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Impact of aging on fingerprint ridge density: anthropometry and forensic implications in sex inference

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ABSTRACT

The variation in the epidermal ridge's width between the sexes, during various growth stages, and among different populations has been previously assessed. However, the changes that occur with aging are barely known.

The goal of this study was to analyse the degree of variation in epidermal ridge width due to aging. So that, fingerprint ridge density was estimated to establish their relationship with body and hand size changes that typically occur in adulthood.

In this study, a sample of 213 adults of both sexes from a Spanish native population of different age ranges—18–30 years old ("junior" group) and 50–66 years old ("senior" group)—was used. Ridge density was assessed in three counting areas of the distal

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phalanx of each finger (radial, ulnar, and proximal). Height, weight, and a set of anthropometric measurements for both hands were also taken.

Our results show that ridge density is higher in females than males throughout adulthood and decreases with aging in the radial and ulnar areas (as the hands widen) but not in the proximal region. Thus, a relationship between hand dimensions and ridge density was found.

The data indicate that aging changes may conceal the recognized sex differences in ridge density, and so a better understanding of the topological variations in the epidermal ridge width throughout the life cycle and the factors involved would facilitate the interpretation of the differences between the sexes and different age groups.

KEYWORDS

Fingerprints; Ridge density; Sex inference; Aging; Anthropometry

1. INTRODUCTION

Nowadays, dermatoglyphics are studied in different fields of knowledge, such as physical anthropology, forensic sciences, medicine, and technology. However, there is still no clear consensus regarding how some dermatoglyphic traits should be analysed. Studies on the breadth of the epidermal ridges started with Hecht [1], Abel [2], Cummins et al. [3], and Ohler and Cummins [4]. Since then, the methodology for these types of studies has undergone numerous changes. The epidermal ridge width has been analyzed in several ways [5-8], though the most widely used method is currently through the ridge density (RD), which is calculated by the number of ridges throughout the diagonal of a 5 × 5 mm square, as proposed by Acree [9].

Currently, it is accepted that changes in the width of the epidermal ridges are linked to age, sex, adult body size, hand size, and ethnicity [3,10-17]. Beyond the general trend of an increase in the width of the ridges throughout growth, it is not well-known how these changes are produced on the friction ridge skin in adulthood. A better understanding of this process would potentially allow the age determination of an unknown subject from fingerprints alone.

Abel [2] was the first researcher who showed a relationship between epidermal ridges and anthropometric measurements in adults. He found a link between the length of distal phalanges and the number of epidermal ridges. Some years later, Cummins et al. [3]

established a relationship between hand measurements and epidermal ridges located in different areas of the hand. One year later, Ohler and Cummins [4] found clear sex differences in epidermal ridge width. Babler [18] has shown a relationship between epidermal ridges and the size of hand bones during embryologic development, specifically between distal phalanx length and epidermal ridge configuration. The number of ridges does not change throughout the life cycle [19], and in the absence of wounds, it remains unaffected until it is lost by decomposition after death [20,21]. Nevertheless, the changes that occur during adulthood are not well-known; there has only been a longitudinal study [22] that found significant differences in friction ridge skin between adulthood and old age.

To understand the great variability of dermatoglyphics, their development should be considered. The epidermal ridges start to develop from around 11th week until sixth month of gestation. At this point, the system of epidermal ridges has the same morphology as in adulthood [23,24], but the width and the distance between epidermal ridges will change throughout the life cycle [3,10,11,13,15,18,25]; this process is controlled by the interaction of multiple genetic and environmental factors that affect ridge width. So that, the arrangement of the ridges comes from both polygenic inheritance and physical stresses, to which the ridges are subjected during development. This makes the path that epidermal ridges follow unique and unrepeatable [21,26].

Much like the rest of the skin, friction ridge skin undergoes changes from wear and tear throughout the ontogeny [27]. So that, it is expected to find in an elderly individual's fingerprints evidence of aging, as observed by Silva et al. [22]. Epidermal ridges undergo slight changes while the person ages, even though the arrangement of ridges and grooves do not change throughout the ontogeny. This stability of dermatoglyphics throughout the life cycle is because of the regulation of productivity and differentiation of keratinocytes that lie over the basement membrane; as these keratinocytes rise, a process of flattening and keratinization occurs. Cellular communication ensures that the stimulation and inhibition of basal cell proliferation occurs in a synchronized way [23,27]. As basal keratinocytes are divided, communication between adjacent cells ensures the movement of cells to the surface, depending on the needs of regeneration. Thus, the epidermis keeps the thickness of the stratum corneum over the life of the individual [28]. However, the ability of basal keratinocytes to proliferate decreases by 30–50% from 30 to 80 years [29]. The slower rate of proliferation results in a thinning of the living layers of epidermis. This contributes to the flattening of the epidermal ridges with age [30], which

could affect their density. In the same way, the gradual increase of the size of pores as a person ages [31] could affect the epidermal ridge breadth.

Regarding the aging process of the surface of the dermis, according to Maceo [27], the papillae tend to intensify their differentiation as the individual ages and as exposure to sheering stress rises, so that an increased number of papillae improve the adhesion between the dermis and the epidermis.

Over the years, the ridges' surface tends to flatten because of a combination of epidermal atrophy and the remodeling of the dermal papillae. This flattening of the epidermal ridges occurs slowly over several decades and does not affect the ridges' pattern. However, as the ridges flatten, their sharpness decreases [32]. This complicates tracking ridges and furrows in a fingerprint and is a handicap when it comes to estimating the ridge density of older individuals [22].

In addition, changes in body composition over the ontogeny could potentially affect the epidermal ridges. Some authors [13,15] showed that during the growth and development of the body (and consequently growth and development of the hand), the epidermal ridges increase in width. During adulthood, changes in body size still occur, with a clear tendency to gain weight with age [33-36]. This fact, coupled with the development of the muscles by the continued use of the hands, could produce slight changes in the size hands, which might affect the width of the epidermal ridges [3,4,37]. Overall, the evidence leads to the following hypothesis: Changes in body size and hand size throughout the aging process, coupled with wear and tear of friction ridge skin, could have a relationship with the possible variation in the width, and hence density, of the epidermal ridges that comes with aging.

Therefore, the aim of the present work is to study the variations of the breadth the epidermal ridges that come with age; these will be estimated from fingerprint ridge densities (number of epidermal ridges per unit area, or RD) in adults of both sexes to find its likely relationship with indicators of body and hand size.

2. MATERIALS AND METHODS

2.1. Sample

The sample comprises 213 healthy unrelated subjects (108 males and 105 females) belonging to a native Spanish population (born in Spain, and their parents and grandparents also born in Spain) grouped into two age ranges: a group of young adults from 18–30 years ("junior" group) and a group of elder adults from 50–66 years ("senior" group). All the analysed subjects were students from University of Alcalá (Madrid); the

"junior" group consists of undergraduate students majoring in biology, and the "senior" group comprises participants in complementary science courses for the elderly. All the participants were recruited through opportunity sampling.

The participants were requested to fill out a personal data sheet in order to ensure the homogeneity of the sample (age, gender, birthplace, handedness, relevant illness, etc.). The data showed that the sample and their parents and grandparents mostly belong to Madrid county and the surrounding counties, which agrees with the Spanish migratory pattern during the last century [38].

As for age groups considered, for the junior group, 18 years old was established as lower limit, because at that age the sexual dimorphism in the width of epidermal ridges and significant differences between the radial and ulnar areas has been already settled [15,25,39]. Regarding the senior group, the lower age limit was established at 50 years because around this age, women undergo major physiological changes associated with menopause. These changes usually involve significant weight variations [35]. On the other hand, factors such as abundant water loss in the elderly and the increasing prevalence of arthritis that can deform the joints of the hands could cause variations in the width of the epidermal ridges. All these drawbacks make it difficult to obtain fingerprints with enough quality to allow for a proper analysis. To prevent the above-mentioned changes, individuals older than 66 years were excluded. In addition, individuals with any disease or abnormality that could affect the width of the epidermal ridges, such as osteoarthritis, were rejected. Before taking the fingerprints, informed consent was obtained in accordance with the World Medical Association Declaration of Helsinki [40].

2.2. Analysed characters

The technique used to collect fingerprint impressions [41] is a variation of the adhesive paper and graphite method [42]. The finger ridges were homogenously stained with graphite powder and then rolled (from the ulnar to radial side of the fingertip) on the sticky side of an appropriately sized label. Thereafter, these adhesive labels were stuck on a transparent acetate, in which a template with 10 separate areas (one for each finger) had been previously printed (Fig. 1). All the fingerprint samples were obtained by two trained members of the research team. The impressions so obtained are a mirror image of the fingertip surface, similar to that obtained with the classic ink method. The fingers were assigned the numbers 1 through 10, starting from the right thumb, or finger 1 (F1), and ending with the left little finger, or finger 10 (F10). Once the samples were obtained, the

fingerprints were photocopied and amplified (x2), and the contrast was increased to facilitate the counting of the ridges.

The analysed traits included fingerprint features and anthropometric measurements to measure the level of association between the width of the epidermal ridges with body and hand size. The anthropometric measurements comprised of height and weight as body size indicators (BMI was calculated as Weight (kg) / height^2 (m)) while hand length, palm length, palm width, finger length, phalanx length, finger width, and wrist width were taken for both hands as hand-size indicators. All the anthropometric measurements were taken from the actual hand and finger by means of a GPM (Martin type) sliding caliper, by following the methodology described in Hall et al. [43] (Table 1 and Fig. 2a). The fingerprint features considered were the type of pattern (arch, radial or ulnar loop, and whorl), the pattern height (Table 1 and Fig. 2b), and the epidermal ridge density (RD). Because ridge breadth in fingerprints varies with the amount of pressure exerted when taking samples, we evaluated the breadth of a ridge as defined by Penrose [44], 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." Accordingly, the RD was assessed as the number of ridges that cross the diagonal of a 5 x 5 mm square, as proposed by Acree [9]. But, according to the methodology described in recent studies on RD variability, this was calculated in three different areas of the tip of every finger (radial, ulnar, and proximal) [16,45,46]. So, 30 counting areas were assessed for each individual. To set up the three counting areas, the fingerprint was divided into four sectors by two perpendicular axes that would cross two ridges above the pattern core (considering the core as the first ridge that gives a full turn). In the case of arches, the axes intersect at nearest ridge to the midpoint of the fingerprint. Just above the horizontal axis, the radial and ulnar areas (each one on its proper side of the vertical axis) were drawn. The proximal area was drawn from the first epidermal ridge above the interphalangeal flexion crease (Fig. 1, a-c).

In addition, the 10-finger mean for each counting area (radial, ulnar, and proximal) for each subject was estimated and used as additional variables.

2.3. Statistical analysis

For each of the analysed variables, descriptive statistics (mean, standard deviation, minimum, and maximum) were estimated for every group considered: junior males (JM), junior females (JF), senior males (SM), and senior females (SF).

The topological variation was analysed by comparing, for each finger, the RD on each count area using the Friedman test (comparison of three areas: radial, ulnar, and proximal) and the Wilcoxon test (comparison of radial and ulnar and ulnar and proximal) for related samples. A Student t-test for related samples was used for analysing the bimanual variations in every analysed trait (both anthropometric measurements and fingerprint features). The finger width was compared using a Wilcoxon test for related samples because the distribution patterns did not fit normal distributions in any of the four groups (Kolmogorov-Smirnov test, $p < 0.05$).

Sexual variability was analysed by separately comparing the means of each variable in both sexes in the two age groups, so a Student t-test was used to assess sex differences for RD and the anthropometric variables for each finger, except for finger width, for which the Mann-Whitney test was used. These same tests were used for the statistical analysis of variation with age (comparison between junior and senior groups in males and females).

Subsequently, a principal component analysis (PCA) was performed to simplify how hand anthropometric variables explain the variation observed in the four study groups. The factor scores were estimated for each individual on the extracted component and stored as a variable for a subsequent regression analysis. In this analysis, the 10-finger average RD of each counting area (radial, ulnar, and proximal) was used as the dependent variable, whereas the first PCA factor was entered as the independent variable. In addition, a partial correlation analysis between this first PCA factor and RD controlling for BMI for each count area was performed to establish the degree of relationship between the anthropometric indicators and RD.

The frequencies of the main pattern types (whorls, ulnar loops, radial loops, and arches) were estimated, and their association with different fingers were assessed using a chi-squared test. In addition, the relative frequency (%) of the pattern type by age-sex group was calculated, and their dependence was assessed using a chi-squared test and correspondence analysis (CA).

Fisher's least significant difference (LSD) at a 95% confidence level was used to assess the interaction of the mean RD by area (radial, ulnar, proximal) and pattern type for each age-sex group.

All the statistical analyses were performed using IBM SPSS v 21, except for the regression analysis, for which Statgraphics v 17.0 was used and the CA, for which

Statistica v12.5 was used. In all cases, significant differences were considered when the p-value was less than 0.05.

3. RESULTS

Because this is a cross-sectional study, a chi-squared analysis was performed to identify possible differences in pattern type frequencies by finger (that could affect the RD values) between the junior and senior groups. No significant differences ($p > 0.12$) were found between the age groups for any finger. So the observed variations in RD among the age–sex groups could not be attributed to the variations of pattern type frequencies.

3.1. Ridge density and anthropometric measurements

RD was estimated in the three count areas (radial, ulnar, and proximal) of the 2,130 fingerprints taken, and this involved assessing 6,390 count areas. This allowed for an estimate of the mean RD for each area for each subject. Table 2 shows the descriptive statistics of RD (10-fingers mean) by count area for every age–sex group. As can be seen, a decreasing gradient of the 10-finger mean RD according to topological area appears; the radial means are significantly higher than the corresponding ulnar means, and the proximal means are the lowest.

When RD variation by finger is considered, this is very wide, but the same pattern (radial >ulnar>proximal) was found in the four age–sex groups, though the differences between the ulnar and proximal areas were not always significant, especially in senior males, where even the proximal area shows a higher RD than the ulnar for both thumbs. Also, the RD variation among fingers in the proximal area is lower than in the radial and ulnar areas, where the thumb and index fingers of both hands have a lower RD than the middle, ring, and little fingers (Fig.3). For both sexes, the junior groups showed a higher RD in the radial and ulnar areas than the senior groups. Nevertheless, no defined trend between the age groups was found in the proximal area. Similarly, variations among the four groups were found for every anthropometric measurement (Table 3). All hand measurements showed a clear sexual dimorphism (significant higher values in males than females; $p < 0.001$), whereas only the widths, but not the lengths, changed significantly ($p < 0.001$) with aging (Table 3).

3.2. Bimanual variation

First, over 90% of the individuals analysed were right-handed while a very small percentage was left-handed or both-handed (ambidextrous). The differences between the left and right hands in each individual for RD and anthropometric measurements were evaluated using a student t-test for the related samples.

Regarding the RD, a trend in the bimanual variation was found in the radial areas of the index fingers (F2, F7), showing significant differences in the four groups ($p < 0.05$), with a higher RD in left hand. In the SF, the bimanual differences were found in the ulnar area in both the thumbs and middle fingers (F1, F6; F3, F8), while in JF, the bimanual differences were found in the proximal regions of both index fingers (F2, F7) and in the ulnar area of the ring fingers (F4, F9). However, significant differences ($p < 0.05$) in bimanual variations were found in the proximal region of the little finger (F5, F10) of both male groups (JM and SM). These differences in the homologous regions follow a different pattern in the distal regions than in the proximal region. The RD is higher in the distal regions of the left hand, while in the proximal region, the RD is higher in the right hand. No significant differences were found among the rest of homologous finger regions (Fig. 3).

Regarding the anthropometric measurements, a significant bimanual variation ($p < 0.05$) was found in the finger width for all groups (except for the little finger of the senior groups) (Fig.4). Whereas for finger length, bimanual significant differences were found for the index fingers and middle fingers of SM, JM, and SF, in addition to the ring and little fingers of SM. However, bimanual significant differences were not found in the finger length of JF. Regarding the phalanx length (Fig. 5a), bimanual significant differences were found for the thumbs of both senior groups, in addition to the index finger of SM and little finger of JM. Bimanual variation was not found in the phalanx length of JF. Regarding the other hand measurements, a bimanual significant variation ($p < 0.05$) was found in the palm width of all groups. In addition, bimanual differences were found in the wrist width of the female groups and hand length of SM.

3.3. Sexual dimorphism and variation with age

A student t-test for independent samples was used for the junior and senior groups to analyse sexual dimorphism on RD for each counting area. Significant differences ($p <0.05$) were found for all areas of each finger (except for the proximal area of F1, F5 and F8 in the senior groups). Females always had a higher RD than males in the same age group (Fig. 3).

In the same way, variations with age were analysed, showing that the radial RD and ulnar RD of all fingers significantly decreased with age in both sexes. However, significant differences were not observed in the proximal area between the junior and senior groups of both sexes (Fig. 3). These same results were obtained when the 10-finger mean RD is compared (Table 2). There was similarity of the RD values between JM and SF, showing

no significant differences in 17 of the 30 count areas: differences in six proximal areas (F3, F4, F7, F8, F9, F10), four radial areas (F2, F3, F4, F6), and three ulnar areas (F3, F4, F9). JF and SM were the age–sex groups that differed the most when it came to RD values.

Anthropometric measurements were taken to establish a relationship between hand and body size with RD variation, and they are shown in Table 3. Significant differences between the sexes were found in both the junior and senior groups ($p < 0.001$), with males showing higher values than females in all considered traits. Regarding variations with age, the senior groups tended to have bigger hand sizes than the junior groups. There were significant differences ($p < 0.05$) in weight, height, BMI, palm width, wrist width, and finger width between the junior and senior groups of each sex, but not in the hand or palm length. Furthermore, significant differences ($p < 0.05$) were found in the phalanx length of the thumbs (F1, F6) and index fingers (F2, F7) between the male groups, whereas between the female groups, significant differences ($p < 0.05$) were found in finger (F1, F6) and phalanx length (F1, F2, F3, F4, F6, F8, F9, F10).

As it can be seen in Fig. 3 and Fig. 4, there is an inverse relationship between the RD gradient (JF>JM≈SF>SM) in the distal regions (ulnar and radial) and the finger width gradient (SM>SF≈JM>JF) for each group. The groups that have a higher RD have the lowest finger width values. Finger width did not show significant differences between JM and SF in six fingers (F1, F2, F3, F7, F8, F10). A similar pattern was found in phalanx length (Fig. 5a), whereas the rest of anthropometric measurements in these two groups (JM and SF) showed significant differences ($p < 0.05$), as can be seen in the pattern height in Fig. 5b.

Given the substantial number of hand variables assessed, a principal component analysis (PCA) was performed to identify any anthropometric factor that could simplify the variability among the four groups. The first factor (hand factor) could explain 68% of the variance. When the individual factor scores for the hand factor were used as an independent variable and a 10-finger mean RD of each count area (radial, ulnar, and proximal) was used as the dependent variable in a regression analysis, the results showed to what extent RD can be predicted by the hand factor in each area (radial: $R^2=0.39$; ulnar: $R^2=0.38$; proximal: $R^2=0.20$; $p < 0.001$). The regression plots in Fig. 6 show a negative relationship between the hand factor and RD. The results of the analysis of the partial correlations controlling for BMI (Table 4) show a significant negative correlation between the hand factor and RD (higher with ulnar and radial RD).

3.4. Pattern type and variation by age and sex

A significant association was found between pattern type and finger in the four age-sex group. Here, the whorls were associated with the thumbs (F1, F6) and ring finger (F4, F9); ulnar loops with the middle (F3, F8) and little (F5, F10) fingers; and arches and radial loops with the index finger (F2, F7) (SM: Chi^2=173.64 df=27 p<0.0001; JM: Chi^2=162.90 df=27 p<0.0001; SF: Chi^2=112.18 df=27 p<0.0001; JF: Chi^2=139.47 df=27 p<0.0001).

Despite the fact that significant differences in the pattern type frequencies between age groups were not found for any finger, the global frequencies (without considering the finger) were calculated for comparison (Fig. 7a). A CA was performed to assess the association between pattern type and age-sex groups (Fig. 7b); here, the results showed a significant dependence (Chi^2 = 44.787, df= 9, p<0.0001), which explains 98.92% of the inertia. The first dimension, which explains 95.87% of the inertia, separates males (associated with whorls and radial loops) from females (associated with ulnar loops).

The values of the mean RD for each counting area by pattern type were assessed, and the results are shown in Fig. 8. Significant sex differences ($p < 0.05$) were found for each counting area (females higher RD than males), except for radial RD and proximal RD of the senior group's radial loops.

Regarding the age variation in radial and ulnar areas, significant differences were found for the four pattern types (juniors higher RD than seniors), except for the ulnar RD in arches in both sexes. However, in the proximal area, significant age differences were found in females for each pattern type (except the ulnar loops); but this was not case for the males.

Moreover, the RD analysis for pattern type revealed that the groups with the most similar RD values (junior males and senior females) showed some significant differences: radial RD in the loops, ulnar RD in the ulnar loops, and proximal RD in the whorls, arches, and ulnar loops. However, although junior males showed a higher RD than senior females in distal region, the proximal region followed the opposite tendency.

4. DISCUSSION

Compared to other features, such as pattern type, ridge breadth has been studied less within the field of dermatoglyphics. Few studies have assessed age changes of the ridge breadth during the growth period [10,11,13,15], and only one longitudinal study looked at these changes throughout adulthood [22]. The latter only considered the age changes in ridge breath in an area of 1 cm^2 in the right index finger. The present study is the first

one to examine the aging changes of epidermal ridge breadth in all 10 fingers; moreover, in the current study, the relationship between ridge breadth and anthropometric measurements were assessed, following the steps marked by Abel [2], Cummins et al. [3], Loesch and Lafranchi [14], and, more recently, Mundorff et al. [37].

The methodology used to take the fingerprints may affect the results. Therefore, the standardisation method used must be taken into consideration when it comes to evaluating the results. Some of these influential factors might be how the fingerprints were taken (flat or rolled, pressure control) and the position of the counting area. Some attempts have been made to control the force applied to the fingerprint deposition [47,48]; for example, a device has been designed for flat impressions [49,50], but it was not considered in the present study because of the rolled technique we used.

The RD differences showed a clear pattern of distribution. A high RD was found in the radial and ulnar areas where the epidermal ridges are narrower than in the proximal area. The RD gradient radial > ulnar > proximal obtained in the present study fit the proposed distal-proximal gradient from the fingertips to the proximal region of the hand [3,4,17]. However, the differences found in the senior group between the ulnar and proximal areas are lower compared with the junior groups' ulnar and proximal areas both in the present study and in previous studies in Spanish [45,46,51] and Indian populations [52]. The lower RD observed in the proximal area could be because of wider ridges than what are found in the distal region, though a more oblique arrangement of the ridges when crossing the count area, especially in the case of ulnar loops, the most common pattern type, could also have affected this. This association between pattern type and proximal RD, which has already been assessed in other studies [16,45,46], has also been corroborated in the present study.

Generally, thumbs have the lowest RD in the radial and ulnar areas, meaning they have wider epidermal ridges, while the ring fingers often show the highest RD values, meaning they have the narrowest epidermal ridges. However, in the proximal area, the thumbs, together with the ring fingers, show higher RD values than the other fingers, though they are lower than the values obtained in the distal region. This pattern of variation was previously found in studies performed with the same methodology in Spanish [45], Argentinean [46,53], Indian [52], and Sub-Saharan populations [16].

As mentioned before, in previous studies [16,45,46], there was an association observed between whorls and higher RD values in the proximal area. The highest RD values shown in the proximal area of the thumbs (F1, F6) and ring fingers (F4, F9) could be because of

the high frequency of the whorls in these fingers, as was found in our study. This implies that the RD in the proximal region could be determined by the number of ridges that are horizontal (which could swing depending on the type and height pattern), as well as by the epidermal ridge width and distance between ridges. This fits with the observed values of pattern height, which tend to show higher scores in the thumbs and ring finger for all groups (Fig. 5b), that is, the fingers in which a higher RD in the proximal area was found. However, this does not explain the differences between the sexes for the proximal area because significant differences for the pattern height were found between sexes in the present study: males showed to have higher pattern height values than females, though they showed lower RDs than females in the proximal area. That is, despite having a higher surface to accommodate more epidermal ridges, the RD values were lower. The lower RD values showed in males in the proximal area could be because of the greater width of epidermal ridges and the distance between the ridges, and this would be encouraged by the greater phalanx length in males compared to females, which would act as a longitudinal force widening the horizontal ridges of the proximal area during growth (Fig. 9).

Regarding bimanual variation in the epidermal ridge breadth, a clear trend was only found in the radial area of the index fingers for all groups (higher RD in F7 than F2). In the rest of the fingers, bimanual differences fluctuated to a great degree. In previous studies, bimanual variations have not followed a clear pattern. In some studies [54,55,56], no relevant bimanual differences for RD were found. However, in other studies, bimanual variations were found for epidermal ridge width [3,4,57], showing wider ridges in the right hand compared to the left. Recently, using a similar method to the one in the present study, significant bimanual differences for RD were found for the mean radial and ulnar areas [16,45,46], showing higher RD values in the left hand than in the right hand. Some authors [39,46] have linked a higher RD in the non-dominant hand to its lowered usage and hence less muscle development, which translates to narrower epidermal ridges.

Variations in the breadth of the epidermal ridges between the sexes have been studied since the 1940s when Cummins et al. [3] and Ohler and Cummins [4] showed that males tend to have wider epidermal ridges than females. However, the growing interest of dactyloscopy has allowed more recent studies [9,15,45,52,55,58-62] to confirm significant sex differences in the RD values in several populations, though not all of the studies used the same RD estimates or analysed the same count areas. In all these studies, a pattern arises, showing narrower epidermal ridges in females than in males. In the

present study, significant differences between the sexes were found in all three areas in both the junior and senior groups, and there were always wider ridges in males than females. Some previous studies [46,51-53,58] have also shown RD differences between the sexes in all three areas.

The main factors that can be attributed to sexual variation in the epidermal ridges' breadth are body size differences, which can be assessed by weight and height, and hand size differences [3,4,14]. Observed sex differences can be explained by the larger male hand and its further development of the muscles, which would lead to a larger area that could accommodate the ridges, making the hand wider and decreasing RD [9,17,46,52,55,58-60]. Nevertheless, in all the studies where this explanation has been proposed, no anthropometric measures were taken to assess this relationship. Only a few studies have tried to link the RD with height and weight [37] and finger width measures [54,63]. The present study focused on anthropometry to give a more precise explanation about patterns of variation in epidermal ridges. Although many anthropometric traits have shown to contribute, to a greater or lesser extent, to RD variation, finger width and phalanx length provide a more direct relationship with the epidermal ridge breadth.

In all forensic studies that have analysed the sex differences in epidermal ridge breadth, either the sample has been composed of adults of all ages without consideration of age [9,56,59], or the age of individual was not specified [14,46]. In other studies, it has been common for the sample to be composed only of young adults [45,52,61-63]. Nevertheless, studies involved in the development and improvement of systems for fingerprint recognition have emphasized the assessment of sex differences for very specific age ranges [64-66] because in these studies, the aim is on identification problems of elderly people. Also, in studies on growth and development, children were classified in strict age groups, and here, the sex differences that emerged during adolescence were assessed [13,15,25].

Regarding variations with age in epidermal ridge breadth, there is only one previous study that analysed age changes in adults [22], and in this study, significant differences in epidermal ridge breadth on a delimited area of right index finger were found. In the present study, where the distal region (radial and ulnar areas) of each fingertip was studied more thoroughly than in Silva et al. [22], an increase in the ridge breadth of the male and female senior groups was found, following the same trend shown in Silva et al. [22]. Most likely, the increment in hand size (especially in finger width), which can be associated with a higher BMI in the senior groups of both sexes, is the main cause of the

variation of the epidermal ridge width with aging. Epidermal ridges become wider as the hand and body widen. Therefore, the same as with the sex differences, variations in body size, hence hand dimensions, might be the cause of the lower RD observed in older people. Specifically, the variations with aging in the breadth of the epidermal ridges could be determined by increased width of the fingers while the length measurements would not be a relevant factor. Proof of this was the lack of variation with aging in the proximal area, where both RD and pattern height did not show differences between the young and elderly groups, but rather between the sexes. As mentioned by Silva et al. [22], the decrease of skin moisture with aging and the reduction of cellular proliferation to produce elastin added to a reduction in epithelium layers, and the remodeling of the dermal papillae and other factors such as surface size, stress level, or chafing could explain the width variations with aging. On the other hand, for both sexes, the size of the pores of the epidermal friction ridges has been shown to increase with aging [31], so this factor could also affect how aging changes ridge width. The different patterns observed among the counting areas could be explained by a differential contribution of these factors.

Taking into account that the epidermal ridges of the proximal and distal regions follow different directions, the changes or differences in body composition, and consequently hand size (i.e., the width of the fingers), will not affect in the same way to the ridge breath. The epidermal ridges of the proximal region are located parallel to the spreading axis, and with aging, they tend to have narrower ridges, whereas the epidermal ridges of the distal region remain oblique to the spreading axis, so the ridge breadth increases (RD will decrease) as the finger width increases (Fig. 9). Moreover, the finger pad in the proximal region is flatter and less deformable than in the distal region. The proximal area shows this trend, but it would not be strong enough to obtain a significant difference in the epidermal ridge breadth. This, together with the fact that the number of ridges that remain horizontal changes depending on the pattern type, could affect the proximal RD in different ways. This may explain the lower prediction of the RD proximal in the regression analysis.

When comparing different age–sex groups, the link between finger width with radial and ulnar RD is best appreciated. Senior males and junior females differed the most because of a high difference in finger width, whereas the RD values of junior males and senior females tended to be very similar, insomuch as the finger width of the women while aging tended to approach that of junior men. Therefore, the similarities observed in finger width and RD of the distal regions in the junior males and senior females, despite their huge

differences in other anthropometric measures, indicate that finger width prevails over the other variables in explaining the variation with aging in the epidermal ridge breadth in the distal region. Nevertheless, the proximal RD variation across age–sex groups seems to fit the tendency of pattern height because there is no clear aging differences, but there is strong sexual dimorphism.

Considering that the pattern type may affect ridge breadth (especially in the proximal area), the ridge density by area and pattern type was assessed. For each age–sex group, the global frequencies of the four types of patterns showed statistically significant sexual differences in both age groups. Females presented a higher frequency than males when it came to ulnar loops and arches, whereas males showed higher values than females when it came to whorls and radial loops, despite ulnar loops being the most common pattern type in all four groups. These results follow the observed pattern in other populations [67-69].

The analysis of the RD by pattern type showed significant sexual differences in all three areas, except for the radial loops in both senior groups (where no differences were found in the radial and proximal areas). Therefore, whatever the pattern type, the obtained sexual differences in the RD, added to those observed in previous studies [9,15,25,45,46,51-53,55,56,58-62], strengthen the hypothesis of a universal pattern of sexual dimorphism for the RD.

Regarding the aging process, the RD values showed age differences in both distal areas for all pattern types, except for the arches in the ulnar area. As for proximal RD, significant age differences for all pattern types were only found in females (except for the ulnar loop).

An interesting fact revealed in the current study was the similar values for the RD between junior males and senior females. However, when considering the pattern type, the radial and ulnar RD values are clearly different in the ulnar loops, whereas in the proximal area, the RD values are different in all pattern types, except for the radial loops (the least common pattern type in all human populations).

In order to evaluate the impact that these factors could have when analysing the differences between adults of different age and sex, it would be advisable to assess indexes of hand shape to establish a link to the pattern of variation of the epidermal ridge width in different counting areas. An example is the difference in the pattern of variation of RD in the proximal region with sex and age, something that more recent studies [55,63] dealing with the inference of sex from fingerprints have not taken into account.

In view of these results, the study of sex inference from an unknown fingermark by means of RD should not only consider the sex of individuals, but also age because age could have a confounding effect. In this way, the results of the current study revealed that gender could be inferred from ridge density in the ulnar, radial, or proximal areas, whereas age could be inferred from the distal areas (ulnar or distal). However, proximal RD is the most discriminant factor between older females and young male adults; this is why the ridge density in this area should be taken into account regarding the sex and age inference from fingermarks.

The fingerprint analysis method used so far for inferring the sex of an individual from a fingermark of unknown origin should be reconsidered because individuals of a different age and sex can have a very similar RD; here, the RD at the proximal area could be of great relevance. However, within the same sex, these differences in the RD that come with aging could be used to distinguish between age groups, which would be of forensic utility. Thus, once forensic experts have selected those fingermarks that may be relevant for the investigation, the suggested age inference from the RD could be applied to the fingermarks of interest as possible suspects since men perpetrate most of offences [70,71]. This would be especially useful in those unknown fingermarks that, after being searched in the Automated Fingerprint Identification System (AFIS), do not obtain a match; this would guide investigators and help track down possible suspects.

In any case, a better understanding of the topological variation in the epidermal ridge breadth throughout the human life cycle and the factors involved will improve the interpretation of the differences between different sex and age ranges.

5. CONCLUSION

Sex differences in ridge density remain throughout adulthood and will always present as females showing thinner ridges than males of the same age group. The epidermal ridge breadth on the radial and ulnar areas (but not the proximal area) tends to increase with age in adults, parallel to the increase of hand size, especially finger width. This pattern of changes that comes with aging leads to the ridge breadth of older females tending to approach that of young adult males; this is why the proximal ridge density must be taken into account to distinguish these groups.

CONFLICT OF INTEREST

None

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REFERENCES

[1] A.F. Hecht, Über das Hand- und Fussflächenrelief von Kindern, Ztschr. f. d. ges. exper. Med. 39 (1924) 56-66 (Cited in H. Cummins and C. Midlo, Finger Prints, Palms and Soles, Dover Publications, New York, 1961).

[2] W. Abel, Kritische Studien über die Entwicklung der Papillarmuster auf den Fingerbeeren, Z. Menschl. Vererb. Konstitutionsl. 21 (1938) 497-529.

[3] H. Cummins, W.J. Waits, J.T. McQuitty, The breadths of epidermal ridges on the finger tips and palms: a study of variation, Am. J. Anat. 68 (1941) 127-150.

[4] E.A. Ohler, H. Cummins, Sexual differences in breadths of epidermal ridges on finger tips and palms, Am. J. Phys. Anthropol. 29 (1942) 341-362.

[5] L.S. Penrose, D. Loesch, A study of dermal ridge width in the second (palmar) interdigital are with special reference to aneuploid states, J. Intellect. Disabil. Res. 11 (1967) 36-42. https://doi.org/10.1111/j.1365-2788.1967.tb00201.x

[6] D.Z. Loesch, N.G. Martin, Finger ridge patterns and tactile sensitivity, Ann. Hum. Biol. 11 (1984) 113–124.

[7] D.Z. Loesch, N.G. Martin, Relationships between minute characteristics of finger ridges and pattern size and shape, Ann. Hum. Biol. 11 (1984) 125–132.

[8] R.T. Moore, An analysis of ridge-to ridge distance on fingerprints, J. Forensic Ident. 39 (1989) 231–238.

[9] M.A. Acree, Is there a gender difference in fingerprint ridge density?, Forensic Sci. Int. 102 (1999) 35-44.

[10] D. Loesch, J. Godlewska, Breadth of the dermal ridges in the a-b area in children aged 0–6 years, Folia Morphol. (Warsz) 30 (1971) 511–514.

[11] D. Loesch, J. Czyzewska, Ridge breadth in the a-b segment in children aged 0-14 years, Folia Morphol. (Warsz) 31 (1972) 249–254.

[12] R.L. Jantz, K.R. Parham KR, Racial differences in dermal ridge breadth, Hum. Biol. 50 (1978) 33-40.

[13] T.J. David, Distribution, age and sex variation of the mean epidermal ridge breadth, Hum. Hered. 31 (1981) 279-282.

[14] D.Z. Loesch, M. Lafranchi, Relationship of epidermal ridge patterns with body measurements and their possible evolutionary significance, Am. J. Phys. Anthropol. 82 (1990) 183-189.

[15] E. Gutiérrez-Redomero, M.C. Alonso, J.E. Dipierri, Sex differences in fingerprint ridge density in the Mataco-Mataguayo population, HOMO 62 (2011) 487-499.

[16] E. Gutiérrez-Redomero, J.A. Quirós, N. Rivaldería, M.C. Alonso, Topological variability of fingerprint ridge density in a sub-Saharan population sample for application in personal identification, J.Forensic Sci. 58 (2013a) 592-600.

[17] E. Gutiérrez-Redomero, C. Alonso-Rodríguez, Sexual and topological differences in palmprint and ridge density in the Caucasian Spanish population, Forensic Sci. Int. 229 (2013) 159-169.

[18] W.J. Babler, Embryologic development of epidermal ridges and their configurations, in: C.C. Plato, R. Garruto, B. Schaumann (Eds.), Dermatoglyphics: Science in Transition, March of Dimes Birth Defects Foundation, New York, 1991, pp. 95-112.

[19] F. Galton, Finger Prints, Macmillan and Company, London, 1892.

[20] L.S. Penrose, P.T. O' Hara, The development of the epidermal ridges, J. Med. Genet. 10 (1973) 201-208.

[21] D.R. Ashbaugh, Quantitative-Qualitative Friction Ridge Analysis: An Introduction to Basic and Advanced Ridgeology, CRC Press, Boca Raton, 1999.

[22] L.R.V. Silva, L.L. Mizokami, P.R. Vieira, S.A.S. Kuckelhaus, Longitudinal and retrospective study has demonstrated morphometric variations in the fingerprints of elderly individuals, Forensic Sci. Int. 259 (2016) 41-46.

[23] H. Seidenberg-Kajabova, V. Pospisilova, V. Vranakova, I. Varga, An original histological method for studying the volar skin of the fetal hands and feet, Biomed. Pap. Med. Fac. Univ. Palacky Olomouc Czech Repub. 154 (2010) 211-218.

[24] K. Wertheim, Embryology and morphology of friction ridge skin, in: National Institute of Justice (U.S.) (Ed.), The Fingerprint Sourcebook, U.S. Dept. of Justice, Office of Justice Programs, National Institute of Justice, Washington DC, 2011, pp. 3.1-3.26. https://www.ncjrs.gov/pdffiles1/nij/225320.pdf

[25] P. Soanboon, S. Nanakorn, W. Kutanan, Determination of sex difference from fingerprint ridge density in northeastern Thai teenagers, Egypt, J. Forensic Sci. 6 (2016) 185-193.

[26] C. Champod, C. Lennard, P. Margot, M. Stoilovic, Fingerprints and Other Ridge Skin Impressions, second ed., CRC Press, Washington DC, 2016.

[27] A.V. Maceo, Anatomy and Physiology of Adult Friction Ridge Skin, in: National Institute of Justice (U.S.) (Ed.), The Fingerprint Sourcebook, U.S. Dept. of Justice, Office of Justice Programs, National Institute of Justice, Washington DC, 2011, pp. 2.1-2.26. https://www.ncjrs.gov/pdffiles1/nij/225320.pdf

[28] R.M. Lavker, P. Zheng, G. Dong, Aged Skin: A Study by Light, Transmission Electron, and Scanning Electron Microscopy, J. Invest. Dermatol. 88 (1987) 44-51.

[29] B. Gilchrest, Skin and Aging Processes, CRC Press, Boca Raton, 1984.

[30] R.M. Lavker, P. Zheng, G. Dong, Morphology of Aged Skin, Clin. Geriatr. Med. 5 (1989) 53–67.

[31] K.R. Nagesh, S. Bathwal, B. Ashoka, A preliminary study of pores on epidermal ridges: Are there any sex differences and age related changes? J. Forensic Leg. Med. 18 (2011) 302–305.

[32] M. Okajima, Dermal and epidermal structures of the volar skin, Birth Defects Orig. Artic. Ser. 15 (1979) 179-98.

[33] A. Kuskowska-Wolk, S. Rössner, Prevalence of obesity in Sweden: cross-sectional study of a representative adult population, J. Intern. Med. 227 (1990) 241-246.

[34] E.T. Poehlman, M.J. Toth, L.B. Bunyard, Physiological predictors of increasing total and central adiposity in aging men and women, Arch. Intern. Med. 155 (1955) 2443-2448.

[35] G. Dubnov, A. Brzezinski, E.M. Berry, Weight control and the management of obesity after menopause: the role of physical activity, Maturitas 44 (2003) 89-101.

[36] J.C.K. Wells, The Evolutionary Biology of Human Body Fatness: Thrift and control, Cambridge University Press, New York, 2010.

[37] A.Z. Mundorff, E.J. Bartelink, T.A. Murad, Sexual dimorphism in finger ridge breadth measurements: a tool for sex estimation from fingerprints, J. Forensic Sci. 59 (2014) 891-897.

[38] Instituto Nacional de Estadística (INE), http://www.ine.es/ (accessed 25 January 2018)

[39] S. Nanakorn, W. Kutanan, Variability of Finger Ridge Density among Thai Adolescents, J. Forensic Res. S1 (2012) 005. https://doi.org/10.4172/2157-7145.S1-005.

[40] World Medical Association, Declaration of Helsinki, amended by 64thWMA General Assembly, Fortaleza, Brazil, October, 2013. https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/

[41] E. Gutiérrez-Redomero, N. Rivaldería, C. Alonso-Rodríguez, L.M. Martín, J.E. Dipierri, M.A. Fernández-Peire, R. Morillo, Are there population differences in minutiae frequencies? A comparative study of two Argentinian population samples and one Spanish sample, Forensic Sci. Int. 222 (2012) 266-276.

[42] J.M. Aase, R.B. Lyons, Technique for recording dermatoglyphics, Lancet 297 (1971) 432-433.

[43] J.G. Hall, J.E. Allanson, K.W. Gripp, A.M. Slavotinek, Handbook of Physical Measurements, second ed., Oxford University Press, New York, 2007.

[44] L.S. Penrose, Memoradum on dermatoglyphics nomenclature, Birth Defects Orig. Artic. Ser. 4 (1968) 1-13.

[45] E. Gutiérrez-Redomero, C. Alonso, E. Romero, V. Galera, Variability of fingerprint ridge density in a sample of Spanish Caucasians and its application to sex determination, Forensic Sci. Int. 180 (2008) 17-22.

[46] E. Gutiérrez-Redomero, A. Sánchez-Andrés, N. Rivaldería, C. Alonso-Rodríguez, J.E. Dipierri, L.M. Martín, A comparative study of topological and sex differences in fingerprint ridge density in Argentinian and Spanish population samples, J. Forensic Leg. Med. 20 (2013) 419-429.

[47] G. Langenburg, Deposition of bloody friction ridge impressions, Journal of Forensic Identification 58 (2008) 355–89.

[48] O.P. Jasuja, M.A. Toofany, G. Singh, G.S. Singh, Dynamics of latent fingerprints: the effect of physical factors on quality of Ninhydrin developed prints – a preliminary study, Sci. Justice 49 (2009) 8–11.

[49] S. Fieldhouse, Consistency and reproducibility in fingermark deposition, Forensic Sci. Int. 3 (2011) 96–100.

[50] S. Fieldhouse, An Investigation into the Effects of Force Applied During Deposition on Latent Fingermarks and Inked Fingerprints Using a Variable Force Fingerprint Sampler, J. Forensic Sci. 60 (2015) 422-427.

[51] E. Gutiérrez-Redomero, N. Rivaldería, C. Alonso-Rodríguez, A. Sánchez-Andrés, Assessment of the methodology for estimating ridge density in fingerprints and its forensic application, Sci. Justice 54 (2014) 199-207.

[52] K. Krishan, T. Kanchan, C. Ngangom, A study of sex differences in fingerprint ridge density in a North Indian young adult population, J. Forensic Leg. Med. 20 (2013) 217-222.

[53] N. Rivaldería, A. Sánchez-Andrés, C. Alonso-Rodríguez, J.E. Dipierri, E. Gutiérrez-Redomero, Fingerprint ridge density in the Argentinean population and its application to sex inference: A comparative study, HOMO 67 (2016) 65-84.

[54] J.F. Wang, C.L. Lin, Y.H. Chang, M.L. Nagurka, C.W. Yen, C.B. Yeh, Gender determination using fingertip features, Internet Journal of Medical Update 3 (2008) 22-28.

[55] N. Kapoor, A. Badiye, Sex differences in the thumbprint ridge density in a central Indian population, Egypt J. Forensic. Sci. 5 (2015) 23-29.

[56] R.J. Taduran, A.K. Tadeo, N.A.C. Escalona, G.C. Townsend, Sex determination from fingerprint ridge density and white line counts in Filipinos, HOMO 67 (2016) 163-171.

[57] S.B. Holt, Genetics of dermal ridges: bilateral asymmetry in finger ridge-counts, Ann. Hum. Genet. 17 (1952) 211-231

[58] J.K. Dhall, A.K. Kapoor, Fingerprint ridge density as a potential forensic anthropological tool for sex identification, J. Forensic Sci. 61 (2015) 424-429.

[59] S. Gungadin, Sex determination from fingerprint ridge density, Internet Journal of Medical Update, 2 (2007) 4-7.

[60] K. Krishan, A. Ghosh, T. Kanchan, C. Ngangom, J. Sen, Sex differences in fingerprint ridge density, causes and further observations, J. Forensic Leg. Med. 17 (2010) 172-173.

[61] V.C. Nayak, P. Rastogi, T. Kanchan, S.W. Lobo, K. Yoganarasimha, S. Nayak, N.G. Rao, G.P. Kumar, B.S. Kumar-Shetty, R.G. Menezes, Sex differences from fingerprint ridge density in the Indian population, J. Forensic Leg. Med. 17 (2010) 84-86.

[62] V.C. Nayak, P. Rastogi, T. Kanchan, K. Yoganarasimha, G.P. Kumar, R.G. Menezes, Sex differences from fingerprint ridge density in Chinese and Malaysian population, Forensic Sci. Int. 197 (2010) 67-69.

[63] G.A. Eshak, J.F. Zaher, E.I. Hasan, A.A. El-Azeem Ewis, Sex identification from fingertip features in Egyptian population, J. Forensic Leg. Med. 20 (2013) 46-50.

[64] N.C. Sickler, S.J. Elliott, An evaluation of fingerprint image quality across an elderly population vis-à-vis an 18-25 year old population, 39th Annual International Carnahan

Conference on Security Technology, 12-14 October, Las Palmas, Gran Canaria, 2005, pp. 68-73. http://ieeexplore.ieee.org/document/1594817/

[65] S.K. Modi, S.J. Elliott, J. Whetsone, H. Kim, Impact of Age Groups on Fingerprint Recognition Performance, IEEE Workshop on Automatic Identification Advanced Technologies, 2007, pp. 19-23. https://doi.org/10.1109/AUTOID.2007.380586

[66] P. Gnanasivam, S. Muttan, Estimation of age through fingerprints using wavelet transform and singular value decomposition, Int. J. Biom. Bioinformatics 6 (2012) 58-67.

[67] K. Wertelecki, C.C. Plato (eds.), Dermatoglyphics: Fifty years later, Alan R. Liss, New York, 1979.

[68] R.J. Meier, Anthropological Dermatoglyphics: A Review, Yearb. Phys. Anthropol. 23 (1980) 147-178.

[69] P.M. Parker (ed.), Dermatoglyphic: Webster's Timeline History, 1929-2007, ICON Group International, San Diego (CA), 2009.

[70] United Nations Office on Drugs and Crime (UNODC), Global Study on Homicide 2013, United Nations publication, Sales No. 14.IV.1. https://www.unodc.org/gsh/ (accessed 27 February 2018).

[71] European Comission-Eurostat, Suspects and offenders by sex-number and rate for the relevant sex group. http://ec.europa.eu/eurostat/web/crime/database/, last update: 17 May 17 (accessed 27 February 2018).

FIGURE CAPTIONS

Fig. 1. Transparent acetate sheet showing the 10 fingerprints obtained per subject. Fingers: from F1 (right thumb) to F10 (left little finger). (a-c) Technique used to locate the counting areas for different pattern types. (a) Whorl (right hand, thumb) (b): Loop (right hand, middle finger) (c) Arch (left hand, index finger).

Fig. 2. (a) Hand anthropometric measurements (taken from the actual hand or finger). (b) Pattern height (taken from the finger impression).

Fig. 3. Mean ridge density by area and finger for each age–sex group. JM, junior male; SM, senior male; JF, junior female; SF, senior female. Finger: Fi = 1,…, 10.

Fig. 4. Mean finger width by finger for each age–sex group. JM, junior male; SM, senior male; JF, junior female; SF, senior female. Finger: Fi = 1,…, 10.

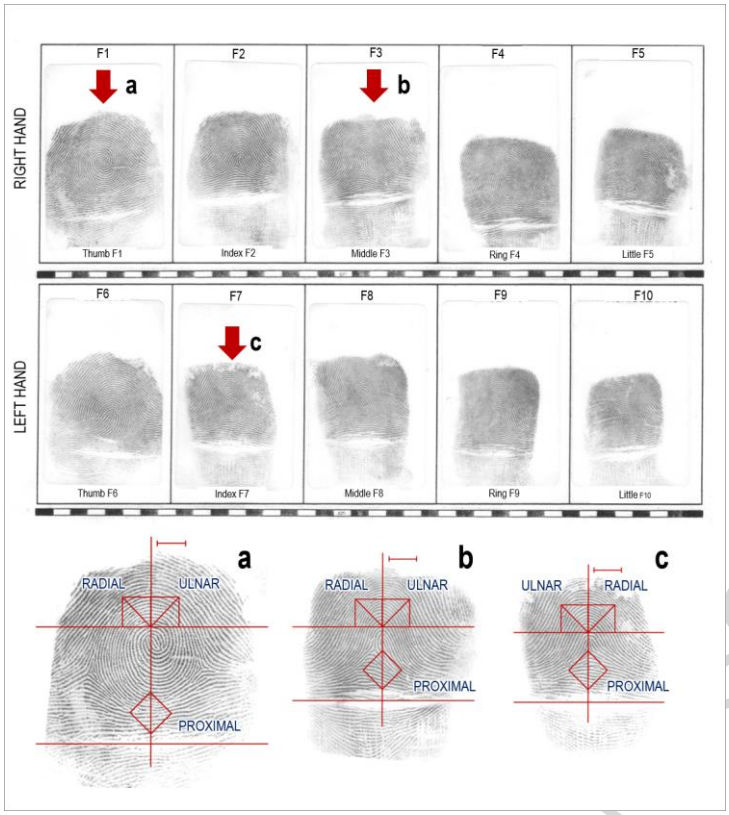
Fig. 5. (a) Mean phalanx length by finger for each age–sex group. (b) Mean pattern height by finger for each age-sex group. JM, junior male; SM, senior male; JF, junior female; SF, senior female. Finger: Fi = 1,…, 10.

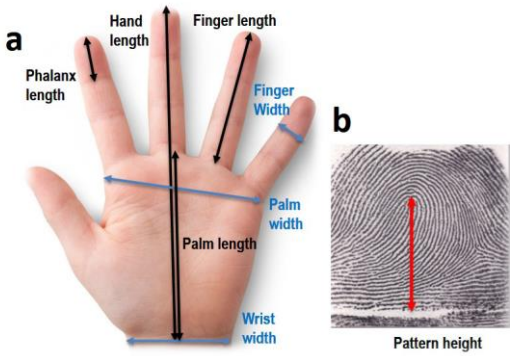
Fig. 6. Regression plots between the 10-finger mean RD for each count area and hand factor. Junior male: red squares; Senior male: blue squares; Junior female: purple circles; Senior female: green circles.

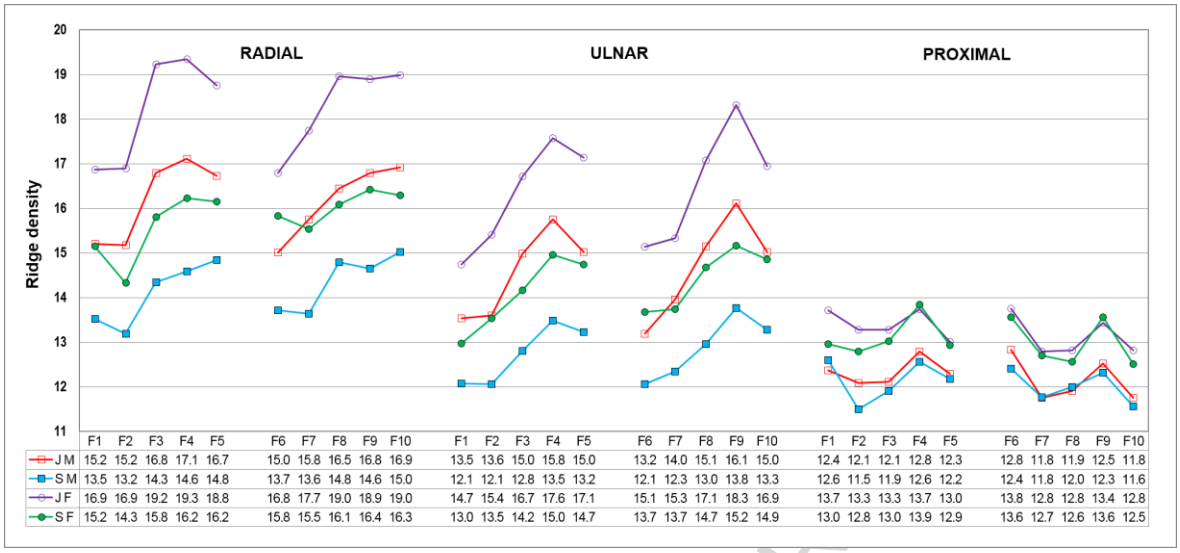
Fig. 7. (a) Relative frequency (%) of pattern type by age–sex group. (b) Analysis of correspondence between pattern type and the age–sex groups. JM, junior male; SM, senior male; JF, junior female; SF, senior female.

Fig. 8. Mean ridge density (RD) by area (radial, ulnar, proximal) and pattern type for each age–sex group. Fisher's LSD at a 95% confidence level is shown. SM, senior male; JM, junior male; SF, senior female; JF, junior female.

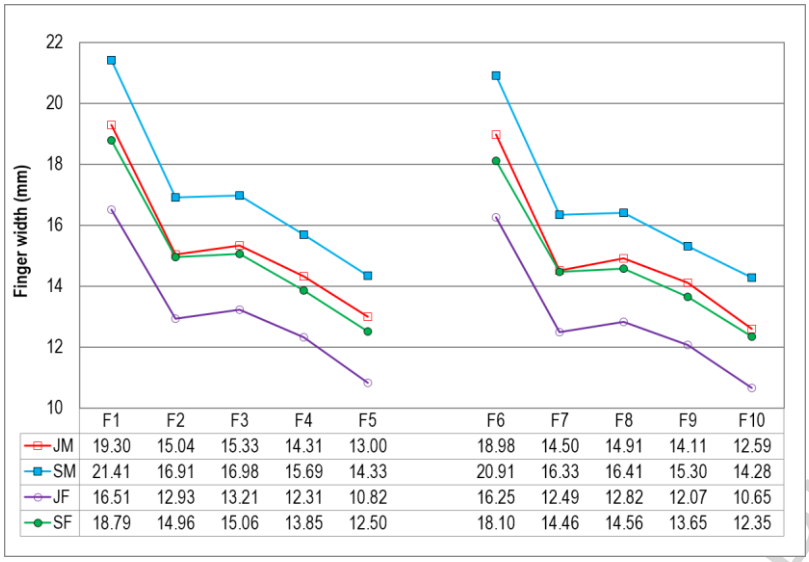
Fig. 9. Hypothetical model of the epidermal ridge width variation in the distal and proximal regions as the finger width (left) or phalanx length (right) increases.



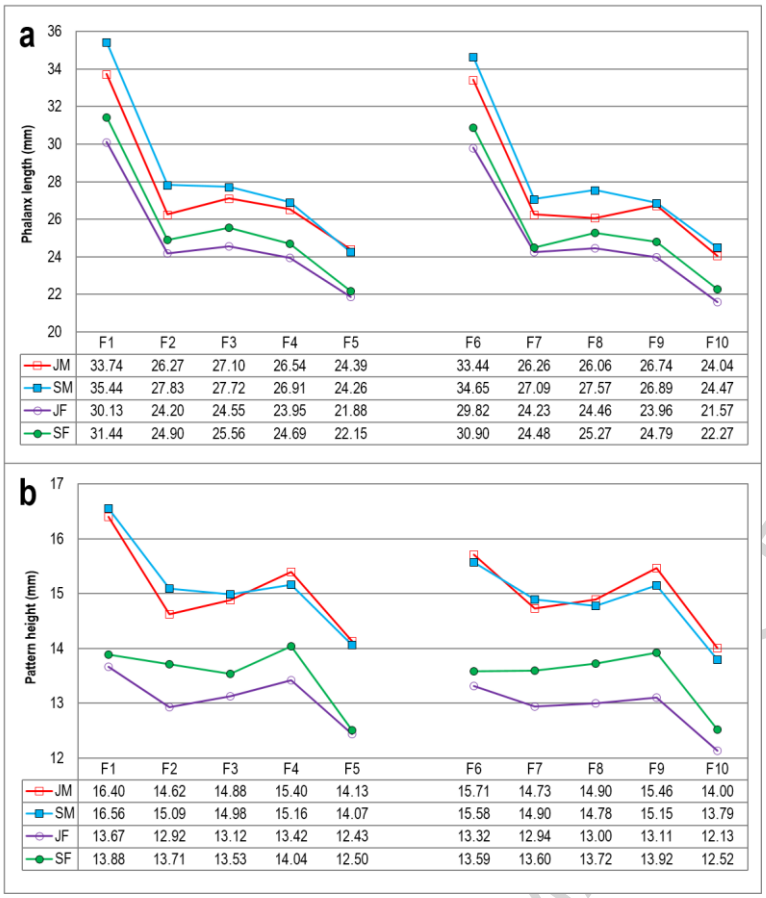




	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	15.2	15.2	16.8	17.1	16.7	15.0	15.8	16.5	16.8	16.9	13.5	13.6	15.0	15.8	15.0	13.2	14.0	15.1	16.1	15.0	12.4	12.1	12.1	12.8	12.3	12.8	11.8	11.9	12.5	11.8
SM	13.5	13.2	14.3	14.6	14.8	13.7	13.6	14.8	14.6	15.0	12.1	12.1	12.8	13.5	13.2	12.1	12.3	13.0	13.8	13.3	12.6	11.5	11.9	12.6	12.2	12.4	11.8	12.0	12.3	11.6
JF	16.9	16.9	19.2	19.3	18.8	16.8	17.7	19.0	18.9	19.0	14.7	15.4	16.7	17.6	17.1	15.1	15.3	17.1	18.3	16.9	13.7	13.3	13.3	13.7	13.0	13.8	12.8	12.8	13.4	12.8
SF	15.2	14.3	15.8	16.2	16.2	15.8	15.5	16.1	16.4	16.3	13.0	13.5	14.2	15.0	14.7	13.7	13.7	14.7	15.2	14.9	13.0	12.8	13.0	13.9	12.9	13.6	12.7	12.6	13.6	12.5

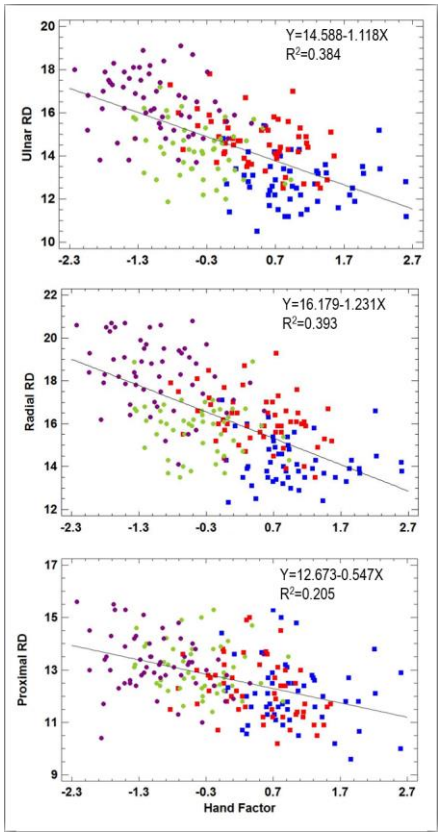


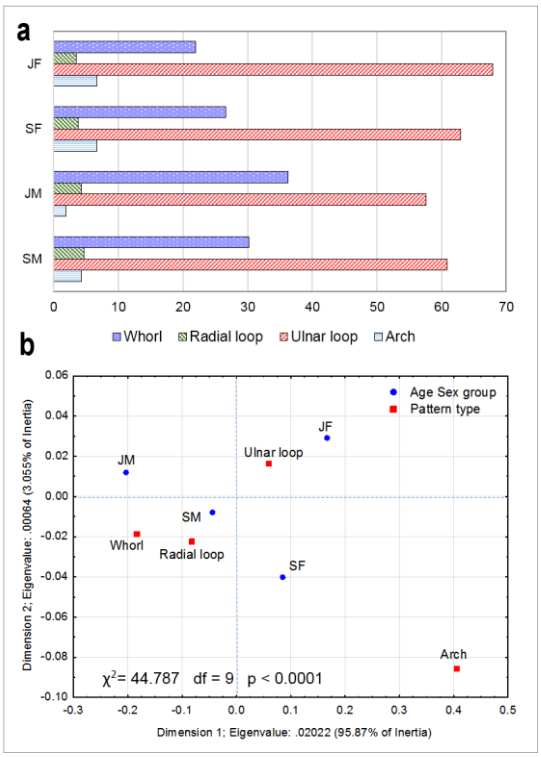
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	19.30	15.04	15.33	14.31	13.00	18.98	14.50	14.91	14.11	12.59
SM	21.41	16.91	16.98	15.69	14.33	20.91	16.33	16.41	15.30	14.28
JF	16.51	12.93	13.21	12.31	10.82	16.25	12.49	12.82	12.07	10.65
SF	18.79	14.96	15.06	13.85	12.50	18.10	14.46	14.56	13.65	12.35

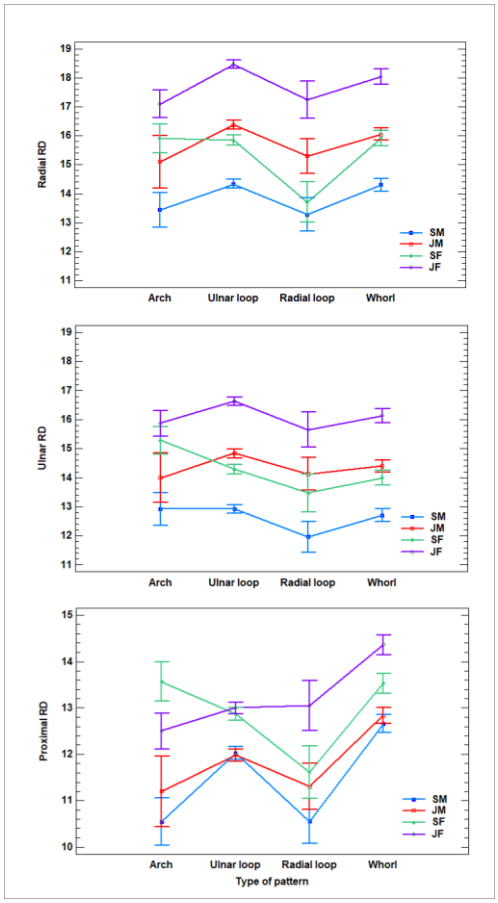


	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	33.74	26.27	27.10	26.54	24.39	33.44	26.26	26.06	26.74	24.04
SM	35.44	27.83	27.72	26.91	24.26	34.65	27.09	27.57	26.89	24.47
JF	30.13	24.20	24.55	23.95	21.88	29.82	24.23	24.46	23.96	21.57
SF	31.44	24.90	25.56	24.69	22.15	30.90	24.48	25.27	24.79	22.27

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	16.40	14.62	14.88	15.40	14.13	15.71	14.73	14.90	15.46	14.00
SM	16.56	15.09	14.98	15.16	14.07	15.58	14.90	14.78	15.15	13.79
JF	13.67	12.92	13.12	13.42	12.43	13.32	12.94	13.00	13.11	12.13
SF	13.88	13.71	13.53	14.04	12.50	13.59	13.60	13.72	13.92	12.52







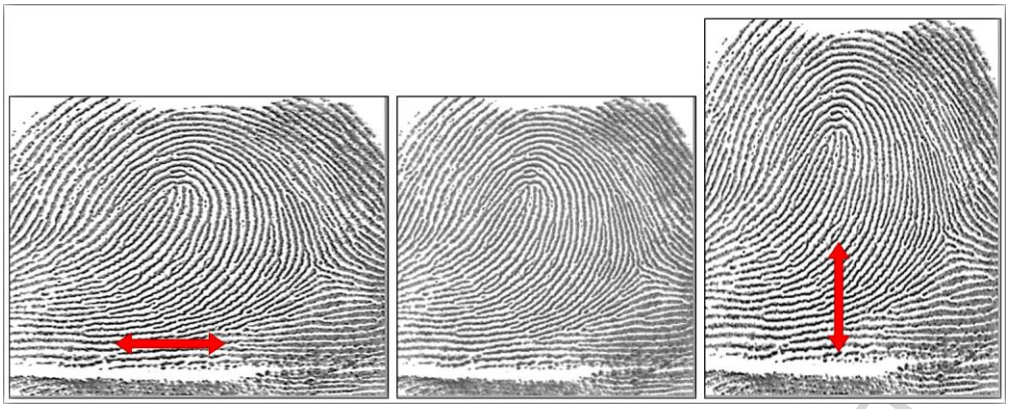


Table 1. Description of body and hand anthropometric measurements, taken from the actual hand according the methodology described in Hall et al. [43], except for pattern height (taken from the finger impression).

Measurement (unit)	Description
Height, H (cm)	Distance from the vertex to the ground
Weight, W (kg)	Total body mass
Wrist Width, WW (mm)	Distance between the styloid process of the radius and the ulna
Hand Length, HL (mm)	Distance from the distal flexion crease of the wrist to the tip of the middle finger
Palm Length, PL (mm)	Distance from the wrist flexion proximal crease to the middle finger flexion proximal crease
Palm Width, PW (mm)	Distance between both ends of the hand at the level of the metacarpophalangeal joints, with fingers forming an angle of 90° with the palm
Finger Length, FL (mm)	Distance from the finger proximal flexion crease to dactylion
Phalanx Length, PhL (mm)	Distance from the crease of interphalangeal flexion of the finger to the dactylion
Finger Width, FW (mm)	Width at the level of the joint between the middle and distal phalanx
Pattern Height, PH (mm)	Distance between the distal interphalangeal crease and defined epidermal ridge count for RD. Measured on the fingerprint

Table 2.- Descriptive statistics of ridge density (10-finger mean) by age and sex.

	Males (n=108)**			Females (n=105)**		
	Radial	Ulnar	Proximal	Radial	Ulnar	Proximal
Junior group (18-30 years) (n= 111)*						
n	54	54	54	57	57	57
Mean	16.19	14.63	12.25	18.24	16.44	13.27
SD	1.22	1.20	1.11	1.66	1.40	1.10
Minimum	13.50	12.5	10.20	14.10	13.70	10.40
Maximum	19.30	17.80	15.00	20.80	19.10	15.60
Senior group (50-66 years) (n=102)*						
n	54	54	54	48	48	48
Mean	14.22	12.81	12.07	15.81	14.25	13.05
SD	1.07	1.08	1.23	1.21	1.24	0.95
Minimum	12.33	10.50	9.60	13.50	11.88	11.40
Maximum	17	15	15.3	18	17	15.3

	.10	.40	0	.90	.20	0

SD: standard deviation

*Within the same age group, significant ($p < 0.001$) sex differences were found for radial, ulnar and proximal areas.

**Within the same sex, significant ($p < 0.001$) age differences were found for the radial and ulnar areas, but not for the proximal area.

Within the same age-sex group, significant differences were found when comparing radial vs. ulnar areas ($p < 0.001$), and when comparing ulnar vs. proximal areas ($p < 0.01$ for Senior males; $p < 0.001$ for the other 3 age-sex groups).

Table 3. Descriptive statistics for anthropometric measurements in different age groups and sex. Sex differences for each age-group and age differences for each sex-group. BMI, body mass index; WW-R, right wrist width; WW-L, left wrist width; HL-R, right hand length; HL-L, left hand length; PL-R, right palm length; PL-L, left palm length; PW-R, right palm width; PW-L, left palm width; SD, standard deviation.

	Male						Female						Sex differences	
	Junior			Senior			Junior			Senior				
	M	SD	Min-Max	Mean	SD	Min-Max	Mean	SD	Min-Max	Mean	SD	Min-Max	Junior	Senior
BMI	17	1.84	15 2-110	18	2.11	15 4-110	16	0.41	1 0.28 46 -90	16	5.49	1 1.64 49-107	6.76[c]	7.25[c]
HL-R	171	7.01	158-197	172.18	6.21	160-187	163.29	5.87	151-176	158.87	5.71	143-173	10.97[c]	11.22[c]
HL-L	172	3.49	157.3-185.5	177.63	3.05	170.8-187.2	162.63	3.54	151.4-172.7	155.91	4.08	139.38-140.77	1.89	2.43[a]
PL-R	105	3.16	95-145	106.28	3.67	99-164	96.72	2.82	91-141	100.48	2.77	95-159	12.79[c]	8.92[c]
PL-L	105	3.00	96-146	106.26	3.25	101-163	97.25	3.08	91-139	100.98	2.86	95-159	11.43[c]	10.24[c]
PW-R	81	8.63	69-169	85.52	8.51	68-212	68.74	8.45	52-188	70.13	6.67	149-184	9.95[c]	10.08[c]
PW-L	81	8.59	66-166	86.39	9.27	66-213	68.63	9.03	50-188	70.25	6.83	151-184	9.68[c]	9.91[c]
HW-R	95	5.98	83-93	105.93	5.42	94-117	96.26	5.30	85-109	97.13	4.07	82-105	8.59[c]	9.18[c]
HW-L	95	5.64	84-94	106.63	5.50	97-118	96.42	5.21	84-105	97.58	4.10	86-107	8.72[c]	9.33[c]
BMI	24	4.45	16 9-69	23.85	4.22	17 6-93	17.39	3.84	6 -80	17.41	3.73	6 82	11.34[c]	12.21[c]

7	4	6	8	4	7	6	3	60	7	3	66-	1	11
	.62	9-69	2.22	.36	3-93	9.82	.87	-79	3.23	.60	83	1.67[c]	.27[c]

[a] p<0.05; [b] p<0.01; [c] p<0.001

Table 4. Partial correlation analysis between hand factor (first PCA component) and RD at each counting area controlling for BMI.

	Hand Factor		
	r	df	p
Radial RD	-0.567	203	<0.001
Ulnar RD	-0.546	203	<0.001
Proximal RD	-0.455	203	<0.001

HIGHLIGHTS

- Sex differences in ridge density (RD) remain throughout adulthood (RD females > RD males)
- RD decreases with aging in radial and ulnar areas, but not in proximal
- Finger width prevails over other variables in explaining the aging changes in RD
- Ridge densities in elder females and young adult males tend to be very similar
- Aging changes may conceal the assumed sex differences in ridge density

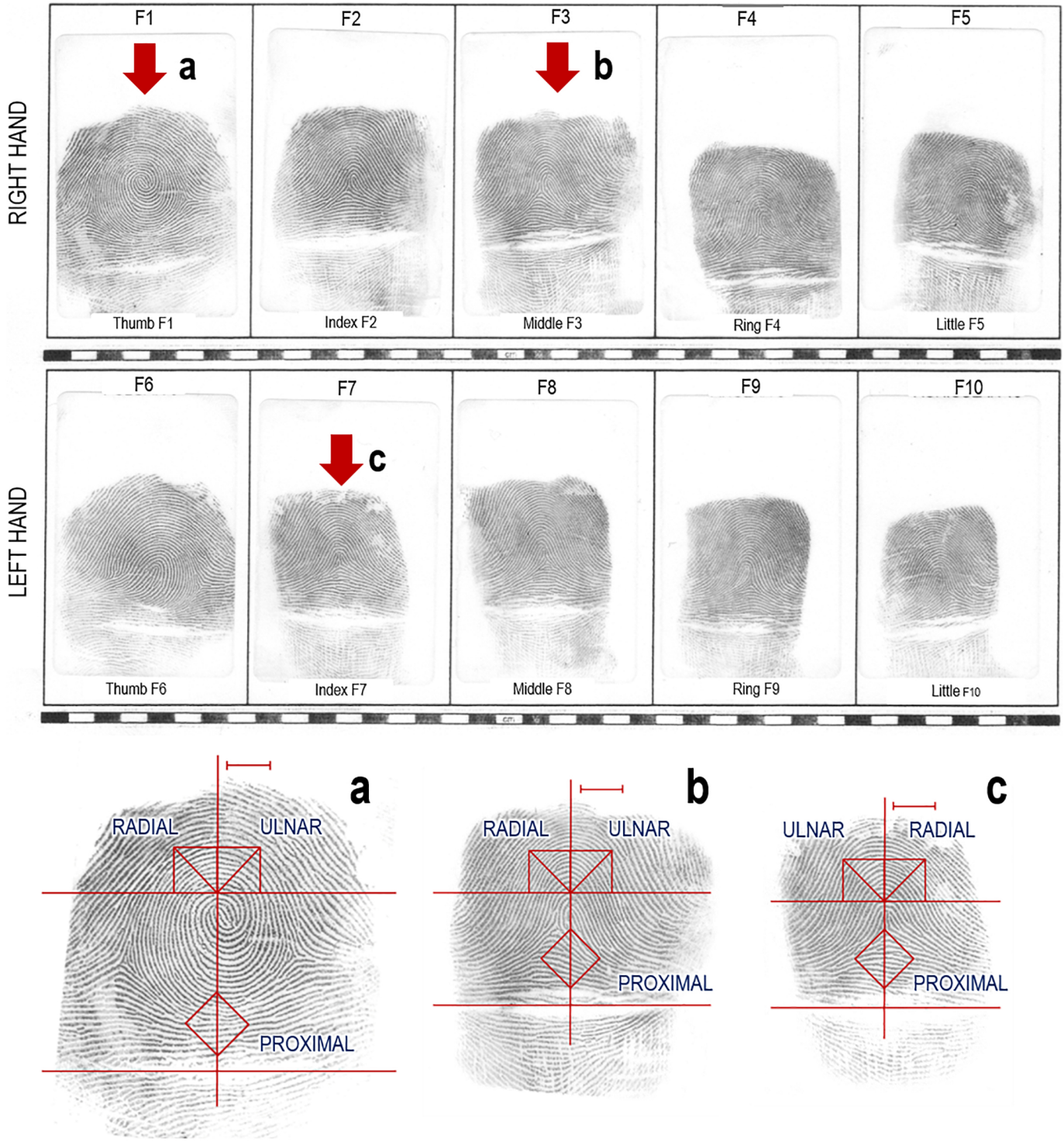

RIGHT HAND
F1
a
Thumb F1
F2
Index F2
F3
b
Middle F3
F4
Ring F4
F5
Little F5
LEFT HAND
F6
Thumb F6
F7
c
Index F7
F8
Middle F8
F9
Ring F9
F10
Little F10
a
RADIAL
ULNAR
PROXIMAL
b
RADIAL
ULNAR
PROXIMAL
c
ULNAR
RADIAL
PROXIMAL

Figure 1

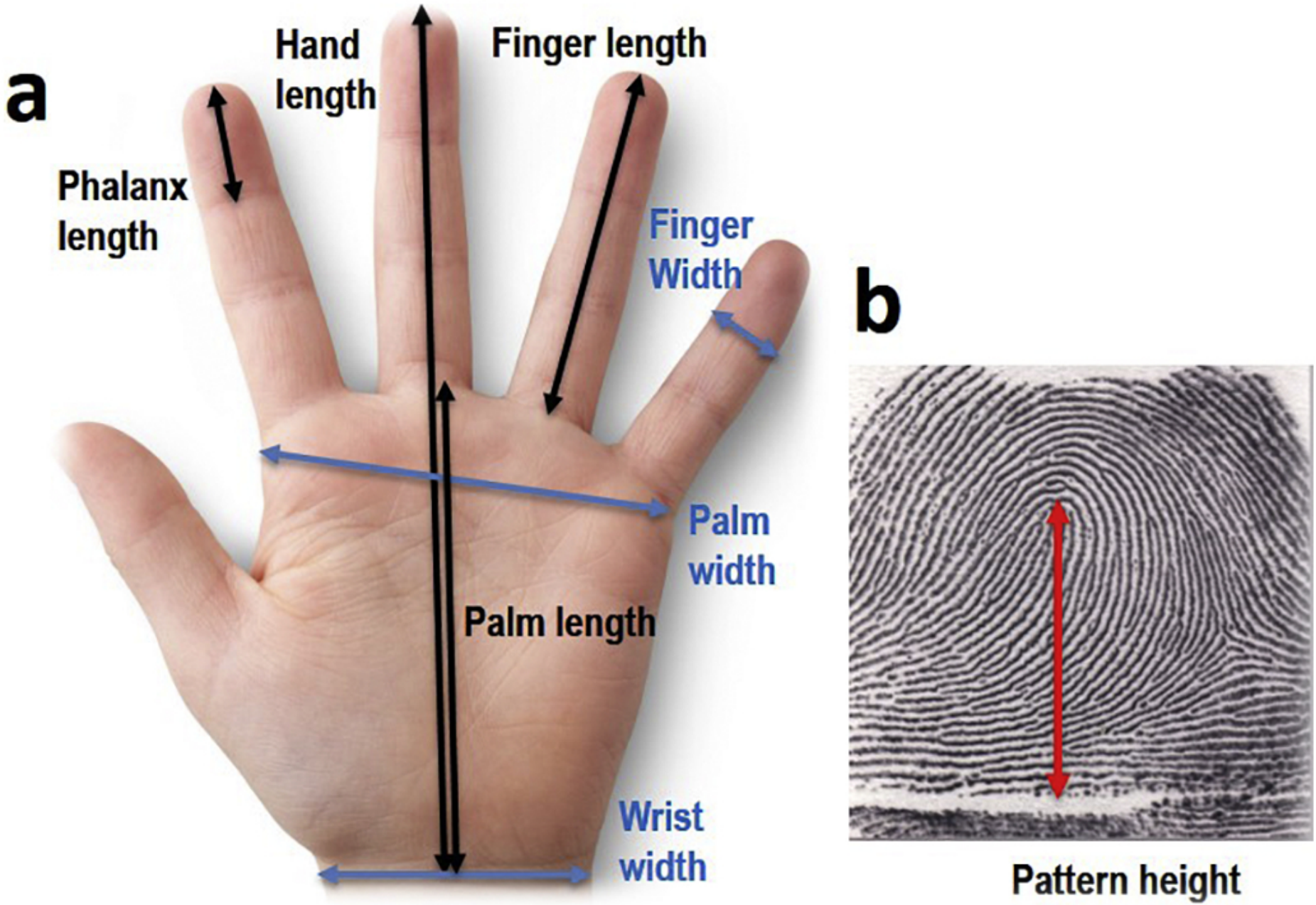
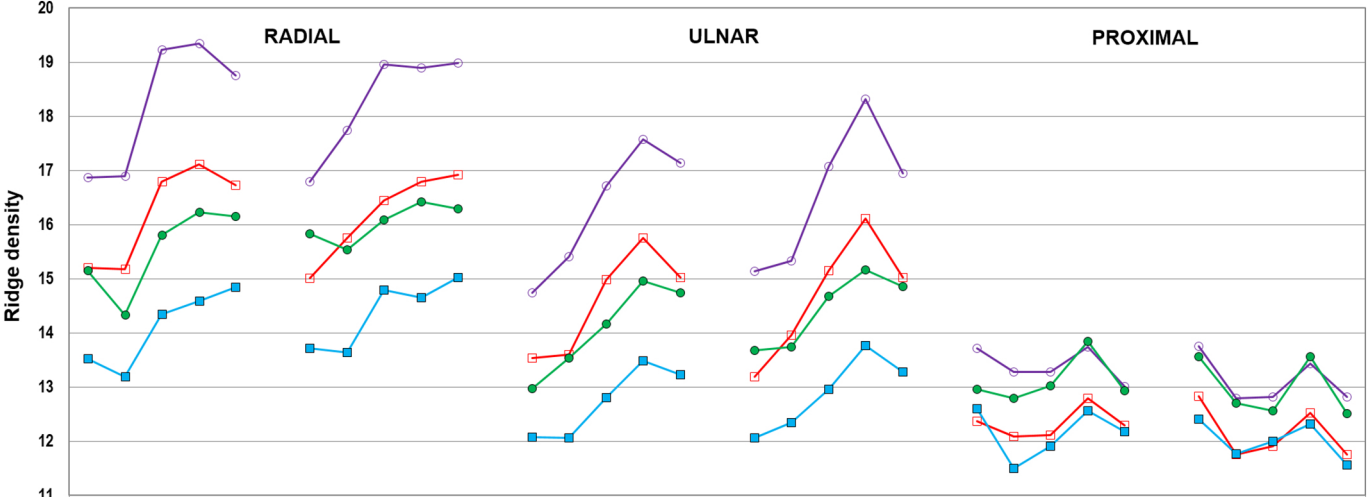
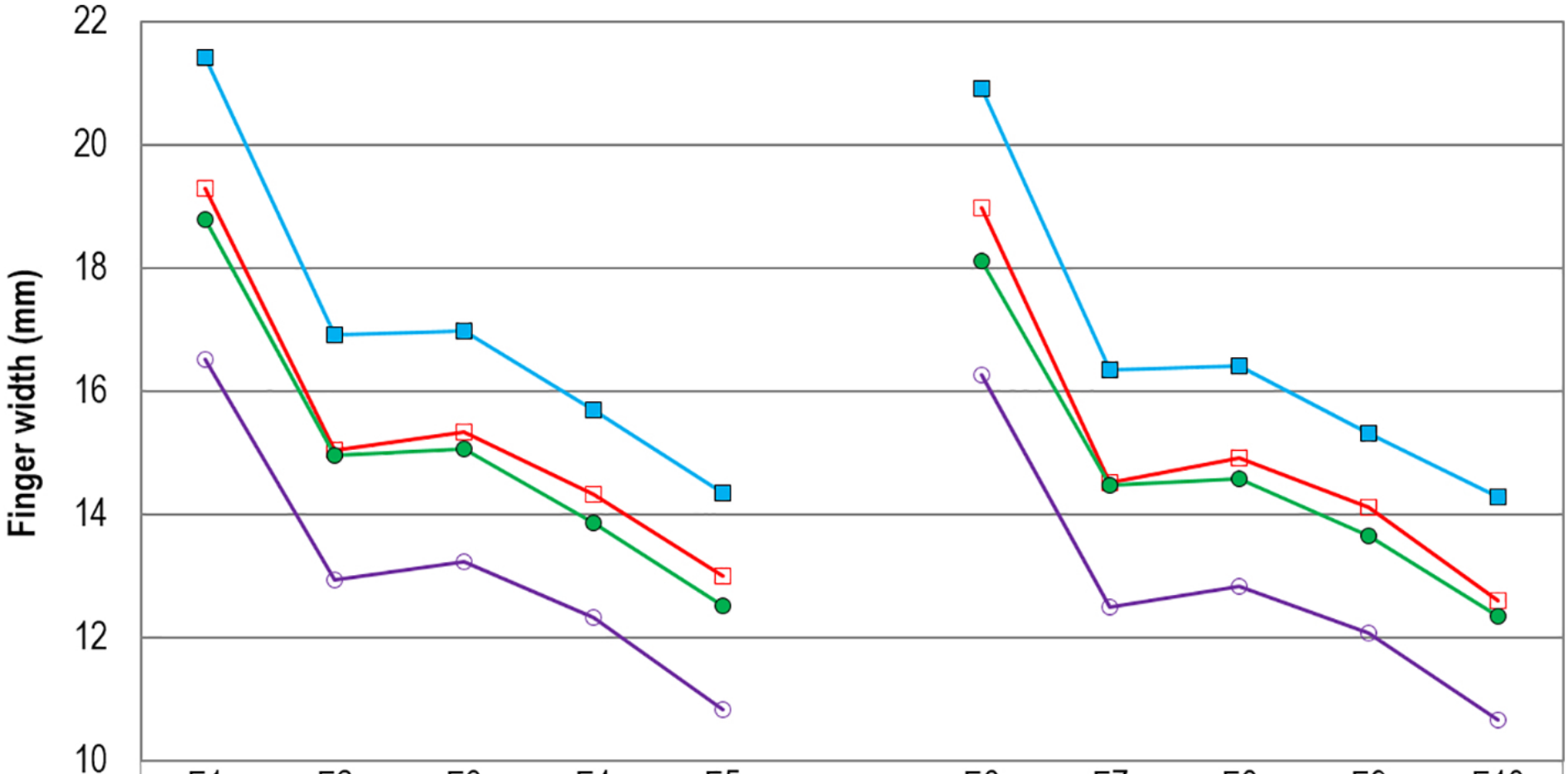

a
Hand length
Finger length
Phalanx length
Finger Width
Palm width
Palm length
Wrist width
b
Pattern height

Figure 2



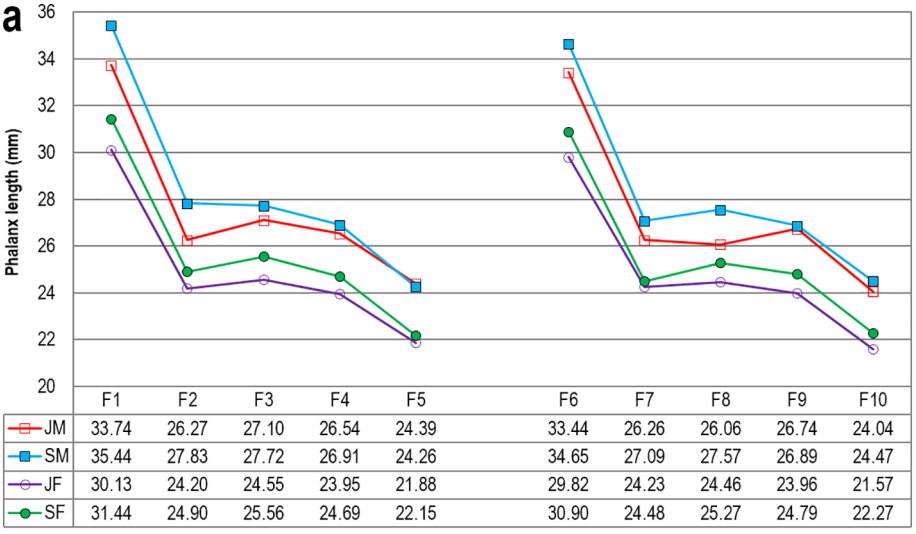
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	15.2	15.2	16.8	17.1	16.7	15.0	15.8	16.5	16.8	16.9	13.5	13.6	15.0	15.8	15.0	13.2	14.0	15.1	16.1	15.0	12.4	12.1	12.1	12.8	12.3	12.8	11.8	11.9	12.5	11.8
SM	13.5	13.2	14.3	14.6	14.8	13.7	13.6	14.8	14.6	15.0	12.1	12.1	12.8	13.5	13.2	12.1	12.3	13.0	13.8	13.3	12.6	11.5	11.9	12.6	12.2	12.4	11.8	12.0	12.3	11.6
JF	16.9	16.9	19.2	19.3	18.8	16.8	17.7	19.0	18.9	19.0	14.7	15.4	16.7	17.6	17.1	15.1	15.3	17.1	18.3	16.9	13.7	13.3	13.3	13.7	13.0	13.8	12.8	12.8	13.4	12.8
SF	15.2	14.3	15.8	16.2	16.2	15.8	15.5	16.1	16.4	16.3	13.0	13.5	14.2	15.0	14.7	13.7	13.7	14.7	15.2	14.9	13.0	12.8	13.0	13.9	12.9	13.6	12.7	12.6	13.6	12.5

Figure 3

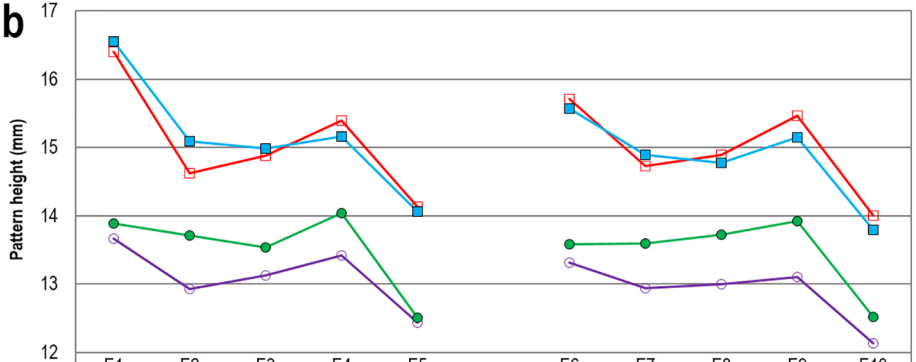


	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	19.30	15.04	15.33	14.31	13.00	18.98	14.50	14.91	14.11	12.59
SM	21.41	16.91	16.98	15.69	14.33	20.91	16.33	16.41	15.30	14.28
JF	16.51	12.93	13.21	12.31	10.82	16.25	12.49	12.82	12.07	10.65
SF	18.79	14.96	15.06	13.85	12.50	18.10	14.46	14.56	13.65	12.35

Figure 4



	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	33.74	26.27	27.10	26.54	24.39	33.44	26.26	26.06	26.74	24.04
SM	35.44	27.83	27.72	26.91	24.26	34.65	27.09	27.57	26.89	24.47
JF	30.13	24.20	24.55	23.95	21.88	29.82	24.23	24.46	23.96	21.57
SF	31.44	24.90	25.56	24.69	22.15	30.90	24.48	25.27	24.79	22.27



	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
JM	16.40	14.62	14.88	15.40	14.13	15.71	14.73	14.90	15.46	14.00
SM	16.56	15.09	14.98	15.16	14.07	15.58	14.90	14.78	15.15	13.79
JF	13.67	12.92	13.12	13.42	12.43	13.32	12.94	13.00	13.11	12.13
SF	13.88	13.71	13.53	14.04	12.50	13.59	13.60	13.72	13.92	12.52

Figure 5

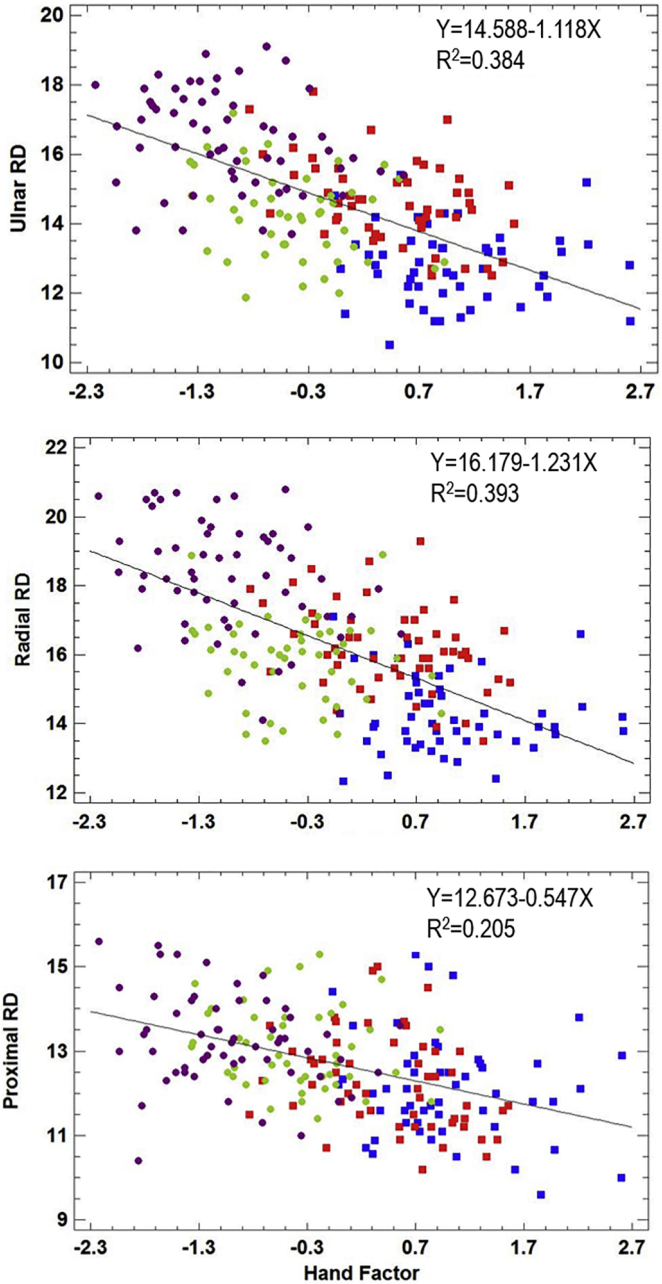

Y=14.588-1.118X
R2=0.384
Ulnar RD
20
18
16
14
12
10
-2.3
-1.3
-0.3
0.7
1.7
2.7
Y=16.179-1.231X
R2=0.393
Radial RD
22
20
18
16
14
12
Y=12.673-0.547X
R2=0.205
Proximal RD
17
15
13
11
9
Hand Factor

Figure 6

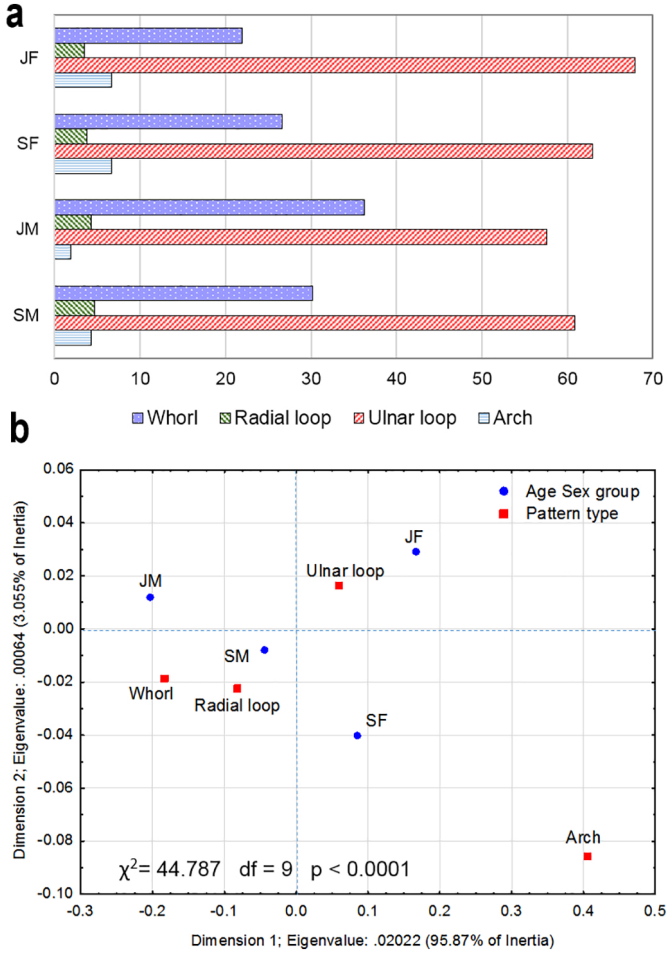

a
JF
SF
JM
SM
0
10
20
30
40
50
60
70
Whorl
Radial loop
Ulnar loop
Arch
b
Age Sex group
Pattern type
JF
Ulnar loop
JM
SM
Whorl
Radial loop
SF
Arch
χ²= 44.787 df = 9 p < 0.0001
Dimension 2; Eigenvalue: .00064 (3.055% of Inertia)
Dimension 1; Eigenvalue: .02022 (95.87% of Inertia)
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

Figure 7

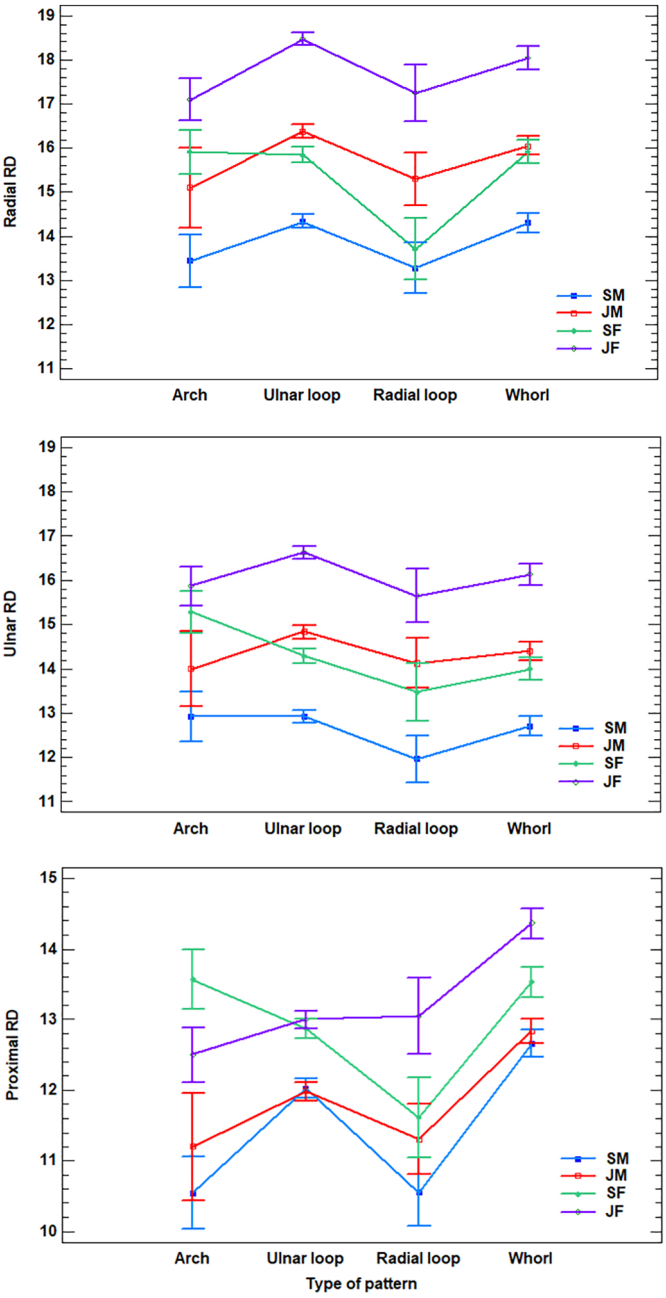

Radial RD
19
18
17
16
15
14
13
12
11
Arch
Ulnar loop
Radial loop
Whorl
SM
JM
SF
JF
Ulnar RD
19
18
17
16
15
14
13
12
11
Arch
Ulnar loop
Radial loop
Whorl
SM
JM
SF
JF
Proximal RD
15
14
13
12
11
10
Arch
Ulnar loop
Radial loop
Whorl
Type of pattern
SM
JM
SF
JF

Figure 8

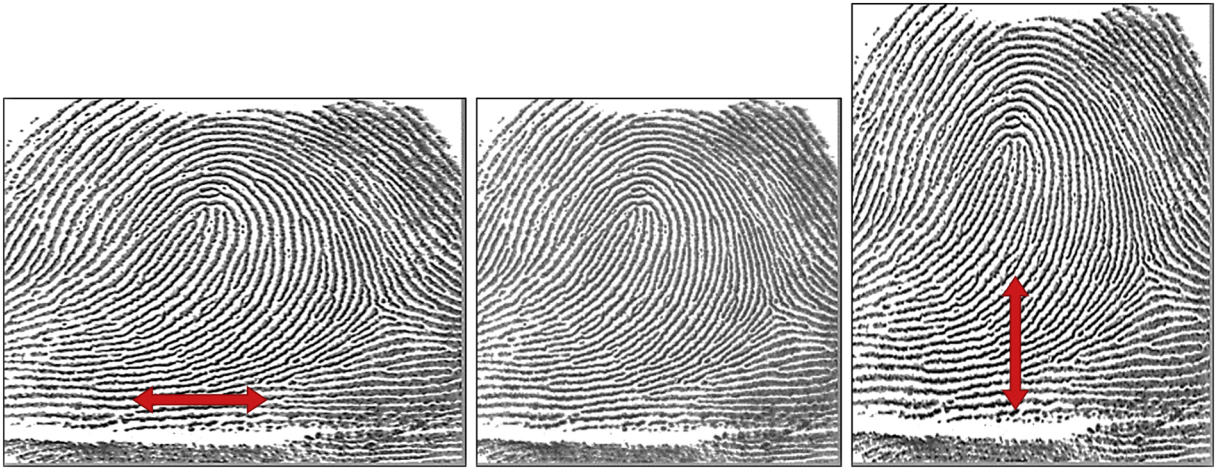


Figure 9