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Fingerprints identification on 3000 year old Egyptian mummies

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With 8 figures and 2 tables

Abstract: The Djehuty Project (Dra Abu el-Naga; Luxor, Egypt) contains a reused burial chamber, UE165. The human remains include 6 disarticulated, mummified human digits, of which five have very well-conserved prints. The most plausible dating is the Twenty-Second Dynasty (945–715 BCE). High resolution photographs were taken of these and studied in order to identify the main pattern, delta types and minutiae, ridge density and ridge breadth. First, however, a contemporary mummified body was studied in order to calculate the percentage of contraction that can occur in mummified digit tissue. The remains consisted of 4 fingers (a thumb, two index fingers and a middle finger) and a hallux toe, all from the right side, indicating that they came from at least two different people. As regards sex, all the fingers presented values typical of females. Estimated age ranged from 10.62 (middle finger) to 16.25 (thumb) years old, within the sub-adult category. The individual's height was estimated for all the fingers, obtaining values between 135.87 cm for the middle finger and 162.60 cm for the thumb. With regard to the possible ancestral origins of the remains, the type of delta o triradius identified presents high frequencies in contemporary Nigerian and Romanian populations. These results demonstrate that it is possible to work with fingerprints as much as 3,000 years old. It has been possible to identify the main patterns and the minutiae with a precision that exceeds the numeric standard —2 minutiae— currently applied in many countries for forensic identification.

Keywords: 22nd Dynasty; mummies; Ancient Egypt; fingerprints; ridge density

Introduction to dermatoglyphics and its application in archaeology

The lines that cover the fingers, palms, toes and soles in all primate species, including humans, are known within the field of human biology as epidermal ridges (Cummins & Midlo 1926). The main biological characteristics that determine these through polygenic, multifactorial inheritance (Holt 1968; Machado et al. 2010; Ho et al. 2016) generate a very wide variability in patterns, which are determined by environmental and genetic factors up until 24 weeks of gestation (Dell & Munger 1986; Babler 1990; Durham & Plato 1990; Loesch & Lafranchi 1990; Medland et al. 2007). Past that time, they remain substantially unchanged throughout everyone's life, and even after death if the tissues are preserved (Cummins & Midlo 1961; Loesch 1983; Ashbaugh 1991). Consequently, their study has aroused great interest in various scientific fields, including the genetics of human populations, to establish relationships between populations (Mavalwala 1977; Figueras 1993; Kumbnani 2007), clinical genetics, to characterise syndromes and diseases (Schaumann & Alter 1976; Wertelecki & Plato 1979; Durham & Plato 1990; Schaumann & Opitz 1991), and human identification, where they have been used in forensic science for more than a century (Ashbaugh 1991; Faigman et al. 2008; Gutiérrez-Redomero & Hernández-Hurtado 2011; Champod et al. 2016; Houck 2016).

Within this latter field, several studies have recently been conducted on variability in ridge density and its use to infer age, sex or population of origin. Preliminary works by Cummins et al. (1941) and Ohler & Cummins (1942) revealed differences in ridge breadth between fingers and sexes. More recently, studies have attempted to infer sex from epidermal ridge density in the American population of European and

African descent (Acree 1999) and in Spanish (Gutiérrez-Redomero et al. 2008), Indian (Nayak et al. 2010a), Chinese and Malayan (Nayak et al. 2010b), Philippine (Taduran et al. 2016), Argentinian (Gutiérrez-Redomero et al. 2011; Gutiérrez-Redomero et al. 2013b; Rivaldería et al. 2016), Turkish (Oktem et al. 2015), Egyptian (Eshak et al. 2013) and Sudanese populations (Ahmed & Osman 2016), among others. This research has revealed sex, digital and topological differences in ridge density and therefore breadth. Other studies have explored differences between populations, for example between the Spanish and sub-Saharan African population (Gutiérrez-Redomero et al. 2013a) or between the Spanish and Argentinian population (Gutiérrez-Redomero et al. 2013b).

In addition, numerous studies have examined differences in ridge density between individuals of different ages. These have shown that although patterns remain the same throughout life, the distance between ridges widens with age, increasing during childhood, becoming stable in adulthood and increasing again in old age, and thus ridge density can be used to infer age (Loesch & Godlewska 1971; Loesch & Czyozewska 1972; David 1981; Kamp et al. 1999; Gutiérrez-Redomero et al. 2011a; Sanchéz-Andres et al. 2018).

In archaeology, Bartsocas suggested using the term paleodermatoglyphics “for the study of dermatoglyphics through antiquity in archeological and anthropological material (mummies), as well as in the ancient texts” (Bartsocas 1982: 142). However, there is a widespread notion that finger, and palm prints are rarely preserved and therefore do not merit study, since they cannot provide relevant scientific statistical information. As a result, they have received little research attention from archaeologists or art historians and restorers and are rarely listed in the corresponding documentation (Králík & Nejman 2007). Nevertheless, an analysis of ancient prints on pottery has sometimes made it possible to determine the age and sex of the individuals involved in its production (Cummins et al. 1941; Kamp et al. 1999; Králík et al. 2002; Králík & Novotný 2003; Králík & Nejman 2007; Jägerbrand 2007; Králík & Einwögerer 2010; Alarcón-García 2015; Míguez et al. 2016).

Dermatoglyphic research in archaeology also involves the analysis of epidermal ridges in naturally and artificially mummified bodies. However, whereas mummified human remains have been extensively studied anthropologically, dermatoglyphic analyses remain an exception. Nonetheless, an analysis of prints could be of interest in the study of mummies, because their characteristics can be used to analyse other biological features of the human body in ancient populations (Loesch & Lafranchi 1990). This is still only a theoretical possibility, because the degree of conservation of mummified skin sometimes precludes implementation of the procedures commonly used in forensic science to analyse epidermal ridges, or because the high value of the specimen precludes the use of destructive treatments. Mummies are rare in archaeological sites in general and research on them has been relatively limited; however, efforts should be made to obtain the dermatoglyphic information they could provide in the event that they retain their fingerprints (Schmidt et al. 2000).

For dermatoglyphic purposes, the best preserved mummies are without doubt those from the Scandinavian peat bogs (known as “bog bodies”). Skin from the hands and feet of Grauballe Man, impressed on silicon, was studied by Vogelius Andersen (1956). Similarly, the right thumb of Tollund Man has been studied, revealing that it presents a typical fingerprint pattern (http://www.tollundman.dk/fingeraftryk.asp; http://www.forensicgenealogy.info/contest_448_results.html). More recently, the excellent preservation of the female bog body “Moora”, found in 2000 on marshland near Uchter in Lower Saxony (Germany) and dated to 650 BCE, has permitted an analysis of fingerprints from her right hand (Mull et al. 2011). In contrast, the bloody fingerprints found on the arrows carried by Ötzi (a mummy found in the Ötztal Alps) have not yet been analysed (Králík & Nejman 2007).

Many of the best-known and most extensively studied mummies are those from Egypt. Studies have been conducted of the fingerprints —impressed on silicon— from the pharaohs Ramses II, Seti II and Siptah (Prominska et al. 1986). In addition, eighty-three pre-dynastic specimens from the Gebelein necropolis, dating from 5000 to 3000 BCE and held in the University of Turin Museum of Anthropology and Ethnography, have been examined by Saliset al.(2012). Furthermore, Knaap et al. (2011) have examined and recorded friction ridge detail in a 2500-year-old Egyptian mummy.

In light of the above, the aim of the present study was to determine whether the visible characteristics of fingerprints from the mummified digits found at the Djehuty and Hery (TT11-TT12) sites (Luxor, Egypt) could provide sufficient information to infer age, sex, finger type and laterality.

Material and methods

Historical introduction to the UE 165 burial site

The hill of Dra Abu el-Naga rises on the northern edge of the necropolis of ancient Thebes, on the western banks of the Nile (Miniaci 2009) (Fig. 1A). The Spanish Djehuty Project excavation site encompasses several tombs and intervention areas, including what is known as Sector 10, which contains four burial chambers associated with chapels (Díaz-Iglesias 2019). The largest of these, known as UE 165, has a rectangular opening measuring 2.70 m × 1.20 m and is edged with mud bricks (3.64 m × 2.31 m) (Fig. 1B).

The UE 165 shaft is 5.40 m deep, and its rock-cut walls are finished to a higher standard than the other shafts in Sector 10. The burial chamber opens at the western side, with an entrance measuring 1.35 m × 1.00 m. Before reaching the burial chamber, there is a corridor or antechamber

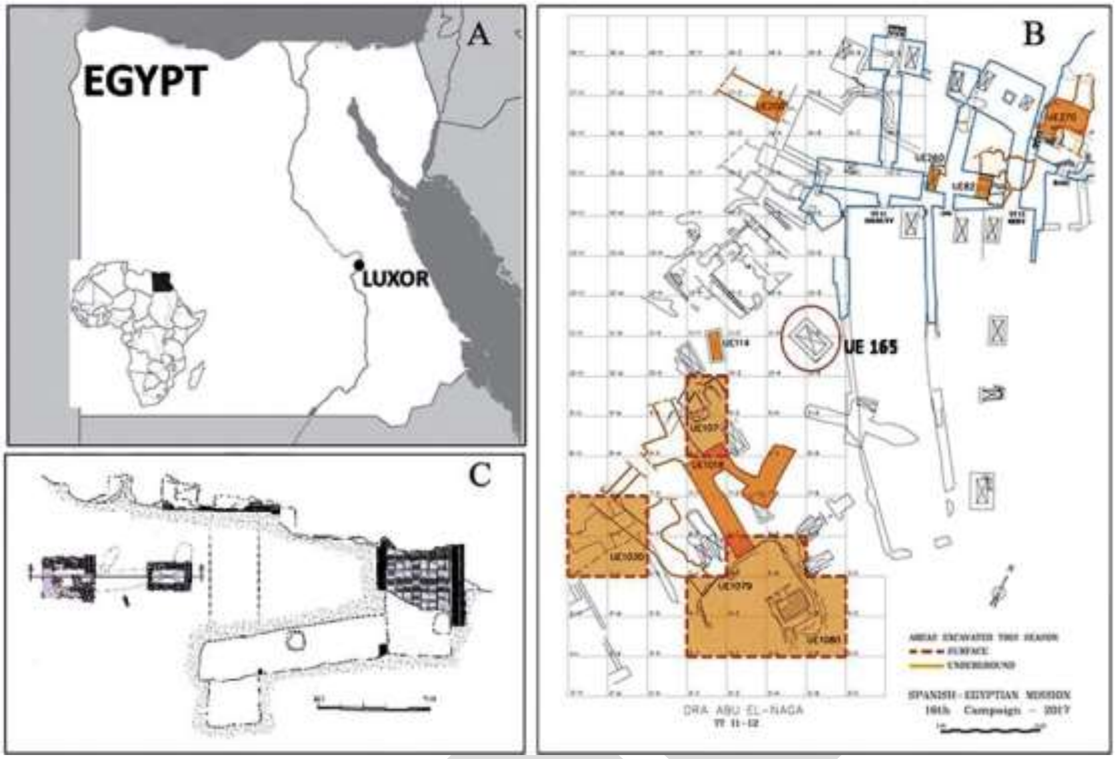

Fig. 1. A) Geographical location of Luxor, Ancient Tebas (Egypt). **B)** Plan of the Spanish Mission Dhejuthy Project. UE165 (red circle). **C)** Geological section of the shaft UE165.

that measures 5.70 m × 1.60 m and 1.75 m high, which also has well-finished walls. Measuring 3.10 m × 2.00/1.35 m and 1.70 m high, the burial chamber itself was originally closed with a mud-brick wall and has a recess in the middle of the floor, measuring 2.20 m × 1.04 m and 1.90 m deep, which was intended to hold a large coffin (Fig. 1C).

The chamber was filled with rocks, sand and a multitude of pottery remains, bandages, cartonnage and skeletonised, mummified human remains presenting a very broad chronological range from the 17th Dynasty to the present (Galán 2008). The homogeneity of the fill and the different levels at which fragments of the same objects were found indicate that the shaft had been reused, robbed, emptied and refilled several times, most recently at the beginning of the twentieth century (Díaz-Iglesias 2019).

The different types of cartonnage and shabtis, together with the human remains found in the shaft, indicate that it was reused several times during the Twenty-Second Dynasty. At least six individuals were buried here, two of them husband and wife (according to the inscriptions recovered from some of the cartonnage). The bodies deposited in the shaft were all violently dismembered by robbers.

Six disarticulated digits were found among the many skeletonised and mummified human remains, five of which were so well preserved that it was possible to conduct a detailed macroscopic examination of the epidermal ridges.

Methods

An examination was conducted of the remains of the five digits presenting well-preserved soft tissues. First, a macroscopic examination was performed to confirm the presence of regular ridge patterns on the digit surfaces. Subsequently, the volar surfaces were photographed using a mirrorless Sony NEX camera equipped with an APSC sensor and a 30 mm macro lens, in order to carry out a more detailed dermatoglyphic analysis. Photographs of the digit fragments were taken using a resolution of 76 pixels per millimetre, equivalent to a resolution of 13 microns, for images of the complete fragments, and of 124 pixels per millimetre, or a resolution of 8 microns, for close-ups.

Lighting was provided by a circular LED ring attached to the lens, with a colour temperature of 4000 K. The camera was adjusted to this temperature in order to eliminate shadow on the tissue caused by deformation due to dehydration, and thus render the epidermal ridges visible.

Before taking photographs of each of the digits, these were placed on separate mounts with a black background. This colour background was chosen in order to highlight the samples and avoid the reflections that would occur on a lighter background, which would have reduced the colour quality and resolution of the final image.

All photographs included a metric reference to maintain homogeneity when enlarged. A forensic scale was used, placed in the median plane of the sample and coinciding with the focal plane in order to increase the proportionality of the scale and reduce optical inaccuracy.

The images were subsequently enlarged and processed using Adobe Photoshop to obtain a higher quality and clarity of epidermal skin ridge details.

To identify the main pattern type, the traditional classification was employed based on four different types of pattern: arch, radial loop, ulnar loop and whorl (Galton 1892; Cumins & Midlo 1961) (Fig. 2A).

Digit type and laterality were determined according to the differential distribution of pattern types in populations and on digits, as well as the criteria proposed by the Directorate-General for Spanish Scientific Police (García-Ayala 1981) and by Singh et al. (2005). The following criteria were assessed: tracing ridges on the second phalanx, relative frequency of the main pattern type, ridge count between the delta or *triradius* and the core, rotation of centrally circular ridges, slope of apex ridges, slant of whorl axis and ridge tracing.

Ridge count between the delta or *triradius* and the core: in whorls, higher ridge counts between the *triradius* located on the left and the core are more frequently associated with whorls on the right hand and vice versa.

Rotation of centrally circular ridges: rotation of central ridges, whether clockwise or anti-clockwise.

Slope of apex ridges and slant of whorl axis: apex ridges that slope towards the right side of the print are termed right-sloping, while outermost ridges that slope towards the left are considered left-sloping. The whorl axis is defined as the imaginary line from top to bottom of a whorl that passes through the central pattern area in which the pattern could be rotated (Brazelle & Brazelle 2018).

Ridge tracing: the ridge that runs from the lower side of the left delta to the point nearest the opposite (right) delta; if the ridge tracing passes inside or above the right delta, it is termed an ‘I’ (inner) type; if the ridge tracing passes outside or below the right delta, it is called an ‘O’ (outer) type; and if the ridge tracing meets the right delta without any intervening ridges or no more than two such ridges inside or outside the right delta, the whorl is designated an ‘M’ (meeting) whorl. Outer (O) or meeting (M) types are more frequent on

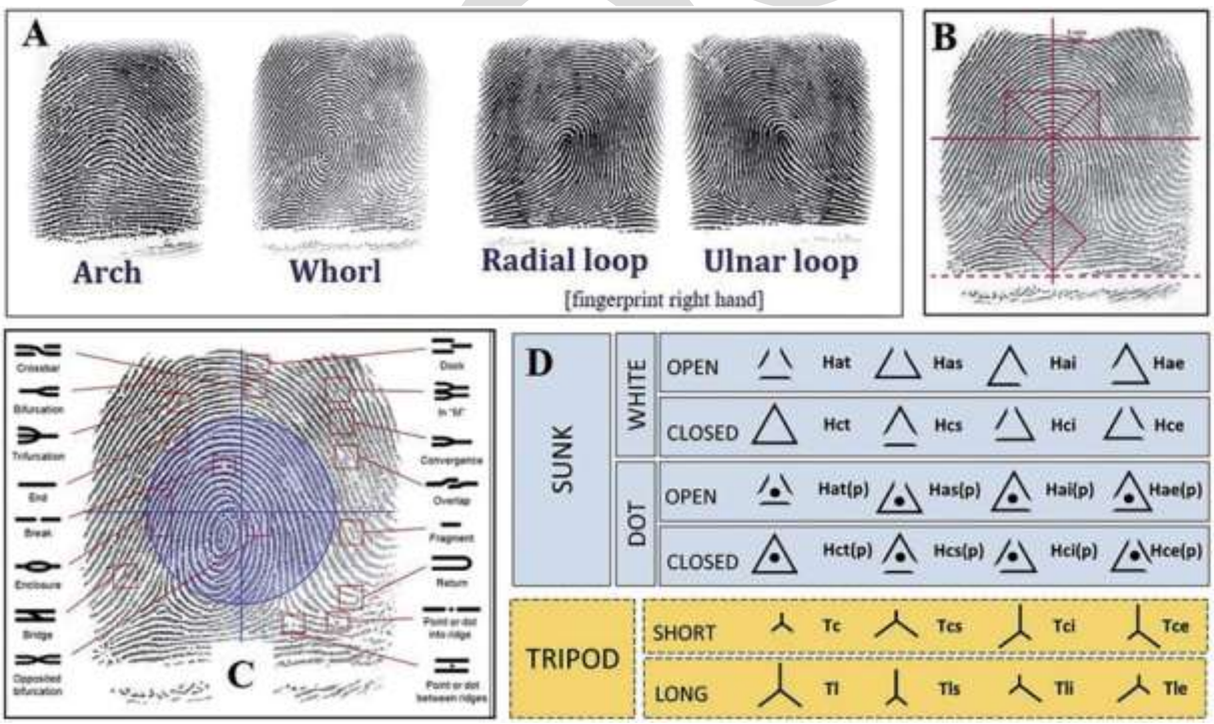

Fig. 2. **A)** Types of pattern. **B)** count areas ridge density. **C)** types of minutiae, **D)** types of deltas o triradii: **Hat**, sunk white open total, **Has:** sunk white open up**, Hai**: sunk white open in, **Hae**: sunk white open out **Hct**: sunk white closed total, **Hcs**: sunk white closed up, **Hci**: sunk white closed in, **Hce**: sunk white closed out; **Hat (p)**, sunk white open total with point, **Has(p)**: sunk white open up with point, **Hai(p)**: sunk white open in with point, **Hae(p)**: sunk white open out with point, **Hct (p)**,: sunk white closed total with point, **Hcs(p):** sunk white closed up with point, **Hci(p)**: sunk white closed in with point, **Hce(p)**: sunk white closed out with point, **Tc**: Tripod short, **Tcs**: Tripod short up, **Tci**: Tripod short in, **Tce**: Tripod short out, **Tl**, Tripod long, **Tls**: Tripod long up, **Tli**: Tripod long in, **Tle**: Tripod long out.

right-hand fingers, whereas inner (I) types are more frequent on left-hand fingers.

In the present study, manual identification of delta or *triradius* types and minutiae was based on the classification system used by the Spanish Scientific Police (Barberá & de Luis-Turégano 1993; Gutiérrez-Redomero et al. 2011b) (Figs. 2C-B).

Wherever possible, ridge density was estimated by counting ridges on three topological areas of the digit following the method described by Acree (1999) and Gutiérrez-Redomeroet al.(2008) (Fig. 2D).

In order to apply these methods, developed for living persons and modern populations, it was necessary to take into account the percentage of contraction that occurs in mummified tissues during dehydration. To the best of our knowledge, no formula exists for calculating the percentage of contraction that may occur in mummified finger tissue; consequently, an estimate was performed. To do this, we conducted a study of digits from a naturally mummified corpse that had been exhumed in 1999, 10 years after burial in a niche, and donated to the Physical Anthropology Teaching Unit in the Department of Life Sciences at the University of Alcalá (Spain). The fingers from the left hand were rehydrated following the method used by the Spanish Scientific Police, whereas the fingers from the right hand were preserved in their mummified state. The percentage of contraction was calculated from the differences observed between the fingers from the right and left hands regarding six anthropometric measurements. These were: phalanx length, proximal phalanx width, phalanx width at the base of the nail, nail width in the middle, anteroposterior distance at the proximal end of the phalanx and anteroposterior distance in the middle (Fig. 3).

The sex and the age of the individual to whom each of the mummified digits belonged were inferred by comparison with the current population. **Sex was inferred** from ridge density in three areas of the dactylogram using Likelihood Ratio (LR) values obtained for the population of Sudan by Ahmed & Osman (2016) due to its geographical proximity. In the present study, mean ridge density for each area on all 10 fingers for each subject and distribution frequency were used to calculate the LR in order to obtain the probability of inference of sex from ridge density values. Where RD is ridge density, C the male donor and C´ the female donor, LR = probability of observing a given ridge density if the donor was male (C)/probability of observing a given ridge density if the donor was female (C´) = P(RD/C)/P(RD/C´). The LR value provides strong support for one of the hypotheses: C (male) or C´ (female). The posterior probabilities P(C│RD) and P(C´│RD) were then calculated using Bayes' theorem (Grieve & Dunlop 1992; Aitken & Taroni 2004). The odds in favour of the most likely sex were obtained using the LR and the posterior probabilities for a given ridge density P(RD│C) and P(RD│C´).

Age and height were estimated from ridge breadth calculated from ridge counts of the best preserved areas of the prints, using the equations proposed by Kamp et al. (1999) and Králík & Novotný (2003). We evaluated ridge breadth as defined by Penrose (1968), namely as "the distance between the centre of one epidermal furrow and the centre of the next furrow along a line at right angles to the direction of the furrow". Hence, the number of ridges transversely crossing a line is counted and ridge breadth is the result of dividing the two figures.

Results and discussion

Type of finger and main pattern

Of the five digits examined, four were fingers and one was a toe. Based on their anatomy (shape and size) and pattern type frequencies, were identified as: Fig. 4A: thumb; Fig. 4B: index finger; Fig. 4C: middle finger; Fig. 4D; little finger; Fig. 4E; hallux or big toe.

Despite the time elapsed, the epidermal tissue on the volar surface of the digits was so well preserved that it was possible to identify the **main pattern type** on all of them (Fig. 4). Thus, the pattern on the digit identified as a thumb (Fig. 4A) was a double loop whorl, while the little finger (Fig. 4D) and hallux toe (Fig. 4E) both presented a loop and the pattern on the index and middle fingers (Fig. 4B and 4C) was a plain whorl.

Laterality

Laterality was determined based on the following traits: relative frequency of the main pattern type in populations, and differences between hands and digits; ridge counts between the delta or *triradius*, slope of apex ridges, slant of whorl axis and ridge tracing.

The most common pattern in human populations is the ulnar loop (with frequencies that, depending on population and finger type, range between 40% and 80%), followed by whorls (with frequencies between 20% and 70%). The frequency of arches and radial loops is considerably lower in all populations, varying between 0% and 16% (Cummins & Midlo 1961; Durham & Plato 1990; Champod et al. 2016), but index fingers present the highest values.

Variability in the distribution of pattern types by finger was evaluated using data from the FBI fingerprint collection collated by the National Institute of Standards and Technology in 1993. These data are based on 17,951,192 10-print forms from male donors and 4,313,521 10-print forms from female donors (Champod et al. 2016). They show that ulnar loops are the most frequent type of pattern, and on both hands these present a higher frequency on middle fingers (>70%) and little fingers (>80%). Whorls also present a high frequency, albeit lower than ulnar loops, with higher frequencies on the right than the left hand, and

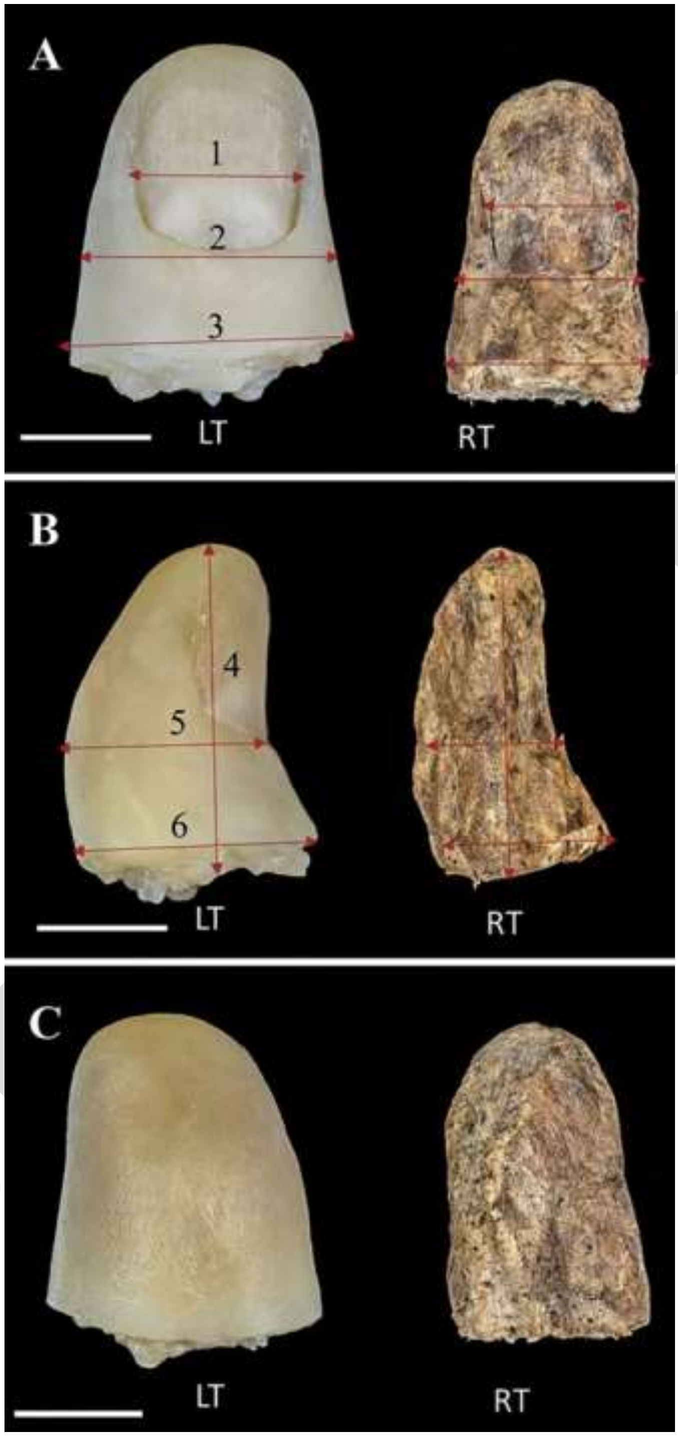

Fig. 3. Anthropometric measurements in rehydrated left thumb (LT) and mummified right thumb (RT). 1: nail width in the middle, 2: phalanx width at the base of the nail, 3: proximal phalanx width, 4: phalanx length, 5: anteroposterior distance in the middle, 6: anteroposterior distance at the proximal end of the phalanx. A: dorsal view, B: lateral view, C: ventral view.

Fig. 4. Types of patterns and finger: 1) thumb finger: double loop; 2) index finger: whorl; 3) middle finger: whorl; 4) little finger: loop; 5) hallux toe: loop.

on both hands, a higher frequency on the ring finger (37% right and 24.1% left) followed by the thumb (34.8% right and 20.2% left) and the index finger (24.2% right and 22.1% left). Arches and radial loops present significantly lower values, but are most frequent on the index fingers of both hands. These results are consistent with those reported in many others studies, and are considered a universal distribution pattern (Schaumann & Alter 1976).

As regards the other indicators employed (ridge counts between the delta or *triradius*, slope of apex ridges, slant of whorl axis and ridge tracing), studies consistently show that whorls on the right hand are statistically more likely to present a right-sloping apex (74–96%), an outer or meeting ridge tracing (90–95%) and a ridge count from delta to core on the left side (80–85%). In contrast, on the left hand, the apex ridge slopes towards the left, ridge tracing is inner and the ridge count is more on the right side (García-Ayala 1981; Cowger 1983; Cowger 1993; Singh et al. 2005; Nagesh et al. 2012; Kapoor & Badiye 2015; Mandrah & Kanwal 2016; Brazalle & Brazalle 2018). The frequency of these traits is unaffected by finger type. Thus, Nagesh et al. (2012) observed that the frequency of right-sloping was highest on the little finger, followed by the ring finger and thumb. For the right hand, the accuracy of laterality determination using ridge tracing was highest on the little finger, followed by the thumb and ring finger, while for the left hand it was highest on the little finger followed by the ring and middle fingers. However, Singh et al. (2005) observed the highest accuracy on the little and middle fingers of both hands (100%), followed by the thumb (97.10%) and the ring finger (96.02%). Clockwise rotation is prevalent on the left hand and anti-clockwise on the right hand. Singh et al. (2005) found that the percentage clockwise rotation was 98.25% on the left-hand ring finger and 98% on the left-hand little finger, followed by 97.78% on the left-hand middle finger and anti-clockwise rotation was 97.35% on the right-hand ring finger and 95.84% on the right-hand middle finger. Rotation is absent in the pattern with true round circles. Nagesh et al. (2012) reported that ridge rotation on the right hand was anti-clockwise in 81.7% of cases, clockwise in 3.8% and absent in 14.5%, whereas on the left hand, rotation was clockwise in 84.2% of cases, anti-clockwise in 2.3% and absent in 13.5%. In a study by Kapoor & Badiye (2015), anti-clockwise rotation was found to be more prevalent in the whorl pattern on the right hand (84.4%), while clockwise rotation was more prevalent in prints from the left hand (80%). However, it was not possible to use this trait in the present study because on the index and middle fingers presenting a plain whorl type pattern, this was not visible in part of the core area on the middle finger labelled C in Figure 4, due to adhesions of remains of textiles used for mummification, and in the index finger labelled B, it was a true round circle.

Laterality of the **thumb labelled A in Fig. 5:** this finger presents a pattern identified as a double loop whorl. This type of pattern presents the highest frequency on thumbs (Champod et al. 2016). The whorl axis (red line) on this finger slants towards the left, and thus an impression taken from it would show ridges slanting towards the right, which occurs with a frequency of 92.7% (Brazalle & Brazalle 2018) and 100% (Singh et al. 2005) on right-hand fingers with whorls. Similarly, considering the ridge tracing (yellow line) and given that the relative positions of the deltas can be established, as shown in Figure 5, the tracing pattern in the impression taken from this finger would be an 'O' (outer). This tracing type has been found by Singh et al. (2005) with frequencies of 97% on right-hand thumbs as opposed to 13% on left-hand thumbs. Nagesh et al. (2012) reported frequencies for outer tracing of 65.1% on the right hand and for inner tracing of 85.1% on the left hand, while Mandrah & Kanwal (2016) found that outer tracing occurred in 97.10% of cases

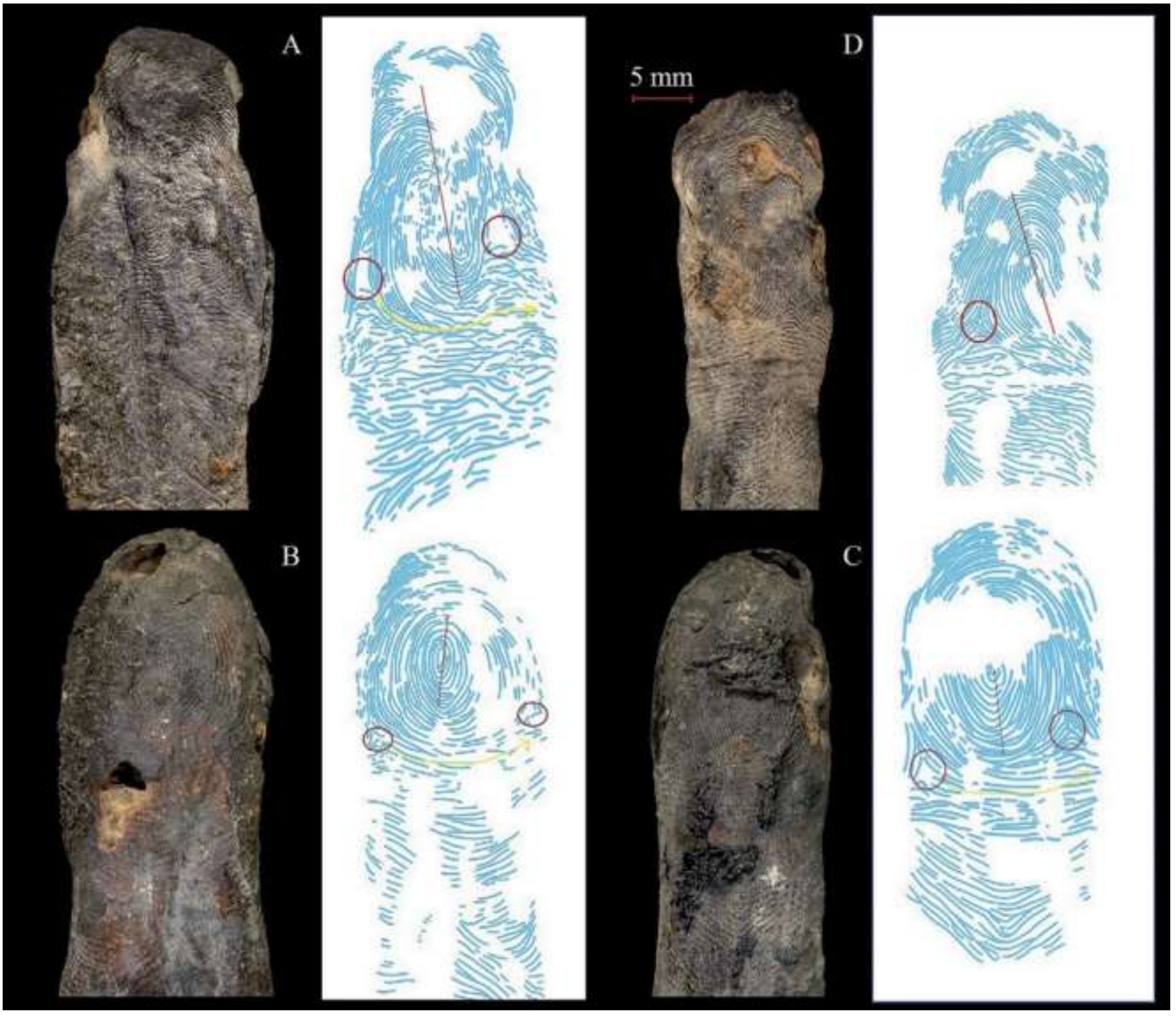

Fig. 5. Determination of finger and hand.

on the right thumb and the inner type in 86.72% of cases on the left thumb. Consequently, there is a high probability that this is a **right-hand thumb**.

Laterality of the **index finger labelled B in Fig. 5:** The pattern type identified on this finger corresponds to a plain whorl. The whorl axis (red line) on this finger slants towards the right, and therefore towards the left in the impression. A slant towards the left has been found with most frequency on left-hand fingers (Singh et al. 2005; Nagesh et al. 2012), so this might be a left-hand finger. However, the ridge tracing (yellow line) between deltas once their relative positions had been estimated gave an 'O' (outer) type tracing in the impression, which, as with the previous finger, would indicate a higher probability of this being a right-hand finger. It was difficult to conduct a ridge count between deltas and core on this finger because the deltas were more eccentric. Nevertheless, given the different heights at which they were located on the finger, a higher count could be inferred between the delta and core on the right side. Kapoor & Badiye (2015) have reported that on the right hand, the distance between left delta and core was greater (89.2%) than the analogous distance on the right side, while on the left hand, the distance between right delta and the core was greater (86.8%). This implies that in an impression taken from this finger, the distance between the delta and the core on the left side would be greater, which would also yield a higher ridge count, indicating a higher probability of a right-hand finger. For this finger, the results obtained from the indicators analysed to infer laterality differed: two of the traits assessed (ridge tracing and ridge count) indicated right laterality while one (whorl slant) indicated left laterality. However, Brazalle & Brazalle (2018) found that the left-hand index finger presented the highest percentage of right-slanting whorls (90.5%), while the right-hand index finger presented the highest percentage of left-slanting whorls (85.0%). Since this was an index finger, these findings support the other two indicators, suggesting that this was also a **right-hand index finger**.

Laterality of the **middle finger labelled C in Fig. 5:** the pattern type identified on this finger was a plain whorl. The middle finger has a lower frequency of whorl than the index, ring and thumb fingers (14–13%), but the ridges in the medial phalanx show the characteristic concave pattern of the middle finger. In this case, the whorl axis (red line) slants towards the left, and thus an impression taken from it would slant towards the right. Singh et al. (2005) have reported frequencies of 70% for a slant towards the right on the right-hand index finger, 29% for absence (true round circle) and 0% for the left-hand index finger. Considering the ridge tracing (yellow line), and having established the relative positions of the deltas, an impression taken from this finger would indicate an 'O' (outer) type tracing. Singh et al. (2005) have reported frequencies for this tracing on the right-hand thumb of 85%, compared to 22% on the left. In addition, the ridge count between the delta and the core is higher on the right side, which in an impression would correspond to the left side. A higher ridge count on the left side of whorls on the right-hand index finger has been reported with a frequency of 91.51% by Singh et al. (2005) and 82.1% by Nagesh et al. (2012). Consequently, this is also probably a **right-hand finger**.

The laterality of the **little finger labelled D in Fig. 5** was determined in accordance with its main pattern type, which in this case was a loop. This pattern can be sub-divided into two types, the radial loop, when loops flow in the direction of the radial bone, and the ulnar loop, when loops flow in the direction of the ulna bone. It is known that radial loops account for approximately 4.0% of loops, whereas ulnar loops account for approximately 96.0% of loops (Cowger 1993). Hence, the ulnar loop was the most probable type of pattern given its high frequency in all human populations. Thus, if the print from this finger were an ulnar loop, it would have to be a right-hand little finger. All studies to date have found that right-sloping loops are more frequent on the right hand and left-sloping loops are more frequent on the left hand (García-Ayala 1981; Champod et al. 2016; Brazalle & Brazalle 2018). The loop on this finger sloped towards the left, and thus an impression taken from it would slope towards the left; consequently, it is probably a **right-hand finger**.

These results show that the thumb, middle, index and little fingers come from the right hand and, therefore, the remains studied are likely to have come from the same individual.

Laterality of the **hallux toe labelled E in Fig. 4:** this digit presented a loop pattern. Since fibular loops are by far the most frequent pattern on toes (Cummins & Midlo 1961; Fox & Plato 1987), for the impression taken from this toe to be of this type, it must be a right-foot hallux toe.

Identification of types of delta and minutiae

Delta type was determined on two of the fingers: the little finger (Fig. 5D) and the middle fingers (Fig. 5C). In the first case, it was a sunk white open in delta (Hai) and in the second, it was a sunk white open out delta (Hae) Fig. 2. Delta variability has received little research attention, but in a study carried out on population samples from five countries (Spain, Romania, Colombia, Nigeria and China), this type of delta was found to present a low frequency in fingerprints (from 2.16 to 6.38) but was significantly more frequent in the Romanian (6.38) and Nigerian (5.55) samples (Rivaldería et al. 2017).

Besides the main pattern, a considerable number of **minutiae** were located, analysed and determined on all four fingers, as can be seen in Fig. 6. A higher number of minutiae was identified than that currently required under the Spanish legal system —12— for a positive identification. In consequence, if the fingerprints had belonged to people in a present-day population, these individuals could have been identified.

Fig. 6. Location and types of minutiae.

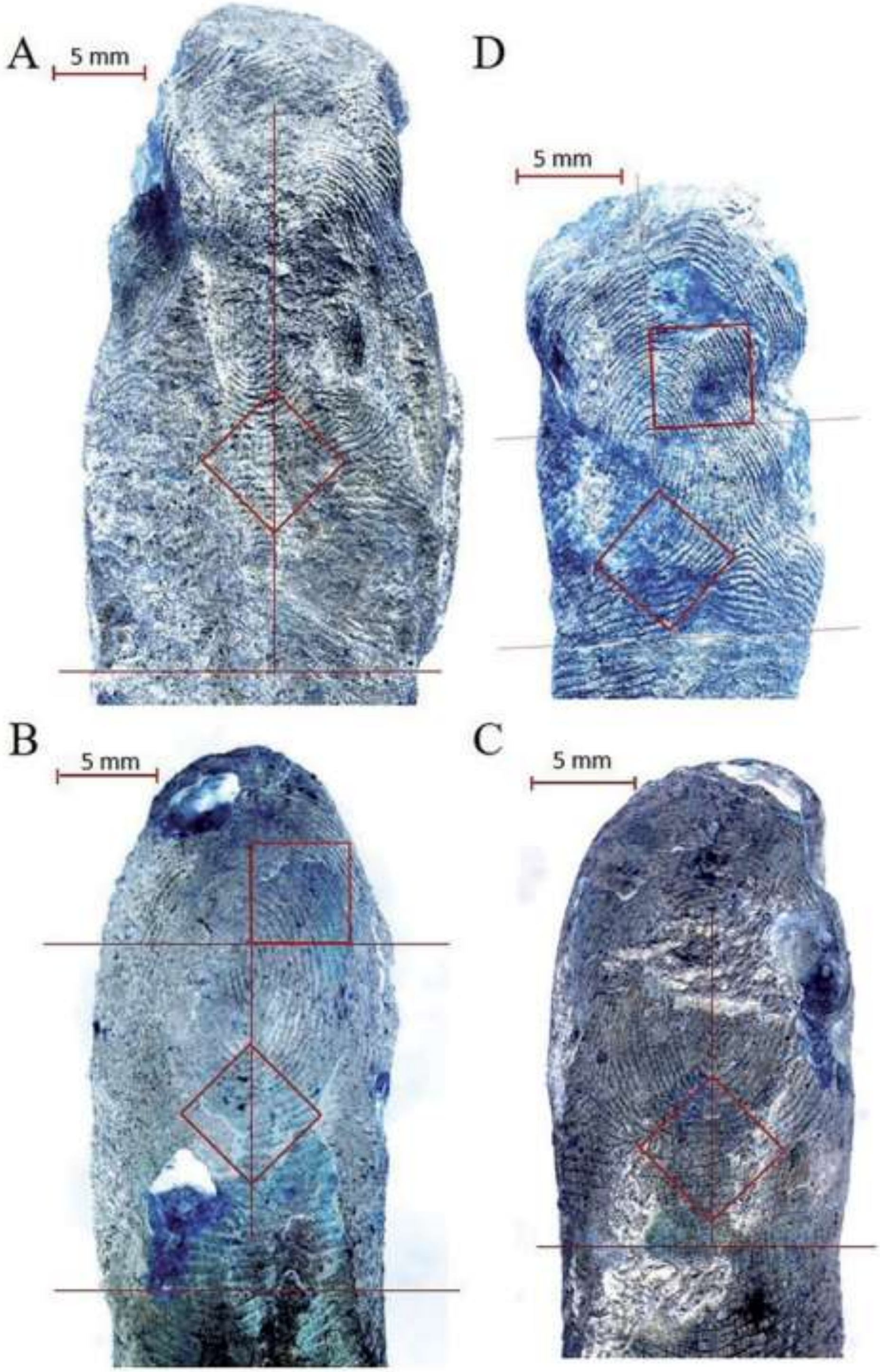

Fig. 7. Location of the count areas of the density ridges.

Estimate of sex based on epidermal ridge density and breadth

Epidermal ridge breadth or thickness presents topological, finger and sex variability as well as differences between populations (Cummins et al. 1941; Ohler & Cummins 1942; Penrose & Loesch 1967; Jantz & Parham 1978; Loesch & Lafranchi 1990; Acree 1999; Gungadin 2007; Gutiérrez-Redomero et al. 2008; Nayak et al. 2010a; Nayak et al. 2010b; Nithin et al. 2011; Gutiérrez-Redomero & Alonso-Rodríguez 2013; Gutiérrez-Redomero et al. 2013a; Gutiérrez-Redomero et al. 2013b; Mundorff et al. 2014). All studies on epidermal ridge breadth have found that this presents sexual dimorphism, whereby women have thinner ridges than men. However, the age at which this sexual dimorphism is established has been less extensively studied. Gutiérrez-Redomero et al. (2011) found evidence of sexual dimorphism in ridge breadth at 12 years old, but not before. These results are consistent with a previous study reporting no significant difference in mean ridge breadth in the second interdigital area between males and females up to the age of 12 years; however, in older children, the sex difference was significant (Loesch & Czyozewska 1972). David (1981) found significant differences in ridge breadth between males and females aged 16-19 years and adults, but were unable to assess a younger age group due to sample size.

More recently, Králik & Novotný (2003) analysed epidermal ridge breadth in human fingerprints on ceramic artefacts from contemporary pottery workshops; they showed that mean epidermal ridge breadth in a given ethnic group can be used as an indicator of sex and age (from birth to maturity).

To estimate sex from ridge density on the mummified fingers, a ridge count was conducted along the diagonal of a square measuring 5 mm × 5 mm (Acree 1999) and sited in one of the three areas of the distal phalanx in the photograph, in line with the method described by Gutiérrez-Redomero et al. (2008). Ridge density was assessed on all four fingers recovered from the site; however, it was not possible to conduct a ridge count in all three areas, on all the fingers. On the thumb (Fig. 7A) and on the middle fingers (Fig. 7C), ridge density could only be assessed in the proximal area, while on the little finger (Fig. 7D) and the index finger (Fig. 7B), ridge density was assessed in two areas, one of the distal areas, the ulnar, and the proximal area. Since the count areas were positioned on photographs rather than impressions, assessments in the proximal region of the distal phalanx would be the most accurate, due to the convex nature of the distal part of fingers.

In order to assess and compare ridge density by count area, it was necessary to estimate the *percentage of contraction* the mummified tissue might present. This percentage was calculated on the basis of changes observed between thumbs, index fingers and middle fingers in six anthropometric measurements of a mummified corpse exhumed in 1999 (Fig. 3). The results obtained for each finger are shown in Table 1. The finger that presented the highest percentage of contraction was the thumb (19.49%), followed by the middle finger (13.65%), while the lowest percentage of contraction was presented by the index finger (11.93%).

The reference LR values for inferring sex were obtained from a study of the Sudanese population conducted by Ahmed & Osman (2016), who calculated ridge density probabilities from ridge density frequency distribution in order to determine the likelihood ratios and posterior probabilities. They found that on the basis of the assumption of equal prior probabilities for both sexes, i.e. P(C) = P(C´) = 0.5, the threshold for the radial and ulnar areas was 13–14 ridges/25 mm^2, and for the proximal area it was 9–10 ridges/25 mm^2. Thus, a ridge count of ≤ 13 ridges/25 mm^2 in either the radial or ulnar areas or ≤ 9 ridges/25 mm^2 in the proximal area would indicate that the subject was most probably male, whereas a ridge count of ≥ 14 ridges/25 mm^2 or ≥ 10 ridges/25 mm^2 in the distal or proximal areas, respectively, would indicate that the subject was most probably female.

Based on these values, and taking into account ridge density once the skin contraction coefficient estimated for each finger type had been applied, the following results (Table 2) were obtained:

- The **thumb (Fig. 7A)** presented a ridge count in the proximal area of 12.9 ridges/25 mm^2 as opposed to > 9/25 mm^2 in the reference population, and there is an 83% likelihood that it came from a woman according to the posterior probabilities given in the reference study (Ahmed & Osman 2016).
- The **little finger (Fig. 7D)** presented a ridge count in the distal ulnar area of 17.8 ridges/25 mm^2 and in the proximal area of 12.8 ridges/25 mm^2, which was higher than the values obtained for the reference population (13/25 mm^2 in the distal area and 9/25 mm^2 in the proximal); thus, for the distal area there is a 100% likelihood that it came from a woman and for the proximal area, an 83% likelihood, according to the posterior probabilities given in the reference study (Ahmed & Osman 2016).
- The **middle finger (Fig. 7C)** presented a ridge count in the proximal area of 12.1 ridges/25 mm^2, which was higher than the value obtained for the reference population (9/25 mm^2 in the proximal); thus, there is a 100% likelihood that it came from a woman according to the posterior probability given in the reference study (Ahmed & Osman 2016).
- The **index finger (Fig. 7B)** presented a ridge count in the distal area of 17.6 ridges/25 mm^2 and in the proximal area of 13.1 ridges/25 mm^2, which was higher than the values obtained for the reference population (13/25 mm^2 in the distal area and 9/25 mm^2 in the proximal); thus, for both areas there is a 100% likelihood that it came from a woman according to the posterior probabilities given in the reference study (Ahmed & Osman 2016).

Table 1. Linear shrinkage by finger.

	Thumb finger				Index finger				Middle finger			
	Tissue mummified	Tissue rehydrated	% shrinkage	%	Tissue mummified	Tissue rehydrated	% shrinkage	%	Tissue mummified	Tissue rehydrated	%	% shrinkage
Phalanx lenght	23	23	100.00	0.00	22	19	115.79	–15.79	19	19	100.00	0.00
Proximal phalanx width	14	18	77.78	22.22	12	14	85.71	14.29	11	13	84.62	15.38
Anteroposterior distance in the middle	8	14	57.14	42.86	6	8	75.00	25.00	6	10	60.00	40.00
Nail width in the middle	13	17	76.47	23.53	12	13	92.31	7.69	11	12	91.67	8.33
Phalanx width at the base of the nail	11	12	91.67	8.33	7	9	77.78	22.22	8	8	100.00	0.00
Anteroposterior distance at the proximal end of the phalanx	12	15	80.00	20.00	9	11	81.82	18.18	9	11	81.82	18.18
Total			**80.51**	**116.94**			**88.07**	**71.59**			**86.35**	**81.90**
Total shrinkage by finger	**19.49**				**11.93**				**13.65**			
Shrinkage mean	**15.02**											

Table 2. Density ridge by area and finger in the mummified tissue and % shrinkage.

Count area ridge density	Density of ridges in the mummified tissue				Corrected ridge density for % shrinkage			
	Thumb	Index	Middle	Little	Thumb (19.5%)	Index (11.9%)	Middle (13.65%)	Little (15.02%)
Distal area (ulnar)		20		21		17.6		17.8
Proximal area	16	14	14	15	12.9	13.1	12.1	12.8

The Penrose method (Penrose 1968) was employed to calculate mean ridge breadth, conducting 20 ridge counts along a 2 mm line located perpendicular to ridge direction. As with ridge density calculations, ridge breadth was calculated taking mummified tissue contraction into account by increasing the value obtained in each direct count from the image by the percentage of contraction observed for each finger, to facilitate comparison of the ridge breadth values obtained with those obtained from samples from living individuals. The mean ridge breadth obtained from 20 counts after correcting for tissue contraction was 0.50 mm for the thumb (Fig. 8A), 0.46 mm for the index finger (Fig. 8B), 0.41 mm for one middle finger (Fig. 8C), and 0.39 mm for the little finger (Fig. 8D). The ridge breadth distribution pattern obtained for each finger coincided with that found in all population samples in which ridge breadth has been assessed for the different fingers. These studies have reported that the thumb presents the thickest ridges, followed by the index finger, whereas it is the ring finger that presents the thinnest ridges, followed by the middle finger and the little finger (Cummins et al. 1941; Ohler & Cummins 1942; Gutiérrez-Redomero et al. 2008; Redomero et al. 2013a; Redomero et al. 2013b; Subhashree 2017). Even across individuals, ridge breadth variability seems to remain within narrow margins, and thus relationships between the different fingers also remain stable.

Cumins et al. (1941) and Ohler & Cummins (1942) found than in women, ridges were 10.2% thinner than in men (with a mean ridge breadth of 0.42 for women and 0.48 for men). These results are consistent with those found in the Spanish population in the radial area (10%) but are higher than those reported in a sample of the Mataco-Mataguayo population (7%).

The ridge breadth detected among the Sudanese (Ahmed & Osman 2016) was higher than that reported for Spanish, Argentinian, Sub-Saharan males and north Indians, using the same methodology (Gutiérrez-Redomero et al. 2008; Gutiérrez-Redomero et al. 2013a; Krishan et al. 2013; Rivalderia et al. 2016). Conversely, ridge densities were lower than those assessed using the Acree (1999) method for the radial area, e.g. Afro-American, European American, Malaysian, Chinese and Indo-Mauritian populations (Ohler & Cummins 1942; Acree 1999; Nayak et al. 2010a; Nayak et al. 2010b; Agnihotri et al. 2012). This may indicate that Sudanese individuals have coarser ridges. Based on samples from 200 individuals from four major ethno-linguistic populations in the Punjab, Tamil Nadu, West Bengal and Rajasthan (India), Subhashree (2017) found that ridge breadth in females ranged from 300 to 470 µm, while in males it ranged from 500 to 550 µm.

Králik & Novotný (2003) attempted to evaluate the effect of age and sexual dimorphism on ridge breadth, and proposed

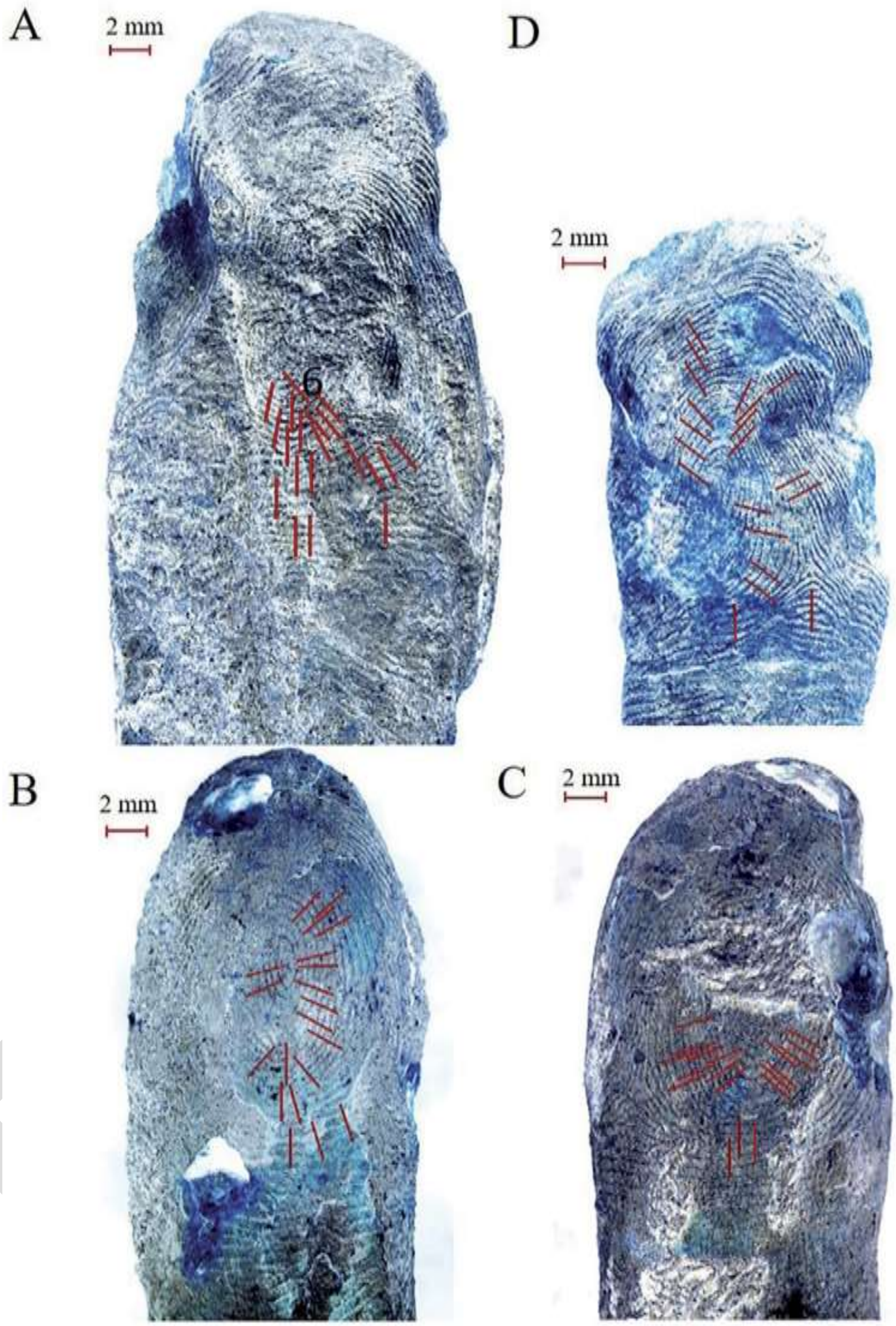

Fig 8. Location of the twenty lines of counting of ridges.

several equations to estimate age from ridge breadth in a large sample of impressions on pottery. In general, an epidermal ridge breadth of less than 0.39 mm indicates a sub-adult individual less than 15 years of age, whereas epidermal ridge breadth values over 0.52 mm come solely from adult males. However, age changes in ridge breadth in adolescents overlap with adult sexual dimorphism and therefore, in the case of epidermal ridge breadth values between 0.39 and 0.52 mm, variability in both age and sex should be taken into account. According to this proposal, the ridge breadth observed on all the fingers studied here would correspond to **female fingers**. These results, based on ridge breadth, agree with those obtained for ridge density per count area. Thus, according to Králik and Novotný's proposal regarding ridge breadth, the fingers could be from a sub-adult individual or an adult female but probably not from an adult male (Králik & Novotný 2003).

Estimates of age and height

Several studies have shown that during growth and development of the body (and consequently growth and development of the hand), epidermal ridge breadth increases (Loesch & Godlewska 1971; Loesch & Czyozewska 1972; David 1981; Gutiérrez-Redomero et al. 2011a). Although the hand stops growing in adulthood, ridge dimensions may change again with ageing, manual activity (which increases hand muscle mass) and changes in body size, which present a clear tendency towards weight gain with age (Kuskowska-Wolk & Rössner 1990; Silva et al. 2016; Sanchez-Andrés et al. 2018). Subirá & Malgosa (1988) did not observe any significant differences in hand dimensions in women aged between 17 and 33 years or men aged between 17 and 39 years. However, when comparing younger individuals (18–30 years old) with older individuals (50–66 years old), Sánchez-Andrés et al. (2018) found significant changes in finger width between groups, which could be responsible for the also significant differences in epidermal ridge breadth found between them. Specifically, epidermal ridge breadth variations with ageing might be determined by increased finger width, whereas length would not be a relevant factor (Sánchez-Andrés et al. 2018).

Based on samples of Czech origin, Kamp et al. (1999) developed a linear regression model of epidermal ridge breadth growth during postnatal development and maturation (from 5.4 to approximately 21 years of age), and a model of the relationship between ridge breadth and body height during postnatal development. Brazelle et al. (2017) also found a correlation between ridge breadth and body height.

Age was estimated by applying the methods based on ridge breadth developed by Kamp et al. (1999) and Kralik & Novotny (2003).

Kamp et al. (1999) proposed the following equation:

$$\text{Age (in months)} = 614 * \text{ridge breadth (in mm)} - 112$$

The results obtained were transformed into years, yielding the following ages: 10.62 years for the little finger; 11.65 years for the middle fingers; 14.20 years for the index finger; and 16.25 years for the thumb.

Kralik & Novoty (2003) proposed estimating age from epidermal ridge breadth using the following linear regression equation (sexes combined):

$$\text{Age (in years)} = 52.18087 * \text{ridge breadth (in mm)} - 7.89682$$

The results obtained using this equation yielded the following ages: 12.45 years for the little finger; 13.50 years for the middle fingers; 16.11 years for the index finger; and 18.19 years for the thumb.

Experiments have shown that this kind of age estimation yields results that diverge from real age by only 1.9 years, with a standard deviation of 1.36 years. The majority of the estimates never vary by more than 4 years from the real age (Králík 2004).

Height was estimated using the regression equation developed by Kamp et al. (1999):

$$\text{Height (cm)} = 243 * \text{ridge breadth (in mm)} + 41.1$$

The results obtained were as follows: 135.87 cm for the little finger; 140.73 cm for the middle finger; 152.88 cm for the index finger; and 162.60 cm for the thumb.

Since ridges are significantly thicker on the thumb and index finger than on the other three types of finger (Cummins et al. 1941; Ohler & Cummins 1942; Gutiérrez-Redomero et al. 2008; Gutiérrez-Redomero et al. 2011a; Gutiérrez-Redomero et al. 2011b; Gutiérrez-Redomero et al. 2013), inferences of age and height based on general equations will yield higher values for these finger types, as was the case for the results obtained. Consequently, it would be desirable to develop equations to infer age or height based on ridge breadth that take into account the differences between finger type. This would yield more accurate inferences.

Conclusions

The epidermal ridges that make up fingerprints may survive for a period of at least 3000 years.

From the samples reported here, it has been possible to identify the main patterns, ridge minutiae and the type of delta or *triradius*.

The main pattern type observed on the four fingers was the whorl on three of them and the loop on one of them. No arch was detected.

The number of minutiae found exceeded that currently required in many countries for forensic identification, namely 12.

In the two cases in which it was possible to identify the type of *triradius*, this was a lateral open delta, which presents a low frequency in the populations studied to date but is higher in Nigerian and Romanian populations.

It has been estimated that the four fingers all came from right hands. The toe probably corresponded to a right foot.

Methods for inferring sex based on ridge density should take into account tissue contraction during mummification. An overall mean value of 15% was obtained for mummified tissue contraction in the experimental assessment conducted for this study; by finger, these values were 19.49% for the thumb, 13.65% for the middle finger and 11.93% for the index finger.

Sex was inferred from ridge density per area and mean ridge breadth, and the results suggest that all the fingers probably came from sub-adult individuals or women, but not from men.

Age was inferred from epidermal ridge breadth, and the results suggest that most of the fingers came from sub-adults. Height was inferred from mean ridge breadth and corresponded to the ages estimated. However, it should be borne in mind that the equations generated from mean ridge breadth for the ten fingers do not take into account significant differences in ridge breadth between the different finger types, and this may have influenced the results for sex, age and height.

Conflict of interest

The authors declare that they have no conflict of interest.

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