Sex, Ancestral, and Pattern Type Variation of Fingerprint Minutiae: A Forensic Perspective on Anthropological Dermatoglyphics

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ABSTRACT

Objectives: The majority of anthropological studies on dermatoglyphics examine the heritability and inter-population variation of Level 1 detail (e.g., pattern type, total ridge count), while forensic scientists concentrate on individual uniqueness of Level 2 and 3 detail (e.g., minutiae and pores, respectively) used for positive identification. The present study bridges the gap between researcher–practitioner by examining sex, ancestral, and pattern type variation of Level 2 detail (e.g., minutiae).
Materials and Methods: Bifurcations, ending ridges, short ridges, dots, and enclosures on the right index finger of 243 individuals ($n = 61$ African American ♀; $n = 61$ African American ♂; $n = 61$ European American ♀; $n = 60$ European American ♂) were analyzed. The overall effect of sex, ancestry, and pattern type on minutiae variation was assessed using a MANCOVA. ANOVA was used to identify Level 2 detail variables responsible for the variation. Logistic regression was used to classify individuals into groups.
Results: The effect of sex is insignificant. Ancestry is significant (Wilks' $\lambda = 0.053$ F value = 2.98, DF = 4,224, P value = 0.02), as is pattern type (Wilks' $\lambda = 0.874$ F value = 2.57, DF = 12,592.94, P value = 0.003). The ANOVA reveals that bifurcations are responsible for the variation between ancestral groups, while bifurcations and ending ridges vary between patterns. Logistic regression results suggest that total bifurcations can predict the ancestry of an individual (ChiSq = 6.55, df = 1, Prob > ChiSq = 0.01).
Discussion: Significant minutiae variation between ancestral groups yields information that is valuable in both a forensic and anthropological setting. Am J Phys Anthropol 000:000–000, 2015.

The term dermatoglyphics was coined by Harold Cummins in 1926 to refer to the patterns of epidermal ridges on the palms, fingers, toes, and soles of the feet when researching their development, population structure, variation, and other aspects that are not immediately concerned with identification (Cummins, 1946, 1967). Ridge patterns had previously been used mainly in a forensic context and were referred to as fingerprints. However, Cummins (1946) proposed the broader term of dermatoglyphics to reflect the growing interest in nonidentification aspects of epidermal ridges, as well as to promote research on other parts of the body that contain ridged skin. Physical anthropologists were among those who adopted the term. Anthropological dermatoglyphics has come to be recognized as an area of research concerning the intrauterine development and population structure of dermatoglyphic traits (Mulvihill and Smith, 1969). Given the applicability of ridge traits to a forensic and anthropological context, it is argued here that these traits should be studied from both perspectives, ideally through collaboration. The present study is the result of collaboration with latent fingerprint examiners from the City County Bureau of Identification in Raleigh, NC, whose insights guided the authors to design this study to be equally beneficial to physical anthropologists and forensic practitioners. The purpose of this study is to explore the influence of sex, ancestry, and pattern type on minutiae in an African and European American male and female sample. In doing so, the goals of anthropological dermatoglyphic research (i.e., population structure) will be combined with a variable (i.e., minutiae) that has rarely been studied on a group level but is the primary variable considered in forensic research on individual fingerprints. Identifying the factors that influence the phenotype of dermatoglyphics as well as the underlying hereditary and environmental factors causing this influence would strengthen latent fingerprint examination and contribute new information to anthropological dermatoglyphics. Given previous anthropological literature stating the influence of ancestry and sex on Level 1 detail, it was hypothesized that these relationships would be upheld to some degree on Level 2 detail, meaning variation in minutiae counts would be observed between the sexes and populations. In addition, because minutiae form during the time of pattern formation, it was also hypothesized that pattern type would cause significant variation in minutiae.

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Because of the interdisciplinary nature of this study, the review includes literature on dermatoglyphic development, as well as the characteristics of these traits that make them useful for identification purposes. Dermatoglyphics contain three levels of detail. Level 1 detail consists of ridge flow or the ridge count and pattern type that the ridges assume. This level is used to create systems that classify fingerprints according to pattern type including arch, tented arch, left loop, right loop, double loop whorl, central pocket loop whorl, and accidental whorl. Because there are a limited number of possibilities, Level 1 detail is not specific enough to be used for positive identifications (Ashbaugh, 1992; Langenburg, 2004). Level 2 detail refers to the shape, direction, and orientation of the traits that form the friction ridges (Langenburg, 2004). These characteristics are called minutiae or Galton Details after Sir Francis Galton who was the first to suggest using them for identity purposes in criminal cases (Nickell and Fischer, 1999). Minutiae are unique in their quantity and orientation in each individual fingerprint (Cummins, 1967). Therefore, unlike Level 1 detail, Level 2 detail can be used for identifications (Cole, 1999; Huckerman et al., 2008; Bennett and Perumal, 2011). The final and most microscopic level of detail, Level 3, is the individual ridge structure (ridge shapes and pores) and is also unique to each fingerprint (Langenburg, 2004). Therefore, ridge shape and pores are also sometimes considered by fingerprint examiners during forensic examinations in addition to Level 2 detail.

The characteristic of dermatoglyphics that make them an excellent trait to study is their permanence throughout an individual's lifetime. This is essential to their use in forensic identifications, as comparisons would be meaningless if ridge appearance changed. It is also crucial for the anthropological goals of studying population structure. Additionally, the uniqueness of some dermatoglpyphic traits make them an ideal indicator of identity, while the similar trends seen within populations concerning other dermatoglyphic traits have long been an area of interest to anthropologists. Anthropological research has explored the genetic and environmental influence on dermatoglyphic development in addition to inter- and intra-population phenotypic variation (Holt, 1951, 1954; Rothhammer et al., 1977; Froehlich and Giles, 1981; Martin et al., 1982; Jantz and Chopra, 1983; Houle, 1991; Reddy et al., 2000). The work of forensic scientists, namely latent fingerprint examiners and researchers, has sought to confirm and explain the permanence and uniqueness of fingerprints, thereby supporting their use as an identification tool (Galton, 1892; Cummins, 1946; Cummins, 1967; Ashbaugh, 1992; Champod, 1995; Cole, 1999; Zhao and Tang, 2006; Huckerman et al., 2008).

Permanence and uniqueness of fingerprints

To understand the permanence and uniqueness of dermatoglyphics, it is essential to understand dermatoglyphic development. The first step in their development is the appearance of volar pads during the 6th to 7th week of gestation (Mulvihill and Smith, 1969; Borecki et al., 1985). These pads are made up of mesenchymal tissue and are similar to those seen in dogs and several other animals. In humans, however, they regress in utero beginning in the 10th and 11th week of gestation following the initiation of primary ridges forming in the basal layer of the epidermis (Cummins, 1946; Mulvihill and Smith, 1969; Babler, 1978). They extend into the dermis and increase in number as secondary ridges form between them and on the periphery of the pattern (Hale, 1952). The process of primary and secondary ridge growth is referred to as the period of differentiation. Minutiae form as the ridge path is being laid down. It is the shape of the volar pads during differentiation that determines which pattern type is formed (Mulvihill and Smith, 1969; Babler, 1977; Jantz and Chopra, 1983; Ashbaugh, 1992). The role of shape is explained by the ontogenetic hypothesis, which states that ridge configurations are the result of the topography of the volar surface, growth forces, and an inherent tendency to form ridges perpendicular to the lines of stress (Mulvihill and Smith, 1969; Babler, 1977). The height is a factor of the stage in the regression process that the pad is in when primary ridge development begins. Early regression or low volar pads result in arches. Likewise, later regression or high pads produce whorls. A volar pad that is intermediate in height and raised more on one side will create a loop that coils on the higher side (Babler, 1978; Wertheim and Maceo, 2002). The symmetry of the volar pad and other elements of finger growth during the period of primary ridge formation also contribute to pattern development. Symmetrical patterns (arches and whorls) result from symmetrical volar pads, while asymmetrical patterns (loops) result from asymmetrical volar pads (Wertheim and Maceo, 2002). Ridge configurations complete their formation after the 17th week of fetal development and remain unchanged throughout life (Hale, 1952; Babler, 1978; Borecki et al., 1985).

The permanence of dermatoglyphics is a consequence of the developmental process that was just described. In their comprehensive review Wertheim and Maceo (2002) state that the principle of permanence is based upon the fact that the various layers of skin are attached to one another. At the most superficial layer, cells of the epidermis are joined together. Next, the basal layer of the epidermis is attached to the basement membrane, an area referred to as the epidermal-dermal junction and the basement membrane is then attached to the dermis. As a result of the attachment within the layers, the unique positional properties of the basement membrane that were established during fetal development, i.e. the pattern type and minutiae, are continually transferred up through the layers to the outer layer of the epidermis throughout life (Wertheim and Maceo, 2002).

Uniqueness of dermatoglyphics is also a consequence of their development. As previously stated, the minutiae that form along the ridge path as the surface continues to become ridged are responsible for the individuality or uniqueness of fingerprints. This is because the formation and placement of any type of minutia within the developing ridge field is controlled by a random assortment of interdependent factors at any given moment during development. Mechanical stress, physiological environment, and variation in the timing of development could affect minutiae placement (Wertheim and Maceo, 2002). To illustrate the unlikelihood of duplicating such random and accidental events, Wertheim and Maceo (2002) use the following hypothetical situation. If a dump truck that was filled with sticks drove down a road and suddenly tipped over, the sticks would be scattered along the road. To repeat such a scenario exactly, the truck would need to tip over at the same location on that road, with each stick landing in precisely the same position.

The unlikelihood of such a situation is suggested as an analogy for the duplication of the entire process of biological formation of minutiae on two pieces of skin making them indistinguishable.

Because of the permanence and uniqueness of minutiae orientation, these traits have been utilized in several systems establishing identification on a comparison of matching points on unknown latent prints to known prints. Several such systems required a certain number of concurring points on a known and unknown fingerprint in order to establish a positive identification. Edmond Locard developed the tripartite rule for establishing a minimum number of minutiae necessary for identification in 1914. The tripartite rule states that 1) if more than 12 concurring points are visible and the fingerprint is clear then certainty of identity is beyond doubt, 2) if 8–12 concurring points are seen then certainty is borderline and depends on the clarity, rarity of type, and the presence of the core and delta in the usable portion of the print, 3) if a limited number of characteristic points are present, the fingerprint cannot provide certainty for an identification but only a presumption proportional to the number of points available and their clarity (Champod, 1995). The United States used Locard's standard of 8–12 points of concordance as stated in the tripartite rule until 1973, when the International Association of Identification (IAI) made the decision that identification cannot be reduced to counting a standard number of matching minutiae because each identification represents a unique situation (Champod, 1995). Henry Faulds opposed the point counting methodology as early as the 19th century, arguing that it was too simplistic and that more scientific approaches needed to be taken to demonstrate the statistical improbability that two fingerprints are identical (Cole, 1999). Faulds' critique of using a minimum number of matching points to confirm identity has inspired a change in perspective in many researchers.

Recent research has resulted in models illustrating how to weight the various components of fingerprints such as minutiae and the area of the print in which they are found (Wertheim, 2000). For instance, Gutierrez-Redomero et al. state that the greatest number of minutiae is concentrated around the core and delta of a fingerprint (Gutierrez-Redomero et al., 2010). This study also estimated the frequency with which each minutiae type occurs. Their findings indicate that ending ridges occur with frequencies ranging from 55 to 65%, bifurcations 13–18%, while others including dots, enclosures, and short ridges, occurred at a frequency of <3%. The percentage within the range varied according to the area of the print. Specifically, ending ridges were more concentrated in the periphery of the fingerprint than in the central region closest to the core. Conversely, bifurcations and convergences, a minutiae type recognized in the Gutierrez-Redomero study that is not considered here, are more concentrated in the central region (Gutierrez-Redomero et al., 2010).

Clearly, several systems have been adopted to compare the minutiae of an unknown print to a known and as of yet, there is no agreed upon standard. To select the most accurate system as the standard, more research must be done. Specifically, research into how minutiae form and which factors influence that process, is required. Previous research such as the literature just described has contributed to that knowledge and inspired the questions raised by the present study.

Genetic and environmental influence on dermatoglyphic development

Fingerprint characteristics are indirectly inherited because it is the form and timing of volar pads described by the ontogenetic hypothesis that is heritable rather than the pattern itself (Wertheim and Maceo, 2002). The size of the volar pads is inherited in a way that is similar to the size of other anatomical features (Mulvihill and Smith, 1969). According to Cummins (1946) the size (ridge count) and form (type) of the pattern are, for this reason, at least partially under genetic control.

Inheritance of fingerprint traits is polygenic, which makes them less susceptible to stochastic processes such as genetic drift. Though polygenic traits are more difficult to genetically define, they remain preferable for tracing population relationships because of their stability (Froehlich and Giles, 1981). For this reason, intra- and inter-group variation in the frequency of pattern types has been examined by anthropologists (Grace, 1974; Jantz and Chopra, 1983). For example, Dankmeijer (1938) compared the frequency of arches, loops, and whorls in individuals from each of the major geographical regions and found significant differences between populations and sexes.

Dermatoglyphic variation is often compared to other measures of population structure such as blood groups, linguistics, and/or genetic markers (Froehlich and Giles, 1981; Sokal et al., 1996; Reddy et al., 2000). The majority of these studies reflect the aforementioned statement that dermatoglyphic traits have more temporal stability, a slower rate of evolutionary change and are less vulnerable to such forces as genetic drift as a result of their polygenic inheritance (Froehlich and Giles, 1981; Houle, 1991). One such study compared dermatoglyphic traits with serological parameters for two populations on the island of Cyprus, an isolated mountain population and a coastal group. The results show that the two populations differed significantly from each other on serological parameters but their dermatoglyphic traits were similar (Plato, 1970; Froehlich and Giles, 1981). A striking piece of evidence of the temporal stability of dermatoglyphic traits is the exceptionally close dermatoglyphic resemblance seen in different Jewish populations after 2,000 years of separation (Sachs and Bat-Miriam, 1957; Froehlich and Giles, 1981).

Though the size and shape of the volar pads is predetermined genetically, intrauterine stresses during their formation may alter their outcome (Ashbaugh, 1992), particularly because the period of fetal development during which ridges form is also the time when the fetus is most susceptible to growth disturbances from environmental factors (Babler, 1978). The fingerprints of elective and spontaneously aborted fetuses have been studied to assess the influence of stress on dermatoglyphic development. Results of these studies show that the electively aborted fetuses exhibit arch frequencies similar to the living population, which is low in comparison with loops and whorls. Conversely, a much higher frequency is observed in the spontaneously aborted group. As arches are associated with late ridge differentiation relative to volar pad regression, the presence of arch frequencies deviating so much from the norm could suggest an alteration in overall developmental timing driven by intrauterine environmental influences that is not well-suited for survival (Babler, 1978; Jantz, 1987; Wertheim and Maceo, 2002). It is important to note that it currently remains unknown whether the high frequency of arches that results from changes in developmental timing is due to early pad regression or late ridge differentiation as both contribute to the same result (Babler, 1978). Another source of alteration to predetermined pattern type is any deviation in the normal developmental symmetry of the volar pad (Wertheim and Maceo, 2002). A previously symmetrical volar pad that becomes asymmetrical will result in a loop rather than an arch or a whorl. Environmental influences on the development of Level 1 and 2 detail is important to remember when studying dermatoglyphics as a measure of population structure. Drift and other processes are less of a concern with these traits, but intrauterine stresses acting on an individual level remain a possible confounding factor for representing a group as a whole on the basis of their dermatoglyphic phenotype.

Summary

It has been shown that dermatoglyphic traits possess some important qualities that make them extremely useful traits to study. Among these are their polygenic inheritance, uniqueness, and permanence throughout life. Consequently, as was previously stated, anthropologists have used dermatoglyphic traits as a measure of population structure, exploring the extent to which groups resemble each other or differ. Meanwhile, forensic scientists have sought various ways of empirically demonstrating the individual uniqueness of fingerprints. These goals seem similar, yet anthropologists and forensic scientists rarely collaborate in their efforts. Anthropologists use Level 1 detail such as pattern type (e.g., arches, loops, and whorls) and ridge counts (e.g., total ridge count, radial/ulnar counts) to study population structure of dermatoglyphics (Dankmeijer, 1938; Grace, 1974; Jantz and Chopra, 1983), while forensic scientists focus on Level 2 and 3 detail because these are used in making positive identifications. They are, in essence, speaking different languages. To further the science, it is argued here that effort must be taken to examine anthropological questions of population variation using dermatoglyphic characteristics that are relevant to forensic science and to increase collaboration between researchers and practitioners. In doing so, it will be possible to speak to the heritability and individuality of Level 2 detail and identify the biological factors such as sex and ancestry that influence the development of minutiae, which are the ultimate goals of the present study. This information could have significant implications for both anthropology and forensic science and would answer the call to action outlined in the National Academy of Science (NAS) Report of 2009, which expresses an immediate need to incorporate biology into the process of latent fingerprint identifications and to take a statistical approach to minimizing the error rate associated with fingerprint identification decisions (NAS, 2009).

MATERIALS AND METHODS

Sample

All fingerprints used in this study were obtained from the City County Bureau of Identification (CCBI) in Raleigh, NC. Maintaining the privacy and anonymity of study subjects was of the utmost concern. As such, personal and identifiable information about the individuals was excluded from all documentation. Because this study involved living human subjects, the protocol was submitted to the North Carolina State University IRB and was determined to be exempt from any further review.

TABLE 1. Description of sample

	Male	Female	Total
African American	61	61	122
European American	60	61	121

Databases. The Biometric Image Software (NBIS) developed by the forensic science division of the National Institute of Standards and Technology (NIST) was used to search for individuals of European and African American ancestry (NIST, 2013). Once individuals who fit the ancestry needs were identified, their prints could be searched in the local and state databases using PrintQuest® AFIS-APIS System. PrintQuest is a standalone PC system for matching fingerprints by SPEX Forensics (SPEX, 2013). The database also provides birthplace for each individual. These aspects were useful in selecting the study sample. Combining the information provided by NIST and PrintQuest® allowed an appropriate sample to be selected for this study.

Study sample. The study sample consists of 243 nail-to-nail rolls of the right index finger from tenprint cards in a local and state database in PrintQuest® and in NIST. The right index finger was selected because this is among the most common prints to be left as latent fingerprints. A description of the sample is illustrated in Table 1.

Friction ridge characteristics. The fingerprints included in this study are classified as one of the three main pattern types, arches, loops (left and right), and whorls. The five minutiae selected in the present study include bifurcations, ridge endings/ending ridges, short ridges, dots, and enclosures. A bifurcation is defined as the point at which a friction ridge divides into two friction ridges. An enclosure is a single friction ridge that bifurcates and then rejoins to continue as a single ridge, making it a variation on a bifurcation. A ridge is considered an ending ridge when it terminates along the ridge path. An ending ridge that travels only a short distance before it ends is called a short ridge. Finally, a dot is a friction ridge that is as long as it is wide (SWGFAST, 2011). The pattern and minutiae types selected for this study are illustrated in Figures 1 and 2, respectively.

Methods

Sample selection. Spex PrintQuest® was set to show 10 print cards, which show a complete nail-to-nail roll recorded for comparison, and the right index finger was selected to appear on the screen. To be selected, each fingerprint had to fulfill the following criteria. The print had to be a complete roll with no smudging or scars that would alter the ridge flow and minutiae. Once a fingerprint was determined to be of sufficient quality, sex and ancestry were ascertained based on self-identification on the individual's record. Ancestry information, therefore, was based on *a priori* knowledge of self-identification and demographic information of Wake County, NC

Fig. 1. Pattern types. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

(Konigsberg et al., 2009). Specifically, only those individuals who self-identified as "white" or "black" were chosen for the study, racial groups that make up 62.2 and 20.3% of the 2010 population of Wake County, respectively (Smith, 2014). This selection process was continued until a sufficiently large sample size was obtained.

Minutia selection. The five minutiae selected for this study were chosen because they are sufficiently distinct from each other. The decision to use them was supported by latent fingerprint analysts at the City County Bureau of Identification (CCBI) in Raleigh, NC who were consulted with regard to which types of minutiae they frequently identify in comparisons. A major goal of this study is to apply the results to forensic investigations and thus, it was important to choose variables with a high degree of relevance.

Minutiae quantification. Prior to quantifying minutiae, the pattern type was recorded for each fingerprint so that pattern type could be included in the statistical analysis to test whether any of the minutia variables were influenced by pattern type. Next, the feature of PrintQuest® that marks the minutiae on fingerprints and codes them using color and shapes was unselected. The decision to do so was based on two reasons. First, the program only marks bifurcations and ending ridges leaving the majority of the minutiae considered in this study to be hand-counted. Second, having the minutiae preidentified would likely have influenced the visual assessment and introduced bias into the results. The first author collected and recorded all of the data. After all minutiae were unidentified on the computer screen, each fingerprint was split into four quadrants using the reference center feature in PrintQuest®. This was done to decrease the viewing field when counting the minutiae in order to avoid omitting or double counting them. The quadrants were all designated based on the center of the fingerprint. The five minutia types were counted in each quadrant until all four quadrants were counted. This step was repeated two times for each fingerprint to lessen the chance of observer error. The sum of the resulting totals from each quadrant was then obtained.

Following latent fingerprint examiner guidelines, both ends of a short ridge and ending ridge were counted since this minutia is defined by the end of the line, not the line itself. In the instance that an ending ridge crossed into more than one quadrant, only the end point

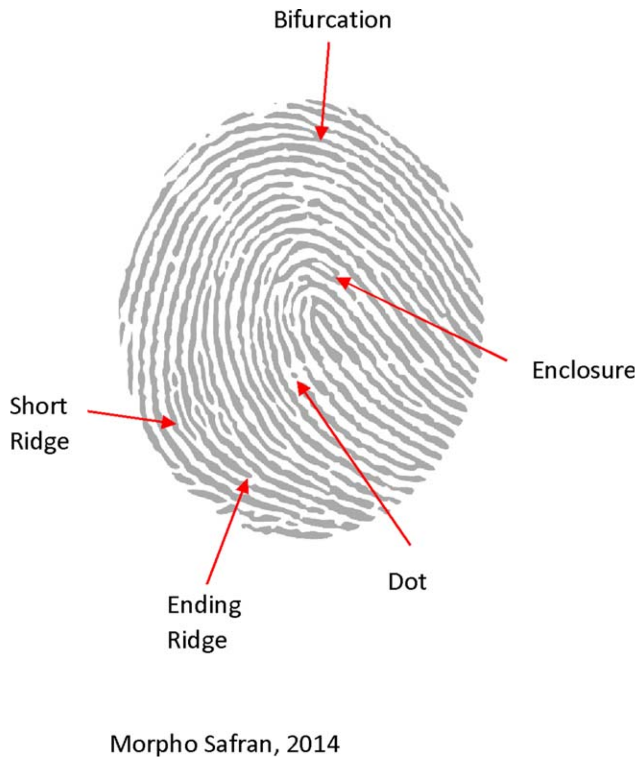

Fig. 2. Minutiae types. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

that fell within the quadrant being examined was counted, while the other end counted toward whichever quadrant it fell within. Because enclosures consist of two joining bifurcations, the enclosure was counted a single time for whichever quadrant held the majority of it if it covered more than one quadrant. Because the minutiae types were totaled for all quadrants, counting in this manner assured that all minutiae would be accounted for.

Statistical analysis. Descriptive summary statistics were calculated in Microsoft Excel ®. A multivariate analysis of covariance (MANCOVA) was performed to test whether sex, ancestry, and pattern type have significant effects on average minutiae variables (e.g., total bifurcations, total ending ridges, total short ridges, total dots, and total enclosures).

Because the primary interest is in the potential variation between biological groups, additional analyses were performed to test for relationships between minutiae and sex and ancestry. Logistic regression was used to determine whether any of these five minutiae variables can effectively predict the sex or ancestry of an individual who leaves a fingerprint, for instance, at a crime scene. Like discriminant function analysis, the basic purpose of logistic regression is the classification into groups using categorical dependent variables by measuring the predictive value that variables can have for those effects (Mertler and Vannatta, 2005). In addition, logistic regression has several advantages over discriminant function analysis in that it can be used to analyze continuous, discrete, and dichotomous variables, does not require assumptions to be made about the predictor variables, which do not have to be normally distributed, linearly related or have equal variances (Mertler and Vannatta, 2005). Expected to actual ancestry was examined via a contingency table. The true positives versus the false positives were examined using a Receiver Operator Characteristic or ROC curve. Specifically in this instance, the question is how accurately minutiae variables can predict the biological characteristics of a person rather than whether the biological characteristics affect the outcome of minutiae on a fingerprint. All multivariate statistical analyses were performed in JMP Pro 11.1.

RESULTS

Descriptive statistics of the pattern and minutiae types represented in the study sample are presented in Tables 2 and 3, respectively. Interestingly, the frequency of arches is higher in European males and females than in African males and females. Right loops have the highest frequency among all sexes and ancestry groups in this study, followed by whorls and left loops. Table 3 presents the comparative relative frequencies of each type of minutia. Ending ridges showed the highest frequency in all of the groups. In order from most to least common, the remaining minutia are bifurcations, short ridges, enclosures, and finally dots.

The MANCOVA results are presented in Table 4. The MANCOVA procedure detected no significant interactions (sex*ancestry, sex*pattern type, ancestry*pattern type nor sex*ancestry*pattern type). Sex does not have a significant influence on minutiae, while both ancestry and pattern types are significant. The one-way analysis of variance (ANOVA) results show that total bifurcations (TB) are the only variable significant for ancestry, while TB and TER (total ending ridges) were significant for pattern type (Table 5).

Logistic regression results suggest that the model is useful at predicting ancestry (ChiSq = 6.80, df = 1, *P* value = 0.009). The parameter and effect Wald test indicate total bifurcations are a significant predictor of ancestry (ChiSq = 6.80, df = 1, *P* value = 0.009). The odds ratio of 5.61 signifies that African Americans are nearly six times more likely to have bifurcations than European Americans. The lack of fit measure indicates the model is adequate, meaning there is no evidence of lack of fit (Prob > ChiSq = 0.297). Results show that the total bifurcations (TB) on a fingerprint can be used to predict the ancestry of an individual (ChiSq = 6.55, df = 1, Prob > ChiSq = 0.01). The contingency table (Table 6) shows that 20% (49) of individuals classified as African Americans are actually European American and 22% (54) classified as European American are African American. In total 103 of 243 individuals were misclassified for an estimated overall error rate of 42%. The area under the ROC curve is 0.59, which does not meet the standard of a good classification rule for a logistic regression of 0.90 or higher.

TABLE 2. Descriptive statistics: Pattern

	Pattern type	*n*	Frequency
African American Males	Arch	7	11.5%
	Left loop	5	8.2%
	Right loop	28	45.9%
	Whorl	21	34.4%
African American Females	Arch	4	6.5%
	Left loop	5	8.2%
	Right loop	34	55.7%
	Whorl	18	29.5%
European American Males	Arch	12	20%
	Left loop	7	11.7%
	Right loop	28	46.7%
	Whorl	13	21.7%
European American Females	Arch	16	26.2%
	Left loop	11	18%
	Right loop	23	37.7%
	Whorl	11	18%

DISCUSSION

The results of this study provide insights regarding the biological factors that influence fingerprint minutiae development, which has both biological and forensic implications. The finding of a higher frequency of arches in European American males and females differs from previous studies that have shown higher arch frequencies among African individuals. Africans range from 5 to 25%, while Europeans are typically between 6 and 9%. Both ranges exceed the 5% or lower frequency seen in the global population as a whole. Therefore, it was expected to find a frequency above 5% for both ancestry groups in the present study but European American individuals exhibited the highest frequency of arches (Cummins and Midlo, 1943). Of the minutiae, ending ridges exhibited the highest frequency, followed by bifurcations. This finding supports the relative minutiae frequencies suggested by previous studies (Gutierrez-Rodemero et al., 2010).

Sex was not found to have a significant influence on minutiae. This was somewhat unexpected given the

TABLE 3. Descriptive statistics: Minutiae types

		Total bifurcations	Total ending ridges	Total short ridges	Total dots	Total enclosures
European American males	Mean	21.6	51.267	10.733	1.550	1.767
	Standard deviation	1.174	2.440	0.862	0.209	0.220
	Frequency	24.9%	59.0%	12.3%	1.8%	2.0%
European American females	Mean	19.148	21.267	8.754	1.148	1.250
	Standard deviation	1.073	2.440	0.664	0.187	0.168
	Frequency	24.5%	61.2%	11.2%	1.5%	1.6%
African American males	Mean	23.05	48.672	9.820	1.918	1.787
	Standard deviation	1.278	1.60	0.897	0.259	0.178
	Frequency	27.0%	57.1%	11.5%	2.3%	2.1%
African American females	Mean	24.114	44.541	7.180	1.180	1.918
	Standard deviation	1.371	1.529	0.621	0.207	0.213
	Frequency	30.6%	56.4%	9.1%	1.5%	2.4%

TABLE 4. Multivariate analysis of covariance (MANCOVA) results for sex, ancestry and pattern type

	Wilks' lambda	F-ratio	d.f	$P > F$
Overall model	0.707	1.36	60876.61	0.04
Sex	0.021	1.61	4,224	0.329
Ancestry	0.053	2.98	4,224	0.02
Pattern type	0.874	2.57	12592.94	0.003
Sex*ancestry	0.021	1.16	4,224	0.33
Sex*pattern type	0.939	1.19	12592.94	0.28
Ancestry*pattern type	0.959	0.79	12592.94	0.66
Sex*ancestry*pattern type	0.975	0.47	12592.94	0.93

TABLE 5. Oneway analysis of variance (ANOVA) results for ancestry and pattern type

	d.f.	SS	MS	F-ratio	$Pr > F$
Ancestry					
TB	1	629.22	629.22	6.84	0.009
Pattern type					
TB	3	1122.2	374.07	4.13	0.007
TER	3	2265.22	755.07	3.72	0.01

TABLE 6. Contingency table of predicted to actual ancestry

Count total % expected Ancestry	Ancestry AA	EA	
AA	68	49	117
	22.98	*20.16*	48.15
	58.74	58.26	
EA	54	72	126
	22.22	29.63	51.85
	63.26	62.74	
Actual total	122	121	243
	20.21	49.79	

established influence that sex has on pattern type development (Dankmeijer, 1938). It was therefore hypothesized that this influence would still be present on minutiae, as their formation occurs during the period of ridge differentiation in utero. In addition, Gutierrez-Redomero et al. (2010) observed a significant influence of sex on minutiae using many of the same minutia types considered here. In keeping with our expectations, both ancestry and pattern types did have a significant influence on minutiae. The overall effect of pattern type on minutiae variation is not surprising given that the timing of volar pad regression dictates pattern type and also, to some extent, minutiae development. Although this finding supports what we know to be true about dermatoglyphic development, it would be interesting to conduct future research on a larger and more even sampling of pattern types to see if the significance level changes.

The influence of ancestry on minutiae development is of particular interest because it suggests that some level of population trends seen in Level 1 detail of fingerprint traits is upheld in Level 2 detail. From this, a genetic component to the formation of minutiae can be inferred. Although the degree of heritability of these traits cannot be assessed based on these results, they do provide promising evidence that this question should be further explored (Mulvihill and Smith, 1969; Babler, 1978; Ashbaugh, 1992).

Similarly, the role of intrauterine environment needs further examination. The uniqueness of fingerprints among individuals, particularly among monozygotic twins, supports the effect of the fetal experience in the womb (Martin et al., 1982). The results of this study indicate that bifurcations are the only minutiae that vary significantly in the total number seen on fingerprints of individuals of African American and European American ancestry. Bifurcations also varied significantly among the pattern types, as did ending ridges. Neither short ridges and dots, nor enclosures varied significantly, meaning these minutiae are not responsible for the variation observed between African American and European American individuals or among the arches, loops, and whorls. Interestingly, bifurcations and ending ridges are the most common minutiae (Gutierrez-Redomero et al., 2010). It has been suggested that, due to their prevalence, bifurcations and ending ridges are likely less indicative of population structure (Gutierrez-Rodemero et al., 2010). Per contra, the results of the present study show significant population variation in total bifurcations, underscoring the complexity of this system.

The logistic regression results suggest that bifurcations can be used to classify individuals into ancestry groups, a finding that could lend support to the use of statistical models based on the total number of bifurcations present to estimate biological information regarding the individual who leaves a latent fingerprint, in conjunction with point-by-point inspections in latent fingerprint comparison. However, because only one minutia type can be used to classify individuals with a low level of accuracy in this case, this particular model may not be accurate enough to correctly classify individuals based on their minutiae. The finding of a low level of accuracy of correct classification supports the idea of the uniqueness of individual fingerprints, which is driven by a complex biological system that is influenced by a wide variety of genetic and environmental factors. It is therefore essential to maintain the inclusion of biology in the process and explanation of fingerprint comparisons (Ashbaugh, 1992). Essentially, intergroup trends can be observed but intragroup variation remains high. Consequently, some would argue that no model is sufficient at predicting classificatory information about an individual fingerprint, meaning that the development of any model is not the way to minimize error rate associated with fingerprint comparisons. It is argued here that predictive models have potential as corroborative evidence to substantiate the decisions made by latent fingerprint examiners during fingerprint comparisons, especially if some of the more rare minutia types are discovered to vary among other populations, as these would be weighted more heavily in fingerprint comparisons.

This study suggests that ancestry influences the type and quantity of minutiae, just as it has been found to influence Level 1 detail such as pattern type and ridge count (Jantz, 1987). Sokal et al. (1996) found that finger patterns display spatial patterns like those found for blood markers and thus argue that dermatoglyphics reflect the factors responsible for structuring human genetic variation in Europe. The findings from the present study support the hypothesis that although developmental timing and womb environment also influence fingerprint minutiae, the genetically driven timing of volar pad regression creates population trends that are still acting on Level 2 detail. These results suggest a new direction for anthropological dermatoglyphic research, to explore population structure of an additional nonmetric trait that has now been shown to vary among two ancestral groups. Minutiae variation could be studied in individuals of other populations in the future. The results also reinforce the complexity of the biological system responsible for fingerprint development and the necessity for latent fingerprint examiners to have a strong understanding of that system. It is argued in the NAS (2009) report that gaining such an understanding will bolster the science of fingerprints and with that the validity of their use in forensic investigations. The results of this study showcase the role that biology plays in dermatoglyphics and support exploring these biological factors in order to increase our understanding behind the uniqueness of fingerprints and minimize the error rate involved with making identifications. Future directions might include whether the minutiae that form are significantly impacted by the location on the fingerprint. For example, a certain type of minutia might occur more frequently near the delta region of the fingerprint. This additional information would enhance knowledge regarding minutiae variation and add to the effort of lowering the error rate associated with fingerprint identification. In the future, all dermatoglyphic research would benefit from cross-field collaborations, which provide a more complete perspective on the relevant questions to be explored.

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