ABSTRACT

FOURNIER, NICHOLE ALLYSE. Minutiae Variation Between Sexes, Ancestries, and Pattern Types: A Study to Strengthen and Validate the Science of Fingerprints. (Under the direction of Dr. Ann H. Ross, Dr. D. Troy Case, Dr. David Hinks, and Andy Parker.)

Dermatoglyphics have been studied extensively in physical anthropology to examine the inter-population variation of friction ridge traits. The majority of the previous studies have tested these relationships on Level 1 Detail (e.g. pattern type, total ridge count). Therefore, the results are largely irrelevant to the field of forensic science, where identifications are made based on Level 2 and 3 Detail (e.g. minutiae and pores, respectively). The present study applies methodologies developed in physical anthropology for quantifying Level 1 fingerprint traits to Level 2 Detail and tests whether population, sex, and/or pattern type has a significant effect at the level of minutiae. Five types of minutiae were analyzed and include bifurcations, ending ridges, short ridges, dots, and enclosures, as well as a variable for the sum total of all minutiae. Each type of minutia was visually counted on the right index finger of 115 individuals (29 African American females; 29 African American males; 29 European American females; 28 European American males). A multiple analysis of variance (MANOVA) was used to analyze the overall effect of sex, pattern type, and population on the minutiae variables. Results of the MANOVA show that only population significantly affects minutiae (p-value=0.019). Additional testing was explored using contrast statements in the MANOVA model to identify which of the minutiae variables are being influenced by the main effect of population. Logistic regression results show that the minutiae found to be significantly influenced by population cannot be used to predict
population. The results of this study show that fingerprint development is driven by a complex biological system that is influenced by a wide variety of factors. This finding partially explains fingerprint uniqueness and emphasizes the importance of including biology in the process and explanation of fingerprint comparisons.
Minutiae Variation Between Sexes, Ancestries, and Pattern Types: A Study to Strengthen and Validate the Science of Fingerprints

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DEDICATION

I dedicate this thesis to my 5th grade teacher, Mrs. Hoffmann, who first inspired me to love learning and sparked my interest in anthropology, and to Mr. Moore for always insisting I am capable of more than I think I am. This is the product of the support of a long list of people, including my parents, John and Francesca, my sister, Elaina, Uncle Paul, and Auntie Jean. Mom and dad, you supported me in every way while I was away from home and I am eternally grateful for that. Elaina, you gave me laughter and iTunes when I needed it most. Auntie and Uncle, your letters/emails were incredibly encouraging and made me feel not so far away. I thank you all and love you to infinity.
BIOGRAPHY

Nichole has been interested in studying culture and evolution since 5th grade, but it was not until high school that she realized she could combine these interests by studying anthropology. She entered college at Boston University as a biology major but chose BU partially because the school allowed for the possibility of majoring in biological anthropology, which she strongly believed she would end up doing. During the spring semester of freshman year, she took her first anthropology course and promptly changed her major. Since then she has taken every opportunity to learn more about the field and in doing so, realized that she wanted to pursue forensic anthropology as a career.

This decision led her to attend a forensic anthropology field school in Albania, which provided her with the priceless opportunity to reassemble highly fragmented human remains and analyze the bones to construct a biological profile. The hands-on experience provided by the field school, as well as the helpful mentor relationship with the directors of the school confirmed that forensic anthropology was the right choice for her.

Due in part to the encouragement of Dr. Crist, her field school mentor, Nichole decided to attend North Carolina State University to continue studying anthropology for a Master’s degree and focus on forensic anthropology. This choice has led to a tremendous amount of opportunities for her and has transformed her academic interests in ways she never could have anticipated. Though she may not have always realized it, she has been on this path since 5th grade and has been extraordinarily lucky to have encountered such wise and generous guides along the way.
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# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................... vii

LIST OF FIGURES .......................................................................................................... viii

INTRODUCTION ........................................................................................................... 1

REVIEW OF THE LITERATURE .................................................................................... 6
  Dermatoglyphics Development ............................................................................. 6
  Skin Structure ......................................................................................................... 6
  Friction Ridge Development ................................................................................. 7
  Genetics of Fingerprint Development .................................................................. 10
  Intrauterine Environmental Effects ...................................................................... 11
  Fingerprint Traits .................................................................................................... 12
  Level 1 Detail .......................................................................................................... 12
  Level 2 Detail .......................................................................................................... 14
  Level 3 Detail .......................................................................................................... 16
  Usefulness of Fingerprint Traits to Anthropology and Forensics ...................... 17
    Anthropological Dermatoglyphics .................................................................... 19
    Forensic Use ......................................................................................................... 21
    Challenges ........................................................................................................... 25
    National Academy of Sciences Report ............................................................... 25

MATERIALS AND METHODS .................................................................................... 27
  Materials .................................................................................................................. 27
  Fingerprint Servers ............................................................................................... 27
  Study Sample .......................................................................................................... 29
  Methods .................................................................................................................... 30
    Sample Selection .................................................................................................. 30
    Minutiae Selection ............................................................................................... 31
    Minutiae Quantification ...................................................................................... 31
    Statistical Analysis .............................................................................................. 33

RESULTS ..................................................................................................................... 35
  Summary and Descriptive Statistics for the Sample .......................................... 35
  Sex, Population, and Pattern Type Variation Analysis ........................................ 38
    Population .......................................................................................................... 41
    Pattern Type ........................................................................................................ 43
  Summary of Results ............................................................................................... 44
### LIST OF TABLES

Table 3.1. Description of Sample ................................................................. 29

Table 3.2. Dependent and Independent Variables Selected for this Study .......... 29

Table 4.1. Sample Summary: Frequencies of Pattern ...................................... 35

Table 4.2. Sample Summary: Frequencies of Minutiae .................................. 36

Table 4.3. Summary Statistics for African American Males ............................ 37

Table 4.4. Summary Statistics for African American Females .......................... 37

Table 4.5. Summary Statistics for European American Males ........................ 37

Table 4.6. Summary Statistics for European American Females .................... 38

Table 4.7. MANOVA for the Hypothesis of No Overall Effect of population*sex*pattern .......................................................... 39

Table 4.8. MANOVA for the Hypothesis of No Overall Effect of sex*pattern .... 39

Table 4.9. MANOVA for the Hypothesis of No Overall Effect of sex*population .. 39

Table 4.10. MANOVA for the Hypothesis of No Overall Effect of population*pattern .......................................................... 39

Table 4.11. MANOVA for the Hypothesis of No Overall Effect of Sex ............. 40

Table 4.12. MANOVA for the Hypothesis of No Overall Effect of Population ...... 40

Table 4.13. MANOVA for the Hypothesis of No Overall Effect of Pattern .......... 40

Table 4.14. MANOVA for the Hypothesis of No Overall Effect of Population ...... 41

Table 4.15. Canonical Axis For Population ...................................................... 42

Table 4.16. Total Canonical Structure For Population ...................................... 42

Table 4.17. MANOVA for the Hypothesis of No Overall Effect of Pattern .......... 43

Table 4.18. Canonical Axes For Pattern ......................................................... 44
LIST OF FIGURES

Figure 2.1. Diagram of the anatomy of skin .......................................................... 7

Figure 2.2. Images illustrating the three main pattern types ............................... 13

Figure 2.3. Image showing the subdivisions of the three main pattern types .......... 14

Figure 2.4. Chart illustrating the five types of minutiae used in this study .......... 16

Figure 2.5. Image illustrating the features of Level 3 Detail ............................... 17
INTRODUCTION

Dermatoglyphics refers both to the patterns of ridges on friction skin, as well as to the scientific study of skin patterns (Merriam-Webster, 2013). Friction skin is found on the palms and fingers of the hands and the soles and toes of the feet and is aptly named because its ridges help to prevent slipping on surfaces (Cummins, 2000). Dermatoglyphics have been studied extensively by anthropologists, forensic scientists, and geneticists (Leguebe, 1982). The interest in dermatoglyphics spans many disciplines due to their relation to genetics. The heritability of dermatoglyphic traits is what draws the attention of anthropologists and geneticists in particular (Holt, 1951; Holt, 1954; Rothhammer et al., 1977; Froehlich and Giles, 1981; Martin et al., 1982; Loesch et al., 1982; Jantz and Chopra, 1983; Houle, 1991; Reddy et al., 2000). The forensic interest in dermatoglyphics is drawn by the permanence and uniqueness of fingerprints (Galton, 1892; Cummins, 1967; Ashbaugh, 1992; Champod, 1995; Cole, 1999; Cummins, 2000; Zhao and Tang, 2006; Huckerman et al., 2008).

These two ideas seem contradictory; after all, heritability suggests that related people will have similar fingerprint phenotypes because they share genotypes; this suggestion has been shown to be accurate (Dankmeijer, 1938; Qazi et al., 1977; Jantz, 1987; Froehlich and Giles, 1981; Ashbaugh, 1992; Reddy et al., 2000). However, this does not diminish the uniqueness and individuality of fingerprint traits. There are two key reasons for this. The first is that the anthropologists who study heritable trends within and between populations and the forensic scientists who study uniqueness at the individual level are doing so using different variables. Anthropologists use Level 1 Detail such as pattern type (arches, loops, and whorls) and ridge counts (total ridge count, radial/ulnar counts) to study population structure of
dermatoglyphics (Dankmeijer, 1938; Rothhammer et al., 1973; Grace, 1974; Jantz and Chopra, 1983), while forensic science practitioners and researchers study Level 2 and 3 Detail for fingerprint comparisons. Level 1 Detail refers to ridge flow and this level is useful for classifying fingerprints but is not specific enough to be used for positive identifications (Ashbaugh, 1992; Langenburg, 2004). Level 2 and 3 characteristics are the variables focused on in the present study and are discussed further below. The second key reason why heritability of fingerprint traits does not diminish their ability to individualize is that the traits that are genetically controlled are also susceptible to intrauterine environmental influence (Babler, 1978; Ashbaugh, 1992). This is true for Level 1 Detail, but again, there are not enough potential outcomes to make pattern type or ridge count a unique trait so the environmental effect is not as operative. In contrast, there are more possible forms for the environmental influences to take with regards to minutiae.

More specific information that constitutes the microscopic structure of the print is found within the first level of detail. As previously mentioned, latent fingerprint examiners analyze Level 2 and 3 Detail when making comparisons. Level 2 characteristics are called Galton Details, or minutiae, and are the traits that make up the ridge path (Langenburg, 2004). The three basic paths that ridges can take are to bifurcate, to end, or to end very abruptly and punctuated, hence the minutiae are referred to as bifurcations, ending ridges, and dots. Several other types have been defined as variations of the three (FBI Law Enforcement Bulletin, 1972). Other minutiae frequently identified in the literature include short ridges and enclosures (Cummins, 1967). Regardless of how many minutiae are defined, it is the count and distribution of the minutiae within the friction ridges that is unique to each
individual. Though Level 2 Detail is under the same genetic and environmental influences as Level 1, and is to some degree influenced also by pattern type, the sheer number of possibilities of count, position, and directionality within the fingerprint is what makes these characteristics unique. Level 3 Detail is also sometimes used by fingerprint examiners during forensic investigations. This level of detail is thought of as the individual ridge structure (ridge shapes and pores) and is also unique to each fingerprint (Langenburg, 2004).

Anthropologists and forensic scientists are currently studying diverse research questions by looking at different fingerprint characteristics. 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. In this way, it will be possible to speak to the heritability and individuality of Level 2 Detail and identify the biological factors, such as sex, pattern type, and ancestry that influence the appearance of fingerprints.

The paucity of incorporation of the scientific theory behind the uniqueness and permanence of fingerprints into comparisons is one of the concerns put forth by the National Academy of Science (NAS) in their 2009 Report. The NAS stated there is an immediate need to incorporate biology into the explanation and reporting of latent fingerprint identifications and to take a statistical approach to minimizing error rate associated with fingerprint identification decisions (NAS, 2009). In order to reach this point, steps must be taken to quantify the difference between individuals (Stoney et al., 1987). In other words, it is necessary to measure how much people vary from each other and which factors influence
variation before it will be possible to reduce the error rate associated with the visual act of fingerprint comparison.

It has become common for researchers to incorporate biology and statistics by quantifying the variability of friction ridge characteristics used in the process of making comparisons, such as minutiae (Gutiérrez-Rodemero et al., 2010). Determining how variable minutiae counts and distribution are from person to person can only be partially achieved by quantifying minutiae on a sample of individuals taken as representative of the entire population. Exploring the same questions within and between groups of people who are related genetically is a critical area of study. For this reason, twin studies have long been of interest, as have studies comparing populations with the same ancestry, as a means for exploring how even genetically similar people show marked differences in their fingerprints (Dankmeijer, 1938; Babler, 1977; Qazi et al., 1977; Froehlich and Giles, 1981; Martin et al., 1982; Jantz and Chopra, 1983; Reddy et al., 2000). Many of the studies of this nature have been conducted by anthropologists. The development of friction ridge patterns can be thought of as heritable nonmetric traits that are used in much the same way that metric traits of the skull are used by anthropologists- to measure differentiation within and between groups (Dankmeijer, 1938).

As previously stated, studies that have combined the techniques used by physical anthropologists with the level of detail used by forensic scientists are rare, and based on the statements made by NAS (2009), are necessary to further the understanding of fingerprint science and its reliability as a forensic tool. The purpose of the present study is to quantify minutiae on individuals, both male and female, of two different ancestry populations in order
to study the relationship between minutiae and sex, ancestry, and pattern type. The reason for studying this relationship is to identify which factors are significantly influencing the type and number of minutiae present on a fingerprint and therefore, which factors need to be taken into consideration for standardizing fingerprint comparison and minimizing error rate.

Maintaining a working knowledge of the factors that influence the appearance of a fingerprint, such as the results from the present study, would be an excellent tool in the arsenal for any fingerprint examiner who will then have the ability to reference the biological processes that created the uniqueness in each fingerprint, in addition to relaying their expert opinion on a visual assessment. In doing so, they will be able to apply the scientific conclusions based on the biological system that is responsible for fingerprints as part of their scientific methodology to each individual case.
REVIEW OF THE LITERATURE

1. Dermatoglyphics Development

Skin Structure

Skin is made up of two main layers, the epidermis and the dermis. The epidermis is the outer layer and the location of the friction ridges, furrows, and pores. This layer is comprised of three thinner layers. The innermost layer, stratum germinativum, generates new cells that are pushed up to the surface (Ashbaugh, 1991). This basal layer contains the primary ridges that correspond to the friction ridges seen on the surface of the epidermis. The furrows on the surface of friction skin also extend from the basal layer and are the secondary ridges of the fingerprint (Wertheim and Maceo, 2002). The next layer, stratum spinosum, is involved in immune defense. The durability of skin is achieved from the strata granulosum, lucidum, and corneum (SEER, 2012). The dermis lies beneath the epidermis and contains blood vessels, nerves, and sweat glands that travel up through the epidermis and exit through the pores (Ashbaugh, 1991).
Friction Ridge Development

The process of ridge development is integral to the understanding of fingerprints and their purpose in forensic and anthropological investigations. The first step to the development of fingerprints is the appearance of the volar pads during the 6th-7th week of gestation (Mulvihill and Smith, 1969; Borecki et al., 1985). These pads are made up of mesenchymal tissue and are similar to the raised pads seen in dogs and several other animals. In humans, however, they eventually regress in utero following the initiation of primary ridges (Mulvihill and Smith, 1969; Cummins, 2000). Development of epidermal ridges is first seen in the 10th-11th week of gestation and is marked by cell proliferations in the basal layer of the
epidermis (Mulvihill and Smith, 1969; Babler, 1978). These proliferations form the primary ridges, which extend into the dermis and increase in number as new ridges, secondary ridges, form between them and on the periphery of the pattern (Hale, 1952). The configurations of the fingerprint enlarge as the hands and feet grow, but the characteristics of the print remain unchanged once the dermal ridges become fully differentiated at about the 17th week of fetal development (Hale, 1952; Babler, 1978; Borecki et al., 1985). This permanence of fingerprints is one of the characteristics that makes them so useful to anthropology and forensic science, an idea further discussed below.

A popular hypothesis for ridge development, called the ontogenetic hypothesis, argues 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). As previously stated, the volar pads regress during the period of ridge differentiation but it is their shape during differentiation that determines which pattern type is formed (Mulvihill and Smith, 1969; Babler, 1977; Jantz and Chopra, 1983; Ashbaugh, 1992). What is meant by shape is the height and symmetry of the volar pads. 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, results in arches. Likewise, later regression, or high pads, produces 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 other component of the shape of fingerprints is the symmetry of stress across the surface of the finger. For instance, if the volar pad and other elements of finger growth are symmetrical during the period of primary ridge formation, then
a whorl or arch will form. These are the symmetrical pattern types. Loops, however, are asymmetrical and result from asymmetrical growth factors during primary ridge formation. The degree of symmetry in the growth factors of the volar pad corresponds directly to the symmetry of the pattern (Wertheim and Maceo, 2002). It has been shown that the variety in construction of pattern types is a reflection of the variations in the form and duration of volar pads (Jantz and Chopra, 1983; Cummins, 2000).

Evidence for the ontogenetic hypothesis includes reoccurring interpretations from the literature (Bonnevie, 1924; Wilder, 1930; Gall et al., 1966), results of primate studies (Cummins, 1933, Mulvihill and Smith, 1969), theoretical mathematical reasoning (Wilder, 1904; Mulvihill and Smith, 1969), embryologic studies (Mulvihill and Smith, 1969), and observations of fingerprints in malformed hands (Cummins, 1926; Penrose, 1965; Mulvihill and Smith, 1969). Dermatoglyphic traits ought to be viewed as the products of the developmental processes of the fetus as a whole (Babler, 1978).

Fingerprints are not solely found in humans. They are also present with similar complexity on other apes and monkeys, as well as marsupials (Cummins, 2000). The fingerprint structure in each of these animals is identical to the types found within humans. A specialization as definite in structure and widespread among species is assumed to have a functional value. The first of these functions is to provide security of grasp and firmness in contact during locomotion and suspension. The purpose is similar to milling on the hilt of a tool (Whipple, 1904; Cummins, 2000). They are reminiscent of walking pads seen on many animals (Whipple, 1904). The second is to enhance tactile sensibility (Cummins, 2000).
Genetics of Fingerprint Development

Fingerprint characteristics are inherited, though it is the form of the hand mechanism and timing of development involving the volar pads described by the ontogenetic hypothesis that is heritable rather than the pattern itself. Therefore, the inheritance is indirect (Wertheim and Maceo, 2002). The size of the volar pads can be inherited in much the same way as the size of other anatomical features (Mulvihill and Smith, 1969). According to Cummins (2000), 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 controlled by multiple genes. This polygenetic inheritance, as well as the fact that intrauterine environmental factors can influence the predestined size and shape of the volar pads, contributes to the individuality of fingerprints that make them useful in forensics. The polygenetic inheritance means that fingerprint traits are more stable, meaning they are less susceptible to stochastic processes such as genetic drift (Froehlich and Giles, 1981). The hypothesis that polygenetic traits show reduced susceptibility to the effects of genetic drift was proposed by Birdsell (1950) who observed that genetically complex traits are likely preferable for tracing population relationships, despite polygenic traits being more difficult to genetically define (Froehlich and Giles, 1981). A few different explanations have been offered for the lower susceptibility of polygenic traits to drift. One such explanation is that because gene changes resulting from drift are random by definition, they are likely to cancel each other out in a trait that is controlled by several loci (Froehlich and Giles, 1981). Another explanation says that the stability of fingerprints is due to the number of genes involved and the proportionately low probability of altering all of them in a single direction (McHenry and Giles, 1971). However,
it must be remembered that fingerprint characteristics are indirectly inherited, and therefore are still vulnerable to environmental influences despite the polygenic inheritance (Wertheim and Maceo, 2002).

_Intrauterine Environmental Effects_

As previously mentioned, the intrauterine environment also has an effect on the resulting fingerprint pattern. The period of fetal development in which ridges grow and form is also the time when the fetus is most susceptible to growth disturbances from various environmental factors and genetic actions such as cell differentiation and growth rate control (Babler, 1978). As such, though the size of the volar pads is predetermined genetically, intrauterine stresses during the period of formation may alter their potential size and shape and thus alter their predetermined pattern configuration (Ashbaugh, 1992). One way that researchers have explored this idea is to study the fingerprints of elective and spontaneously aborted fetuses. Results of these studies show statistically significant differences between them (Babler, 1978). The electively aborted fetuses exhibit arch frequencies similar to the living population, while the spontaneously aborted group is elevated, suggesting a developmental alteration that is not well-suited for survival (Babler, 1978; Jantz, 1987). A possibility commonly suggested in the literature is the timing of development, which could be driven by environmental influences within the womb (Babler, 1978). As previously mentioned, arches are associated with late ridge differentiation relative to volar pad regression and the opposite is true with whorls (Babler, 1978; Wertheim and Maceo, 2002). However, it is unknown whether the high frequency of arches that results from changes in
developmental timing is due to early pad regression or late ridge differentiation (Babler, 1978). Another source of alteration to predetermined pattern type is deviation in the normal developmental symmetry of the volar pad as a result of the numerous genetic or environmental factors at work during the critical stage of primary ridge development (Wertheim and Maceo, 2002).

II. Fingerprint Traits

Level 1 Detail

Level 1 Detail refers to how ridges flow to form the pattern type (Langenburg, 2004). It is the macroscopic view of the fingerprint that provides the initial and least specific piece of information about the surface of friction skin. Pattern type is the basis for fingerprint classification systems. In 1823, Purkinje was the first to systematically classify pattern types and several classification systems have since been created (Babler, 1978; Ashbaugh, 1992). The Henry System, created in 1899, is most widely used to classify fingerprints in forensic science. As described by the Scientific Working Group on Friction Ridge Analysis, Study and Technology (SWGFAST, 2011), the Henry System is divided into three basic pattern types (Figure 2.2). These basic patterns are then subdivided into eight patterns. Arches can be either plain or tented, where tented arches have a central upthrust or a clear angle. Loops are either radial or ulnar, depending on the direction of the flow of the ridges in relation to the radius and ulna of the forearm. The whorl type has the most number of subdivisions: plain, central pocket loop, double loop, and accidental (Nickell and Fischer, 1999; SWGFAST, 2011). The subdivisions provide additional information with which to classify fingerprints.
that aids in sorting and searching databases. In the literature, discussions on pattern type can refer to either the three main pattern types or the subdivisions of those main patterns.

Figure 2.2. Images illustrating the three main pattern types (Minkin, 2008)
**Level 2 Detail**

Level 2 Detail is described as the ridge path. In other words, Level 2 Detail refers to the shape, direction, and orientation of the traits that constitute the ridges (Langenburg, 2004). These are referred to as minutiae or Galton Details, after Sir Francis Galton who is a founding father of fingerprint science (Nickell and Fischer, 1999). Level 2 Detail marks the microscopic level of fingerprint traits and where uniqueness can first be measured. Minutiae are unique in their number and distribution in each individual fingerprint (Cummins, 1967). Therefore, Level 2 Detail is the lowest level that is usable for comparisons (Cole, 1999;
Huckerman et al., 2008; Bennet and Perumal, 2011). Minutiae are characterized by type, orientation, and position relative to any neighboring minutiae. Type, the character used to distinguish minutiae in the present study, refers to the form of the minutia. There are three fundamental types of minutiae (bifurcation, ending ridge, and dot) and other forms are recognized as variations of these and/or when the fundamental types are close together, as is the case with enclosures (Stoney et al., 1987). Several other varieties have been defined, including, for example, the short ridge. A bifurcation is defined as the point at which a friction ridge divides into two friction ridges. Similarly, an enclosure is a single friction ridge that bifurcates and then rejoins to continue as a single ridge. A ridge is termed an ending ridge when it terminates within the structure of the friction ridge. When an ending ridge travels only a short distance before it ends, it is then classified as a short ridge. Finally, a dot is defined as a friction ridge that is as long as it is wide in size (SWGFAST, 2011). The types are shown in Figure 2.4.
Figure 2.4. Chart illustrating the five types of minutiae used in this study. Adapted from ZKO ECO 2011.

**Level 3 Detail**

Level 3 Detail is the individual ridge structure, e.g. ridge shapes and sweat pores (Langenburg, 2004). In other words, Level 3 Detail refers to the dimensional attributes of friction ridges (SWGFAST, 2011). This is the most intricate detail of a fingerprint and is used in conjunction with Level 2 to make comparisons. Ridges must be magnified to observe level 3 Detail. Figure 2.5 shows a close-up of a portion of friction skin, demonstrating sweat pores and ridge width and shape.
III. Usefulness of Fingerprint Traits To Anthropology and Forensics

Scientists began recognizing the characteristics of fingerprints that make them ideal for human identification in the 19th Century. These characteristics include the minimal variations in pattern form allowing for classification systems, their permanence throughout life, and uniqueness of select fingerprint traits. The most widely used classification system is the Henry System (see Level 1 Detail), though it is not the only one still in use. The topological classification system of Penrose and Loesch (1969, 1970) was specifically designed to aid genetic studies of dermatoglyphic traits and is therefore frequently used in comparisons of populations (Jantz and Chopra, 1983).

The second characteristic, fingerprint permanence throughout life, was first asserted by Herman Welcker in 1856 when he demonstrated on his own prints that they remain unchanged over a period of time (Nickell and Fischer, 1999). Since then, permanence has been asserted by many scientists and practitioners (Babler, 1978; Laguebe, 1982; Wertheim,
To truly understand the permanence of fingerprints, one must have a grasp of the subsurface structure of human friction skin, as described above, and the features of the structure that make fingerprints insusceptible to aging (Wertheim, 2000). Wertheim and Maceo (2002) describe these features in detail. In their review, they state that the principle of permanence is based upon attachment of the various layers of skin to each other. Cells of the epidermis are joined to each other; the basal layer of the epidermis is attached to the basement membrane (the epidermal-dermal junction), which is then attached to the dermis. As a result of the attachment between the layers, the unique positional properties of the basement membrane are continually transferred up through the layers to the outer layer throughout life (Wertheim and Maceo, 2002).

Another of the fingerprint characteristics that makes them useful for forensic science is the uniqueness of some of the traits, i.e. minutiae and pores. Uniqueness has its foundation in the fetal development of friction skin (Wertheim, 2000). Specifically, the formation of minutiae as the surface continues to become ridged is responsible for uniqueness because the formation and placement of any particular minutia within the developing ridge field is controlled by a random collection of interdependent stresses and tensions across an area of skin at any given moment. Mechanical stress, physiological environment, and variation in the timing of development could, at any point prior to secondary ridge formation, affect minutiae placement (Babler, 1978; Wertheim and Maceo, 2002). Wertheim and Maceo (2002) use the hypothetical situation of a dump truck filled with sticks being scattered along the same piece of road with each stick landing in exactly the same position twice as an analogy for the
duplication of the entire process of biological formation on two pieces of skin, making them indistinguishable.

The characteristics of fingerprints that make them so suitable to study in anthropology and forensic science are strongly rooted in science and require study of human biology in order to fully appreciate their effectiveness in these types of applications (Wertheim, 2000). This much is clear from the discussion on fingerprint development. The following sections discuss how fingerprints are used in these two particular fields.

*Anthropological Dermatoglyphics*

The use of fingerprints to examine similarities and differences within and between groups of people rather than individuals is the focus of anthropological study of dermatoglyphics. Dermatoglyphics are defined as configurations, or specific groups of epidermal ridges, on palms, fingers, soles, and toes that are not used for identification purposes (Mulvihill and Smith, 1969). Classification systems described above facilitate genetic studies of dermatoglyphics and therefore are the focus of anthropologists because the interest is in describing genetically relevant differences between populations (Rothhammer et al., 1973; Grace, 1974; Jantz and Chopra, 1983). Such relevant differences include variation in the frequency of each pattern type. Comparisons of this kind are broken down further by examining differences between sexes (Dankmeijer, 1938). For example, Dankmeijer (1938) compared the frequency of arches, loops, and whorls in populations from each of the major geographical regions of the world and found statistically significant differences between populations and sexes. Another relevant difference between populations that is studied is in
timing and intensity of ridge maturity (Babler, 1977). Quantitative studies of variation focus on either the counts of ridges (total ridge count, ulnar ridge counts, radial ridge counts) (Holt, 1968; Mendenhall et al., 1989) or minutiae (Gutiérrez-Redomero et al., 2010).

Researchers often compare dermatoglyphic variation to other measures of population structure, including blood groups and/or genetic markers (Froehlich and Giles, 1981; Sokal et al., 1996; Reddy et al., 2000). The majority of results show that dermatoglyphic traits have more temporal stability, a slower velocity of evolutionary change and are less susceptible to such forces as genetic drift due to their polygenetic inheritance (Froehlich and Giles, 1981; Houle, 1991). Froehlich and Giles (1981) found that fingerprint variation conforms closely to language affiliations of groups, remaining relatively undisturbed by environmental variation and genetic drift. They conclude, therefore, that fingerprints maintain underlying structural differences related to population origins separated by time and space (Froehlich and Giles, 1981). Several examples have been cited in the literature supporting these claims. For example, in support of the assertion that fingerprints are less affected by genetic drift and periods of genetic isolation, Plato found that an isolated mountain population on the island of Cyprus was similar to a coastal group from the same island on the basis of dermatoglyphics, but the same groups of people differed significantly from each other based on serological parameters (Plato, 1970; Froehlich and Giles, 1981). The example cited as the most striking evidence of temporal stability in fingerprint traits is the extremely close resemblance between varying Jewish populations after 2,000 years of separation (Sachs and Bat-Miriam, 1957; Froehlich and Giles, 1981).
Methodology varies between studies. As has already been shown, some researchers use pattern type frequencies as a measure of interpopulation variation (Dankmeijer, 1938) while some use ridge count. Variable selection is not the only place where research differs. There is also the question of whether to use all ten fingers in the study or to choose only one. Selecting all ten fingers as the study material necessitates a solution for overcoming the variation in finger size that will introduce bias for comparing quantitative variables such as ridge count and minutiae count (Gutiérrez-Redomero et al., 2010). One possible solution is to apply a circle of a standardized size to each finger, thereby creating an equally sized area within which to count minutiae regardless of finger size (Gutiérrez-Redomero et al., 2010). A similar method has been adopted by histologists (Kerley and Ubelaker, 1978). If, however, a single finger is the subject chosen for a study the decision must be made as to which finger to use when it has been shown that digits differ in pattern frequencies and counts (Jantz, 1987; Gutiérrez-Redomero et al., 2010). Typically, either the thumb or index finger from the right hand is used because these are the fingers that most commonly leave latent fingerprints.

Forensic Use

Fingerprint identification is one of many biometric approaches used by forensic investigators. Biometrics refers to accurately identifying an individual based on his or her distinctive physiological (fingerprints, face, retina) or behavioral (gait, signature) characteristics. Of all biometrics, fingerprints are one of the most reliable personal identification methods (Zhao and Xiaou, 2006).
Use of fingerprints for identification began with two men, William Herschel and Henry Faulds. In 1858, Herschel used them in place of signatures for labor contracts and to prevent pension fraud in the British colonies (Cole 1999). Henry Faulds first noticed fingerprints in Japanese pottery in the 1820s and in 1880 he sent a letter to the scientific journal *Nature* suggesting the idea of using fingerprints for scientific endeavors. It was Faulds who suggested that impressions might lead to the scientific identification of criminals and asked all of the scientific questions about fingerprint patterns that are still at the core of the scientific methodology today (Cole, 1999). For instance, he took fingerprints from a Gibraltar monkey to see whether other primate species had the same patterns as humans. He also compared the fingerprint patterns of different populations, the English and Japanese, and suggested the possibility of using fingerprints to determine heredity (Cole, 1999). Faulds wrote a letter to Charles Darwin in 1879 describing fingerprint patterns, which Darwin then forwarded to Francis Galton who, as a result, became interested in fingerprints and published a book in 1892 entitled *Finger Prints*. This book gives an account of fingerprint development and proposes a statistical model for a “point” threshold for identification using his Galton Details, or minutiae (Cole, 1999).

Galton’s model was the first of many attempts at creating a model to find a reliable and scientifically based “point” threshold for identification. This simplistic model divided a print into a grid of 35 squares and calculated probabilities for the presence or absence of minutiae points in each grid area. Galton concluded that the odds of two people sharing points in the same squares when all 35 squares are included is $1 \text{ in } 2^{47}$ (Wertheim, 2000). This model did not account for the direction of ridge flow, the shapes of ridges, the presence
of prominent sweat pores, scars, creases, or incipient ridges. Edmond Locard first developed
a set of rules for establishing a minimum number of minutiae necessary for identification.
His tripartite rule (1914) 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, the presence of the
core and delta in the usable portion of the print, and the presence of pores 3) if a limited
number of concurring points are available, the fingerprint cannot provide certainty for an
identification, but only presumption proportional to the number of concurring points
available and their clarity (Champod, 1995). There has yet to be a consensus for a single
successful model and some believe that a model for “point” threshold is not appropriate at all
(Gutiérrez-Redomero et al., 2010). For example, Finland uses 12 minutiae as the minimum
number needed, whereas Sweden uses 7 and Italy 16-17. The United States used Locard’s
standard of 8-12 until 1973, when the International Association of Identification (IAI) made
the decision that identification cannot be reduced to counting minutiae because each
comparison represents a unique situation (Champod, 1995). To do so is thought to be
unscientific. This decision was upheld in the Ne’urim Declaration following a conference of
latent fingerprint examiners from 21 countries in Ne’urim, Israel in 1995 (Cole, 1999).

Other researchers wish to create a model illustrating how to weight different elements
of fingerprints, such as minutiae, and the area of the print in which they are found
(Wertheim, 2000). Gutiérrez-Redomero and colleagues report that the greatest number of
minutiae is concentrated around the core and delta portion of a fingerprint (Gutiérrez-
Redomero et al., 2010). With regard to how to weight minutiae as evidence, they determined
the frequency with which each type occurs. Their findings show that ridge endings occur with frequencies ranging from 55-65%, bifurcations 13-18%, while others including dots, bridges, and trifurcations all occurred at a frequency of less than 3%. The percentage within the range depended upon the area of the print and the sex of the individual (Gutiérrez-Redomero et al., 2010).

One of the major proponents of the scientifically based method of ridgeology, e.g. the umbrella term that encompasses every science and concept that is related to the application of fingerprint identification that resulted from Faulds’ critique of the point estimate of minutiae, is David Ashbaugh (Cole, 1999). He argues that the individuals who built the foundations of fingerprint identification sought a model for a point-based approach because at the time they lacked the biological and statistical knowledge needed to prove the idea that nature never precisely duplicates itself. They therefore devised point counting methods and associated probabilities as a buffer against their uncertainty that fingerprints are not exactly duplicated (Cole, 1999). However, the later research into morphology lends support for the uniqueness of friction ridge traits and the idea that they are not duplicated can now be scientifically demonstrated (Cole, 1999; NAS, 2009). This new application of morphological literature is needed to improve the ability to explain the process of making a comparison and presenting it in court as certainty, not to change the comparison methods themselves. Ashbaugh and others (Cole, 1999; Wertheim, 2000), believe that the correct methods for that are in place already.

The method for fingerprint comparison is referred to as ACE-V (analysis, comparison, evaluation, and verification) (Langenburg, 2004). At the analysis stage, an
unknown print is examined first to determine if it is friction skin and if so, it is examined for clarity of Level 1, 2, and 3 Detail. A comparison is then made from a list of known fingerprints that are possible matches, observing the three levels of detail to check for correspondence, or lack there of. Once a known that is consistent with the latent is found, the two prints are examined together in the evaluation stage, beginning with finding features in the unknown print and then searching for them in the known. Finally, the conclusion is verified by another fingerprint expert to ensure that the comparison is repeatable with the same results (Wertheim, 2000; Langenburg, 2004). The ACE-V method was devised based on the scientific method as part of the effort to center all aspects of fingerprint comparison on science (Wertheim, 2000).

IV. Challenges

National Academy of Science Report

The 2009 Report of the National Academy of Science (NAS) outlined the current issues faced by the latent fingerprint community. In the report, NAS states that better documentation is needed for each of the steps in the ACE-V process, particularly in the analysis stage. As of yet, there is no requirement to provide the courts with documentation of which features within a latent fingerprint support their identification. The next and significantly more difficult issue facing fingerprint science is error rate. With any judgment-based or subjective method, errors are possible. Though the ideas behind the method (e.g. uniqueness and persistence) are generally accepted as fact, it does not exclude error by the examiner in the analysis. The process is complicated by the fact that impressions differ
slightly each time they are taken due to changes in pressure. One way NAS proposes to limit error is additional research into ridge flow, crease pattern distribution, and discriminating values of ridge formations (NAS, 2009). Information such as this will provide latent print examiners with a stronger understanding of the prevalence of these fingerprint traits and thus could be used in a statistical approach to limit the possible ancestries of an individual that is responsible for leaving a latent print. From the literature, it is clear that researchers have begun trying to tackle the issues presented by NAS (2009). However, further research is still needed and should be grounded in the biological basis of the development, uniqueness, and permanence of fingerprints (NAS, 2009).
MATERIALS AND METHODS

I. Materials

All fingerprint materials used in this study were obtained from the City County Bureau of Identification (CCBI) located in Raleigh, NC. Permission to access fingerprint files was granted by Andy Parker, Deputy Director of CCBI. All personal and identifiable information about the individuals was excluded from all documentation to uphold the privacy and anonymity of all involved. Due to the use of living human subjects, the protocol for this study was submitted to the North Carolina State University IRB and was deemed to be exempt from further review.

Fingerprint Servers

The National Institute of Standards and Technology (NIST) is a non-regulatory federal agency whose mission it is to advance the measurement of science, standards, and technology in the United States (National Institute of Standards and Technology, 2013). To fulfill this mission, NIST conducts research and develops technologies for a multitude of research areas. One such area is forensic science. The forensic science division of the Information Technology Laboratory has developed the NIST Biometric Image Software (NBIS) for the Federal Bureau of Investigation and the Department of Homeland Security for the purpose of biometrics processing and analysis (National Institute of Standards and Technology, 2013). Fingerprints are included as one of the biometrics provided in NBIS. The record for each individual recorded in NBIS also includes a photograph and information regarding ethnicity, height, and weight (National Institute of Standards and Technology,
2013). Essentially, the NIST servers are electronic filing cabinets that store biometric information, such as fingerprints, at either the federal, state, or local level. The local fingerprint server, Dataworks Plus NIST Manager, was used to search for individuals whose ancestry fit the parameters necessary for this study. Once individuals who fit the ancestry needs were identified, they could then be searched by name in the local and state databases using PrintQuest®.

PrintQuest® AFIS-APIS System (SPEX Forensics, 2013) was the primary program utilized in this study for searching and viewing fingerprints from the local and state databases. It is a stand-alone PC system for matching fingerprints produced by SPEX Forensics. The system is capable of viewing tenprint, a complete nail-to-nail roll recorded for comparison, and latent fingerprint entries, as well as palm prints. For the purpose of this study, only tenprint entries were viewed and only for the right index finger. Features of the program include the ability to identify the pattern, core, and delta of fingerprints, as well as extract minutiae and provide a total minutiae count and ridge count (SPEX Forensics, 2013). PrintQuest® was used in this study to search and view fingerprints from individuals who fit the parameters required of the sample, such as quality prints of the right index finger and European American or African American ancestry. The database also provides birthplace as part of the records for each individual. These aspects were useful in collecting the study sample. PrintQuest® was also used in the methodology of this study. For example, the reference center feature was especially helpful in dividing the fingerprints into quadrants to aid in counting minutiae. Combining the information provided by NIST and PrintQuest® allowed an appropriate sample to be selected for this study.
Study Sample

The sample for this study consists of 115 nail-to-nail rolls of the right index finger from tenprint cards stored in a local and state criminal database in PrintQuest® and in NIST. Tenprint, rather than latent fingerprints, were selected because there is consistency with how the prints are taken, allowing for comparison. All of the prints were chosen because they fit the criteria of the study.

Table 3.1. Description of Sample

<table>
<thead>
<tr>
<th>Group</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>African American</td>
<td>29</td>
<td>29</td>
<td>58</td>
</tr>
<tr>
<td>European American</td>
<td>28</td>
<td>29</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 3.2. Dependent and Independent Variables Selected for this Study

<table>
<thead>
<tr>
<th>Effects Considered</th>
<th>Variables Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>Total Minutiae</td>
</tr>
<tr>
<td>Population (Ancestry)</td>
<td>Total Bifurcations</td>
</tr>
<tr>
<td>Pattern Type</td>
<td>Total Ending Ridges</td>
</tr>
<tr>
<td>Sex*Population Interaction</td>
<td>Total Short Ridges</td>
</tr>
<tr>
<td>Sex*Pattern Interaction</td>
<td>Total Dots</td>
</tr>
<tr>
<td>Population*Pattern Interaction</td>
<td>Total Enclosures</td>
</tr>
<tr>
<td>Sex<em>Population</em>Pattern Interaction</td>
<td></td>
</tr>
</tbody>
</table>
II. Methods

Sample Selection

Spex PrintQuest® was set to show tenprint cards and the right index finger was selected to appear on the screen. Each record in PrintQuest® was examined for quality, searching to fulfill the following criteria. Fingerprints used in this study had to be a complete roll with no smudging or scars that would disrupt the ridge flow and prevent minutiae distinction. Once a fingerprint was determined to be of sufficient quality, the record for each individual was checked for sex and ancestry. Ancestry was determined from the self-identified ethnicity listed for each individual in his or her record and corroborated with images stored in NIST taken at the time of arrest. Only those individuals with acceptable quality prints who self-identified as “white” or “black” were chosen for the study. Quality was assessed visually, as well as by the quality score supplied by SPEX PrintQuest® for each fingerprint. A quality score of 80 or above was required, followed by visual concordance with the score, in order for the individual to be incorporated into the sample. This process was repeated until a sufficiently large sample size was obtained (refer to Table 3.1). For the purposes of this study and given time constraints for data collection, as well as funding restrictions, the goal was to obtain roughly 30 individuals of each sex and ancestry. The results produced from this sample dictate whether it is justified to continue exploring this research with a larger sample.
Minutiae Selection

The five minutiae selected for this study were chosen because they were thought to be sufficiently different from each other and clearly discernible in fingerprints. Many other minutiae have been identified and studied by other researchers, but the other minutiae types are simply variations on the five chosen here. The decision to use only bifurcations, ending ridges, short ridges, dots, and enclosures in this study was supported by latent fingerprint analysts, who were consulted with regard to which types of minutiae they frequently identify in comparisons. Some minutiae, particularly short ridges and dots, can be mistakenly identified as minutiae when they are in fact incipient ridges, or incomplete ridges (SWGFAST, 2011). Care was therefore taken to ensure that pores were visible along the ridge, which indicates a completely formed ridge.

Minutiae Quantification

Before any work was completed on the minutiae, the pattern type was recorded for each fingerprint. This was done so that pattern type could be included as a factor in the statistical analysis to test whether any of the minutiae variables were influenced by pattern type. SPEX PrintQuest® provides pattern type; however, the conclusion was visually confirmed by the researcher of the study, especially in the rare instances where one fingerprint was cross-referenced as two different pattern types (SPEX Forensics, 2013). PrintQuest® also marks the minutiae on fingerprints and codes them using color and shapes. This feature was unselected for the purposes of this study, however, for two reasons. First, the program only marks bifurcations and ending ridges so the majority of the minutiae
considered in this study would have had to be hand-counted regardless. Second, having the minutiae highlighted would likely have influenced the visual assessment made and introduced bias into the results. A single human observer was deemed more appropriate and desirable to produce reliable results.

Each fingerprint was split into four quadrants using the reference center feature in PrintQuest®. In doing so, the quadrants were all designated based on the core of the fingerprint. The five minutiae types (bifurcations, ending ridges, short ridges, dots, and enclosures) were counted in each quadrant in that order until all four quadrants were counted. The step was repeated twice for each fingerprint to lessen the chance of observer error. The counts were recorded in a chart created by the researcher.

While counting minutiae, the following decisions were made by the researcher. Ridges along the edge of a fingerprint were not included in the minutiae count because it would be unclear what the ridge would have continued to be, i.e. whether it did indeed terminate and was not simply cut off during the roll and thus should be counted as an ending ridge, or whether it was cut off and thus eliminates the ability to determine with certainty what path the ridge would have followed on the actual fingerprint. Also, per the advice of latent fingerprint examiners, both ends of a short ridge and ending ridge were counted because what is classed as the minutia is the fact that the ridgeline terminates at each end. If, however, a short ridge crossed multiple quadrants, only the end point that fell within that quadrant was counted while the other end counted towards whichever quadrant it fell within. Due to the fact that enclosures consist of joining bifurcations, in the instance that an enclosure covered more than one quadrant, the enclosure was counted a single time for
whichever quadrant held the majority of it. Otherwise, the minutia would have been counted as two bifurcations in two different quadrants.

*Statistical Analysis*

Descriptive summary statistics were provided by Microsoft Excel (2004) to determine the mean and standard deviation of the minutiae within the African American males and females and European American males and females. The frequencies of each pattern type and minutiae type were also analyzed for each group. These results were obtained first and are presented first in the results as well.

The first statistical analysis performed on the dataset was multiple analysis of variance (MANOVA) using the GLM procedure in SAS 9.2 (2011). The decision to use MANOVA to study the relationship between the variables in this study was based in part on the literature (Laguebe, 1982; Reddy et al., 2000). The purpose of the MANOVA was to determine whether any of the main effects considered in this study (sex, ancestry, and pattern type) significantly influence the six minutiae variables (total minutiae, total bifurcations, total ending ridges, total short ridges, total dots, and total enclosures). The second and third order interactions of the main effects were also considered. In order to specify the percentage of variation between the groups caused by each of the minutiae, canonical correlation was performed (Jantz and Chopra, 1983) using the canonical option in the GLM procedure in SAS 9.2 (2011). Contrast statements were also employed in the MANOVA to provide additional information regarding the variation within the model.
Logistic regression was used in this study in order to determine whether minutiae variables that were selected for analysis can effectively predict the sex, pattern type, or ancestry of an individual who leaves a fingerprint. It is similar to analysis of variance in that logistic regression illustrates how variables are related to each other, but logistic regression measures the predictive value that minutiae can have for those effects (McDonald, 2009). Specifically in this instance, the question is how certainly a variable can predict the biological characteristics of a person rather than whether the biological characteristics affect the outcome of minutiae on a fingerprint. The null hypothesis is that the probability of the dependent variable is not related to the value of the independent variables (minutiae). In other words, the relationship between the variables has a slope of zero. As with all other statistical tests performed in this study, the logistic regression was done using SAS 9.2 (2011).
RESULTS

I. Summary and Descriptive Statistics for the Sample

Table 4.1 shows the frequencies of each pattern type in the study sample. The results consistently show arches having the lowest frequency, for all but the European American males where the frequency of arches is closer to the frequency of whorls. With the exception of European American females, all groups have a higher frequency of right loops compared to left loops, which is expected on the right hand. The loops are the most frequently represented pattern type in this sample, particularly the right loops, followed by whorls, and lastly arches.

Table 4.1 Sample Summary: Frequencies of Patterns (AA=African American, EA=European American)

<table>
<thead>
<tr>
<th>Sex</th>
<th>Ancestry</th>
<th>Pattern Type</th>
<th>n of Pattern Type</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>AA</td>
<td>Arch</td>
<td>1</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left Loop</td>
<td>2</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right Loop</td>
<td>13</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whorl</td>
<td>13</td>
<td>45%</td>
</tr>
<tr>
<td>M</td>
<td>EA</td>
<td>Arch</td>
<td>6</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left Loop</td>
<td>3</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right Loop</td>
<td>12</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whorl</td>
<td>7</td>
<td>25%</td>
</tr>
<tr>
<td>F</td>
<td>AA</td>
<td>Arch</td>
<td>2</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left Loop</td>
<td>2</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right Loop</td>
<td>14</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whorl</td>
<td>11</td>
<td>38%</td>
</tr>
<tr>
<td>F</td>
<td>EA</td>
<td>Arch</td>
<td>5</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left Loop</td>
<td>9</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right Loop</td>
<td>8</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whorl</td>
<td>7</td>
<td>24%</td>
</tr>
</tbody>
</table>
Table 4.2 Sample Summary: Frequencies of Minutiae (AA=African American, EA=European American)

<table>
<thead>
<tr>
<th>Sex</th>
<th>Ancestry</th>
<th>Frequency of Bifurcations</th>
<th>Frequency of Ending Ridges</th>
<th>Frequency of Short Ridges</th>
<th>Frequency of Dots</th>
<th>Frequency of Enclosures</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>AA</td>
<td>27%</td>
<td>54%</td>
<td>14%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>M</td>
<td>EA</td>
<td>27%</td>
<td>60%</td>
<td>10%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>F</td>
<td>AA</td>
<td>34%</td>
<td>54%</td>
<td>8%</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>F</td>
<td>EA</td>
<td>27%</td>
<td>61%</td>
<td>10%</td>
<td>1%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table 4.2 illustrates the comparative frequencies of each minutia type in each of the study groups. Ending ridges have the highest frequency in all of the groups, making them the most common minutia type in this sample. This finding follows the expectation suggested by previous studies (Ashbaugh, 1995; Gutiérrez-Rodemero et al., 2010). The next most frequent are bifurcations, followed by short ridges, enclosures, and finally dots. Interestingly, all of the groups have the same frequency of dots (1%) except African American males (3%). This group also has a slightly higher frequency of short ridges when compared with the other groups. Similarly, all groups have a 2% frequency of enclosures apart from African American females. More variation is seen between males and females of the African American group while males and females of the European American group have even frequencies for all minutiae other than ending ridges, which only differ by 1%. For further information, tables 4.3-4.6 present the descriptive summary statistics for the minutiae of African American males and females and European American males and females.
Table 4.3. Summary Statistics for African American Males

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Minutiae</td>
<td>95.69</td>
<td>19.82</td>
</tr>
<tr>
<td>Total Bifurcations</td>
<td>25.55</td>
<td>9.64</td>
</tr>
<tr>
<td>Total Ending Ridges</td>
<td>52.03</td>
<td>10.96</td>
</tr>
<tr>
<td>Total Short Ridges</td>
<td>13.66</td>
<td>9.81</td>
</tr>
<tr>
<td>Total Dots</td>
<td>2.62</td>
<td>3.00</td>
</tr>
<tr>
<td>Total Enclosures</td>
<td>1.83</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Table 4.4. Summary Statistics for African American Females

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Minutiae</td>
<td>86.66</td>
<td>15.86</td>
</tr>
<tr>
<td>Total Bifurcations</td>
<td>29.21</td>
<td>9.76</td>
</tr>
<tr>
<td>Total Ending Ridges</td>
<td>46.72</td>
<td>12.07</td>
</tr>
<tr>
<td>Total Short Ridges</td>
<td>7.21</td>
<td>4.42</td>
</tr>
<tr>
<td>Total Dots</td>
<td>1.07</td>
<td>1.51</td>
</tr>
<tr>
<td>Total Enclosures</td>
<td>2.45</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 4.5. Summary Statistics for European American Males

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Minutiae</td>
<td>94.07</td>
<td>27.39</td>
</tr>
<tr>
<td>Total Bifurcations</td>
<td>25.07</td>
<td>8.48</td>
</tr>
<tr>
<td>Total Ending Ridges</td>
<td>56.61</td>
<td>21.22</td>
</tr>
<tr>
<td>Total Short Ridges</td>
<td>9.32</td>
<td>5.90</td>
</tr>
<tr>
<td>Total Dots</td>
<td>1.14</td>
<td>1.48</td>
</tr>
<tr>
<td>Total Enclosures</td>
<td>1.93</td>
<td>1.92</td>
</tr>
</tbody>
</table>
Table 4.6. Summary Statistics for European American Females

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Minutiae</td>
<td>85.21</td>
<td>18.07</td>
</tr>
<tr>
<td>Total Bifurcations</td>
<td>22.59</td>
<td>9.00</td>
</tr>
<tr>
<td>Total Ending Ridges</td>
<td>51.83</td>
<td>15.05</td>
</tr>
<tr>
<td>Total Short Ridges</td>
<td>8.24</td>
<td>5.20</td>
</tr>
<tr>
<td>Total Dots</td>
<td>0.93</td>
<td>1.10</td>
</tr>
<tr>
<td>Total Enclosures</td>
<td>1.62</td>
<td>1.42</td>
</tr>
</tbody>
</table>

II. Sex, Population, and Pattern Type Variation Analysis

According to the MANOVA with factorial design, the three-way interaction of population, sex, and pattern type is insignificant (F-value=0.94, DF=15, 262.65, p-value=0.517). The two-way interactions are also insignificant (sex*pattern- F-Value=0.89, DF=15, 262.65, p-value=0.574, sex*population- F-value=1.53, DF=5, 95, p-value=0.187, population*pattern- F-value=0.67, DF=15, 262.65, p-value=0.814). These results are presented in Tables 4.7-4.10. Of the main effects, sex and pattern type are insignificant (F-value=1.75, DF=5, 105, p-value=0.130 and F-value=1.45, DF=15, 290.26, p-value=0.124, respectively). Therefore, population is the only main effect that significantly influences the six minutiae variables according to these results (F-value=2.84, DF=5, 105, p-value=0.019), which can be found in Tables 4.11-4.13.
Table 4.7. MANOVA for the Hypothesis of No Overall Effect of population*sex*pattern

<table>
<thead>
<tr>
<th>Statistic</th>
<th>F-value</th>
<th>DF</th>
<th>p-value alpha=.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ Lambda</td>
<td>0.94</td>
<td>15, 262.65</td>
<td>0.517</td>
</tr>
</tbody>
</table>

Table 4.8. MANOVA for the Hypothesis of No Overall Effect of sex*pattern

<table>
<thead>
<tr>
<th>Statistic</th>
<th>F-value</th>
<th>DF</th>
<th>p-value alpha=.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ Lambda</td>
<td>0.89</td>
<td>15, 262.65</td>
<td>0.574</td>
</tr>
</tbody>
</table>

Table 4.9. MANOVA for the Hypothesis of No Overall Effect of sex*population

<table>
<thead>
<tr>
<th>Statistic</th>
<th>F-value</th>
<th>DF</th>
<th>p-value alpha=.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ Lambda</td>
<td>1.53</td>
<td>5, 95</td>
<td>0.187</td>
</tr>
</tbody>
</table>

Table 4.10. MANOVA for the Hypothesis of No Overall Effect of population*pattern

<table>
<thead>
<tr>
<th>Statistic</th>
<th>F-value</th>
<th>DF</th>
<th>p-value alpha=.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ Lambda</td>
<td>0.67</td>
<td>15, 262.65</td>
<td>0.814</td>
</tr>
</tbody>
</table>
The remaining results are presented with the sexes combined, as sex is not found to significantly influence the minutiae (Table 4.11). As a result, population and pattern type are the only two main effects remaining in the model. Although pattern type has already been found not to influence minutiae, the effect is tested again to see if combining the sexes changes this result. Results concerning each effect are presented separately below.
Population

Because the sex effect is not significant, it was removed from the model. Results of this second MANOVA are presented in Tables 4.14 and 4.17. With the sexes combined, the results remain similar. The effect of population is still significant (F-value=2.84, DF=5, 106, p-value=0.019). The effect of pattern is still insignificant, though the p-value is slightly lower and approaching significance after sex has been removed from the model (F-value=1.50, DF=15, 293.02, p-value=0.105).

Table 4.14. MANOVA for the Hypothesis of No Overall Effect of Population

<table>
<thead>
<tr>
<th>Statistic</th>
<th>F-value</th>
<th>DF</th>
<th>p-value alpha=.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ Lambda</td>
<td>2.84</td>
<td>5, 106</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Table 4.15 presents the significant canonical axis showing that approximately 100% of the variation between populations is accounted for by CAN1. According to the total canonical structure, the variation on CAN1 separates the population groups based on total ending ridges (TER) and total dots (TD). TER is positively correlated and TD negatively correlated with population (Table 4.16).
Table 4.15. Canonical Axis For Population

<table>
<thead>
<tr>
<th>Number</th>
<th>Eigenvalue</th>
<th>Proportion</th>
<th>Canonical Correlation</th>
<th>Approximate F-value</th>
<th>DF</th>
<th>Pr &gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1338</td>
<td>1.0000</td>
<td>0.343579</td>
<td>2.84</td>
<td>5, 106</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Table 4.16. Total Canonical Structure For Population

<table>
<thead>
<tr>
<th>Variable</th>
<th>CAN1</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>0.1727</td>
</tr>
<tr>
<td>TB</td>
<td>-0.3586</td>
</tr>
<tr>
<td>TER</td>
<td>0.6388</td>
</tr>
<tr>
<td>TSR</td>
<td>-0.1969</td>
</tr>
<tr>
<td>TD</td>
<td>-0.5033</td>
</tr>
<tr>
<td>TE</td>
<td>-0.2958</td>
</tr>
</tbody>
</table>

Contrast statements between the two population groups were analyzed to determine if any of the minutiae types differ significantly on any of the four individual pattern types. According to the contrast statements, none of the minutiae differ significantly between the populations on arches. However, the total number of ending ridges on right loops is significantly different between African Americans and European Americans (F-value=5.31, DF= 1, p-value= 0.026), while total bifurcations differs significantly on left loops in these populations (F-value=9.50, DF=1, p-value=0.008). Total dots differ significantly on whorls (F-value=6.06, DF=1, p-value=0.019).

Based on the logistic regression analysis with population as the response variable for each of the pattern types considered separately, the likelihood ratio is not statistically
significant for any of the pattern types (Pr> 0.05), indicating that the null hypothesis that the regression coefficients equal zero should be accepted. For whorls, the probability is approaching significance (Pr> ChiSq=0.057), however the maximum likelihood estimates for each of the minutiae variables are all highly insignificant. According to these results, despite the influence that population appears to have on the outcome of minutiae on fingerprints, the minutiae variables tested in this study are not appropriate predictors of the populations considered (African American and European American).

Pattern Type

Just as was the case before the sexes were combined, pattern type is not significantly influencing minutiae variation (Table 4.17). The canonical correlation analysis indicates that there are three canonical axes for pattern type (CAN1, CAN2, CAN3), though not surprisingly given the lack of variation determined by the MANOVA, these three variates were all found to be insignificant (Pr>0.05). These results are presented in Table 4.18.

Table 4.17. MANOVA for the Hypothesis of No Overall Effect of Pattern

<table>
<thead>
<tr>
<th>Statistic</th>
<th>F-value</th>
<th>DF</th>
<th>p-value alpha=.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ Lambda</td>
<td>1.50</td>
<td>15, 293.02</td>
<td>0.105</td>
</tr>
</tbody>
</table>
III. Summary of Results

In summary, the two-way interactions between all of the main effects (sex, population, and pattern type) are insignificant, as is the three-way interaction. Because sex is not a significant factor in influencing minutiae, it was removed from the model for all further analyses. In doing so, pattern type remains insignificant according to the MANOVA and corresponding canonical correlation analysis, while population continues to show significant influence on the minutiae. Canonical correlation analysis for population indicates that CAN1 is responsible for approximately 100% of the variation, with total ending ridges and total dots carrying the most weight of the minutiae variables. Results of the logistic regression analysis indicate that these particular minutiae are unsuccessful at predicting which of these two population groups an individual belongs to.
DISCUSSION

I. Relationship Between the Minutiae and Sex, Pattern Type, and Population

The frequency summary tables for pattern type and minutiae are presented in Table 4.1 and Table 4.2, respectively. They illustrate the frequencies for both sexes and populations. These results suggest that there are different frequencies of pattern type and minutiae between sexes and populations. However, the differences in frequency are subtle in some cases and in others do not exist at all. Therefore, interpreting the effect that sex and population have on pattern type and minutiae is difficult based on the frequency tables. A MANOVA was performed in order to measure variation between the groups or more specifically, the significance of the effects of sex, pattern type, and population on minutiae variables. The MANOVA is the chosen method of analysis in this study because the multivariate nature of the procedure allows for the multitude of factors involved in the complex biological system of fingerprint development to be explored in the same model. Nonetheless, multivariate methods like the MANOVA produce less descriptive results because they do not specify which level of a factor is the source of variation and the power of the test can be lessened by insignificant variables (Juliano and Fader, 2012). The canonical correlation analysis and contrast statements were employed in order to tease out which variables are responsible for the variation.

The first question of interest was whether there is variation in minutiae between sexes because if the answer is no, sexes would be combined to increase sample size. Due to the lack of significance for sex in the overall model both by itself and as an interaction with other effects, sex was indeed removed from the model. In all additional statistical analyses, the
sexes were combined and population and pattern type became the only two effects considered. The finding of an insignificant effect of sex on minutiae was surprising based in part on the literature. For example, a study by Dankmeijer (1938) concluded that Level 1 Detail (pattern type) is affected by both population and sex and therefore it was expected that this influence would still act on Level 2 Detail. It is also surprising considering that males tend to have larger fingerprints than females and thus would logically have more minutiae.

With the sexes combined, population is shown to be significant, meaning there is significant variation in minutiae between the African American and European American groups. This finding is quite interesting because it indicates that some level of population trends seen in the Level 1 Detail of fingerprint traits is upheld at Level 2 Detail. This implies that genetic influence is still visible even in traits that are so strongly influenced by environment and development (Mulvihill and Smith, 1969; Babler, 1978; Ashbaugh, 1992). According to the canonical correlation analysis, all variation is centered on the first canonical axis (CAN1), with total ending ridges and total dots carrying the highest weights. Total ending ridges are positively correlated with population, whereas total dots are negatively correlated. Interestingly, of all the minutiae, the two that were found to carry the most weight in the variation are one of the most common of minutiae types (ending ridges) and one of the most rare (dots) (Gutiérrez-Rodemero et al., 2010). This finding indicates that variation in numbers of both very common and very rare minutiae carry weight in differentiating between these two populations.

The results of the contrast statements comparing the minutiae types within each individual pattern type between African Americans and European Americans indicate that,
indeed certain minutiae do vary in their count between the ancestry groups for certain pattern types. Specifically, the total number of ending ridges that occur on right loops is significantly different between the two groups, while the total number of bifurcations varies between them on left loops. The presence of dots on whorls is statistically different between populations. Again, ending ridges and dots are among the minutiae that vary significantly between the populations. Based on the results of this study, the occurrence of minutiae on arches does not differ between African Americans and European Americans in this sample. This could be due to the limited sample size of arches available for analysis in this sample, as this pattern type was by far the least represented. Although, low representation of arches is to be expected in a sample that is selected randomly for pattern type, as the arch has been found to be the least frequent of all pattern types (Dankmeijer, 1938; Jantz, 1987).

Among the most important findings of this study are the results of the logistic regression analysis of population, with each of the pattern types regressed separately with population as the response variable. The likelihood ratio is not significant for any of the pattern types, causing the null hypothesis to be accepted and suggesting that minutiae variables chosen in this study are not appropriate predictors of these ancestry groups. This means that it was not possible to estimate the probability of correctly assigning an individual into one of the two ancestries considered in this study based on minutiae. This finding was unexpected given the substantial variation in these populations based on these minutiae. This result could be attributed to not having a large enough sample size for each of the pattern types as well, but it could also be indicative of the widely accepted view among latent fingerprint examiners that there is simply too much variation between individuals based on
Level 2 Detail (Champod, 1995; Cummins, 2000; Wertheim, 2000; Wertheim and Maceo, 2002). It is for this reason that the results of the logistic regression are among the most interesting findings from this study.

The overall effect of pattern type on minutiae variation was not found to be significant based on the results of the MANOVA. The canonical correlation analysis for pattern type indicates that there are three canonical axes (CAN1, CAN2, CAN3), with CAN1 being responsible for approximately 71% of the variation; however, all of them are insignificant. This is not surprising given that the MANOVA suggests no variation based on pattern type. It is, however, surprising that pattern type is not a significant influence on minutiae because the timing of volar pad regression dictates pattern type and to some extent minutiae. Perhaps the lack of significance of pattern shown in this study is a consequence of the small and varying sample sizes of the individual pattern types. Future research should be conducted on a larger and more even sampling of pattern types to see if the significance level changes.

As has been previously mentioned, the number of individuals representing each of the four main pattern types (arches, left loops, right loops, and whorls) was small and uneven. For instance, the number of people exhibiting whorls in this sample far exceeded the number of people exhibiting arches. This was especially true once the individuals were separated based on population, which of course was a major requirement of this study. This fact most likely is influencing the results concerning pattern type. In the future, it would be interesting to conduct the same study on a much larger sample of individuals, making sure there is enough of each pattern type represented in the sample. Power analysis will be conducted in
order to determine which number of individuals is appropriate. It is important to point out, however, that the subjects chosen in the present study were randomly selected on the basis of pattern type, and the percentage of the sample represented by each pattern type reflects the percentage of the population thought to have arches, loops, and whorls. Therefore, the results retain their meaning in the sense that they are an accurate representation of the actual spread of pattern type in the total population. As was previously stated, the individuals chosen for the sample were selected merely based on the quality of the print, their sex, and the ethnicity that they self-identified with.

II. Implications of this study

The results of this study provide some interesting information regarding the factors that influence fingerprint minutiae separately and in correlation with the other factors. The canonical correlation results presented in this study indicate which types of minutiae are actually varying between the ancestry groups. This information is helpful because it contributes knowledge that could be useful for determining which minutiae should carry more weight during latent fingerprint analysis. Information like this from the present study and others like it has the potential to lead to a decrease in error rate associated with fingerprint comparisons, like NAS suggests (NAS, 2009). Minutiae that are found to vary most between groups should be weighted more, especially if they are more rare. Therefore, dots should be weighted highly as evidence according to the results of this study because they are shown to vary significantly between ancestry groups and are among the more rare minutiae. Essentially, any information regarding the variation of fingerprint traits has the
potential to reduce the error rate associated with fingerprint comparison. Ranking minutiae by the weight that their presence and number carries as evidence in a print comparison is essential but equally as important is knowing the circumstances in which those weights can fluctuate, like for example on less common pattern types such as arches.

It is also essential to recognize the complexity of the issue. There are a great number of possibilities for the phenotype of a fingerprint. For instance, the four main pattern types can be subdivided into several other categories (plain arch, tented arch, ulnar loop, radial loop, plain whorl, central pocket loop whorl, double loop whorl, accidental whorl). Within the pattern type, the ridges can take on any number of ridge paths to form minutiae. To add to the complexity that is inherent to fingerprints based on the vast variation in phenotypes, these patterns and minutiae are displayed on ten different digits, which could be driven by unique genes (Juberg et al., 1980). The complexity of the biological system that generates fingerprints is what drives their uniqueness and their usefulness in forensic investigations.
CONCLUSION

The results of this study suggest that ancestry influences the type and quantity of minutiae that appear on fingerprints, just as it has been found to by physical anthropologists on Level 1 Detail such as pattern type and ridge count (Jantz, 1987). Sokal (1996) found that finger patterns show spatial patterns like those found for blood markers and thus argues 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 genetic factor that drives timing of volar pad regression, which ultimately determines pattern type development, creates population trends in Level 1 Detail and is still acting on Level 2 Detail. These results reinforce the complexity of the biological system responsible for fingerprint development and the necessity for latent fingerprint examiners to have a strong understanding of the biological factors involved in fingerprint development. NAS (2009) argues 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 indicate the role that biology plays in fingerprints and support exploring these biological factors in order to increase understanding behind the uniqueness of fingerprints and minimize the error rate involved with making comparisons.
Limitations Of This Study and Future Directions

As has been mentioned, the sample sizes of the pattern types were small and highly inconsistent. Because the sample was randomly selected based solely on ancestry and sex of the individuals, an uneven number of pattern types are represented for the four groups that make up the sample (African American males and females, and European American males and females). This is especially true for arches in the African American group, with only one arch for the males and two for the females (Table 4.1). From this table it is clear that there is not a balanced representation of each pattern type and even for the patterns that have a higher frequency in the sample, the sample size is still below 20. It is unclear whether this negatively affected the results and it is inevitable to have a slight imbalance with a randomly selected sample, but it is worth mentioning and possibly worth exploring how the results would change with a different assortment of pattern types.

A much larger limitation of this study is that, while the results provide critical information about how biology affects fingerprints, it would be difficult to apply these results to latent fingerprints. The reason for this is that latent fingerprints are by their very nature incomplete and the totals of each minutia type will most definitely not be available on an incomplete print. However, one way to ameliorate this issue is to take the information obtained in this study regarding which minutiae are specifically influenced by biological factors like sex and ancestry, and even by pattern type, and expand the research question to include whether the location on the fingerprint is a factor. For example, a certain type of minutia might tend to occur near the delta region of the print and this information could be helpful if that is the portion of the whole print left behind as a latent impression. Information
regarding the location of minutiae (within four consistently defined quadrants) was also collected while counting them as part of the present study but was elected to be excluded from analysis at this time. In light of the results obtained from analyzing the entirety of the print from the perspective of minutiae totals, the next stage in the study could utilize the remaining data collected on location within the quadrants of each type of minutiae quantified. This additional information would enhance knowledge regarding minutiae variation and add to the effort of decreasing the error rate associated with fingerprint comparison.

Despite these limitations, the results presented here support the incorporation of biology into the process of latent fingerprint comparisons and the explanation of results in a courtroom. Regardless of the fact that a latent print is incomplete, it represents a portion of the whole print. Therefore, the factors found to influence the development and appearance of the complete fingerprint remain relevant and should still be considered in forensic science as they are in anthropology.
REFERENCES


Cummins, Harold. 1926. Epidermal-ridge configurations in developmental defects, with particular reference to the ontogenetic factors which condition ridge direction. The American Journal of Anatomy 38(1): 89-152


Sachs, Leo and Bat-Miriam, Mariassa. 1957. The genetics of Jewish populations. Am J Hum Genet. 9(2): 117-126


SPLEX Forensics. 2013. SPEX PrintQuest AFIS-APIS System.


Whipple, Inez L. 1904. Ventral Surface of the Mammalian Chiridium with special reference to the conditions found in man. Erwin Nagele.