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FINGERPRINTS AND ANCESTRY: IS IT IN THE DETAILS?

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Abstract

Fingerprint analysis has become one of the most widely known and consistently used means of forensic identification. Specifically, fingerprints have proven to be a reliable means of identification worldwide for more than 100 years and fingerprints are among the most common types of evidence found at a crime scene. Fingerprint analysis was the first forensic discipline to have organizational certification and today fingerprint exams outnumber all other forensic examinations, solving nearly ten times more crimes than DNA analysis. The ability to identify a fingerprint to an individual is based on the assumption of fingerprint uniqueness and the persistence of friction ridge detail throughout the duration of a person's lifetime. Using ACE-V methodology in conjunction with AFIX-Tracker technology and the fingerprint databases of Automated Fingerprint Identification System (AFIS) and Next Generation Identification System (NGI) fingerprint experts are able to form conclusions of identification, inconclusive, or elimination when comparing unknown prints collected from a crime scene to known prints of suspects. These concepts and methodology are supported by scientific research and have aided law enforcement in detaining and removing some of our most heinous criminals from society. While there has been questioning to the legitimacy of this discipline, diligent research from many renowned scientists has supported fingerprints as being permanent and unique and fingerprint analysis as being a valid and reliable methodology. Although the different levels of analysis allow for fingerprints to be potentially identified to a specific individual, fingerprints hold little value if there are no known or suspect prints that latent prints can be compared to.

Current research is assessing if an individual's ancestry can be determined based solely on fingerprint characteristics. Specifically, it has been suggested that level two detail of fingerprint analysis or the analysis of Galton features or minutiae types could yield significant

evidence in regard to a person’s ancestry (Fournier & Ross, 2015). While this is a novel concept in forensic science, it could be an investigative aid used to include and exclude potential suspects based on ancestry or as corroborative evidence in a case. Preliminary studies have been conducted focusing on comparing Galton features of African Americans and European Americans. For this study, 243 right index fingerprints were chosen; specifically, 61 African American females and 61 African American males (total of 122 African Americans) and 60 European American males and 61 European American females (total of 121 European Americans).

After all data was collected and recorded, descriptive summary statistics were ran using a Multivariant Analysis of Covariance (MANCOVA) to test whether sex, ancestry, and pattern type have significant effects on average minutiae variables (Fournier & Ross, 2015). Interestingly, it was found that the frequency of arches is higher in European American males and females than in African American males and females. It was also found that bifurcations are a significant predictor of ancestry; African Americans are nearly six times more likely to have more bifurcations when compared to European Americans. However, further research is needed to strengthen the validity of the study and expand the scope of the research to individuals of other ancestral descent. Research needs to continue to expand upon what we know about fingerprints and how we can practically use them. In turn, the purpose of this research study will be to expand upon the previous research of Fournier & Ross (2015). It will look specifically at how ancestry has significant effects on the number of average minutiae variables. With this new research, the ancestral backgrounds analyzed will be expanded to include Asian descendants, Hispanic descendants, and Native American descendants as well as European and African

descendants included in the previous study of Fournier & Ross (2015). This will enable research to more closely relate to the diverse demographics present in the United States.

Key words: forensic science, fingerprints, fingerprint analysis, minutiae, ancestry

Fingerprints and Ancestry: Is it all in the Details?

Introduction

Over the years, fingerprint identification has evolved, now making it one of the most common ways to identify both unknown and suspected criminals. Fingerprints are believed to be both unique and permanent. From the collection of prints obtained from all over the world thus far, analysts have found that no two prints are exactly the same supporting the notion that no two people in the world possess the exact same fingerprints (Jain, 2005). This uniqueness is not limited to mankind, but to primates as well, which was first observed and documented by Johannes (John) Evangelista Purkinje in 1823 (Hawthorne, 2008). Aside from fingerprints being unique to a single individual, they are also persistent throughout a person’s lifetime (Jain, 2005). The friction ridge skin does not change under normal conditions from the time of formation until mid to late stages of decomposition after death. The exception is that, like other parts of the anatomy, the fingerprints or friction skin will get larger as the body grows (Hawthorne, 2008). This allows a latent or visible print from a crime scene to be identified to a known suspect. While this is extremely important, there are still gaps within the discipline and the need for further research. Specifically, whether a person’s ancestry can be derived from fingerprint minutiae needs to be investigated. Being able to predict an ancestral background could assist law enforcement in including or excluding suspects and potentially aid in the advancement or completion of cold cases. As with all scientific research, there is always more to be discovered. With diligent research, the gaps in the discipline of fingerprint analysis can be narrowed and law enforcement can be provided with new types of probative evidence.

History

Since the beginning of civilization, the identification of criminals has proven to be crucial to maintain structure in society. The Chinese were the first culture known to have used friction ridge impressions as a means of identification for the purposes of criminal justice. The earliest example comes from a Chinese document entitled “The Volume of Crime Scene Investigation—Burglary” from the Qin Dynasty (221 to 206 B.C.). The document contains a description of how handprints were used as a type of evidence (Xiang-Xin & Chun-Ge, 1988). The first recorded use of fingerprints specifically for identification purposes occurred in 1684 when Dr. Nehemiah Grew issued a report to London’s Royal Society describing the ridges and pores on the hands of humans (Benasconi, 2001).

German anthropologist Hermann Welcker (1822–1898) of the University of Halle also conducted research in the study of friction ridge skin, specifically in regard to the permanence of friction ridges. Welcker began by printing his own right hand in 1856 and then again in 1897, thus likely being the first person to start a permanence study. However, Welcker’s studies proved to be limited and in the paper Welcker published in 1898, he sought no credit, but rather seemed only to offer assistance to prior claims of permanence in reference to friction ridge skin (Wilder &Wentworth, 1918). Welcker is not often cited regarding fingerprint studies. Generally, the credit for being the first person to study the persistence of friction ridge skin goes to Sir William James Herschel. In 1858, Herschel experimented with the idea of using a handprint as a signature by having a man named Rajyadhar Konai put a stamp of his right hand on the back of an official public contract. The contract was received and accepted as valid. This spontaneous printing of Konai’s hand thus led to the first official use of friction ridge skin as a means of identification by a European. The success of this experiment led Herschel to begin a long exploration of friction ridge skin and over the next year he went on to collect multiple fingerprints from family, friends, colleagues, and even himself. In 1860, Herschel recognized more identification possibilities for the use of friction ridge skin, especially in fighting and preventing fraud (U.S Department of Justice, 2014).

In the late 1800s, Henry Faulds conducted independent research by collecting various individual’s fingerprints. In a letter dated February 16, 1880 to Charles Darwin, Faulds wrote that friction ridges were unique and classifiable, while also implying their permanence (Lambourne, 1984). In October 1880, Faulds submitted an article for publication to the journal *Nature* in order to inform other researchers of his findings (Faulds, 1880). In that article, Faulds proposed using friction ridge individualization at crime scenes and gave two practical examples. In one example, a greasy print on a drinking glass revealed who had been drinking distilled spirits. In the other, sooty fingermarks on a white wall exonerated an accused individual (Faulds, 1880). Faulds was the first person to publish in a journal the value of friction ridge skin for individualization. Faulds is also the researcher that yielded his inclinations to Sir Francis Galton, who then expanded on the research.

When personally presented with the dilemma of how to identify criminals, Sir Francis Galton, a cousin to renowned scientist Charles Darwin, coined a revolutionary way of identification with the use of individual fingerprint characteristics. In 1888, while preparing for a lecture on Personal Identification for the Royal Institution and while exploring the commonly used method of Bertillon measurements, Galton began to further explore the value assigned to fingerprints for identification (Galton, 1899). Bertillon measurements, the common identification method at this time, used a person’s anthropometric measurements to collectively compose a profile of that person. After exploring the possibility of fingerprints as a means for identification, Galton stated, “Let no man despise the ridges on account of their smallness, for they are in some respects the most important of all anthropological data” (1899). This started the revolution for fingerprint analysis by showing the extreme importance and uniqueness of the ridge detail. While fingerprint characteristics were noted and observed prior to Galton, their significance as it relates to individual identification were not formally introduced until Galton’s research. His research lead Galton to be known as the “Father of Fingerprints”.

While Galton was not the only scientist to complete initial and clarifying work in regard to fingerprint analysis, it was Galton who officially pointed out that there are specific types of fingerprint patterns and the significance of ridge detail in assessing individuality. Galton’s (1899) work assisted in the acceptance of fingerprint analysis as a viable form of evidence for use in courts. Galton (1899) further contributed to the field by defining fingerprint minutiae. Two terms coined by Galton that are central to the discipline of fingerprint analysis include: fingerprint minutiae and fingerprint patterns. According to Galton (1899):

> “Each ridge is characterized by minute peculiarities called *minutiae*; whenever an interspace is left between the boundaries of different systems of ridges, it is filled by a small system of its own, which will have some characteristic shape, and be called a *pattern*” (p. 54).

Additionally, Galton also conducted classification studies on the three main patterns of fingerprints: *loops, whorls, and arches*. This simple classification of patterns has enabled analysts to include or exclude suspects using the most basic level of fingerprint characteristic identification.

As mentioned, before fingerprint analysis the Bertillon method was used as the official identification system in prisons. However, law enforcement was puzzled when two inmates proved to have the exact same Bertillon measurements; this showed the need for a better identification system. If collected properly, Galton discovered that fingerprints could not only include or exclude a suspect, but could definitively identify them. With an initial sample of 500 sets of fingerprints, Galton was able to arrive at the assumption that no two fingerprints are exactly alike. This came to be especially interesting when studying twins, particularly identical twins who are genetically identical. Galton (1889) stated, “It would be totally impossible to fail to distinguish between the fingerprints of twins, who in other respects appeared exactly alike” (p. 167). Due to the issues with the anthropometric measurements of the Bertillon methods and the diligent research of Galton, fingerprints came to replace the Bertillon method as a more accurate means of identification starting in 1903.

Consistent with the findings of Weckler and Hershel, one of Galton’s (1899) most significant findings in the area of fingerprint identification is credited to expanding the previous notions that fingerprints were not only unique to a single individual, but also persistent throughout that individual’s lifetime. Galton’s evidence that minutiae persist throughout life is derived from the comparison of various duplicate impressions taken over a period of several years (Galton, 1899). The fingerprint characteristics proved to be persistent, even after many years. Galton’s initial study took place with his own fingerprint, as well as the fingerprints of 14 others. It was the print of the right fore-finger that was taken for each sample. Each print was enlarged photographically and each characteristic was marked numerically in blue ink, this included: bifurcations, beginning of ending ridge, end of ending ridge, and pattern type. The time between the first prints taken and the second set taken spanned approximately 31 years, a long enough time to ensure that fingerprints are most likely persistent throughout the duration of a person’s life. Whereas Galton only performed this longevity study on 15 individuals, himself included, subsequent research by other fingerprint examiners have supported the validity of Galton's findings for persistence, even with individuals whom attempt to alter their fingerprints for reasons of eluding identification by law enforcement. Interestingly, most often when individuals attempt to alter their fingerprints through mutilation, scarring occurs and adds an additional characteristic for comparison. Scars are unique for the very same reason the friction skin is unique: developmental noise (i.e., chance events that occur during development). Richard Lewontin, research professor at Harvard University, describes developmental noise in the following manner: "Wherever cell growth and division are involved, we can expect such noise to contribute its effects. The exact placement of hair follicles on our heads, the distribution of small moles on our bodies, a hundred such small details of our morphology, are largely under the influence of such random events in development" (Lewontin, 1995, p. 26). This makes fingerprints more unique and easily distinguished by law enforcement.

After his initial studies, Galton's research continued to significantly contribute to the field of forensic science. His research supports the idea that an identification can be confirmed from prints taken decades ago, as prints remain persistent throughout a person's lifetime due to the permanence of ridge skin. Whereas scars and imperfections may develop over a person's lifetime, an individual's original minutiae pattern will remain constant, even after death and into early stages of decomposition. With the permanence of fingerprints researched by Galton, fingerprints now remain a reliable form of identification. In addition to Galton's early research from the 1800s, many other researchers have sought out to study the uniqueness of fingerprint patterns and minutiae, however Galton is accredited with the statistical analysis given to fingerprint identification.

Since identical twins are genetically indistinguishable with the same deoxyribonucleic acid (DNA) sequence, fingerprints pose as a crucial tool in identification purposes. In a recent study, researchers Tao, Chen, Yang, and Tian (2012) collected a total of 3,984 fingerprints, four fingerprints each, from 83 pairs of identical twins. Each print was scanned six times to ensure at least one clear fingerprint from each person for analysis. For the comparison of these fingerprints, each one was uploaded into the VeriFinger 6.1 SDK system.

The conclusions of the researcher's analysis showed that the VeriFinger 6.1 SDK system could distinguish between twin fingerprints in only a minutely less accurate way than it was able to distinguish between non-twin fingerprints. Specifically, it was found that the automatic fingerprint verification matcher VeriFinger 6.1 SDK could distinguish between identical twins with a slightly lower accuracy than in non-twins of 5.8333% vs. 5.3843% (Tao et al., 2012). With newer means of research and substantially larger sample sizes than Galton's initial research on fingerprint individuality in twins, we are now left with strong evidence Galton's, as well as other researcher's, initial observations and research studies remain valid.

Fingerprint Characteristics

The permanence and individuality of fingerprints can be attributed to the unique characteristics found within the fingerprint to include level one, level two, and level three detail. Level one detail consists of ridge flow or the ridge count and pattern type (Ashbaugh, 1992; Langenburg, 2004). Ridge count, can be identified by the summation of ridges between the core (the center of the fingerprint) and the delta (the point on a fingerprint at or nearest to the point of divergence of two type lines, which resembles the Greek letter Delta) on loop patterns. Both the delta and the core aids fingerprint examiners in systematically placing fingerprints in different classes: arch, which makes up 5% of all fingerprint patterns, loop, which makes up 65% of all fingerprint patterns, or whorl, which makes up 30% of all fingerprint patterns. For a fingerprint that has no cores or deltas, it is classified as an arch pattern. For a fingerprint that has one core and one delta, it is classified as a loop pattern. Fingerprints with multiple deltas is classified as a whorl. In his 1823 thesis titled “Commentary on the Physiological Examination of the Organs of Vision and the Cutaneous System,” Dr. Johannes E. Purkinje (1787–1869), professor at the University of Breslau in Germany, classified fingerprint patterns into nine categories and gave each a name (Lambourne, 1984; Galton, 1892). Although Dr. Purkinje went no further than naming the patterns, which led his research to be lesser known than Galton’s, his contribution is significant because his nine pattern types were the precursor to the Henry classification system, which is often used in criminal fingerprint analysis as the official identification system (Herschel, 19165; Galton, 1892). The three initial classes are subdivided into more specific types. An arch fingerprint can be identified as a plain arch, which has an even flow of ridges from one side of the finger to the other, with no significant “upward thrust” or tented arch, which has a significant up thrust and appears to form a “tent”. A loop can be classified as a radial loop, which indicates that the loop runs in the direction towards the thumb, or ulnar loop, which indicates that the loop runs towards the little finger. Classification as an ulnar or radial loop is dependent on which hand the finger is on. Sometimes loops are referred to as left loops and right loops based on the direction the loop enters and exits the fingerprint. Whorls can be classified as a plain whorl, which consists of one or more ridges that make a complete circuit and contain two deltas; double loop whorl, which consists of two separate, distinct shoulders for each core with two deltas; an accidental whorl, which consists of two different types of patterns, not including the arch, and has more than two deltas; or a central pocket loop whorl, which consists of at least one recurring ridge with an obstruction at a right angle to the line of flow with two deltas. See *Figure 1* for a chart consisting of all of these specific sub-pattern types and their visual characteristics. Level one detail can be used to include and exclude known prints but does not offer enough unique features to individualize to a single person.

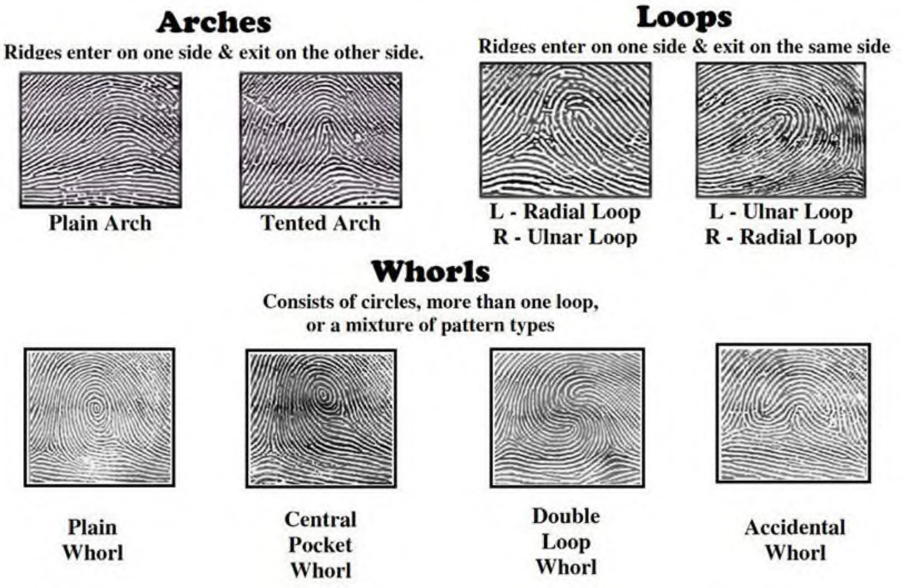


Figure 1. Fingerprint sub-patterns within Arch, Loop, and Whorl classification types (Thakkar, 2007).

Level two detail refers to the shape, direction, and orientation of the traits that form the friction ridges (Langenburg, 2004). These characteristics are called minutiae, also known as Galton characteristics or ridge characteristics (Nickell & Fischer, 1999). Minutiae include the identifiable features within the fingerprint which include: ending ridges, bifurcations, islands, dots, and enclosures. *Figure 2* presents a visual representation of the aforementioned minutiae. These characteristics are unique in quantity and orientation, therefore, using both level one and level two characteristics allow for identifications as well as exclusions to be made. The final level of detail, level three, examines the individual ridge structure, specifically edge shapes of the ridges, the end shapes of the ridges, and pore size and location. This level of analysis requires microscopic evaluation as these details are also unique to each fingerprint (Langenburg, 2004).

Level three characteristics can be used in conjunction with level two details in the positive identification of an individual. The more levels of detail used in analysis, the more certain an analyst can be of their conclusions. Level one, level two, and level three detail representations are shown in *Figure 3.*

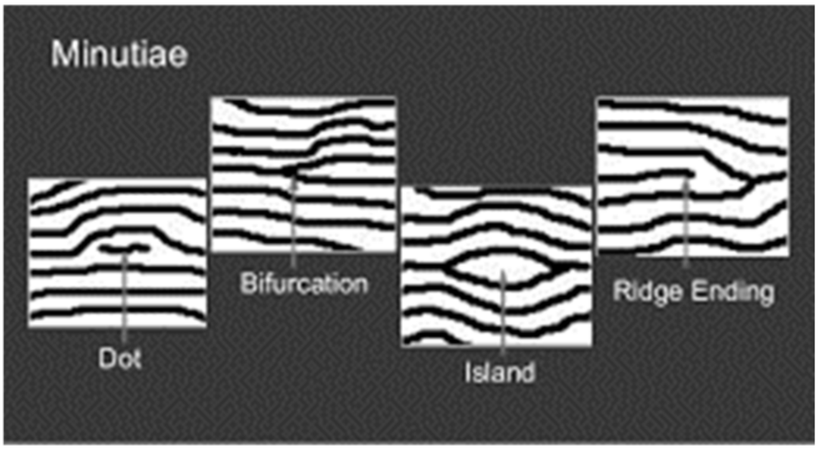


Figure 2. Galton features, or ridge characteristics, found within friction ridge skin (Warren, 2013).

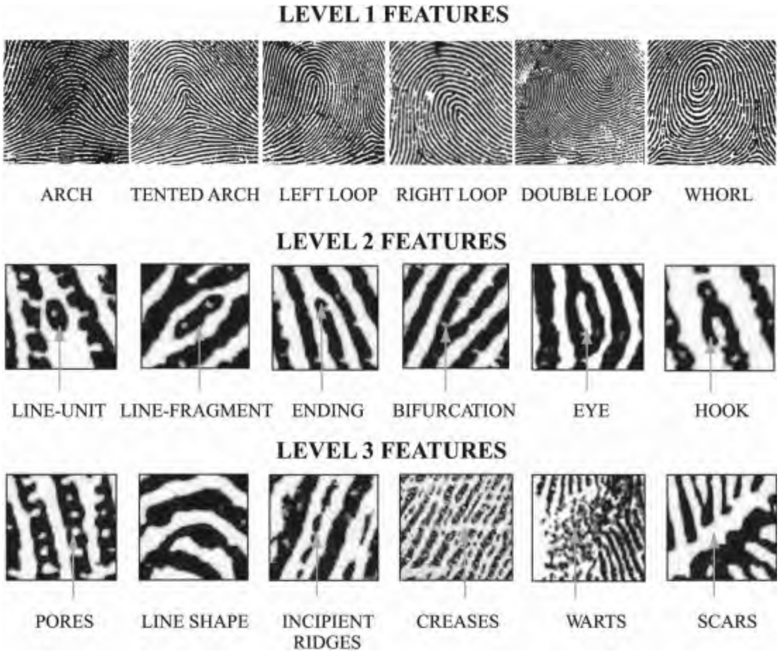


Figure 3. Level one, level two, and level three details found within friction ridge skin (Jain, 2007)

Fingerprint Development

By using the three levels of fingerprint characteristics, we can support the notion that fingerprints are both unique and permanent. To understand the permanence and uniqueness of fingerprints, it is important to understand how they initially develop. First and foremost, the outer morphology of the friction ridge skin is a direct reflection of its evolutionary function. The ridges allow the hands to grasp surfaces firmly and the creases allow the skin to flex (U.S Department of Justice, 2015). The friction ridge skin persists because of the attachments throughout the layers of skin and the regulation of keratinocyte production and differentiation. The three-dimensional morphology of the surface ridge is maintained by the combination of increased cell production in the suprabasal layer of the primary ridges (under-the-surface ridges) and the enhanced anchorage of the basal cells in the secondary ridges (under-the-surface furrows). The basal layer of keratinocytes provides the template for the surface ridges and furrows. Cell communication ensures that basal cell proliferation is stimulated and inhibited in a coordinated manner. As the basal keratinocytes divide, the cell-to-cell attachments ensure that the cells move toward the surface (U.S Department of Justice, 2015). The uniqueness of friction ridge skin falls under the larger umbrella of biological uniqueness. No two portions of any living organism are exactly alike. The intrinsic and extrinsic factors that affect the development of any individual organ, such as human skin, are impossible to duplicate, even in very small areas. The uniqueness of skin can be traced back to the late embryological and early fetal development periods (U.S Department of Justice, 2015).

Fingerprints are formed in utero. The first step in their development is the appearance of volar pads or transient swellings on the fingers during the sixth and seventh week of gestation (Borecki, Malhotra, Mathew, Vijayakumar, Poosha, & Rao,1985; Mulvihill & Smith, 1969). The interdigital pads appear first, around the sixth week of gestation, followed closely in time by the thenar and hypothenar pads. At approximately seven to eight weeks, the volar pads begin to develop on the fingertips, starting with the thumb and progressing toward the little finger in the same radioulnar gradient that ridge formation will follow. Additionally, development in the eighth week includes forming the thenar crease in the palm, followed by the flexion creases in the fingers closer to nine weeks (Kimura, 1991). The pads remain well rounded during their rapid growth around nine to ten weeks, after which they begin to demonstrate some individual variation in both shape and position (Babler, 1987; Burdi et al., 1979; Cummins, 1926, 1929). Beginning in the tenth and eleventh week of gestation, the formation of primary ridges is initiated forming in the basal layer of the epidermis. As a result of the volar pads' slowing growth, the primary ridgecontour becomes progressively less distinct on the more rapidly growing surface. This process has been defined as "regression" (Lacroix et al., 1984). It is important to understand that the pad is not actually shrinking; rather, the volar pads are overtaken by the faster growth of the larger surrounding surface. At around ten to ten and a half weeks, basal cells of the epidermis begin to divide rapidly (Babler, 1991; Holbrook & Odland, 1975). As volar epidermal cells divide, shallow "ledges" (Hale, 1952) can be seen on the bottom of the epidermis. The volar pads of the palm begin to regress as early as eleven weeks followed closely by the volar pads of the fingers. These ledges delineate the overall patterns that will become permanently established on the volar surfaces several weeks later (Babler, 1991; Evatt, 1906). Primary ridges are the first visual evidence of interaction between the dermis and epidermis and are first seen forming as continuous ridges. By sixteen weeks, volar pads have completely merged with the contours of the fingers, palms, and soles of the feet (Cummins, 1929). Volar pads regress and friction ridges grow until about sixteen weeks, when the minutiae become set.

As the fetus grows, these primary ridges extend into the dermis and increase in number. Secondary ridges begin to form between primary ridges and the periphery pattern develops (Hale, 1952). The crucial events for the establishment of the epidermal ridge pattern take place from the tenth to the sixteenth week of gestation (Babler, 1991; Bonnevie, 1927; Hale, 1951; Hirsch, 1973). At the tenth week, embryonal volar skin consists of the layered epidermis on top of the more amorphous fibrous dermis. The innermost layer of the epidermis at the interface to the dermis is called the basal layer and consists of columnar cells whose axis is perpendicular to the skin surface. It is then observed in embryos of the tenth to thirteenth week that the basal layer becomes undulated; they have a wavy form or outline. These undulations quickly become more prominent and form folds of the epidermis into the dermis. These folds are called primary ridges. They already establish the future surface pattern, which becomes established at the sixteenth week. The pattern type is determined by the height of the volar pads under the epidermis (Fournier & Ross, 2015). Low volar pads result in arches, whereas high volar pads result in 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 & Maceo, 2002). In addition, since the ridges are formed using several layers of skin, they are not something that can be erased due to burns, cuts, scrapes, or other superficial injuries, thus establishing their permanence. The formation and placement of any type of minutiae within the developing ridge field is controlled by a random assortment of interdependent factors at any given moment (Fournier & Ross, 2015). Mechanical stress, physical environment, and variation in the timing of development can affect minutiae placement (Wertheim & Maceo, 2002).

In addition, researchers Kucken and Newell (2005) sought to further explain some of the discrepancies and unknowns about the development of fingerprint minutiae and patterns. In order to do so, the researchers took into account previous notions and hypotheses presented on fingerprint minutiae and pattern development, studied both human and animal embryonic development and then developed a computer program written to simulate the conditions that are assumed present when fingerprint formation takes place. These assumptions were taken from previous researchers mentioned above in the area of fingerprint development. After all of the computer configured data was analyzed, it was hypothesized by Kucken and Newell (2005) that:

> “The epidermal ridge pattern is established as the result of a buckling instability acting on the basal layer of the epidermis and resulting in the primary ridges. The buckling process underlying fingerprint development is controlled by the stresses formed in the basal layer, not by the curvatures of the skin surface. The stresses that determine ridge direction are themselves determined by boundary forces acting at creases and the nail furrow and normal displacements, which are most pronounced close to the ridge anlage. The geometry of the volar pads influences this process.”

Another plausible theory is that developing nerves may interact with epidermal cells to stimulate clustered interactions that blend together in the early stages of ridge development. At the time of embryonic friction ridge formation, the central nervous and cardiovascular systems are undergoing a critical period of development (Hirsch, 1964). Innervation has been reported at the sites of ridge formation immediately preceding the appearance of friction ridges suggesting that innervation could be the trigger mechanism for the onset of proliferation (Bonnevie, 1924; Dell & Munger, 1986; Moore & Munger, 1989). Several researchers even postulate that the patterning of the capillary–nerve pairs at the junction of the epidermis and the dermis is the direct cause of primary ridge alignment (Dell & Munger, 1986; Hirsch & Schweichel, 1973;

Moore & Munger, 1989; Morohunfola et al., 1992). Early research on pattern distribution established “developmental fields” or groupings of fingers on which patterns had a greater tendency to be similar (Meier, 1981; Roberts, 1982; Siervogel et al., 1978). Later discoveries confirmed the neurological relation of spinal cord sections C–6, C–7, and C–8 to innervation of the fingers (Heimer, 1995).

Other interesting hypotheses have been published regarding the connection between innervation and friction ridge patterning, but the main consideration for the purposes of friction ridge formation is that specific parts of the nervous system are undergoing development at the same time that ridges begin to appear on the surface of the hands. The presence of nerves and capillaries in the dermis before friction ridge formation may be necessary for friction ridge proliferation. It would seem that complex simultaneous productions such as friction ridge formation would benefit from being in communication with the central nervous system or the endocrine and exocrine (hormone) systems (Smith & Holbrook, 1986). However, it is doubtful that nerves or capillaries independently establish a map that directly determines the flow of the developing friction ridges. It seems more likely that the alignment of the nerves and capillaries is directed by the same stresses and strains on the developing hand that establish ridge alignment (Babler, 1999; Smith & Holbrook, 1986). It is well recognized in cell biology that physical pressure on a cellular system can trigger electrochemical changes within that system. Merkel cells occupy the epidermis just prior to innervation along those pathways (Holbrook, 1991a), suggesting that even before ridge formation the stresses created by the different growth rates of the dermis and epidermis are causing differential cell growth along invisible lines that already delineate pattern characteristics (Loesch, 1973). Regardless of the trigger mechanism controlling the onset of the first primary ridge proliferations, the propagation of primary ridges rapidly continues. The cell growth during this phase of development is along the primary ridge, in what has been labeled the proliferative compartment. The proliferative compartment encompasses basal and some suprabasal cells, ultimately governed by stem cells, and is responsible for new skin cell production of the basal layer of skin (Lavker & Sun, 1983).

Although the exact mechanisms for formation of minutiae are unclear, the separate accounts of many researchers who have examined fetal tissue allow for a fairly accurate reconstruction of the morphogenesis of friction ridges in successive stages of the development process. Many events happen during this rapid period of primary ridge growth. The finger rapidly expands, new primary ridges form across the finger, and the existing primary ridges begin to separate because of growth of the digit. As existing ridges separate, the tendency of the surface to be continually ridged creates a demand for new ridges. Hale reports that new ridges pull away from existing primary ridges to fill in these gaps, creating bifurcations by mechanical separation. Ending ridges form when a developing ridge becomes sandwiched between two established ridges. According to this theory, “fusion between adjacent ridges [which have already formed] seems improbable, although there is no evidence for or against this process” (Hale, 1952, p. 167). Other models explain ridge detail in nature as a chemical reaction – suppression scheme in which morphogens react and diffuse through cells, causing spatial patterns (Murray, 1988). According to these models, hormones circulate first through newly formed capillaries just before ridge formation in the epidermis, offering another potential factor in the genesis of ridge formation (Smith &Holbrook, 1986). A recent model of the process of friction ridge morphogenesis has been likened to mechanical instability (Kücken &Newell, 2005). Building on the folding hypothesis of Kollmann (1883) and Bonnevie (192), Kücken and Newell (2005) consider the basal layer as “an overdamped elastic sheet trapped between the neighboring tissues of the intermediate epidermis layer and the dermis", which they mathematically model as "beds of weakly nonlinear springs" p. 74). They developed a computer program that models the results of forcing enough compressive stress to cause a buckling instability on a virtual three-dimensional elastic sheet constrained by fixed boundaries on two sides. The resulting ridge patterns are similar to all three major fingerprint pattern types oriented by the upper fixed boundary of the nailbed and the lower fixed boundary of the distal interphalangeal flexion crease.

Other research presents that by 15 weeks, the primary ridges are experiencing growth in two directions: the downward penetration of the sweat glands and the upward push of new cell growth. Generally, the entire volar surface is ridged by the fifteenth week of gestation. Okajima (1982) shows a fully ridged palm of a fourteen-week old fetus. Between fifteen and seventeen weeks of gestation, secondary ridges appear between the primary ridges on the underside of the epidermis (Babler, 1991). Secondary ridges are also cell proliferations resulting in down folds of the basal epidermis. At this time in fetal development, the randomly located minutiae within the friction ridge pattern become permanently set (Hale, 1952), marking the end of new primary ridge formation (Babler, 1990).

As the secondary ridges form downward and increase the surface area of attachment to the dermis, the primary ridges are pushing cells toward the surface to keep pace with the growing hand. These two forces, in addition to cell adhesion cause "in folding" of the epidermal layers above the attachment site of the secondary ridges (Hale, 1952). As secondary ridges continue to mature from sixteen to twenty-four weeks gestation, this structure is progressively mirrored on the surface of friction ridge skin as the furrows (Burdi et al., 1979)

Dermal papillae are the remnants of dermis left projecting upward into the epidermis when anastomoses bridge primary and secondary ridges. They begin to form at approximately twenty-three weeks gestation (Okajima, 1975) and continue to become more complex throughout fetal formation and even into adulthood (Chacko &Vaidya, 1968; Misumi & Akiyoshi, 1984). It is observed throughout the physical world that ridges tend to align perpendicularly to physical compression across a surface. Ridges also form transversely to the lines of growth stress in friction skin. The predominant growth of the hand is longitudinal (lengthwise) and ridges typically cover the volar surface transversely (side to side). This phenomenon is seen in the ridge flow across the phalanges. A reconstruction of the secondary ridges continuing to form on the underside of the fetal volar epidermis between existing primary ridges with sweat ducts. A scanning electron microscope view of the complex understructure of human epidermis as the dermis has been removed (inverted).

Bonnevie first hypothesized in 1924 that volar pad height affects friction ridge patterns (Bonnevie, 1924). Disruptions in the shape of the volar surfaces of the hands and feet create stresses in directions other than longitudinal. The ridges flow in a complex manner across these three-dimensional structures. The distinction between the size, height, and shape of the volar pad and the effects of differences in each of these elements on a friction ridge pattern, is a difficult topic to study (Chakraborty, 1991; Jamison, 1990; Mavalwala et al., 1991). However, almost all research points to the conclusion that the shape of the volar pad influences the stress across the skin that directs ridge alignment. One contrary viewpoint to this conclusion exists. In 1980, Andre G. de Wilde proposed a theory that pattern formation is directed much earlier in fetal life, before volar pads form, while the hand is still in a paddle-like shape. He hypothesized that ridges direct the size and shape of the volar pads. However, no other theoretical or empirical support for this theory could be found. All other research indicates that friction ridges align according to volar pad shape and symmetry at approximately ten and a half weeks gestation.

The size, particularly the height, of the volar pad during primary ridge formation affects the ridge count from the core to the delta of normal friction ridge patterns (Bonnevie, 1924; Mulvihill & Smith, 1969; Siervogel et al., 1978). Researchers have observed that ridges that form on high, pronounced volar pads conform to the surface as high-count whorl patterns. Conversely, ridges that form on a finger with a low or absent volar pad create low-count or arch-type patterns (Babler, 1987). Holt (1968) reported that the total finger ridge count (TFRC) of all 10 fingers, taken by adding the ridge counts from the core to the delta in loops, or the core toward the radial delta in whorls, is the most inheritable feature in dermatoglyphics. This combined information points directly to the conclusion that timing events related to volar pad and friction ridge formation affect friction ridge patterns.

The ridge count of a friction ridge pattern is related to two different events: the timing of the onset of volar pad regression and the timing of the onset of primary ridge formation. Differences in the timing of either event will affect the ridge count of that particular pattern. For example, early onset of volar pad regression would lead to a volar pad that was in a more regressed state at the time of the onset of primary ridge formation and a relatively low-ridge-count pattern (or arch) would likely result. Conversely, overall late onset of volar pad regression would mean that the pad was still relatively large when primary ridges began forming, and a high-ridge-count pattern would more likely result (*Figure 3–22*). This theory is supported by a study that found that “late maturers” had higher-than-average ridge counts, and “early maturers” had lower-than-average ridge counts (Meier et al., 1987).

If the onset of volar pad regression occurred at the normal time, then earlier-than-average onset of primary ridge formation would occur on a larger-than-average volar pad, leading to a higher-than-average ridge count. Likewise, later-than-average onset of primary ridge formation would occur on a smaller-than-average volar pad, leading to a lower-than-average ridge count. When both early and late timing factors are taken into account, the results become even more complex. To convolute the matters more, the size of the volar pad with respect to the finger is also multifactorial. Diet and chemical intake of the mother (Holbrook, 1991b), hormone levels (Jamison, 1990), radiation levels (Bhasin, 1980), and any other factors that affect the growth rate of the fetus during the critical stage could all indirectly affect the ridge counts of the developing friction ridges on the finger. It is important to remember that anything that affects the tension across the surface of the finger could affect the resulting ridge alignment and pattern type. However, Holt’s findings seem to indicate that timing events, rather than environmental factors, play the dominant role in determining TFRC (Holt, 1968).

The onset of cellular proliferation, which begins during primary ridge formation, occurs in three distinct areas: (1) the apex of the volar pad (which corresponds to the core of the fingerprint pattern); (2) the distal periphery, or tip of the finger (near the nailbed); and (3) the distal interphalangeal flexion crease area (below the delta(s) in a fingerprint). As ridge formation continues, new proliferation occurs on the edges of the existing ridge fields in areas that do not yet display primary ridge formation. These three “fields” of ridges converge as they form, meeting in the delta area of the finger. This wavelike process of three converging fields allows for the visualization of how deltas most likely form. The concept of “converging ridge fields” also offers a way to visualize the difference between the formation of high versus low-ridge-count patterns. If ridges begin forming on the apex (center) of the pad first and proceed outward before formation begins on the tip and joint areas, then by the time the fields meet, a relatively large distance will have been traversed by the field on the apex of the pad; in that instance, a high-count pattern will be formed. However, if the ridges form first on the two outermost portions and proceed inward and formation begins at the last instant on the apex of the pad, then only a few ridges may be formed by the time the fields meet; in that instance, a very low-count pattern is observed. The combined observations of different researchers examining friction ridges on the finger during the critical stage of development further support the validity of this model (Babler, 1991, 1999; Dell & Munger, 1986; Hirsch & Schweichel, 1973).

When it is understood that timing and symmetry control two very different elements of ridge flow, it becomes easy to see how both small and large loop and whorl patterns form. A finger pad that regresses symmetrically will form a whorl pattern, regardless of early or late timing of friction ridge formation with respect to volar pad regression. If the timing of the onset of primary ridge formation in this situation is early in fetal life, then the volar pad will still be high on the finger, and the whorl pattern will have a high ridge count. If timing is later in fetal life, after the pad has almost completely been absorbed into the contours of the finger, then a low-count whorl pattern will result. With further regression, an arch pattern will form. Likewise, asymmetrical finger pads will form loop patterns and will also be affected by timing. If ridges begin forming early with respect to volar pad regression on an asymmetrical pad, then the pad will be large, and a high-count loop will result. Later timing leads to a low-count loop or arch-type pattern. Again, volar pad placement is not simply symmetrical or asymmetrical; a continuum of volar pad symmetry occurs and accounts for the variety of pattern types observed. A regression scheme seems to exist whereby the volar pad is symmetrical at the onset and becomes progressively more asymmetrical as it regresses. This is supported by general fingerprint pattern statistics that show that more than half of all fingerprint patterns are ulnar loops. More specifically, this scheme is supported by fetal research that has determined that early timing of primary ridge formation leads to a higher percentage (95 percent) of whorls (Babler, 1978). Also, low- and high-ridge-count patterns occur less frequently than average-count patterns (Cowger, 1983). All research tends to indicate that volar pads regress from an early symmetrical position to an asymmetrical position later in the fetal stage.

Regardless of the exact mechanism of minutiae formation (mechanical or static; fusion or chemical), the precise location of any particular bifurcation or ridge ending within the developing ridge field is governed by a random series of infinitely interdependent forces acting across that particular area of skin at that critical moment. Slight differences in the mechanical stress, physiological environment, or variation in the timing of development could significantly affect the location of minutiae in that area of skin. While there is still much research needed in regard to the formation of fingerprint minutiae and pattern development, we now have a better understanding of the complex formations that occur in utero.

Methodology Used in Field

The methodology most widely used by fingerprint analysts is ACE-V (analysis, comparison, evaluation, and verification) methodology. This methodology provides a framework and guides analysis to allow for more reliable and valid conclusions. Additionally, this methodology provides a way to measure reproducibility and to reduce bias through a verification step. The “Law of ACE” was originally coined by Roy Huber, an Assistant Commissioner from the Royal Mounted Canadian Police (RMCP) (Speckels, 2011). In the late 1950s, he was accredited for developing a systematic approach for comparing any two things, regardless of their subject matter. Later, in the 1980s, David Ashbaugh, also of the RCMP, added “V” to the end of ACE, thus developing the ACE-V methodology used in fingerprint analysis today.

The ACE-V methodology is accepted by most latent print examiners as a scientific process that is applied in order to objectively observe and form conclusions on friction ridge data (Speckels, 2011). Since the initial development by Huber in 1959, the methodology has fallen under scrutiny with critics claiming it does not adhere to the scientific method and has low reliability. However, professionals like analysts in the Federal Bureau of Investigation’s (FBI) Latent Print Unit, have described ACE-V as being a sound scientific method that if employed properly can produce accurate and reliable results.

ACE-V methodology begins with the analysis or procedural stage in which fingerprint analysts determine the characteristics present within the latent print and then the characteristics in known prints. This includes the examination of level one, level two, and level three detail. In addition, analysts will take into consideration matrix (the composition of sebaceous sweat, blood paint, etc.), substrate, development process, pressure applied when leaving the print, and print orientation. Analysis is followed by the comparison stage where the characteristics found in the latent print are compared to the known print to determine if the two have the same level one and level two detail. During the evaluation stage, a conclusion is formed based on the comparison of the known print and latent print. This conclusion will be either an identification, elimination, or inconclusive. An identification will be made when the examiner can prove that the fingerprint is a match to a certain one individual and no other individual using a number of fingerprint minutiae matches between the known and unknown print. An elimination will be made when the print could not be matched definitively to a single individual or is inconsistent with that of a known print. An inconclusive result will be made when the analyst in unable or uncomfortable making a definitive conclusion of either identification or elimination. In the verification stage, a second fingerprint examiner verifies the conclusion of the primary examiner by repeating analysis, comparison, and evaluation of the latent and known prints. This increases the validity of the analysis and significantly reduces bias in the results. In a study conducted by Pacheco, Cerchiai, and Stoiloff (2015) of Miami-Dade, the researchers sought out to determine just how reliable this new technology is, specifically the technology of ACE-V methodology. Tests were assembled using 80 latent prints with varying quantity and quality of information from ten known sources and were distributed to 109 latent print examiners across the United States (Pacheco, 2014). Participants had at least one year of latent print examination experience and employed the ACE methodology when comparing unknown latent prints to known sources. Responses from the participants yielded 5,963 sufficiency determinations, 4,536 ACE decisions, 532 ACE-V decisions, 1,311 repeatability decisions, 326 ACE decisions under biased conditions, and 333 repeatability decisions under biased conditions. This study took into account inconclusive responses in determining error rates and established a False Positive Rate (FPR) of 3.0% and False Negative Rate (FNR) of 7.5% for ACE examinations, as well as a FPR of 0.0% and FNR of 2.9% for ACE-V examinations. This represents a significant difference in the efficiency of older fingerprint analysis methods such as ACE methodology and newer employed methods such as ACE-V methodology.

ACE-V methodology is the basis for both Automated Fingerprint Identification Systems (AFIS) and the Integrated Automated Fingerprint Identification System (IAFIS). These systems are very similar in nature, the main difference being that AFIS functions as a local and state database, whereas IAFIS is a national database maintained by the FBI. AFIS and IAFIS are both computerized systems for storing, comparing, and exchanging fingerprint data in a digital format. The technology permits comparisons of fingerprints in a fast and accurate manner (Cuthbertson, n.d). Over the past few decades, collectively, these systems have been compiling fingerprints from millions of people. Whenever a criminal is apprehended and taken into police custody, their fingerprints are collected and then submitted into these systems. Additionally, whenever an employee submits their fingerprints for background checks or someone applies to purchase a firearm, their prints are also submitted into these databases. The FBI'S IAFIS system alone, currently houses more than 70 million subjects in the criminal master file and over 34 million civil prints (Criminal Justice Law International, n.d.). Of the millions of prints submitted to AFIS and IAFIS, no two sets of fingerprints from different individuals have proven to be an identification. This provides further evidence that no two individuals have the same exact fingerprints.

These systems have proven to be an essential tool for both local law enforcement as well as the FBI at a national level. By having these systems, law enforcement officials are able take a latent or patent print found at a crime scene, submit it into the database, and determine if it can be identified to one of millions of prints collected from criminals, known terrorists, and even those who have submitted their prints for job related inquires or firearm possessions. This not only aids law enforcement in removing dangerous criminals from society but does it in a manner that is quicker and more efficient than the methods, or lack thereof, used before this technology.

AFIX Tracker, one of many AFIS systems, first launched in 1998, works in conjunction with IAFIS, AFIS and ACE-V Methodology. The current system accepts images scanned from ten-print cards and most live scan devices, exchanges files between agencies in accepted EFTS/NIST formats, plots minutiae automatically, and matches both fingerprints and palms with superior technology (National Institute of Justice, 2018). By using such computer program, this was intended to take out some of the subjectivity and guess work out of fingerprint comparisons. This technology also holds the potential to eliminate human errors often made in fingerprint analysis. Unfortunately, despite being a computer program aimed to eliminate some of the potential of human error, there are still not standards in place for determining how many matching points are needed to confirm a positive match or on an acceptable error rate. Additionally, it is imperative that someone checks all of the matches made by the system, as the system has proven to make fatal errors in regard to identifications or matches.

Recently, digital enhancement use of latent fingerprints using Photoshop processing has become a preferred methodology amongst law enforcement and forensic experts. Using Photoshop methodology is intended to enhance, not alter, latent fingerprints for easier viewing and clearer ridge lines. Most often, the enhancements are made to adjust colors in contrast, with the goal being to make the print background as light as possible and the ridge lines of the prints as dark as possible, or the reverse of that if the print was deposited or collected onto a dark background. Enhancing this contrast and not manipulating the print assists examiners with annotation and analysis of fingerprint detail. Such enhancement methods are intended to bring into better visual range potentially significant structures that are present in the original image that are not easily visualized (Carasso, 2013). This methodology has proven successful over the years and is beginning to be widely employed by law enforcement agencies as Photoshop programs are generally cheaper to purchase than traditional fingerprint analysis programs and the reliability of this methodology has proven successful with enhancements, not alterations used in conjunction with ACE-V methodology.

In addition, in 2014, The Next Generation Identification (NGI) system officially replaced the FBI’s IAFIS system as a new, enhanced means of fingerprint comparisons. NGI uses a

Friction Ridge Investigative File that is three times more accurate than the previous latent search system of IAFIS (FBI, 2014). Prior to the NGI System, latent images were searched automatically only against the criminal repository. Now, latent images can be searched against the criminal, civil, and Unsolved Latent File (ULF) repositories, meaning that incoming criminal and civil submissions can generate new investigative leads in unsolved and/or cold cases. Within NGI, there is Advanced Fingerprint Identification Technology (AFIT) and the National Palm Print System (NPPS). AFIT employs enhanced fingerprint and latent processing services. This new system has increased accuracy with a new fingerprint-matching algorithm that improved matching accuracy from the 92 % of IAFIS to more than 99.6 %. NPPS is searchable by all law enforcement and is able to make comparisons for palm prints in the same way that is done with fingerprints. This greatly expands law enforcement's investigative capabilities because one-third of crimes with prints found at the crime scene are palm prints rather than fingerprints.

Challenges of Legitimacy

Criticism of ACE-V methodology as a method for fingerprint analysis has developed in recent years due to the many discrepancies within the discipline. Concerns about and recommendations for enhancing the discipline of fingerprint analysis have been made by the PCAST Working Group and the National Institute of Justice. A common critique is that this methodology lacks a universal number of characteristics that need to be found in order to identify two prints as coming from the same source to the exclusion of all others. In the report made by the PCAST Working group, it is suggested to establish point criteria for matches, as the British do, who use a 16-point standard for declaring identifications (Holdren & Lander, 2016). Establishing a similar universal number for match qualifications of fingerprints could enhance the discipline immensely and settle some of the discrepancies that many have about the discipline of fingerprint analysis.

In the 1993 case of Daubert v. Merrell Dow Pharmaceuticals, a ruling was made that outlined criteria concerning the admissibility of scientific expert testimony based somewhat on criteria used in the broader scientific community (Abraham, 2013). For expert testimony to be admissible in court, the methodology used in analysis must follow the scientific method and meet the following criteria: must be testable and falsifiable theories or techniques, must be subjected to peer review and publication, must have known or predicted error rates, must have standards or controls concerning its applications, and must be generally accepted by the scientific community (Abraham, 2013). While fingerprint analysis is widely accepted by courts, certain critics have publicly doubted that the guidelines for expert testimony admissibility have been met.

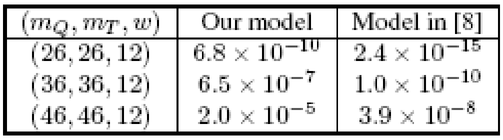
A major area of criticism is in regard to the lack of error rates associated with the analysis of friction ridge skin. The National Institute of Justice (2018), states “It is needed to establish a scientific methodology to quantify the accuracy and error rates of forensic evidence.” In turn, researchers at the National Institute of Justice set out to develop an accurate and quantitative metric for measuring the difficulty of latent fingerprints for any given comparison. Instead of simply looking at how well examiners perform on a given task, the researchers said, “We are interested in whether they have the meta-awareness, regarding both their own performance and the potential performance of fingerprint examiners more generally on that print.” The intention of this study is to explore objective print characteristics that can account for the difficulty of a single comparison and presents the benefits of creating objective measures of difficulty for print match candidates. The overall aim of this research is to explore the “feasibility of an automated system that could grade the difficulty of print comparisons and predict likely error rates.” This study, led by Jennifer Mnookin, dean of the UCLA School of Law, created a database to determine fingerprint comparison difficulty by collecting prints from 103 different fingers from participants. The prints were first collected using fingerprint ink and a ten-print card, the fingerprints were rolled similarly to the way that is done at police stations. Next, the researchers had participants touch various objects using the same fingers to create latent fingerprints. The prints were dusted with powder, lifted, and then scanned using an imaging system. The researchers took 200 latent and known fingerprint pairs. Half of these pairs were a match and the other half of the pairs were non-matches, but presented very similar characteristics to one another. Fifty-six fingerprint experts each made match or non-match, identification or exclusion, judgments for each print and provided confidence and difficulty ratings. This was done for a total of 2,282 trials, or comparisons. It was found that matches were made at a 91% accuracy. On average, the researchers said, “Examiners were generally able to recognize when they were likely to make an error on a comparison and in aggregate were able to recognize when other examiners were likely to err as well.” The researchers said their study, “demonstrates that error rates are indeed a function of comparison difficulty.” The research also provided strong evidence that prints vary in difficulty and that the variations affect the likelihood of error in making comparisons. This advancement in the discipline of fingerprint analysis pushes it closer to becoming an irrefutable form of criminal identification.

Criticism of Galton’s initial research has arisen over the years, specifically in regard to the likelihood that every individual possesses fingerprint characteristics unique to them and only them. A measure of fingerprint individuality is given by the probability of a random correspondence, which is the probability that two minutiae, one from the query and the other from the template fingerprint, randomly correspond with each other (Dass, 2010). This is because the formation and placement of any type of minutiae within the developing ridge field is controlled by a random assortment of interdependent factors at any given moment during development (Wertheim & Maceo, 2002). Mechanical stress, physiological environment, and variation in the timing of development could affect minutiae placement. Taking into account the theory of randomness in which fingerprints are formed in utero and adding that with the millions of prints in AFIS and IAFIS systems, none of which that have been a match to each other, we can conclude the high probability that supports the notion that fingerprints are unique to each individual. This continues to support Galton's original notion stating that fingerprints are unique to an individual.

Research Supporting Legitimacy

Despite these claims against the legitimacy of fingerprint analysis, the evidence supporting individuality of fingerprints is overwhelming. As mentioned before, AFIS and IAFIS have recorded, analyzed, and stored millions of fingerprints and to this date, no two individuals have been discovered to have the same fingerprints. Additionally, due to the unique way that fingerprints are formed in utero and the scars that a person may develop over their lifetime, the probability of every individual having a unique set of fingerprints is relatively high. Many researchers have also conducted research to support the concept of the individuality of fingerprints. In a study conducted by Yongfang Zhu and S.C Dass (2006), quantitative measures were developed to characterize the extent of uniqueness of a fingerprint. The researchers developed compound stochastic models that accounted for three sources of minutiae variability, namely, (i) the variability in the minutiae distributions in different fingers, (ii) variability due to local perturbations arising from non-linear distortion effects in multiple impressions of a finger, and (iii) variability due to the size of partial prints (or the area of finger region captured) in multiple acquisitions of a finger (Zhu, 2006). These compound stochastic models were then used for synthesis as well as for obtaining estimates of fingerprint individuality. To compare their research findings to previous findings on fingerprint individuality, the researchers derived fingerprint individuality estimates using the IEEE Transactions on Pattern Analysis and Machine Intelligence. The IEEE Transactions on Pattern Analysis and Machine Intelligence computes the individuality estimate based on the number of minutiae in the query and template that occur in the overlap area (Zhu & Dass, 2006). Their findings are shown in *Table 1.* A query fingerprint is represented by *Q*, minutiae are represented by *mQ*, and a template is represented by *T*. This shows that statistically speaking, the probability of each individual having a unique fingerprint is high. Results support each individual having a unique set of fingerprints.

Table 1. *Fingerprint Individuality results from study conducted by Zhu and Dass* (2006)



(m_Q, m_T, w)	Our model	Model in [8]
$(26, 26, 12)$	6.8×10^{-10}	2.4×10^{-15}
$(36, 36, 12)$	6.5×10^{-7}	1.0×10^{-10}
$(46, 46, 12)$	2.0×10^{-5}	3.9×10^{-8}

Gender Differences in Fingerprint Ridge Density

Previous assumptions in fingerprint literature have stated that women tend to have “fine” fingerprint ridge detail, whereas men tend to have “coarse” ridge detail. However, before Acree’s (1999) study, the concept was not clearly demonstrated. Proving the validity of such concept could enable law enforcement to determine an unknown suspect’s gender solely based on a fingerprint left behind at a scene. This study took 400 randomly picked ten-print cards representing 400 subjects with a demographic composition of 100 Caucasian males, 100 African American males, 100 Caucasian females and 100 African American females, all within the age range of 18–67. Interestingly, results showed that women tend to have a significantly higher ridge density than men, both in Caucasian and African American sample groups. For this study, the application of Bayes' theorem was used, which describes the probability of an event, based on prior knowledge of conditions that might be related to the event. This suggested that a given fingerprint possessing a ridge density of 11 ridges (25 mm or less) is most likely to be of male origin and a fingerprint having a ridge density of 12 ridges (25 mm or greater) is most likely to be of female origin, regardless of race (Acree, 1999). In more recent research endeavors, Kanhan, et al. (2012) set out to determine if a forensic identification of gender can be made from palm print ridge density. The results of this particular study were as follows:

> "The mean palm print ridge density was significantly higher among women than men in all the designated areas in both hands except for the interdigital area in the right hand. Statistically significant differences were observed in the palm print ridge density between the different palm areas in men and women in right and left hands. No significant right–left differences were observed in the palm print ridge density in any of the four areas of palm prints among men. In women, right-left differences were observed only in the interdigital areas of palm prints. This preliminary study indicates that though the palm print ridge density is a sexually dimorphic variable, its utility for estimation of sex in forensic identification may be limited owing to significant overlapping of values."

While this seems to contradict earlier research, it is possible that fingerprint ridge density varies not only amongst gender, but also amongst fingerprint and palm print.

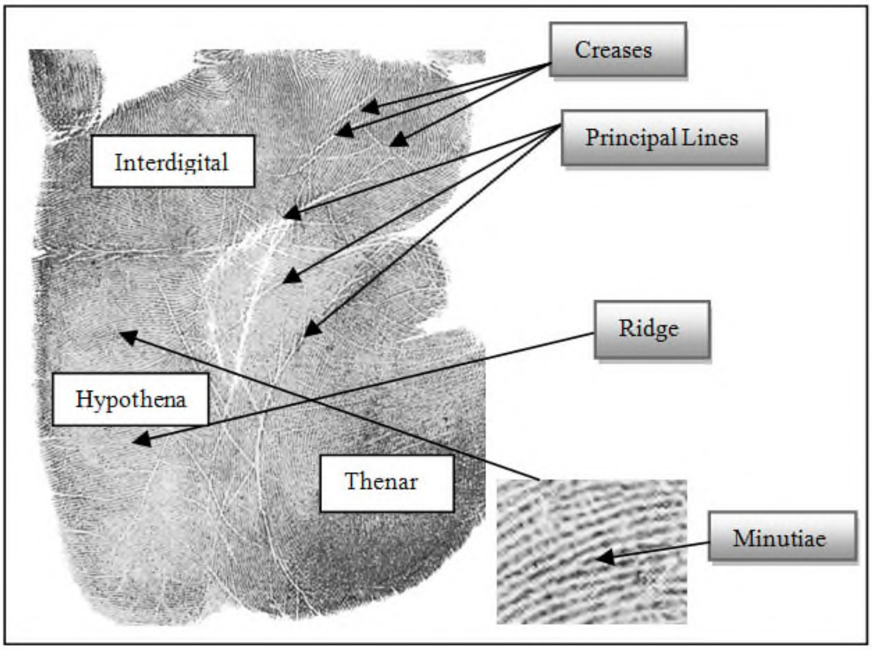


Figure 4. Structure of palm print (principal lines, ridges, creases and minutiae in a palm print) by Sonawe (2013*)*.

Fingerprints and Ancestry

Determining an individual's ancestry from fingerprint minutiae characteristics has been a research question addressed by many studies and is a dilemma that Galton himself delved into. Galton studied and compared the fingerprints of English pure Welsh, Hebrew, African, and some Basques from Cambo in the French Pyrenees to look for differences in patterns and minutiae characteristics. His study had a sample size of over 100 individuals. After conducting the study, Galton (1899) arrived at the conclusion that:

> "It requires considerable patience and caution to arrive at trustworthy conclusions, but it may emphatically be said that there is no *peculiar* pattern of characteristics of any of the above ancestries. There is no particular pattern that is special to any one of them, which when met enables us to assert, or even to suspect, the nationality of the person on whom it appeared" (p. 193).

Although Galton did not seem to arrive at any evidence of determining ancestry from characteristics within an individual’s fingerprint, he (1899) did state:

> “Still whether it be from pure fancy on my part, or from the way in which they were printed, or from some personal peculiarity, the general aspect of the [African] print strikes me as characteristic. The width of the ridges seem more uniform, their intervals more regular, and their courses more parallel than with [Caucasians]” (p. 196).

Galton only observed the initial level of fingerprint characteristics. Accordingly, more in-depth research needed to be conducted to analyze the possibility of ancestry, or even sex, as being derived from fingerprint characteristics. Being able to determine a person’s sex or ancestral background from a complete or partial fingerprint collected from a crime scene could be groundbreaking and provide investigative leads to law enforcement in cases where there is no suspect.

Fournier and Ross (2015) conducted a study with the purpose of exploring the influence of sex, ancestry, and pattern type on minutiae in African descendant and European descendant males and females. Their study was based on the concept of dermatoglyphics or the nonidentification aspects of epidermal ridges (Cummins, 1946). With the assistance of the City-County Bureau of Identification, researchers gathered fingerprints taken on 10-print cards. The right index finger was used in this study due to the high statistical likelihood of latent prints found at crime scenes to be those deposited by the right index finger. To qualify for the study, each card was carefully analyzed to ensure no smudging or scarring was present in any of the prints that could potentially alter ridge flow and minutiae. Once a fingerprint was determined to be of sufficient quality, the sex and ancestry of each participant were ascertained based on self-identification and demographic information within the database (Fournier & Ross, 2015). Overall, 243 right index fingerprints were chosen to include 61 African American females and 61 African American males for a total 122 African Americans as well as 60 European American males and 61 European American females for a total of 121 European Americans. Each pattern type was recorded and the five minutiae types were analyzed and quantified: bifurcations, enclosures, dots, ending ridges, and short ridges. Next, analysts submitted the prints to PrintQuest for the analysis of minutia, divided the print into four quadrants to simplify counting, and then counted the amount of each minutiae type in all four quadrants. This method was used for all 243 prints.

After all data was collected and recorded, descriptive summary statistics were ran using Multivariant Analysis of Covariance (MANCOVA) to test whether sex, ancestry, and pattern type have significant effects on average minutiae variables (Fournier & Ross, 2015). Interestingly, it was found that the frequency of arches is higher in European American males and females than in African American males and females (Fournier & Ross, 2015). It was also determined that bifurcations are a significant predictor of ancestry. African Americans are nearly six times more likely to have bifurcations as opposed to European Americans. It was also found that sex does not have a significant influence on minutiae. Based on this study, fingerprint minutiae, specifically the total number of bifurcations shows promise as a method to predict the ancestry of an individual to some degree of certainty. This is something that could prove to be beneficial to law enforcement when including or excluding suspects based solely on latent prints found at a crime scene.

Gaps in the Research

The research conducted by Fournier and Ross (2015) indicates that there is the possibility of deriving a persons' ancestry from the amount of bifurcation minutiae in their fingerprints. However, one of the biggest gaps in this research is the fact that only two ancestries are explored, African descendants and European descendants. The diversity of individuals in the United States where AFIS and IAFIS technology is utilized indicates the need to expand this research to incorporate more ancestral backgrounds and ethnicities, for example individuals of Asian descent, Native American descent, and Hispanic descent. Also, gathering more data from individuals of African descent and European descent would increase the statistical power and validity of the current study. Collecting fingerprints from the aforementioned ancestry groups might prove valuable to law enforcement for including and excluding suspects based on minutiae features and corresponding ancestral determinations.

Materials and Methods

Sample

All fingerprints obtained and analyzed for use in this study were recorded from willing participants attending the University of Central Oklahoma, a four-year institution, and from participants living in the greater Oklahoma City Metro area. Participants did not receive any incentives for partaking in the study. All personal and identifiable information was excluded from the study in order to protect the privacy of the participants. As this study involved living, human participants, permission was sought from the University of Central Oklahoma's Institutional Review Board. The aim of this research was to collect 40 right index fingerprints (20 males and 20 females) from each ancestral category for a total of 200 participants.

- 20 Hispanic descent males, 20 Hispanic descent females

- 20 Asian descent males, 20 Asian descent females
- 20 Native American descent males, 20 Native America descent females
- 20 African descent males, 20 African descent females
- 20 European descent males, and 20 European descent females

Ancestry was determined based on participants' answers to a questionnaire presented prior to collection of fingerprints. Collecting information through this questionnaire presented a limitation within the study as we were relying on self-identification of ancestral background. However, it proved to be the most efficient and least costly means of collecting the data required for this research. For future studies, ascertaining an individual's ancestral background through genealogical measures would further validate the results of the study.

Methods

For this particular study, it was hypothesized that ancestral background would significantly correlate with the number of minutiae, specifically bifurcations, found in the individual's fingerprint. In order to test this hypothesis, each participant initially completed a brief demographic questionnaire to determine the participant's ancestry as well as any other information needed to categorize and organize the data in the study. In order to collect the prints, each participant had their prints rolled on a blank index card using inkless fingerprint pads. Each print showed a complete nail-to-nail roll, similar to methods used in police stations and correctional facilities. Because of the statistical likelihood that the right index finger is the print most often encountered at crime scenes, those prints were the ones chosen to be used for analysis. To be viable for this study, each print contained minimal to no smudging or profound scars that would alter the ridge flow or minutiae. Additionally, each participant must have been able to identify, to their best knowledge, their ancestral background with some degree of certainty. Once a fingerprint was determined to be viable, ancestry and sex were recorded on the back of each rolled print based on the information provided by each individual on their questionnaire. Participant's demographic survey and IRB consent for research participation was then separated from the prints to ensure each participant's anonymity.

With assistance of Adobe Photoshop, each print was enhanced using adjustment layer levels in the attempt to achieve the darkest ridge lines with the lightest background as possible, thus making the prints easier to visualize during analysis. An example of this enhancement is shown below in *Figure 7*. No other manipulations were made to the prints beyond changing the contrast of the prints. Each print was analyzed and marked for each of the five main fingerprint minutiae characteristics: bifurcations, enclosures, dots, ending ridges, and short ridges. Additionally, the pattern type for each fingerprint was determined and labeled as a loop, whorl or arch. For the purpose of this study, ridges that split into two separate ridges were labeled bifurcations, ridges with no direction or flow that were minute in length were labeled short ridges, ridges with no direction or flow and that were as wide as they were long were labeled dots, ridge lines that came to an abrupt stop and were not connected to another ridge line were labeled as ending ridges and two bifurcations that met each other to form a surrounded void of ridges were labeled enclosures. Once every print was marked for the desired fingerprint minutiae, each print was divided into four quadrants to decrease the viewing field for easier summation, which helped avoid double counting and omitting of minutiae. Each quadrant was counted three times to reduce error. If an enclosure crossed over more than one quadrant, it was counted a single time for whichever quadrant held the majority of the enclosure. Minutiae counts for each print were recorded. This study differed from Fournier and Ross's (2015) study in that Asian descendants, Native American descendants and Hispanic descendants were added to the ancestral backgrounds analyzed along with African descendants and European descendants which were included in the previous study. Expanding upon Fournier and Ross (2015) study by adding additional ancestral backgrounds strengthened the external validity as it relates to the diverse population within the United States.

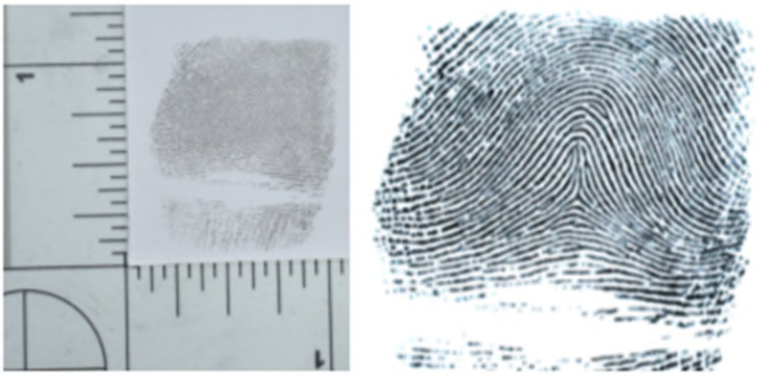
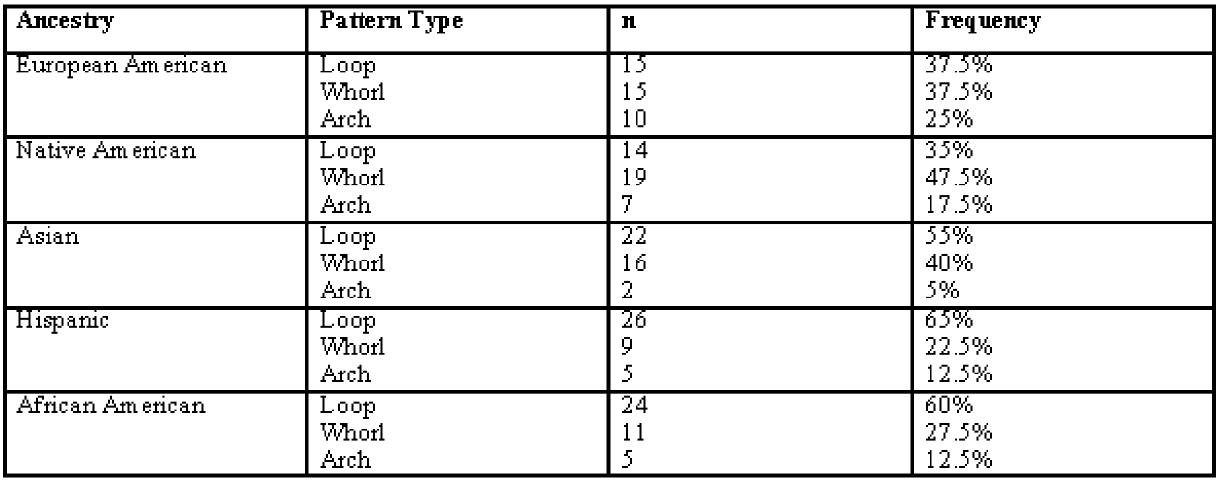


Figure 5. Raw (left) and Enhanced (right) prints using Adobe Photoshop

Results

Once the pattern type and the total count for each type of minutiae in each index fingerprint was obtained, the data was then submitted for statistical analysis. Initially, descriptive summary statistics were determined to account for pattern type frequency amongst the five ancestries. Interestingly, it was observed that all of the ancestries tended to follow the Federal Bureau of Investigation’s (FBI) research findings that the majority of the population (65%) tend to have loops, followed by whorls (30%) and then arches (5%). Prints from the Native American Ancestral group did not follow this assumption with 35% exhibiting a loop pattern, 47.5% exhibiting a whorl pattern and 17.5% exhibiting an arch pattern. These findings are shown in *Table 2*.

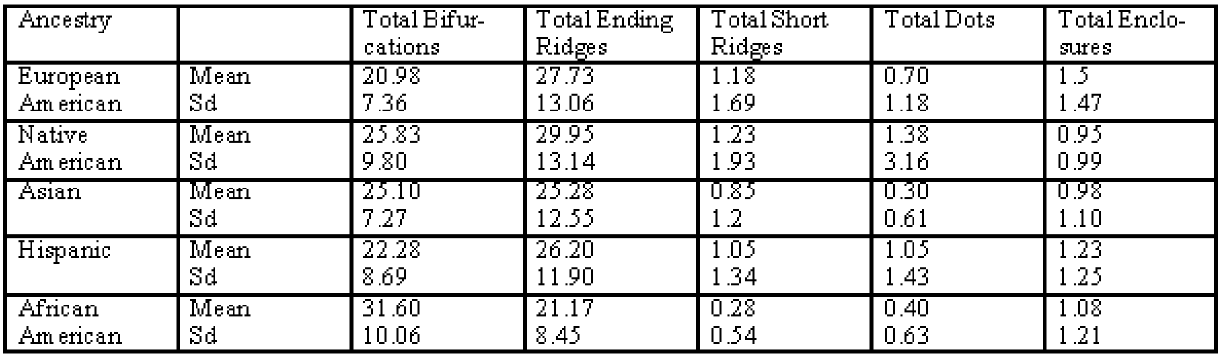
Table 2. Descriptive Statistics: Pattern Type



Ancestry	**Pattern Type**	**n**	**Frequency**
European American	Loop Whorl Arch	15 15 10	37.5% 37.5% 25%
Native American	Loop Whorl Arch	14 19 7	35% 47.5% 17.5%
Asian	Loop Whorl Arch	22 16 2	55% 40% 5%
Hispanic	Loop Whorl Arch	26 9 5	65% 22.5% 12.5%
African American	Loop Whorl Arch	24 11 5	60% 27.5% 12.5%

Next, descriptive statistics were determined for ancestry and the five minutiae types (Galton details). Of the five ancestries, the African descent group was the only of the five ancestries that had a higher mean of bifurcations as opposed to ending ridges. Additionally, Hispanic and Native American descendants were the only groups with a mean higher than 1.0 when looking at dot minutiae in the fingerprint. This suggests that a prevalence of dots may suggest Native American or Hispanic ancestry when analyzing a fingerprint. These findings are shown in *Table 3*.

Table 3. Descriptive Statistics: Minutiae Types



Ancestry		Total Bifurcations	Total Ending Ridges	Total Short Ridges	Total Dots	Total Enclosures
European American	Mean Sd	20.98 7.36	27.73 13.06	1.18 1.69	0.70 1.18	1.5 1.47
Native American	Mean Sd	25.83 9.80	29.95 13.14	1.23 1.93	1.38 3.16	0.95 0.99
Asian	Mean Sd	25.10 7.27	25.28 12.55	0.85 1.2	0.30 0.61	0.98 1.10
Hispanic	Mean Sd	22.28 8.69	26.20 11.90	1.05 1.34	1.05 1.43	1.23 1.25
African American	Mean Sd	31.60 10.06	21.17 8.45	0.28 0.54	0.40 0.63	1.08 1.21

A multivariant analysis of variance (MANOVA) test was used to determine if sex can predict pattern type or minutiae quantities. MANOVA results showed statistically insignificant results for sex and pattern type (p = .559 > .05). It also showed statistically insignificant results for sex and the five Galton details or minutiae types for dots with a p value of .079 >.05, ending ridges with a p value of .470 > .05, bifurcations with a p value of .340 >.05, enclosures with a p value of .325 > .05 and short ridges with a p value of .068 > .05. This suggested that sex cannot predict pattern type or quantities of the five analyzed minutiae types. These results are shown below in *Table 4.*

Table 4. MANOVA Results: Sex, Galton Details and Pattern type

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	DOTS	8.820[a]	1	8.820	3.120	.079
	ENDINGRIDGES	78.125[b]	1	78.125	.525	.470
	BIFURCATIONS	80.645[c]	1	80.645	.916	.340
	ENCLOSURES	1.445[d]	1	1.445	.975	.325
	SHORTRIDGES	6.845[e]	1	6.845	3.365	.068
	PATTERN	.180[f]	1	.180	.343	.559
Intercept	DOTS	109.520	1	109.520	38.747	.000
	ENDINGRIDGES	135876.845	1	135876.845	913.348	.000
	BIFURCATIONS	126554.805	1	126554.805	1436.840	.000
	ENCLOSURES	262.205	1	262.205	176.978	.000
	SHORTRIDGES	167.445	1	167.445	82.328	.000
	PATTERN	537.920	1	537.920	1025.103	.000
SEX	DOTS	8.820	1	8.820	3.120	.079
	ENDINGRIDGES	78.125	1	78.125	.525	.470
	BIFURCATIONS	80.645	1	80.645	.916	.340
	ENCLOSURES	1.445	1	1.445	.975	.325
	SHORTRIDGES	6.845	1	6.845	3.365	.068
	PATTERN	.180	1	.180	.343	.559
Error	DOTS	559.660	198	2.827		
	ENDINGRIDGES	29456.030	198	148.768		
	BIFURCATIONS	17439.550	198	88.079		
	ENCLOSURES	293.350	198	1.482		
	SHORTRIDGES	402.710	198	2.034		
	PATTERN	103.900	198	.525		
Total	DOTS	678.000	200			
	ENDINGRIDGES	165411.000	200			
	BIFURCATIONS	144075.000	200			
	ENCLOSURES	557.000	200			
	SHORTRIDGES	577.000	200			
	PATTERN	642.000	200			
Corrected Total	DOTS	568.480	199			
	ENDINGRIDGES	29534.155	199			
	BIFURCATIONS	17520.195	199			
	ENCLOSURES	294.795	199			
	SHORTRIDGES	409.555	199			
	PATTERN	104.080	199			

The MANOVA with Tukey’s Post Hoc tests revealed no significant mean differences between any of the descent groups and pattern types. The test did reveal a near significant (p=.053) mean difference between the Native American descent and Hispanic descent groups regarding the loop pattern type with Hispanic descendants having a higher frequency (65%) for loops as opposed to the Native American descent group (35%) These findings are shown below in *Table 5*.

Table 5. Tukey's Post Hoc: Ancestry and Pattern Types

Multiple Comparisons

Tukey HSD

Dependent Variable	(I) ANCESTRY	(J) ANCESTRY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LOOP	EUROPEAN	NATIVE	.0250	.10987	.999	-.2775	.3275
		ASIAN	-.1750	.10987	.504	-.4775	.1275
		HISPANIC	-.2750	.10987	.094	-.5775	.0275
		AFRICAN	-.2250	.10987	.247	-.5275	.0775
	NATIVE	EUROPEAN	-.0250	.10987	.999	-.3275	.2775
		ASIAN	-.2000	.10987	.365	-.5025	.1025
		HISPANIC	-.3000	.10987	.053	-.6025	.0025
		AFRICAN	-.2500	.10987	.157	-.5525	.0525
	ASIAN	EUROPEAN	.1750	.10987	.504	-.1275	.4775
		NATIVE	.2000	.10987	.365	-.1025	.5025
		HISPANIC	-.1000	.10987	.893	-.4025	.2025
		AFRICAN	-.0500	.10987	.991	-.3525	.2525
	HISPANIC	EUROPEAN	.2750	.10987	.094	-.0275	.5775
		NATIVE	.3000	.10987	.053	-.0025	.6025
		ASIAN	.1000	.10987	.893	-.2025	.4025
		AFRICAN	.0500	.10987	.991	-.2525	.3525
	AFRICAN	EUROPEAN	.2250	.10987	.247	-.0775	.5275
		NATIVE	.2500	.10987	.157	-.0525	.5525
		ASIAN	.0500	.10987	.991	-.2525	.3525
		HISPANIC	-.0500	.10987	.991	-.3525	.2525
WHORL	EUROPEAN	NATIVE	-.1000	.10610	.880	-.3921	.1921
		ASIAN	-.0250	.10610	.999	-.3171	.2671

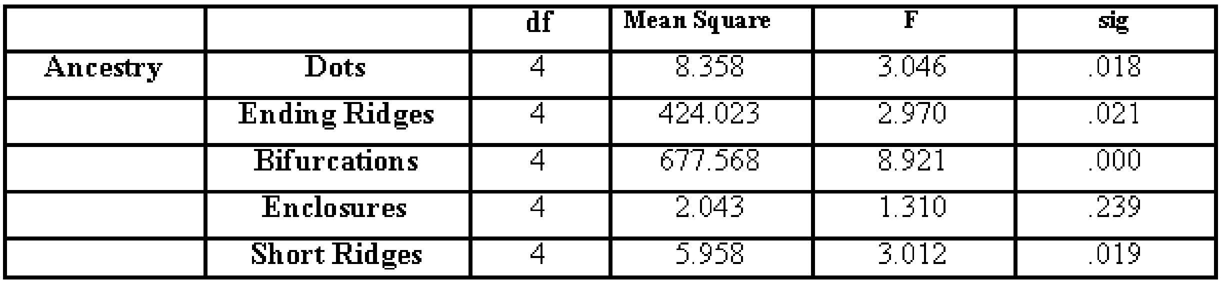
		NATIVE	-.2000	.10610	.329	-.4921	.0921
		ASIAN	-.1250	.10610	.764	-.4171	.1671
		HISPANIC	.0500	.10610	.990	-.2421	.3421
ARCH	EUROPEAN	NATIVE	.0750	.07832	.874	-.1407	.2907
		ASIAN	.2000	.07832	.083	-.0157	.4157
		HISPANIC	.1250	.07832	.502	-.0907	.3407
		AFRICAN	.1250	.07832	.502	-.0907	.3407
	NATIVE	EUROPEAN	-.0750	.07832	.874	-.2907	.1407
		ASIAN	.1250	.07832	.502	-.0907	.3407
		HISPANIC	.0500	.07832	.969	-.1657	.2657
		AFRICAN	.0500	.07832	.969	-.1657	.2657
	ASIAN	EUROPEAN	-.2000	.07832	.083	-.4157	.0157
		NATIVE	-.1250	.07832	.502	-.3407	.0907
		HISPANIC	-.0750	.07832	.874	-.2907	.1407
		AFRICAN	-.0750	.07832	.874	-.2907	.1407
	HISPANIC	EUROPEAN	-.1250	.07832	.502	-.3407	.0907
		NATIVE	-.0500	.07832	.969	-.2657	.1657
		ASIAN	.0750	.07832	.874	-.1407	.2907
		AFRICAN	.0000	.07832	1.000	-.2157	.2157
	AFRICAN	EUROPEAN	-.1250	.07832	.502	-.3407	.0907
		NATIVE	-.0500	.07832	.969	-.2657	.1657
		ASIAN	.0750	.07832	.874	-.1407	.2907
		HISPANIC	.0000	.07832	1.000	-.2157	.2157

Based on observed means.

The error term is Mean Square(Error) = .123.

A Multivariance Analysis of Variance (MANOVA) was performed to determine if ancestry could significantly predict minutiae types. Results indicated ancestry can significantly predict: dots (p= .018 < .05), ending ridges (p= .021 < .05), bifurcations (p=.000 < .05) and short ridges (p= .019 < .05). It indicated ancestry cannot significantly predict: enclosures (p= .239 > .05). These results are shown below in *Table 6*.

Table 6. Multivariate Analysis of Variance (MANOVA) results: Ancestry and Minutiae Types



		df	Mean Square	F	sig
Ancestry	**Dots**	4	8.358	3.046	.018
	Ending Ridges	4	424.023	2.970	.021
	Bifurcations	4	677.568	8.921	.000
	Enclosures	4	2.043	1.310	.239
	Short Ridges	4	5.958	3.012	.019

Tukey’s Post Hoc tests were performed post MANOVA to determine if there are significant differences amongst the ancestries and minutiae types. Tukey’s Post Hoc tests revealed a significant (p=.033) mean difference between the Native American descent and Asian descent groups regarding the number of dots present in the friction ridge impression with the number of dots being higher in the Native American descent group (mean= 1.38) than in the Asian descent group (mean= 0.30). Tukey’s Post Hoc tests revealed a significant (p=.011) mean difference between the Native American descent and African descent groups regarding the number of ending ridges present in the friction ridge impression with the number of ending ridges being higher in the Native American descent group (mean= 29.95) than in the African descent group (mean= 21.17). Tukey’s Post Hoc tests revealed a significant (p=.000) mean difference between the African descent and European descent groups regarding the number of bifurcations present in the friction ridge impression with the number of bifurcations being higher in the African descent group (mean= 31.60) than in the European descent group (mean 20.98). Tukey’s Post Hoc tests revealed a significant (p=.028) mean difference between the Native American descent and African descent groups regarding the number of bifurcations present in the friction ridge impression with the number of bifurcations being higher in the African descent group (mean= 31.60) than in the Native American descent group (mean 25.83). Tukey’s Post Hoc tests revealed a significant (p=.009) mean difference between the African descent and Asian descent groups regarding the number of bifurcations present in the friction ridge impression with the number of bifurcations being higher in the African descent group (mean= 31.60) than in the Asian descent group (mean 25.10). Tukey’s Post Hoc tests revealed a significant (p=.000) mean difference between the African descent and Hispanic descent groups regarding the number of bifurcations present with the number of bifurcations being higher in the African descent group (mean= 31.60) than in the Hispanic descent group (mean 22.98). Tukey’s Post Hoc tests revealed no significant mean differences between any of the descent groups regarding the number of enclosures. Tukey’s Post Hoc tests revealed a significant (p=.037) mean difference between the African descent and European descent groups regarding the number of short ridges present in the friction ridge impression with the number of short ridges being higher in the European descent group (mean= 1.18) than in the African descent group (mean 0.28). Lastly, Tukey’s Post Hoc tests revealed a significant (p=.024) mean difference between the Native American descent and African descent groups regarding the number of short ridges present in the friction ridge impression with the number of short ridges being higher in the Native American descent group (mean= 1.23) than in the African descent group (mean 0.28). The results are shown below in *Table 7*.

Table 7. Tukey's Post Hoc: Ancestry and Minutiae Types

Multiple Comparisons

Tukey HSD

Dependent Variable	(I) ANCESTRY	(J) ANCESTRY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
DOTS	EUROPEAN	NATIVE	-.8000	.37039	.200	-1.8199	.2199
		ASIAN	.2750	.37039	.946	-.7449	1.2949
		HISPANIC	-.4750	.37039	.702	-1.4949	.5449
		AFRICAN	.1750	.37039	.990	-.8449	1.1949
	NATIVE	EUROPEAN	.8000	.37039	.200	-.2199	1.8199
		ASIAN	1.0750*	.37039	.033	.0551	2.0949
		HISPANIC	.3250	.37039	.905	-.6949	1.3449
		AFRICAN	.9750	.37039	.068	-.0449	1.9949
	ASIAN	EUROPEAN	-.2750	.37039	.946	-1.2949	.7449
		NATIVE	-1.0750*	.37039	.033	-2.0949	-.0551
		HISPANIC	-.7500	.37039	.258	-1.7699	.2699
		AFRICAN	-.1000	.37039	.999	-1.1199	.9199
	HISPANIC	EUROPEAN	.4750	.37039	.702	-.5449	1.4949
		NATIVE	-.3250	.37039	.905	-1.3449	.6949
		ASIAN	.7500	.37039	.258	-.2699	1.7699
		AFRICAN	.6500	.37039	.403	-.3699	1.6699
	AFRICAN	EUROPEAN	-.1750	.37039	.990	-1.1949	.8449
		NATIVE	-.9750	.37039	.068	-1.9949	.0449
		ASIAN	.1000	.37039	.999	-.9199	1.1199
		HISPANIC	-.6500	.37039	.403	-1.6699	.3699
ENDINGRIDGES	EUROPEAN	NATIVE	-2.2250	2.67170	.920	-9.5814	5.1314
		ASIAN	2.4500	2.67170	.890	-4.9064	9.8064
		HISPANIC	1.5250	2.67170	.979	-5.8314	8.8814
		AFRICAN	6.5500	2.67170	.106	-.8064	13.9064
	NATIVE	EUROPEAN	2.2250	2.67170	.920	-5.1314	9.5814
		ASIAN	4.6750	2.67170	.406	-2.6814	12.0314
		HISPANIC	3.7500	2.67170	.626	-3.6064	11.1064
		AFRICAN	8.7750*	2.67170	.011	1.4186	16.1314
	ASIAN	EUROPEAN	-2.4500	2.67170	.890	-9.8064	4.9064
		NATIVE	-4.6750	2.67170	.406	-12.0314	2.6814
		HISPANIC	-.9250	2.67170	.997	-8.2814	6.4314
		AFRICAN	4.1000	2.67170	.541	-3.2564	11.4564
	HISPANIC	EUROPEAN	-1.5250	2.67170	.979	-8.8814	5.8314
		NATIVE	-3.7500	2.67170	.626	-11.1064	3.6064

		NATIVE	-3.7500	2.67170	.626	-11.1064	3.6064
		ASIAN	.9250	2.67170	.997	-6.4314	8.2814
		AFRICAN	5.0250	2.67170	.331	-2.3314	12.3814
	AFRICAN	EUROPEAN	-6.5500	2.67170	.106	-13.9064	.8064
		NATIVE	-8.7750*	2.67170	.011	-16.1314	-1.4186
		ASIAN	-4.1000	2.67170	.541	-11.4564	3.2564
		HISPANIC	-5.0250	2.67170	.331	-12.3814	2.3314
BIFURCATIONS	EUROPEAN	NATIVE	-4.8500	1.94870	.097	-10.2157	.5157
		ASIAN	-4.1250	1.94870	.217	-9.4907	1.2407
		HISPANIC	-1.3000	1.94870	.963	-6.6657	4.0657
		AFRICAN	-10.6250*	1.94870	.000	-15.9907	-5.2593
	NATIVE	EUROPEAN	4.8500	1.94870	.097	-.5157	10.2157
		ASIAN	.7250	1.94870	.996	-4.6407	6.0907
		HISPANIC	3.5500	1.94870	.364	-1.8157	8.9157
		AFRICAN	-5.7750*	1.94870	.028	-11.1407	-.4093
	ASIAN	EUROPEAN	4.1250	1.94870	.217	-1.2407	9.4907
		NATIVE	-.7250	1.94870	.996	-6.0907	4.6407
		HISPANIC	2.8250	1.94870	.596	-2.5407	8.1907
		AFRICAN	-6.5000*	1.94870	.009	-11.8657	-1.1343
	HISPANIC	EUROPEAN	1.3000	1.94870	.963	-4.0657	6.6657
		NATIVE	-3.5500	1.94870	.364	-8.9157	1.8157
		ASIAN	-2.8250	1.94870	.596	-8.1907	2.5407
		AFRICAN	-9.3250*	1.94870	.000	-14.6907	-3.9593
	AFRICAN	EUROPEAN	10.6250*	1.94870	.000	5.2593	15.9907
		NATIVE	5.7750*	1.94870	.028	.4093	11.1407
		ASIAN	6.5000*	1.94870	.009	1.1343	11.8657
		HISPANIC	9.3250*	1.94870	.000	3.9593	14.6907
ENCLOSURES	EUROPEAN	NATIVE	.5500	.27110	.256	-.1965	1.2965
		ASIAN	.5250	.27110	.302	-.2215	1.2715
		HISPANIC	.2750	.27110	.849	-.4715	1.0215
		AFRICAN	.4250	.27110	.520	-.3215	1.1715
	NATIVE	EUROPEAN	-.5500	.27110	.256	-1.2965	.1965
		ASIAN	-.0250	.27110	1.000	-.7715	.7215
		HISPANIC	-.2750	.27110	.849	-1.0215	.4715
		AFRICAN	-.1250	.27110	.991	-.8715	.6215
	ASIAN	EUROPEAN	-.5250	.27110	.302	-1.2715	.2215
		NATIVE	.0250	.27110	1.000	-.7215	.7715
		HISPANIC	-.2500	.27110	.888	-.9965	.4965

		AFRICAN	-.1000	.27110	.996	-.8465	.6465
	HISPANIC	EUROPEAN	-.2750	.27110	.849	-1.0215	.4715
		NATIVE	.2750	.27110	.849	-.4715	1.0215
		ASIAN	.2500	.27110	.888	-.4965	.9965
		AFRICAN	.1500	.27110	.981	-.5965	.8965
	AFRICAN	EUROPEAN	-.4250	.27110	.520	-1.1715	.3215
		NATIVE	.1250	.27110	.991	-.6215	.8715
		ASIAN	.1000	.27110	.996	-.6465	.8465
		HISPANIC	-.1500	.27110	.981	-.8965	.5965
SHORTRIDGES	EUROPEAN	NATIVE	-.0500	.31449	1.000	-.9159	.8159
		ASIAN	.3250	.31449	.840	-.5409	1.1909
		HISPANIC	.1250	.31449	.995	-.7409	.9909
		AFRICAN	.9000*	.31449	.037	.0341	1.7659
	NATIVE	EUROPEAN	.0500	.31449	1.000	-.8159	.9159
		ASIAN	.3750	.31449	.756	-.4909	1.2409
		HISPANIC	.1750	.31449	.981	-.6909	1.0409
		AFRICAN	.9500*	.31449	.024	.0841	1.8159
	ASIAN	EUROPEAN	-.3250	.31449	.840	-1.1909	.5409
		NATIVE	-.3750	.31449	.756	-1.2409	.4909
		HISPANIC	-.2000	.31449	.969	-1.0659	.6659
		AFRICAN	.5750	.31449	.360	-.2909	1.4409
	HISPANIC	EUROPEAN	-.1250	.31449	.995	-.9909	.7409
		NATIVE	-.1750	.31449	.981	-1.0409	.6909
		ASIAN	.2000	.31449	.969	-.6659	1.0659
		AFRICAN	.7750	.31449	.103	-.0909	1.6409
	AFRICAN	EUROPEAN	-.9000*	.31449	.037	-1.7659	-.0341
		NATIVE	-.9500*	.31449	.024	-1.8159	-.0841
		ASIAN	-.5750	.31449	.360	-1.4409	.2909
		HISPANIC	-.7750	.31449	.103	-1.6409	.0909

Based on observed means.

The error term is Mean Square(Error) = 1.978.

*. The mean difference is significant at the .05 level.

Discussion

As stated, fingerprints have proven to be a reliable means of identification worldwide for more than 100 years and are among the most common types of evidence found at a crime scene. While fingerprint analysis has significantly progressed over the years, there is still critical research to be conducted in the discipline. From determining that fingerprints are permanent and unique, to determining how fingerprints are formed, to using those fingerprints to exclude and include suspects, and even using them to positively identify a person, fingerprints have proved to be a vital part of our criminal justice system. Because of the permanence and uniqueness associated with fingerprints, we are able to make positive identifications of latent prints collected from a crime scene to a suspect. Being able to determine an ancestral profile from a print left at a crime scene would aid law enforcement substantially in investigations. While this is a novel concept in forensic science, it could be an investigative aid used to include and exclude potential suspects based on ancestry or as corroborative evidence in a case aiding law enforcement in combatting and identifying criminal offenders.

The results of this study provide important insights into the frequencies and likelihood of certain fingerprint patterns coming from certain ancestral groups. For example, past FBI studies have shown that the loop pattern is the most common type of fingerprint pattern with 65% of documented fingerprints belonging to this pattern type. Loops are followed in frequency by whorls at 35% and then arches at 5%. Interestingly, all of the ancestral groups in this study followed the percentages identified by the FBI, except for the Native American ancestral group who had the highest pattern frequency of whorls at 47.5%, followed by loops at 35%, and then arches at 17.5%. Having the knowledge that this study has shown the highest frequency in whorls within the Native American ancestral group could help investigators narrow down an immeasurably vast suspect pool particularly when a whorl is collected at a crime scene and there is no known exemplar for comparison.

Looking at the descriptive statistical output for minutiae types and ancestral background also provides significant insight into the study of fingerprint analysis and identification. As previous studies suggested, the African ancestral group was the only ancestral group to have a higher mean of bifurcations with a mean of 31.60 as opposed to the mean of ending ridges, which had a mean of 21.17. Additionally, the Asian and African ancestral groups had the lowest means for short ridges at .85 (Asian descendants) and .28 (African descendants). The Native American ancestral group and the Hispanic ancestral group had the highest means for dots at 1.38 (Native American descendants) and 1.05 (Hispanic descendants). These ancestral groups were the only two of the five groups that had a mean for dots higher than 1.0. Tukey's Post Hoc tests further confirmed the significant differences amongst the ancestries in regards to minutiae types. It is worth noting that while there were differences found, most of the differences lie between only two ancestral groups when looking at each minutiae type. Having multiple ancestries hinders the ability to make any determinations using this approach with most minutiae types, except for with bifurcations. The African descent group had statistically more bifurcations than all other population groups in this study. This could serve as a valuable tool for prediction of fingerprints found at a crime scene if the suspect pool is limited to those of African descents versus other ancestral descent groups. As stated, the results of this study and others like it can only be used as a forensic tool for potentially limiting suspects and would not be admissible in court or stand alone as evidence as this could set dangerous precedents such as profiling behaviors within law enforcement. Additionally, as Fournier and Ross (2015) and the MANOVA results from this study showed, minutiae types cannot predict sex. Previous studies pertaining to gender and fingerprints have shown that there is a measurable difference, specifically in ridge density, however, this has shown it does not apply to the quantity of minutiae types.

While this study had similar results to Fournier and Ross (2015) previous study, it also differed in several ways. As with Fournier and Ross study, this study showed that the African ancestral group tended to have more bifurcations when compared to other ancestry groups. This study also confirmed that sex is not a significant predictor of pattern type, whereas ancestry can serve as a significant predictor of pattern type. Additionally, both studies concluded that the frequency of arch patterns is higher within European descendants than with African descendants. In this study, European descendants frequency for arch patterns was double the frequency for arch patterns within African descendants. This study also differed from Fournier & Ross in that five ancestry groups were compared rather than two and that the fingerprints from this study were obtained from live participants rather than prints in a database.

Limitations and Implications

The ideal method of assessment for ancestral background would involve qualitative genotype testing measures, such as commercial ancestral tests. Unfortunately, these assessments were not feasible for this study. This study relied on the self-assessment from individual participants to identify ancestral background, which could contain inaccuracies Additionally, in future research, it would be beneficial to expand with a larger sample size to include more ancestral descendant groups such as Alaskan Native, Middle Eastern, and West Indian. Lastly, this research has been limited to right index fingers due to their high prevalence at crime scenes, expanding to include all fingers may yield more accurate results.

Future Research

As stated, fingerprints currently hold little to no value if there are no known or suspect prints that latent prints can be compared to. In an initial investigation, where no suspects are known, this research could provide law enforcement with an additional tool of narrowing down an otherwise overwhelming pool of suspects. Predictions of ancestry from a fingerprint left at a crime scene could serve as probative evidence. The future goals of this study would be to develop an algorithm of sorts for if a fingerprint is found at a crime scene, the print could be analyzed and predictions could be made on which ancestral group could have deposited the fingerprint.

Further studies should also be conducted to include more ancestral backgrounds and to obtain a larger sample size. For example, it would ideal to expand the research to include Middle Eastern descendants, Polynesian descendants, Aboriginal descendants, Indian descendants, and many more. In addition, it would be ideal to continue to enlarge the sample size to ensure the results accurately reflect the population.

It is worth noting that it may be worth researching if certain pattern types tend to exhibit more of a specific Galton feature. To date, there is limited empirical research looking into this theory. Such research could provide further insights into being able to predict someone's ancestry from fingerprint patterns. From the results of this study, it was shown that Native Americans tend to have a larger frequency for whorls than other ancestries, therefore, predicting a pattern type from the amount of specific minutiae types within a partial print could predict pattern type, which in turn could predict the ancestry of the individual who deposited the print. In addition, there is a newly studied phenomenon known as "ridge drift" which refers to the natural aging process of latent fingermarks over time. These alterations are characterized as caused by an extrinsic action, which affects entire areas of the deposition and alters the overall flow of a series of contiguous ridges, thus causing slight print degradation (Alcaraz- Fossoul, 2016). Most of the studies in this area have been done on latent, unprocessed fingermarks on hard, non-porous surfaces that were allowed to age and then processed. The aged prints were then compared to prints that were processed in a timely manner from the time the fingermarks were deposited. The comparison between fresh and aged depositions revealed that under certain environmental conditions an individual ridge could randomly change its original position regardless of its unaltered adjacent ridges (Alcaraz- Fossoul, 2016). While the exact causes of the drift phenomenon are not well understood at this point, Alcaraz- Fossoul (2016) believes it is exclusively associated with intrinsic natural aging processes of latent fingermarks. For the purpose of the current study regarding fingerprints and ancestry, prints were rolled onto notecards. To date, there is limited study on the phenomenon of ridge drift and how it relates to prints inked onto paper substrates. It is unknown if ridge drift could have definitively affected the results of this study, however, the above research suggested that the “drift” of aged latent prints was minor and did not alter minutiae types. This could have implications with the current study if you are examining an aged fingerprint from a crime scene for the purpose of predicting an ancestry background of a potential suspect.

Forensic Science is continuously evolving to ensure not only success in apprehending those guilty of a crime, but also ensuring that our methods and technology are of the highest accuracy and standard. Over the past several years, fingerprint analysis has slowed in innovation. By conducting further research, we can ensure that fingerprint analysis continues to move forward and meet the high standards commensurate with the field of forensic science.

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