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Shape variability of the adult human acetabulum and acetabular fossa related to sex and age by geometric morphometrics. Implications for adult age estimation

Marta San-Millán, Carme Rissech*, Daniel Turbón

Secció de Zoologia i Antropologia, Departament de Biologia Evolutiva, Ecologia i Ciències Ambientals, Facultat de Biologia, Universitat de Barcelona, Av. Diagonal 643, 08028 Barcelona, Spain

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ABSTRACT

This study aims to explore shape variability of the acetabulum during the human adult life span, in relation to sex and age. The human acetabular shape was analysed in 682 os coxae from three different documented skeletal collections from the Iberian Peninsula. Two landmarks and thirty-two sliding semi-landmarks were used for the geometric morphometric procedures and a clock-wise standard was used for orientation. The 180° meridian (6:00) line was positioned over the midpoint of the acetabular notch and 36 reference points in 10° increments along the rim were marked. Data showed that size, sex and age significantly influence acetabular shape variation. Sex differences were significant in individuals younger than 65 years old and were characterised by males exhibiting relatively extended acetabular rim profiles from 10:00 to 1:00, narrower acetabular notches, and reduced acetabular fossae. In addition, three main age-related changes occurred to the acetabular shape in both sexes: outer acetabular profile modification, with extension from 10:00 to 1:00 and reduction from 7:00 to 9:00, acetabular notch narrowing, and acetabular fossa reduction. The age-related changes that were observed are shared by both sexes and seem to be related to bone production associated with age. Specifically, age appears to affect the entire border of the lunate surface: the acetabular rim, both acetabular horns, and the outer edge of the acetabular fossa. Furthermore, shape data confirmed the clover-leaf shape of the acetabular fossa in both males and females. These results improve our understanding of acetabular shape, and assist in refining age-estimation methods and enhancing hip surgery and rehabilitation.

1. Introduction

The acetabulum, a part of its locomotor implication, is important because of its utility in sex estimation (e.g., [1–6]), and because recently it has been identified as a good adult age marker [7–16]. The original acetabular method [8] for estimating adult age-at-death studied exclusively acetabular age changes in males [9]. Some authors reported no sex differences in their obtained age estimations when Rissech's method was applied in both males and females [10,13,17]. However, in these studies there was not any specific analysis on sex differences. Recently some authors have indicated the existence of possible sex differences in acetabular ageing rate between males and females [14,16,18]. Specifically, females seem to show a slower rate of ageing than males in this anatomical area. These discordances between authors highlight the necessity of having a better and more detailed knowledge of this anatomical element, taking into account age and sex.

The metric variation of the acetabulum in relation to sex and its functional anatomy have been extensively studied for anthropological [1–6], medical and biomechanical ([19,20–30] among others) purposes. However, the acetabular and fossa morphology have rarely been analysed in detail and much less from an anthropological point of view [31,32]. To have the maximum information possible and precise knowledge of this anatomical area it is important to improve our understanding of the biology and physiology of this complex joint, which can lead to improvements in the current ageing methodologies based on the acetabulum (e.g. [8,16]) and provide new data for hip surgery and rehabilitation.

Geometric morphometrics is the study of shape variation and its covariation with other variables [33,34], where "shape"

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[*] Corresponding author at: Unit of Anatomy, Dept. of Medical Sciences, Faculty of Medicine, University of Girona, Carrer Emili Grahit, 77, 17071 Girona, Spain.
E-mail address: carme.rissech@gmail.com (C. Rissech).

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describes the geometric properties of an object that are invariant to location, scale, and orientation [35]. Geometric morphometrics has developed considerably in recent years [33,34,36–44]. It has been shown to be a powerful tool for accurately determining and describing subtle morphological shape changes in human skeletal structures that classical measurements could not record. In fact, the use of landmark-based techniques has rapidly increased in the anthropological and anatomical sciences in the last decade (e.g., [45–54]). However, many areas of biological structures, such as the lunate surface or acetabular fossa of the acetabulum, have few or no identifiable landmarks, as their structure is represented only by surfaces, curves, or outlines [55]. In these cases, the methodological problem has been recently overcome through the use of sliding semi-landmarks, which allows for capturing shape variation across the sample [56–58].

In this study, we present a two-dimensional geometric morphometric analysis of the human acetabulum and its fossa using recently defined landmarks and sliding semi-landmarks [54]. The objective is to assess shape and size differences of the acetabulum related to sex and age. Although the functional implications of acetabular variability have long been identified, this study is the first to use geometric morphometrics to explore the shape and size variation of the human acetabulum and its fossa across the entire adult life span.

2. Materials and methods

2.1. Osteological material

We analysed a total of 682 individuals (327 ♀, 355 ♂), coming from three modern documented skeletal collections: (1) Madrid collection [59], housed in the School of Legal Medicine at the Faculty of Medicine of the Complutense University of Madrid (Madrid, Spain); (2) Valladolid collection [60], housed in the Anatomical Museum at the Faculty of Medicine of the University of Valladolid (Valladolid, Spain); (3) Lisbon collection [61], housed in the Museo Bocage of Lisbon (National Museum of Natural History, Lisbon, Portugal). The Madrid and Valladolid collections comprise individuals who died in the 20th century while the specimens of the Lisbon collection died between the end of the 19th and the end of the 20th centuries. The three skeletal collections used in this research come from three different geographical regions of the Iberian Peninsula. They were chosen in order to include a representative sample of different regions of the Iberian population, taking into account their availability and their potentially large age ranges. All of these collections are derived from modern cemeteries and have documented demographic information, and records of birth and death are available. Further information concerning the three Iberian collections can be found in a range of publications (i.e. [59–64]).

Individuals with mature acetabula (completely fused) were selected in order to cover the entire period of acetabular maturity. In our sample, the complete fusion of the acetabulum occurs at 15 years in males and at 12 years in females [65–67], which is in accordance with the given standard intervals for acetabular maturity (14–17 y. ♂; 11–15 y. ♀) in the current population [68]. In order to create the same age intervals in both sexes, we chose exclusively individuals with fused acetabula 15 years of age and older. Thus our sample has an age range from 15 to 101 years. Table 1 presents detailed information regarding the age, sex and collection of the individuals analysed in this study.

The left os coxa, without any pathology and/or deformity that might affect the analysis, was chosen from each individual. We included individuals with non-inflammatory osteoarthritis or diffuse idiopathic skeletal hyperostosis (DISH) because these conditions are related to age [69,70]. In the case of a missing, broken (where the positioning of the complete set of landmarks described subsequently is infeasible) or pathological left os coxa, the right bone was analysed (see below). Furthermore, we excluded fused pelves (os coxa and sacrum), as it was impossible to maintain our photographic protocol due to the limited space of the box used to position each of the os coxa.

Table 1

Distribution of specimens by sex, age and collection. UVA: Valladolid collection; UCM: Madrid collection; LISBON: Lisbon collection.

	UVA		UCM		LISBON		TOTAL	
	Male	Female	Male	Female	Male	Female	Male	Female
15–19 years	0	0	0	0	12	13	12	13
20–29 years	1	0	7	3	24	25	32	28
30–39 years	4	1	19	9	23	15	46	25
40–49 years	8	3	18	9	29	20	55	32
50–59 years	15	3	23	4	20	46	58	53
60–69 years	17	12	5	9	30	28	52	49
70–79 years	15	14	13	21	23	20	51	55
80–89 years	17	16	9	17	21	21	47	54
90–99 years	0	5	2	2	0	10	2	17
>100 years	0	1	0	0	0	0	0	1
Total	77	55	96	74	182	198	355	327
	132		170		380		682	

2.2. Photography technique

High-resolution orthogonal photographs of the acetabulum were taken using a Nikon D-3100 digital camera mounted in a fixed position, and equipped with an 18–55 mm objective set at a focal distance of 55 mm. The position and inclination of the camera were fixed using a tripod associated with a spirit level—this instrument indicates whether a surface is horizontal. Following the same protocol used by San-Millán et al. ([54]; Appendix 1), the position of the acetabulum was standardized relative to the optical axis of the camera by placing the os coxa in a wooden box filled with packing peanuts. The acetabulum was positioned upwards, with the acetabular rim parallel to the camera lens. The camera was always positioned at a height of 320 mm directly above the acetabular fossa. The opening plane of the acetabulum was defined by three different references: (i) the position of the acetabular fossa with respect to the camera lens and the levelling of the acetabular rim; (ii) the definition of three anatomical points (a–c) with respect to metric references of the box (Fig. 1A), which were used to define the vertical and the horizontal axes; and (iii) the established grid of the camera's screen. The acetabular rim was positioned lying parallel to the ground and the camera lens by a spirit level. Thus, it was first calibrated in the ground and then, it was used to check if the camera lens and the acetabular rim were parallel to the same plane. The bone was placed inside the box with the iliac crest on the top and the pubic symphysis at the left. The vertical midline of the box crossed through point "a" (the most posterior point of the ilium over the acetabular rim just below the anterior border of the ilium) and "b" (the apex of posterior horn) (Fig. 1A). A horizontal line, positioned exactly 11 centimetres from the bottom of the box, passed through point "c" (the apex of anterior horn) (Fig. 1A). Possible ageing osteophytes were not considered at either points "b" or "c". These three anatomical points were used to ensure that each os coxa was correctly positioned within the camera's established grid, visible on the LCD monitor. Additionally, a 10 mm × 20 mm scale was included in each photograph. In the cases where the right os coxae were examined (16.98% of the total specimens), the protocol was identical, except that the obtained images were mirrored/reflected to obtain a left-oriented os coxa shape. Although some of these procedures may not be required for the implementation of geometric morphometric methods, they minimized digitising error and greatly improved the quality of the shape data obtained.