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The acetabulum as an adult age marker and the new IDADE2 (IDADE2 web page)

Short running title: IDADE2 web page

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ABSTRACT

Objective: In 2006, an age estimation method was proposed utilizing Bayesian inference to interpret age-progressive changes in the acetabulum. This was accompanied by the IDADE2 software to facilitate calculations. However, the MS-DOS operating system on which the software was based became obsolete. The main goal of this paper is to present the new IDADE2, which incorporates web-based facilities.

Methods: The original IDADE2 has been re-written in R and presented as a web page. As in the original, this web page uses Bayesian inference to estimate age of unidentified individuals. The materials used to create the reference datasets of this web page include acetabular scores from documented skeletal samples from Spain (n = 24♀ and 52♂), Portugal (n = 317♀ and 294♂), and the US (n = 370♀ and 456♂).

Results: The IDADE2 website has 8 sections. Six of these are informative to guide the user. The other two (Option 1 and Option 2) are dedicated to estimating age at death. Option 1 allows users to estimate the age of individual(s) in their test sample based on our reference data of acetabular scores. Option 2 allows users to estimate age from the acetabulum with their own reference and test collections or—if the users prefer—another age marker and method of choice.

Discussion: The IDADE2 website is applicable both to forensic anthropological casework on single individuals and to bioarchaeological analyses of large skeletal samples. This website is easy to use and freely accessible, responding to previous critiques and incorporating method advancements.

Keywords: adult age, age estimation, aging process, acetabulum

INTRODUCTION

At the beginning of the 21st century, biological anthropologists began to observe that the age-progressive changes of the acetabulum could be useful to estimate age at death in adults (Rissech, 2001; Rissech & Malgosa, 2000; Rissech, Sañudo, & Malgosa, 2001; Rougé-Maillart, Telmon, Rissech, Malgosa, & Rougé, 2004). In 2006, Rissech and colleagues (Rissech, Estabrook, Cunha, & Malgosa, 2006) proposed seven variables of the acetabulum (1. acetabular groove; 2. acetabular rim shape; 3. acetabular rim porosity; 4. apex activity; 5. activity on the outer edge of the acetabular fossa; 6. activity of the acetabular fossa; 7. porosities of the acetabular fossa) to be used in adult age estimation (Figure 1). The method was based on a Portuguese sample of 242 males from the documented skeletal collection of Coimbra, Portugal. Each of the seven variables of the acetabulum was broken into different states describing the different morphological conditions of the acetabular region (e.g., acetabular groove can be scored as: no groove [0], groove [1], pronounced groove [2], and very pronounced groove [3]). Bayesian inference was used to evaluate the method's accuracy (Rissech et al., 2006). Results indicated the potential value and applicability of the seven acetabular variables, showing 89% accuracy by Bayesian prediction. In 2007, the same authors tested the method proposed in 2006 (Rissech, Estabrook, Cunha, & Malgosa, 2007) based on 394 males aged between 15 to 99 years old, from four documented Western European skeletal collections. These collections were: the Coimbra and Lisbon collections from Portugal, the UAB collection from Spain, and the St. Bride collection from England. Their results showed significant correlation between all the acetabular variables and chronological age, demonstrating the potential value of the acetabulum as an age marker for young, middle-aged, and older adults. After these observations, the acetabulum became a focus of interest in the adult aging research field (Calce, 2012; Mays, 2012; Miranker, 2016; Powanda, 2008; Rissech et al., 2018; Rougé-Maillart, Jousset, Vielle, Gaudin, & Telmon, 2007; San-Millán, Rissech & Turbón, 2017a, 2017b, 2019; Stull and James, 2010; Venara et al., 2013; Winburn, 2018; among others).

However, the broader application of this method was impeded by the nature of IDADE2, the computer program used to perform the probabilistic calculus and obtain the age estimates. The original IDADE2 was a free, downloadable program created by the late Professor George Estabrook from the University of Michigan to facilitate calculations for age estimation by Bayesian inference (Rissech et al., 2006). However, this program was written in the MS-DOS computer operating system for x86-based personal computers. Although MS-DOS was the main operating system for personal computers during the early 1990s, it was gradually superseded by the Microsoft Windows operating system, offering a graphical user interface. In addition, because of the non-visual appearance of the MS-DOS system, running the old IDADE2 was difficult (Calce, 2012; Winburn, 2017). To solve these problems, the original IDADE2 has been re-written in the open source programming language and statistical environment R (R Core Team, 2018) and presented as a PHP (Hypertext Preprocessor) web server and a web page user interface (IDADE2 web page) with an easier performance and broader applicability. PHP is a widely used, open source general-purpose scripting language that is especially suited for web development. The advantage of using this method compared with the old MS-DOS method is that the new IDADE2 does not need to be locally installed in any computer and can be launched through the web page from any computer with only an Internet connection. We have also improved the speed of the calculations, and in only a few seconds, the server is capable of returning the results.

The objective of this paper is to present the new IDADE2 web page (http://bass.uib.es/~jaume/IDADE2/https/index.html) and its utilities. The new IDADE2 incorporates the most recent information on the acetabulum as an adult age marker (Mays 2012; Rissech et al., 2018; San-Millán et al., 2017a, 2017b, 2019; Winburn, 2018) as well as method refinements (San-Millán et al., 2017b) that have improved the clarity and repeatability of acetabular variable scoring (San-Millán et al., 2019).

MATERIALS AND METHODS

The material used to construct the database of the IDADE2 web page is constituted by a total of 711 females and 802 males coming from three modern documented skeletal collections in Europe and North America. Specifically, these collections are: Valladolid, Lisbon, and the Bass Collections. Details regarding these European and European-American collections appear in Table 1. Allysha P. Winburn (Powanda, 2008) collected the Valladolid data, and Marta San-Millán collected the Bass data (San-Millán et al., 2019), both using the Rissech et al. (2006) method. Marta San-Millán collected and updated the Lisbon and Bass data using the SanMillán-Rissech method (San-Millán et al., 2019).

Statistical and mathematical procedures

The IDADE2 web page uses the same Bayesian method as the old IDADE2 software (Rissech et al., 2006), with mathematical procedures previously described by Lucy et al. (1996). The IDADE2 web page uses observations of known-age skeletal individuals in a reference collection to estimate a relative probability distribution of ages for other observed individuals. For each individual, the IDADE2 web page calculates an age likelihood distribution over age classes and estimates age as the expected value of age, calculated as the sum over age classes of the center of the age class times the probability of the age class. The spread of the estimating probability distribution is expressed as a 95% confidence interval, which is a sequence of one or more consecutive age classes containing at least 95% of the distribution. In addition, two measures of accuracy (error and fit) are also calculated. The error is calculated as the difference between estimated age and chronological age. Fit is calculated as the sum over age classes of the minimum number of years that must be added to or subtracted from the known age to get an age that falls into that age class times the probability of that age class. Smaller values of Fit indicate that the estimating distribution is more closely centered around the known age.

In the IDADE2 web page, prior probability (the probability that the age at death of an unknown individual falls in an age class before any bones have been examined) is estimated as the fraction of individuals in the reference collection with known age at death in that age class. The posterior probability (the probability that the age at death of an unknown individual falls in an age class after a skeletal reference sample has been examined) is based on conditional probability distributions of age (class) at death given that a particular osteological feature had been observed in the test specimen (Aykroyd, Lucy, Pollard, & Roberts, 1999). These distributions are estimated by observing frequencies in the reference collection. Therefore, our underlying assumptions are: variables are independent; and test individuals are at least as old as the youngest individuals in the reference sample and belong to a population whose survivorship is similar to that of the reference collection.

Probability calculation

Suppose a reference collection (hundreds of individuals) has been described for N variables (for instance: groove, rim shape, rim porosity, apex activity, etc), and for each individual, age at death is known. The collection is used as a training set.

Also, a specimen whose age at death is to be estimated would be described with states (values) for those N variables observed for that specimen. Let c1, c2, .., cN be the observed values of the N variables.

IDADE2 estimates the probability that the age at death of that specimen is in age class 'a', an age interval (for instance, from 20 to 25 years), given that those states were observed, as described below.

Let C mean the event that c1 and c2 and .. and cN were observed.

Let A mean the event that the specimen is in age class 'a', the age interval.

Using Bayes law:

$\mathrm{Pr}\ (A/C) = \mathrm{Pr}\ (\mathrm{C/A}).\frac{PrA}{PrC},$

which means that the probability that a specimen with variables C be in an interval class ‘a’ can be calculated as a function of the probability that the values C be observed in the interval ‘a’, the probability that an individual be in the class ‘a’ and the probability of observing the values C in all the training population.

Assuming that variables are independent within the age class A, we have:

$\mathrm{Pr}\ (A/C) = Pr(c1/A).Pr(c2/A).....Pr(cN/A).\frac{PrA}{PrC}.$

This formula enables us to use observed frequencies to estimate a predicted probability distribution over age classes for a specimen with observed values for the N indicators.

Denote with the following notation:

- nfage[a] = number of reference specimens in age class 'a',
- nf = total number of reference specimens,
- fre[i,a,ci] = number of reference specimens in age class 'a' and in state ci for variable i.

  Then,
- Pr(A) is estimated by nfage[a] / nf,
- Pr(ci/A) is estimated by fre[i,a,ci] / nfage[a].

These estimates are substituted in the equation above to begin to calculate an estimated probability that the specimen is of age 'a'.

Without further information, Pr(C) is basically unknown. However, Pr(C), the probability of observing the values or states in the N variables, is unconditional (does not consider the age of the specimen), and so we use it as a scaling factor chosen so to make the sum of the probabilities of all the age classes equal 1. When Pr(C), estimated in this way, is low, it suggests that the combination of states is unusual in the context of the reference collection, meaning that there are only few specimens with these observed states. Where the scaling constant is too small the accuracy of the estimate is called into question. This is because a very small scaling constant is the result of the availability of only a few specimens with the observed states for possible predicted ages, which presses the limits of computational accuracy. When the scaling constant falls below 0.0000001, this indicates the data is too little to obtain accurate calculations and because of this IDADE2 does not attempt to calculate a predicted age distribution. In this case, an NA (not available) is returned for the software.

RESULTS

The work mentioned in the above section resulted in the IDADE2 web page. This website uses observations of known-age skeletal individuals from a documented reference collection (reference sample) to estimate a relative likelihood distribution of ages and a specific estimated age at death in other skeletal individual or individuals (test sample). For an easy utilization, the site was structured in eight different sections (called "utilities"), which are described below.

The IDADE2 web page and its utilities

This web page has eight sections or utilities (see Figure 2). Six of these sections (at the top of the web page, see Figure 2) are informative (Home, Usage, Methods, Benchmark, Help, and Contact). These sections guide the user through the website, provide information on the acetabulum as an adult age marker, and describe the mathematical procedure of the IDADE2 age estimation. The remaining two sections (Option 1 and Option 2)—the two buttons at the bottom of the web page (Figure 2)—are dedicated to the probabilistic calculus of estimating age. These two sections (Option 1 and Option 2) are accessible through the initial page of IDADE2 (Figure 2), and they can also be found as quick accesses at the bottom of each page on the website. These two sections provide the user with the opportunity to estimate the age of a test sample based on a reference sample by Bayesian inference. This test sample can be either a large sample or one individual; for example, if you want to estimate the age of one (or several) individual(s), you can directly copy and paste your data in the window called “Test collection” (Figure 3). If your test collection is large, you can upload it using the button called “Test collection file” (Figure 3). The “Test collection” window and “Test collection file” button can be found in both Option 1 and Option 2. After the calculations, the IDADE2 web page will provide the results.

Option 1 allows users to estimate the age of their test sample based on our reference data of acetabular scores collected from documented skeletons using the “Rissech” and “SanMillán-Rissech” methods (Rissech et al., 2006; San-Millán et al., 2017b). Using each of these two methods—and based on previous studies which observed population (Rissech et al., 2007; Rissech et al., 2018) and sex differences (Mays, 2012; San-Millán et al., 2017a, 2017b)—the user can work with different types of datasets from the Iberian Peninsula and from North Americans of European ancestry. The method and reference sample can be chosen by clicking the “Reference collection” button (Figure 3). Thus, if the user chooses the original method (Rissech et al., 2006), they can work with the Valladolid collection (Spanish) or with the Bass collection (European-American). If the user chooses the revised SanMillán-Rissech method (San-Millán et al., 2017b), they can work with the Lisbon collection (Portuguese) or the Bass collection (European-American). In addition, Option 1 allows the user to work with specific male and female datasets, as well as combined-sex samples from these collections by clicking the “Select sex” button (Figure 3). Although males and females have the same acetabular aging pattern (San-Millán et al., 2017a) they differ in the rate of acetabular aging (Mays, 2012; San-Millán et al., 2017b): Males tend to enter advanced stages of the acetabular traits earlier than females.

Whenever possible, we encourage the use of the newer method (San-Millán et al., 2017b), as its revised fossa variable descriptions incorporate and address previous critiques (Calce and Rogers, 2011; Calce, 2012; Mays, 2012). These critiques pointed out some difficulty of scoring and a low correlation with age for variables related to the acetabular fossa (V5 to V7). In the revised method (SanMillán-Rissech method), these three variables are redefined for clarity and repeatability (San-Millán et al., 2017b). The other four variables (V1 to V4) are the same as in the Rissech method (San-Millán et al., 2017b). We also provide the option of the original method (Rissech et al., 2006) for users who may be conducting a method test of the original method or estimating age in samples scored prior to the 2017 revision (San-Millán et al., 2017b). In Option 2, there are no reference datasets. This option (Option 2) not only allows you to estimate age from the acetabulum by Bayesian inference with your reference and test collections, but also allows you to estimate age probabilistically with any adult age marker and scores from the method of your choice. See below for detailed usage instructions.

Required Inputs

In the IDADE2 website, the test sample and the reference sample must have the same organization and the same variables, entered in the same order (Table 2), with the following headings: Ind: individual identification; age: known age of death of the individual; and V1 to Vn: values of the variables—except that the age at death need not be known for the test individual(s), in which case "0" is entered. If you are not using the Rissech et al. (2006) or SanMillán-Rissech (San-Millán et al., 2017b) methods, you do not need to use the same variables as the variables in IDADE2 reference data (our reference datasets). That is to say, choosing Option 2, you can use your own reference sample and your method of choice (as long as both datasets correspond in terms of the herein-described order and organization).

In both Options (Option 1 and Option 2), data can be formatted as a *.CSV file in EXCEL, whether they are reference or test samples (Table 2, Example A). In the event that you have a small test sample (i.e., constituted by one individual or several), you can paste the information of these fields (separated by a comma, tab, or semicolon) directly into the box entitled "Test collection: One or few individuals" (Figure 3). Table 2 (Example B) shows a hypothetical example of a small test sample, in which data are separated by tabs.

How to interpret the obtained Outputs

After submitting your datasets, a results file is open in your screen (Figure 4). You can copy and paste its contents into your text editor to examine, edit, print, or incorporate it into other documents. The IDADE2 web page also allows you to download this results file. The output consists of a table for each specimen listing the estimated age, various measures of accuracy, and the estimating probability distribution over age classes (Figure 4). The information for each individual corresponds to a line. Figure 4 shows the results for the three hypothetical individuals of Table 2, Example B (the input). In this output, we have the individual identification (ID), chronological age (AD), estimated age (EAD), two measures of accuracy (error and Fit), and the two extremes of the confidence interval (CI-l and CI-r). The remaining values are the probabilities for each age class, corresponding to the estimating probability distribution over age classes in per-thousand. Each age class ("19," "24," "29," etc) corresponds to a 5-year age interval (e.g., age class "24" encompasses ages 24-28 years).

DISCUSSION

The IDADE2 web page is an easy, freely accessible web server that allows the user to estimate the age of skeletal remains based on Bayesian inference, using either acetabular methods (e.g., Rissech et al., 2006; San-Millán et al., 2017b) or other methods chosen by the user. Besides incorporating the most recent information on the acetabulum as an adult age marker, the new IDADE2 website also incorporates revisions that address previous methodological critiques. The new IDADE2 also maintains a commitment to Bayesian inference and the potential that it holds for skeletal age-at-death estimation. With the creation of the new IDADE2 website, we offer the possibility to work with one of two methodologies: the original Rissech et al. (2006) or the revised SanMillán-Rissech (San-Millán et al., 2017b) methods, depending on the user's needs. In addition, we are pleased to offer to the IDADE2 user the options of several sex-specific acetabular reference datasets originating from European and European-American populations. The acetabulum's resistance to the influence of physical activity and obesity—the latter a particularly important concern when estimating age in modern individuals—makes the acetabular methods relevant to forensic anthropological as well as bioarchaeological analyses of European and European-American samples (San-Millán et al, 2019; Winburn, 2018). We wish to update the available reference samples as new populations are scored using acetabular aging methods, and we encourage users to contact us to share ideas, suggestions, and population data.

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FIGURE LEGEND

Figure 1. Traits of the acetabulum scored for age estimation using the Rissech method (Rissech et al., 2006): 1. Presence of a groove along the acetabular rim; 2. Shape of the acetabular rim; 3. Porosities of the acetabular rim; 4. Osteophytic activity of the apex of the posterior cornu; 5. Activity (i.e., crest formation) on the outer edge of the acetabular fossa; 6. Activity of the acetabular fossa; 7. Porosities of the acetabular fossa.

Figure 2. Homepage of the IDADE2 website. The navigation bar shows the six informative sections (home, usage, methods, benchmark, help, and contact). The age-estimation utilities (Option 1 and Option 2) appear as buttons at the bottom of the page.

Figure 3. An image of the options provided when the Option 1 age-estimation button is clicked.

Figure 4. An example results file from the hypothetical input of Example B in Table 2. “ID” = individual identifier; “AD” = known age at death; “EAD” = estimated age at death; “ERROR” = difference between ED and AD; and “CI-l and CI-r” = the two extremes of the 95% confidence interval. Each age class (“19,” “24,” “29,” etc) corresponds to a 5-year age interval (e.g., age class “24” means 24-28 years).

Sample	Housed	Females	Males	Total	Ages
Valladolid Collection (20th-century)	University of Valladolid (Spain)	24	52	76	23 to 101 y
Lisbon Collection (19th-20th-century)	National Museum of Natural History (Portugal)	317	294	611	15 to 98 y
Bass Collection (20th-century)	University of Tennessee (US)	370	456	826	19 to 101 y

Table 1. Sex and age distribution for the European and European-American individuals used as reference samples in the IDADE2 web page. The time period given for each collection is based on general birth years.

ind	age	V1	V2	V3	V4	V5	V6	V7
56	20	1	1	1	3	1	1	0
397	22	1	3	3	0	3	2	2
520	22	0	0	0	0	0	1	0
62	23	1	1	2	2	4	4	3
145	23	1	4	3	2	2	1	1
102	24	1	3	3	1	3	1	1
293	26	1	1	1	2	2	2	1
420	26	1	2	1	1	1	4	4
476	27	1	2	3	1	2	3	3
574	27	1	1	2	1	1	1	1
4	29	1	4	3	1	2	2	2
53	29	1	2	3	1	2	1	4
499	32	1	3	2	2	2	3	2
528	32	2	4	3	1	2	3	2
301	33	1	2	2	1	3	3	3
500	33	2	1	2	1	3	3	3

Example A

ind age V1 V2 V3 V4 V5 V6 V7

1 74 2 5 3 4 5 5 5

4 29 1 4 3 1 2 2 2

5 75 1 4 3 4 5 4 6

Example B

Table 2. Two examples of hypothetical input data. Reference or test data formatted as a *.CSV file in EXCEL (Example A). Small test dataset (Example B), in which data are separated by tabs (commas or semicolons can also be used). In both examples, each row represents a single skeletal individual. E.g., in Example A, line 2 corresponds to individual "56," age 20, who is in state 1 for variable 1, in state 1 for variable 2, in state 1 for variable 3, in state 3 for variable 4, etc. In Example B, line 2 corresponds to individual "1," age 74, who is in state 2 for variable 1, in state 5 for variable 2, etc. "Ind"= individual identification; "age"= actual age at death ("0" if unknown); and "V1 to V7"= values of the variables (for Rissech or SanMillán-Rissech methods [IDADE2 Option 1]; substitute "n" variables populating "n" columns if other aging methods are used [IDADE2 Option 2]).

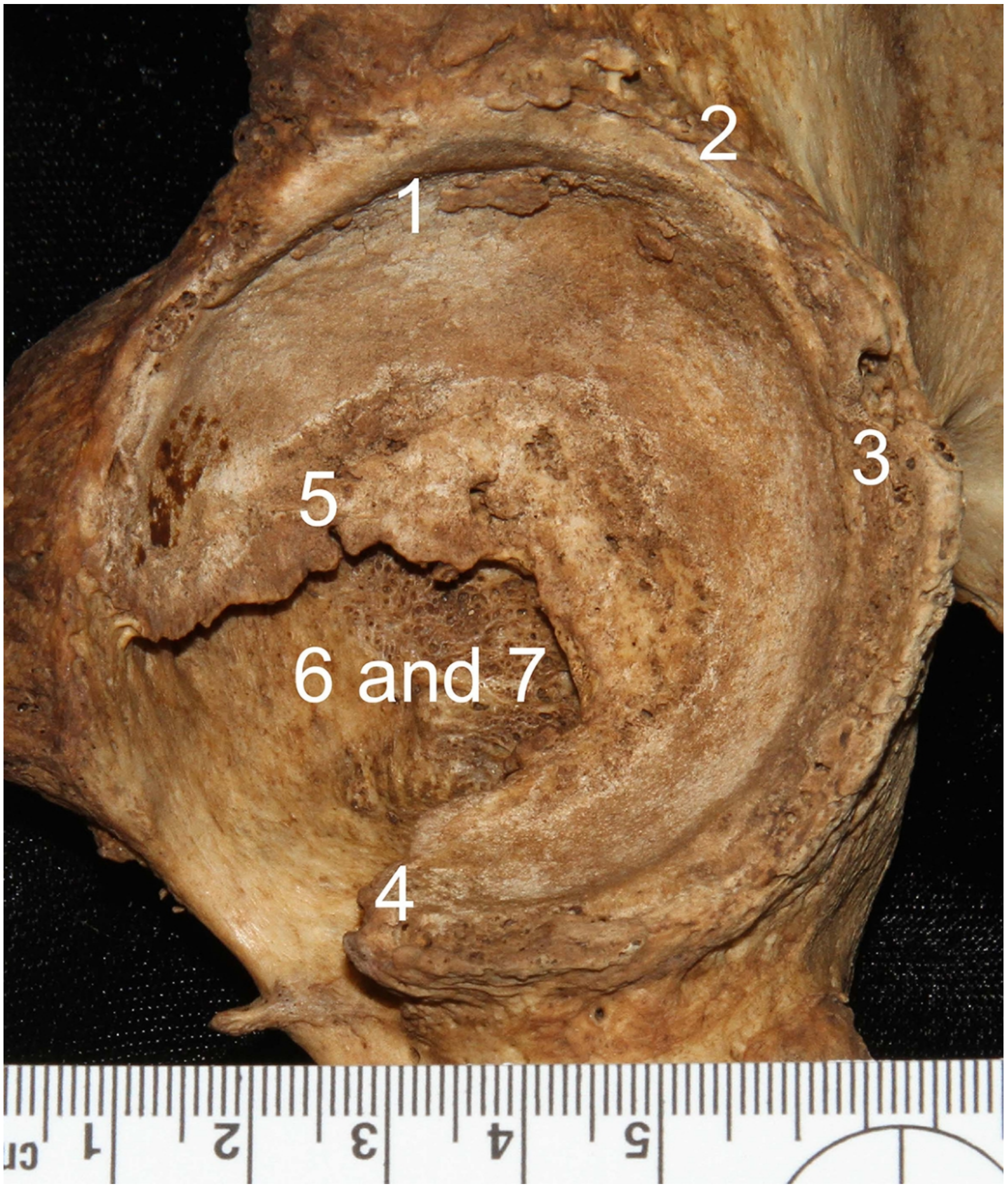
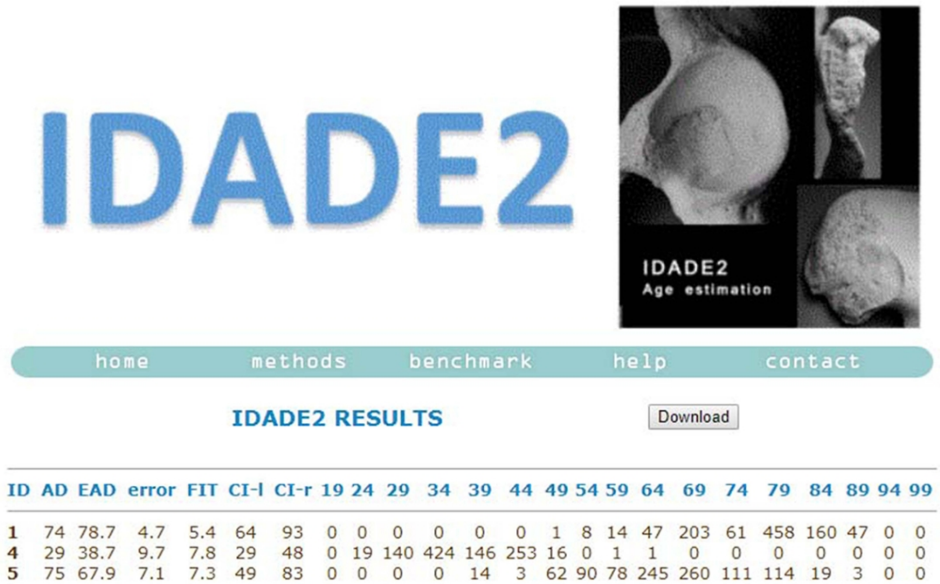


Figure 1. Traits of the acetabulum scored for age estimation using the Rissech method (Rissech et al., 2006): 1. Presence of a groove along the acetabular rim; 2. Shape of the acetabular rim; 3. Porosities of the acetabular rim; 4. Osteophytic activity of the apex of the posterior cornu; 5. Activity (i.e., crest formation) on the outer edge of the acetabular fossa; 6. Activity of the acetabular fossa; 7. Porosities of the acetabular fossa.

Figure 2. Homepage of the IDADE2 website. The navigation bar shows the six informative sections (home, usage, methods, benchmark, help, and contact). The age-estimation utilities (Option 1 and Option 2) appear as buttons at the bottom of the page.

Figure 3. An image of the options provided when the Option 1 age-estimation button is clicked.



ID	AD	EAD	error	FIT	CI-l	CI-r	19	24	29	34	39	44	49	54	59	64	69	74	79	84	89	94	99
1	74	78.7	4.7	5.4	64	93	0	0	0	0	0	0	1	8	14	47	203	61	458	160	47	0	0
4	29	38.7	9.7	7.8	29	48	0	19	140	424	146	253	16	0	1	1	0	0	0	0	0	0	0
5	75	67.9	7.1	7.3	49	83	0	0	0	0	14	3	62	90	78	245	260	111	114	19	3	0	0

Figure 4. An example results file from the hypothetical input of Example B in Table 2. "ID" = individual identifier; "AD" = known age at death; "EAD" = estimated age at death; "ERROR" = difference between ED and AD; and "CI-I and CI-r" = the two extremes of the 95% confidence interval. Each age class ("19," "24," "29," etc) corresponds to a 5-year age interval (e.g., age class "24" means 24-28 years).