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Fingerprint ridge density in the Argentinean population and its application to sex inference: A comparative study

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ABSTRACT

Fingerprint ridge density (RD) is known to vary according to sex and population, and such variation can be used for forensic purposes. The aim of this study was to analyze the fingerprint RD of two samples of the Argentinean population in order to assess their topological, digital, bilateral, sexual, and population differences for subsequent application in the inference of sex. Data were collected from the fingerprints of 172 individuals from the Buenos Aires province and 163 from the Chubut province. RD was assessed for three different count areas for all 10 fingers of each individual. In both sexes and both samples, significant differences among areas were obtained, so that radial-RD > ulnar-RD > proximal-RD. Females presented greater RD than males in all areas and on all fingers. Regarding population differences, no significant differences were found between the Buenos Aires and Chubut samples (except

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for proximal RD in males). However, both samples showed RD significantly different from that of the Jujuy province. The application of Bayes' theorem allowed for the identification of an RD threshold for discrimination of sexes in these Argentinean samples.

In conclusion females consistently exhibit narrower epidermal ridges than males, which may evidence a universal pattern of sexual dimorphism in this trait that can be useful in forensics in the identification of individuals.

Introduction

Epidermal ridges and their arrangement are formed very early in embryonic development, and from the 26th week of gestation the dermatoglyphic patterns retain their configuration essentially unchanged during the lifetime of an individual and even after death if the tissues are preserved (Seidenberg-Kajabova et al., 2010; Wertheim, 2011). However, although the number of ridges is independent of age, their size will increase to accommodate the overall growth of the body, particularly on the hands and feet, until adult size is reached.

The formation of these patterns is determined by both environmental and genetic factors. They are considered polygenic traits with multifactorial inheritance, where the environmental influences are limited to the first months of intrauterine life (Holt, 1968; Loesch, 1983). Some of these features, such as the number of epidermal ridges, are highly heritable and almost entirely genetically determined (90–95%), while others, such as *minutiae*, are mainly determined by the environment (Chakraborty, 1991; Wertheim, 2011). Therefore, dermatoglyphics are a reflection of the environment during an early period of gestation, and their study opens a window onto an important time period for tissue differentiation and organogenesis (Holt, 1973; Schaumann and Alter, 1976). Because of these characteristics, dermatoglyphics have been widely used to study the variability in human populations at both the intra- and intergroup levels, demonstrating their usefulness for understanding the evolution and genetic structure of human populations and the characterization of syndromes and diseases, as well as for personal identification (Arrieta et al., 1987; Champod et al., 2004; Fañanas et al., 1996; Figueras, 1993; Rosa et al., 2000; among others).

Therefore, the forensic interest in dermatoglyphic traits lies in the fact that the configuration of epidermal ridges, after their early formation, remains unchanged for the remainder of life. Moreover, dermatoglyphics display a high variability that, however, can be classified, which has allowed their use in personal identification for over a century (Champod et al., 2004; Dankmeijer et al., 1980; Faigman et al., 2008; Galton, 1892; Holder et al., 2011; Jamieson and Moenssens, 2009). In this field, and even with the increasing role of forensic genetics, dermatoglyphics still enjoy a pivotal role. However, despite the great interest in the study of fingerprints in the field of forensic science, most studies focus on pattern type (arch, loop, and whorl) and size (ridge count from triradius to core), while some of fingerprints most relevant characteristics, such as the *minutiae* or the epidermal ridge breadth, have been less studied (Champod, 1996; Champod et al., 2004; Gutiérrez-Redomero et al., 2011b, 2012; Gutiérrez et al., 2007; National Research Council (NAS), 2009; Neumann et al., 2007, 2006). Regarding ridge breadth, surprisingly, few systematic studies have been carried out on the changes that these undergo during pre- and postnatal development (Babler, 1990; David, 1981; Gutiérrez-Redomero et al., 2011a; Hotz et al., 2011; Králík and Novotný, 2003; Loesch and Czyżewska, 1972; Loesch and Godlewska, 1971). In addition to age, variation in ridge breadth has been shown to be related to sex, hand size, adult body size, and ethnicity. All these variables are interrelated, since variation in body size and its parts (hands and feet) is largely determined by the sex and ethnicity (Cummins et al., 1941; Cummins and Midlo, 1943; Loesch and Lafranchi, 1990; Ohler and Cummins, 1942; Penrose and Loesch, 1967; Plato et al., 1991).

The ridge count on fingerprints has been a focus of the classic studies on dermatoglyphics. Thus the ridge count between the *triradius* and core (or Galton line) has been the foundation for the classification

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of fingerprint records through its decadactilar formulation, which has enabled the archiving of and subsequent quest for fingerprints for identification. Similarly, both the total ridge count (TRC) and absolute ridge count (ARC) have allowed the characterization and comparison of the dermatoglyphic patterns among and within human populations.

Furthermore, it should be noted that the breadth or thickness of the epidermal ridges is determined by two parameters: (1) the width of the ridges and (2) the distance between them. Since the ridge amplitude of the finger or palm print varies with the pressure intensity exerted when the impression is taken, the width of a ridge has been assessed as defined by Penrose (1968): "the distance between the center of one epidermal furrow and the center of the next furrow along a line at right angles to the direction of the furrow." Thus, to assess the true breadth of the epidermal ridges, indirect methods have been used in which the number of ridges crossing a line transversely is counted, and ridge breadth is obtained by dividing the two figures. Some authors have used a line of a defined length and placed it transversely to the ridges on different fingerprint areas (Cummins et al., 1941; Ohler and Cummins, 1942). Others, such as Mundorff et al. (2014), measured the length of a line perpendicularly intersecting 10 ridges that do not show minutiae. Loesch and Martin (1984) used an equilateral triangle, where the two long sides (10 mm each) are perpendicular to the stream of ridges of the distal parallel system and the apex of which lies at the center of a fingerprint pattern. Moore (1989) measured "ridge to ridge distance" from the center of one ridge to the center of the neighboring ridge, and Acree (1999) counted all ridges out diagonally on a square measuring 5 mm × 5 mm, thus obtaining the number of ridges per 25 mm^2.

The sustained interest of forensic sciences to extract as much information as possible from fingerprints of unknown origin has led to statistical methods that have been applied in quantifying some dermatoglyphic traits, such as epidermal ridge breadth, to facilitate the inference of sex, age, or geographic origin of an individual from a print of unknown origin (Acree, 1999; Agnihotri et al., 2012; Badawi et al., 2006; Eshak et al., 2013; Gungadin, 2007; Gutiérrez-Redomero and Alonso-Rodríguez, 2013a; Gutiérrez-Redomero et al., 2008, 2013a,c, Kapoor and Badiye, 2014; Karmakar et al., 2008; Krishan et al., 2013; Mundorff et al., 2014; Nayak et al., 2010a,b; Nithin et al., 2011). Therefore, the aim of this work was to study the variability presented by epidermal ridges in the fingerprints of two samples of the Argentinean population, one from the Buenos Aires province and another from the Chubut province, in order to analyze their topological, digital, bilateral, sexual, and population differences for subsequent application in the inference of sex from marks of unknown donors.

Materials and methods

Samples and sample sizes

The data used in the present study were drawn from the fingerprints of individuals of two Argentinean provinces: Buenos Aires and Chubut (Fig. 1). The sample from the Buenos Aires province was collected at the Instituto Universitario de la Policía Federal Argentina (IUPFA) in the City of Buenos Aires, and that of the Chubut province was collected in the Police Academy at Rawson. The sample size was 335 individuals, of whom 172 individuals were native to Buenos Aires (89 females and 83 males) and 163 to Chubut (80 females and 83 males). This allowed the analysis of 3.350 fingerprints. Since ridge breadth varies according to age during the growing period to adapt to the overall growth of the hand (David, 1981; Gutiérrez-Redomero et al., 2011a; Loesch and Czyżewska, 1972; Loesch and Godlewska, 1971), all individuals in the sample were older than 18 years. All volunteers gave written informed consent to participate in the study and provided information about their ancestry. Ethics approval for this study was obtained from the Ministerio de Salud Ethics Committee of the Jujuy province.

Regarding the Chubut sample, those individuals were identified as autochthonous people of the province of Chubut, whose parents and grandparents were also born in Chubut. Regarding the sample from Buenos Aires, given the great heterogeneity found befitting a large metropolis that collects much of the rural exodus, those individuals were determined as autochthonous people of the province of Buenos Aires, whose parents and at least three grandparents also were born in this province. In cases

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Fig. 1. The geographic location of samples in Argentina. BA: Buenos Aires; CH: Chubut; JU: Jujuy.

where only three grandparents were born in Buenos Aires, the fourth grandparent needed to have been born in a province bordering Buenos Aires.

Fingerprint procedure

Fingerprints were obtained using a variation of the adhesive paper and graphite method (Aase and Lyons, 1971) developed by Gutiérrez-Redomero et al. (2013c) (Fig. 2a). With this technique, a mirror image of the fingertip surface is obtained, similar to that achieved with the classic ink method. In order to facilitate the tasks of counting, fingerprints were scanned and enlarged twice their original size. The fingers were numbered from 1 to 10, beginning with the right thumb (F1) and ending with the left little finger (F10) (Fig. 2b).

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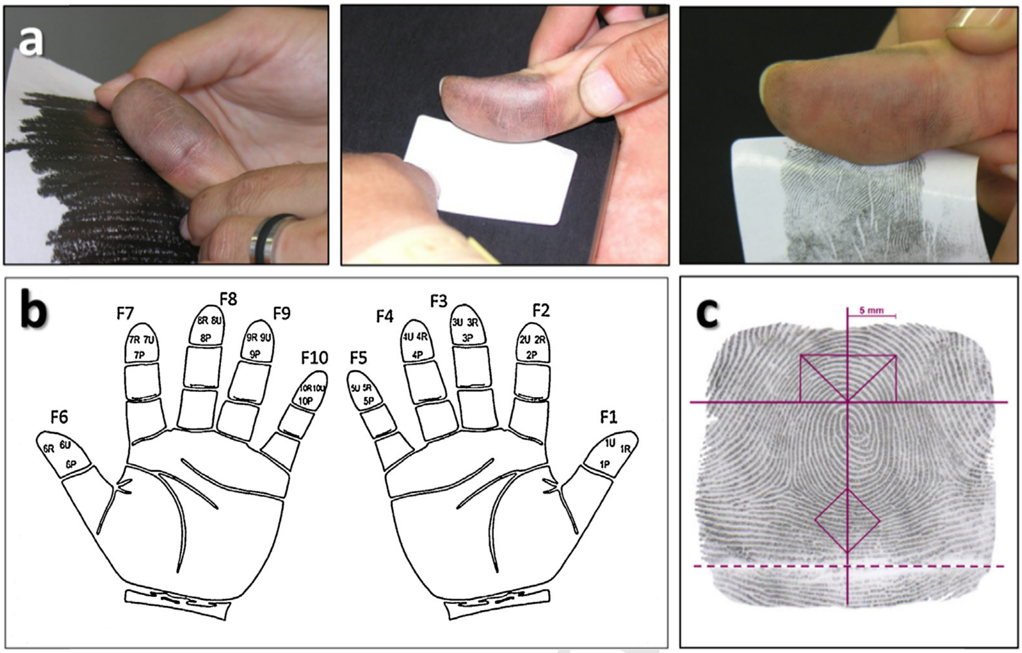

Fig. 2. (a)Technique used to collect fingerprint impressions. (b) Fingers (Fi = 1, . . ., 10). U: ulnar; R: radial; P: proximal. (c) Location of count areas.

The ridge density (RD) assessment was conducted on a fingertip surface area of 25 mm^2 designed as a 5 mm × 5 mm square according to the method described by Acree (1999). The ridge count was performed on the diagonal of the square (number of ridges/7.07 mm). Following the method proposed by Gutiérrez-Redomero et al. (2013c, 2008), the assessment of the RD was performed on three count areas, two on the distal portion of the fingertip (on the radial and the ulnar sides) and another on the proximal portion. To locate the three count areas, four sectors were defined by two perpendicular axes that intersect at the center of the dactylogram, two ridges above the core, with the horizontal line positioned parallel to the interphalangeal joint. In the case of arches, without a defined nucleus, the axes intersect at the center of the dactylogram on top of the arch (Fig. 2c).

Statistical analyses

Ridge count was performed on the above-described three areas of 3350 fingerprints (1720 from the Buenos Aires sample and 1630 from the Chubut sample) from the 10 fingers of each individual in both samples and in both sexes, which involved the assessment of 10,050 count areas. The mean RD by area (ulnar, radial, and proximal) and finger were estimated from these data. The differences between the sexes were analyzed for each of the three count areas individually (mean for each finger) and globally (mean for all 10 fingers).

The frequencies of the main types of patterns (arches, ulnar loops, radial loops, and whorls) and their association with different fingers were assessed by correspondence analysis.

The RD for the three areas (ulnar, radial, and proximal) was compared between sexes using a Student's *t*-test, while for comparisons among populations an ANOVA test was performed. The Friedman's test for related samples was used for comparisons among the three count areas on the same finger, and the Wilcoxon's test for paired samples was performed for comparing the RD between fingers two by two.

The likelihood ratio (LR) was calculated to obtain the probability of inferring sex based on ridge density values (Grieve and Dunlop, 1992).

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Let RD be the ridge density, C the male donor, and Ćthe 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') = $P(\text{RD}|C)/P(\text{RD}|C')$.

The value of LR gives the strength of support for one of the hypotheses, C or C'. Posterior probabilities $P(C|\text{RD})$ and $P(C'|\text{RD})$ were calculated using Bayes' theorem (Grieve and Dunlop, 1992). Information obtained from both LR computations and posterior probabilities was used to show favored odds for support of the most likely hypothesis for a given ridge density $P(\text{RD}|C)$ and $P(\text{RD}|C')$. The prior probability of males $P(C)$ and females $P(C')$ depends on the degree of evidence that we have for the donor.

The results from this study were statistically compared with those reported in a previous study on an Argentinean population sample from the Jujuy province (Gutiérrez-Redomero et al., 2013c). Moreover principal component analysis (PCA) was performed to compare different populations. Statistical analyses were performed by using SPSS 15.0 and Statistica 7.0 software. In all cases, the level of significance was set at $p < 0.05$.

Results

Relationship between pattern types, finger, and sex

Fig. 3a shows the overall frequency rates found for the main types of patterns, by finger, for the two Argentinean samples (no significant sex differences were found in the frequencies). In both samples, a similar frequency distribution between homologous fingers can be seen – the thumbs and ring fingers (F1, F6, and F4, F9) showing more whorls and the middle and little fingers (F3, F8, and F5, F10) more ulnar loops. The index fingers (F2, F7) displayed, in both samples, a greater frequency of arches and radial loops, with whorl and ulnar loop frequencies being very similar between them. The distribution of pattern types by finger showed no significant differences between the two analyzed samples.

In both samples, correspondence analysis between the main types of patterns and fingers showed a significant association (Chubut: $\chi^2 = 466.64$; df = 27; $p < 0.001$; Buenos Aires: $\chi^2 = 218.13$; df = 27; $p < 0.001$) between whorls and thumbs (F1, F6) and ring (F4, F9) fingers, between ulnar loops and middle (F3, F8) and little (F5, F10) fingers, and between arches and radial loops and index fingers (F2, F7) (Fig. 3b). In the Chubut sample, the correspondence analysis explained 99.11% of the inertia found compared to 94.10% in the Buenos Aires sample. In both samples, the first dimension separated the fingers that displayed the most frequent pattern types (ulnar loops and whorls) from those that showed the least frequent patterns (arches and radial loops). The second dimension separated the thumbs (F1, F6) and ring fingers (F4, F9) associated with whorls from the rest of the fingers.

The results found in the present study were statistically compared with those obtained by Gutiérrez-Redomero et al. (2013c) in another two samples from Argentinean population of the Jujuy province (Puna-Quebrada and Ramal) analyzed with the same methods. Fig. 4a shows the frequencies found for the main types of patterns in each of the analyzed samples. The results reveal statistically significant differences among the four population samples, showing the Buenos Aires and Chubut samples having greater ulnar loop frequency, while the Jujuy samples displayed the highest whorl frequency.

Significant dependence is found between the main pattern types and the studied samples ($\chi^2 = 52.598$; df = 9; $p < 0.0001$). The correspondence analysis shown in Fig. 4b explains 99.89% of the inertia. The first dimension, which accounts for 85.37% of the variation, separates both samples of the Jujuy province (Puna-Quebrada and Ramal) from the Buenos Aires and Chubut samples.

Relationship between ridge density, finger, count area, and sex

The mean RD obtained for each count area and finger by sex is shown in Table 1 for both Argentinean populations (Chubut and Buenos Aires). In both samples, the radial area shows significantly greater ($p < 0.001$) RD than the ulnar area and, in turn, the distal region (radial > ulnar) presents greater RD than the proximal area. The three count areas showed statistically significant ($p < 0.001$) differences between sexes, females having a greater RD than males in all cases.

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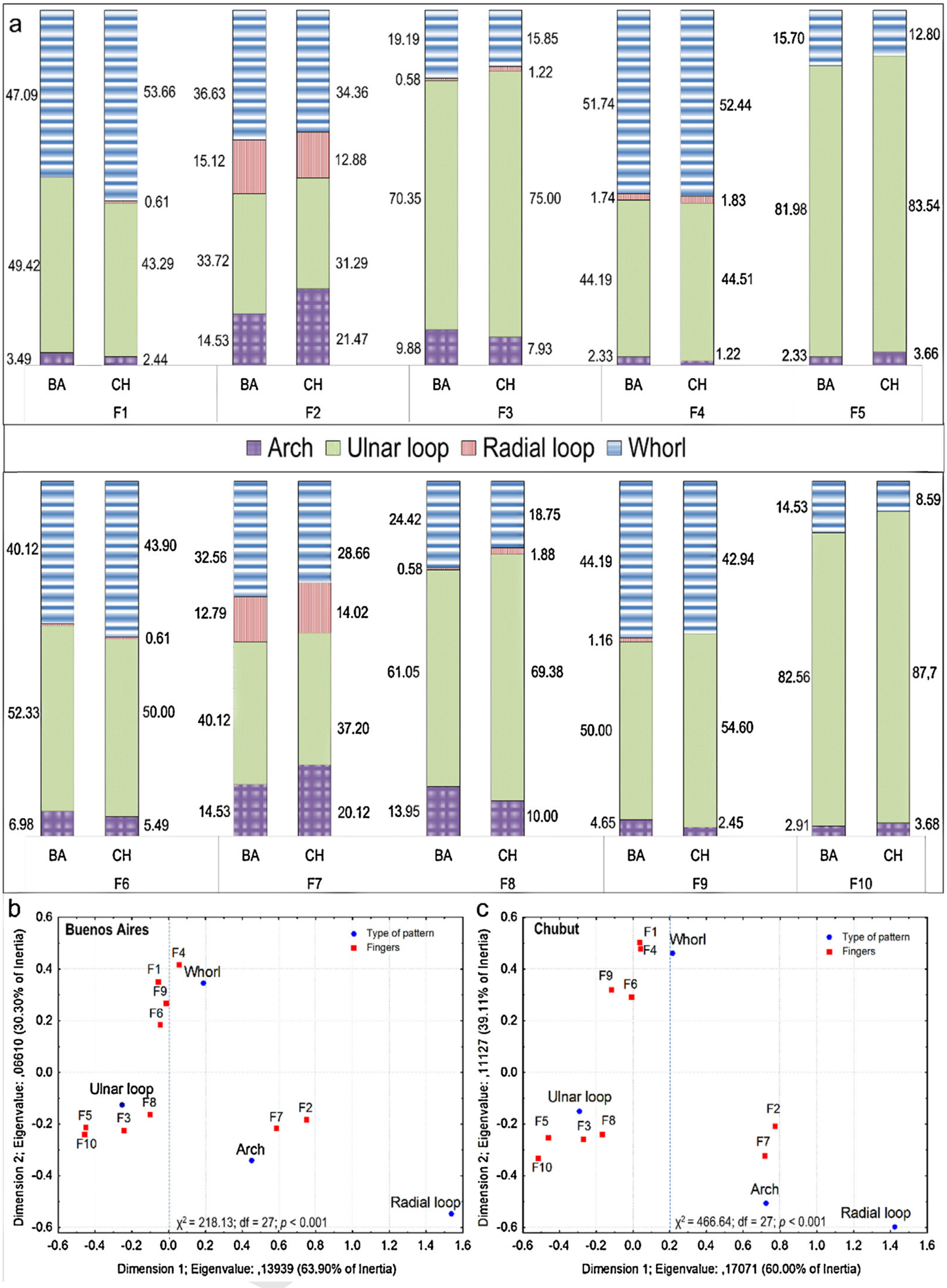

Fig. 3. (a) Relative frequencies for the type of pattern by finger in the Argentinean samples. (b) Correspondence analysis between type of pattern and finger in Buenos Aires sample. (c) Correspondence analysis between type of pattern and finger in Chubut sample. BA: Buenos Aires; CH: Chubut. Finger: Fi = 1, . . ., 10.

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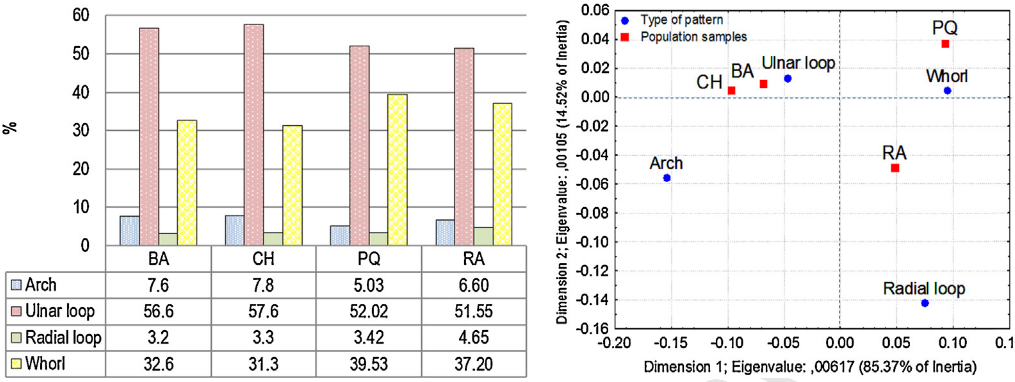

	BA	CH	PQ	RA
▨ Arch	7.6	7.8	5.03	6.60
▨ Ulnar loop	56.6	57.6	52.02	51.55
▨ Radial loop	3.2	3.3	3.42	4.65
▨ Whorl	32.6	31.3	39.53	37.20

Fig. 4. (a) Relative frequencies for the type of pattern. (b) Correspondence analysis between type of pattern and the population samples. BA: Buenos Aires; CH: Chubut; PQ: Puna-Quebrada; RA: Ramal.

Fig. 5 displays mean RD for each area, finger and sex for both samples. When comparing the RD of the three areas on each finger, highly significant differences (Friedman's test for related samples) were obtained for all 10 fingers, in both sexes, and in both samples. When comparing finger by finger, it can be seen that the radial area always shows greater RD than the ulnar area, except for the female index finger (F2) and the male ring finger (F4) and little finger (F5) of the Buenos Aires sample. In both samples and both sexes, the radial and ulnar areas of the thumb (F1, F6) and index fingers (F2, F7) show lesser RD than the other fingers. The highest RD was found in the ring fingers (F4, F9), followed by middle (F3, F8) and little fingers (F5, F10). This indicates the presence, at the distal region of the fingertip, of thicker ridges in thumbs and index fingers and thinner ridges in ring, middle, and little fingers. In the proximal area, RD was greater in the thumbs (F1 and F6) and ring fingers (F4 and F9). Therefore, the ring finger exhibits the thinner ridges in both the distal and proximal regions, and the thumb – as it presents the thicker ridges in the distal region and the thinner ones in the proximal region – is the finger with fewer topological differences. RD is significantly and positively correlated in the three areas, whereby individuals who display a high RD in one of the areas also show a high RD in the other two areas.

Table 1
Descriptive statistics of ridge density (mean for all 10 fingers) in Argentinean samples by sex and count area.

	Males			Females		
	Ulnar	Radial	Proximal	Ulnar	Radial	Proximal
Buenos Aires						
n	83	83	83	89	89	89
Mean	14.96[a,b]	15.56[a,c]	13.27[a,d]	17.00[a,b]	17.82[a,c]	14.27[a,d]
SD	1.55	1.49	1.11	1.68	1.36	1.18
Minimum	11.80	12.00	10.80	13.80	15.00	11.23
Maximum	19.43	19.80	15.60	20.60	21.40	17.30
Chubut						
n	83	83	83	80	80	80
Mean	14.65[a,b]	16.08[a,c]	14.07[a,d]	16.58[a,b]	18.36[a,c]	14.78[a,d]
SD	1.48	1.47	1.42	1.68	1.83	1.34
Minimum	12.30	12.80	11.50	12.50	13.90	11.90
Maximum	17.90	19.90	17.88	20.50	22.30	18.50

SD: standard deviation.

[a] Significant differences among count areas (ulnar, radial, and proximal) within each sample and sex.

[b] Significant differences between males and females for the ulnar area within each sample.

[c] Significant differences between males and females for the radial area within each sample.

[d] Significant differences between males and females for the proximal area within each sample.

All comparisons were significant at $p < 0.0001$.

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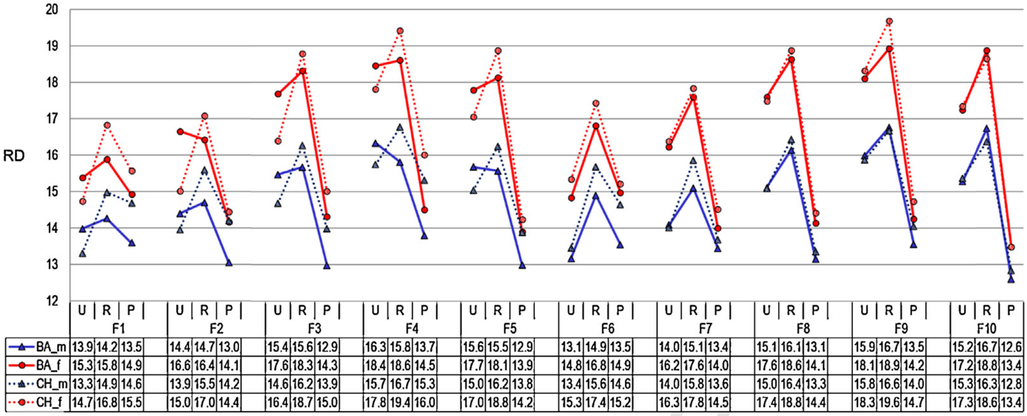

	F1			F2			F3			F4			F5			F6			F7			F8			F9			F10		
	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P
BA_m	13.9	14.2	13.5	14.4	14.7	13.0	15.4	15.6	12.9	16.3	15.8	13.7	15.6	15.5	12.9	13.1	14.9	13.5	14.0	15.1	13.4	15.1	16.1	13.1	15.9	16.7	13.5	15.2	16.7	12.6
BA_f	15.3	15.8	14.9	16.6	16.4	14.1	17.6	18.3	14.3	18.4	18.6	14.5	17.7	18.1	13.9	14.8	16.8	14.9	16.2	17.6	14.0	17.6	18.6	14.1	18.1	18.9	14.2	17.2	18.8	13.4
CH_m	13.3	14.9	14.6	13.9	15.5	14.2	14.6	16.2	13.9	15.7	16.7	15.3	15.0	16.2	13.8	13.4	15.6	14.6	14.0	15.8	13.6	15.0	16.4	13.3	15.8	16.6	14.0	15.3	16.3	12.8
CH_f	14.7	16.8	15.5	15.0	17.0	14.4	16.4	18.7	15.0	17.8	19.4	16.0	17.0	18.8	14.2	15.3	17.4	15.2	16.3	17.8	14.5	17.4	18.8	14.4	18.3	19.6	14.7	17.3	18.6	13.4

Fig. 5. Mean ridge density for each count area and finger by sex. U: ulnar; R: radial; P: proximal. Finger: Fi = 1, . . ., 10. BA: Buenos Aires; CH: Chubut. m: male; f: female.

The RD by sex and sample (Buenos Aires and Chubut) was compared by finger, and the significance of the differences is shown in Table 2. At the bottom left side (in darker type), differences between fingers compared two by two for the ulnar area are shown, and the same data are given for the radial area in the top right side (in lighter type). The significant differences are shown with an asterisk symbol to indicate that $p < 0.05$, and a hyphen appears when $p > 0.1$. In both sexes and both samples, the results show the existence of numerous significant differences between fingers in both the ulnar and radial areas. In the radial area, of the 45 possible comparisons between pairs of fingers, males showed significant differences in 35 cases (in both the Buenos Aires and Chubut samples), representing 77%, while females from Buenos Aires had 37 significant comparisons (82%) and those from Chubut 36 (80%). Regarding the ulnar area, the females of both samples showed 34 statistically significant comparisons (75%); however, Buenos Aires males presented 38 significant comparisons (84%), while those from Chubut showed 24, which represents 53% of significant interdigital comparisons. In the proximal area, of the 45 possible comparisons between pairs of fingers, significant differences in 51% of cases for Buenos Aires males and 53% for Buenos Aires females were obtained. In the sample of Chubut, the differences were significant in 71% of comparisons for males and in 66% for females. The percentage of statistically significant interdigital comparisons is very similar for both samples in the distal areas (radial and ulnar); however, in the proximal area, the Chubut sample had a higher percentage of significant comparisons than that of the Buenos Aires sample.

The mean RD of each hand by area, sex, and population is shown Fig. 6. When comparing the RD between count areas, somewhat different results were observed for both hands. Thus, in the left hand, statistically significant differences between areas compared two by two (radial vs. ulnar, radial vs. proximal, ulnar vs. proximal) were found, in both sexes and in both samples (Buenos Aires and Chubut). Instead, in the right hand, no significant differences between radial-RD and ulnar-RD were detected in the Buenos Aires sample, in either males or females, while differences were maintained in the remaining cases.

If the RD between the two samples of Argentinean population are compared, again the results differ on the right and left hands: while the RD of the samples from Buenos Aires and Chubut did not differ significantly in the left hand, both samples of Argentinean population presented significantly different RD in the right hand, in both sexes, and for the three count areas (Fig. 6).

Sexual variability in ridge count

The distribution of RD frequencies for the mean for all 10 fingers is shown in Fig. 7. From the relative frequencies of RD, probabilities $P(\mathrm{RD}|\mathrm{C})$ (males) and $P(\mathrm{RD}|C')$ (females) were calculated. This analysis, based on Bayes's theorem, allows the identification of the most likely sex, given the number of ridges

Table 2
Q4 Significant differences between the mean ridge density of the fingers (Fi = 1, . . ., 10) on the radial and ulnar areas are shown through the *p*-value.

		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	
F1	BA_m		0.073	*	*	*	*	-	*	*	*	
	CH_m		*	*	*	*	-	*	*	*	*	
	BA_f		*	*	*	*	*	*	*	*	*	
	CH_f		-	*	*	*	*	*	*	*	*	
F2	BA_m	*		*	*	*	*	-	*	*	*	
	CH_m	*		*	*	*	0.051	-	*	*	*	
	BA_f	*		*	*	*	*	-	*	*	*	
	CH_f	-		*	*	*	0.070	*	*	*	*	
F3	BA_m	*	*		*	-	*	*	0.065	*	-	
	CH_m	*	*		*	0.055	*	*	*	*	0.070	
	BA_f	*	*		*	-	*	*	-	-	*	
	CH_f	*	*		*	*	*	-	*	*	*	
F4	BA_m	*	*	-		*	*	*	*	-	*	
	CH_m	*	*	0.051		*	*	*	*	-	0.090	
	BA_f	*	*	-		*	*	*	*	-	*	
	CH_f	*	*	0.1		*	*	*	-	*	-	
F5	BA_m	*	*	-	-		*	*	*	-	0.092	
	CH_m	*	*	-	-		*	*	-	*	-	
	BA_f	*	*	-	*		*	*	-	-	*	
	CH_f	*	*	-	-		*	0.090	-	*	-	
F6	BA_m	*	-	*	*	*		*	*	*	*	Radial
	CH_m	0.090	-	*	*	*		*	*	*	*	
	BA_f	*	*	*	*	*		*	*	*	*	
	CH_f	*	-	*	*	*		*	*	*	*	
F7	BA_m	*	*	*	*	*	-		*	*	*	
	CH_m	*	0.095	-	*	-	-		*	*	*	
	BA_f	*	*	*	*	0.053	*		*	*	*	
	CH_f	*	*	*	*	*	*		*	*	*	
F8	BA_m	*	*	*	-	*	*	*		*	-	
	CH_m	*	*	-	-	-	*	0.060		*	-	
	BA_f	*	*	-	-	0.071	*	*		*	-	
	CH_f	*	*	-	*	-	*	*		*	-	
F9	BA_m	*	*	*	*	*	*	*	*		*	
	CH_m	*	*	*	-	*	*	*	-		*	
	BA_f	*	*	*	-	*	*	*	-		*	
	CH_f	*	*	*	-	*	*	*	*		*	
F10	BA_m	*	*	*	*	*	*	*	*	-		
	CH_m	*	*	-	-	-	0.090	*	-	-		
	BA_f	*	*	*	-	*	*	*	-	-		
	CH_f	*	*	-	*	-	*	*	-	*		

ULNAR

BA: Buenos Aires; CH: Chubut. m: males; f: females.

* $p < 0.05$.

\- $p > 0.1$.

per unit area (Table 3). The results show that, in the Buenos Aires sample, 16 ridges/7.07 mm or less have an LR > 1 for the radial area; 15 ridges/7.07 mm or less have an LR > 1 for the ulnar area, and 13 ridges/7.07 mm or less have an LR > 1 for the proximal area. In the Chubut sample, 17 ridges/7.07 mm or less have an LR > 1 for the radial area; 14 ridges/7.07 mm or less have an LR > 1 for the ulnar area, and 14 ridges/7.07 mm or less have an LR > 1 for the proximal area. Since posterior probabilities depend on prior probabilities, these have been estimated for $P(C) = P(\acute{C}) = 0.5$, and for $P(C) = 0.7$, $P(C') = 0.3$. The results show that depending on the prior probabilities of males and females the favored odds change.

The favored odds for the three count areas (radial, ulnar, and proximal) were calculated, although only the radial area of the Buenos Aires sample is shown (Table 4). When assuming equal prior probabilities for both sexes ($P(C) = P(C') = 0.5$), 16–17 ridges/7.07 mm determine the threshold for sex differentiation. One could then infer that a count equal to or less than 16 ridges/7.07 mm would

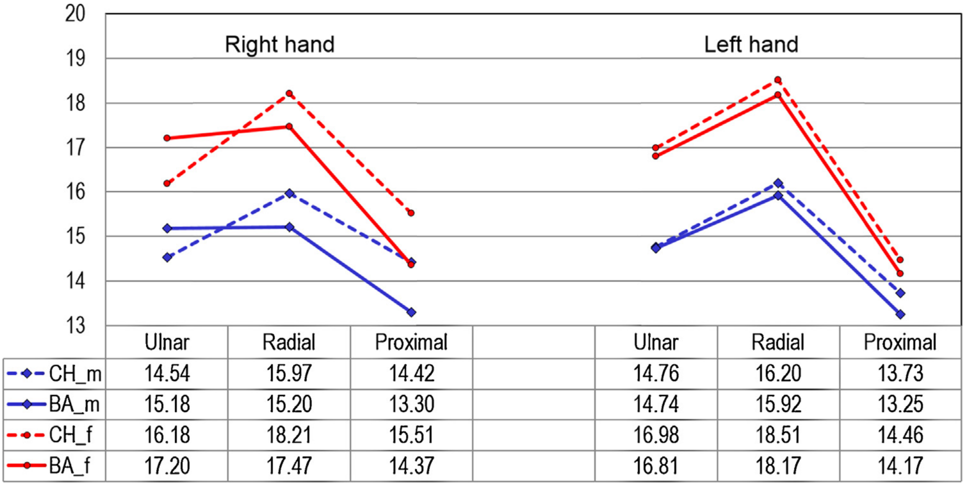

Fig. 6. Mean ridge density for each count area and hand by sex. BA: Buenos Aires; CH: Chubut. m: male; f: female.

Table 3
Likelihood ratios for the ridge count area by sex and sample. LR > 1 is shown in bold. BA: Buenos Aires; CH: Chubut.

Ridge density	LR C (male)/LR C' (female)					
	Radial		Ulnar		Proximal	
	BA	CH	BA	CH	BA	CH
≤12				**11.43**	**3.31**	**2.59**
13			**7.51**	**5.71**	**1.25**	**1.25**
14			**2.68**	**2.26**	0.52	**1.05**
15	**4.78**	**5.00**	**1.56**	0.90	0.28	0.57
16	**1.79**	**1.71**	0.73	0.65		0.56
17	0.45	**1.19**	0.27	0.36		0.20
≥18	0.10	0.17	0.15			

Table 4
Data of probability densities and likelihood ratios derived from observed ridges in the radial area for the Buenos Aires sample. C: male; C': female. The dark areas are LRs in favor of male.

Ridge density	Probability distributions		Likelihood ratio	Odds	
(RD radial)	Males $P(RD/C)$	Females $P(RD/C')$	$P(RD/C)/P(RD/C')$	$P(C)=0.5$; $P(C')=0.5$	$P(C)=0.7$; $P(C')=0.3$
≤15	0.59	0.12	4.78	Male 0.83 > female 0.17	Male 0.92 > female 0.08
16	0.24	0.13	1.79	Male 0.64 > female 0.36	Male 0.81 > female 0.19
17	0.12	0.27	0.45	Male 0.31 < female 0.69	Male 0.51 > female 0.49
≥18	0.05	0.47	0.10	Male 0.10 < female 0.90	Male 0.19 < female 0.81

indicate a great likelihood that the fingerprint comes from a male individual, while a count of 17 or more ridges per unit area would suggest a possible female origin. In cases where the prior probability for males is higher, as indeed happens in the field of crime, being of $P(C)=0.7$, for example, the favored odds would also move, placing the threshold between 17 and 18 ridges/7.07 mm.

Comparison among Argentinean samples

The results were statistically compared with two other samples of the Argentinean population from the Jujuy province (Puna-Quebrada and Ramal) (Gutiérrez-Redomero et al., 2013c). Since no

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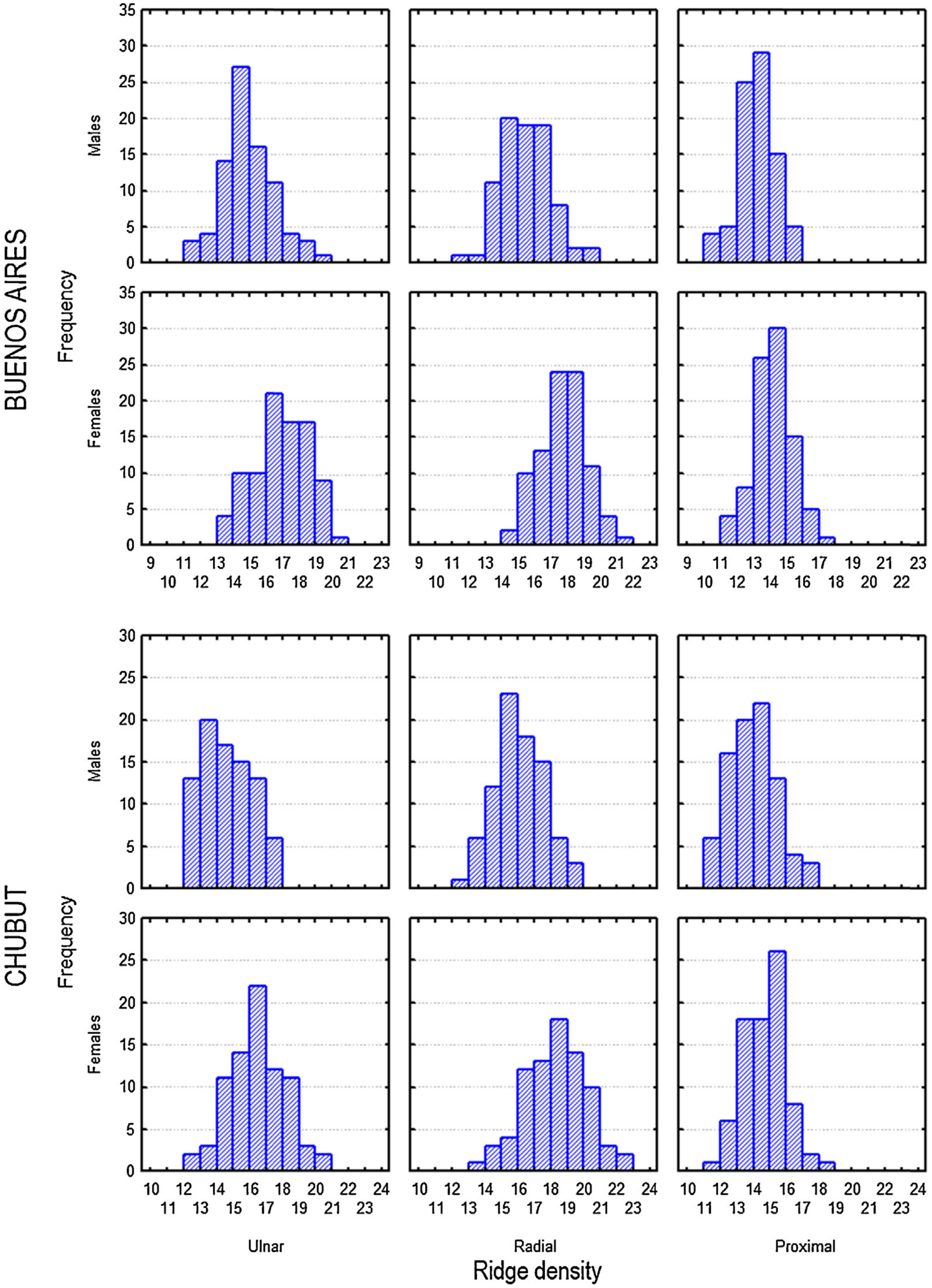

Fig. 7. Absolute frequency distribution of dermal ridge density. Buenos Aires ($n = 83$ males and 89 females); Chubut ($n = 83$ males and 80 females).

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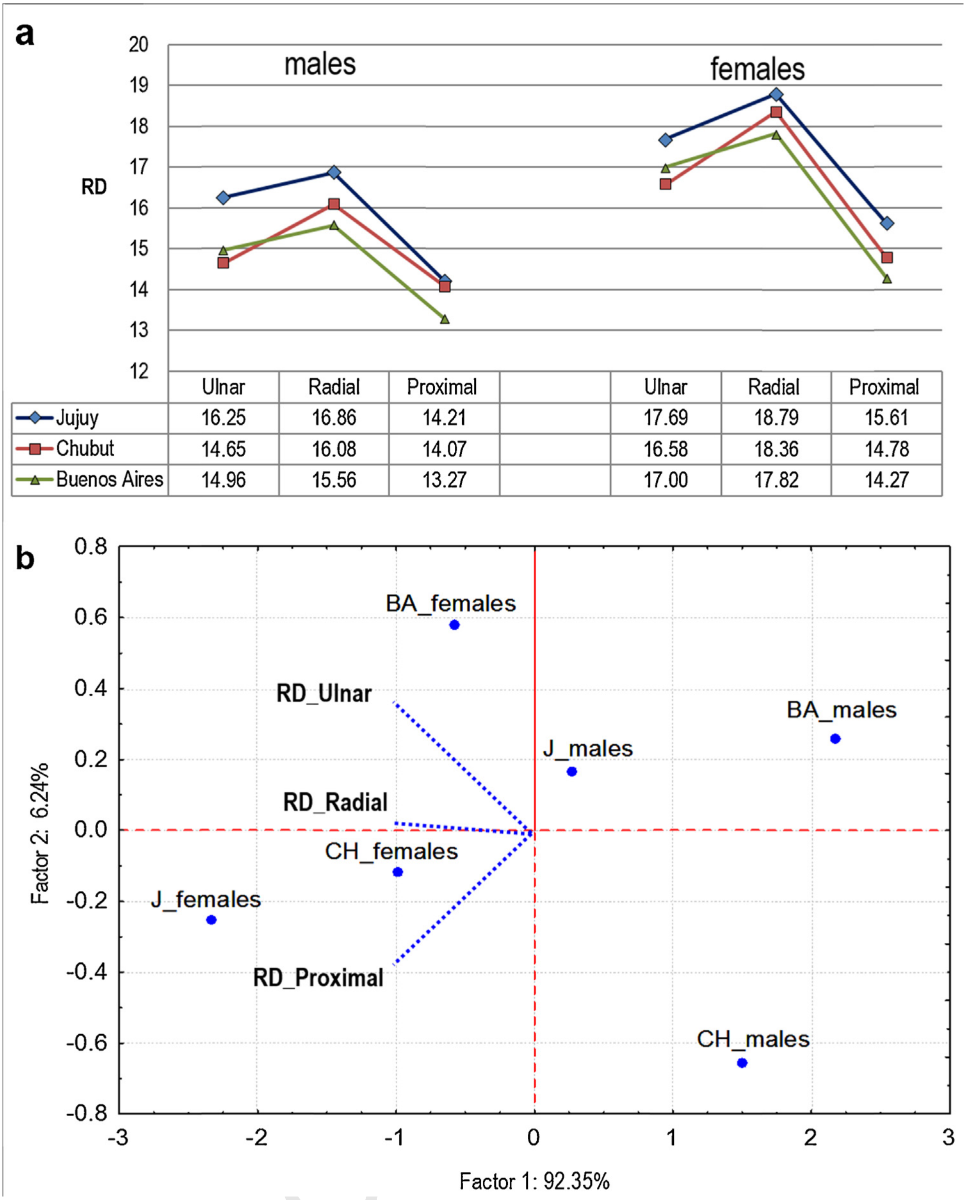

Fig. 8. (a) Mean ridge density for each area by sex and population. (b) Principal component analysis (PCA) for count area and population sample by sex. BA: Buenos Aires; CH: Chubut; J: Jujuy.

statistically significant differences in RD between the populations of Puna-Quebrada and Ramal were found, these samples were considered together to perform this comparison.

Fig. 8a shows the results obtained for the mean for all 10 fingers, by count area and by sex, for the three studied samples. In both sexes, the sample from Jujuy presented statistically significant differences in the ulnar area, with both the Chubut sample (males: $p < 0.001$; females: $p < 0.001$) and the Buenos Aires sample (males: $p = 0.004$; females: $p < 0.001$). In the radial area, males from Jujuy presented significantly different RD with respect to males from Buenos Aires ($p < 0.001$) and Chubut

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($p < 0.001$), while females from Jujuy only presented significant differences with the females from Buenos Aires ($p < 0.001$). In both sexes, no significant differences in the RD of the Buenos Aires and Chubut samples were found, either in the radial or the ulnar areas, while in the proximal area only males showed differences ($p < 0.001$).

As shown in Fig. 8a, the mean RD of females is significantly higher than that of men of the same origin. This is true for the three count areas analyzed, although the sexual dimorphism is lesser in the proximal area.

A PCA was applied to all three counting areas and the three population samples by sex (Fig. 8b). The PCA results show that 97.65% of the data variance can be described by two principal components. The first component (PC1: 92.35%) separates females from males (with greater RD in the former). The second component (PC: 6.24%) separates the proximal area from the count areas in the distal region of the fingertip (radial and ulnar areas).

Discussion

Despite the widespread idea that the population of Argentina is mostly of European origin, several studies have shown that the process of admixture had a strong impact on the entire population of Argentina – this being the result of admixture among various groups, including the Indigenous American, European, and African populations (Avena et al., 2009, 2010, 2012; Fejerman et al., 2005; García and Demarchi, 2009; Rothhammer, 1990). Thus, the average genetic ancestry of Argentinean samples has been estimated as 65% European, 31% Indigenous American, and 4% African, although statistically significant differences were found across Argentinean regions, ranging in the European component from 76% in the Buenos Aires province to 33% in the Northwest, and intermediate values (54%) in the Northeast and South (Avena et al., 2012).

The samples analyzed in this study come from the provinces of Buenos Aires and Chubut and were compared with data previously obtained in the Jujuy province (Northwestern Argentina) and analyzed using the same methods.

The city of Buenos Aires, which housed about 70,000 people in the mid-nineteenth century, received an important contribution of European immigration (mostly from Italy and Spain), mainly from 1880 to the end of the Second World War. However, beginning in the 1930s (1930–1980), according to information provided by the population census of the National Institute of Statistics and Census (Avena et al., 2006), together with a decrease in the presence of Europeans, an increasing number of local migrants from the rural areas and, more recently, of immigration from bordering countries, both with a high Hispano-Amerindian genetic ancestry was recorded. These population movements have changed the composition of the population of the Buenos Aires Metropolitan Area. At present, the city of Buenos Aires and the first and second urban belts have a percentage of Amerindian contribution of 17%, 16%, and 29%, respectively (Avena et al., 2012). The African component, however, does not show a significant variation by area (ranging between 3% and 4%), demonstrating that this is an old genetic component in these populations, while the increasing indigenous element would result from the successive migrations' arrivals to the Buenos Aires suburbs throughout the twentieth century and not from a mixture or blending between individuals. In addition, maternal Amerindian ancestry decreases as we approach the city of Buenos Aires and increases northward and southward, but even in the most European population, namely Buenos Aires, almost one in two people have native maternal ancestry (Avena et al., 2010; Dipierri et al., 1998; García and Demarchi, 2009; Parolin et al., 2013).

On the other hand, the province of Chubut is located in the Patagonia region, which also includes the provinces of La Pampa, Neuquén, Río Negro, Santa Cruz, and Tierra del Fuego. The Chubut province is currently one of the Argentine geographic areas with a larger population that self-identifies as belonging to and/or being first-generation descendant of indigenous peoples. The indigenous group most represented is the Mapuche, so Chubut is the second greatest province in the country with regard to people so recognized after the Rio Negro province. However, migration from the center of the country has had a great impact on the urban centers of the region, which is reflected in a greater contribution of European genetic markers compared with the other samples from Chubut studied earlier (from Comodoro Rivadavia and Esquel) (Avena et al., 2009, 2010). Thus, the data recently provided by the autosomal markers indicate 67.2%, 29.4%, and 3.4% of European, Amerindian, and African contributions, respectively

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(Parolin et al., 2013). Differences in sex-specific indigenous contribution are also observed, where Amerindian ancestry represented 59.9% in maternal lineage and 8.7% in paternal lineages (Parolin et al., 2013). The increased presence of Amerindian descent through the mother, regarding the paternal route, is consistent with a model where the crossing of a native woman with a man of other origins prevails, which has been widely observed in many countries in South America (Bedoya et al., 2006; Dipierri et al., 1998; García and Demarchi, 2006; Marino et al., 2007; Marrero et al., 2007; Sans et al., 2002).

The frequencies of the main types of patterns found in the two analyzed samples from Argentina (Buenos Aires and Chubut) fall within the distribution range described for South American populations. These populations show a greater variation in their frequencies than any other American populations (Inuit, North American Indians, and Central American Indians) (Demarchi and Marcellino, 1998; Garruto et al., 1979). The pattern type frequencies recorded for the samples from Buenos Aires and Chubut are not significantly different, but both presented significant differences with those described for the Jujuy province (Gutiérrez-Redomero et al., 2013c). These differences reveal a larger number of whorls in the Jujuy samples (Puna-Quebrada and Ramal) against a greater presence of ulnar loops in the samples from Buenos Aires and Chubut.

In addition to age, the variation in the epidermal ridge breadth is related to sex, hand size, height, and weight (Cummins et al., 1941; Jantz, 1977; Jantz and Owsley, 1977; Jantz and Parham, 1978; Loesch and Lafranchi, 1990; Mundorff et al., 2014; Ohler and Cummins, 1942; Penrose and Loesch, 1967). All these variables are interrelated since the variability of body size and their segments (hand and foot) is largely determined by sex and population.

Traditionally, studies assessing the differences in ridge number have been performed by means of the classic ridge count (number of ridges crossing a line from the delta or triradius to the core, the so-called Galton line, without considering the origin or the end) (Cummins and Midlo, 1943). This method does not allow evaluation of the topological differences of RD on the same finger, nor does it permit its assessment in patterns without triradius, such as arches. In contrast, the method used in this study allows the performance of a topological comparison of the ridge thickness of the fingertip surface in all types of patterns.

The variability in the RD found on the three analyzed count areas has revealed differences in the fingerprint ridge breadth of the samples. These differences show a distribution pattern of higher density, and therefore thinner ridges, in the distal region (both in radial and ulnar areas); conversely, RD is considerably lower in the proximal area, revealing the presence of thicker ridges in this region. These results are consistent with those obtained for populations from Jujuy (Gutiérrez-Redomero et al., 2013c), Spain (Gutiérrez-Redomero et al., 2008), sub-Saharan Africa (Gutiérrez-Redomero et al., 2013b), and North India (Krishan et al., 2013) – all of these were analyzed using the same methods. Studies by Cummins et al. (1941) and Ohler and Cummins (1942) had already revealed the existence of a disto-proximal topological gradient from the distal phalanx of the fingers to the proximal region of the palm. The data obtained so far on the distal phalanges also show this gradient within them. The differences in RD observed between the distal and the proximal regions of the phalanx are lower in the three Argentinean samples analyzed in comparison to the remaining analyzed populations, revealing a greater uniformity in the ridge thickness of the finger surface in the Argentinean population.

The results of this study indicate that, in both sexes, the distal region of the thumb and index fingers of both hands has the lowest RD, and so the thicker ridges, while the ring fingers show the highest RD, and thus thinner ridges than the other fingers. However, in the proximal area, the thumbs and ring fingers are those having a higher density and therefore thinner ridges. Again these results are consistent with those found in Argentinean population samples from Jujuy (Gutiérrez-Redomero et al., 2013c) and the rest of the samples analyzed with the same methods (Gutiérrez-Redomero et al., 2008, 2013b, Krishan et al., 2013), as well as with the results obtained for Euro-American and African-American populations by Cummins et al. (1941) and Ohler and Cummins (1942). Kahn et al. (2001) hypothesized that these differences in the ridge count between fingers probably represent a gradient of cephalocaudal growth in the fetus, since each finger is neurologically related to a section of the spinal cord, C6–C8, and so this may be a universal pattern.

In both sexes, statistically significant differences were found between the radial and ulnar areas, with the exception of the right hand in the Buenos Aires sample, which showed a greater uniformity in ridge thickness in this hand. In both sexes, the two Argentinean samples displayed a similar RD in all three count areas in the left hand, while the right hand of Chubut individuals had thicker ridges in the ulnar area and thinner ridges in the radial and proximal areas as compared to the individuals in the Buenos Aires sample. Thus, individuals from Buenos Aires and Chubut show a great similarity in ridge thickness in the left hand, but not in the right hand. However, the overall RD (average of all 10 fingers) showed no significant differences between the two groups (Buenos Aires and Chubut) in either sex.

In both samples, sex differences were found for the three count areas, both globally and by finger, always presenting greater RD in females, and thus thinner ridges, than in males.

Recently, studies have empirically assessed sex differences for the epidermal RD in different populations, proving to be a useful tool for inference of sex from latent fingerprints of unknown origin (Acree, 1999; Agnihotri et al., 2012; Eshak et al., 2013; Gungadin, 2007; Gutiérrez-Redomero et al., 2008, 2011a, 2013a,c, 2014; Kaur and Garg, 2011; Krishan et al., 2013; Mundorff et al., 2014; Nayak et al., 2010a,b; Nithin et al., 2011). Table 5 shows the averages found in populations in which the average RD of the 10 fingers in an area of 25 mm^2 has been assessed in both the radial and the ulnar and proximal areas. In all these populations, females have a significantly higher RD, and therefore thinner ridges, than males, which could suggest a universal pattern of sexual dimorphism for this feature. The average RD obtained for the radial area in different populations (Table 5) shows a remarkable interpopulation variability. Thus, the mean RD in the North American population samples studied by Acree (1999) and in several Asian population samples (Agnihotri et al., 2012; Gungadin, 2007; Kaur and Garg, 2011; Nayak et al., 2010a,b; Nithin et al., 2011) are significantly lower than that obtained in samples that were analyzed following the same methods of Gutiérrez-Redomero et al. (2008, 2013b,c). However, it should be taken into account that these studies show methodological differences in relation to the location of the counting area and the method for obtaining the fingerprints. As revealed by Gutiérrez-Redomero et al. (2014), significant differences in RD appear depending on the method of obtaining the fingerprints (rolled or plain) and the count area position (near the core or outermost area). Therefore, it is essential to standardize the location of the count area when comparative studies of any kind are made. This normalization is particularly important in view of the forensic applications of this feature related to the sex inference of an individual from latent prints of unknown origin. Consequently, the results can only be directly compared when the studies have followed the same methods of counting so that the differences between them can be associated with interpopulation variation. Comparisons between methodologically comparable studies have revealed significant differences between the Spanish sample and other population samples: sub-Saharan Africa (Gutiérrez-Redomero et al., 2013b), the Jujuy province (Gutiérrez-Redomero et al., 2013c), and Mataco-Mataguayos (Gutiérrez-Redomero et al., 2011a).

Regarding the Argentinean samples analyzed in the present study, the ulnar area of both sexes showed statistically significant differences in RD between the Jujuy samples and the Chubut and Buenos Aires samples, which presented a greater RD and thus thinner ridges. Likewise, the radial area of males from Jujuy showed statistically significant differences (narrower ridges) with males from Buenos Aires and Chubut, while Jujuy females presented only differences with those from Buenos Aires. For the proximal area, the Buenos Aires sample showed significant differences (thicker ridges) with the Jujuy sample for both sexes and with the Chubut sample only for males, while the differences between the Chubut and Jujuy samples were significant only in females, the former showing thicker ridges.

Therefore, the samples from Jujuy (Northwest Argentine), with the largest indigenous ancestry, presented the greatest differences in ridge morphology with other Argentinean provinces (Buenos Aires and Chubut), while the samples from Buenos Aires and Chubut were relatively similar between themselves. Avena et al. (2012) revealed the correlation between number of Europe-born grandparents and European ancestry as measured by genetic markers. In the present study, given that all four of the participants' grandparents were born in Chubut and that at least three of the participants' grandparent were born in the Buenos Aires province (and the fourth born in a bordering province), it is very likely the indigenous component is increased in the samples of both provinces, which would explain the morphological similarities found between them.

The RD probabilities were used for inferring the most likely sex by means of the likelihood ratios (LRs) for three areas (radial, ulnar, and proximal). The value of the calculated LR informs about the

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Table 5
Mean and standard deviation (SD) of fingerprint ridge density (mean for all 10 fingers) in different studies for the radial, ulnar, and proximal areas in males and females.

Sample	Reference	Ridge density mean (SD)					
		Radial area		Ulnar area		Proximal area	
		Male	Female	Male	Female	Male	Female
Afro-American (USA)	Acree (1999)	10.90 (1.15)	12.61 (1.43)				
European American (USA)	Acree (1999)	11.14 (1.31)	13.32 (1.24)				
Malaysia	Nayak et al. (2010b)	11.44 (0.99)	13.63 (0.91)				
China	Nayak et al. (2010b)	11.73 (1.07)	14.15 (1.04)				
India	Nayak et al. (2010a)	11.05 (1.11)	14.20 (0.63)				
Southern India	Gungadin (2007)	12.80 (0.90)	14.60 (0.09)				
Southern India	Nithin et al. (2011)	12.57 (1.49)	14.15 (1.68)				
Northern India	Krishan et al. (2013)	15.84 (1.23)	17.94 (1.23)	15.51 (1.08)	17.11 (1.21)	11.29 (1.11)	12.05 (0.87)
Northern India (Sikh Jat)	Kaur and Garg (2011)	12.05 (0.97)	14.14 (0.72)				
Northern India (Bania)	Kaur and Garg (2011)	12.99 (1.19)	15.61 (1.43)				
Indo-Mauritania	Agnihotri et al. (2012)	11.37	13.98				
sub-Saharan	Gutiérrez-Redomero et al. (2013b)	14.33 (1.22)		14.51 (1.29)		12.07 (1.15)	
Argentina (Mataco-Mataguayo)	Gutiérrez-Redomero et al. (2011a)	16.62 (2.71)	17.82 (2.87)	16.54 (2.80)	17.29 (1.76)	14.20 (2.01)	14.63 (1.42)
Argentina (Jujuy)	Gutiérrez-Redomero et al. (2013c)	16.86 (1.73)	18.79 (1.73)	16.25 (1.68)	17.69 (1.66)	14.21 (1.30)	15.61 (1.55)
Spain	Gutiérrez-Redomero et al. (2014)	16.85 (1.76)	19.11 (1.79)	15.38 (1.49)	16.84 (1.58)	12.62 (1.45)	13.76 (1.52)
Buenos Aires	Present study	15.56 (1.49)	17.82 (1.36)	14.96 (1.55)	17.00 (1.68)	13.27 (1.11)	14.27 (1.18)
Chubut	Present study	16.08 (1.47)	18.36 (1.83)	14.65 (1.48)	16.58 (1.68)	14.07 (1.42)	14.78 (1.34)

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strength of support for one of the hypotheses, male or female. Information obtained from both LR values and posterior probabilities was used to exemplify the favored odds for support of the most likely hypothesis for a given RD. The results show that depending on the prior probabilities of males and females, the favored odds change. So, with a prior probability equal for both sexes, the threshold for sexual differentiation would be between 16 and 17 ridges/7.07 mm in the radial area for the Buenos Aires sample. It can then be inferred that an RD equal to or less than 16 would indicate a greater likelihood that the fingerprint belongs to a male individual (64%) compared to 36% indicating it belonging to a female. The likelihood that the fingerprint comes from a male individual becomes greater when the ridge number found in the count area diminishes, so a count equal to or lesser than 15 ridges would give a probability of 83% of belonging to a male. In actual situations within the police context, the prior probabilities are not equal for both sexes, but the chances that a male individual is related to the scene where a crime has allegedly been committed are higher than those of a female. Thus, if the prior probabilities change, being greater for males (e.g. 70%), the threshold of sexual differentiation would be between 17 and 18 ridges/7.07 mm. Similarly, an RD equal to 17 at the radial area would imply a probability of 51% that the fingerprint comes from a male, but if the count in the area is 15 or less, the likelihood of it belonging to a male rises to 92%. The application of degrees of probability in inferring sex could facilitate the laborious process of seeking for and identifying subjects based on their fingerprints in the field of forensic science.

In any case, it should be noted that conclusions based on likelihood ratios and posterior probabilities derived from applying Bayes's theorem are merely inferences based on a specific population and the assumption of prior probabilities. Therefore, the posterior probabilities should be applied in those cases where the ethnicity of the donor can be known a priori as a result of the differences found in the RD among the studied population (Acree, 1999).

The sex differences in RD found in all populations where they have been assessed supports the existence of a universal pattern of sexual dimorphism that could be applied in the identification of individuals.

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