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Prevalence of Pores in Latent Fingerprints

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Thesis submitted to the Eberly College of Arts and Sciences at West Virginia University

in partial fulfillment of the requirements for the degree of

Master of Science in Forensic & Investigative Science

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ABSTRACT

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Of the many biometric traits recognized today, fingerprints are the most prevalent and familiar. The analysis of fingerprints involves level 1, level 2, and/or level 3 detail in the identification of a potential match. Traditionally, fingerprint matching was completely performed by hand, utilizing the ACE-V method. Thanks to the development of rapidly evolving technology, fingerprint matching has become an automated procedure through the use of fingerprint matching algorithms. In the literature, there has been an increase in the interest of developing Automatic Fingerprint Identification System (AFIS) algorithms that include level 3 details in the matching process. These studies have utilized live scanned and/or inked fingerprints, rather than latent fingerprints. However, practical use of AFIS algorithms involves unknown fingerprints, such as those collected at crime scenes, which are often latent in nature. In addition, research has also found that there is a wide variety in size and shape of pore structure, making automatic detection of pores difficult.

The resultant quality of latent fingerprints is subject to various factors at the time of deposition, such as the deposition surface, environmental conditions, and composition of the fingerprint itself. Consequently, these factors, in addition to the inherent variance in pore structure, may very well affect the observance and use of level 3 details within a fingerprint. If the prevalence of pores proves to be unreliable and inconsistent in latent fingerprints, the push for including level 3 detail in the AFIS matching process may all be for nothing. For this reason, the effects of latent fingerprint deposition factors on pore identification needs to be considered and currently appears to be greatly under studied.

In effort to begin to fill this gap in the current research, newly deposited latent fingerprints were collected and developed using both black fingerprint powder and cyanoacrylate fuming. Developed fingerprints were subsequently imaged via digital scan or digital camera, and enhanced using either Image J or Adobe[®] Photoshop[®]. Following image enhancement, pores were manually identified and marked using the Federal Bureau of Investigation (FBI) developed Universal Latent Workstation (ULW) software.

Qualitative assessment of the 633 fingerprints collected resulted in 380 usable fingerprints for the remainder of the study. Observations regarding pore count within the replicate fingerprint sets indicated that total pore count/presence was not consistent. The Mann Whitney U test indicated that neither development method, black fingerprint powder nor cyanoacrylate fuming, produced pore data any better or worse than the other. Lastly, assessment of pore location resulted in a greater number of similarity scores being lower than the established threshold, indicating that pore location is not as easily assessed nor interpreted as hoped.

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1. Introduction

Fingerprints are the impressions left behind by the friction ridge skin found on the surface of the fingertip after an individual has touched a surface. Friction ridge skin is not just found on the fingertips, but also along the palms of the hands and soles of the feet, functioning as a means of increasing the grip strength of the skin in those areas. In order for a fingerprint to be left behind, the friction ridge skin should be covered in natural secretions and/or other material [1].

All over the body, there are sudoriferous and sebaceous glands. Sudoriferous glands are further comprised of eccrine and apocrine glands. Eccrine glands are found all over the body with high density on the palms of your hands and soles of your feet, and release a mixture of 98% water and 2% organics, such as amino acids, proteins, and polypeptides. Apocrine glands are found within the armpit and pubic regions, releasing a mixture of water and organics, such as proteins, carbohydrates, and cholesterol. Lastly, the sebaceous glands, while found all over the body, are high in density on the face and scalp, but not found on the hands or feet. These glands release water and lipids, such as glycerides, fatty acids, cholesterol, and squalene. Based upon the natural secretions of the glands located on your hands, and the activity of your hands prior to deposition, a fingerprint could be comprised of a variety of these components [2].

The development of friction ridge skin occurs during embryo and fetal development, signifying the potential for uniqueness. Specifically, on the fingertips, the friction ridge skin forms a pattern which has been studied greatly for uses in personal identification. Since the establishment of personal identification, fingerprints have seen widespread use within forensic applications, biometric applications, and civil applications, such as within the criminal justice system, authentication and identification purposes, and for personal security access.

There are three fundamental principles that have been established in order for fingerprints to be used for personal identification. The first principle is that the fingerprint patterns are unique, leading to the belief that no two individuals can have the same fingerprint. Second, is persistence, in that the fingerprint will not change over the course of an individual's lifetime, apart from major injury. Third, is that fingerprint patterns display general ridge characteristics which allow them to be classified for easy data basing, search, and retrieval.

Among all characterized fingerprints, common features have been identified that are used for the purpose of categorizing fingerprints. These identified features are broken up into three feature levels: level 1, level 2, and level 3. Level 1 detail consists of the fingerprint pattern type and the general ridge flow. Level 2 detail consists of the ridge characteristics and minutiae found within a fingerprint, and level 3 detail consists of the dimensional attributes of the ridge, to include the shape of the edges and pore detail [3]. The general classification of fingerprints relies only upon information contained within level 1 detail. The Henry Classification System, devised by Sir Edward Henry, was the first classification system used. However, a more simplistic, easier approach has been developed with the National Crime Information Center (NCIC) Fingerprint Classification System and the Integrated Automated Fingerprint Identification System (IAFIS), which are more widely used today [4].

Within level 1 detail, the general ridge flow refers to the direction of one or more ridges, which encompass the overall pattern of the fingerprint. Fingerprint patterns include radial and ulnar loops, plain and tented arches, and plain, double-loop, central-pocket-loop, and accidental whorls. In general, loop patterns are defined by containing a single delta formation and ridges that enter on one side of the finger, loop around, and then exit on the same side as to which the ridges entered. Arches are defined by having no delta(s) and ridges that enter on one side of the finger, loop around, and then exit on the same side as to which the ridges entered. Arches are defined by having no delta(s) and ridges that enter on one side of the finger. Whorls, while a bit more complicated, generally are defined as containing two deltas, and ridges that curve over on themselves and complete full circuits [3].

Level 2 detail refers to the ridge characteristics which were first described by Francis Galton. Galton defined these characteristics to be features of the ridges that were identifiable. Such features include, but are not limited to, ridge endings, bifurcations, ridge islands, and short ridges. These features were known was Galton Details, but are now commonly referred to as the minutiae detail, or points, within a fingerprint [5].

Lastly, level 3 detail entails the specific details relating to the ridges themselves, such as the shape of the edges and the presence of pore detail. In 1912, Dr. Edmund Locard examined the pore detail within fingerprints and referred to the study and use of pores as "poroscopy." He believed that identification could be based upon the size, shape, relative position, and frequency of pores within a fingerprint [6]. Later, in 1962, a man by the name of Salil Chatterjee introduced "edgeoscopy" as an identification process that utilized the shape or characteristics along the edge of the ridges. He even detailed a set of specific characteristics that could be found along the edges that could be used for comparison purposes [6].

Within a forensic setting, there are multiple types of fingerprints that can be encountered. There are exemplar fingerprints, which can be collected in a variety of ways, consisting of inked or live-scanned, or there are those fingerprints encountered in the field. Fingerprints encountered in the field could be patent fingerprints, latent fingerprints, and/or fingerprint impressions. A fingerprint that is patent is one that is visible to the naked-eye, without any assistance or enhancement. A fingerprint that is latent, is one that is not visible to the naked-eye, and requires development to be seen. Fingerprint impressions are those that have three-dimensional structure to them. The most commonly encountered fingerprints within a forensic context are latent fingerprints, as they are often collected at the scene of a crime. Latent fingerprints are considered unknown fingerprints and collected for analysis, in order to be compared to fingerprint records contained on file, in effort to find a positive identification.

Fingerprints are evaluated and analyzed, using the Analysis-Comparison-Evaluation and Verification, or ACE-V, method [3]. ACE-V is an internationally used and accepted scientific method for analyzing fingerprints. During the "analysis" step, fingerprints are assessed to determine if the quality and quantity of detail present is enough and suitable for comparison. The "comparison" step involves examining a set of fingerprints to identify points of similarity and/or dissimilarity. The set of fingerprints under examination include an unknown fingerprint and a known fingerprint, that was likely provided within a list of potential matches. The "evaluation" step is where the examiner performing the analysis considers the details and points of similarity/dissimilarity amongst the two fingerprints to form a conclusion regarding whether the two fingerprints originated from the same source. Once a conclusion is reached, the "verification" step is performed, which entails the independent application of the ACE process by another examiner to either concur or refute with the original conclusion [3].

The ACE-V methodology works, as everyone mentally carries out the process of an examination in the same way, due to the inherent human ability to identify objects in our everyday lives. This is how it is possible for one to scan a crowded room and recognize a familiar face, as "the ability to identify patterns and shapes [is] a natural process [that is] instinctive to the human brain..." [7].

For many years, it was standard within the fingerprint community to use a set number of minutiae points in agreement to reach an identification conclusion. In the early 1970s, the fingerprint community began to steer away from this idea, as rather than a specific number of points, fingerprint examiners were now evaluating all levels of detail and forming a conclusion in regards to all of the information available to them within the fingerprint [7]. When conducting an ACE-V analysis, fingerprint examiners utilize all levels of detail, whether consciously knowing it or not. Level 1 detail helps establish the overall fingerprint pattern and orientation, while level 2 detail allows for the individualization of the fingerprint. The minutiae detail of the fingerprint is clearly examined, marked, and compared across the list of fingerprints that are potential matches to the unknown. Inherently though, the examiner is also using level 3 detail, without necessarily realizing it. Fingerprint examiners also examine and consider the general shape of the ridges, presence or lack thereof of pores, and other minute details during their examination.

Within the identification process, the purpose is to individualize, or find a so-called "match" by comparing the details of an unknown fingerprint to a set of known fingerprints. Utilizing all levels of detail, especially level 3, in the analysis of a fingerprint came to have many names, such as ridgeology. According to David R. Ashbaugh, ridgeology is a proper evaluative method for fingerprint identification as it is based on scientific principles and procedures which have been verified on multiple occasions through years of research [6]. This evaluative method includes all ridges, not just those on the fingertips, and the sciences of edgeoscopy, poroscopy, and areas of dermatoglyphics.

Level 3 detail can be found in both tenprints and latent fingerprints. The method in which a fingerprint is collected and/or captured plays an important role in the ability of an automated system to detect level 3 detail, such as pores. The amount of detail present within a fingerprint for comparison is highly dependent upon the clarity of the fingerprint. Relative to the other types of fingerprints, level 3 detail is more easily distinguishable and readily available in tenprints, as the collection of tenprints is performed in a controlled manner producing a quality fingerprint, which provides a higher level detail. However, the same cannot necessarily be said for latent fingerprints, as collection of latent fingerprints is from surfaces of less

than ideal conditions, often producing a low quality fingerprint and/or a partial fingerprint. Additionally, the sweat pores on a finger are not all active at all times, limiting the sole use level 3 detail for identification purposes [8]. However, the addition of level 3 detail to level 1 and level 2 detail for identification purposes has proven to be advantageous.

Level 3 detail of a fingerprint consists of the dimensional attributes of a ridge, including the path deviation, width, shape, edge contour, as well as the pores, incipient ridges, breaks, creases, and scars within a fingerprint [9]. Studies have shown that level 3 features are unique and persistent, just as the minutiae of a fingerprint are, and can add quantitative as well as qualitative information to the identification of an individual [10, 11]. As it currently stands, the FBI standard for fingerprint image resolution is that of 500 ppi, which has shown to be unsatisfactory in reliably capturing level 3 detail in fingerprints [12]. While few studies have suggested alternative image resolutions, the common consensus is that an image resolution of at least 1000 ppi is needed to adequately and reliably detect level 3 details [12].

2. Historical Context

Long before any studies were undertaken to prove the uniqueness and persistence of fingerprints, friction ridge impressions were used as a means of identification. Originating from ancient China or from the walls of caves in Spain, fingerprints have long existed for some purpose [13], as one of the first recorded records of the use of fingerprints was by the Chinese during the Qin Dynasty [1]. Despite the inherent usefulness of fingerprints, it would not be until centuries later that findings were published regarding descriptions of friction ridge skin, the patterns associated with friction ridge skin, the uniqueness and persistence of the ridges, the classification of fingerprints, and its use as evidence [1].

During the period of 1880 to 1898, major discoveries and inventions in the field of fingerprints lead to their widespread adoption. Further, 1895 to 1905 saw the consolidation of ideas and techniques, leading to the practical utility of fingerprints and a successful classification system. Still remained though, were two major questions that quite possibly are still under question today: 1) are the ridge patterns on fingerprints unique, and 2) are the ridge patterns permanent and unchanging throughout someone's life [13]?

Francis Galton first thoroughly addressed these two questions in his 1892 book, Finger Prints. With his book, Galton provided a scientific background, specifically addressing the uniqueness and permanence of fingerprints by building off the work and ideas of others, and he developed a classification and filing system that would be improved upon in the coming years [5, 14]. His accounts were not entirely accurate or complete though. Published in 1823, Johannes Purkinje wrote of his ideas on classifying ridges into overall patterns. Using these ideas, Galton realized the importance of personal identification employing what we now refer to as minutiae [14]. He was the first to define specific minutiae found in fingerprints, leading to them being known as Galton details. Galton did not, however, seem to be aware of the observations published by Dr. Nehemiah Grew in 1684, in which he described sweat pore openings along the ridge patterns of the palms of hands and soles of feet [15]. Galton also appeared to ignore, or refused to acknowledge, the work and ideas put forth by Henry Faulds [13].

In 1880, Faulds wrote a letter to Charles Darwin, that was later published in Nature, about his observations relating to fingerprints [13, 16]. One of Faulds' observations was that fingerprints could have value in criminal investigations to identify suspects or victims. Darwin reportedly forwarded this letter to his cousin, Francis Galton, as he thought Galton would be of greater assistance to Faulds. Galton never publicly acknowledged receiving such a letter, and even later went on to state that Faulds contributed little to the subject of fingerprints [13]. However, a short 4 weeks after the publication of Faulds' letter in Nature, a response letter was written by Sir William James Herschel, which was also subsequently published in Nature. In the mid-1800s, through his time working as an administrative officer in India, Herschel began observing his own fingerprints and the fingerprints of others. As a result of his observations, Herschel noted that fingerprints remained constant from childhood through adulthood, and he was willing to state that these features had lifelong permanence, effectively answering the second of the two major questions of the fingerprint field [17].

Through Galton's years of studying fingerprints, he was also able to calculate the probability that two living individuals would have one single identical fingerprint, as well as the odds of having all ten identical fingerprints [13, 14]. For a single identical fingerprint, the probability of two individuals having the same fingerprint was 1 in 64 billion, and the odds that all fingerprints were identical was "far beyond the capacity of human imagination" [13]. Despite such assertions, it would take many years for the uniqueness of fingerprints to be acknowledged by the justice and legal systems.

Galton's classification system would be greatly improved upon by Sir Edward Henry, who studied Galton's methods, which allowed him to refine his ideas and put them to use [13, 18]. In the early 1900s, Henry's classification system proved to be successful and lead to police departments all around the world to adopt his system, as Henry's book was considered the standard for the application of fingerprints [14]. Thanks to demonstrations of how fingerprints could be collected and stored by users in London, fingerprinting services and databases first arose in the United States in New York and St. Louis, Missouri [13]. Similar circumstances were taking place in South America as well in regards to the study and use of fingerprints. In Buenos Aires, fingerprint evidence was first used within a criminal conviction of a woman in 1891. Juan Vucetich established his own classification system, which was used in support of the conviction, to show that the bloody fingerprint found on scene belonged to the mother of the murdered victim, rather than an alternate suspect, as the mother had claimed [19]. Later on, in the early 1920s, shortly after the Federal Bureau of Investigation (FBI) was founded, a man by the name of J. Edgar Hoover, who would become the director, was responsible for the improvement of handling and filing of fingerprints. Hoover created a centralized fingerprint database, which would contain a far greater number of fingerprints than anyone thought was possible [13, 20].

With the official use of fingerprints gaining traction, public perception was also increasing. In the United States, Mark Twain published two novels within the late 1800s in which fingerprints were used in a criminal context to help identify the suspect [21, 22]. It has been speculated that Twain's novels helped the general public become aware of the use of fingerprints and its acceptance for identification purposes [13].

Up until the work performed by Edmond Locard, the science behind fingerprints focused on level 1 and level 2 detail. In 1912, Locard published a book regarding his work, introducing the science of poroscopy. With this new science, Locard determined that along with the pattern and minutiae of a fingerprint, the pores were also unique and permanent, allowing for their use in identification purposes [10]. David R. Ashbaugh, a Canadian police officer, furthered the ideas of Locard, as well as other aspects of fingerprints. Ashbaugh discussed using pore location and pore shape within personal identification using fingerprints, as well as defining a threshold for the number of pores needed to claim a match with pore data. He also made sure to discuss the shortcomings of the science of poroscopy and attempted to provide avenues for areas of improvement. In addition to his work with pores, Ashbaugh introduced the ACE-V method of analysis and created the terms level 1, level 2, and level 3 detail [6, 11].

For nearly a century, the fingerprint field was left to its own devices, with few challenging the practicality, utility, and/or validity of the use of fingerprints. In 1924, fingerprint evidence was challenged, but the challenge was based upon the fact that fingerprints could be lifted and transferred, not that they were unreliable for identification [14]. Further, the FBI had handbooks in the 1930s that provided court cases in which fingerprints were used as definitive proof of identification, but the handbooks did not speak of the uniqueness of the prints [14, 20]. By the late 1920s, fingerprints seemed to be universally accepted, possibly due to three definitive reasons: 1) the similarity of fingerprints displayed in court were undeniable, 2) there were a few massively successful cases involving fingerprint evidence, and 3) a long period of time had passed before instances of wrongful convictions over similar fingerprints had occurred [14].

Despite no outward voicing of question, the field did not remain static. By means of scientific and technological advancements, the field has found a way to capitalize and subject computer technology to good use. Through capture and developmental techniques, and databases for automatic filing and storage, the field continued to grow and improve. Automated Fingerprint Identification Systems (AFIS) have demonstrated to be revolutionary to the field, enabling rapid fingerprint filing, searching, and matching.

Despite continual advancement, the past two decades have seen tremendous critique of forensic science. Use of forensic science in court and its role in wrongful convictions have brought to question the scientific validity and reliability of multiple disciplines within the field. Due to the emergence of the National Academy of Sciences (NAS) and President's Council of Advisors on Science and Technology (PCAST) reports, the field has seen a greater push for improvement.

The National Academy of Sciences, along with other scientific groups and committees, composed an extensive report on the science, or lack thereof, within the forensic science community. This report, published in 2009, titled "Strengthening Forensic Science in the United States: A Path Forward," or more commonly known as the NAS Report, was three years in the making. Those working on the report conducted research and interviewed qualified members within the field to get a more in-depth understanding of the work performed and what was needed to be improved upon. When published, the report divided those within the forensic science community; while many were upset and disagreed with the report's findings, there were also those who agreed. Regardless of personal feelings towards the NAS report, the community understood that the only way forward was working on correcting and improving upon the recommendations put forth by the report [23].

The findings of the NAS report called for an overhaul of many aspects of forensics within the community. The report further stated that only with the support of the federal and state governments, assembly of national standards, and sufficient funds could the overhauling be accomplished. One of the largest identified problems facing forensic science was that lack of appropriate and substantial scientific and statistical evidence supporting the work many forensic disciplines employ. A second identified problem was that the analyses performed

were often conducted with influence from personal interpretation, bias, and other subjective matters. These reported problems were said to be the result of a lack of enough protocols and standards governing the work performed to ensure objectivity throughout the entire analysis process [23].

In relation to the science of fingerprinting, the report recommended research on the accuracy, reliability, repeatability, and reproducibility of the examinations completed by fingerprint examiners, development of objective, standard approaches to reaching conclusions, a clearer method to stating the strengths and limitations of the results reached during a fingerprint examination, and greater AFIS interoperability [23].

In 2016, the President's Council of Advisors on Science and Technology report titled, "Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods" was released indicating additional steps that could be taken. Outside of what was addressed with the NAS report, the PCAST report identified two areas of concern aimed at featurecomparisons within forensic science, such as fingerprint identification. The two identified areas surrounded scientific standards for validity and reliability, stating that feature-comparison methods need clear scientific standards regarding the validity and reliability of the method, as well as evaluative measures that can be taken to ensure a forensic method is valid and reliable. More so, the report discussed the importance of scientific validity for feature-comparison methods used within the court room [24].

The recommendations made by the PCAST report were mainly directed toward the National Institutes of Standards and Technology (NIST), the Federal Bureau of Investigation (FBI), the White House Office of Science and Technology Policy (OSTP), and the Attorney General. The recommendations, aimed to strengthen the use of feature-comparison forensic methods in court, called for NIST and the FBI to become leader organizations for research and evaluation of feature-comparison methods, OSTP to create national forensic science research and development programs, and for the Attorney General to ensure that expert testimony admitted in court meets current scientific validity and reliability standards [24].

As a result of these two reports, many fields within forensic science have taken it upon themselves to support the work that has been employed for years. Not only has research been published on the front of scientific validity and reliability, but researchers and scientists have also polled those working in the field to further improve and advance the techniques and methods employed within the field. With or without external inquisition, the current state of forensic science recognizes and values the ever-evolving need for research and improvement. In the wise words of David Ashbaugh, "the pursuit of understanding through continual inquiry and research will ensure the science is prepared to meet the challenges of the future" [6].

3. Friction Ridge Development

At the most basic level, fingerprints are constructs of the layers of skin indicating that fingerprint formation, at its core, is involved in the formation and growth of epidermal skin. Through the study of embryo and fetal development during a pregnancy, it is understood that fingerprint formation, or the formation of epidermal ridges, must occur during embryogenesis and fetal period of human gestation. The embryogenesis stage of human development occurs during the 3^{rd} through 8^{th} week of gestation, with the fetal development stage beginning during week 9 and encompassing the remaining of the gestational period [25]. In effort to describe epidermal ridge formation, researchers commonly refer to the overall process as fingerprint embryogenesis.

3.1 Embryology of a Fingerprint

Over the past century or so, many researchers have attempted to study and describe epidermal ridge development. Currently, it is believed that fingerprint formation is influenced by volar pad geometry and the effects of stress caused by differential growth and cell proliferation in the basal layer of skin during embryogenesis and fetal development of human gestation. Volar pads are temporary elevations of skin that form around the 7^{th} week of gestation at the fingertips (apical pads), the area at the base and between the fingers along the palm (interdigital pads), and the in the thenar and hypothenar regions of the hand (Figure 3.1) [26, 27].



Figure 3.1: Volar Pad Locations. A1-A5 represent the apical pads, I1-I4 represent the interdigital pads, Th represents the thenar pad, and HTh represents the hypothenar pad. Adapted from [27].

Volar pads slowly become less prominent around the 10th week of gestation, before completely disappearing [26]. Human skin is composed of two main layers, the epidermis and dermis layers [28]. The epidermis is the top most layer of skin, with the dermis below. The epidermis layer itself is composed of many layers, the bottom most being the stratum basale, or basal layer, which connects to the dermis layer below [28].

The first researchers to suggest the connection between volar pad geometry and ridge formation, in the absence of human subjects, examined primate species that have similar volar pad structures on their fingertips to humans. As a result of their observations, Schlaginhaufen and Whipple found that the fingers of primate species with larger, more prominent volar pad structures had whorl-like ridge patterns, and those that had flatter and longer volar pads had loop-like ridge patterns [29–31]. When it came to studying fingerprint embryogenesis on human embryos, Bonnevie and Cummins reported similar findings. In her 1924 and 1929 studies, Bonnevie argued that the symmetry of the volar pad influenced the resulting ridge pattern. She proposed that symmetrical volar pads give rise to whorl and arch patterns, and asymmetrical volar pads give rise to radial or ulnar loops, depending on the angle at which the pad slanted [32, 33]. Bonnevie's observations were confirmed by Cummins in his 1926 study [34]. Both studies help provide a strong link between volar pad geometry and friction ridge pattern development.

During the 10th-16th week of gestation, critical events occur for the formation of epidermal ridge patterns [26]. Within the 10th-13th week of gestation, the basal layer becomes undulated, forming folds of the epidermis that move into the more amorphous dermis layer (Figure 3.2) [26]. The folds and the effect they have on the dermis are referred to as primary ridges, and establish the future surface fingerprint pattern [26]. It is for this reason that it is believed fingerprints are unchanged by injury to the surface of the skin; however the same cannot be said for deeper injuries.



Figure 3.2: Basal Layer Undulations. Undulations form within the basal layer, creating folds into the dermis layer below. Adapted from [26].

Across the human embryo, primary ridge formation does not begin at the same time. Previous studies have examined the timing of primary ridge formation and found that overall, ridge formation begins in the hands first, followed by the feet [35–37]. Within hands, it has been found that ridge formation is a result of the convergence of three ridge systems. One ridge system starts around the center of the volar pad, called the ridge anlage. The second ridge system starts along the nail furrow, and the third system starts along the interphalangeal flexion crease (Figure 3.3) [26]. The three ridge systems eventually converge at an angle of roughly 120 degrees, and form the tri-radius, commonly known as a delta [26].



Figure 3.3: Ridge Systems. (a) Ridge formation at the center of the volar pad and along the nail furrow. (b) The core of loops or whorls usually form where ridges first arise on the volar pad. (c) Ridges form along the interphalangeal flexion crease, all ridge systems spread over the fingertip area. Adapted from [26].

It has been shown that these primary ridge formations can multiply and change with the growing of the hands, which is believed to be the cause of minutiae formation. These changes can take place up until the 16th-19th week of gestation, at which point the pattern will become permanent and becomes visible on the surface of the finger [26, 27, 38]. Once primary ridge development has been completed, sweat glands/ducts begin to form and grow between the dermis and epidermis layer of the skin, forming a pore opening at the surface of the epidermis layer at regular intervals [39].

3.2 Proposed Hypotheses

There are many studies detailing fingerprint embryogenesis, some indicating possible links to other human characteristics such as gender and others proposing methods that attempt to explain the specifics of epidermal ridge formation [26]. However, to this day, despite the long-time use and study of fingerprints, there is still no consensus and definitive knowledge on how the epidermal ridges on a fingertip form. There have been multiple hypotheses proposed thus far, three of which are most prominent: the nerve hypothesis, the fibroblast hypothesis, and the folding hypothesis.

3.2.1 The Nerve Hypothesis

The nerve hypothesis states that ridge formation is influenced by the pattern of nerves and/or capillaries within the fingertips, given that the fingertip becomes innervated before ridge formation starts. Studies published regarding this hypothesis make the claim that the developed fingerprint pattern is linked to the pattern of the nerves and blood vessels within the skin [39-41]. Specifically, Dell and Munger believed that the grid formed by nerve fibers assists in the spacing and arrangement of the ridges. The evidence presented by these studies suggests that the nervous system may play an important role in the development of ridges, however it is not very likely that the nervous system is the sole contributor. A two-part study conducted by Morohunfola *et al.* found that when nerve fibers were removed from the hind paws of opossum, ridge formation was still observed. While ridge formation did occur, the formation was slightly delayed and the ridges were more shallow, which suggests that the nervous system is not the primary force behind ridge formation [42, 43].

3.2.2 The Fibroblast Hypothesis

The fibroblast hypothesis implores a similar concept as the nerve hypothesis, stating that the pattern created by the fibroblast cells can influence the formation of the ridges. In culture, the undifferentiated fibroblast cells align themselves into patterns similar to fingerprints [27]. Due to the similar topological patterns, ridge patterns are thought to be induced by the pattern in the dermis layer caused by the fibroblast cells. Studies by Bentil, Bentil and Murray, and Murray and Oster attempted to develop mathematical models demonstrating how tensile forces, created by the fibroblast cells, can act on the surrounding matrix, inducing the fingerprint pattern [44–47]. Despite these studies, there is an overall lack of evidence supporting the connection between fibroblast patterns and fingerprint patterns.

3.2.3 The Folding Hypothesis

The folding hypothesis was first proposed by Kollmann in 1883 where he speculated that ridge pattern is established as a result of the folding within the basal layer, a process which is induced by differential growth and cell proliferation [48]. Bonnevie also researched into the matter, agreeing with Kollmann that cell proliferation in the basal layer causes folding toward the dermis to evade stress, resulting in the formation of primary ridges [35, 49, 50]. This process is known in mechanics as the buckling process [27]. Cummins also hypothesized in relation to the folding hypothesis, stating that as a result of the stress created by the differential growth and cell proliferation in the basal layer, the primary ridges that form are in parallel to the greatest stress [34]. The folding hypothesis was not accepted by all. In fact, the hypothesis was outright rejected by some, as it was thought that the primary ridges form as a direct result of cell proliferation of the basal layer, not the combined effect of differential growth and cell proliferation on the dermis layer [31].

In support of the folding hypothesis, a few studies have been conducted attempting to provide an explanation on the mechanics of how primary ridges are formed and the specifics of pattern development. The folding hypothesis is the best supported and it leads to primary ridge formation in a straightforward way. It utilizes curvature and stress force concepts to explain the relationship observed between volar pads and ridge pattern formation [26]. In 2005, Kucken and Newell tested their modeled hypotheses with computer simulations. Their model involved the use of the von Karman equations of elasticity, which translate the mechanical properties associated with ridge formation to mathematics [27]. Their results determined pattern type, ridge spacing, and to a degree, ridge direction, which was consistent with previously observed data. The model only works up until a certain degree of ridge depth, suggesting that other biological mechanisms are at play with ridge formation [27].

Through experimentation, Kucken and Newell found that ridges form perpendicular to the largest stress, which is in opposition to Cummins original thought that ridges form parallel [26]. The authors also hypothesized an explanation for why some ridges have the same direction formation across all individuals. They state that this is due to the ridges aligning parallel to the creases and furrows of the hand, but this is only true when the creases and furrows are formed prior to ridge formation [26]. Overall, the authors concluded that primary ridges, which form the basis of the resulting fingerprint pattern, are influenced by the geometry of the volar pads and are formed as a result of the buckling instability created by compressive stress [26].

The takeaway from the folding hypothesis is that during differential growth and cell proliferation of the basal layer, compressive stress beings to build and as it reaches a certain limit, buckling, or folding, occurs. Compressive stress also builds as the volar pads begin to shrink, inducing curvature effects. The combination of the buckling and curvature is thought to be specific to the embryonic environment and as such, specific to each individual [27]. Further, the way in which these forces give and take with each other is what causes the formation of the many fingerprint patterns we know of today [27]. This process is what creates the unique fingerprint patterns. As previously described, once the ridges have formed, the sweat glands/ducts begin to form. If pattern formation of the ridges is specific in an individual, then presumably, the formation and placement of sweat ducts and their pores must be as well.

4. Poroscopy

Upon development, the sweat glands within the skin form sweat ducts that extend upwards into the top layers of the skin. The opening that forms as a result of the sweat duct reaching the epidermis layer is referred to as a pore. Within the ridges of the finger, pores can be located to the left or to the right, but usually align along the center of the ridge [7]. While the physical presence of the sweat duct and opening does not alter, the appearance of the pore can. As a result of perspiration or deposition pressure, the appearance of the pore can change. Pores may be completely closed, appearing as complete circles within the ridge, or partially open, appearing as open to one or both edges of the ridge. Due to this, there is no way to reproduce pores by means of fingerprint development [7].

Within their book, "Personal Identification: Methods for the Identification of Individuals Living or Dead," Wilder and Wentworth discussed how ridges and sweat pores form, stating that the sweat pores were present along the ridges in equal intervals. They asserted that due to the individual differences and persistence throughout a lifetime, pores are invaluable features to be used within personal identification. This was especially true when fingerprints lacked a sufficient amount of ridge detail and clarity. At the time, the studies undertaken by Locard, Wilder, and Wentworth were the only detailed works regarding pores in fingerprints. It was the suggestion of Wilder and Wentworth, that given the limited amount of work conducted thus far, pores in fingerprints should be continuously examined and studied [51].

With the invention of the microscope, Marcello Malpighi was the first to examine the pores of a fingerprint [11]. Over 200 years later, Locard examined pores with much greater detail. In his published work, Locard detailed how he used pores, or the science of poroscopy, as an independent method for identification. Locard was even successful in proving the identification of individuals on two occasions within the court system using the pore detail of a fingerprint [11]. In 1912, Locard detailed and published his work with poroscopy, supporting its use for identification purposes [10]. Through his studies, Locard determined that pores vary in many ways, in size, shape, position, and frequency. He found that the size of pores across fingerprints is not uniform, and within a single fingerprint, the size of pores can also vary. Pores were observed to be of various shapes, including oval, elliptical, square, rhomboid, and/or triangular. Further, pores also seemed to vary in their location along the ridge, some were located in the center, others to the left and/or right. Lastly, Locard noted how the number of pores and frequency varied across individuals. Locard determined frequency by either calculating the average number of pores that occur on a set length of ridge, or the average number of pores within a set area [10, 11].

Locard also conducted statistical analyses on his findings, and came to the conclusion that

20-40 pores that are in agreement between two fingerprints is sufficient enough to establish a positive identification [10, 11]. Of the hundreds, if not thousands of pores, that can be available within a single fingerprint, this range should be achievable. Locard believed that with the addition of the pore information to the level 1 and level 2 detail within the fingerprint, a jury or court would no longer argue the strength of a positive identification with fingerprint evidence [10, 11].

Despite the success Locard had with using pores within identification, the field was cautious of the science due to a few shortcomings [7, 11]. The major shortcomings were: 1) powder dusting of latent fingerprints fills in the pores, 2) there was a lack of quality inked impressions for comparison purposes, 3) there was a lack of adequate visual aids to observe the pores, 4) the lack of knowledge regarding which region of the fingerprint to look within for pore detail, 5) there was a low percentage of fingerprints that displayed pore detail when developed with ink, and 6) the degree of study required to gain expertise in poroscopy was unknown.

In his work, Ashbaugh spoke of these shortcomings and provided ways in which they could be improved upon. He believed that with proper training and technique, powdered fingerprints and inked impressions would display greater pore detail. He claimed that the invention of the microscope was instrumental and serves as a great visual aid for viewing pores. In addition, ridge characteristics and surrounding minutiae detail would have to be observed first, before pore examination could begin, in order to orient oneself with the fingerprint. Regarding the low percentage of fingerprints that display pore detail, Ashbaugh made it clear that due to the inherent nature of a pore, pore detail would not be seen in all developed or inked fingerprints; adding that this level of detail would more so be considered in addition to minutiae detail, rather than stand alone. Lastly, Ashbaugh believed that as with anything, time and experience would lead to expertise of poroscopy. He argued that as fingerprint examiners, we already examine countless fingerprints on a daily basis, and simply making the effort to look for pores will be enough to make pore examination become second nature, as ridge and minutiae examination is [11].

In order to gain an understanding of pores in the same way that Locard did, Ashbaugh undertook his own study. Similar to that of Locard, Ashbaugh examined five aspects of pores: 1) the size of the pores, 2) the shape(s) of the pores, 3) the position of the pores, 4) the number and frequency of the pores, and 5) the validity of pores for personal identification [11]. After examining rolled inked fingerprints, Ashbaugh came to the following conclusions: 1) the size of the pores varied within the fingerprint to a degree, however overall, there was a general tendency for pores within the same print to be of similar size, 2) pores were a variety of shapes but the shape could be difficult to distinguish depending on visualization/examination tools utilized, 3) as with size, position along the ridge also seemed random, in some cases the pores were aligned along the center of ridge, others were more disorderly, 4) he did not perform any mathematical measurements, but observed that sometimes pores were more packed together, other times more spaced, and noted that the spacing appeared to depended on the pore size, and finally 5) Ashbaugh felt that Locard had proven the usefulness of pores for identification with his court appearances and studies [11]. In regard to Locard's claim that 20-40 pores were sufficient for positive identification, Ashbaugh gave his support. Based upon the idea that pores are independent of each other and calculations performed on reported numbers of pores seen in fingerprints and across individuals, Ashbaugh believed that 20-40

pores would be sufficient for positive identification [11].

In addition to the previously mentioned aspects of pores, Ashbaugh also examined the reason(s) why pore detail is not always present in every fingerprint impression. He found that pressure distortion can change the basic shape of the pore, and that the overall assessment of pressure is easier to see throughout a greater area of the fingerprint, rather than at the pore unit level. Beyond this, Ashbaugh insisted that it is good practice to understand the types of distortion that one can encounter in fingerprint examination and how the distortion/pressure can affect the pores [11].

At the conclusion of his "Poroscopy" article, Ashbaugh closed by reiterating that experience with pores is a requirement if one were to present this type of evidence in court. Further, he emphasized that evaluating pore detail within a fingerprint will add strength to the ridge and minutiae detail already present in the comparison process. Poroscopy is not a new fingerprint science, as it has been previously accepted and presented in court, but there is a great need for further study [11].

Due to the minuteness of the detail, and the lack of reproducibility, poroscopy was once believed to be of little value to the field of fingerprints. Since the published works of Locard and Ashbaugh, technological advances have enabled the detection of pores and use of pores within the ACE-V process [7]. Unlike the way in which Locard used Poroscopy, today, level 3 detail is rarely used alone but rather in conjunction with level 1 and level 2 detail to aid in the identification of an unknown fingerprint. Over the years, studies have shown that pore structure, such as the size and shape, is not consistent enough to be used within forensic comparison. However, there has been plenty of information gathered that demonstrates the immutability of pore location. For this reason, Ashbaugh believed that if pores were to be used for identification purposes, only the relative location of the pores should be compared [6]. Ashbaugh further stated that comparing relative pore positions is still considered a new technique, and therefore requires additional study of practical application to verify its use. With the increased interest of including pore detail within fingerprint assessment, the fingerprint community should question that while the science exists to support the use of pores, are pores readily available in the fingerprints collected from crime scenes, and does there exist a logistical method to introduce pores in the comparison process [6]?

5. Previous Research

With such extensive research in the formation of fingerprints during development, to the uniqueness of fingerprints across individuals, and their use for identification purposes, fingerprints have been implemented in many applications and contexts. A prime example of the use of fingerprints is their long term implementation within biometric applications for personal identification. Biometric recognition with fingerprints has been successfully implemented in both forensic and civil applications; subsequently, the market for further advancing fingerprint acquisition devices and fingerprint matching algorithms has blossomed.

As the most common type of forensic evidence left behind at a crime scene, latent fingerprints are critical to the criminal justice system [52]. Due to criticism of many fields in forensic science, scientific working groups have been established and many studies undertaken to expand and improve upon the knowledge and statistical backing of forensic evidence. Recommendations for how to improve latent fingerprint analysis include addressing the utility of latent fingerprint analysis, development of standard methodology and metrics for latent fingerprint analysis, improvement and expansion upon the ability/accuracy of automated fingerprint identification systems (AFIS), and to increase the interoperability amongst databases, AFIS systems, and local, state, and federal departments [52]. Due to this, much of the research in the field of fingerprints focuses on identifying at what image resolution, also referred to as pixels per inch (ppi), can level 3 detail be extracted from a fingerprint image, development of extraction methods for level 3 detail, as well as development of matching algorithms to include the level 3 detail in addition to level 1 and level 2 detail in the matching process.

5.1 Use of AFIS

The analysis of fingerprints can involve level 1, level 2, and/or level 3 detail in the identification of a unknown fingerprint to a potential match. Traditionally, fingerprint matching was completely performed by hand, utilizing the ACE-V method. With the development of rapidly evolving technology, fingerprint matching has become an automated procedure through the use of fingerprint matching algorithms. In a fully "Lights-Out" system, the entire matching process is performed automatically by the algorithm with no human intervention, whereas a "Semi-Lights-Out" system involves human intervention, during the feature extraction phase, where for example, the examiner could orient the print or mark a region of interest [53]. No matter the type of system used, a match score is computed, which is a measure of similarity between the two fingerprints being compared. Not all fingerprint matching algorithms utilize the same methods in computing the match score. There are correlation-based methods, minutiae-based methods, and other feature-based methods [54]. Correlation-based methods are rather basic in nature, as the fingerprint images are simply scaled, translated, rotated, and equalized, followed by the computation of the match score based on a correlation measurement. For this reason, correlation-based methods are not commonly used in AFIS systems [54].

Minutiae-based methods compute a match score based on the minutiae found on the two fingerprints being compared. In most instances, the two minutia used are the ridge ending and ridge bifurcations, due to their stability and robustness [55]. The higher the correspondence between minutiae of two fingerprints, the higher the match score. Correspondence of two minutiae is determined by the spatial distances and directional differences between the two, and is called a correspondence if below a set threshold [54]. Both global and local algorithms exist, in which the global uses all of the minutiae of the fingerprints, whereas the local compares the minutiae of localized regions of the two fingerprints. Local algorithms are more commonly used, as they permit for greater accuracy and less computational time [54].

Lastly, there are other feature-based methods, which either utilize other features in addition to the minutiae, or directly use the other features for the match score computation. "Other features" can consist of texture analysis using level 1 detail, or the newly studied, level 3 pore detail [54]. In the literature, there has been an increase in the interest of developing AFIS algorithms that include level 3 detail in the matching process of unknown fingerprints [56]. In a majority of the AFIS systems that are able to detect level 3 details, the first step in the process is pore detection. Due to the wide variety of size and shape seen in pore structure, the detection of pores can be a rather difficult task [56]. The second step is the establishment of pore correspondence, in which the pore(s) of one fingerprint are corresponded to the pore(s) on a second fingerprint [57]. Lastly, the AFIS matching algorithm will compute a match score based on the pore correspondences established, in effort to determine if the match is a true or false positive [56].

With most fingerprint matching systems using minutiae as the main feature used in the identification of an individual, several studies have proposed the solution of including pore detection in addition to the minutiae as a means to strengthen the accuracy of such systems. Of the pore extraction methods used by AFIS systems, most utilize a static isotropic pore model to detect the pores within the fingerprint [58]. However, more recently, the level 3 features of pores and ridge contours have been extracted through the use of Gabor filters and wavelet transform, followed by being matched with the Iterative Closest Point (ICP) algorithm [9]. The first automated system to detect pores was developed by Stosz and Alyea, in which both the minutiae and pores of a fingerprint were used to identify an individual [59]. Further studies conducted by Kryszczuk *et al.* indicated the benefit of utilizing the pores of a fingerprint when the area of fingerprint captured is small [60, 61].

5.2 Fingerprint Image Resolution

One of the main factors affecting the performance of an AFIS system is the resolution of the fingerprint image. Currently, the FBI standard for image resolution is 500 ppi, however at this resolution the level 3 detail cannot be reliably extracted from the fingerprint image [12]. Thus, many studies were conducted to determine at what image resolution could level 3 detail be reliably extracted from. While most studies have concluded and reliably extracted level 3 detail from images at a minimum of 1000 ppi [59, 60, 62], Zhang *et al.* determined that an image resolution of 800 ppi was sufficient to extract pore detail [12].

Further, many studies have also developed their own methodology for pore extraction from fingerprint images. Stosz and Alyea proposed the first skeletonized-based pore extraction and matching method. In summary, this method first converts the fingerprint image to a gray binarized image, followed by creating a skeletonized version of the image to reduce the objects within the image to one pixel in size, and lastly, "cleaning" of the fingerprint image to locate minutiae and pores [59]. In contrast to the skeletonized-based method, a study conducted by Jain *et al.* utilized Gabor filters and Mexican hat wavelet transform for pore extraction [62]. This study also notes that while 1000 ppi is required for pore extraction, it does not necessarily mean that pores will be present in the image, as individual pores within a fingerprint open and close depending on bodily conditions.

Given that there is limited availability of commercial AFIS matching systems that utilize the extended feature set of level 3 detail in the matching scheme, the studies that extracted pores also had to develop a matching scheme which included the addition of the level 3 detail. Jain *et al.* proposed a hierarchical matching system with the Iterative Closest Point (ICP) Algorithm. Within the hierarchal matching system, the comparison of two fingerprint images starts with using level 1 and level 2 detail. If an exclusion cannot be made at this point, the system will then compare the images using both the level 2 and level 3 detail, followed by score fusion [62]. In comparison, the method for pore matching proposed by Zhao *et al.* starts with establishing initial pore correspondences between the two fingerprint images. From the initial pore correspondences, the RANdom Sample Consensus (RANSAC) algorithm is applied to remove falsely identified pores. Using both the initial and refined pore correspondences between two fingerprint images, a match score is calculated [57]. While the studies discussed here are not an exhaustive list of the research that has been conducted on the relevant topics, it is a brief overview of the many proposed pore extraction and matching methods.

5.3 Utilization of Level 3 Detail

Due to the nature of latent fingerprints and the likelihood that such fingerprints are distorted and incomplete, the fingerprint community has been eager to extend the usable features of a fingerprint to level 3 detail in the use of fingerprint identification. Level 3 detail, specifically pores, have been reported to similar discriminatory power as the combination of level 1 and level 2 detail in determining the identity of an individual. Over the past two decades, poroscopy has been frequently studied, examining pore area, shape, and size. Multiple researchers have embarked upon studies that show the use, extent, and reliability of third level detail in personal identification, focusing on the extraction of level 3 detail and its implementation within AFIS systems.

With societal advancements and the growing reliance on technology, there has been a growing need for personal authentication, especially with biometrics. Evaluating system performance is currently an extensive and time consuming process through establishing error rates. A study conducted by Roddy and Stosz proposed a new method to evaluate system performance, which they tested on a pore-based automated fingerprint matching method. The authors also presented pore statistics and discussed the effectiveness and value of using pores within AFIS systems to improve performance [63].

It has been established that once pores form along fingerprint ridges, their position is fixed and does not change. When identifying fingerprints with the use of minutia, knowing the relative position, orientation, and type is sufficient. When using pores, the position, size, and shape are possible features to be considered. For purposes of identification and use of pores, the pore position is defined as its center of mass. Roddy and Stosz described how the key element in matching fingerprints is to establish a common reference point or origin (x,y) within each fingerprint or area being examined [63]. The established reference point should be properly identified within each reference image before the matching process begins. Establishing reference points is critical as the relative location of a pore within an unknown fingerprint image may be shifted to come degree (delta) as a result of rotation, plasticity, or other distortion. To overcome the distortion, a search area is associated with each feature or fingerprint detail under examination. The search area is calculated by summing the degree of difference in each direction of the reference point, $\Sigma([x - \Delta x, x + \Delta x], [y - \Delta y, y + \Delta y])$ so that if a feature is found within a given search area in an unknown fingerprint, that feature will match, in respect to position, to the original point in the reference fingerprint [63].

During fingerprint identification, apparent distortions of a fingerprint are accounted for when manual comparison by an examiner is performed. However, within an automated process, tolerances of the search area have to be incorporated in the matching method [63]. Match scores can be defined in many ways, Roddy and Stosz chose to define their match score by subtracting the number of pores that do not match from the number of pores that do match, divided by the total number of pores. The match score result will range from -1 to +1, where +1 represents a perfect alignment of the pores in the two compared images or area under examination [63]. The authors selected a +/- resolution of 3 pixels for their search area for the detection of a pore. They felt that the range of 3 pixels was large enough to detect a variant pore location, but not too large to result in a pore mismatch [63].

When examining pore reliability, Roddy and Stosz considered the pore feature type (position, shape, and size), the capture method, and skin condition. Within latent fingerprints, the ability to detect pores and clearly define the shape and size are considered variable, as the surface on which the fingerprint was located and the development method used can influence pore identification. Inked fingerprint impressions provide good pore detection, as too much ink could fill the pore, best size representation, and variable shape identification due to potential bleeding of the ink. Live-scanned fingerprints provide the best opportunity to detect pores and variable opportunity for identifying pore shape and size. However, with live-scanned fingerprints, all pore features could be affected by the moisture level of the hand/fingers [63].

Further, Roddy and Stosz reported on statistics related to pore features. They found that pore density is approximately 2700 to 3350 pores per square inch (in²) which equates to 4.19 to 5.19 pores per millimeter squared (mm²). Intra-ridge density, or the separation of pores on a ridge, was found to be on average 0.39 mm, with about 25.6 pores per cm of ridge. Lastly, while each pore shape is considered unique, shape generally varies from square to circular and is less than 220 μ m across, with an average diameter or 109 μ m [63].

For the application of poroscopy, the reproducibility of pores within both latent fingerprints and reference fingerprints needs to be examined. Due to the way in which a latent fingerprint is deposited and developed, it can look different from its reference counterpart; and is why it cannot be assumed that observations made within a reference fingerprint will be seen in all subsequent latent fingerprints. For this reason, pore area reproducibility was examined by Gupta *et al.* in their 2008 study [64]. These authors examined the reproducibility of pore area in inked fingerprints in a previous study, so this study aims to examine the same, but in latent fingerprints developed by cyanoacrylate fuming and ninhydrin.

For the collection of the latent fingerprints, participant hands were made to perspire for 60 minutes while in latex gloves, followed by the deposition of the left index finger onto plain black CD cases and glossy paper. The fingerprints deposited onto the CD cases were superglue fumed, while the fingerprints deposited onto the glossy paper were processed with ninhydrin. Developed fingerprints were visualized and digitally photographed. Within the fumed fingerprints, 50 were used for data collection, with 7 pores in each fingerprint selected for measurement. Within the ninhydrin fingerprints, 10 were used for data collection, with 5 pores in each fingerprint selected for measurement. Pore area was measured for each of the selected pores and within each group of fingerprints, mean area (μ m²), standard deviation, and percent coefficient of variance (%CV) was calculated. To ensure reliability of the measurement method, within one fumed fingerprint, the 7 pores were measured 10 times, with the same statistics calculated [64].

Results from the Gupta *et al.* study indicated that the measurement method used proved to be reliable with a %CV below the 5% threshold level. For the fumed fingerprints, the pore area was shown to not be reproducible with a %CV above the 5% threshold. During measurement of the pores within the ninhydrin fingerprints, differences were observed showing that pore area was not reproducible across replicates; in addition to a %CV above the 5% threshold [64]. The findings of this study supported the findings of Ashbaugh in that pore area is not reproducible in latent fingerprints [11]. Ashbaugh further stated that pore features such as shape and size are inconsistent in inked and latent fingerprints. Roddy and Stosz also concluded that pore size and shape are variable within latent fingerprints, with the detection of pores being dependent upon the method applied for development [63]. The results of all three studies raises doubt on the reliability of pore area in latent fingerprints.

Currently, there is no public domain or database of fingerprints with ground truth data for pore information, or any extended features; meaning that any study looking to utilize such data needs to establish ground truth for themselves within their own data set. In 2010, Zhao and Jain examined the utility of extended fingerprint features, specifically pores [65]. Within this study, a small database of partial fingerprints was utilized. A small sample size was required due to the time consuming and tedious nature of manual markup of extended features within a fingerprint. Manual markup was necessary to obtain a level of ground truth to assess how their pore extraction method performed. Fingerprint images were separated into good, medium, and bad quality groups using the symmetric derivative based fingerprint image quality assessment proposed by Fronthaler *et al.* [66]. In comparing the fingerprint images, given a detected pore, if a ground truth pore was located within a distance of 5 pixels, the detected pore was considered a true detected pore. This study concluded that in general, pores should only be used when obtained from high resolution fingerprint images of good quality [65]. Zhao and Jain stated that future work should focus on improving the performance of automatic pore extraction and matching methods.

Nagesh *et al.* attempted to find if there is any influence of sex and age on pore morphology [67]. Inked fingerprints were collected and assessed for multiple pore characteristics, such as the number of pores per centimeter of ridge, the type of pore (open or closed), position of the pore along the ridge, and the size of the pore. With each pore characteristic, averages were calculated, with significance tests performed with independent t-test and ANOVA. These characteristics were compared between males and females within the defined age groups. The results obtained from this study showed that between males and females, the number of pores per centimeter of ridge and pore shape were not shown to be significant. Assessment of pore type, size, and location showed that the majority of pores were closed, medium in size (101-200 μ m), and located along the center and periphery edges of the ridge. Further, no significance was found with pore characteristics, such as pore size, with change in age within males, but not females. Overall, the study concluded that pore characteristics are not influenced by sex, however characteristics such as pore type, size, shape, and position may be influenced by age [67].

One of the major limitations of pores is the variability of pore appearance from one fingerprint impression to another, despite originating from the same individual. The lack of research in this area prevents robust application of pores to casework, in which fingerprints are of varying quality. In effort to address this lack of research, Anthonioz and Champod attempted to assess the forensic contribution of features associated with pores by evaluating the strength of the evidence of a comparison between an unknown fingerprint and a reference fingerprint [68]. The authors considered pores in conjunction with minutia formation by designing a pore detection algorithm, defining a metric to rate the fingerprint comparison, and used likelihood ratios to express the results [68].

Fingerprints were collected at about 2700 ppi in order to study all potential features of the pores. The authors identified this as a potential limitation of their study, but noted that within casework, pores will only be utilized if the quality is sufficient. Two databases were constructed, within variability which contained fingerprints captured under various distortion factors, and between variability. In order to obtain relevant results, a large amount of data was needed, so it was not realistic to measure pore features by hand. The metrics examined in this study were the distance between the pore and the closest minutia point, the angle between the two, and the center mass between the two. Metrics were compared between fingerprints, and if within defined boundaries, they were considered compatible; providing three scores which were summed and used within the likelihood ratio. Results indicated that when considering the pore in reference to a minutia point, pores have good discrimination capability [68].

As a result of a limited number of fingerprints that contain pores of sufficient quantity and clarity and the lack of consensus among practitioners regarding the contribution of pores in relation to identification, pores currently have a limited role within fingerprint identification. While initial research reveals pore limitations, there still appears to be a greater need for pore integration within the identification process; as expressed by the fingerprint community. As shown by previously cited literature regarding biometric system utilizing pores, including level 3 detail such as pores, in addition to level 2 detail, improves the accuracy of the AFIS system.

Practical use of AFIS algorithms involves unknown fingerprints, such as those collected at crime scenes, which are often latent in nature. The resultant quality of latent fingerprints is subject to various factors at the time of deposition, such as the deposition surface, environmental conditions, and composition of the fingerprint itself. Consequently, these factors, in addition to the inherent variance in pore structure, may very well affect the observance and use of level 3 details within a fingerprint. If the prevalence of pores proves to be unreliable and inconsistent in latent fingerprints, the push for including level 3 detail in the AFIS matching process may all be for nothing. For this reason, the effects of latent fingerprint deposition factors on pore identification needs to be considered and currently appears to be greatly under studied [66].

6. Present Study

In effort to begin to fill the gaps within the current research, the present study aimed to assess the prevalence of pores within latent fingerprints as well as determine if pore detail changed in association with various deposition factors. To do so, newly deposited latent fingerprints were collected and developed using both black fingerprint powder and cyanoacrylate fuming. Developed fingerprints were subsequently imaged via digital scan or digital camera, and enhanced using ImageJ and Adobe[®] Photoshop[®]. Following image enhancement, pores were manually identified and marked using the Federal Bureau of Investigation (FBI) developed Universal Latent Workstation (ULW) software. Analysis of the data aimed to determined if the number of pores seen was associated with factors such as age, sex, and environmental temperature. Further, the number and location of pores between depositions of the same finger were compared.

6.1 Latent Fingerprint Collection and Development

Depending on the surface upon which a fingerprint was deposited onto, the method used to develop the latent fingerprint will differ. The nature of the surface, such as porous or non-porous, color, as well as the environmental conditions, such as wet or dry, influences the selection of the development method [69].

Cyanoacrylate fuming, also known as superglue fuming, is a common chemical enhancement method used for non-porous surfaces such as plastic or glass. Upon heating the cyanoacrylate compound, the vapors it forms interact and bind to the components of the eccrine secretions left behind in a latent fingerprint, forming polymer chains and producing a white color [70]. Once the fuming is complete, the latent fingerprint is considered stable and can be further enhanced with a multitude of techniques, if necessary. Various lighting techniques such as oblique, axial, reflected, and transmitted light can be used to increase the contrast of the ridges and valleys for imaging. Further, the latent fingerprint could be additionally enhanced via fluorescent dye stains or with the application of fingerprint powders.

Utilizing fingerprint powders for enhancing latent fingerprints has been the most common and universal method for non-porous substrates [71]. Powders work best when they are composed of small, finely-milled particles, of a color that provides the greatest contrast to the substrate the latent fingerprint is deposited onto [71]. Unlike superglue fuming, where binding takes place, the fingerprint powders physically stick to the sweat and oils released from the glands on the fingertips. Powders can generally be classified into three different types, regular, magnetic, and fluorescent; all of which perform well with their intended functions [71]. One disadvantage to fingerprint powders is that the method is destructive to a varying degree, depending on the experience of the analyst performing the dusting. Application of most fingerprint powders is with fingerprint brushes composed of either animal hair, fiberglass filaments, or feathers. The degree of contact between the brush and the fingerprint can impart destruction of the fingerprint.

A fingerprint examiner must consider the surface upon which the fingerprint is found, the environmental conditions surrounding the fingerprint, and the potential composition and/or residues that make up the fingerprint. Understanding the composition of a latent fingerprint, as well as characteristics of the environment the fingerprint is found in, will greatly improve the quality of the developed fingerprint. Consideration of and adherence to correct processing techniques and sequences maximizes the possibility of developing all latent fingerprints found on an object, greatly increases the effective recovery of the best quality latent fingerprints, and reduces the possibility of destroying latent fingerprint evidence.

6.2 Image Enhancement

In order to perform post processing on the fingerprint images, both ImageJ via Fiji and $Adobe^{\textcircled{R}}$ Photoshop^R were utilized. ImageJ is an open source image processing program designed specifically with the scientific community in mind [72]. Both the ImageJ application and its source code are available for free for user download. Users are able to create and reuse workflows, and the application is interoperable with many script languages. There are a variety of functions and uses of ImageJ with many plugins and additional scripts for furthering its capability. ImageJ has a larger user base and an active forum for sharing ideas and asking questions [72]. Fiji is an image processing package distributed by ImageJ, which bundles many packages that are specific for scientific image analysis [73]. In total, the ImageJ ecosystem provides great tools and assistance to the scientific community.

A detailed description of the steps taken during the image enhancement process can be found within section 7.2.3.

6.3 Universal Latent Workstation

The Universal Latent Workstation (ULW) was specifically developed in effort to increase interoperability between departments and jurisdictions [74, 75]. Currently, there are about 200 departments utilizing ULW for their latent fingerprint searches [75]. ULW allows for searching multiple AFIS systems through the use of a single encoding of a fingerprint, such as FBI IAFIS, Cogent, or Sagem Morpho [74, 75]. The software does this by recording the data of the latent fingerprint and translating the data into the format used by the AFIS systems. At no charge to the agency or department, the ULW software can be obtained from the FBI and any training needed to learn the system [75]. The ULW software also has the options to specify descriptor variables to limit the search, such as sex and eye color [74, 75]. Search records within ULW are formatted in accordance with the ANSI/NIST-ITL standard: Data Format for the Interchange of Fingerprint, Facial, & Other Biometric Identification [76].

In comparison to other fingerprint feature extraction algorithms, the ULW system will perform an auto-extraction of the minutia and ridge counts from the fingerprint and assign a confidence score to each identified minutia and ridge count based on the image quality [75]. Examiners can adjust a confidence score threshold in efforts to eliminate falsely identified minutia. In addition to ridge and minutiae detail, ULW has the ability to mark images using extended fingerprint feature sets. Among the features included within the extended feature sets is the option to markup dots, incipient ridges, and pores. All features included with the extended feature sets are defined in the ANSI/NIST-ITL standard [76]. The inclusion of the extended feature sets provides a quantifiable and repeatable method for characterizing the information contained within a fingerprint image [74].

6.4 Data Analysis Tools

For the purpose of performing statistical analyses and creating graphical visualizations of the data collected within the present study, both R via RStudio[®] and Microsoft Excel[®] were utilized.

R is a programming language environment for statistical computing and graphics [77]. The environment space is a system for data handling, calculation, and graphical display which is well developed and simple to learn and use. It is a free, open-source software, available for multiple computer platforms under the GNU General Public License. RStudio[®] is an integrated development environment (IDE) for R, which is also free and open-source [78]. RStudio[®] contains a set of integrated tools made to increase productivity and ease-of-use within R. RStudio[®] is available in desktop and server editions and contains multiple additional packages and add-ins, increasing the functionality within the R environment.

7. Experimental Design

7.1 Research Objectives and Data Collected

Within the scope of the present study, there were two main objectives:

- 1. Determine the prevalence of pores within latent fingerprints.
- 2. Identify conditions/factors that influence the presence or absence of pore detail within latent fingerprints.

Determining the prevalence of pores within latent fingerprints was the main goal, as pore detail has been studied in other types of fingerprints, such as inked and live-scan; however, not so much within latent fingerprints. The second objective, identifying conditions/factors that influence the presence or absence of pore detail with in latent fingerprints, was to gain a better understanding of the factors that influence the quality of pore detail within latent fingerprints.

To best reach the research objectives, the following information and data were collected during the course of the study:

- Qualitative descriptions of fingerprint quality and pore detail.
- Information associated with each participant (sex, age, activities prior to fingerprint deposition).
- Conditions associated with the day and environment during fingerprint collection (day, month, year, time of day, inside temperature, outside temperature, outside humidity).
- Total pore count for each fingerprint.
- X,Y coordinates of each pore detected.

7.2 Data Acquisition

In order to analyze the prevalence of pores within latent fingerprints associated with various categorical factors, newly deposited latent fingerprints were collected from 35 participants for use in this study. Participants comprised of volunteers who were asked to provided numerous depositions of their fingerprints. IRB approval (Protocol Number: 1807190502) was obtained prior to fingerprint collection from the participants.

7.2.1 Latent Fingerprint Collection

At the start of the collection process, participants were assigned a random identification number and completed the required questionnaire (refer to Figure 10.1 in Appendix A). The questionnaire asked for participants to provide information regarding their age, sex, the date of collection, the time of collection, the temperature (both inside and outside), the humidity outside, and a brief description of their activity (such as physical activity, hand washing, or application of lotion) prior to volunteering. This information gathered by the questionnaire formed the basis of the categorical factors considered in association with the prevalence of pores. The source of the inside temperature was the thermostat in the lab space used, and for the outside temperature and humidity, The Weather ChannelTM app for iOS was used.

Upon completion of the questionnaire, participants were directed on how to deposit their fingerprints onto the substrates. Participants were instructed to start with either the left or right hand, and using gentle and consistent-as-possible pressure, provide "slap" impressions of the three required fingers simultaneously and in sequential manner, to result in the three (3) replicate depositions of each finger.

Each participant was asked to provide a total of eighteen (18) depositions of their fingerprints, consisting of the index, middle, and ring fingers of both the left and right hand, to produce the required latent fingerprints. The participants deposited their fingerprints onto two substrate types: flat, white ceramic tiles (American Olean Starting Line White Gloss 4-in by 4-in Ceramic Wall Tile, Item# 1224, Model# SL1044HCBP at Lowe's) and flat, plastic compact disk (CD) cases with black backings (Staples 5mm Slim Jewel Cases, 50/Pack, Item# 445567, Model# 10378-CC at Staples). A single unit of the ceramic tile and a single unit of the CD case was provided for each participant, with the ceramic tiles being used for the deposition of fingerprints from the left hand, and the CD cases being used for the deposition of the fingerprints from the right hand. For each finger used in this study (i.e. the index, middle, and ring fingers), three (3) depositions were requested, totaling nine (9) depositions on each substrate type. To ensure a clean surface for fingerprint deposition, each substrate was wiped down with acetone prior to the start of collection.

7.2.2 Development and Digitization

Provided the use of two substrates, two development methods were used to develop the latent fingerprints. Latent fingerprint dusting and chemical enhancement with cyanoacrylate glue are easy to use and are common methods implemented within many laboratories. For this reason, these methods were chosen for latent fingerprint development within this study. Development of the fingerprints took place within 24 hours of deposition. The utility of such methods for level 3 detail extraction from latent fingerprints will not be examined within this study and it is outside the scope of this study as to if the proposed methods are the best methods.

The latent fingerprints deposited onto the white ceramic tiles were dusted with a black fingerprint powder (Lynn Peavey Company, 2 oz.) using a fiberglass filament fingerprint brush. To secure the fingerprints, transparent fingerprint lifting tape (Sirchie) was placed overtop the surface of the ceramic tile. Each tile, containing nine (9) total fingerprints, was then scanned at 1000 ppi and saved in TIFF file format, using an Epson Perfection[®] V700

Photo scanner (Model: B11B178011) (refer to Figure 10.2 in Appendix A).

The latent fingerprints deposited onto the plastic CD cases underwent cyanoacrylate (superglue) fuming. Utilizing the Air Science USA SafefumeTM Automatic Cyanoacrylate Fuming Chamber Printbuster V3 (Serial no. CA50690), the CD cases were placed inside the chamber to conduct the superglue fuming. Prior to beginning the fuming cycle, the humidifier water supply was filled, and using Evident[®] Cyanoacrylate Glue, 4-5 drops of glue were placed in a small aluminum dish, which was placed on the hot plate inside the fuming chamber. The fuming time was set to fifteen (15) minutes and would start after the chamber reached a relative humidity of 80%. The temperature reading on the instrument was approximately 71°F across all fume cycles. Upon completion of the fuming process, the developed fingerprints on each CD case were imaged with a Nikon[®] D7500 digital single-lens reflex (SLR) camera.

Using the Nikon[®] D7500 digital SLR camera with a Nikon[®] 60 mm macro lens, images were captured at 1000 ppi in both JPEG and RAW (NEF) formats. To capture images at this resolution, FBI and SWGIT (Scientific Working Group on Imaging Technology) guidelines for capturing latent impressions was followed [79, 80]. Following the guidelines, the maximum field of view to obtain an image at 1000 ppi, with a pixel pitch of 4.2 microns, was determined as well as the camera-to-subject distance. Based upon the calibration settings, the CD cases were placed plane parallel at a distance of 14 inches from the lens of the camera. Oblique lighting was used to best enhance the contrast between the developed latent fingerprints and the black surface in which the prints were developed on. Given the settings utilized, all nine fingerprints could not be captured within a single image due to their placement on the CD surface, so multiple images were taken of each CD case. A photo log was kept to keep track of each CD and which image(s) it corresponded to.

7.2.3 Post Imaging Processing

Post image processing was required on both the tile images and the CD images, in order to set all images to the appropriate size and to further enhance the contrast between the developed fingerprints and the substrate surface. The methodology used for this enhancement differed between the two substrate types.

All scanned images of the tiles were saved to their own folder, "Initial Scans (Tiles)", with the file name corresponding to the ID number of the participant the fingerprints belonged to, example "ID Number.tif". Each tile image was then opened in the program, ImageJ, to set the size/scale. Using the straight line tool, the length/width of the tile was selected, and the size/scale was set to 4.25 inches using the Set Scale function under the Analyze tab (refer to Figure 10.3). The Global option was selected so that the scale would be applied to all opened images within ImageJ, which included all tile images.

The sized images were then saved to a new folder, "Sized (Tiles)", again with the file name corresponding to the ID number of the participant and in TIFF format. Next, each sized image was opened again in ImageJ for enhancement. One image at a time, the image was enhanced using the Enhance Local Contrast (CLAHE) function under the Process tab. This plugin implements Contrast Limited Adaptive Histogram Equalization (CLAHE) to enhance the local contrast within the image. As an image processing technique, adaptive histogram equalization enhances the contrast within an image using several histograms across an image,
which are specific to that region of the image. Within each histogram, the lightness values of the contained pixels are redistributed. Implementing adaptive histogram equalization tends to amplify the noise within an image. To avoid excess noise, contrast limited adaptive histogram equalization can be used instead, which prevents the noise by limiting its amplification. After image enhancement, each image was then saved over the sized image in the "Sized (Tiles)" folder, which now contained images that were both sized and enhanced.

Following enhancement, each image was next opened in $Adobe^{(\mathbb{R})}$ Photoshop^(\mathbb{R}). Within $Adobe^{(\mathbb{R})}$ Photoshop^(\mathbb{R}), the image was duplicated nine (9) times, each one of the nine duplicates for one of the nine (9) fingerprints within the image. Using a duplicate, the image was cropped down to contain a single fingerprint. Each cropped image was then saved in JPEG file format (refer to Figure 10.4 in Appendix A) to a new folder, "Cropped (Tiles)", with a name corresponding to the ID number of the participant, the specific finger, and deposition sequence. From left to right on each tile, the fingerprints corresponded to the left ring finger, left middle finger, and left index finger and were associated with the variables A, B, and C, respectively. Further, the top, or first, row of fingerprints on the tile corresponded with the first deposition, each further deposition sequentially following the first. Therefore, the fingerprints deposited first were identified with the number "1", those deposited second, with the number "2", and those deposited third, with the number "3". For example, a file name would be "ID Number_A1". After cropping the tiles images into each individual fingerprint, this completed the post image processing.

All images taken of the CD cases were uploaded and saved to their own folder, "Initial Images (CDs)," with the file name corresponding to the ID number of the participant and a number, corresponding to which image of the CD it was. Of the CD case images, the RAW (NEF) files were individually opened with $Adobe^{(\ensuremathbb{R})}$ Photoshop^(\ensuremathbb{R}), no changes were made within the Camera Raw window. Within $Adobe^{(\ensuremathbb{R})}$ Photoshop^(\ensuremathbb{R}), using the Image Size tool, the resolution was set to 1000 ppi, without resample (see Figure 10.5 in Appendix A). Setting the resolution should not alter the image size, due to the calibration steps taken earlier when capturing the image at 1000 ppi with a sensor size of 23.5 x 15.6mm on the Nikon D7200. Each image was then saved in TIFF format to a new folder, "CDs (TIFF)," with no image compression, interleaved pixel order, and IBM PC byte order (refer to Figure 10.6 in Appendix A).

Following sizing, each image was then enhanced using the Auto Contrast tool in Adobe[®] Photoshop[®] and duplicated the appropriate number of times; as unlike the tile images, not all nine (9) fingerprints were able to be captured within a single image. Similar to the tile images, each duplicate was for one of the fingerprints within the original image. Using one of the duplicate images, a crop ratio of 4:5 was set, and the image was cropped down to contain a single fingerprint. Each cropped image was then saved in JPEG file format (refer to Figure 10.4 in Appendix A), to a new folder, "Cropped (CDs)", with a name corresponding to the ID number of the participant, the specific finger, and deposition sequence. From left to right on each CD case, the fingerprints corresponded to the right index finger, right middle finger, and right ring finger and were associated with the variables A, B, and C, respectively. Note that this is different from the tile images. Further, the top, or first, row of fingerprints on the CD case corresponded with the first deposition, each further deposition sequentially following the first. Therefore, the fingerprints deposited first were identified with the number "1", those deposited second, with the number "2", and those deposited third, with the number "3". For

example, a file name would be "ID Number_A1". After cropping the CD case images into each individual fingerprint, this completed the post image processing.

7.2.4 Pore Identification

Universal Latent Workstation 2017 (version 6.6.7) software was used during the course of this study. The software is comprised of three applications, the ULW Latent Editor, the ULW Comparison Tool, and the ULW Transaction Manager. The present study utilized the Latent Editor application of the software.

Upon opening an image with the ULW Latent Editor software, the resolution had to be specified. Of the provided options to select from for specifying image resolution, "The image was scanned at 1000 pixels per inch" was selected. Following the specification of image resolution, the region of interest was marked. For the purpose of this study, the region of interest was the entirety of the fingerprint, therefore a polygon shape was drawn surrounding the whole fingerprint within each image. Located within the "Features Toolbar" on the left side of the screen, the finger position was specified under the "Latent Info" section, and the "Feature Set" was set to "Full Annotation (EFS)" in order to be able to mark-up the pore data. From the available features within the extended feature set, "Pore" was selected. Each visible pore within the fingerprint image was then manually marked-up/selected. The approximate center of mass of each pore was marked and visualized by a green dot. Afterwards, the file and "Summary Output" was saved using the same identification scheme as the original image. The summary output contains the data/information of the image in the ANSI/NIST format. The relevant information related to the pore data is found within the Type 9 Record. For every marked pore, the ULW software notes the location via an x, v coordinate pair. Each x and y coordinate value are in units of 10 micrometers (0.01 millimeters), as described by the ANSI/NIST-ITL 1-2011 Update: 2015 Data Format for the Interchange of Fingerprint, Facial & Other Biometric Information document [76].

7.2.5 Data Extraction

Utilizing RStudio[®] software (version 1.2.1335), the pore information contained within the summary output file for each fingerprint was extracted and saved as a CSV file (See ULW Data Extraction code in Appendix B).

8. Data Analysis and Results

Assessment of the data collected was divided into five separate parts:

- **Part 1** Qualitative assessment of fingerprints and pore detail in effort to explain the types of fingerprints obtained and quality of pore detail observed.
- Part 2 Determination of statistical significance between associated variables and total pore count.
- **Part 3** Observations regarding total pore count in relation to the replicate fingerprints.
- **Part 4** Determination of statistical significance between development method and pore data.
- Part 5 Examination of pore location between replicates to determine if relative pore location changes significantly between depositions.

Each part of the data assessment assisted in providing information to reach the first and main objective of the study. All parts examined the pore data collected, providing many angles of approach when determining how prevalent pores are within latent fingerprints. More specifically, Parts 1 and 2 provided information for analysis of the second objective of the study. Part 1 provided an overview of the data collected and a qualitative means of pore assessment in relation to the examined factors; while Part 2 provided statistical means of looking at significance of the examined factors.

8.1 Part 1

An overall assessment of the data collected was crucial, as doing so provided clarity on the usable data obtained from the original starting data set. A qualitative assessment of the entire data set aided the decision making process in the determination of whether or not a fingerprint and its associated data was usable for purposes of the current study.

The following is a breakdown of the data collected:

- Total # of participants: 35
- Total # of fingerprints collected per person: 18 (9 per hand)
- Total # of fingerprints collected overall: 633
 - Participant #1320 inadvertently provided four replications per finger with their right hand, adding an additional three fingerprints to the data set. These three

fingerprints were subsequently removed, leaving 630 total fingerprints collected (315 fingerprints from the left and right hands).

Of the 315 fingerprints collected from the left hand (tile fingerprints):

- All collected fingerprints developed to some degree.
- Participant #1067 provided poor quality fingerprints (9 total), these nine fingerprints were subsequently removed from the data set.
- The fingerprint identified as #1176_L_B2 was never marked-up and subsequently not included in the data set.
- These considerations yielded 305/315 fingerprints as usable for the current study.

Overall, the fingerprints obtained from the tile collection process developed well and produced good quality fingerprints in terms of ridge definition and pore presence. It was crucial that a fingerprint contain both ridge definition or clear fingerprint pattern and the presence of pores, as one without the other made for difficult determination in locating and marking pore detail. Figures 8.1 and 8.2 show a set of images representing good quality and bad quality fingerprints, respectively, deposited onto the tile substrate. Within the "good" set of images, while the quality of ridge detail differs slightly, fingerprint pattern is detectable and pore detail is actively present. In comparison, the first two images within the "bad" set lack ridge detail and/or fingerprint pattern, despite the possibility of pore detail being present. Without sufficient ridge detail or pattern identification, marking pore location was difficult and not a matter of fact decision. Within the third image of the "bad" set, ridge detail and fingerprint pattern are clearly defined, yet pore detail appears to be missing, as such, despite the overall fingerprint being of sufficient quality, for purposes of this study in detecting pores, this image is considered less than ideal.



Figure 8.1: A selection of three images representing the good quality fingerprints obtained from the tile/left hand set of fingerprints.



Figure 8.2: A selection of three images representing the bad quality fingerprints obtained from the tile/left hand set of fingerprints.

Of the 315 fingerprints collected from the right hand (CD fingerprints):

- Not all fingerprints developed well enough for visual examination.
 - Only 15/35 participants provided fingerprints that were able to be developed, totaling 135 available fingerprints.
 - The participants that produced developed fingerprints include: #1055, #1065, #1066, #1073, #1176, #1184, #1201, #1223, #1241, #1320, #1445, #1476, #1868, and #1870.
 - Various combinations of finger and replication sequences were removed due to insufficient development/detail, resulting in the set of sufficiently developed fingerprints being not representative of full-sets for each participant.
- Of the 135 sufficiently developed fingerprints, not all contained quality ridge and pore detail usable for mark-up, and were subsequently removed from the data set.
- These considerations yielded 75/315 fingerprints as usable for the current study.

Unlike the fingerprints deposited onto the tile substrate, the fingerprints deposited onto the CD cases did not develop as well as hoped. An overwhelming number of fingerprints did not develop at all or sufficiently enough for use. Of the fingerprints that did develop, the same considerations were made regarding the ridge definition/pattern identification and the presence of pore detail. Figure 8.3 shows three examples of fingerprints that developed well and contained sufficient ridge definition, pattern identification, and presence of pore detail, which made for easy pore identification and marking.

One notable difference however, was the added consideration of the textured background of the CD case/substrate. The textured background introduced an inherent question as to whether or not the lack of cyanoacrylate development within the fingerprint was due to the



Figure 8.3: A selection of three images representing the good quality fingerprints obtained from the CD case/right hand set of fingerprints.

presence of a pore or the texture itself; most especially in cases of poor ridge definition and pattern identification. Examples of this additional consideration can be seen in Figure 8.4 where not only are the ridge definition and pattern identification less than ideal, but the possible pore detail is questionable given the textured substrate.



Figure 8.4: A selection of three images representing the bad quality fingerprints obtained from the CD case/right hand set of fingerprints.

After assessing each fingerprint image based upon the conditions described above, the total number of usable fingerprints available for use in the remainder portions of the current study were 380 out of the 633 original fingerprints.

8.2 Part 2

For purposes of addressing the second objective of the study, conditions/factors that influence the presence or absence of pore detail within latent fingerprints were identified. The factors selected were chosen to gain a better understanding of the influence said factors have on the quality of pore detail within latent fingerprints. Factors considered included information associated with the participants, such as sex, age, and activities prior to fingerprint deposition, and conditions associated with the day and environment during fingerprint collection, such as day, month, year, time of day, inside temperature, outside temperature, and outside humidity – inside humidity was unable to be measured, and therefore not included as a considered factor.

When assessing the data obtained regarding the information associated with the participants themselves, it was clear that not enough participants volunteered within each age in order to compare and achieve significant results. In addition, the study did not receive an equal amount of female and male participants, therefore a comparison to see if sex played a role in pore presence would likely lead to skewed results given the higher number of female participants. Figure 8.5 depicts the distribution of participant sex and age.



Figure 8.5: Participant age and sex distribution from the 35 total participants.

Further, due to the open-ended nature of the prior activities question, it was difficult to group the responses in a manner that would allow comparison to determine if a specific activity affected the presence of pores. Most participants mentioned the act of washing their hands, use of lotion, and general activity prior to volunteering; however, due to the combination of activities taken by a participant prior to volunteering, the activity effect on the presence/absence of pores was unable to be determined. In order to achieve this aim within the study, proper controls needed to be put in place to ensure results obtained were due to a specific activity. A full list of participant responses to the prior activities question can be found in Tables 10.1, 10.2, and 10.3 in Appendix A.

As a result of the research design, limited sample size, the data collected, and the results obtained, proper assessment of the second objective was unable to be met. After countless trial and error attempts, a method could not be determined to assess the significance of the conditions/factors in relation to the total pore count for each fingerprint. As a result of the research design, the conditions/factors could not be separated from each other, as the fingerprints collected were associated with each factor all at once. Given this, in assessing the data, it would not be clear as to whether or not the total pore count was found to be significant due to the temperature or humidity, or any other combination of the factors considered. The only foreseeable means to assess the data would be as compounding variables through multivariate methods; which would not provide the information or results required to properly assess the second objective.

Regardless of the inability to separate the conditions/factors for proper assessment, each population (or factor) was not sufficiently sampled to be representative nor provide significant results. Tables 8.1 through 8.5 detail the number of participants who provided fingerprints in association with each considered factor, as well as the total number of fingerprints collected for each factor. It is important to remember that the number of participants, and subsequently the number of fingerprints, listed within each table are not independent from the participants and fingerprints within another table. Moreover, the number of fingerprints displayed within these tables represent the original data set, not the working data set, which removed fingerprints that were insufficient and underdeveloped for comparison.

Date	# of Participants	# of Fingerprints
Oct. 15	4	72
Oct. 19	6	108
Oct. 22	7	126
Oct. 26	1	18
Nov. 02	7	126
Nov. 09	9	162
Nov. 26	1	18

Table 8.1: The total number of participants who volunteered per collection date and the total number of fingerprints collected.

Table 8.2: The total number of participants who volunteered per hour and the total number of fingerprints collected.

Time	# of Participants	# of Fingerprints
1400 hrs	13	234
$1500 \ hrs$	16	288
$1600~{\rm hrs}$	6	108

Table 8.3: The total number of participants who volunteered under each recorded inside temperature and the total number of fingerprints collected.

Inside Temperature	# of Participants	# of Fingerprints
69 °F	9	162
70 °F	14	252
$71~^{\circ}\mathrm{F}$	12	216

Table 8.4: The total number of participants who volunteered under each recorded outside temperature and the total number of fingerprints collected.

Outside Temperature	# of Participants	# of Fingerprints
41 °F	1	18
48 °F	9	162
$53~^{\circ}\mathrm{F}$	1	18
54 °F	7	126
$55~^{\circ}\mathrm{F}$	7	126
$61~^{\circ}\mathrm{F}$	6	108
$63~^{\circ}\mathrm{F}$	4	72

Table 8.5: The total number of participants who volunteered under each recorded outside humidity and the total number of fingerprints collected.

Outside Humidity	# of Participants	# of Fingerprints
$34~^{\circ}\mathrm{F}$	6	108
$37~^{\circ}\mathrm{F}$	7	126
64 °F	1	18
66 °F	7	126
$71~^{\circ}\mathrm{F}$	1	18
$93~^{\circ}\mathrm{F}$	9	162
94 °F	4	72

In addition, the limited sample size and dependency inherently found within the study would have made it difficult to support statistical significance if the factors could have been separated. The research design included replicate depositions, which introduced dependency that was not expected. This dependency would have made the number of fingerprints associated with each factor, that were not dependent upon another fingerprint, smaller than preferred to support any statistical significance, if found.

Reflecting on this aim of the study, it is more clear that the factors considered would be better assessed as factors applied after the deposition of the fingerprint, rather than at the time of deposition. It is arguably a rare occurrence, if at all possible, to the know the factors associated with the time of deposition for a true latent fingerprint found at a crime scene. Overall, it is of the opinion of the researcher that the research design was not overtly flawed, nor that the study was incorrectly carried out. However, to properly assess the second objective, the research design was not correct in order to obtain the results required for proper assessment. In order to better achieve the desired results, the current study could be broken up into smaller projects or objectives. A separate, new set of fingerprints would be collected for each factor under consideration, introducing more control within the study. Each set of fingerprints would then be subjected to a factor for "X" amount of time and assessed. If the current study were to be repeated, with changes, it would be easier to use one development method for all fingerprints. In addition to this, it would be necessary to collect additional sets of fingerprint replicates for the remainder portion of the study. Such a study, with a much larger amount of fingerprints to examine, would add more time to the mark-up and analysis process. One major factor as to why the current study could not be designed this way, was due to the educational setting and reliance upon volunteers for the deposited fingerprints.

8.3 Part 3

To determine if pore count differed between the replicate fingerprints of a given finger, pore count in relation to fingerprint replicate was examined.

From the data collected from the right hand of the participants, 32 total fingerprint sets were assessed. These 32 total fingerprint sets were comprised of the 75 usable fingerprints obtained from the right hand of the participants. In order for a fingerprint set to be assessed, the set needed to contain pore data from at least two of the three replicates. As a result of only one replicate being of sufficient quality for pore identification, 7 of the 32 sets of fingerprints were unable to be examined.

Of the 25 sets of replicate fingerprints assessed, 6 sets contained total pore counts that were similar across the replicates. Table 8.6 depicts the total pore count for each replicate of the right-ring finger of participant #1445 and Figure 8.6 provides a visual representation, detailing the marked-up fingerprint images associated with the replicates. Alternatively, of the 25 sets, 19 sets contained total pore counts that were dissimilar across the replicates. Table 8.7 depicts the total pore count for each replicate of the right-pointer finger of participant #1055 and Figure 8.7 provides a visual representation, detailing the marked-up fingerprint images associated with the replicates.

Table 8.6: Total pore count for each replicate fingerprint of the right-ring finger of participant #1445.

$\mathbf{Replicate}$	Total Pore Count
C1	N/A
C2	237
C3	239

Table	8.7:	Total	pore	count	for	each	replicate	fingerprint	of	the	right-	pointer	finger	of	partic-
ipant	#10.	55.													

Replicate	Total Pore Count
A1	169
A2	229
A3	252

From the data collected from the left hand of the participants, 102 total fingerprint sets were assessed. The 102 total fingerprint sets were comprised of the 305 usable fingerprints obtained from the left hand of the participants. Within the usable fingerprints collected from the left hand, all but one of the fingerprint sets contained data from all three replicates. The one fingerprint set had data from two replicates rather than all three.

Of the 102 sets of replicate fingerprints assessed, 14 sets contained total pore counts that were similar across the replicates. Table 8.8 depicts the total pore count for each replicate of



Figure 8.6: The marked-up images depicting pore location for each replicate of the right-ring finger of participant #1445.



Figure 8.7: The marked-up images depicting pore location for each replicate of the right-pointer finger of participant #1055.

the left-middle finger of participant #1612 and Figure 8.8 provides a visual representation, detailing the marked-up fingerprint images associated with the replicates. Alternatively, of the 102 sets, 88 sets contained total pore counts that were dissimilar across the replicates. Table 8.9 depicts the total pore count for each replicate of the left-pointer finger of participant #1728 and Figure 8.9 provides a visual representation, detailing the marked-up fingerprint images associated with the replicates.

Table 8.8: Total pore count for each replicate fingerprint of the left-middle finger of participant #1612.

Replicate	Total Pore Count
B1	613
B2	623
B3	682



Figure 8.8: The marked-up images depicting pore location for each replicate of the left-middle finger of participant #1612.

Overall, the observations made indicated that pore count was different across the replicates of a single fingerprint. Of the 134 fingerprint sets assessed, 14.93% (20/134) had similar pore data across the replicates, whereas 79.85% (107/134) had dissimilar pore data across the replicates. The differences observed in pore count across the replicates within a single fingerprint could be due to one of two reasons. The first reason is that the same quality of pore information in the latent print is not reproduced nor reflected across all three replicates. The second reason, which relies upon the accuracy of the manual mark-up of pores, is that the examiner did a poor job identifying and marking the pores, imposing a highly subjective result. To provide a measure of accuracy, an intra-marking variability could have been assessed; however, given that one examiner did all of the pore marking, any possible reason for lack of expertise in pore detection and marking would be reflected among all fingerprints marked.

Table 8.9: Total pore count for each replicate fingerprint of the left-pointer finger of participant #1728.

Replicate	Total Pore Count
C1	153
C2	277
C3	177



(a) $1728_{-}L_{-}C1$

(b) 1728_L_C2

(c) 1728_L_C3

Figure 8.9: The marked-up images depicting pore location for each replicate of the left-pointer finger of participant #1728.

Ultimately, this data suggests that while pore information is available within and across multiple replicates of the same fingerprint, the number of available pores is not consistent across multiple replicates.

8.4 Part 4

To assess which fingerprint development method produced more pore data, pore density was used within the Mann Whitney U Test (Wilcoxon Rank Sum Test).

Pore density was calculated from the convex hull area for each fingerprint. Within each set of replicate fingerprints, the print associated with the largest density was selected for further analysis. Using the largest density values, found in Appendix C, the Mann Whitney U test (Wilcoxon Rank Sum test) was performed to assess if the two population distributions, black powdered vs. cyanoacrylate fumed, were equal or not.

The Mann Whitney U test is a popular non-parametric test to compare the outcomes of two independent groups. This test examines whether or not two groups could come from the same population, ie. have the same shape or distribution [81]. Often performed as two-sided, as to not specify directionality, the test assumes that the two groups being assessed are independent of each other and the data are ordinal, but do not have to be normally distributed. Further, under the null hypothesis there would be equal population distributions whereas under the alternative hypothesis, there would be unequal population distributions [81]. Mathematically, the U statistics for the test are defined by equations 8.1 and 8.2,

$$U_x = n_x n_y + ((n_x(n_x+1))/2) - R_x$$
(8.1)

$$U_y = n_x n_y + ((n_y(n_y+1))/2) - R_y$$
(8.2)

where n_x is the number of observations within one group, n_y is the number of observations in the second group, R_x is the sum of the ranks for the first group and R_y is the sum of the ranks for the second group [81].

Utilizing R and RStudio, the x and y coordinate points for each pore within a fingerprint were used to create the convex hulls. Convex hulls are the smallest possible convex polygons that enclose all points. The convex hulls produced from a set of replicate fingerprints, associated with their respective marked-up fingerprint images can be seen in Figure 8.10.

In addition to the convex hull plots, the area of the polygon, as well as the density of pores within that area were calculated. The R code used to plot the coordinate points, create the convex hulls, and calculate the hull area utilized the R packages of "sp"[82], "splancs"[83], and "xlsx"[84]. The complete script can be found within Appendix B.

To calculate the area of the convex hulls, the coordinate points of the pores were utilized. Each x and y coordinate pair are in units of 10 micrometers (0.01 millimeters), as described by the ANSI/NIST-ITL 1-2011 Update: 2015 Data Format for the Interchange of Fingerprint, Facial & Other Biometric Information document [76]. The original area calculated by the R code was in "units squared" and needed to be converted to "millimeters squared". To do



Figure 8.10: The convex hull plots with the associated marked-up images depicting pore location for each replicate of the left-ring finger of participant #1215.

this, the square root of the area was taken, the result then multiplied by 0.01, as 1 unit is equivalent to 0.01 mm. The value obtained was then squared to reach the final area value with a unit of mm^2 .

From there, Excel was used to calculate the pore density by dividing the hull area into the total number of pores found within each fingerprint. The highest density values and the associated fingerprints were then used within the Mann Whitney U Test, where the null hypothesis stated that the population distributions between the black powdered and cyanoacrylate fumed fingerprints were equal; and the alternative hypothesis stated that the population distributions were not equal.

Calculation of the test statistic was performed within R and RStudio. The R script for this computation can be found in Appendix B. The resulting p-value of 0.7013 was greater than the established significance level of 0.05, leading to acceptance of the null hypothesis. This result signified that the two population distributions of the black powdered and cyanoacrylate fumed fingerprints were equal, thus implying that neither development method is better or worse than the other at capturing pore data. Below details the results from the test within R/RStudio.

```
1 > #Perform Wilcoxon Rank Sum Test
2 > wilcox.test(All$BP, All$CA)
```

3

```
Wilcoxon rank sum test with continuity correction

data: All$BP and All$CA

W = 1706, p-value = 0.7013

alternative hypothesis: true location shift is not equal to 0
```

8.5 Part 5

When examining pore location between replicates in order to determine if relative pore location changed significantly between depositions, the x and y coordinates of each pore were utilized. Again, R and R Studio were used, in which an R code was written for manual alignment of the pores between two compared replicate fingerprints, and for calculation of a similarity score.

With each fingerprint collected, there were three replicates. To assess if the relative location of the pores changed between the replicates, the coordinates of the pores were compared between each replicate pair. As such, replicate 1 was compared to replicate 2, replicate 1 to replicate 3, and replicate 2 to replicate 3. Within the R code, the file containing the pore data for one replicate was referred to as "R". The second file, containing the pore data for the other replicate was referred to as "S".

Comparison of the pore locations began with manual alignment of the two fingerprints using the pore data. Manual alignment of the pores was completed by adjusting three parameters: ΔX , ΔY , and θ (theta). Adjusting the parameters was a critical step as to get the pores to a close enough "match" before running the iteration code to achieve a similarity score. Adjusting ΔX moved all pores within the "S" fingerprint along the x-axis, adjusting ΔY moved all pores within the "S" fingerprint along the y-axis, and lastly, adjusting θ (theta) rotated all pores within the "S" fingerprint in the counterclockwise direction. Once the adjustments were made, the "S" file was then referred to as the "S" file. Parameters were adjusted and visualized until best alignment of the pores was achieved. Following identifying the set of parameters that worked best for matching purposes, the iteration code was run to calculate the list of similarity scores.

The iteration code calculated a similarity score for the fingerprints under comparison, using the parameters the examiner set, as well as any combination of the parameters within a desired range. For the purposes of the current study, the range used was set by a max distance of 0.15 units (0.0015 mm). As a result, a .csv file was created containing all of the calculated similarity scores. Within the list of similarity scores produced for each comparison performed, the best/highest similarity score and its associated parameters were selected for use in further assessment. In some instances, a similarity score could not be calculated due to the occurrence of double pores. A "double pores" result occurred when one pore from one replicate aligned/matched-up with more than one pore from the second replicate fingerprint. The R script for the coordinate matching code can be found within Appendix B.

Due to the time consuming nature of the manual alignment process for each set of compared fingerprint replicates and the large number of comparisons to be performed, not all fingerprints nor replicates were able to be compared. Of the fingerprints/replicates that were compared, Tables 8.10 to 8.16 detail the highest similarity score obtained and the associated parameters used to obtain that score. For visualization of what the similarity scores represent, Figures 8.11 to 8.17 depict the coordinate plots associated with the lowest and highest similarity score for each fingerprint set examined. Within each figure, open blue circles represent the pores within the "R" file, the closed green circles represent the pores within the "S1" file, the open black circles represent the matching "R" pores, and the closed red circles represent the matching "S1" pores.

Comparison	Similarity Score	$\Delta \mathbf{X}$	$\Delta \mathbf{Y}$	$\mid \theta$
A1 v A2	0.39267	-0.95	4.5	5.5
A1 v A3	0.303571	-0.35	0.6	16
A2 v A3	0.387435	0.85	-3.5	6.5
B1 v B2	0.307453	-0.8	2.7	4.5
B1 v B3	0.327715	0.5	-0.45	-2.5
B2 v B3	0.338509	0.3	-3.35	1.5
C1 v C2	0.505137	1.05	0.4	0.5
C1 v C3	0.522013	0.5	0.5	0.5
C2 v C3	0.549266	-0.6	0.1	1

Table 8.10: Final similarity score results and associated parameters for the replicates of the LEFT hand of participant #1055.

Table 8.11: Final similarity score results and associated parameters for the replicates of the LEFT hand of participant #1065. Comparisons with a * resulted in double pores, so no similarity score was possible.

Comparison	Similarity Score	$\Delta \mathbf{X}$	$\Delta \mathbf{Y}$	θ
A1 v A2	0.409524	-1.25	-2.75	3.5
A1 v A3	0.290909	-0.05	-1.05	7.5
A2 v A3	*	*	*	*
B1 v B2	*	*	*	*
B1 v B3	0.170732	-0.35	1.3	-0.5
B2 v B3	*	*	*	*
C1 v C2	0.349398	-1.15	-2.45	-1.5
C1 v C3	0.197368	-1.35	-1.65	3.5
C2 v C3	*	*	*	*



(a) A1 v A3 Similarity Score: 0.303571



(b) C2 v C3 Similarity Score: 0.549266

Figure 8.11: The coordinate plots for the lowest (a) and highest (b) similarity score for the LEFT hand of participant #1055.



(a) B1 v B3 Similarity Score: 0.170732



(b) A1 v A2 Similarity Score: 0.409524

Figure 8.12: The coordinate plots for the lowest (a) and highest (b) similarity score for the LEFT hand of participant #1065.

Table 8.12: Final similarity score results and associated parameters for the replicates of the LEFT hand of participant #1066. Comparisons with a * resulted in double pores, so no similarity score was possible.

Comparison	Similarity Score	$\Delta \mathbf{X}$	$\Delta \mathbf{Y}$	θ
A1 v A2	0.164179	-0.1	-0.55	2.5
A1 v A 3	0.145161	-0.15	-0.15	6.5
A2 v A3	0.419355	0.05	0.4	2.5
B1 v B2	0.197531	-1.2	-0.5	0
B1 v B3	0.177778	-0.95	0.3	4.5
B2 v B3	0.209877	-0.05	1	0
C1 v C2	0.258929	-0.8	-0.35	4
C1 v C3	*	*	*	*
C2 v C3	0.232143	0.2	-0.55	2.5

Table 8.13: Final similarity score results and associated parameters for the replicates of the LEFT hand of participant #1073.

Comparison	Similarity Score	$\Delta \mathbf{X}$	$\Delta \mathbf{Y}$	θ
A1 v A2	0.515924	-0.85	-0.8	1
A1 v A3	0.433121	-0.55	-1.6	0
A2 v A3	0.463659	0.05	-0.9	0
B1 v B2	0.394558	-0.05	0.1	1.5
B1 v B3	0.612245	-0.1	-1.55	2.5
B2 v B3	0.545	0.1	-1.7	3.5
C1 v C2	0.304878	1.1	0.05	2.5
C1 v C3	0.536585	0.95	0	0
C2 v C3	0.652174	-0.2	-0.1	3

Table 8.14: Final similarity score results and associated parameters for the replicates of the LEFT hand of participant #1176.

Comparison	Similarity Score	$\Delta \mathbf{X}$	$\Delta \mathbf{Y}$	θ
A1 v A2	0.358108	2.25	2.7	1
A1 v A3	0.304054	2.95	2.8	1
A2 v A3	0.652695	0.75	0	-0.5
C1 v C2	0.283951	0	3.4	-1.5
C1 v C3	0.148148	0.7	3.75	0
C2 v C3	0.207792	0.65	0.6	4.5



(a) A1 v A3 Similarity Score: 0.145161



(b) A2 v A3 Similarity Score: 0.419355

Figure 8.13: The coordinate plots for the lowest (a) and highest (b) similarity score for the LEFT hand of participant #1066.



(a) C1 v C2 Similarity Score: 0.304878



(b) C2 v C3 Similarity Score: 0.652174

Figure 8.14: The coordinate plots for the lowest (a) and highest (b) similarity score for the LEFT hand of participant #1073.



(a) C1 v C3 Similarity Score: 0.148148



(b) A2 v A3 Similarity Score: 0.652695

Figure 8.15: The coordinate plots for the lowest (a) and highest (b) similarity score for the LEFT hand of participant #1176.

Comparison	Similarity Score	$\Delta \mathbf{X}$	$\Delta \mathbf{Y}$	θ
A1 v A2	*	*	*	*
A1 v A3	*	*	*	*
A2 v A3	0.164948	0.6	2.55	1
B1 v B2	0.5	1	0	3
B1 v B3	0.206897	0.95	0.45	2.5
B2 v B3	0.193103	-0.25	0.45	-2.5
C1 v C2	0.517483	1.25	-0.2	5.5
C1 v C3	0.353293	0.75	-1.3	7
C2 v C3	0.244755	-0.3	-1.2	7.5

Table 8.15: Final similarity score results and associated parameters for the replicates of the LEFT hand of participant #1184. Comparisons with a * resulted in double pores, so no similarity score was possible.

Table 8.16: Final similarity score results and associated parameters for the replicates of the LEFT hand of participant #1201. Comparisons were not completed for this set of fingerprints.

Comparison	Similarity Score	$\Delta \mathbf{X}$	$\Delta \mathbf{Y}$	θ
A1 v A2	0.263158	0.5	2.5	4



(a) A2 v A3 Similarity Score: 0.164948



(b) C1 v C2 Similarity Score: 0.517483

Figure 8.16: The coordinate plots for the lowest (a) and highest (b) similarity score for the LEFT hand of participant #1184.



Figure 8.17: The coordinate plot for the only similarity score calculated for the LEFT hand of participant #1201.

As a general guide to follow, a similarity score of at least 0.5 would signify that the pore location between the replicates did not significantly differ. This threshold was set to provide a preliminary basis in which to assess the similarity score data.

Of the 52 comparisons performed, 7 did not produce a similarity score due to the presence of double pores, 18 produced a similarity score less than 0.3, 16 resulted in a similarity score between 0.3 and 0.5, and 11 resulted in a similarity score of 0.5 or greater.

When examining the coordinate plots, a similarity score of at least 0.5 was needed to see a clear indication that not only were pores present in each replicate fingerprint, but that the locations were roughly the same to call a "match point". Promising results were seen in comparisons resulting in similarity scores of 0.3 to less than 0.5. Figures 8.11(a) and 8.13(b) both represent similarity scores in this range, depicting many aligned pores; however, these two examples also show plenty of un-aligned pores.

9. Conclusions

In review, the two main objectives of the current study aimed at determining the prevalence of pores within latent fingerprints, and identifying factors that influence the presence or absence of pore detail within latent fingerprints. As a means to meet these objectives, data obtained from the collected set of latent fingerprints and assessed in five different ways.

Part 1 of the study provided a general overview of the data collected and gave insight into which fingerprints were of use for further analysis. Of the original 633 total fingerprints collected, only 380 were found to be of sufficient quality for use in the remainder of the study. Further data breakdown revealed that of the usable 380 fingerprints, 305 came from the left hand, ie. the tile fingerprints, while 75 came from the right hand, ie. CD case fingerprints. Fingerprint development, overall quality, as well as ridge and pore detail clarity suffered in the fingerprints collected from the right hand. The lack of development seen within the right hand fingerprints was likely due to little material transfer when deposition of the fingerprint took place. For fingerprints that did develop, quality suffered due to an excess of moisture or in-part due to the textured background of the chosen substrate. When quality of the fingerprint was low, pore detail, while detectable, was difficult to confidently identify and mark. It is of no surprise however, that the smooth substrate produced higher quality fingerprints.

Part 2 of the study aimed to address the second objective, in identifying conditions/factors that influenced the presence or absence of pore detail within latent fingerprints. Unfortunately, the data obtained could not be assessed in a manner that would properly assess this objective. This was a major limitation of the current study, which was further addressed in section 8.2 and moving forward, in section 9.2.

Part 3 of the study examined total pore counts across the replicate fingerprints to determine if the pore counts differed. Of the 134 sets of replicate fingerprints assessed, 20, or 14.93% had similar total pore counts across the replicates; whereas 107, or 79.85% had dissimilar total pore counts across the replicates. Overwhelmingly, results indicated that all pore information is not reproduced nor reflected across multiple, successive replicates of latent fingerprints. Based on this data, it can be inferred that of a random selection of latent fingerprints sourced from the same individual and finger, the pore data is likely to be unequally reproduced in each print. This certainly begs the question as to the consistency and availability of level 3 detail in latent fingerprints for fingerprint identification purposes.

Part 4 of the study created convex hulls around the pores within each fingerprint, from which hull area and pore density were calculated. Utilizing the Mann Whitney U test, pore density

values were used to assess if there was a significant difference between the two development methods employed within the study. With a resulting p-value of 0.7013, the data indicated that neither development method is better or worse at capturing pore data.

Part 5 of the study assessed pore location using the x,y coordinate data associated with each pore, during the mark-up process within ULW. The coordinate data was compared between two replicates, producing a similarity score as well as a plot of the overlay, depicting each pore and those that align between the two. Similarity scores above the established threshold of 0.5 indicated that pore location between the replicates did not significantly differ.

Rather than the aligned pores, it was actually the un-aligned pores that provided more insight into the pore location assessment. Un-aligned pores could result for one of two reasons, one being that the pores within one replicate were not present in the other and vise versa, or that pore location does not align well enough between two replicates to be considered a "match point". The appearance of rough pore location could change as a result of pressure and/or other factors present during the deposition of a fingerprint. However, given the research into pore development and the evidence indicating that pore openings and their locations do not change throughout a lifetime, it is more likely that the poor similarity scores obtained within the present study are the result of unequal reproduction across replicates.

The evidence presented here leads one to believe that when pore detail is present, it can provide useful information to an examiner, however in the cases of unequal presence of pores or the complete lack of pore detail, the added value of level 3 detail in unclear.

9.1 Forensic Significance

Fingerprints have a long history of use within personal identification, and the many applications identification is used for. As with many fields within forensic science, a great push for the increase of statistically sound and unbiased methodology, as well as the introduction of innovative technology, ushered in new frontiers within the fingerprint community. In effort to build-up and support the science of fingerprint identification, researchers began looking more closely at the introduction of level 3 detail within the identification process. While level 3 detail, and pores, were not new to the community, implementation and applicability needed research.

Existing research on pores has provided a strong foundation on which researchers strive to know more in regard to the utility of pores in fingerprint identification. Studies have determined at what image resolution, the quality is greatest for observance and usage of level 3 detail. There has also been development of novel auto-extraction methods for pore detail as well as attempts at integrating pores within an AFIS matching system. Overall, these studies have detected pore detail within a range of fingerprint types, to include inked and live scanned; however, few have used pores detected within latent fingerprints.

Previous studies use fingerprints that have been captured via methods which achieve a high level of detail. While fingerprints of high detail are important subjects within this area of research, they rarely are the types of fingerprints found and examined in relation to a crime scene. Latent fingerprints are most often encountered in practice, thus for all of the current research on pore detail to be practically implemented, pore detail needs to be reliably captured and assessed within latent fingerprints. Given that few studies have examined pore detail within latent fingerprints, the current study aimed to begin filling the established gap.

9.2 Limitations and Future Directions

Within the present study, there are three main limitations worth addressing:

- Research design
- Sample size and dependency
- Manual mark-up

The major limitation to the current study was the design flaw in how the factors under consideration were applied and/or related to the latent fingerprints. This design flaw resulted in the inability to address which conditions/factors influence the presence or absence of pore detail within latent fingerprints, rendering a major portion of the study essentially useless. Very rarely will one know environmental factors such as temperature and humidity or deposition factors such as prior activity or oil/sweat components at the time of latent fingerprint deposition. For this reason, to better assess the factors considered within this study, and to evaluate the factor influence on the presence/absence of pores, the factors should be applied post latent fingerprint deposition/collection and one factor at a time. A second inherent error in the collection methods was the lack of consideration for how the proposed factors would produce correlation/dependency into the data set. As designed, all factors associated with each deposited fingerprint were associated all at once, which made it impossible to determine which factor had an effect on the resulting pore detail, if at all. This dependency would confound a clear assessment as to which factors, if any, affected the resulting outcome of pore presence and quality within latent fingerprints.

In addition, as a result of the method in which the fingerprints were collected and the use of replicate depositions, the sample sizes obtained for each assessment were less than ideal to achieve statistical significance. The replicate depositions introduced dependency into the results that was not expected. For each set of collected fingerprints, each replicate had a level of dependency on the previously deposited fingerprint due to the succession of deposition. To avoid dependency within the results, sample sizes were smaller than anticipated and not statistically large enough for significance, despite a total of 633 fingerprints collected.

Lastly, as the researcher can personally attest to, manual mark-up of pore detail is extremely time consuming and potentially difficult to the untrained eye. As seen within this study, substrate surfaces as well as fingerprint composition have an affect on the appearance of pores, which can make detection and proper identification a difficult task. The fingerprints collected from the right hand, on the CD case substrate, were far worse in quality in comparison to those collected on the tile substrate, and especially dry and/or oily fingerprints did not develop well. For this reason, automatic extraction of pore detail is essential to the success of pore implementation within the fingerprint identification process. Depending upon the quality, a single fingerprint could contain hundreds, if not thousands, of pores. Manual mark-up of pore detail in fingerprints under casework examination would likely be extremely time consuming.

However, with the amount of fingerprint evidence examined today, it is certain that there are

instances in which additional fingerprint detail, such as pores, would provide an examiner with more material to determine and support a conclusion regarding the identification of a fingerprint. Latent fingerprints are notoriously not perfect, so where clarity in level 2 detail may not be present, level 3 detail could assist. The present study gave preliminary data supporting continued research into the implementation and utility of pore detail within latent fingerprint identification.

10. Appendices

10.1 Appendix A



Prevalence of Pores in Latent Fingerprints

	I.D. Number:
Participant Age: Participant Sex:	
Date: / Time:	/(Month/Day/Year) AM/PM
Temperature – Outside Temperature – Inside: Humidity – Outside: Humidity – Inside:	B:
In as much detail as po any physical activity, th	ossible, please describe your activity prior to this moment - to include he last time you washed your hands, last time you applied lotion, etc.:

Figure 10.1: Questionnaire Contents.

LIGONOC	Professional Mode
Settings	
Name:	Current Setting 🗸 🗸
	Cause Delete
	Delete
Original	
Document Type:	Reflective -
Document Source:	Document Table 🔹
Auto Exposure Type:	Photo 💌
Destination	
+ Image Type:	16-bit Grayscale 🔹 👻
Resolution:	1000 🔻 dpi
Document Size:	W 8.50 H 11.70 in
🛨 Target Size:	
Adjustments	·
	Reset
🛨 📃 Unsharp Mask	
🛨 🕅 Descreening	
Color Restoration	
🛨 📃 Backlight Correction	
🛨 🥅 Dust Removal	
🛨 🕅 DIGITAL ICE Technolog	y,
[

Figure 10.2: Epson scan settings used, screen shot of the Epson $Perfection^{\mathbb{R}}$ scan settings.

Distance in pixels:	0
Known distance:	4.25
Pixel aspect ratio:	1.0
Unit of length:	inch
Click to	Remove Scale
Global	
Scale: <no scale=""></no>	

Figure 10.3: Settings used to set the scale of the images, screen shot of the function in ImageJ.

JPEG Options	×
Matte: None	ОК
Image Options	Cancol
Quality: 12 Maximum ~	
small file large file	Preview
Format Options	
• Baseline ("Standard")	
O Baseline Optimized	
O Progressive	
Scans: 3 🚽	

Figure 10.4: JPEG file format settings used, screen shot of the function in $Adobe^{\widehat{\mathbb{R}}}$ Photoshop[®].

			×
Image Size:	59.1M		٥.
Dimensions:	S568 px	× 3712 px	
Fit To:	Original Size		
Width:	5.568	Inches	
8 —— Height:	3.712	Inches	
Resolution:	1000	Pixels/Inch	
🔲 Resample:			
ОК	\supset	Cancel	
	Image Size: Dimensions: Fit To: Width: & Height: Resolution: Resample:	Image Size: 59.1M Dimensions: 5568 px Fit To: Original Size Width: 5.568 Height: 3.712 Resolution: 1000 Resample: Automatic	Image Size: 59.1M Dimensions: 5568 px × 3712 px Fit To: Original Size Width: 5.568 Inches Height: 3.712 Inches Resolution: 1000 Pixels/Inch Resample: Automatic OK Cancel

Figure 10.5: Resolution settings used, screen shot of the function in $Adobe^{\textcircled{R}}$ Photoshop^(\textcircled{R}).

TIFF Options		L X
Image Compression • None • LZW	Pixel Order Interleaved (RGBRGB) Per Channel (RRGGBB) 	Ок Cancel
O ZIP O JPEG Quality: Maximum	Byte Order IBM PC Macintosh	
small file large file	Layer Compression CRLE (faster saves, bigger files) ZIP (slower saves, smaller files) Discard Layers and Save a Conv	

Figure 10.6: TIFF file format settings used, screen shot of the function in $Adobe^{\widehat{\mathbb{R}}}$ Photoshop[®].

Table 10.1: Participant responses to the open-ended, prior activities question on the questionnaire. Continued in Tables 10.2 and 10.3.

Participant ID	Response
1728	Recently washed hands (soap and water within 10 minutes of fingerprint
	collection), no strenuous activity other than walking up stairs and down
	the hallway, no lotion applied to hands for several days prior, raining
	outside currently
1065	Detail strip of a firearm, no lotion since 0745 hours, washed hands
	about 45 minutes ago
1223	I put on lotion an hour ago and walked about a mile in the rain
1215	Went to the gym earlier this am (about 6 am), last washed hands
	around 1400 hours, have been sitting in the office for the past few
	hours, cold all day
1449	I washed my hands after I ate around 1245 hours, no lotion, a little
1000	sweat from taking notes and all that
1868	Sat in class for 2-3 hours, walked here (about 10 minutes), washed
1450	hands around 1000 hours, touched a dog earlier
1456	Gym for 50 minutes (weight lifting, 0620 hours), no lotion and washed
	hands 30 minutes ago, typing on the computer and reading articles,
	temperature controlled lab and walked around the building to stretch
1073	Turning and handwriting cold laboratory (hand rubbing) running
1075	hands through bair
1184	Wore Troney Powder Free Nitrile Examination gloves about 10 min-
1104	utes prior to participation washed hands about 10 minutes prior to
	participation worked out the night before (used work out gloves)
1201	No strenuous physical activity other than walking to campus and up
	and down stairs. I have been sitting in a cold lab all day, last time I
	washed my hands was 3-4 hours ago, last time I applied lotion was the
	morning of collection
1612	Walked to class (5 min), walked up stairs, hands are naturally sweaty,
	washed hands two-three hours ago
1255	About 2 hours ago, was on a plane, used lotion/hand sanitizer, walked
	about 2 minutes and up 3 flights of stairs
1285	I workout 4-5 days a week with weights, I run 3 days a week, I washed
	my hands before I ate breakfast today, last time I used lotion was
	probably 2 days ago.
1515	Took notes in various classes, always clammy hands, walked to and
	from class, lotion last night, hand sanitizer
Table 10.2: Participant responses to the open-ended, prior activities question on the questionnaire.

articipant ID	Response
1761	Walked to class this morning and walked around OGH recently, I
	washed my hands approx 10 minutes ago, recently took 3 classes in-
	cluding notes, don't really have clammy or sweaty hands.
1549	I just got out of photography lecture, I walked around campus, last
	time I washed me hands was like 10 minutes ago, I rarely use lotion
	and don't know when I last did, I sweat a decent amount.
1769	Lotion around 0930 hours, washed hands around 1300 hours, always
	clammy hands, walked to and from class (hand down by my side)
1537	Prior to this moment, I walked outside in the cold/rainy weather for ap-
	prox 3 minutes after leaving class from Woodburn. I washed my hands
	about an hour/hour and a half ago and applied lotion this morning.
1870	Washed hands a couple minutes prior
1830	Washed hands 20 minutes ago, I have been writing/typing in the library
	and walking around campus, applied lotion around 9 am this morning,
	hands feel a little clammy
1055	It's hot so I'm starting to sweat.
1066	Washed hands before class at about 1330 hours, my hands are naturally
	clammy most of the time.
1941	Walked here (fast pace) about 10 minutes away, took a shower before
	I came, so hands were washed appox. 30 minutes ago, no lotion
1690	Played sports (basketball), a bit sweaty, washed hands about 30 min-
	utes ago.
1229	I was at work before this, I had lunch about two hours ago, washed
	my hands after that. I sat on my computer the whole time. Wrote in
	my notes. The last time I put lotion on was this morning and I'm a
1 1	naturally sweaty person
1721	Typing on computer, writing, watching Netflix, washed hands about
1005	an hour ago, left handed
1067	Washed hands about two hours ago, hands are normally dry, worked
1470	with tools for most of the day
1470	DPT have not applied lation to day
1700	PRI, have not applied lotion today
1700	biy hands, typed on a keyboard for the last few hours, washed hands
1941	I think I washed my hands about an hour ago after eating naches. I
1441	have not applied lotion for a while definitely not today. I was onny
	lanton for alittle while afterw ashing my hands then walked over here
	haptop for antitle while after w ashing my hands then walked over here.

Participant ID	Response

Table 10.3: Participant responses to the open-ended, prior activities question on the questionnaire.

Participant ID	Response			
1410	In class, cooked lunch then washed hands at 1300 hours, went to			
	physics, came here.			
1176	I was in class. I washed my hands last at 1300 hours. I applied lotion			
	this morning.			
1445	LSB two times, other stairs, computer lab in LSB, washed hands this			
	afternoon around 1230 hours and also applied lotion.			
1320	I took notes approximately thirty minutes ago during class (left ha			
	only). I washed my hands about two hours ago and the last time I			
	applied lotion was this morning (7 am). I was on a public bus this			
	morning and spent the rest of the day in OGH			
1568	About 2 hours since I washed my hands, no lotion, my hands are warm			
	and sweaty			

10.2 Appendix B: R Scripts

10.2.1 ULW Data Extraction

3 4

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36 37 38

39 40

41 42 43

44

R script detailing the extraction of the pore data from the summary file produced by ULW.

```
content#Setting & Using Working Directory
setwd ("C: /Users/G4T7500/Desktop/Research/RStudioWork")
wd <- ("C:/Users/G4T7500/Desktop/Research/RStudioWork")
# Extracting Pore Info from Left Hand Prints
#Identify all .txt files within the Left folder of wd
left_files <- list.files(path = "Left", pattern = ".txt")</pre>
#Reads the first .txt file in Left, then cycles through
for (i in 1:length(left_files)) {
  #Paste the location of the specific .txt file
  fname <- paste0(wd, "/Left/", left_files[i])</pre>
  ULW <- readLines(fname)
  \#If 9.345 is contained in the .txt file, continue (specifically, R will
      return "integer (0)" if 9.345 is not in the file; to make sure it is, we
       use !identical())
  if (!identical(grep("9.345", ULW), integer(0))) {
    pores <- grep ("9.345", ULW)
    dots <- grep("9.346", ULW)
    starter <- pores[1]+1
    ender <- dots[1]-1
    outPores <- data.frame(ULW[starter:ender])</pre>
    names(outPores) <- "pore"</pre>
    n_{-} pores <- length (outPores $pore)/2
    posPores <-c()
    Pore_no <- c()
    Pore_X <- c()
    Pore_Y <- c()
    counter <-1
    outCounter <- 1
    while(counter <= length(outPores$pore)){</pre>
      poreX <- outPores$pore[counter]</pre>
      poreX<-gsub("
                      "," ", poreX)
```

```
"," ", poreX)
"," ", poreX)
           poreX<-gsub("
45
           poreX<-gsub("</pre>
46
                            "," ", porex
"," ", poreX)
           poreX<-gsub("
47
                           "," ", poreX)
           poreX<-gsub("
48
           poreX<-gsub(" ",",", poreX)
49
           poreX <- unlist(strsplit(poreX, split=","))</pre>
50
           poreY <- outPores$pore[counter+1]</pre>
                                "," ", poreY)
"," ", poreY)
53
           poreY<-gsub("
           poreY<-gsub("</pre>
54
                             "," ", poreY)
           poreY<-gsub("
                            "," ", poreY)
           poreY<-gsub("
56
                            "," ", poreY)
           poreY<-gsub("
57
           poreY<-gsub(" "," ", poreY
poreY<-gsub(" ",",", poreY)
58
           poreY <- unlist(strsplit(poreY, split=","))</pre>
59
60
           Pore_no[outCounter] <- as.numeric(poreX[4])
61
           Pore_X[outCounter] <- as.numeric(poreX[5])</pre>
62
           Pore_Y[outCounter] <- as.numeric(poreY[5])
63
           counter <- counter + 2
64
           outCounter <- outCounter + 1
65
         }
66
67
         posPores <- cbind(Pore_no, Pore_X, Pore_Y)</pre>
68
69
         fname <- paste0(left_files[i], "_pores.csv")</pre>
71
         #Save extracted pore data as a csv document in the working directory
72
         write.csv (posPores, fname, row.names = FALSE)
73
74
       }
75
     }
77
78
79
80
81
    # Extracting Pore Info from Right Hand Prints
82
83
84
    #Identify all .txt files within the Left folder of wd
85
     right_files <- list.files(path = "Right", pattern = ".txt")
86
87
    #Reads the first .txt file in Left, then cycles through
88
     for (i in 1:length(right_files)) {
89
90
       #Paste the location of the specific .txt file
91
       fname <- paste0(wd, "/Right/", right_files[i])</pre>
92
      ULW <- readLines(fname)
93
94
95
       #If 9.345 is contained in the .txt file, continue (specifically, R will
96
           return "integer (0)" if 9.345 is not in the file; to make sure it is, we
            use !identical())
       if (!identical(grep("9.345", ULW), integer(0))) 
97
```

```
69
```

```
98
          pores <- grep ("9.345", ULW)
99
100
          dots <- grep ("9.346", ULW)
          starter <- pores[1]+1
          ender \leq - dots [1] - 1
          outPores <- data.frame(ULW[starter:ender])
          names(outPores) <- "pore"</pre>
          n_{-} pores <- length (outPores $pore)/2
106
107
          posPores <-c()
108
          Pore_no <- c()
109
          Pore_X <- c()
          Pore_Y <- c()
111
112
          counter <- 1
113
          outCounter <- 1
114
115
          while(counter <= length(outPores$pore)){</pre>
             poreX <- outPores$pore[counter]</pre>
118
                                  "," ", poreX)
             poreX<-gsub("
119
                                       , poreX)
             poreX<-gsub('
120
                                   ,"", poreX)
                                ,,
             poreX<-gsub("
                               "," ", poreX)
             poreX<-gsub("
122
                              "," ", poreX)
             poreX<-gsub("
             poreX<-gsub(" ",",", poreX)
124
             poreX <- unlist(strsplit(poreX, split=","))</pre>
126
             poreY <- outPores$pore[counter+1]</pre>
127
                              "," ", poreY)
"," ", poreY)
"," ", poreY)
"," ", poreY)
             poreY<-gsub("
128
             poreY<-gsub("
             poreY<-gsub("</pre>
130
             poreY<-gsub("
131
                             "," ", poreY)
             poreY<-gsub("
             poreY<-gsub(" ",",", poreY)
133
             poreY <- unlist(strsplit(poreY, split=","))</pre>
134
135
             Pore_no[outCounter] <- as.numeric(poreX[4])
136
             Pore_X[outCounter] <- as.numeric(poreX[5])
             Pore_Y[outCounter] <- as.numeric(poreY[5])
138
             counter <- counter + 2
139
             outCounter <- outCounter + 1
140
          }
141
          posPores <- cbind(Pore_no, Pore_X, Pore_Y)</pre>
143
144
          fname <- paste0(right_files[i], "_pores.csv")</pre>
145
146
          #Save extracted pore data as a csv document in the working directory
147
          write.csv (posPores, fname, row.names = FALSE)
148
149
        }
152
      }
153
```

```
154
     # Extracting pore info from blind study print=
155
156
     #Identify all .txt files within the Left folder of wd
     blind_files <- list.files(path = "Blind_Test", pattern = ".txt")</pre>
157
158
     #Reads the first .txt file in Left, then cycles through
159
     for (i in 1:length(blind_files)) {
161
       #Paste the location of the specific .txt file
162
        fname <- paste0(wd, "/Blind_Test/", blind_files[i])</pre>
       ULW <- readLines(fname)
164
       \#If 9.345 is contained in the .txt file, continue (specifically, R will
167
            return "integer (0)" if 9.345 is not in the file; to make sure it is, we
             use !identical())
        if (!identical(grep("9.345", ULW), integer(0))) {
168
          pores <- grep("9.345", ULW)
          dots <- grep("9.346", ULW)
171
          starter <- pores[1]+1
172
          ender <- dots [1]-1
173
          outPores <- data.frame(ULW[starter:ender])
174
          names(outPores) <- "pore"</pre>
175
176
          n_pores <- length(outPores pore)/2
178
          posPores <-c()
179
          Pore_no <- c()
180
          Pore_X <- c()
181
          Pore_Y <- c()
182
183
          counter <- 1
184
          outCounter <- 1
185
186
          while (counter \leq  length (outPores $pore)) {
187
188
            poreX <- outPores$pore[counter]</pre>
189
                                  "," ", poreX)
            poreX<-gsub("
190
                                 "," ", poreX)
            poreX<-gsub("
                               "," ", poreX)
191
            poreX<-gsub("</pre>
192
                             "," ", poreX)
            poreX<-gsub("
193
            poreX<-gsub(" "," ", poreX)
poreX<-gsub(" ",",", poreX)
                                "", poreX)
194
            poreX <- unlist(strsplit(poreX, split=","))</pre>
196
197
            poreY <- outPores$pore[counter+1]</pre>
198
                                 ","", poreY)
            poreY<-gsub("
199
                                       , poreY)
            poreY<-gsub('
200
                               "," ", poreY)
            poreY<-gsub("</pre>
201
                                 , " ", poreY)
                              ,,
            poreY<-gsub("
202
                             ,, ,, ,,
            poreY<-gsub("
                                   , poreY)
203
            poreY<-gsub(" ",",", poreY)
204
            poreY <- unlist(strsplit(poreY, split=","))</pre>
205
206
            Pore_no[outCounter] <- as.numeric(poreX[4])
207
```

```
71
```

```
Pore_X[outCounter] <- as.numeric(poreX[5])
208
            Pore_Y[outCounter] <- as.numeric(poreY[5])</pre>
209
            counter <- counter + 2
210
            outCounter <- outCounter + 1
211
          }
212
213
          posPores <- cbind(Pore_no, Pore_X, Pore_Y)</pre>
214
215
          fname <- paste0(blind_files[i], "_pores.csv")</pre>
216
217
          \# Save extracted pore data as a csv document in the working directory
218
          write.csv(posPores, fname, row.names = FALSE)
219
220
        }
221
222
      }
223
224
      . . .
```

10.2.2 Convex Hull Script

R script detailing the formation of the convex hulls around the plotted pore data, saving the convex hull plots, and calculating the area of the convex hulls.

```
#Calculating the convex hull around the coordinate points, plotting it .====
    #Setting & Using Working Directory
2
    setwd ("C: /Users/G4T7500/Desktop/Research/RStudioWork/Extracted_Data")
3
    wd <- ("C:/Users/G4T7500/Desktop/Research/RStudioWork/Extracted_Data")
4
5
    #Enlarging the max print space into the console.
6
    options(max.print=9999999)
7
8
    #Required packages
9
10
    library (sp)
    library (splancs)
    library(xlsx)
13
    #Creating the folder where the outputs of the convex hull plots will be saved
14
        . Hulloutput folder for images without polygon, folder 2 with polygon.
    plot_out <- "C:/Users/G4T7500/Desktop/Research/RStudioWork/Extracted_Data/
15
        HullOutput2/"
    #Creating the function that forms the convex hull around the pore coordinate
17
        data.
    cha<-function(x,y){
18
      chull(x, y) \rightarrow i
19
20
      return (areapl (cbind (x[i],y[i])))
21
    }
    #Visualization of polygon
23
    #k <- chull(dat$Pore_X, dat$Pore_Y)</pre>
24
25
    #Importing the names of all of the files containing the pore coordinate data.
26
    file_list <- list.files(pattern = "*.csv")
27
28
    for (i in 1:length(file_list)){
29
      dat <- read.csv(file_list[i])</pre>
30
      k <- chull(dat$Pore_X, dat$Pore_Y)
31
      #Creating a png file of the plots.
      png(file=paste(plot_out, as.character(sub('\\..*', '', file_list[i])),"plot
33
           .png", sep=""))
34
      #Creating the plot of the pore coordinate data and the convex hull around
35
          the data.
      plot(dat$Pore_X, dat$Pore_Y, xlim=c(0, max(dat$Pore_X)), ylim=c(max(dat$Pore
36
           _Y), 0), axes=TRUE, main = sub('\\..*', '', file_list[i]), xlab = "X
          Coordinates", ylab = "Y Coordinates") +
      polygon (dat $Pore_X[k], dat $Pore_Y[k])
37
      dev.off()
38
39
    }
40
    #End====
41
42
    #Calcualting the Area of the Convex Hull using the Modified Data .====
43
    #Setting & Using Working Directory
44
    setwd ("C: / Users / G4T7500 / Desktop / Research / RStudioWork / Extracted _ Data / ModData")
45
```

```
46
    #Enlarging the max print space into the console.
47
    options(max.print=999999)
48
49
    #Required packages
    library (sp)
    library(splancs)
52
    library(xlsx)
53
54
    #Creating the function that forms the convex hull around the pore coordinate
        data.
    cha<-function(x,y){
56
      chull(x, y) \rightarrow i
57
       return (areapl (cbind (x[i],y[i])))
58
    }
59
60
    #Importing the names of all of the files containing the pore coordinate data.
61
    file_list <- list.files(pattern = "*.csv")
62
63
    #Creating an empty table that will contain the area information of the convex
64
         hulls.
    out <- data.frame(ID = character(0), Area = numeric(0))
65
    for (i in 1:length(file_list)){
66
      dat <- read.csv(file_list[i])</pre>
67
68
      #Outputting the area of the convex hull to a table.
69
      out[i, 2] <- cha(dat X_Mod, dat Y_Mod)
70
71
72
    }
73
    #Renaming the ID column of the table with the names of the pore data files.
74
    out$ID <- as.character(sub('\\..*', '', file_list))</pre>
75
76
    #Saving the table with convex hull area information to an excel file.
77
    write.xlsx(out,"C:/Users/G4T7500/Desktop/Research/RStudioWork/Extracted_Data/
78
        ModData/ConvexHullArea.xlsx")
    #End=
79
```

10.2.3 Mann Whitney U Test

R script detailing the calculation of the test statistic for the Mann Whitney U Test.

```
#Setting & Using Working Directory
1
2
  setwd("/Users/Rachel/Desktop")
3
4
  wd <- ("/Users/Rachel/Desktop")</pre>
5
6
  options (max.print=999999)
7
8
9
  #Read into R the Density Data via CSV file type
10
11
12 All <- read.csv("All.csv", header = TRUE)
13
14 #Perform Wilcoxon Rank Sum Test
  wilcox.test(All$BP, All$CA)
15
```

10.2.4 X,Y Coordinates Script

R script detailing the manual alignment and similarity score calculation for the x, y coordinates:

```
#Install/load required packages:
    install.packages("dplyr")
2
    library("dplyr")
3
4
    #Set your working directory:
5
    setwd("/Users/Rachel/Desktop/Research/X Y Coordinate Files")
6
7
    #Read in the files you plan to use:
8
    R <- read.csv("1055_L_A1.csv")
9
    S \leftarrow read.csv("1055\_L\_A2.csv")
10
    #Removing uncesseary columns of data from the dataframe:
    R < -R[, c(5, 6)]
13
    names(R) <- c("Pore_X", "Pore_Y")</pre>
14
    S < -S[, c(5, 6)]
16
    names(S) <- c("Pore_X", "Pore_Y")</pre>
17
18
    #Centers the pores/plot around point 0,0:
19
    R Pore Y < - -1 R Pore Y
20
    S Pore_Y <- -1*S Pore_Y
21
22
    R Pore X < - R Pore X - mean(R Pore X)
23
    R Pore_Y <- R Pore_Y - mean (R Pore_Y)
24
    S Pore_X <- S Pore_X - mean(S Pore_X)
    S Pore_Y <- S Pore_Y - mean(S Pore_Y)
26
27
    \#Adjust xdel, ydel, and theta parameters, and plot, to find best match
28
        possible between the pores in the replicates:
    # Plot===
29
    xdel <- −0.65#1 # xdel
30
    ydel <- 3.45#-3 # ydel
31
    theta <- 11\#-7 \# theta
32
33
    #plot(S$Pore_X,S$Pore_Y, xlim=c(-750,750),ylim=c(-1100,1100), col="green",
34
        pch=19)
    #plot(R$Pore_X,R$Pore_Y, xlim=c(-750,750),ylim=c(-1100,1100), col="blue")#,
35
        pch=19)
    theta.rad <- (theta/180)*pi
36
    mm \ll matrix(c(cos(theta.rad), sin(theta.rad), -1*xdel)
37
    -1*\sin(\text{theta.rad}), \cos(\text{theta.rad}), -1*ydel,
38
    0, 0, 1),
39
    byrow=TRUE, ncol=3)
40
    S.prime \leftarrow matrix (, nrow = length (S$Pore_X), ncol = 2)
41
    for (ff in 1:length(S$Pore_X)){
42
      outer.Sx <- as.vector(S[ff,1])</pre>
43
      outer.Sy <- as.vector(S[ff,2])
44
      init.S <- as.matrix(c(outer.Sx, outer.Sy, 1), ncol=1)</pre>
45
46
      out.S <- mm %*% init.S
      S.prime[ff,1] \leftarrow out.S[1,1]
47
      S.prime[ff, 2] <- out.S[2, 1]
48
49
    }
```

```
50
    S. prime <-- data . frame (S. prime)
    names(S.prime) <- c("Pore_X","Pore_Y")</pre>
    # points(S.prime$Pore_X, S.prime$Pore_Y, pch=19, col="green", cex=0.75)
    \# newLine <- S.prime [c(100,200,400),]
53
    # points (S$Pore_X[200], S$Pore_Y[200], col="green", pch=19)
54
    # lines(newLine$Pore_X, newLine$Pore_Y, col="green", lwd=2)
    S.match.dist <- matrix(, nrow = length(R$Pore_X), ncol = length(S.prime$Pore
56
         _X))
57
    for (kk \text{ in } 1: length(R\$Pore_X))
       for (ll in 1:length(S.prime$Pore_X)){
58
         S.match.dist[kk,ll] <- sqrt((R$Pore_X[kk]-S.prime$Pore_X[ll])^2+(R$Pore_Y
59
             [kk]-S.prime Pore Y[11])^2
60
       }
    }
61
62
    #
    max.dist <- .15
63
    close.pores <- S.match.dist <= max.dist
64
    \# write.csv(data.frame(close.pores), "close_pores.csv", row.names = FALSE)
65
    # close.pores ==TRUE
66
    \# \min(S.match.dist[,1])
67
    good.pores <- data.frame(which(close.pores, arr.ind = TRUE, useNames = TRUE))
68
    names(good.pores) <- c("R","Sprime")</pre>
70
    good.R <- good.pores $R
71
    good.Sprime <- good.pores$Sprime
    good.R. pores \langle -R [good.R] \rangle
72
    good.Sprime.pores <- S.prime[good.Sprime,]
73
    good.R. pores <- distinct (good.R. pores, Pore_X, Pore_Y, .keep_all= TRUE)
74
    good.Sprime.pores <- distinct(good.Sprime.pores, Pore_X, Pore_Y, .keep_all=
75
        TRUE)
    length (good.R. pores $Pore_X) = length (good.Sprime.pores $Pore_X)
76
    length (good .R. pores $Pore_X)
77
    length (good .R. pores$Pore _X) / (min(length(R$Pore _X), length(S$Pore _X)))
78
    # double.pores[i] <- length(good.R.pores$Pore_X) == length(good.Sprime.pores$
79
         Pore_X)
    # match.pores[i] <- length(good.R.pores$Pore_X)</pre>
80
    # plot (good .R. pores $Pore_X, good .R. pores $Pore_Y, xlim=c(-750,750), ylim=c
81
         (-1100, 1100))#, col="red", pch=19)
    # xdel.value[i] <- xdel[aa]</pre>
82
    # ydel.value[i] <- ydel[bb]</pre>
83
    # theta.value[i] <- theta[cc]</pre>
84
    \# pore.score[i] <- 0
85
    \# cat(i,"\n")
86
    # i <- i + 1
87
88
89
    \min X \cdot R < - \min (R\$ Pore X)
90
    \max X.R \le \max (R\$ Pore_X)
91
    \min Y.R < - \min (R\$ Pore_Y)
92
    \max Y.R \le \max(R\$Pore_Y)
93
    minX.S <- min(S.prime$Pore_X)</pre>
94
    \max X.S <- \max (S. prime \$Pore_X)
95
    minY.S <- min(S.prime$Pore_Y)</pre>
96
    \max Y.S <- \max(S.prime \$Pore_Y)
97
    \min X <- \min(\min X.R, \min X.S)
98
    \max X \leq \max(\max X.R, \max X.S)
99
    \min Y \leq \min(\min Y.R, \min Y.S)
```

```
101
     \max Y \leq \max(\max Y.R, \max Y.S)
103
     plot (R$Pore_X,R$Pore_Y, xlim=c(minX,maxX),ylim=c(minY,maxY), col="blue")#,
104
         pch=19)
     points (S. prime $Pore_X, S. prime $Pore_Y, pch=19, col="green", cex=0.75)
     points(good.R.pores$Pore_X,good.R.pores$Pore_Y)#, col="red", pch=19)
106
     points(good.Sprime.pores$Pore_X, good.Sprime.pores$Pore_Y, pch=19, col="red",
107
          cex = 0.75)
     #End
108
     #Iterations of xdel, ydel, and theta parameters to find the best pore
111
          similarity score=
     xdel <- seq (from = -.75, to = -.55, by = 0.05)
112
     ydel <- seq (from = 3.45, to = 3.75, by = 0.05)
113
     theta <- seq (from = 9.5, to = 11.5, by = 0.5)
114
     length(xdel)*length(ydel)*length(theta)
115
     max.dist <- .15
117
118
     double.pores <- c()
119
     match.pores <- c()
120
     output.pores <- data.frame()</pre>
122
     xdel.value <- c()
     ydel.value <-c()
124
     theta.value <-c()
     pore.score <- c()
126
127
     i <- 1
128
     for (aa in 1:length(xdel)){
130
        for (bb in 1:length(ydel)){
131
          for (cc in 1:length(theta)){
132
133
            \#plot (S$Pore_X, S$Pore_Y, xlim=c(-750,750), vlim=c(-1100,1100), col="
134
                green", pch=19)
            #plot(R$Pore_X,R$Pore_Y, xlim=c(-750,750),ylim=c(-1100,1100), col="blue
                ")\#, pch=19)
            theta.rad <- (theta/180)*pi
136
            mm < -matrix(c(cos(theta.rad[cc]), sin(theta.rad[cc]), -1*xdel[aa]),
137
            -1*\sin(\text{theta.rad}[cc]), \cos(\text{theta.rad}[cc]), -1*ydel[bb],
138
            0, 0, 1),
            byrow=TRUE, ncol=3)
140
            S.prime \langle - \text{ matrix}(, \text{ nrow} = \text{length}(S\$Pore_X), \text{ ncol} = 2)
141
            for (ff in 1: length(S\$Pore_X)){
142
               outer. Sx \ll as. vector(S[ff, 1])
143
144
               outer.Sy <- as.vector(S[ff,2])
               init.S <- as.matrix(c(outer.Sx, outer.Sy, 1), ncol=1)</pre>
              out.S <- mm %*% init.S
146
              S.prime[ff, 1] <- out.S[1, 1]
147
              S.prime[ff, 2] <- out.S[2, 1]
148
149
            S.prime <-- data.frame(S.prime)
            names(S.prime) <- c("Pore_X","Pore_Y")</pre>
151
```

```
152
                                  #points(S.prime$Pore_X, S.prime$Pore_Y, pch=19, col="green", cex=0.75)
                                  \# newLine <- S.prime [c(100,200,400),]
153
                                  \# points (S$Pore_X[200], S$Pore_Y[200], col="green", pch=19)
154
                                  # lines(newLine$Pore_X, newLine$Pore_Y, col="green", lwd=2)
                                  S.match.dist <- matrix(, nrow = length(R$Pore_X), ncol = length(S.
156
                                              prime $ Pore _X))
                                   for (kk \text{ in } 1: length(R\$Pore_X)) 
157
                                         for (ll in 1:length(S.prime$Pore_X)){
158
                                               S. match. dist [kk, 11] \le \operatorname{sqrt}((R \operatorname{Pore}_X[kk] - S. \operatorname{prime} \operatorname{Pore}_X[11])^2 + (R \operatorname{Pore}_X[kk] - S. \operatorname{prime} \operatorname{Pore}_X[11])^2 + (R \operatorname{Pore}_X[kk] - S. \operatorname{prime} \operatorname{P
159
                                                           Pore Y[kk]-S. prime Pore Y[11] <sup>2</sup>
                                         }
160
                                   }
161
                                                         max.dist <- 12
                                  #
                                   close.pores <- S.match.dist <= max.dist
163
164
                                  # write.csv(data.frame(close.pores)," close_pores.csv", row.names =
                                             FALSE)
                                  # close.pores ==TRUE
                                  \# \min(S. match. dist[, 1])
                                   good.pores <- data.frame(which(close.pores, arr.ind = TRUE, useNames =
167
                                             TRUE))
                                   names(good.pores) <- c("R","Sprime")</pre>
168
                                   good.R <- good.pores $R
169
                                   good.Sprime <- good.pores$Sprime
                                   good.R. pores \langle -R [good.R,]
                                   good.Sprime.pores <- S.prime[good.Sprime,]
172
                                   good.R. pores <- distinct (good.R. pores, Pore_X, Pore_Y, .keep_all= TRUE)
                                   good.Sprime.pores <- distinct(good.Sprime.pores, Pore_X, Pore_Y, .keep_
174
                                               all = TRUE)
                                   double.pores[i] <- length(good.R.pores$Pore_X) == length(good.Sprime.
                                               pores $Pore_X)
                                   match.pores[i] <- length(good.R.pores$Pore_X)</pre>
                                  #plot(good.R.pores$Pore_X,good.R.pores$Pore_Y, xlim=c(-750,750),ylim=c
177
                                               (-1100, 1100))#, col="red", pch=19)
                                   xdel.value[i] <- xdel[aa]
178
                                   ydel.value[i] <- ydel[bb]
179
                                   theta.value[i] <- theta[cc]
180
                                   pore.score [i] \leq - length (good.R.pores $Pore_X) / (min (length (R$Pore_X),
181
                                              length(S$Pore_X)))
                                   cat(i, "\setminus n")
182
183
                                   i <- i + 1
                            }
184
                      }
185
                }
186
187
                output <- data.frame(cbind(xdel.value, ydel.value, theta.value, double.pores,
188
                              match.pores, pore.score))
                names(output) <- c("xdel", "ydel", "theta", "double_pores", "match_pores", "</pre>
189
                           pore_score")
190
                write.csv(output,"output_pores.csv", row.names = FALSE)
               #End
```

10.3 Appendix C

Table 10.4: Reported density values are raw data and do not represent scientifically significant digits. Continued in table 12.2.

CA Fume									
ID	Density	ID	Density						
1055_RA2	2.13348439	$1445 R_B2$	1.42185471						
$1065 R_C1$	2.75827762	$1445 R_C3$	2.25719564						
$1066_{R}A3$	2.1060877	1476_R_B1	1.91947493						
1066_R_B3	1.04108877	1476_R_C1	2.35913712						
$1073_{R}A3$	3.37891751	1868_R_A2	2.00416229						
1073_R_B1	2.84431349	1868_R_B2	1.60265091						
1176_R_B2	2.07146166	1870_R_A3	1.60162141						
1176_R_C3	1.76984885	1870_R_B2	1.78765009						
1184_R_A2	1.61711374	1870_R_C3	1.65670086						
1184_R_B1	1.88228231								
1184_R_C1	2.17671131								
1201_RA2	1.28106972								
1201_R_B3	1.34649032								
1201_R_C2	1.85997363								
1223_R_B1	1.48576741								
1223_R_C1	1.37052773								
$1229_{-}R_{-}B3$	0.85173616								
$1229_{R}C1$	1.19039988								
1241_R_B1	1.08613012								
1241_R_C1	1.85029892								
1320 _R_A3	2.82826894								
$1320_{R}B3$	3.24513914								
$1320_{R}C1$	3.2141356								

Table 10.5: Reported density values are raw data and do not represent scientifically significant digits.

Black Powder								
ID	Density	ID	Density	ID	Density			
$1055 L_A3$	2.83542024	1255_L_B2	3.64652432	1568_L_C1	2.45533458			
1055_L_B3	3.05982673	1255 LC2	3.92104738	$1612 L_A3$	3.32432161			
1055 LC1	4.17145132	1285_L_A2	1.42031289	1612_L_B2	3.35501889			
1065_L_A1	3.46463408	1285_L_B1	1.40577886	$1612 L_C1$	3.49771811			
1065_L_B1	2.0021491	1285 LC3	1.18196094	$1690_{L}A1$	1.96041976			
1065_L_C1	2.33986263	1320_LA2	4.39834298	1690_L_B1	2.0426609			
1066_L_A3	1.28822737	1320_L_B2	4.41021998	1690_L_C1	2.02935805			
1066_L_B1	1.66825238	1320 LC3	4.81237037	$1700_{-}L_{-}A3$	1.22821821			
1066_L_C1	1.0358683	$1410 L_A3$	1.19572338	1700_L_B2	0.47694791			
1073_L_A2	3.65156727	1410_L_B2	3.1832966	1700 LC2	0.80581095			
1073_L_B3	4.62394145	1410 LC3	3.63105852	1721_LA1	2.99745646			
1073 LC3	3.26314729	$1445 L_A3$	3.59344786	1721_L_B1	2.12984524			
1176_L_A1	2.1676581	1445_L_B3	3.75603918	1721_LC2	2.0608121			
1176_L_B1	2.28724247	1445 LC2	2.36221997	1728_L_A2	1.79785221			
1176_L_C3	1.97359285	1449_L_A1	1.34627659	1728_L_B2	1.77749148			
1184_LA3	1.15992375	1449_L_B1	1.85282184	1728_L_C2	1.81846888			
1184_L_B1	1.57217723	1449_L_C3	2.44531967	1761_LA3	0.63779943			
1184_L_C1	1.57338325	1456_LA3	2.01079733	1761_L_B3	0.84912592			
1201_L_A3	0.86765452	1456_L_B2	1.28271043	1761_L_C3	0.87675438			
1201_L_B1	0.79729205	1456_L_C3	1.10628822	1769_L_A3	1.9735375			
1201_L_C3	1.06474452	1476_L_A2	2.39921987	1769_L_B3	3.11843			
1215_L_A2	2.28616153	1476_L_B2	2.26823852	1769_L_C2	2.65596291			
1215_L_B2	1.92163879	1476_L_C2	1.7942963	1830_LA2	1.28553982			
1215_L_C1	1.8308325	$1515 L_A1$	1.86516799	1830_L_B3	1.81234522			
1223_L_A2	1.61311137	1515 LB1	2.50983143	$1830_{-}L_{-}C2$	0.96525348			
1223_L_B2	1.5240008	$1515 L_C1$	2.32230919	$1868_{L}A1$	0.75295292			
1223_L_C1	1.69739858	$1537 L_A3$	1.71405077	1868_L_B3	1.48045604			
1229_L_A2	2.80154445	1537_L_B2	0.84610598	1868_L_C1	0.8831158			
1229_L_B2	2.76819489	$1537 L_C3$	0.97996537	1870_LA2	2.66306724			
1229_L_C2	2.74645992	1549_L_A2	1.15176072	1870_L_B1	2.99795904			
1241_LA3	1.31333155	1549_L_B3	1.33648239	1870_L_C2	2.32315019			
1241_L_B3	0.71806534	1549_L_C3	1.36886501	$1941_{-}L_{-}A1$	1.99342618			
1241_L_C1	0.65579655	1568_L_A1	2.716934	1941_L_B1	0.9032719			
1255_L_A2	4.27462651	1568_L_B2	2.68433812	1941_L_C1	1.14515956			

Bibliography

- Jeffrey G. Barnes. The Fingerprint Sourcebook, chapter Chapter 1: History, pages 1–18. National Institute of Justice, 2014.
- [2] Samuel Cadd, Meez Islam, Peter Manson, and Stephen Bleay. Fingerprint composition and aging: A literature review. Science & Justice, 55(4):219–238, JUL 2015.
- [3] SWGFAST. Standard terminology of friction ridge examination (latent/tenprint), MAR 2013.
- [4] Laura A. Hutchins. *The Fingerprint Sourcebook*, chapter Chapter 5: Systems of Friction Rige Classification. National Institute of Justice, 2014.
- [5] Francis Galton. Finger Prints. Macmillan and Co., 1892.
- [6] David R. Ashbaugh. Ridgeology. Forensic Identification, 41(1):16–64, 1991.
- [7] Elizabeth Oliver. Poroscopy and edgeoscopy. In *The Prairie Whorlwind*. Kansas Division of the IAI, JUN 2002.
- [8] Yuqin Li, Chaoying xu, Chang Shu, Xiandeng Hou, and Peng Wu. Simultaneous extraction of level 2 and level 3 characteristics from latent fingerprints imaged with quantum dots for improved fingerprint analysis. *Chinese Chemical Letters*, 28:1961–1964, 2017.
- [9] D. Bennet and Dr. S. Arumuga Perumal. Fingerprint matching using hierarchical level features. International Journal of Computer Sciences Issues, 8:284–288, 2011.
- [10] Edmond Locard. Les pores et lidentification des criminels. Biologica, 2(24):357–365, 1912.
- [11] David R. Ashbaugh. Poroscopy. Identification News, NOV 1982.
- [12] David Zhang, Feng Liu, Qijun Zhao, Guangming Lu, and Nan Luo. Selecting a reference high resolution for fingerprint recognition using minutiae and pores. *IEEE Transactions* on Instrumentation and Measurement, 60(3):863–871, 2011.
- [13] Richard M. Caplan. How fingerprints came into use for personal identification. Journal of the American Academy of Dermatology, 23(1):109–114, JUL 1990.
- [14] Stephen M. Stigler. Galton and identification by fingerprints. *Genetics*, 140(3):857–860, JUL 1995.

- [15] N. Grew. The description and use of pores in the skin of the hands and feet. Philosophical Transactions of the Royal Society, 14(159):566–567, 1684.
- [16] Henry Faulds. On the skin furrows of the hand. *Nature*, 22(574):605–605, OCT 1880.
- [17] W. J. Herschel. Skin furrows of the hand. Nature, 23(578):76–76, NOV 1880.
- [18] E. R. Henry. Classification and Uses of Finger Prints. George Routledge and Sons, 1900.
- [19] J. Vucetich. Dactyloscopia. Tallers Joaquin Seco, 1909.
- [20] J. Edgar Hoover. Classification of Fingerprints. Government Printing Office, 1939.
- [21] Mark Twain. Life on the Mississippi. James R. Osgood & Co., 1883.
- [22] Mark Twain. Pudd'nhead Wilson and Those Extraordinary Twins. Charles L. Webster & Co., 1894.
- [23] National Research Council. Strengthening Forensic Science in the United States: A Path Forward. National Academies Press, JUL 2009.
- [24] President's Council of Advisors on Science and Technology. Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods, SEP 2016.
- [25] OpenStax. Anatomy and Physiology, chapter Chapter 28: Development and Inheritance. OpenStax CNX, 2013.
- [26] Michael Kucken and Alan C. Newell. Fingerprint formation. Journal of Theoretical Biology, 235(1):71–83, JUL 2005.
- [27] Michael Kucken. Models for fingerprint pattern formation. Forensic Science International, 171(2-3):85–96, SEP 2007.
- [28] OpenStax. Anatomy and Physiology, chapter Chapter 5: The Integumentary System. OpenStax CNX, 2013.
- [29] O. Schlaginhaufen. Das hautleistensystem der primatenplanta unter mitberucksichtigung der palma teil ii. Morphologisches Jahrbuch, 33:577–671, 1905.
- [30] O. Schlaginhaufen. Das hautleistensystem der primatenplanta unter mitberucksichtigung der palma teil i. Morphologisches Jahrbuch, 34:1–125, 1906.
- [31] Inez L. Whipple and Harris Hawthorn Wilder. The ventral surface of the mammalian chiridium: With special reference to the conditions found in man. Zeitschrift für Morphologie und Anthropologie, 7(2):261–368, 1904.
- [32] K. Bonnevie. Studies on papillary patterns in human fingers. J. Genetics, 15:1–111, 1924.
- [33] K. Bonnevie. Was lehrt die embryologie der papillarmuster uber ihre bedeutung als rassen- und familiencharakter, part i and ii. Zeitschrift für Induktive Abstammungs- und Vererbungslehre, 50(1):219–248, 1929.

- [34] Harold Cummins. Epidermal-ridge configurations in developmental defects, with particular reference to the ontogenetic factors which condition ridge direction. American Journal of Anatomy, 38(1):89–151, SEP 1926.
- [35] K. Bonnevie. Die ersten entwicklungstadien der papillarmuster der menschlichen fingerballen. Nyt. Magazin for Naturvidenskaberne, 65:19–56, 1927a.
- [36] E. S. Gould. A topographic study of the differentiation of the dermatoglyphics in the human embryo. PhD thesis, Tulane University, 1948.
- [37] J. Schaeuble. Die entstehung der palmaren digitalen triradien. ein beitrag zur entwicklungsgeschichte der hautleistenzüge der distalen palma. Zeitschrift für Morphologie und Anthropologie, 31(3):403–438, 1933.
- [38] Alfred R. Hale. Breadth of epidermal ridges in the human fetus and its relation to the growth of the hand and foot. *The Anatomical Record*, 105(4):763–776, DEC 1949.
- [39] W. Hirsch and J. U. Schweichel. Morphological evidence concerning the problem of skin ridge formation. *Journal of Mental Deficiency Research*, 17(1):58–72, MAR 1973.
- [40] David A. Dell and Bryce L. Munger. The early embryogenesis of papillary (sweat duct) ridges in primate glabrous skin: The dermatotopic map of cutaneous mechanoreceptors and dermatoglyphics. *The Journal of Comparative Neurology*, 244(4):511–532, FEB 1986.
- [41] Susan J. Moore and Bryce L. Munger. The early ontogeny of the afferent nerves and papillary ridges in human digital glabrous skin. *Developmental Brain Research*, 48(1):119– 141, JUL 1989.
- [42] Kehinde A. Morohunfola, Terrel E. Jones, and Bryce L. Munger. The differentiation of the skin and its appendages. i. normal development of papillary ridges. *The Anatomical Record*, 232(4):587–598, APR 1992.
- [43] Kehinde A. Morohunfola, Terrel E. Jones, and Bryce L. Munger. The differentiation of the skin and its appendages. II. altered development of papillary ridges following neuralectomy. *The Anatomical Record*, 232(4):599–611, APR 1992.
- [44] D. E. Bentil. Aspects of Dynamic Pattern Generation in Embryology and Epidemiology. PhD thesis, Wolfson College Oxford, 1990.
- [45] D.E. Bentil and J.D. Murray. On the mechanical theory for biological pattern formation. *Physica D: Nonlinear Phenomena*, 63(1-2):161–190, FEB 1993.
- [46] J. D. Murray and G. F. Oster. Cell traction models for generating pattern and form in morphogenesis. *Journal of Mathematical Biology*, 19(3):265–279, JUL 1984.
- [47] G. F. Oster, J. D. Murray, and A. K. Harris. Mechanical aspects of mesenchymal morphogenesis. *Journal of Embryology and Experimental Morphology*, 78:83–125, DEC 1983.

- [48] A. Kollmann. Der tastapparat der menschlichen rassen und der affen in seiner entwickelung und gliedrung. Voss Verlag, 1883.
- [49] K. Bonnevie. Zur mechanik der papillarmusterbildung. Roux Arch Dev Biology, 117:384– 420, 1927b.
- [50] K. Bonnevie. Zur mechanik der papillarmusterbildung ii. Roux Arch Dev Biology, 126:348–372, 1932.
- [51] Harris Hawthorne Wilder and Bert Wentworth. Personal Identification: Methods for the Identification of Individuals Living or Dead. The Gorham Press, 1918.
- [52] Expert Working Group on Human Factors in Latent Print Analysis. Latent print examination and human factors: Improving the practice through a systems approach. Technical report, U.S. Department of Commerce, National Institute of Standards and Technology, 2012.
- [53] Anil K. Jain and Jianjian Feng. Latent fingerprint matching. IEEE Transactions on Pattern Analysis and Machine Intelligence, 33(1):88–100, 2011.
- [54] Ruggero Donida Labati, Vincenzo Piuri, and Fabio Scotti. Touchless Fingerprint Biometrics, chapter 4 Fingerprint Biometrics, pages 37–81. CRC Press Taylor & Francis Group, 2016.
- [55] Anil Jain and Sharath Pankanti. Advances in Fingerprint Technology, chapter 8 Automated Fingerprint Identification and Imaging Systems, pages 282–333. CRC Press, 2 edition, 2001.
- [56] Mauricio Pamplona Segundo and Rubisley de Paula Lemes. Pore-based ridge reconstruction for fingerprint recognition. Computer Vision and Pattern Recognition Workshops, 2015.
- [57] Qijun Zhao, Lei Zhang, David Zhang, and Nan Luo. Advances in Biometrics, chapter Direct Pore Matching, pages 597–606. Springer, 2009.
- [58] Qijun Zhao, David Zhang, Lei Zhang, and Nan Luo. Adaptive fingerprint pore modeling and extraction. *Pattern Recognition*, 43:2833–2844, 2010.
- [59] Richard J. Mammone and Jr. J. David Murley, editors. Automated system for fingerprint authentication using pores and ridge structure. SPIE, OCT 1994.
- [60] K. Kryszczuk, A. Drygajlo, and P. Morier. Extraction of level 2 and level 3 features for fragmentary fingerprints. 2nd COST Action 275 Workshop, pages 83–88, 2004.
- [61] Krzysztof M. Kryszczuk, Patrice Morier, and Andrzej Drygajlo. Study of the Distinctiveness of Level 2 and Level 3 Features in Fragmentary Fingerprint Comparison. Springer Berlin Heidelberg, 2004.
- [62] Anil K. Jain, Yi Chen, and Meltem Demirkus. Pores and ridges: High-resolution fingerprint matching using level 3 features. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 29(1):15–27, JAN 2007.

- [63] Andrea R. Roddy and Jonathan D. Stosz. Fingerprint features statistical analysis and system performance estimates. In *Proceedings of the IEEE*, volume 85, pages 1390–1421, SEP 1997.
- [64] A. Gupta, K. Buckley, and R. Sutton. Latent fingermark pore area reproducibility. Forensic Science International, 179(2-3):172–175, AUG 2008.
- [65] Qijun Zhao and Anil K. Jain. On the utility of extended fingerprint features: A study on pores. In 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition - Workshops. IEEE, JUN 2010.
- [66] H. Fronthaler, K. Kollreider, J. Bigun, J. Fierrez, F. Alonso-Fernandez, J. Ortega-Garcia, and J. Gonzalez-Rodriguez. Fingerprint image-quality estimation and its application to multialgorithm verification. *IEEE Transactions on Information Forensics and Security*, 3(2):331–338, JUN 2008.
- [67] K.R. Nagesh, Shikha Bathwal, and B. Ashoka. A preliminary study of pores on epidermal ridges: Are there any sex differences and age related changes? *Journal of Forensic and Legal Medicine*, 18(7):302–305, OCT 2011.
- [68] Alexandre Anthonioz and Christophe Champod. Integration of pore features into the evaluation of fingerprint evidence. *Journal of Forensic Sciences*, 59(1):82–93, JAN 2014.
- [69] Robert Ramotowski, editor. Lee and Gaensslen's Advances in Fingerprint Technology, Third Edition. CRC Press, 2012.
- [70] Gurvinder Singh Bumbrah. Cyanoacrylate fuming method for detection of latent fingermarks: a review. Egyptian Journal of Forensic Sciences, 7(1), JUL 2017.
- [71] G. S. Sodhi and J. Kaur. Powder method for detecting latent fingerprints: a review. Forensic Science International, 120:172–176, 2001.
- [72] Curtis T. Rueden, Johannes Schindelin, Mark C. Hiner, Barry E. DeZonia, Alison E. Walter, Ellen T. Arena, and Kevin W. Eliceiri. ImageJ2: ImageJ for the next generation of scientific image data. *BMC Bioinformatics*, 18(1), NOV 2017.
- [73] Johannes Schindelin, Ignacio Arganda-Carreras, Erwin Frise, Verena Kaynig, Mark Longair, Tobias Pietzsch, Stephan Preibisch, Curtis Rueden, Stephan Saalfeld, Benjamin Schmid, Jean-Yves Tinevez, Daniel James White, Volker Hartenstein, Kevin Eliceiri, Pavel Tomancak, and Albert Cardona. Fiji: an open-source platform for biologicalimage analysis. Nature Methods, 9(7):676–682, JUN 2012.
- [74] Federal Bureau of Investigation U.S. Department of Justice. The universal latent workstation/version 6.6.
- [75] Tom Hopper. Universal latent workstation. In *Encyclopedia of Biometrics*, pages 1352– 1356. Springer US, 2009.
- [76] ANSI NIST-ITL. Data format for the interchange of fingerprint, facial & other biometric information, 2011.

- [77] R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, 2019.
- [78] RStudio Team. RStudio: Integrated Development Environment for R. RStudio, Inc., Boston, MA, 2018.
- [79] SWGIT. General guidelines for capturing latent impressions using a digital camera, JUN 2010.
- [80] Scientific Working Group on Imaging Technologies. General guidelines for capturing latent impressions using a digital camera. *Forensic Science Communications*, 2002.
- [81] Nadim Nachar. The mann-whitney u: A test for assessing whether two independent samples come from the same distribution. *Tutorials in Quantitative Methods for Psychology*, 4(1):13–20, MAR 2008.
- [82] Edzer J. Pebesma and Roger S. Bivand. Classes and methods for spatial data in r. R News, 5(2):9–13, NOV 2005.
- [83] Barry Rowlingson and Peter Diggle. *splancs: Spatial and Space-Time Point Pattern* Analysis, 2017. R package version 2.01-40.
- [84] Adrian Dragulescu and Cole Arendt. xlsx: Read, Write, Format Excel 2007 and Excel 97/2000/XP/2003 Files, 2020. R package version 0.6.3.