing a greater percentage of individuals older than 60 years, such as current samples. The different conformation of these two methods in terms of bias and absolute difference highlights the need to evaluate current methodologies before applying them systematically as they are likely to provide different mortality profiles and therefore lead to different conclusions.

This study also suggests that future methods for estimating the age of adult individuals should be tested in different populations and reference collections in order to minimise the space/time differences between the sample with which the method has been developed and the study to which it is applied. Finally, the results of this study suggest that age-estimation methods should provide greater precision in the form of a reduction in the age intervals and greater flexibility in the sense of being able to vary the reference sample according to the characteristics of the sample to be studied. Both these aspects are provided by Bayesian inference-based methods, which are able to convert age indicators into estimated ages whilst reducing the age intervals and mean errors.

Further research on the application of these two methods on Spanish reference samples is necessary prior to applying them systematically in forensic and archaeological contexts.

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