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Assessment of the methodology for estimating ridge density in fingerprints and its forensic application.

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Abstract

In recent times, some studies have explored the forensic application of dermatoglyphic traits such as the epidermal ridge breadth or ridge density (RD) toward the inference of sex and population from fingerprints of unknown origin, as it has been demonstrated that there exist significant differences of fingerprints between sexes and between populations. Part of the population differences found between these studies could be of methodological nature, due both to the lack of standardisation in the position of the counting area, as well as to the differences in the method used for obtaining the fingerprint. Therefore, the aim of this study was to check whether there are differences between the RD of fingerprints depending on where the counting area is placed or how the fingerprints are obtained. Fingerprints of each finger were obtained from 102 adult Spanish subjects (50 females and 52 males), using two methods (plain and rolled). The ridge density of each fingerprint was assessed in five different areas of the dactylogram: two closer to the core area (one on the radial and the other on the ulnar side), two closer to the outermost area of each of the sides (radial and ulnar), and another one in the proximal region of the fingertip. Regardless of the method used and of the position of the counting area, thumbs and forefingers show a higher RD than middle, ring, and little fingers in both sexes, and females present a higher RD than males in all areas and fingers. In both males and females, RD values on the core region are higher than those on the outer region, irrespective of the technique of fingerprinting used (rolled or plain). Regardless of the sex and location of the count area (core or outer), the rolled fingerprints exhibit RD greater than that of the plain ones in both radial and proximal areas, whereas the trend is inverted in the ulnar area, where rolled fingerprints demonstrate RD lesser than that of the plain ones. Therefore, in order for the results of different studies to be comparable, it is necessary to standardise the position of the count area and to use the same method of obtaining the fingerprint, especially when involving a forensic application.

Keywords: Fingerprints, Dermatoglyphic, Ridge density, Identification, Sex difference, Standardisation

Introduction

In the field of human biology, dermatoglyphic studies have traditionally been used for characterizing human populations, at both intra- and intergroup levels, as much for healthy populations [1-4] as for pathological ones [5-7]. In the scope of forensic science, fingerprints have been used for personal identification for over a century [8-17].

Dermal papillae ridges have multifactorial polygenic inheritance, in which environmental influence is limited to the first months of prenatal life [18,19]. Once formed, and in the absence of injury, these ridges remain essentially unchanged throughout the lifetime of the individual. Consequently, the number of epidermal ridges is independent of age, and the ridges will have to increase their size (width), without adding new ridges, to fit the whole body growth and, in particular, the hand and foot growth [20-24]. Some of the dermatoglyphic traits, such as ridge number, are highly heritable since they are almost fully genetically determined (90-95%), whereas other traits, such as the minutiae, are largely determined by the environment during prenatal development [25].

Regarding epidermal ridge breadth or thickness, although few studies have assessed their variability in human populations, these studies have revealed the presence of topological, finger, and sex variability, as well as population differences [26-34].

Some studies have explored their forensic application toward the inference of sex, from fingerprints of unknown origin [35-42]. The only study to date in the North American population has been described by Acree [35] and was carried out on samples of the Caucasian and African-American populations. For the South American population, Gutiérrez-Redomero et al. [42] have published a study on Argentinian population. The Spanish population has been studied by Gutiérrez-Redomero et al. [37], while Gungadin [36], Nithin et al. [40], Nayak et al. [38,39], and Agnihotri et al. [41], have analysed Indian, Chinese, Malayan, and Indo-Mauritian populations, respectively.

Part of the differences found between these studies could be of methodological nature, due both to the lack of standardisation in the location of the counting area and to the differences in the technique for obtaining the fingerprint. Thus, although the ridge density (RD) assessment is always carried out on the same 5 x 5 mm area designed by Acree [35], the position of the counting area has only been standardised by Gutiérrez-Redomero et al. [23,37,42,43] and Krishan et al. [44]. Furthermore, in some cases, the fingerprint has been obtained by rolling the finger onto a surface (a "rolled" fingerprint) while in others, the finger is pressed down on a flat surface (a "plain" fingerprint)`[45]. From all the above follows the need to check whether there are differences in the RD depending on where the counting area is placed and how the fingerprint is obtained (rolled or plain).

Materials and Methods

The study sample consisted of 102 healthy individuals (50 females and 52 males) who were studying at the Department of Life Sciences of the University of Alcalá (Madrid, Spain). All subjects included in the study were native to this country: they were born in Spain, and their parents and grandparents were also born in Spain, mainly in the central and southern regions. Since ridge width varies with age during the growth period all selected individuals had completed their period of growth and were between 18 and 34 years of age.

The technique used in obtaining the fingerprints was a variation of the adhesive paper and graphite method [46], developed by Gutiérrez-Redomero et al. [42]. This technique involves the use of graphite powder to stain homogeneously the fingertip papillae ridges. The graphite powder is then deposited from the fingertips onto the sticky side of a label of the appropriate size. Then, these labels are affixed to a transparent acetate sheet that has been designed with scales and grids in order to allow that each sheet may contain each of the 10 fingerprints obtained from an individual. By using this technique, a mirror image of the fingertip surface is achieved, similar to that obtained with the classic ink method. The fingerprints of each individual were taken twice, firstly by rolling the fingertip in ulnar to radial direction, and then a second time by pressing down the fingertip on a flat surface. As a final result, 20 fingerprints per subject were obtained, 10 rolled and 10 plain (Figure 1). This allowed the analysis of 1,020 rolled and 1,020 plain fingerprints in order to compare the RD presented between both methods.

The assessment of the RD was carried out by means of counting the ridges found diagonally within a 5 mm x 5 mm square, known as count area, which, according to the method described by Acree [35], provides the number of ridges per 7.07 mm on the fingertip surface. The methodology proposed by Gutiérrez-Redomero et al. [37,42,43] was followed so that three count areas were established. To locate these three count areas in whorls and loops, each fingerprint was divided into four sectors by two perpendicular axes that cross two ridges above the core of the pattern, with the horizontal line positioned parallel to the interphalangeal joint. In the case of the arches, without a defined nucleus, the axes intersect at the center of the dactylogram on top of the arch. The proximal area was located on the vertical axis, so that the diagonal of the count area was perpendicular to the direction of the ridges, taking as a starting point the first ridge well defined from the interphalangeal joint. Thus, three count areas were analysed: two on the ulnar (u_core) and radial (r_core) sides of the distal portion of the fingertip and another one on the proximal (p) portion. To determine if the RD varies depending on the location of the count area, two additional areas have been evaluated: one

external radial (r_out) and one external ulnar (u_out), which were placed at a more external location on the rolled fingerprint and the outermost possible location on the plain fingerprint (Figure 2). In all, five count areas are established for each fingerprint method, rolled (R) and plain (P), which provides 10 counts per finger, representing the total assessment of 10,200 count areas.

Subsequently, the fingerprints were scanned, finger by finger, in the Physical Anthropology laboratory at the University of Alcalá (Madrid, Spain). The fingers were numbered from 1 to 10, beginning with the right thumb (F1) and ending with the left little finger (F10). In order to facilitate the tasks of counting, the ridge count was performed using images enlarged to four times their original size, accordingly redefining to a count area of 20 mm x 20 mm.

Statistical analysis

The mean RD for each of the 10 areas by finger was estimated for both sexes. Sex differences for every count area were analysed individually (mean for each finger) and globally (mean for all 10 fingers), using a Student's t-test. For the distal area, the differences between the core and outer count areas (for both radial and ulnar) were statistically assessed using a Wilcoxon test. In addition, in order to highlight the relationship among different radial areas and fingers, principal component analysis (PCA) was applied. The goal of PCA [47,48] is to have a global view of the data that is useful for interpretation. The main use of PCA is to reduce the dimensionality of the data set while retaining as much information as possible. PCA transforms a number of correlated variables into a (smaller) number of uncorrelated variables called principal components (PCs), which are ordered by reducing variability. PCA seeks a few orthogonal linear combinations of the original variables with the largest variance. The first PC is the linear combination with the largest variance. The second PC is the linear combination with the second largest variance and orthogonal to the first PC, and so on. There are as many PCs as the number of original variables, but the original variables are correlated and the PCs are not. Therefore, for many datasets, the first several PCs explain most of the variance, so that the rest can be disregarded with minimal loss of information. PCA is a powerful statistical tool for exploring quantitative data through a graphical representation or map, thereby facilitating analysis, detection, and interpretation of relationships among variables. PCA is a way of identifying patterns in data and expressing the data in such a way as to highlight their similarities and differences [49].

Frequencies for the different types of patterns (arch-A, ulnar loop-UL, radial loop-RL, and whorl-W) were estimated, and their relationship with the types of finger was assessed using a multiple correspondence analysis [16,50].

Statistical analyses were performed by means of the SPSS version 15.0 and Statistica version 7.0 software packages. In all cases, significant differences were considered when the p-value was less than 0.05.

Results

Relationship between type of pattern, finger, and sex

Figure 3a shows the frequencies of the different types of patterns by finger and sex. Multiple correspondence analysis between the type of pattern and finger by sex (Figure 3b) shows a statistically significant dependence between them ($chi^2 = 219.14$; $df = 27$; $p < 0.0001$). Both thumbs (F1 and F6) and ring fingers (F4 and F9) are associated with whorls, whereas middle (F3 and F8) and little fingers (F5 and F10) are associated with ulnar loops, and index fingers (F2 and F7) are associated with arches and radial loops. The first dimension separates ulnar loops from the remaining types of patterns and both index fingers (F2 and F7) from the remaining fingers. The second dimension discriminates males, which exhibit a high frequency of whorls, and females, which show a higher frequency of ulnar loops and arches.

Relationship between RD, fingers, areas and sex

In regard to the radial area, Figure 4 shows the mean RD for rolled (R) and plain (P) fingerprints at the core (core) and external areas (outer) by finger and sex. Regardless of the fingerprint method (rolled or plain) and the location of the count area (core or outer), the thumbs and index fingers (F1, F6; F2, F7) show a lower RD (so, thicker ridges) than that of the other fingers (middle, ring, and little fingers), for both right and left hands and in both sexes. As can be seen also in Figure 4, females show a statistically significant ($p < 0.01$) higher RD than males do for all fingers, regardless of where the counting area is placed (core or outer) or how the fingerprint is obtained (rolled or plain).

When comparing the counting areas between rolled and plain fingerprints, in the core region (circles in Fig. 4), the rolled fingerprints present, for all fingers and for both sexes (excepting F8 and F9 in males), a higher RD than the corresponding plain fingerprints do. Similarly, in the outer location (triangles in Fig. 4), the rolled fingerprints show a higher RD than the plain ones do, except for F4 and F8 in males).

Regarding the plain fingerprints (dashed lines in Fig. 4), the core region consistently shows a higher RD than the outer location in all fingers in both sexes. The same trend is observed in the rolled

fingerprints (solid lines in Fig. 4), which show a higher RD in the core location with respect to the outer location, in all the fingers of males and females, excepting F8 in females.

With respect to the ulnar area, the mean RD for rolled and plain fingerprints in the core and outer locations by finger and sex are displayed in Figure 5. Also, in this case, the thumbs and index fingers of both sexes show a lesser RD than that of the other three fingers (middle, ring, and little), no matter how the fingerprint is collected or where the count area is located. This difference in RD is always statistically significant ($p < 0.01$), higher in females than in males.

But unlike the radial area, when comparing rolled and plain fingerprints in the ulnar area, the plain fingerprints (dashed lines) show higher a RD than the rolled ones (solid lines) in all fingers for both sexes (excepting F5 in females). This is true whether core (circles) or outer locations (triangles) are considered.

As in the radial area, in the ulnar area, both the rolled and the plain fingerprints show a higher RD in the core region than in the outer location for all fingers and for both sexes, except for male little fingers (Figure 5).

Finally, in regard to the proximal area, Figure 6 shows the mean RD values by finger and sex for rolled and plain fingerprints. Unlike that found in the distal region (either ulnar or radial), the thumbs present a higher RD than that of the other fingers, in both sexes. In both rolled and plain fingerprints, females show a statistically significant ($p < 0.05$) higher RD than males in all fingers. For both hands and sexes, rolled fingerprints present a higher ridge count than plain ones, especially in middle, ring, and little fingers.

Significant differences in ridge count between the radial and ulnar areas for the considered areas (core and outer) and for every method (rolled and plain), by finger and sex, are shown in Table 1. Whereas in rolled fingerprints, most of the fingers present significant differences between radial and ulnar areas, in plain fingerprints, these differences only reach statistical significance for a few fingers.

Since ridge density at the radial area has been the most frequently studied [35,36,38-40], principal component analysis (PCA) has been applied for this count area, the results of which are shown in Figure 7. PCA results show that 98.16% of the data variance can be described by two principal components (PC1: 94.84% and PC2: 3.32%). The first principal component (PC1) separates the female from the male prints, while the second principal component (PC2) separates the thumbs (F1, F6), index fingers (F2, F7), and right little finger (F5) from the other fingers.

The mean RD for all 10 fingers by sex, area (ulnar, radial, or proximal), location (core or outer), and method of fingerprint (rolled or plain) are shown in Figure 8. Distal areas (radial and ulnar) show a greater mean count than that of the proximal area. The five considered areas (r_core,

r_out, u_core, u_out, and p), in both rolled and plain fingerprints, show statistically significant differences between sexes ($p < 0.0001$), females always presenting a higher RD than males. In all cases, the sex difference is at least one ridge, sometimes reaching up to a difference of almost three ridges between male and female RD, as is exhibited by the rolled radial core fingerprints (R_r_core).

When the location of the count area is considered, core means are always significantly higher ($p < 0.02$) than outer means, regardless of sex or method of fingerprinting (Figure 8). When comparing RD means for rolled vs. plain fingerprints, different results are found depending on the area considered. Thus, regardless of the sex and the location of the count area (core or outer), the rolled RDs are greater than the plain ones in both radial and proximal areas (except for r_core in males), whereas the trend is inverted in the ulnar area, where rolled RDs are lesser than the plain ones. All these differences reach statistical significance ($p < 0.001$).

Discussion

The data reported in this paper represents a novelty within this topic, since it compares two methods of obtaining fingerprints (rolled and plain) and assesses the differences in ridge density in five different areas of the dactylogram: two closer to the core area (one on the radial and the other on the ulnar side); two closer to the outermost area, on each of the sides (radial and ulnar); and another one in the proximal region of the fingertip. This allows highlighting the differences in ridge density, depending on how the fingerprint is obtained and where the counting area is placed.

The results obtained show topological differences in the ridge width of fingerprints, regardless of the method of acquisition. Thus, in both the rolled and the plain fingerprints, the ridge thickness is lesser in the distal region (radial and ulnar) than in the proximal one, thereby presenting thinner ridges.

The differences found between the ulnar and radial sides, for both the core and outer areas, are considerably lower in plain prints compared to rolled prints. In fact, while in the rolled prints, the radial and ulnar areas significantly differ in almost all the fingers; in the plain prints, these differences were only significant for some fingers. This seems to be due to the effect of distortion in the rolling of the finger (always in ulnar to radial direction), which would enhance the differences between the radial and ulnar side of the fingertip, whereas in plain fingerprints the pressure is more evenly applied on both sides of the finger, which would decrease the count differences between them. Similarly, the differences found in the proximal area between rolled and plain prints, could be determined by the differences in the directions of pressure applied by taking the fingerprint. From all

of this, it follows that the method of obtaining the fingerprint meaningfully affects the assessment of dactylogram ridge density.

On the other hand, regarding the location of the counting area, since finger size determines the margin of separation between core and outer areas, both in the rolled as well as in the plain prints, the biggest differences between ridge counts are observed in the thumb, while the smallest differences are presented in the little finger, where these areas are closer due to its smaller size. Nevertheless, when considering the mean ridge density for all 10 fingers, significant differences are found between core and outer areas, in both the radial and the ulnar sides, in rolled as well as in plain fingerprints. Thus, it can be inferred that the location of the count area in the dactylogram affects the assessment of the ridge density on the fingertip surface.

The observed fingerprint differences between fingers match those found in other studies that have analysed them [26,27,37,42-44], being that the thumbs and index fingers show thicker ridges at the distal region (radial and ulnar, regardless the location of the count area, core or outer) while the middle and ring fingers show the narrowest ridges, independently of the method applied for obtaining the fingerprint (rolled or plain). However, at the proximal region, thumbs show narrower ridges than the other fingers. Therefore, thumbs are the fingers which exhibit greater topological differences in regard to ridge thickness.

The present results also show that females have thinner ridges, regardless of the area, finger, and method of obtaining the prints, than males. Although few studies have empirically assessed sex differences in the thickness of the epidermal ridges in human populations, they have all found significant sex differences in the ridge density on the radial side of the fingertip, which is the most studied (Table 2). Sex differences in other areas of the finger, like the ulnar or the proximal area, have also been highlighted in the few studies that have evaluated them [23,37,42,44].

By comparing the results obtained by those studies that have evaluated the ridge density on an area of 25 mm^2, some differences appear between them, part of which could be due to actual population variations, given the diverse origins or sources of the samples analysed. However, in view of the results presented in this study, at least some of these differences could be explained as methodological differences in relation to the method used for obtaining the fingerprint and/or the position of the counting area. In most of the published studies, the only information about the location of the counting area is, as described by Acree, that it is positioned *"in the right hand directly to the upper left of the central core region and for fingerprints from the left hand the square was placed to the upper right of the central core area"* [35]. Furthermore, the method used for obtaining prints (rolled or plain) varies between the studies. Only the works from Gutiérrez-Redomero et al. [23,37,42,43] and Krishan et al. [44] have standardised the method of counting to assess the density

of ridges on rolled fingerprints, so the population differences can be directly assessed. These studies standardise the location of the counting area: it is placed two ridges above the core of the pattern (see the Material and Methods section), obtaining higher values than those found by other studies. The results obtained in the present study reveal, on the one hand, that the areas located nearest the core of the fingerprint exhibit count values significantly greater than those placed in an outermost position and, on the other hand, that plain fingerprints display lesser count values than rolled ones in the radial area, regardless of the finger. This would explain some of the differences found among the studies.

From this it follows that, in order to properly compare results across studies, it is necessary to standardise both the technique of obtaining the fingerprint and the position of the counting area, especially if the assessment method is proposed as a tool for inference of sex or population origin in the field of forensic identification. However, it should be noted that other factors may affect the estimated ridge density, such as the pressure to take the fingerprint. This aspect has not been specifically evaluated in this study, since it is very difficult to precisely control the pressure on the finger when taking the fingerprint. This will always be a limitation when comparing results from different studies, as well as in forensic applications. But it should be taken into account that these days the problem of pressure is always present in the identification process, in relation to the comparison of marks. For example, the comparison of fingerprints in the Automated Fingerprint Identification System (AFIS), where the pressure of the fingerprints entered into the system has not been controlled.

Regarding the standardized method's application to the forensic field for inference of sex or origin, a fundamental problem arises with the quality of the marks obtained. As is known, the marks recovered from a crime scene may not be as good as those obtained from volunteers, and the enhancement techniques can affect their quality. Even with all the limitations in the application of any method to marks, standardisation is the only way to work with them (by giving reference points for positioning the count areas) in an attempt to extract the desired information.

Conclusion

The greatest differences found in the ridge density between the radial and ulnar areas in the rolled fingerprints could be due to the distortion produced during the rolling process. So the direction in which the finger is rolled has to be the same in all fingers and must be specified to describe the technique.

After selecting the method for obtaining fingerprints (rolled or plain), the standardisation of the count area should be made on the core area (radial core and ulnar core), as it shows the least ambiguity.

There are significant differences in ridge density assessment depending on the method of obtaining the fingerprint and the position of the count area in the dactylogram. Therefore, in order for the results of different studies to be comparable, it is necessary to standardise the position of the count area and to use the same method of obtaining the fingerprint. However, other factors, such as pressure, can potentially affect the process of identification, posing a more difficult problem to solve.

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Figure captions

Fig. 1.- Transparent acetate sheet showing the 20 fingerprints obtained per subject: 10 rolled and 10 plain. Fingers: from F1 (right thumb) to F10 (left little finger).

Fig. 2.- Location of the count areas on the right thumb fingerprint of the same subject. (a) Plain fingerprint. (b) Rolled fingerprint. r: radial, u: ulnar, p: proximal, out: external count area, core: core count area.

Fig. 3.- (a) Relative frequencies for the type of pattern by finger and sex. (b) Multiple correspondence analysis (MCA) between type of pattern, hand, finger, and sex. W:whorl, UL: ulnar loop, RL: radial loop, A: arch. Finger: Fi = 1,…, 10. RH: right hand, LH: left hand.

Fig. 4.- Mean ridge density for the ten fingers by sex in the radial area for rolled (R) and plain (P) fingerprints at the core area (core) and external area (out). Finger: Fi = 1,..., 10.

Fig. 5.- Mean ridge density for the ten fingers by sex in the ulnar area for rolled (R) and plain (P) fingerprints at the core area (core) and external area (out). Finger: Fi = 1,..., 10.

Fig. 6.- Mean ridge density for the ten fingers by sex in the proximal area for rolled (R) and plain (P) fingerprints. Finger: Fi = 1,..., 10.

Fig. 7.- Principal component analysis (PCA) for radial ridge density by finger, sex, count area, and rolled and plain fingerprints. Finger: Fi=1,…,10; R: rolled, P: plain, ma: males, fe: females, core: core area, out: external area.

Fig. 8.- Ten fingers mean ridge density by sex and count area in plain (a) and rolled (b) fingerprint.

Table 1.- Significant differences between the mean ridge density of the radial and ulnar areas for each method (rolled or plain) and location (core or out) considered, by sex and finger: Fi = 1,..., 10. are shown through the p-value. When $p < 0.05$, an asterisk symbol appears, and when $p > 0.1$, a hyphen appears. R: rolled, P: plain.

Table 2.- Mean and standard deviation (SD) of fingerprint ridge density in different studies for radial, ulnar, and proximal areas in males and females.

Table 1

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		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
P_core	♂	-	-	0.086	0.072	0.068	-	-	-	*	0.065
	♀	-	-	*	-	*	-	-	-	-	0.050
P_out	♂	-	-	0.059	-	-	-	*	-	-	-
	♀	*	*	-	*	-	*	-	-	-	-
R_core	♂	*	*	*	*	*	*	*	-	-	*
	♀	*	*	*	*	*	*	*	*	*	*
R_out	♂	*	*	*	*	-	*	*	*	-	-
	♀	*	*	*	*	*	*	*	*	0.062	*

Table 2

Table 2. Fingerprint ridge density in different studies for 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[35]	10.90 (1.15)	12.61 (1.43)				
Caucasian-american (USA)	Acree,[35]	11.14 (1.31)	13.32 (1.24)				
Malaysia	Nayak et al.[39]	11.44 (0.988)	13.63 (0.906)				
China	Nayak et al.[39]	11.73 (1.066)	14.15 (1.038)				
Southern India	Gungadin[36]	12.80 (0.90)	14.60 (0.085)				
Southern India	Nayak et al.[38]	11.05 (1.11)	14.20 (0.63)				
Southern India	Nithin et al.[40]	12.57 (1.49)	14.15 (1.68)				
Northern India	Krishan et al. [44]	15.84 (1.231)	17.94 (1.232)	15.51 (1.081)	17.11 (1.207)	11.29 (1.108)	12.05 (0.870)
sub-Saharan	Gutiérrez-Redomero et al.[43]	14.33 (1.22)		14.51 (1.29)		12.07 (1.15)	
Argentina (Mataco-Mataguayo)	Gutiérrez-Redomero et al.[23]	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 (Puna-Quebrada)	Gutiérrez-Redomero et al.[42]	16.67 (1.78)	18.47 (1.56)	16.39 (1.75)	17.62 (1.62)	14.33 (1.31)	16.13 (1.54)
Argentina (Ramal)	Gutiérrez-Redomero et al.[42]	17.04 (1.68)	19.08 (1.84)	16.10 (1.61)	17.75 (1.69)	14.08 (1.30)	15.12 (1.40)
Spain	present study	16.85 (1.76)	19.11 (1.79)	15.38 (1.49)	16.84 (1.58)	12.62 (1.45)	13.76 (1.52)

Figure 1

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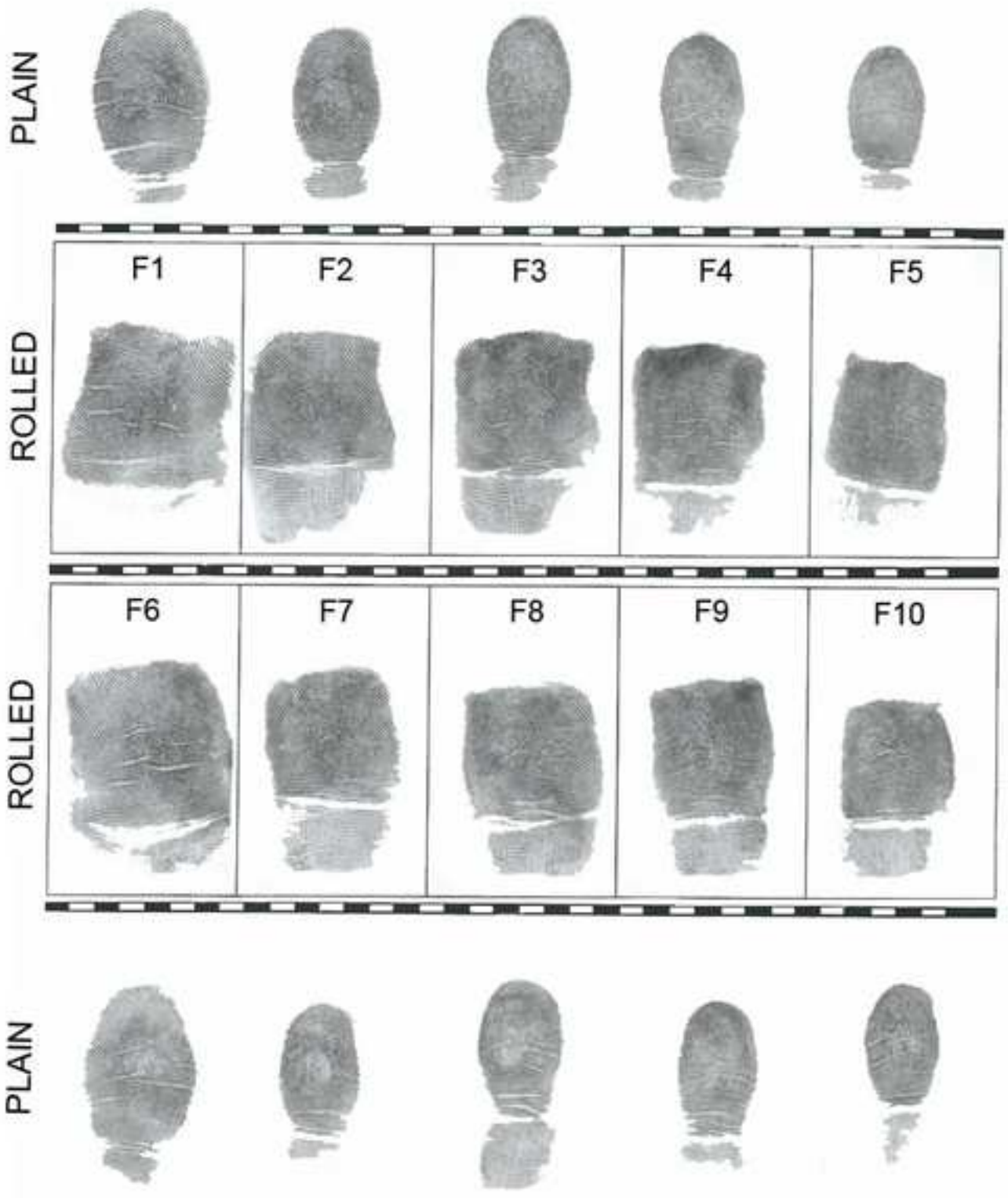

Figure 2

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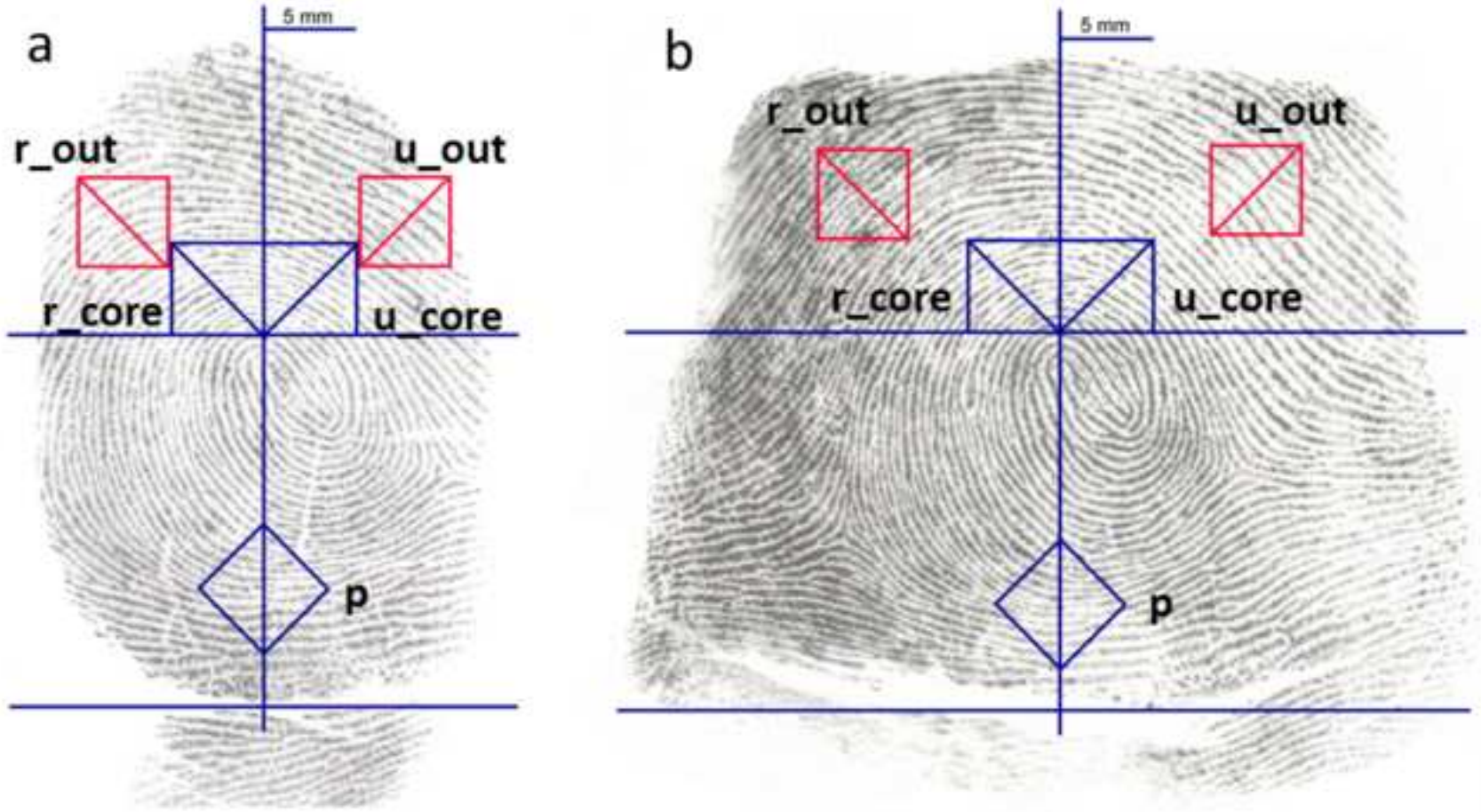

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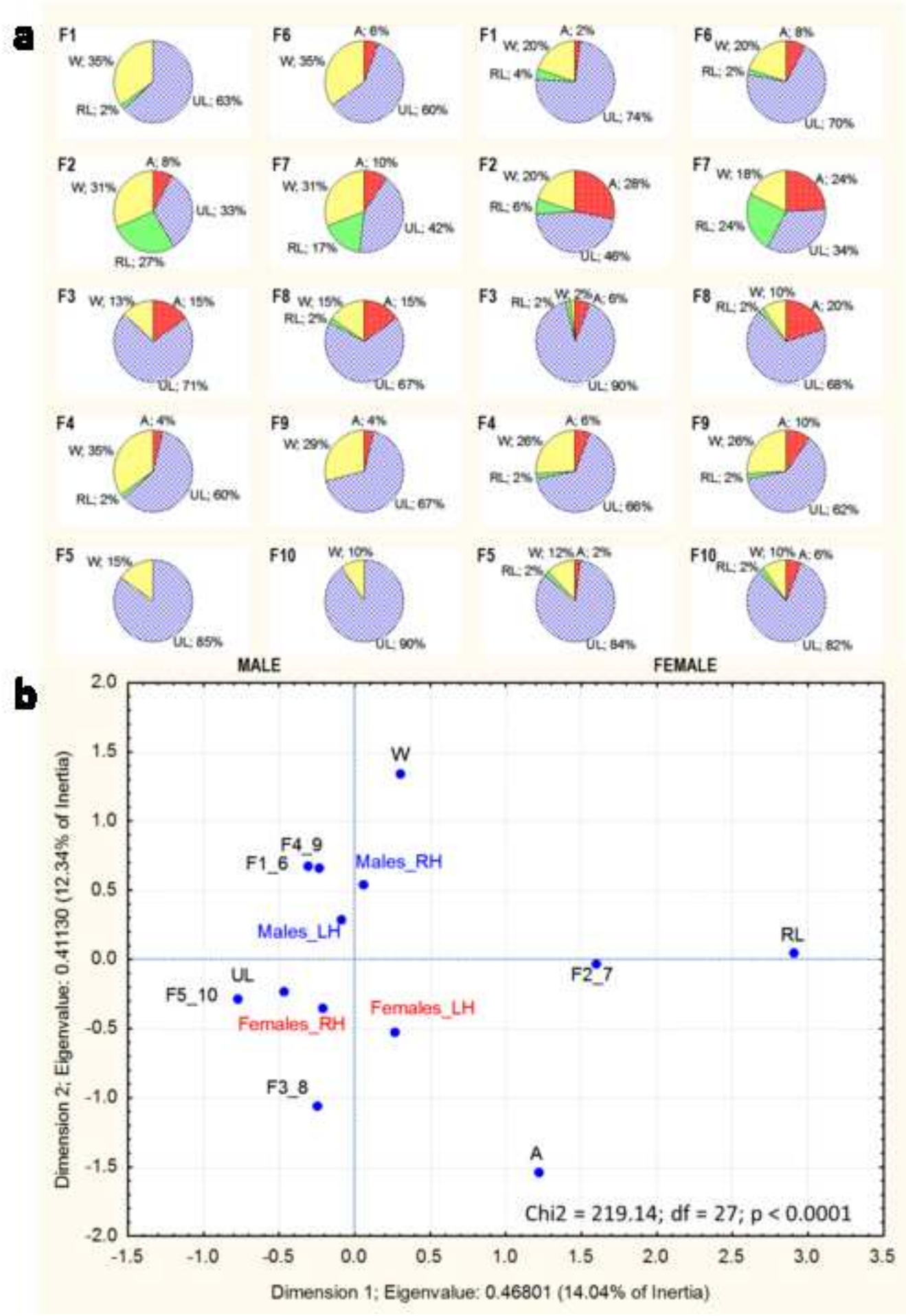

Figure 4

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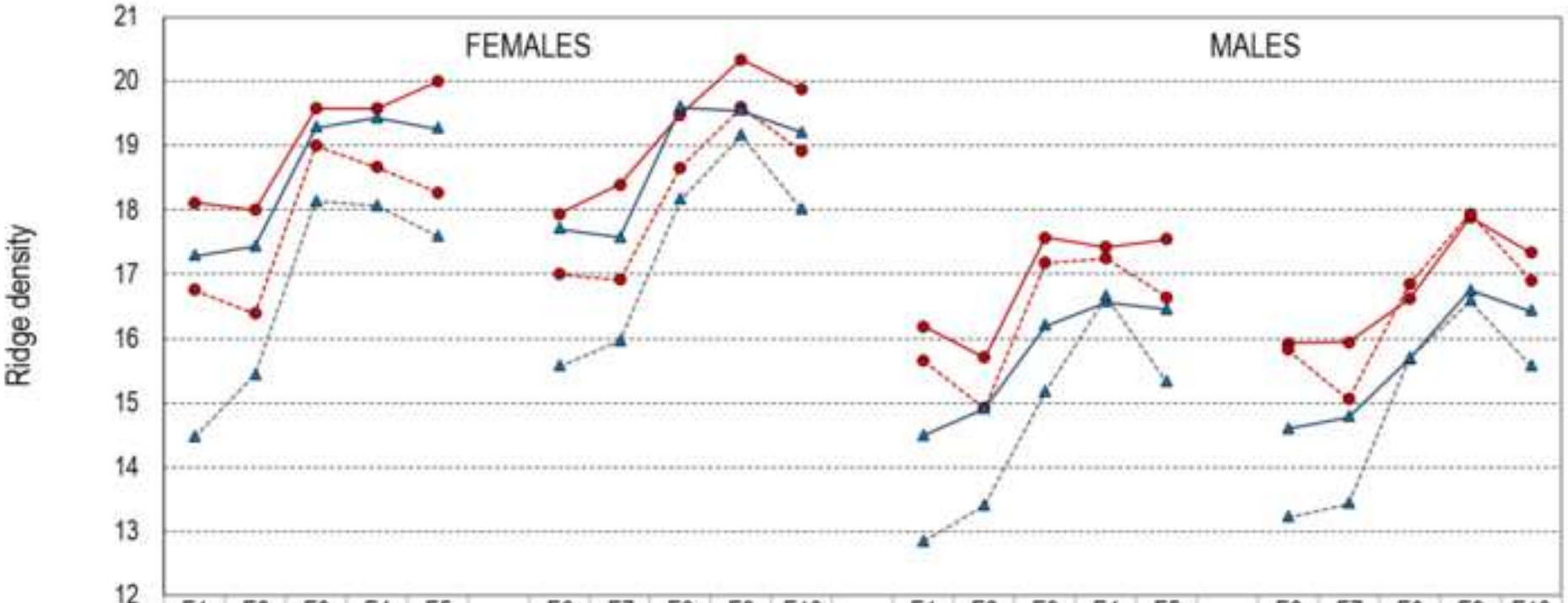

	F1	F2	F3	F4	F5		F6	F7	F8	F9	F10		F1	F2	F3	F4	F5		F6	F7	F8	F9	F10
R_core	18.1	18.0	19.6	19.6	20.0		17.9	18.4	19.5	20.3	19.9		16.2	15.7	17.6	17.4	17.5		15.9	15.9	16.6	17.9	17.3
P_core	16.8	16.4	19.0	18.7	18.3		17.0	16.9	18.7	19.6	18.9		15.7	14.9	17.2	17.3	16.6		15.8	15.1	16.8	17.9	16.9
R_out	17.3	17.4	19.3	19.4	19.3		17.7	17.6	19.6	19.5	19.2		14.5	14.9	16.2	16.6	16.4		14.6	14.8	15.7	16.8	16.4
P_out	14.5	15.4	18.1	18.1	17.6		15.6	16.0	18.2	19.2	18.0		12.8	13.4	15.2	16.7	15.3		13.2	13.4	15.7	16.6	15.6

Figure 5

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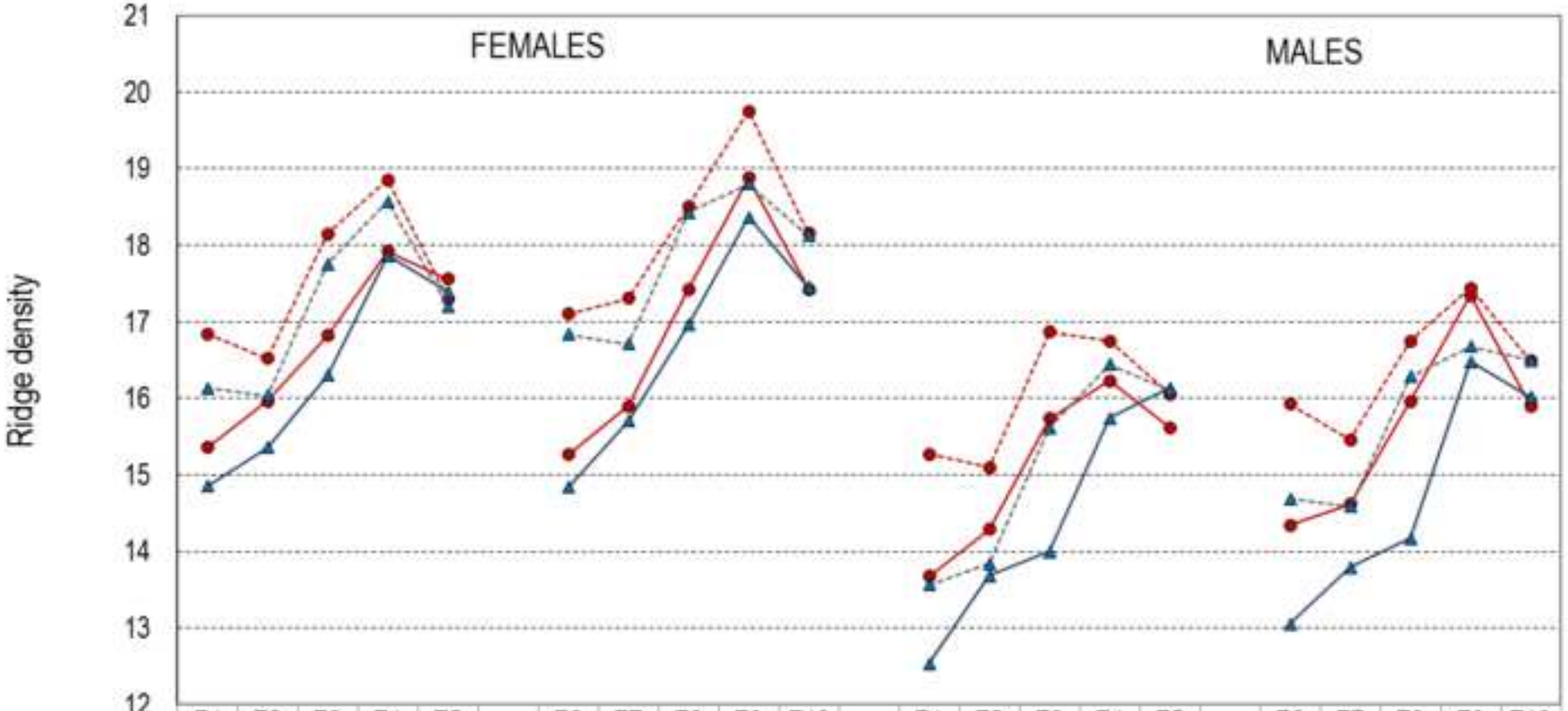

	F1	F2	F3	F4	F5		F6	F7	F8	F9	F10		F1	F2	F3	F4	F5		F6	F7	F8	F9	F10
R_core	15.4	16.0	16.8	17.9	17.6		15.3	15.9	17.4	18.9	17.4		13.7	14.3	15.7	16.2	15.6		14.3	14.6	16.0	17.3	15.9
P_core	16.8	16.5	18.1	18.9	17.3		17.1	17.3	18.5	19.8	18.2		15.3	15.1	16.9	16.8	16.1		15.9	15.5	16.8	17.4	16.5
R_out	14.9	15.4	16.3	17.9	17.4		14.8	15.7	17.0	18.4	17.4		12.5	13.7	14.0	15.7	16.1		13.1	13.8	14.2	16.5	16.0
P_out	16.1	16.0	17.8	18.6	17.2		16.8	16.7	18.4	18.8	18.1		13.6	13.8	15.6	16.4	16.1		14.7	14.6	16.3	16.7	16.5

Figure 6

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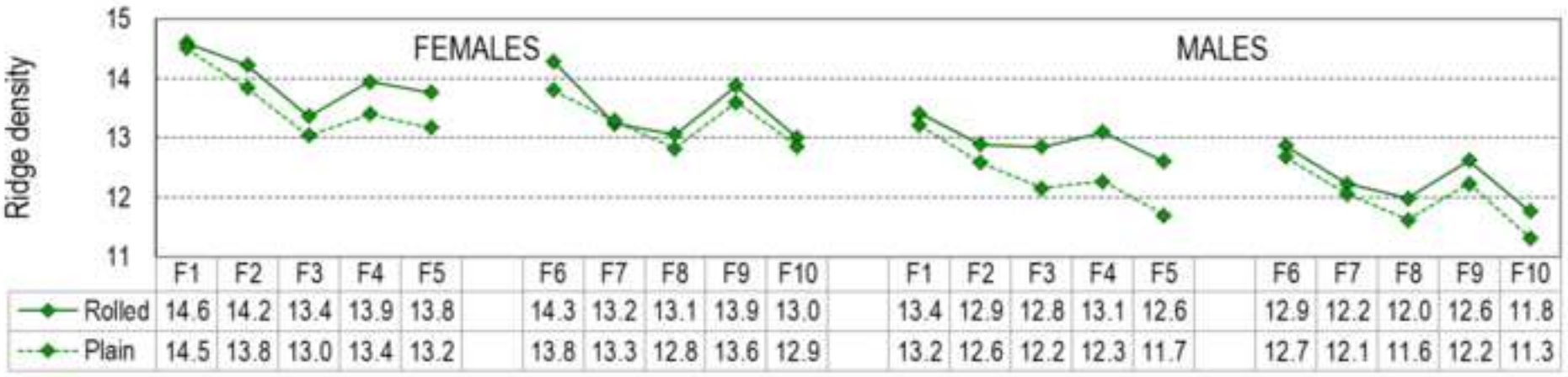

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Rolled	14.6	14.2	13.4	13.9	13.8	14.3	13.2	13.1	13.9	13.0	13.4	12.9	12.8	13.1	12.6	12.9	12.2	12.0	12.6	11.8
Plain	14.5	13.8	13.0	13.4	13.2	13.8	13.3	12.8	13.6	12.9	13.2	12.6	12.2	12.3	11.7	12.7	12.1	11.6	12.2	11.3

Figure 7

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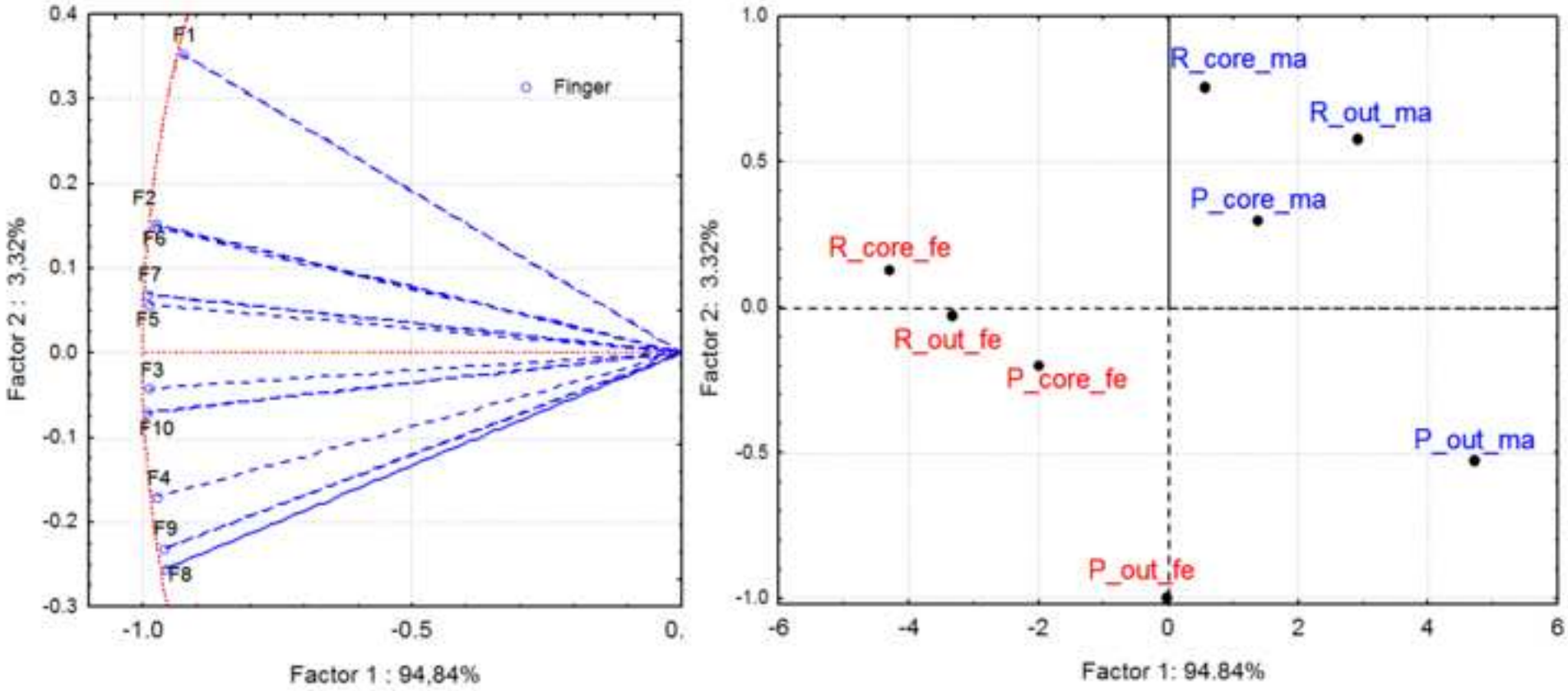

Figure 8

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