Development of new techniques for the recovery of conductive fingermarks

by

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Abstract

Fingerprints are an important type of evidence within the practice of forensic investigation and are growing in importance in terms of security. Fingerprints as evidence are one of the most highly regarded forms of evidence in court. The uniqueness of fingerprints and the admissibility of such evidence has made fingerprints a vital part of forensic investigation. This being said the techniques used for recovering such evidence have not been developed much since the first uses in the 19th and 20th centuries. The modern-day role of fingerprints is becoming more apparent in technology and biosecurity, but this role has not yet been considered when recovering fingerprints throughout a crime. In order to develop a recovery technique that would allow application within technology, a level of conductivity is required to activate many of the sensors used in order to strengthen the level of security. This research highlights there is a way of developing existing techniques implemented within forensic investigation in a way that will consider this technological application. By finding a material that will conduct the current from a human body and capture the details of a fingerprint, a device may be unlocked by someone other than the electronic devices user. The success of this across various surfaces and device types could lead to the development of standard practices within forensic investigation, allowing the uses of such recovered fingermarks to be used more routinely throughout crime scene investigations.

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Chapter1

Introduction and Literature review

1.1 - Forensic Investigation and Fingerprint evidence

1.1.1 – Forensic Investigation

Forensic Investigation, or forensic science, within policing and the Criminal Justice System (CJS) can be defined as the application of natural and physical science to an investigation in relation to criminal or civil law (Siegel, 2020). The area of '*forensic science'* covers many different disciplines each with its own analytical techniques that will be applied. Each of these disciplines will have a contribution to the investigation of a crime, playing a significant role within society from the reporting of a crime to the evidence being presented in court (HM Government, 2018). The techniques involved in forensic investigation can aid in determining the probability of the presence of a person of interest within a crime scene, and establishing possible events taken place. There is also a range of cases such as determining a cause of death, identifying unknown substances and determining if they are illicit, identifying people through biological samples and the analysis of trace evidence such as hairs and fibres as well as many other areas utilising evidence collected from a crime scene. (HM Government, 2018; Incognito Forensic Foundation, 2021).

The process of applying forensic science to an investigation first requires Crime Scene Investigators (CSIs) to examine the scene. They will assess what forensic evidence should be recovered that may hold forensic value, these may include identifying evidence including Deoxyribose Nucleic Acid (DNA), fingermarks, footwear marks, and hair. All evidence will be securely packaged and sent to the laboratories required where an examination will be carried out (HM Government, 2018). Interpretation of the results collected will be written up and reported back to the investigating officer who will use this forensic evidence along with other evidence to determine if the case should be further pursued. The case is then passed to the Crown Prosecution Service (CPS), where it is decided if there is enough evidence to provide a *'realistic prospect of conviction'* (HM Government, 2018) or if more evidence is needed. The forensic scientist may be called upon to present the evidence found in court or in a written statement to explain the findings (HM Government, 2018).

1.1.2 – Fingerprint evidence

Fingerprints are defined as being '*the pattern of curved lines on the end of a finger or thumb that is different in every person, or a mark left by this pattern'* (Cambridge Dictionary, 2022). These lines on the finger are commonly known as ridges or friction ridge skin which are formed of raised skin and valleys creating this pattern. The ridges can be found on both the palmar surface of the hands and feet (Wertheim, 2011).

The reason humans develop fingerprints has been debated for decades with the primary theories being that humans need these to improve grip and to help with touch perception (Adams et al., 2013) similarly to the tread of a tyre aiding in the grip and friction of a wheel. Researchers have conducted numerous studies to understand this development. Research by Ennos (2009) showed that friction is reduced on smooth surfaces due to the valleys of the fingerprint not making contact with the surface (Warman and Ennos, 2009). As a result, researchers questioned the possibility of fingerprints developing to aid in grip when underwater or on rougher surfaces (Warman and Ennos, 2009). This idea was contributed to through the idea that friction ridges allow hypersensitivity when touching objects allowing for humans to determine the correct amount of force required when gripping objects (Prevost, et al, 2009; Scheibert et al., 2009). Debrégeas (2019), believes that this sense of touch evolved alongside grip in a cooperative way which allows humans to more easily handle and manipulate objects (Bryce, 2019).

Researchers have been discovering the individuality of fingerprints (Zhu et al, 2007; Dass et al., 2009) as early as the 1800s, however, there is evidence showing fingerprints were used in the forms of signatures and other identifying uses for thousands of years (Hawthorne, 2009; James and Nordby, 2009). The uses of fingerprints for such reasons involve the use of analysis on the patterns found, using the flow of ridges, or level 1 characteristics, and the details and minutiae that can be found within the fingerprint (Coletta, 2016).

These unique features develop early in foetal development figure 1.1 (Wertheim, 2011)). The fingers begin to separate at approximately 7 - 8 weeks of Estimated Gestational Age (EGA), the bones will harden, or ossify, and the development and regression of volar pads will contribute to the friction skin ridges taking shape. Volar pads are '*transient swellings of tissue called mesenchyme under the epidermis'* (Wertheim, 2011). This process begins with interdigital pads developing between the fingers followed by hypothenar and thenar pads (skin on the little finger and thumb) appearing around 6 weeks EGA, as shown in figure 1.1(a). Around 7 - 8 weeks EGA, figure 1.1(b), the volar pads first begins to form on the fingertips, beginning at the thumb and progressing across to the little finger. These pads will rapidly grow throughout weeks 9 - 10 EGA (figure 1.1(d)) and during this period they will stay well rounded before they begin to develop levels of individualisation in shape and positioning (Wertheim, 2011). Around 10 - 10.5 weeks EGA, the cells of the epidermis begin dividing rapidly, as these volar cells divide '*shallow ledges'* can be seen at the bottom of the epidermis. These are the primary ridges and these '*ledges'* will indicate the overall patterns that will be present within the fingerprint as it develops. The primary ridges will deepen into the dermis as they mature, the duration of which varies between 5.5 to 10.5 weeks, where these will appear at around 16 weeks EGA (Wertheim, 2011). 11 weeks EGA is when the volar pads begin the regression period which can be seen in figure 1.1(f) and onward. This means that the growth of the surrounding area overtakes the growth of the pads. The pads themselves do not shrink but rather the growth slows down, allowing the rest of the skin to grow and merge with the surrounding skin. All volar pads on the hands and feet are completely merged around 16 weeks EGA, as seen in figure 1.1(k) - (l). 15 weeks EGA is when the initial formation of secondary ridges can be seen. By 15 weeks EGA the primary ridges are growing both downward directions, penetrating the sweat glands, and upward with new cell growth. Generally, by 15 weeks the volar surfaces of the skin are completely ridged. Following this, between 15 and 17 weeks EGA, '*secondary ridges appear between the primary ridges on the underside of the epidermis'* caused by cell proliferation. This is the time at which randomly positioned minutiae will become permanently set within the pattern of the ridges. These secondary ridges will continue to mature from 16 to 24 weeks EGA (Wertheim, 2011) and will persist until the body begins decomposition after death with few changes throughout the individual's lifetime.

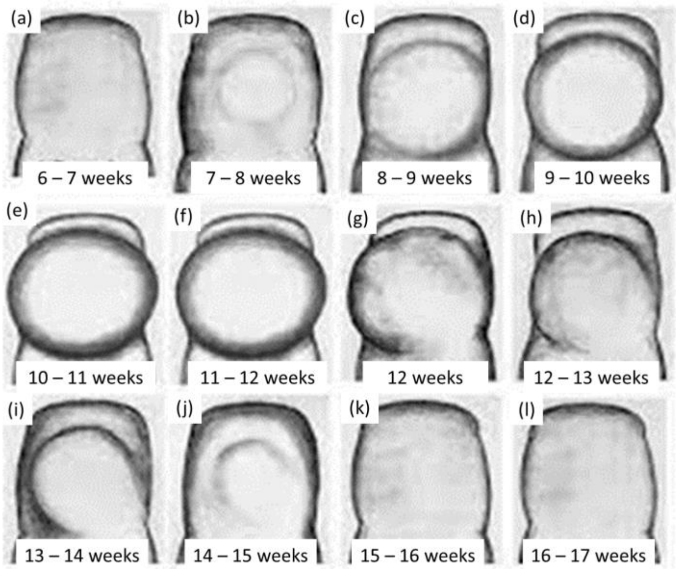

Figure 1.1 - Development of volar pads from initial formation to complete regression (Wertheim, 2011)

Whilst difficult to study, there are many theories as to exactly how and why our fingerprints develop in this manner. Studies have found that friction ridges develop across the path following the '*greatest topographical change*' around the volar pads (Richmond et al, 2004; Wertheim, 2011). Whilst the volar pads do not directly cause the alignment of the ridges, the development of the volar pads contributes to the topology of the surface of the epidermis and the tensions present. This consequently affects the alignment of ridges during the crucial stages of foetal development (Wertheim, 2011). Some hypotheses revolve around fingerprint pattern formation being determined by when the friction ridges start developing and the timing of the development and regression of the volar pads as well as the positioning. Papers (Mulvihill and Smith, 1969; Kücken and Newell, 2005a; Wertheim, 2011) have discussed a relationship between the pattern of fingerprints and thickness of the epidermis, the timing of development, nerves, width and length of fingers and toes and stresses or compressions on the skin during development. Whilst there is no general consensus as to how these fingerprint patterns develop, it would appear that there are many factors that may contribute to how our fingerprints develop (Richmond, 2004; Wertheim, 2011).

The basic pattern and positioning of a person's ridges will remain the same throughout life, persisting into old age and after death. There are however external factors which may affect how the fingerprint will appear. As a person ages, the skin will lose some of its elasticity as the amount of collagen produced within the body will decrease with age (Wilson et al., 2012). Collagen is a protein found throughout the body, with a fibre-like structure, which makes up the connective tissues found within skin, muscles, bones, and cartilage. This contributes to the strength of the skin, and the ability to both heal and withstand stretching. As the amount of collagen the body makes decreases, the body's skin will begin to lose these properties (Wilson et al., 2012; Reilly and Lozano, 2021). This gives the ridges a thicker appearance and the pores may become less lubricated affecting how well these can be captured. The pattern of the ridges does not change but the analysis of these fingerprints may be more difficult (Smart Eye Technology, 2020; Daftardar, 2021). Other factors can also affect fingermark analysis such as in the case of a person carrying out manual labour, including people working in construction and bricklaying. Even frequently washing dishes can cause the fingers to lose some of these ridge details. This however will not cause a complete loss of ridges and when the manual work ceases, ridges have been found to grow back and become prominent again. This is also seen in cases of burning with heat and acid, for example the case of the infamous gangster John Dillinger who went to extraordinary lengths of fingerprints mutilation and plastic surgery to destroy identifiable features. In this case, the fingerprints were sliced through and then coated with acid in an attempt to destroy the ridge patterns. This created a set of fingerprints that were difficult to classify but were easily identifiable (Wertheim, 1998; Feng, Jain and Ross, 2009). This means that other than the degradation with age, most damage done to a finger is temporary. Even in cases where there are scars that remain on the finger, this will simply provide an additional unique identifying feature (Smart Eye Technology, 2020; Daftardar, 2021).

There is a rare genetic condition which has only been identified in a few families worldwide known as adermatoglyphia and is caused by a genetic mutation (Burger et al., 2011, MedlinePlus., 2022). This condition is when a person does not have any ridges present on the skin of their fingers and toes as well as the palms and soles of the feet. As these patterns can be relied upon for identification, it means people with adermatoglyphia cannot be identified in this way (Nousbeck et al., 2011).

The hands and fingers have many nerve endings and receptors in them contributing to the processing of sensations. The main three nerves found in the hands are the radial nerve, the median nerve and the ulnar nerve, each nerve responsible for a different area of the hand and fingers (National Library of Medicine, 2018; Summit Orthopedics, 2022). A recent study published by Jarocka (2021) demonstrated that the ridges found on a person's fingertip may have a greater contribution to the sense of touch than previously thought. Participants of the study had a small card with cones measuring only 0.5 millimetres tall brushed against the fingertips to see if nerve impulses were triggered. This study allowed researchers to not only determine that a single nerve has a receptive field of only 0.4 millimetres wide, which is the approximate width of a ridge, but these receptive fields also follow the pattern in which the ridges flow. This suggests that the ridges on the fingertip are directly involved in a person's touch perception (Jarocka et al, 2021).

1.1.3 – Fingerprints within Forensic Investigation

Friction ridge patterns left by a known source, for example, a fingerprint collected directly from a suspect are referred to as fingerprints, when left by an unknown source such as those recovered from a crime scene, it is known as a fingermark (Hawthorne, 2009). These patterns can be grouped into three general categories of arches, loops, and whorls (Kücken and Newell, 2005b) as can be seen in figure 1.2 (Boyd, 2009).

Figure 1.2 - Examples of the three main types of fingerprint pattern (Boyd, 2009)

Dr. Henry Faulds wrote about the uniqueness of fingerprints in 1880 stating fingerprints could be used as identification within crimes noting that he had been involved in apprehending criminals by locating the fingermarks of individuals at crime scenes (Faulds, 1880). Sir Francis Galton also contributed a great amount to the initial understanding of fingerprints towards the end of the 19th century with his own book '*Fingerprints'* being published in 1892 (Galton, 1892; James and Nordby, 2009). Beginning to be more heavily implemented within the police, Vucetich a member of the police department in Argentina also wrote a book surrounding the identification uses of fingerprints in 1904 (Vucetich, 1904). Sir Edward Henry collected knowledge he had developed from reading the works of Galton whilst travelling and corresponding with him. Sir Edward Henry then brought this information back to the United Kingdom making the official introduction of fingerprints and fingermarks to Scotland yard (Hawthorne, 2009; James and Nordby, 2009). When Sir Edward Henry returned from his travels, he became the assistant commissioner to New Scotland Yard in London. He also developed a system of classification and wrote '*Classification and Uses of Fingerprint*' to be later published as a handbook in 1913, a system still used today (Henry, 1913; Orthmann and Hess, 2012). After becoming Scotland Yard's assistant commissioner, he developed a manual fingerprint system that was implemented and is still used to this day (Hawthorne, 2009). Fingerprints as a biometric method of identification is one of the oldest and most important forms of evidence. As knowledge has been developed fingerprints have become '*universally accepted among scientists and forensic scientists*' and are routinely used within cases. Due to this, fingerprint evidence is usually accepted for connecting a person to a particular place or crime (James and Nordby, 2009).

Due to the level of importance that evidence such as fingerprints can hold, examiners require a considerable amount of training to be able to carry out these analyses and report on their findings. Each policing organisation will have slightly different requirements for the job, however generally to become a trainee fingerprint analyst the person will require a minimum of 5 GCSEs at a C level or above or A level equivalent and it would be beneficial to have an additional degree in an area that is related (HM Government, 2022). Many job roles that may take a person on as a trainee will have courses to expand knowledge and understanding and also develop the skills needed to be reliable in the judgements made. To reach this level of being considered a fingerprint expert, a total of 3-5 years of training needs to be completed (British Transport Police, 2015). Even once a person is a fully qualified fingerprint expert, multiple analyses and opinions are needed for a piece of fingerprint evidence. The use of fingerprints as a means of identification relies on the judgement and professional opinion of the fingerprint examiners unlike many other forms of forensic evidence. As a result, there is a chance for human error and potential for mistakes and so any cases that involve fingerprint evidence must use a secondary independent examiner (Forensic Equity, 2021).

Additionally, the forensic use of fingerprints can be extended to the identification of victims. Particularly used in cases of Disaster Victim Identification (DVI) where mass fatalities occur from a natural or man-made disaster. In cases such as these, fingerprints, DNA and dental records provide the most reliable information as to the identity of the persons found. This requires both the post-mortem (after death) recovery of evidence and fingerprints but also the antemortem (before death) information. As not all people have details such as fingerprints on record, it can be of limited value compared to dental records which most people will have (Interpol, 2021).

Fingerprinting the deceased is a practice that is commonly used and can hold some challenges (Cutro, 2010; Hau Teo et al, 2014). The condition of the body and level of decomposition or mummification are the main factors that could affect an investigator's ability to recover fingerprints from the body. There are five stages of decomposition: fresh, bloated, active decay, advanced decay, and the skeletal stage (Hau Teo et al, 2014). While these stages are useful in the determination of the time of death and other crucial factors relating to the victim, the progression of the decomposition can make it difficult for collecting samples such as fingerprints. When the body is still in the fresh stages and the skin is in a good condition, the fingerprint can be taken much like a living person, using an ink pad and a spoon-shaped tool to aid in curving the fingerprint card around the finger (Cutro, 2010). If rigor mortis had begun to set in and the muscles are stiff then forcibly straightening the digits may be required (Cutro, 2010).

In the initial stages of the decomposition of a body, the epidermis will be affected by biological processes. There will come a point at which the outer dead layer of the epidermis has become fragile and rubbery and has begun to separate from the tissues beneath it (Mulawka, 2014). A similar condition can be observed when the skin has been submerged in water, when the dermal layers separate and the skin becomes wrinkled (Cutro, 2010). This is known as skin slippage (Simmons et al, 2013) and depending on the severity of the separation of the layers of skin, there are several approaches for recovering fingerprints from the deceased. Regardless of the method, the technician must be extremely careful when handling the hands, as the skin is very delicate, and the ridges could be destroyed. If there is only minor skin slippage and many points are still intact, then it may be possible to pull the skin taut and continue with the standard recovery techniques carefully. If the skin has separated from most of the hand with only a few points where the skin is still attached, then there is a process called degloving that can be used (Mulawka, 2014). To do this, the technicians will need to carefully pinch the skin in the places it is still attached, when done the skin should come away from the hand easily. If the skin slippage is too severe then this process needs to be done as quickly as possible (Mulawka, 2014). Once removed, the skin will be rinsed with warm water and placed in a container of rubbing alcohol and gently inverted to clean the skin of any moisture. The skin is removed and thoroughly dried and then it is easier for the technicians to determine the quality of the ridge details. If decomposition is advanced there may not be much detail visible. If there is detail present, then the removed skin can be gently placed over the finger or hand of the technician which will allow them to use recovery techniques such as inking and rolling the finger over the paper to recover these details (Mulawka, 2014).

When a body becomes mummified, or desiccated, the skin on the hand can be rehydrated using traditional methods to provide more structure to the skin of the fingertips. For example, removing the finger and immersing it in a rehydration solution for a minimum of 48 hours. Once the ridges of become visible, the fingertip can be immersed in ethanol to remove this rehydrating solution and then air-dried thoroughly (Chen et al., 2016). This however subjects the skin to potentially damaging techniques to soften it (Cutro, 2010). Less destructive methods have been used more recently that involve taking casts of the fingers. To do this, examiners will carefully dust a physical developer over the surface of the ridges after ensuring the hands are clean and dry. A casting silicone is then applied over each finger or palm and allowed to set for 15 minutes. Once dry, the cast can be peeled off to reveal a '*high contrast, highly detailed, three-dimensional mould'* (Cutro, 2010)

1.2 - Development, recovery, and analysis of fingerprints

1.2.1 – Composition of fingermarks

When a finger touches a surface, whether a countertop, wooden doorframe or piece of paper, a mark is left behind, these can visible or invisible to the naked eye.

Visible fingermarks are characterised this way as these do not need any form of treatment to be visible to the naked eye (Champod et al., 2004). The first of these fingermarks is patent fingermarks, which are created when a finger or palm comes into contact with a transferrable foreign substance such as blood, paint, ink, or grease. If the hand then touches another surface, this substance can then be transferred to the surface, adhering, and capturing the detail of the finger (Hawthorne, 2009). There are also plastic fingermarks, also known as impressed fingermarks, which will occur when a finger is pressed into a soft substance, for example, gum, dried paint, mud, or wax. This can mould around the finger and the ridges present and again will capture those details for analysis (Hawthorne, 2009).

Invisible fingermarks, also known as latent fingermarks, are primarily made up of sweat, sebaceous deposits, amino acids, proteins, lipids as well as other organic and inorganic compounds (Dillon, 2011). These latent fingermarks are made up of some or all of the types of excretions from the skin. There are three glands which contribute to the production of sweat in various places on the body, the sudoriferous glands (eccrine and apocrine) and the sebaceous glands. The eccrine glands are found all over the body but are commonly found on the palms of the hands and soles of the feet but also on the back of the neck and back (Yamashita et al., 2010.). The substance excreted by the eccrine gland is mostly water but has trace amounts of many compounds. For example, organic compounds like amino acids have been detected and have been found to be important in the development of fingermarks. Some lipids can also be found in the sweat from the eccrine glands, while the exact amounts can be difficult to quantify '*one study reported detectable amounts of both fatty acids and sterol compounds'* (Yamashita et al., 2010). The apocrine gland is the other sudoriferous glands which are found primarily in areas of the body with thicker, coarser hair like the underarms and pubic area.

Where eccrine glands will excrete directly onto the surface of the skin, apocrine gland's duct will empty into the hair follicles first. The secretions from these glands have been found to be thicker than that of the eccrine glands and contain proteins, carbohydrates, cholesterol, and iron (Yamashita et al., 2010). Sebaceous glands work in a similar way to apocrine glands by emptying into the hair follicles before the excretions reach the surface of the skin. As a result, it is common to find that the sebaceous and apocrine excretions often mix together before they reach the surface meaning it is difficult to get an uncontaminated sample of either substance for analysis. Associated with body hair, sebaceous glands are often found on the scalp, face, anus, nose, mouth, and external portions of the ear but not on the hands and feet. The sebaceous glands produce sebum instead of sweat, which is a thicker, waxy substance with an oily consistency and is thought to minimise sweat evaporation to retain body heat and lubricate hair and skin (Yamashita et al., 2010).

1.2.2 - Development and recovery

The residue that is left within a latent fingerprint is primarily water which will evaporate over time but contains a complex combination of these varying organic and inorganic compounds (Yamashita et al., 2010). The fingermarks will require physical or chemical treatments that will react with these compounds to be able to make these visible (or enhance visibility) and allow for recovery (Hawthorne, 2009a). The recovery of latent fingermarks will also depend on the surface type upon which the fingermarks are deposited. Non-porous materials include glass, metal or plastic meaning a smooth surface in which the fingerprint could be destroyed if not treated correctly. Porous surfaces are those that the oily residue from the skin can soak into, for example, paper, cardboard, or unfinished woods. Semiporous or '*questionable'* surfaces should be treated as non-porous as there is a possibility of the fingermark wiping off, these surfaces include glossy finished card or magazines and some wooden finishes (Kriel, 2011).

Patent fingermarks can be delicate and are difficult to recover without damaging the details. Plastic fingermarks are also difficult to recover. As a result, the best method to recover these types of fingermarks is through high-resolution photography. With good lighting, the characteristics can be recorded with enough detail to carry out analyses by an expert (Champod et al., 2004). In relation to plastic fingermarks, casting is also a commonly used method to overcome the limitations of photography as this does not always display the full characteristics. Plaster and a silicone casting material, such as that used for tool fingermarks, may also be used to recover a detailed cast (Champod et al., 2004).

The recovery of latent fingermarks will depend on the type of surface they have been deposited onto. In the case of a latent fingerprint being left on a non-porous surface, there are several methods using physical developers to recover the fingerprints found. The use of dark powders such as aluminium or magnetic powders are the oldest (Jakupi and Avziu, n.d.) developed techniques and the most commonly used methods currently followed within this practice (Jakupi and Avziu, n.d.). This process of developing fingermarks using a physical developer requires the application of the powder over the area where the fingerprints are believed to be, creating a contrast between the surface and the oils from the ridges on the fingers. This powdered fingerprint can then be lifted using J-Lar tape and placed onto a piece of acetate or card to help visualise the patterns (Hawthorne, 2009). Various chemical developers are used in the recovery of fingermarks. For example, cyanoacrylate ester fuming (Trozzi et al., 2000), also known as superglue fuming, in which vapours from the cyanoacrylate ester adhere to the ridges left on the object which can be viewed under certain lights (Trozzi et al., 2000). Porous surfaces such as paper or cardboard will also require chemical treatments, such as ninhydrin or DFO (1,2-diazafluoren-9-one), to enhance the fingermarks. Both of these chemicals can be applied by spraying, dipping, or brushing. Development can be promoted by the application of heat or steam once the exhibit has dried (Yamashita et al., n.d.). These treatments react with the oils, amino acids, and salt residues of the fingerprint. In the case of ninhydrin, it will highlight the print in a purple colour (Rhumann's purple) whereas DFO allows the fingerprints to be viewed under a blue/green light where the ridges will fluoresce. In the cases of semiporous or difficult surfaces, different treatments may be used to enhance the fingermarks which will be determined by the examiner at the time (Trozzi et al., 2000).

1.2.3 - Analysis

Once the fingermarks have been collected from the scene, a full analysis will be carried out. The current '*standard methodology used by fingerprint experts to conduct friction ridge examinations is called ACE-V, for analysis, comparison, evaluation, and verification, which are the four fundamental phases utilised in this process'* (Kaushal, 2011). The analysis part of this process focuses on identifying any key details within the fingermark, such as the level 1, 2 and 3 characteristics (see chapter 2, section 2.2.1). This step of the process also involves the determination of the suitability of the fingerprint for this to move onto the comparison stage. For this, the examiner should consider factors such as distortion which could affect the reliability of the fingermark as the skin on a person's fingertips is pliable and will not always look the same. Any poorer quality fingermarks are analysed first followed by clearer fingermarks or known fingerprints taken from any suspects (Kaushal and Kaushal, 2011). The comparison looks at both the recovered fingermark and known fingerprint side-by-side and assesses the information from the analysis. Beginning at a focal point and moving across the ridges of the fingermark, the examiner will first look at the level 1 details and analyse the information provided by the first stage, if the information matches both the known fingerprints and recovered fingermark, the examiners will move onto the level 2 characteristics. Level 3 details are often noted alongside the level 2 assessment and if visible, are also compared. '*For information to match in both the fingerprints, the ridge path should have adequate quality, clarity, relative position and have the same unit relationship'* (Kaushal, 2011). An evaluation is then carried out to assess the information provided by the analysis and comparison phases. From this, one of three conclusions is drawn. First, identification, or individualisation, is determined when there are enough matching details within both fingerprints that a positive match can be made confirming both fingerprints came from the same source. The second conclusion is exclusion, occurring when there is sufficient information present to determine the fingerprints do not match and have not come from the same source. And thirdly an inconclusive decision is reached when a conclusive assessment cannot be completed as the quality of the fingermark recovered is not clear enough (Kaushal, 2011). Although the verification phase is not a part of the identification process, it is an important peer reviewing step that ensures the reliability and accuracy of the results obtained. Positive identifications are peer-reviewed through an independent examination by one or two fingerprint experts, exclusion and inconclusive conclusions can also be peer-reviewed but are not as necessary (Bunter, 2016).

Once the fingerprints have been fully analysed, they are stored in a database for biometric information known as IDENT 1. IDENT 1 is the '*national automated fingerprint system that provides biometric services to the police forces and law enforcement agencies'* and is used in England, Wales, and Scotland (Homeland Security Technology, 2022). The system replaces the previously used National Automated Fingerprint Identification System (NAFIS) and uses similar technology. By storing the fingerprints on IDENT 1, a faster comparison can be achieved. Fingerprints collected will be compared against the system and if already identified will flag up with a match reducing time spent analysing the fingerprints. IDENT 1 does this by using 'Biometric Fusion Technology' and algorithms set up to provide high search accuracy and comparisons. The developers of the systems state that IDENT 1 integrates the latest processor technology to allow the best results possible and it is always improving. The human-computer interface can also be adjusted and enhanced for the business that is using the system to cater for the needs and improve efficiency further (Homeland Security Technology, 2022).

1.2.4 - Grading

Generally, within the field of fingerprinting, the methods used for grading of fingerprints and fingermarks are subjective and unreliable, as discussed in many papers (Evett and Williams, 1996; Fritz et al., 2016; Leadbetter, 2016; Forensic Science Regulator, 2020).

Whilst the standard of sixteen matching characteristics was necessary to confirm a match and determine the value of a fingerprint between 1953 and 2001 (Leadbetter, 2016), this has since been changed to having no minimum standard as long as the identification is to the standards of the Association of Chief Police Officers (ACPO) and Home Office guidelines (Leadbetter, 2016). The current codes of practice as released by the United Kingdom (UK) government states '*the practitioner will establish an opinion as to the level of agreement or disagreement between the sequences of ridge characteristics and features visible in both'* (Forensic Science Regulator, 2020). These methods are determined by the examiner's opinion, as a result, this can lead to differing opinions of the value of a fingerprint or fingermark. To try and combat this, there have been researchers aiming to find a way of objectively assessing the quality of a fingerprint whether it is latent, patent or plastic (Pulsifer et al., 2013; Rajan et al., 2018).

Pulsifer (2013) proposed a method which involves a photograph being taken of the fingermark before and after the latent fingermark is developed. The fingermark is then put through various software processes, the first being the Universal Latent Workstation (ULW), designed to help examiners *characterise fingerprints and then upload them to the Automated Fingerprint Identification System'*. By analysing the characteristics, the image can be converted into a colour coordinated map of background (black) debatable pattern flow (red), debatable (yellow) and definitive (green) minutiae detail, this is known as a raw clarity map (Pulsifer et al., 2013). From here the image will be put into image editing software GIMP where the colours assigned to the details by ULW are changed to fit red, green, and blue colour values. Meaning the colours change to background (black), debatable pattern flow (blue), debatable (yellow) and definitive (white) minutiae. From here the image is transferred to a pixel counting software, Mathematica1. This software is then programmed to count how much of the fingerprint is coloured white corresponding to definitive minutiae. These images were then rated on quality based on the percentage of the image is white and it is thought this will allow examiners to only focus on the portion of the image that is recorded as being white, reducing the time spent manually assessing the fingerprint and taking the subjectivity away (Pulsifer et al., 2013).

An example of a simpler system used for the grading of recovered fingerprints can be seen in table 1.1. This system can allow researchers that have not received the training of a fingerprint expert to follow guidelines of the requirements of a fingerprint. This process of grading only requires the examiners to compare the fingerprint in front of them with the set criteria. Outlining what is considered to be each grade, it takes away a degree of subjectivity. This grading system was detailed in research conducted by Rajan et al (2018), reviewing the use of nanocarbon powders in the development of latent fingerprints. The fingerprints were dusted with nanocarbon powder and a standard black powder for comparison. The grading system seen within table 1.1 was then used to score the quality of the recovered fingermarks allowing the variances between the two powders to be more easily compared (Rajan et al., 2018).

Table 1.1 - Description of grading criteria of fingermark quality (Rajan et al., 2018).

Grade	Description
0	Fully smudged outline of a mark or no evidence of mark
1	Presence of several ridges and cannot lead to identification
2	Major parts of the mark are smudged, several ridge details are present, and analysis cannot be performed
3	Minor parts of mark are smudged, most ridge details are visible, and analysis can be performed
4	Full mark and ridge details are clearly visible, some ridge lines may be thinned or smudged but identifiable mark
5	Full mark and all ridge details are clearly visible; identifiable mark

1.3 - The uses of fingerprints in modern-day technology

1.3.1 – Modern day uses

In this modern-day world of technology, the use of fingerprints is becoming increasingly common in everyday life. Known as biometric authentication, scanners relying on fingerprints or facial recognition use the fact that each person has unique features and implements this into the security of a system (IFSEC Global, 2020). Currently, many uses are being developed or already used for fingerprints. This technology has been replacing everyday items such as payment cards, key cards for hotels and ID cards for work purposes as well as use for travel (Andrejevic and Selwyn, 2020; IFSEC Global, 2020; NEC, 2020).

The most common use of fingerprints for everyday people is the form of security on mobile phones, laptops, and tablets. iPhone first released touch ID into the market in 2013 with the iPhone 5S (Jayaditya, 2020), and although other companies had previously used this technology, Apple's use of the fingerprint scanner encouraged many other companies and manufacturers to do the same resulting in further biometric security added to mobile phones. Currently, most new devices being introduced will have a biometric scanner whether this is fingerprint or facial recognition (NEC, 2020). Another well-known use is within criminal investigations using primarily fingerprints and facial recognition as a means to identify or exclude suspects. Additional uses rely on fingerprints along with other biometric sources as a means of security or identification. For example, recognition of identity using methods like this are becoming more common in airlines. *'Using biometric technology to verify passenger identity has been used in some of the major airports around the world for several years and* *the use of the technology is now becoming more widespread'* (NEC, 2020). Some blood banks also use fingerprint or iris recognition to access medical records regarding the donor to reduce the chances of duplicates or data entry problems (NEC, 2020). Even buildings such as schools and workplaces have begun using fingerprints to allow staff and students access to buildings and rooms and can monitor attendance using them and spending on school meals. Many have also implemented facial recognition to highlight any unauthorised personnel (NEC, 2020).

1.3.2 – Types of scanners

The use of fingerprint authentication within mobile devices is done using several different types of scanners. Firstly, there is the optical scanner. This scanner works by shining a bright light over the details of the finger and taking an optical image or photograph of the fingertip. This image is then input into a computer scanner which uses a '*light-sensitive microchip'* such as a charge-coupled device (CCD) which creates a digital image. The image is analysed by the computer, turned into code, and stored. Every time a finger is then used to unlock the device, a comparison is done between the finger used and the stored image (Woodford, 2020). The mechanism of this type of scanner is shown in figure 1.3 (Triggs, 2021). As shown, the light source is bounced against the fingertip and into the CCD where the digital image is read and stored.

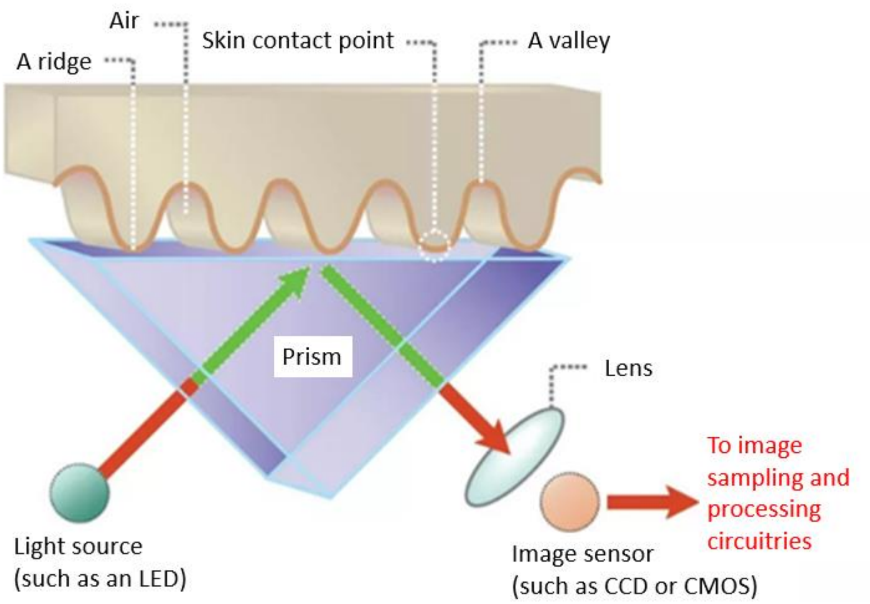

Figure 1.3 - Diagram showing the mechanism of an optical fingerprint scanner (Triggs, 2021)

The most commonly used scanner is a capacitive scanner which has become the preferred choice found in many devices such as phones as these scanners can provide more security benefits compared to an optical scanner. It is more common over ultrasonic scanners as the technology for this scanner can be easily interfered with screen protectors and cases, especially the thicker protectors (Triggs, 2021). This fingerprint scanner works through an '*array of tiny capacitor circuits to collect data',* these capacitors carry an electrical charge and so when connected to conductive plates at the surface of the scanner, they can track the details within a fingerprint. As can be seen in figure 1.4 (Triggs, 2021), the charge that is stored within these scanners will be changed when the surface of a ridge of the finger makes contact with it. As shown in figure 1.4, the area in contact with the ridge will have a slightly changed charge whereas the gap between the ridges will leave the capacitors charge unchanged. '*An op-amp integrator circuit'* will then track these changes and record them through '*an analog-to-digital converter'* (Triggs, 2021). The recorded fingerprint can then be analysed for unique features and saved for later comparison. The more capacitors present within a single scanner, the more detail can be picked up, this will allow for extra security, however, this implies a higher associated cost. As this scanner relies on the electrical signals applied, the security is better as it is harder for errors to occur within this system through the use of images or prosthetics as they will record different changes in charge (Triggs, 2021). These scanners do work faster than optical scanners however they do not work as well with moisture, or grease, on the fingertips as it can affect the ability of the scanner and these are more susceptible to damage from static electricity (Woodford, 2020).

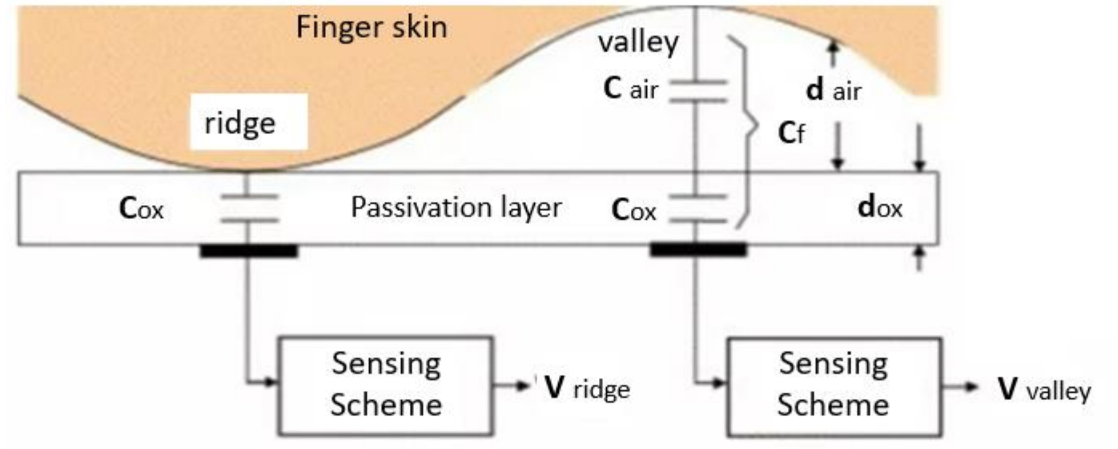

Figure 1.4 - Diagram showing the mechanism of a capacitive fingerprint scanner
(Triggs, 2021)

One of the more recent types of scanners released into the commercial market in 2016 is an ultrasonic scanner. This was firstly incorporated into the Le Max Pro smartphone (Triggs, 2021) just a few years after the capacitive scanner within Apple's touch ID was released in 2013 (Jayaditya, 2020). This method of fingerprint recognition works through having an ultrasonic transmitter and a receiver. The transmitter will then send an ultrasonic pulse against the finger when it is placed against the scanner which will then bounce back to the sensor. Some of this pulse will be absorbed and some of it will bounce back, the amount bouncing back will depend on the ridges and pores and other details within the fingerprint (Jamal, 2020; Triggs, 2021). This mechanism can be seen in figure 1.5 (Jamal, 2020). In this case, these ultrasonic waves capture the fingerprint instead of light, unlike other scanners. As a result, these capture fingerprints in a three-dimensional way and can work better outdoors than optical scanners, however, these are often slower than capacitive scanners (Woodford, 2020).

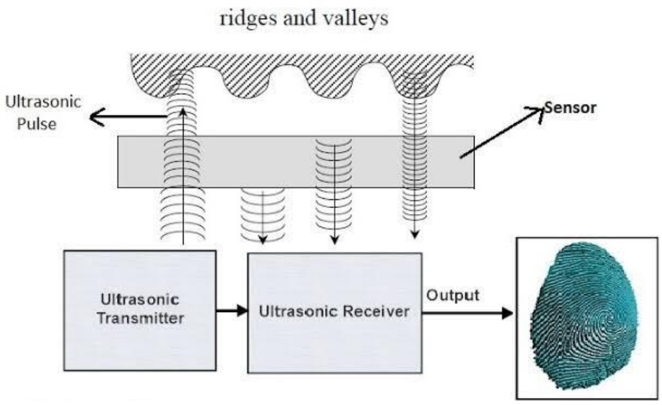

Figure 1.5 - Diagram showing the mechanism of an ultrasonic fingerprint scanner (Jamal, 2020)

1.4 - Existing research

In recent years there have been areas of fingerprints that have been explored. Research published ranges from aiming to develop the way analysis takes place within forensic science to looking into the technological uses of fingerprints and how these can be utilized (Cao and Jain, 2016; Huynh and Halámek, 2016; Levalle, 2020b).

Research conducted by Huynh (2016) focuses on the chemical aspects of fingerprints to determine a method to extract information from the chemical makeup of a fingerprint rather than just the patterns identified. The methods discussed within the paper are mass spectrometry, optical spectroscopy, and nanotechnology (Huynh and Halámek, 2016). The studies described that have researched the applications of mass spectrometry have found that eccrine sweat, apocrine sweat, sebum secretions, epidermic substances, and external contaminations from the environment are the compounds that make up a fingerprint. The quantities of these components can greatly depend on the type of surface the fingermark is deposited onto. For example, when deposited on non-porous and porous surfaces the composition was larger on the porous '*but the amounts of squalene and cholesterol were still comparable between the two'* (Huynh and Halámek, 2016). Mass spectrometry can also allow researchers to determine the fatty acid ratios within the fingermark. Aiming to find '*specific fatty acids or fatty acid ratios that could differentiate between individuals*', the study showed that it is possible to use this to differentiate between males and females as well as African Americans, and Caucasian Americans using the mean fatty acid ratios. Spectroscopy is another area that is commonly used within analysis as its non-destructive and allows for both chemical and visual analysis. The use of different types of spectroscopies has shown a difference in the composition of fingerprints from children and adults with children's fingerprints degrading slower. Additionally, it has been noted that '*ATR-FTIR spectroscopy can be used to obtain both chemical and spatial data from a fingerprint with no sample preparation under controlled conditions'* by creating an image of the fingerprints using the sebum that is present (Huynh and Halámek, 2016). More recently the idea of using nanoparticles has been studied and development of the techniques is still underway. For example, the use of gold nanoparticles to detect latent fingerprints on paper used in conjunction with AuNP-cellulose (Wang et al., 2011; Jaber et al., 2012; Moret et al, 2014; Huynh and Halámek, 2016) as well as the utilisation of CdSe nanoparticle suspension for latent fingermarks. The result of this method is a colourless fingerprint with a coloured background allowing the fingerprint to be visible. There are other similar procedures, while these do not work on all surface types, the methods have been in the process of being developed (Huynh and Halámek, 2016).

Looking towards the development of fingerprints in relation to technological applications, there are considerably fewer studies and sources discussing these possibilities. Most of the research addressing this area are not published in academic sources such as peer-reviewed journals, however, there are a few sources that have looked into these applications of fingerprints in regard to touch ID on electronics. One that closely relates to the study detailed within this paper, is research conducted by Cao (2016). This study was carried out with the idea of a person hacking into a device, whether this would be to access the device in general or more specifically to use the device for money transactions, with the introduction of Apple pay and Google pay using the owner's fingerprint (Cao and Jain, 2016). The methods chosen by the researchers were based on real-life '*spoofing'* attacks on capacitive scanners from lifted fingermarks left by legitimate users. The methods these attacks used involved taking the fingerprint collected and using latex or wood glue to mimic the natural ridges and valleys of fingerprints. This method however could affect the quality of the fingerprints as it is done manually by the hacker, additionally, the drying time for wood glue or latex makes this quite a time-consuming method (Cao and Jain, 2016). The researchers were looking to use this concept and make it a more efficient and effective method for hacking a touch ID sensor. The method evaluated within this paper used silver ink and a printer to create the ridge patterns which would then be used to unlock the phones. To do this, a high-resolution image was taken of the '*target's'* finger, it was then scanned at '*300 dpi or higher resolution'*. The image of the fingerprint was then mirrored horizontally and then printed. A regular inkjet printer was used for this, with three AgCl silver conductive ink cartridges along with a regular black ink one. The image was then printed onto the glossy side of a piece of AgIC special paper. Both a Samsung Galaxy S6 and a Huawei Honor 7 were used to assess this method and in both cases, the device was successfully unlocked (Cao and Jain, 2016). The authors did state that as phone technologies improve, this technique may not be as successful but is shown that it is possible for biometric security such as this can be bypassed. While this paper has begun research into the bypassing of these sensors, it has been done from the point of view of hacking a mobile and seeking to improve the security that is provided through the use of biometric security. This does not address the possible forensic applications of similar techniques while it has been demonstrated as possible, if the techniques were explored in the correct way, then standard procedures could be developed and implemented into everyday investigations.

A more recent study, again looking into the bypassing of biometric systems, was conducted by Levalle (2020) who used an array of different materials to mimic '*grease attacks'* on various different scanner types. This method involved having a legitimate user place their finger onto the sensor and then using different materials in order to try and mimic the capacitance needed to fool the system (Levalle, 2020). Initially, the report describes using moist breath to do this but moves on to the use of gummy bears and silicone fingertips to mimic a person's flesh. This, however, was unsuccessful in fooling any of the sensors tested, as a result, Levalle moved on to enhancing the fingerprint to capture detail better, this was done by trying multiple substances. As stated in the report, these substances should be transparent, so the '*target'* is not aware of it, and an ointment consistency is more effective. Materials tested included hand cream, glycerine, lip balm, and ointment (Levalle, 2020). To do this, the substances tested were placed on the sensor itself, then the legitimate finger was placed on and from there the silicone fingertip was placed on the residual mark. This was more successful with the ointment and lip balm successfully bypassing systems. The study also involved casting 3D impressions using combinations of materials such as silicone, ballistic gelatine, and liquid latex in the impression made in playdoh, hot glue, putty and more. This was found to have mixed results with some being successful and others not. Finally, 3D printing was used to also create false fingerprints. This was done by taking a high-resolution photo and using editing software to enhance the image before using the 3D printer to create the mould. This study has also addressed the possibilities within a scenario of someone hacking in instead of looking at how this can be developed for forensic purposes (Levalle, 2020).

1.5 - Importance of developing this research

Although there have been areas of research focused on forensic development and uses of fingerprints, this field remains relatively unchanged since its first development. Several sources that discuss fingerprints and how they are recovered and used refer to the fact that while the methods and techniques currently used are effective, '*this discipline of identifying individuals by fingerprint analysis has been in use for over 110 years and has seen little improvement'* (Huynh and Halámek, 2016). It is known that the first uses of fingerprints within a criminal investigation can be dated back to the early

20th century when the '*Classification and Uses of Fingerprints'* was written and published by Sir Edward Henry (Henry, 1913). These techniques were then implemented into how the police carry out investigations once Sir Edward Henry became Scotland Yard's assistant commissioner. The manual that was written is still used in the present day (Hawthorne, 2009b).

The post-mortem applications are also important to address. It is well known that humans are capable of producing an electrical charge, a factor that sensors such as capacitive sensors rely on. The elements in a human's body such as sodium, potassium, calcium, and magnesium all have specific electrical charges. The cells within a person's body use these ions to generate electricity. Imbalances of charged ions inside and outside of cells, and the flow of these charges across a cell membrane produces electrical currents. Currents that are required for the nervous system to send signals around the body (Plante, 2022). When the body dies, these electrical impulses are no longer required for function in the body so cease being produced. This means that the body is no longer able to produce this current and will be unable to do something such as unlocking biometrically secure devices. If fingerprint evidence could be used to unlock such devices, then a deceased person's phone can be accessed easily using the fingerprint directly from the person in question.

1.6 - Aims

The study detailed in this paper aims to understand and develop a way to recover fingermarks to be conductive to unlock devices that have fingerprint security such as mobile phones and computers. Additionally, these methods will be developed in a way that will not interfere with the current analytical uses and visual comparison of the fingermarks. Thereby allowing for ridge characteristics of the fingermarks collected whilst still being clear enough for experts to make accurate comparisons of the recovered fingermarks and sample fingerprints.

Chapter 2

Methodology

2.1 - Introduction

The focus of this study is to create a recovery method that allows for traditional techniques of comparison, as detailed within section 1.2, with the added application of unlocking mobile devices. To achieve this, both an understanding of fingerprint classification and the mechanisms of fingerprint sensors and the role that conductivity provides within this mechanism were required. The levels of classification and process of analysing fingerprints has remained relatively unchanged since the earlier development of the procedures with grading systems available for researchers without full training to follow. The role of conductivity within this study is discussed throughout this chapter and the importance of conductivity in relation to activating the fingerprint sensors used is addressed. To create a working technique, the conductivity and analytical techniques will work in conjunction to allow the fingerprint evidence to provide multiple forms of evidence.

2.2 – Fingerprints and fingermarks

Fingerprints and fingermarks have many levels of classification and structures similar to fingerprints are seen across many species as well as humans. As discussed within section 1.1, fingerprints are first developed early on in the womb and persist until death, this has been observed within other animal species as well. For example, gorillas, chimpanzees, and koalas are well known for having fingerprints similar to humans and can be easily mistaken for a human. These have evolved to aid in grip and improve sensitivity to touch, things that will contribute to the animals ability to survive (McVean, 2019; Staughton, 2022). Unique 'fingerprints' appear in the animal kingdom in many ways aside from the traditional fingerprint on the fingers. There are also certain species of monkey that have unique pattern or ridges on the tail as a way to increase grip. Additionally, dogs and pigs have a unique fingerprint in the form of the patterns on the nose (McVean, 2019; Staughton, 2022).

The initial classification is to determine if the fingermark is a known fingerprint, or a collected fingermark as defined within section 1.1.3. after which the level 1, 2 and 3 characteristics will be classified and compared following the process described throughout section 1.2. The identifying of these characteristics allows for a detailed comparison of the known and unknown fingermarks to determine if they have been deposited by the same person.

The grading systems discussed allows for a researcher to follow an objective requirement when analysing fingerprint as a person that has not received the level of training that a fingerprint expert will have received. As detailed within section 1.1.3, this training is extensive so a grading system such as those detailed within this chapter allow for guidelines for a researcher to follow when conducting an analysis.

2.2.1 - Classification of fingerprints

There are several levels to the analysis of fingerprints each of these levels of characteristics provides another layer of details as described throughout section 1.2.3. Although there is much variation in how fingerprints appear, for example '*ulnar loops (when the loop opens toward the small finger) and radial loops (when the loop opens toward the thumb)*', the patterns will conform to one of three categories known as loops, whorls and arches as discussed within section 1.1.3 (Kücken and Newell, 2005). If the fingerprint is classified as a loop, it may be the ulnar or radial loop as previously mentioned or a double loop in which two separate loops curving around one another (Smart Eye Technology, 2022). The whorl pattern may be characterised as a plain whorl (complete concentric circles with two deltas) an accidental whorl (irregularly shaped) or a central pocket loop/whorl (a whorl within a loop) (Smart Eye Technology, 2022). Finally, arches can be separated into plain and tented arches in which there is either a gentle sloping of the ridges from side to side (plain) or where the two sides of the arch come together to form an angle (tented) (Smart Eye Technology, 2022). These pattern types (figure 1.2) and the overall flow of the ridges are known as the level 1 characteristics and are the first step to begin the process of identification through fingerprints (Jain, Chen and Demirkus, 2006). From this, the level 2 characteristics, also known as minutiae, can be analysed. These minutiae include ridge endings, bifurcations, and bridges (figure 2.1) (Alsaidi et al. 2019). The analysis of these details includes the presence or absence of certain characteristics along with their position in relation to the other characteristics found (Jain, Chen and Demirkus, 2006).

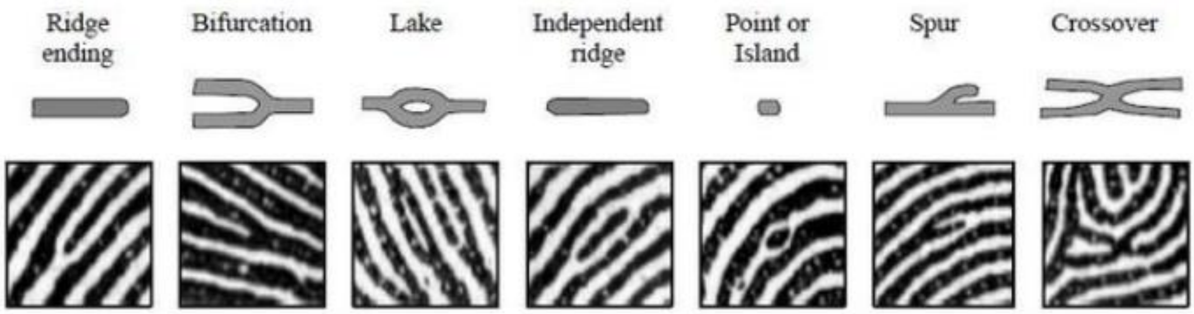

Figure 2.1 - Examples of the Level 2 characteristics found in a fingerprint (Alsaidi et al. 2019)

Level 3 characteristics refer to the shapes and attributes of the ridges themselves. This means going down to the microscopic details of the finger such as the placement of the pores on the ridges, the width and shape of ridges and any breaks, scars or creases that can be found (Bennet and Perumal, 2011; Sharma et al., 2019). The comparison of pores may look at whether open or closed pores are present as well as the placement in the fingerprint. Closed pores are those that are completely enclosed within a ridge, whereas an open pore will intersect between the valley and the ridge (figure 2.2 (a)) (Jain, Chen and Demirkus, 2006). Even if the compared fingerprints have similar ridges patterns and characteristics, the shapes and location of the pores may suggests the fingerprints are not a match (Sharma et al., 2019). Additionally the presence of creases can hold information, although creases may be temporary due to manual labour, there are creases or breaks that can appear from birth and persist throughout an individuals lifetime. These will appear as lines at an angle to the ridges and often appear wider (figure 2.2 (b)), scars may also appear this way and can be characterised similarly (Laseinde, 2012).

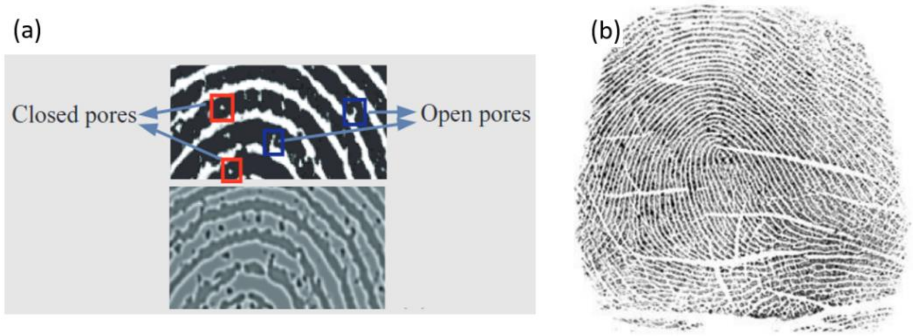

Figure 2.2 - Examples of the Level 3 characteristics found in a fingerprint where (a) shows closed and open pores (Jain, Chen and Demirkus, 2006) and (b) shows how creases and scars may be presented (Laseinde, 2012)

During the analysis of a fingermark, level 1 characteristics or the general pattern have been found to be useful for classification purposes even though they are not unique and do not provide much identifiable evidence. The level 2 characteristics do have '*sufficient discriminating power to establish the individuality of fingerprints'* by looking at the ridge details and their placements. However, examiners will most often perform level 2 and level 3 analysis as the level 3 characteristics that could be identified are '*permanent, immutable and unique*' much like the level 2 features. The analysis will look at the fingermarks collected from the crime scene and compare them to the known fingerprint taken from the suspects or clearer fingermarks that are taken from the crime scene. The use of all three levels of characteristics gives a detailed view of the fingermarks recovered and can confidently match the fingermarks to fingerprints of suspects (Kesharwani and Ugale, 2014).

2.2.2 – Grading systems

Section 1.1.3 summarises fingerprint examiner experience and knowledge and how this is used for determining a match between control and suspect fingermarks. However, for research purposes, it is generally accepted (Pulsifer et al., 2013; Rajan et al., 2018; Bare Conductive, 2021) that comparisons can be made using a grading system. As discussed within section 1.2.4, having a grading system can help to provide a level of objectivity when analysing the details within a fingerprint as well as providing clarity for others looking at the data. For this study a grading system was developed and used for these reasons.

Based on the grading system by Rajan (2018) detailed within section 1.2.4, the criteria was amended to apply to the expectations of the quality of recovered fingermarks within the study. These grading systems were designed to quantify the levels of clarity, durability and flexibility of the lifts produced through the various methods.

For the clarity, there was not a specific number of ridges required for each classification but rather this looked at the number of air pockets present and how this would obscure the details of the ridges. This table of grades can be seen in table 2.1, with a grade 0 being an unsuccessful lift that either did not set or had little to no visible ridges present and a grade 5 meaning there are no visible air pockets, and all of the ridges are clear.

Table 2.1 - Table of grading system for clarity (Rajan et al., 2018)

Clarity	
0	Cast unsuccessful with hardly any visible ridges or cast did not set correctly
1	Some ridges visible, pockets blocking most ridge details
2	Many ridges visible but with considerable air pockets
3	Edges of cast thinned/ missing with minor pockets
4	Cast intact with most ridges clear and visible but minor thinning at edges
5	Cast complete and intact with all details clear

The durability grading system was used to identify the length of life of the various lifts and so this grading system, as seen in table 2.2, looked at how many times the lift could be used before it became unsuccessful or broke apart. The grade of 0 referred to a lift that could not be used for unlocking the device, either due to just being unsuccessful or as a result of the lift not setting correctly or being too difficult to remove from the casts. A grade of 4 would then mean that the lift was successful and could be used to unlock the device for at least 15 uses.

Table 2.2 - Table of grading system for durability (Rajan et al., 2018)

Durability	
0	Material unsuccessful at unlocking devices
1	Material successfully unlocks devices but only lasts up to 3 uses
2	Material successfully unlocks devices and lasts up to 7 uses
3	Material successfully unlocks devices and lasts up to 10 uses
4	Material successfully unlocks devices and lasts 15+ uses

The flexibility was graded as through testing it was found that a degree of flexibility was required when testing the lifts. As the fingerprint sensor needed to be completely covered to register the fingerprint, flexibility was needed as a rounded side meant covering the sensor was difficult. As a result, a grading system was put in place to address how flexible a material was and how well this flexibility would last in that material. For this, a 0 would mean that material was brittle and would break soon after removing from the cast and a grade of 4 would mean the material was soft and usable for over 2 months, this table for these grades can be found within table 2.3.

Table 2.3 - Table of grading system for flexibility (Rajan et al., 2018)

Flexibility	
0	Brittle and flaky almost immediately after removing from cast
1	Soft and flexible for up to one day after removal
2	Soft and flexible for up to one week after removal
3	Soft and flexible for up to three weeks after removal
4	Remained soft and flexible after two months of removal from cast

Each of these attributes of the lifts were found to be an important part of the success of the lifts and played a role in the development of the techniques discussed within this paper. While each of the systems did not all directly relate to one another, they did work in conjunction to determine the success of a lift and how long this lift may be successful for.

2.3 Conductivity

Conductivity can be defined as the property of allowing heat or electricity to pass through a substance or the level of which a material will allow this (Cambridge Dictionary, 2022). There are many materials that have this ability to conduct electricity or heat and there are many ways in which conductivity can be utilised.

There are several metals that conduct as well as some non-metals. Metals are able to conduct due to the structure found within them, valence electrons are able to move around the grouped atoms of the same metal transferring energy as the electrons knock into one another, this allows the electrical charge to move through metals such as silver (Ag), gold (Au), copper (Cu) and aluminium (Al) (All

Metals Fabrication, 2016). Pure metals will be able to provide better conductivity than that of alloys as the added alloying agents could be considered impurities and will restrict the movements of the electrons reducing the level of conductivity (Olsen, 2020). Semiconductors will have a conductivity level between that of most metals and an insulator and will come in the form of element made up of a single type of atom, such as silicon (Si), germanium (Ge), and tin (Sn) or as a compound semiconductor made up of two or more elements such as gallium arsenide (GaAs) (Encyclopaedia Britannica, 2022). Many non-metals will not conduct however the structure of carbon (C) when in the form of graphite allows a current to travel through the material. Graphite has a hexagonal structure however only three of the four outer shells are bonded, this free electron has the ability to move around the carbon layers and this movement allows for the conduction of electricity (Gupta, 2019). There are several commercially available paints and powders that utilise materials such as graphite, silver, or aluminium to create more user friendly and affordable materials.

Natural bodies of water as well as water found in swimming pools are also good at conducting electricity. Whilst water itself is an insulator when there are many impurities within the water, a current is able to travel through (Deziel, 2018). Ions (charged particles) can be found across many natural samples of water due the ease at which water can dissolve minerals. For example, sodium chloride and magnesium sulphate have oppositely charged ions and will break apart in a body of water and can then freely move through the liquid. Metal ions from that of iron and manganese will also break apart again being able to freely move around. Once these ions are suspended within the water, it in turn becomes an electrolyte meaning when electricity comes into contact with the water, this current can easily pass through (Deziel, 2018).

Processes within the human body can allow a person to conduct a certain amount of electricity and gives humans a level of capacitance, or the ability to store a charge (Jonassen, 1998). The human body relies on the electrical signals produced by cells in order the transmit information around the body to allow for quick reactions to environmental changes. The electrical impulses are created through the movement of charged ions across the cellular membrane that are following the electrochemical gradient (Purves et al., 2001; Faber et al, 2018). The elements within a person's body all have specific charges and the movement of these ions also contribute to this current (Plante, 2022). The human body's ability to hold a charge and possibility of discharging the energy, also known as human body capacitance (HBC), is measured in picofarads (pF) which is one trillionth of a farad (Merriam-Webster Medical, 2021). In terms of the human body, this value has been determined to be around 100-150 pF when measured using an AC-bridge measurement. The use of a traditional static charge-sharing method found levels of 200-400 pF being recorded (Jonassen, 1998).

This level of conductivity and capacitance is what leads to biometrically secured devices such as mobile phones to be unlocked. By using a capacitive scanner (section 1.3.2), this charge from the human body is required to activate the sensor to then unlock the device. By creating a material that can conduct this charge required whilst providing fingerprint details from another person's finger, it is thought that a person can use such a technique to unlock another individuals phone without that person being present.

2.4. Materials used

2.4.1 – Conductive paint

The conductive paint used within this project is branded as an electric paint under the name of 'Bare Conductive' sold in both a pot (50ml) and tube (10ml) (Bare Conductive, 2021). The description of the product includes uses such as fixing repairs in circuits, as a capacitive electrode or can function as a conductor in designs that can tolerate high resistivity. This product is designed to have a degree of flexibility and is a fast drying, 'Water-based dispersion of carbon pigment in Natural resin' (Bare Conductive, 2021). The information that is provided within the safety data sheet on the manufacturer's website, lists the following ingredients:

Table 2.4 - Table of ingredients found within 'Bare 'Conductive' electric paint (Bare Conductive, 2021)

3.1 Substances

REACH Regulations EC No. 1907/2006 and Annex VI Regulation (EC) No 1272/2008

Ingredients	%W/W	CAS No.	EC No.	Hazard statement(s)
Water	30-50%	7732-18-5	231-791-2	Not classified.
Natural Resin	20-40%	9000-01-5	232-519-5	Not classified.
Conductive carbon	5-20%	1333-86-4	215-609-9	Not classified.
Conductive carbon	5-20%	7782-42-5	231-955-3	Not classified.
Humectant	5-10%	56-81-5	200-289-5	Not classified
Processing aids and preservatives	0-1%	Mixture - Not applicable	Mixture - Not applicble	Individual levels below 1% do not give rise to classification

2.4.2 – Silicon materials - Provil

One of the silicon materials used as a part of this study was primarily Provil, a casting material developed and manufactured by the company Kulzer. Within the data sheet it is specified that this product is designed with the purpose of being a dentist impression material, with the ingredients listed within table 2.5 below (Kulzer, 2021):

Table 2.5 - Table of ingredients found within Provil (Kulzer, 2021)

· **3.2 Chemical characterisation: Mixtures**
· **Description: -**

· **Dangerous components:**			
CAS: 14464-46-1 EINECS: 238-878-4	Cristobalite	STOT RE 1, H372	50-75%
CAS: 556-67-2 EINECS: 209-136-7 Reg.nr.: 01-2119529238-36-xxxx	octamethylcyclotetrasiloxane	Flam. Liq. 3, H226 Repr. 2, H361f Aquatic Chronic 4, H413 PBT; vPvB	<1%

2.4.3 – Silicon materials – Xantopren

As well as the Provil, Xantopren was also a silicone-based material that was experimented with throughout the study. This material is also manufactured and sold through the company Kulzer and is again labelled as a dental impression material designed to capture details within the safety data sheet. The ingredients listed in this data sheet can be seen in table 2.6 below (Kulzer, 2020):

Table 2.6 - Table of ingredients found within Xantopren (Kulzer, 2020)

· **3.2 Chemical characterisation: Mixtures**
· **Description: -**

· **Dangerous components:**		
CAS: 540-97-6 EINECS: 208-762-8 Reg.nr.: 01-2119717435-42-xxxx	Dodecamethylcyclohexasiloxane Acute Tox. 4, H302; Acute Tox. 4, H312	<1%

· **SVHC**	
540-97-6	Dodecamethylcyclohexasiloxane

2.4.4 – Additional materials – Add-i-gum

The Add-i-gum used within this study was a putty consistency with a viscosity high enough that the material could be kneaded used for medical casting. This putty has both hydrophilic and thixotropic properties. The manufacturers website does not state the ingredients of this material. The chemical characterisation is described as a paste, therefore, it can be considered that the composition of this material is proprietary information.

2.5 – Devices and security features

Biometric security is becoming a more and more common way for securing electronic devices, by using the unique biological aspects of a person to unlock a device. As discussed throughout section 1.3, the uses of facial and fingerprint recognition has become popular not only in regard to personal mobile devices but also uses within airports, schools and police stations. Capacitive scanners within mobiles phones have become the default with more modern phones with a rise in facial recognition alongside this. For the purpose of this study, fingerprint scanners were the focus. These capacitive scanners commonly seen rely on the human capacitance describe in section 2.3 to activate the scanner. From here the saved data from when the fingerprint was set up will be compared to the fingerprint being presented and a positive match will allow for the device to be accessed. This method is much harder to bypass than the earlier used optical scanners.

The details on the mechanisms behind such scanners is not made readily available to the public. This is likely due to the fact that companies wish to protect the technology developed to prevent competitors from accessing this information. As a result, sources in the form of 'help sites' and non-academic journals were required to gain an understanding of the basic mechanisms used (Jamal, 2020; Jayaditya, 2020; Woodford, 2020; Triggs, 2021).

2.5.1 – Primary device used

The primary device used was an iPhone 8 plus by Apple (model number MQ8L2B/A), and was the device that was used to aid in the development of the technique as detailed within this work before additional testing was explored (summarised in subsequent sections). This device uses iOS, or Internet Operating System, and at the time of testing the phone remained using the software version 15.5. This is a phone that has the fingerprint sensor embedded in a home button rather than built into the screen (figure 2.3). This was the personal device of the researcher; however, an additional fingerprint of the researcher was added to the device for the only purpose of testing the lifts produced.

Figure 2.3 - iPhone 8 Plus with red box highlighting fingerprint sensor (Apple, 2021)

2.5.2 – Participant devices used

For the use of participants and the additional devices the researcher obtained ethical approval through Canterbury Christ Church University (application ETH2122-0046).

The devices that were tested for each of the participants were also the personal devices for those involved, with few participants having spare or additional devices that could be tested. As is detailed within chapter 4, there was a spread of both Android devices, using Androids operating systems, and iPhones using iOS. The ages of these phones were determined by the commercial release dates with the earliest release being an iPhone 6 in 2014 and the latest being Samsung Galaxy S22 Ultra released

Figure 2.4 - Image showing the devices fingerprint sensor with (a) a thin button (CeX, 2022) *and (b) no button highlighted* (O2, 2022) *with red boxes*

in 2022. The range of devices tested also allowed exploration of various designs of the sensors. All of the iPhones tested had the signature round button with the sensor as shown in figure 2.3 previously, applying the iPhone 6 through to the iPhone 8 Plus. The Samsung S7 had a smaller thin rectangular button as displayed in figure 2.4 (a). There were also several phones that had the sensor built into the screen of the phone, for example the Samsung S22 Ultra, as displayed in figure 2.4 (b)

2.5.3 – Computer fingerprint sensor

To test the use of a fingerprint scanner for a computer, ethics stated that a University device must be used. To keep everything secure, a false account was created by the IT department that did not have a link to any member of staff or student within the University. This account was agreed to be deleted once the study had been completed and whilst in use did not have access to the internet or any files within the account. The computer used for this purpose was a DELL laptop (Reg Model P26E) with a Windows operating system (version 10).

The laptop used did not have a built-in fingerprint scanner and so a USB plug in sensor was obtained. This sensor was then plugged into a USB extender cable to allow the sensor to be placed facing up on a flat surface rather than at an angle plugged directly into the device (figure 2.5). The brand of fingerprint sensor was Arcanite, and the USB extender was Ugreen. The fingerprint sensor was designed to be used in conjunction with 'Windows Hello' a biometric system within windows computers allowing for fingerprint, facial and voice recognition.

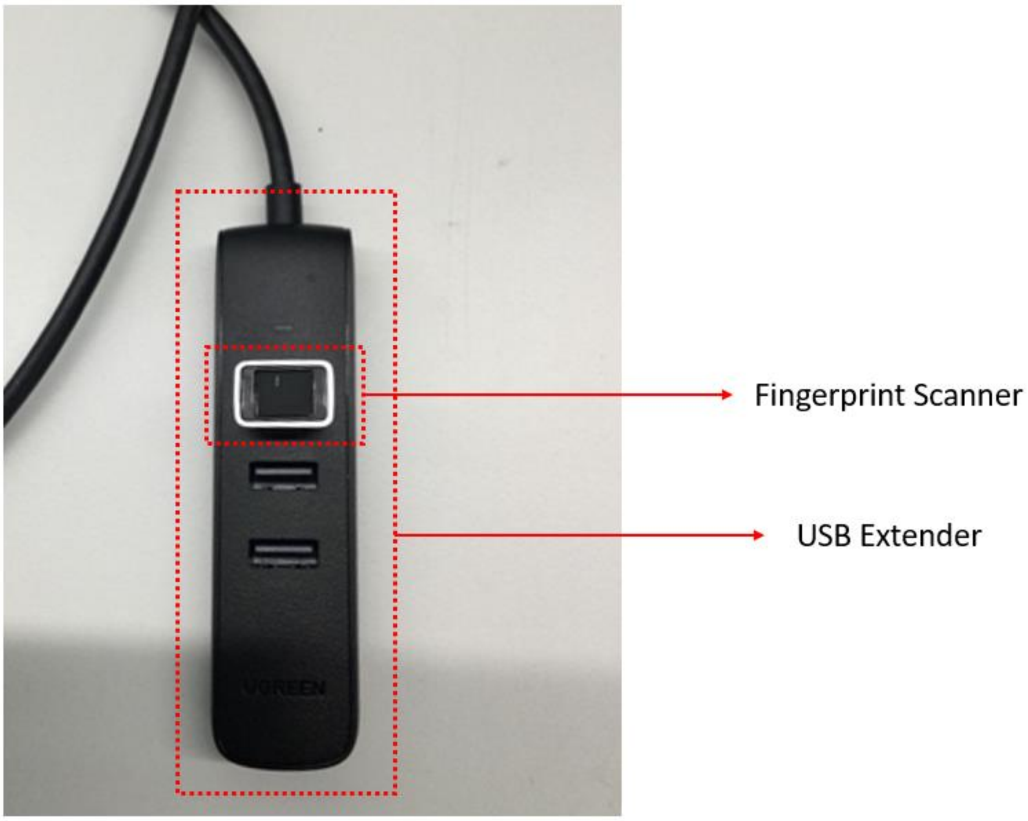

Figure 2.5 - Image showing the USB fingerprint scanner attached using the USB extender

2.6 – Imaging

Photography and imaging are commonly used within forensic investigation as an additional form of evidence alongside any physical items, primarily allowing a broader picture for the court, for example to provide an understanding of the positioning of certain pieces of evidence. Photography can also be used when the pieces of evidence are difficult to recover from the crime scene, such as a wet fingerprint.

When taking photographs of either evidence or a crime scene as a whole, the photographer must ensure that the primary subject is the focus of the image, meaning the positioning should maximise the view of the primary focus whilst minimising or excluding areas of little interest (Robinson, 2010). The 'cardinal rules' of photography as described by Robinson (2010) are to:

1. Fill the frame.
2. Maximize depth of field.
3. Keep the film plane parallel.

By following these general rules, a photograph will draw the focus to a particular piece of evidence or area of the crime scene by filling the frame. Maximising the depth of field will lead to the entire image being in focus, so no areas are blurry or hidden. And the parallel positioning for most pieces of evidence will reduce the risk of distorting the item or area of the crime scene (Robinson, 2010).

Many of the ways in which these 'rules' can be followed is through the use of lighting, exposure and angles. Ambient lighting is the light that is present at a crime scene, whether this is sunlight or artificial light, it will either be utilised or may need to be supplemented with artificial light to get the best image (Robinson, 2010). If there are heavy shadows that are caused by the ambient light then this light may either need to be fully blocked, have the camera flash on or additional lighting angled over the item in question. The aim with the lighting is to create an even level across the image to ensure there is nothing hidden. Other lighting may allow for things to be seen that are not visible to the naked eye, such as UV or blue light (Robinson, 2010). An example of how light can affect the quality of a photo can be seen within figure 2.6. both images are of the same fingerprint on plastic wrap with the only difference being how the picture was taken. In figure 2.6 (a) the camera was angled at 45° using the ambient lighting. Figure 2.6 (b), however used diffused lighting, this resulted in an image with much less noise surrounding the evidence allowing for a clearer photograph of the fingerprint itself.

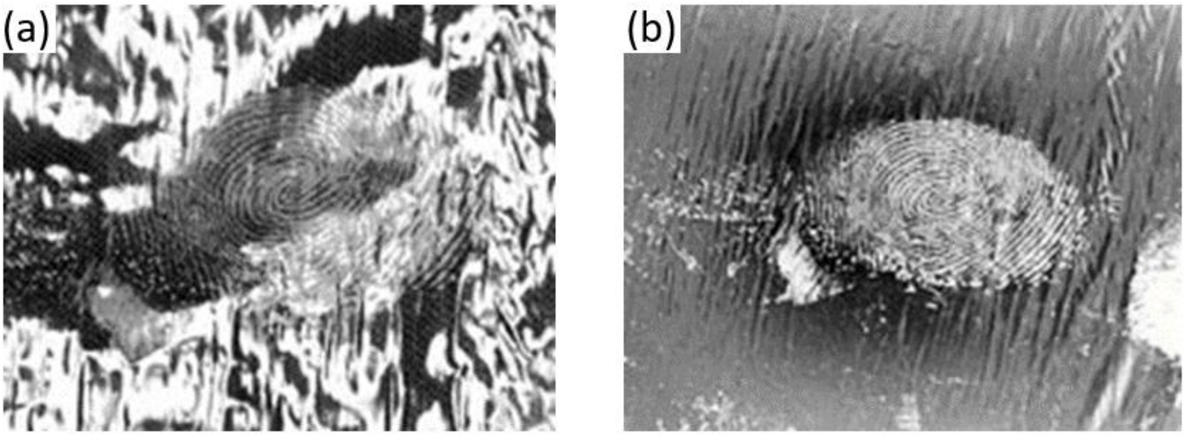

Figure 2.6 - Image showing a fingerprint deposited onto plastic wrap with photograph taken (a) at 45 degrees and (b) in diffused lighting

The exposure can also be an effective way of adjusting how light a photograph is and how much can be seen appears as well as aiding in the focus of the image. For example, adjusting the aperture of the camera can allow different amounts of light into the camera which will affect how bright the image. Over or underexposure can lead to a grainy or blurry image in which there are many shadows or areas of darkness where details are not as visible (Robinson, 2010).

The angles of both the camera and any additional lighting is also a vital part within photography. Figure 2.7 displays some of the commonly used setups for angling the lighting. In certain situations, a slight shadow may be required to highlight details that are not clear under even lighting where a level of contrast is required and so the angling of lights and cameras may assist with this. The angles of view will also be affected by the type of lens used which will affect how longer distance photographs appear (Robinson, 2010).

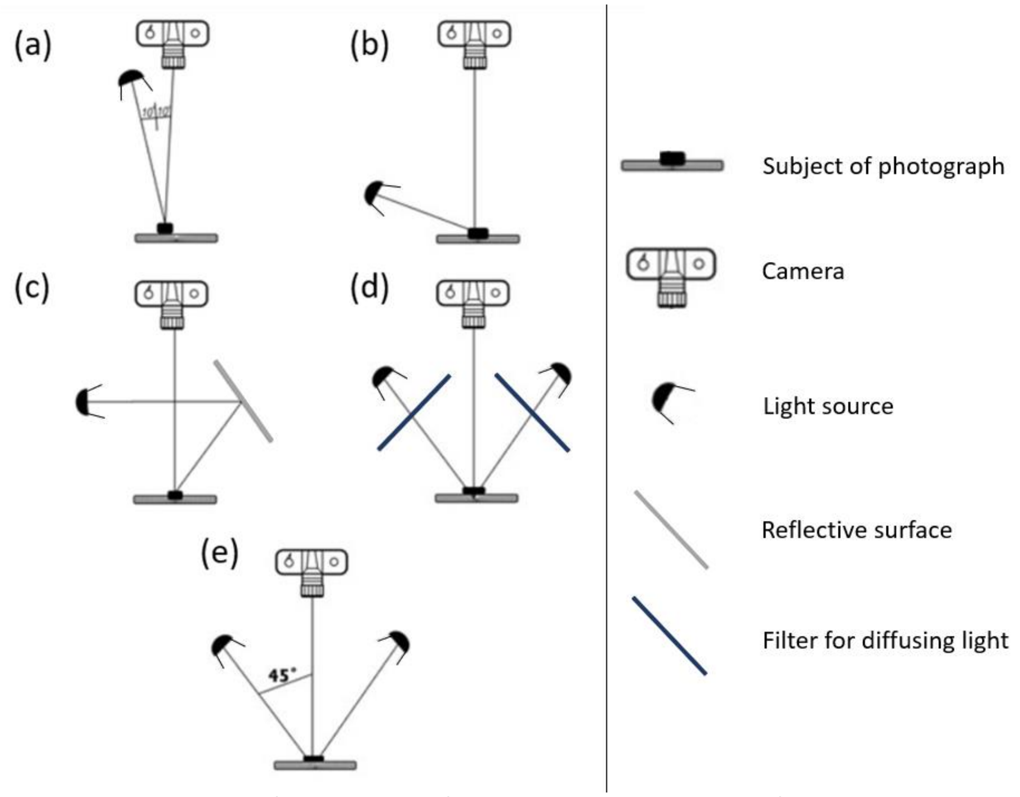

Figure 2.7 - Diagrams of the angling of lights and cameras during forensic photography where (a – b) show angles of light, (c) shows the use of a reflective surface, (d) uses filters for dispersing light and (e) uses multiple light sources

2.6.1 – Imaging used within study

Within this study several types of imaging have been used in order to present the fingerprints and lifts in a way that clearly displays the quality. For this a Nixon D3300 camera with a 18.0 – 55.0 mm lens was used throughout, this was set to the automatic function and varying levels of magnification were used in order to ensure the most clarity could be achieved. Images were taken at 20 – 30 cm from the object and angles used varied between 40° – 90°.

When taking the photographs, a lightbox was used to provide an even level of white lighting across the samples, in addition to providing consistency between different exhibits. The light box provided high quality LED lighting of 2200 lumens. The level of light could be easily adjusted with a dial however for consistency a mark was made on the dial to keep the lighting level the same for each time of using this lightbox. All images taken within the lightbox were captured at 90^o. The lightbox did not always provide good enough lighting for the details to be seen through the camera. In these cases, the uses of alternative lighting, as detailed within section 3.5, produced by a table lamp. Whilst this lighting had more of a yellow hue than the lightbox, this method allowed for slight shadows to be cast between the ridges and valleys of the fingerprint creating a contrast of the pattern. Angling the camera (approx. 40 - 60^o) also contributed to capturing the details of the lifts well.

In the cases where lighting alone did not provide enough detail, a linen tester was used. This is a small magnifying piece of equipment that folds out and provides a x6 level of magnification. Images magnified using a linen tester were captured at 90^o. This gave enough magnification that clear photographs could be taken of the lifts, these images can be seen throughout chapters 3, 4 and 5. Some images throughout this paper have been additionally amplified and highlighted in order to better display points of interest within fingerprints and the lifts created.

Chapter 3

The development and testing of conductive fingermark casts

3.1 – Introduction

To thoroughly evaluate the effectiveness of recovering fingerprints and fingermarks and using the lifts for unlocking biometrically secured devices, a technique firstly needed to be developed. The research focussed on using techniques, methods and materials already used within forensic investigation for the recovery of footwear marks, tool marks and fingermarks (Abhyankar et al, 2008; Shalhoub et al., 2008; Marasco et al, 2014; Larsen and Bennett, 2021).

The individual casting materials used within this research were already well established and known to effectively capture ridge detail. However, this research focussed on the different application methods and combinations of these materials to determine the most effective and reliable process for creating a conductive fingerprint.

For testing the proposed technique, an iPhone 8 Plus was used for all lifts described within this chapter.

The researcher obtained ethical approval for this research from Canterbury Christ Church University (application ETH2122-0046). All fingermark images displayed within this paper have sections voided, hiding some of the central ridges of the fingerprint. This has been done to both comply with the ethical approval and to prevent the individuals involved in this study from being identified.

Further testing of the conductive lifts were designed to consider the durability and how storage conditions may affect the life of usability of the lifts themselves. This was primarily done through testing hot storage, cold storage, and the use of a steam chamber for the effects of humidity. The presentation of the fingermarks recovered was also explored to ensure the detail was visible and that a comparison of characteristics could be accomplished.

3.2 – Development of technique

3.2.1 – Casting

The acquisition of an accurate method for the reproduction of friction ridges was required for this research. Therefore, the first part of this methodology required creating an accurate mould of the finger to be tested. A 3D cast of the finger was determined to be the most reliable method for this study as it is a 3D object (a person’s finger) that is registered for unlocking the device. The product produced by the cast will mimic the shape of a finger with the intention that this will be easier to develop the method.

Casting materials have been used in many fields such as dentistry (CHT, 2022) where a positive model of the patient's teeth and surrounding tissue is produced. Equally within Forensic Investigation, casting is used routinely for recovering micro detail from a variety of objects for comparison to known exhibits, such as toolmarks (Larsen and Bennett, 2021). Additionally, silicone-based casting materials have been used successfully to recover ridge detail (Shalhoub et al., 2008). Two silicone-based casting materials commonly used in Forensic Investigation are Provil (section 2.4.2) and Xantropen (section 2.4.3) (Dittmar, Errickson and Caffell, 2015; McKenna and Butler, 2016). This research firstly focussed upon the use of these materials as casting mediums for fingerprints as these would allow the ridges and details of the fingerprints to be captured with enough accuracy that a sensor would recognise the fingerprint and a comparison may be carried out.

3.2.1.1 – The use of Provil as a casting medium

Provil (Kulzer, 2022c) is a two-part liquid casting material which was deposited through the use of a gun in which the Provil cartridge was placed (figure 3.1(a)). When the trigger was pulled, the two parts (Provil and hardener) were pushed through a nozzle which combines both parts in equal measure as it is released. Using this, the material was deposited across the fingertip using a side-to-side motion from the last joint to the tip to completely cover the area of ridges on the finger, (figure 3.1(b)). When doing the side-to-side motion, the lines were done as close to each other as possible to avoid the presence of air bubbles and gaps in the cast as this would significantly reduce the detail captured. This was then allowed to set before the cast was removed from the finger. Once removed, it was found that the cast was unstable and did not sit flat when trying to place materials in the cast due to the rounded shape that can be seen in figure 3.1(c – e). As a result, an additional putty material called add-i-gum was used to create a base for the cast in order to make this sturdy and secure and to also give the cast a flat base (figure 3.1(f)). This was done according to the add-i-gums preparation method, combining equal parts of the base and activator, and then shaping around the Provil cast to create a flat base and allowing this to set.

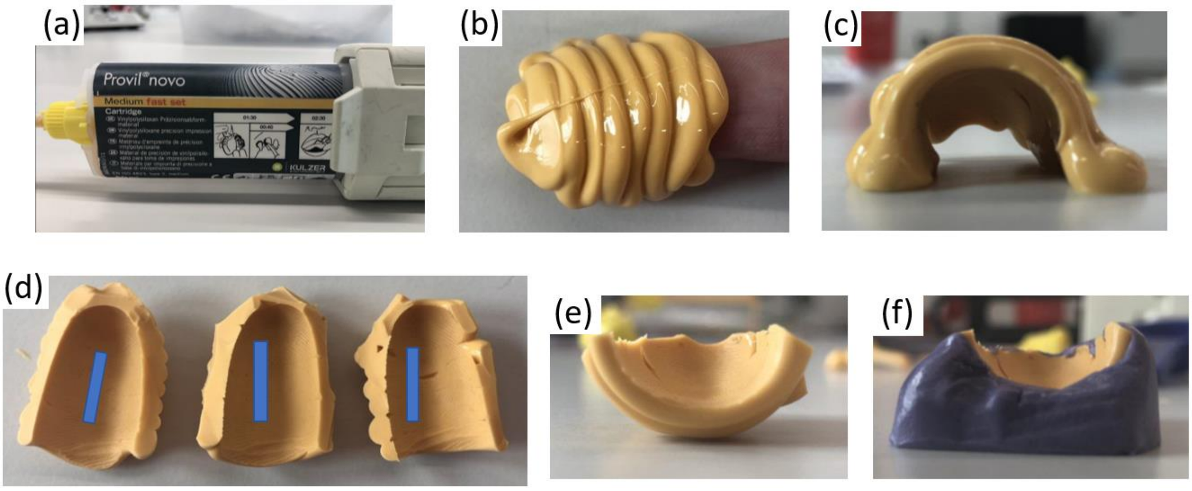

Figure 3.1 - Process of casting using Provil and add-i-gum where (a) shows the label information and the gun used to dispense, (b) shows the level of overlap when applying the Provil, (c) shows the produced cast, (d) shows the cast with the excess material removed and (e – f) showing the curve of the Provil cast and how the add-i-gum provides a base for this curve.

3.2.1.2 – The use of Xantopren as a casting medium

The second casting material used (Kulzer, 2022a), was also a two-part material where the base and activator were kept in separate tubes, as seen in figure 3.2(a), and was measured out using specific weights. The preparation followed manufacturer instructions, a copy of which can be found in appendix A. Following this user guide, Xantopren base (8.5 g) and activator (0.65 g) were weighed into a weigh boat and a metal spatula was used to thoroughly combine the parts until a homogenous blue colour was achieved. To create a more comfortable and user-friendly casting process, this mixture was placed into a small disposable shot glass, as seen in figure 3.2(b). The participant was asked to place their finger into the centre of the mixture and gently move the finger side to side for a few seconds to work any bubbles to the surface, this was done to obtain a clear and detailed cast with as few air pockets as possible. The positioning of the finger in the mixture was considered to be important. Off-centred placement resulted in thinner areas which compromised the integrity of the cast as this led to increased fragility in these areas. Once set, the cast was cut in half and the excess material was cut away and disposed of, as shown in figure 3.2(d - e). Finally, a base was made using the add-i-gum putty material (figure 3.2(f)), to make the cast steadier as this method again created a rounded base causing instability.

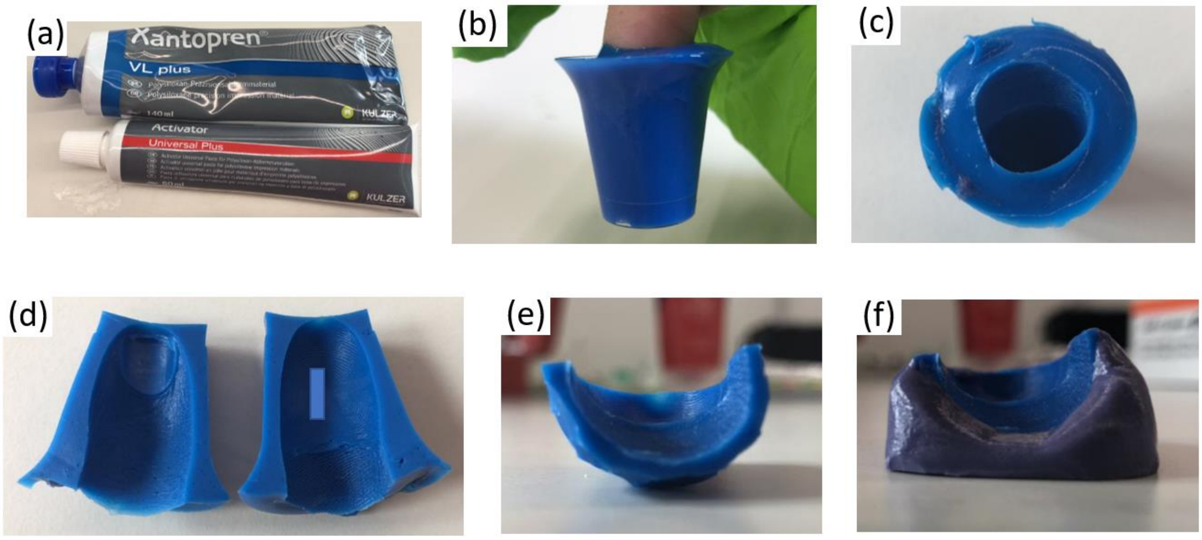

Figure 3.2 - Process of casting using Xantopren and add-i-gum where (a) shows the label information and tubes used to dispense, (b) shows the Xantopren and finger in the shot glass, (c) shows the material removed from the shot glass, (d) shows the cast cut open and (e – f) showing the curve of the resulting cast and how the add-i-gum provides a base for this curve.

3.2.1.3 – Conclusion for casting

The use of both Provil and Xantopren provided an accurate reproduction of friction ridges. As the materials are designed to capture minute details, both displayed good quality ridges with minutiae and characteristics visible, as shown in figures 3.1 and 3.2.

The method and technique of using the Provil is quick and straightforward. As detailed in section 3.2.1.1, the application of the Provil required only the dispensing gun and the add-i-gum putty. The gun dispensed the right amount of product and so no measuring or weighing was needed for making up the material. As a result, this method is quick for setting up and the setting time was also short. This also meant there was less clean-up after the material was used, and when checking the cast produced, only a small amount of excess material needed to be cut away to give better access to the ridges of the cast. The main limitation of this technique was the ease at which bubbles could be introduced to the cast. As discussed within section 3.3.2, if there was even a slight error in the application and overlap of the Provil, air bubbles and gaps were produced which reduced the amount of detail and likelihood of success. Many of the casts with bubbles needed to be destroyed as these casts were unusable, making this casting method take longer on occasions when bubbles were produced.

The use of Xantopren did not introduce bubbles as easily as the Provil due to the application method described in section 3.2.1.2. The lack of bubbles meant that significantly more detail was captured more consistently with the Xantopren compared to the Provil. This meant that fewer repeats were needed as a result of quality and so less material was wasted. The resulting material also had more flexibility than the Provil, a quality which aided in the removal of the lifts from the casts once set. By being able to bend the casts more, less damage was done to the lifts trying to get the lifts out with a spatula of tweezers. Using the Xantopren did require a longer preparation time. As the material is stored in separate tubes and requires weighing, more equipment was required including a balance, weigh boat, shot glass and spatula as detailed in section 3.2.1.2. This meant more of a clean-up after use and due to the consistency being much more fluid, it was easier than the Provil to become messy. The Xantopren was also found to have a longer setting time than the Provil and to a degree, it was found that the temperature of the lab and the hand being cast could have an effect on the setting time causing it to take longer. Additionally, as figure 3.2 shows, more excess material was created due to the use of the shot glass meaning the overall production of the cast took longer than the Provil.

The other limitation encountered, as fully discussed within section 3.3.2, was the usability of the casts with other materials. Some of the materials used to form the conductive lifts would bond too well with the materials of the cast and so some trial and error was required to determine which casts worked better with which materials for the lifts.

3.2.2 – Gelatine

Gelatine was tested as a possible material as it is known to have conductive properties (Kandadai et al, 2012) and has been used in previous research (Abhyankar et al, 2008; Marasco et al, 2014). Various gelatine to water ratios were used to assess the possible role of gelatine as a conductive material for this research. A ratio of 1:5 was used as suggested by the supplier, as well as 0.5:5 and 0.25:5 to determine the most effective mix. The gelatine was weighed into a beaker and the water measured into a measuring cylinder and combined. Once combined, the mixture was left to 'bloom' as instructed, meaning to allow the water to soak into the gelatine crystals and soften them before melting. A hot plate was used to melt and dissolve the gelatine crystals in the water. This mixture was allowed to cool for approximately one minute before carefully pouring into the cast. Once this had become fully set it was removed from the cast and tested on the phone's touch ID sensor.

3.2.3 – Conductive paint

When first looking into the uses of conductive paint, several were assessed to determine which paint was best suited to the purpose required. Three different types of paint were used. These were:

1. Wire glue
2. Bare conductive paint (tube)
3. Bare conductive paint (pot)

As described within section 2.4.1 the composition of both Bare conductive paints are identical however due to the differing dispensing methods of the pot and tube these were considered separately. Each of the three types of conductive paint was applied to the cast using a small artist paintbrush. Paint was applied until this coated the cast in a single thin layer. The cast was then allowed to completely dry, after which tweezers were used to gently peel the paint away from the cast. Each cast was then examined for the clarity of the print as detailed within section 2.2.1.1 and how delicate the lifts were according to the durability grading detailed within section 2.2.1.1 and then tested on the sensor of the phone.

Further research focussed upon increasing the number and thickness of paint layers, to determine how the different amounts of paint and time allowed to dry may affect the quality and usability of the paint lifts. This component of the research utilised, three to five layers of paint. For each of the layers, these were allowed to completely dry overnight before the application of the next layer. Once cured, the paint lift was peeled from the cast.

Other experimental techniques were used to ease the removal of the paint from the cast. Firstly, the paint was combined with either ethanol, methanol, or water in an attempt to thin the paint slightly and create a different consistency. This was done by adding a small amount of the paint into a disposable shot glass and a few drops of each of the liquids were added to each. This combination was mixed with a metal spatula and then spooned into the casts.

Two different lubricants were tested: Vaseline, and hairspray. Firstly, the hairspray was sprayed over the surface of the cast. The cast was inverted to allow for the removal of any excess lubricant. After a few minutes, the paints were brushed over as summarised previously. In relation to the Vaseline, this was melted down using a hotplate in the metal tin in which it was stored. The casts were both then applied to the Vaseline by dipping and painting. When dipping the cast, the excess needed to be wiped away using a tissue to allow the ridges of the cast to show through. When painting, the Vaseline (in solid form) was applied as a fine layer, using a small artist paintbrush to the cast.

3.2.4 – Conductive silicone

Conductive silicone was considered as a way of utilising both casting materials designed to capture the details of a fingerprint or toolmark and the conductive characteristics of the paint previously used in section 3.2.3. As both of the casting materials tested, Xantopren and Provil, are silicone-based these were evaluated as materials to create a conductive silicone. For both materials, the same approach was taken, adding the conductive paint into the substance, in order to determine:

1. Favourable conductive properties of these silicones

2. Ratio of paint to silicone required for the best results

In order to achieve this, application techniques were modified to ensure the quality of the lifts were of the best possible quality.

The use of lubricants was tested for silicone using several different materials and techniques. Four different substances were used: Vaseline, hairspray glycerine and coconut oil.

Similar outcomes as to those discussed previously (section 3.2.3) were obtained for Vaseline and hairspray applications.

Both the glycerine and coconut oil were tested with different techniques as these were liquid form. For both of the lubricants, a spray bottle was used across the cast. Both were also applied by dipping the casts into the liquid, and then the excess was allowed to drip before silicone application. Finally, a paintbrush was used to apply a thin layer across the surface and then the silicone was applied over the top of this.

3.2.4.1 – Xantopren

Several combinations were tested when mixing the paint with the Xantopren, these included:

1. Replacing some of the base with conductive paint
2. Replacing the activator with conductive paint
3. Adding conductive paint to the ratio required by the instructions provided

The weights listed in the instructions were equivalent to a ratio of base to activator of 13:1. When adding conductive paint into this mixture the ratios investigated were base:paint:activator, 10:3:1, 13:0.5:0.5 and 13:4:1.

The process to create this mixture, began with weighing out the components into a weigh boat. Then using a small metal spatula, the materials were thoroughly mixed until a homogenous colour was achieved. A spatula was used to transfer the compound into the cast. Provil casts were used, and the mixture was allowed to set before being removed with the use of tweezers and a spatula to release the lift from the cast. The silicone fingertips produced were then rested on the fingerprint sensor of the phone for testing.

3.2.4.2 – Provil

Due to the storage and dispensing of the Provil (as summarised in section 3.2.1.1), this material was initially combined with the paint as a whole as opposed to adjusting the ratio of base and activator. Following this method, the paint was first weighed and the Provil was pushed to the nozzle and a metal spatula was used to mix the paint and then placed in the cast. By design, Provil has a fast setting time when combined with the hardener which caused difficulties for this research as a longer working time was needed. To achieve this, the Provil and hardener were dispensed without the mixing nozzle, so it did not begin to set until all combined. This was done in the ratios of 1:3, 1:2, and 1:1 paint to Provil to determine the smallest amount of paint required to retain conductivity. After this, a portion of the activator was removed from the mixture giving a ratio of 1:0.5:0.5 base:paint:activator. This was used to determine if any changes occurred in the flexibility or conductivity of the lift.

When looking into the technique for applying the Provil mixture into the cast there were several assessed. Firstly, the use of a small metal spatula was used to smooth the material over the ridged surface pushing it down into the ridges. Secondly, a disposable syringe was used. This was intended to mimic the method of dispensing Provil through the nozzle of the gun. The mixture was mixed thoroughly and inserted into the syringe using the small spatula through the open end. The syringe containing the mixture was then used in a similar way to the Provil gun dispenser (section 3.2.1.1). The spatula was then used to push the Provil to the edges of the cast to ensure all of the ridges were captured.

3.2.5 – Storage conditions

Throughout the development of technique and testing of lifts, storage was a consideration to ensure the usability and quality of the lifts were maintained. For ease of labelling and more efficient storage, resealable plastic bags were used. When packing the lifts into the bags the date, test number, a description of the sample and the participant's code was noted.

Storage methods were also tested to determine if this affected the working life, and therefore the usability of the lifts. For this, a series of worktop tests were carried out, monitoring the condition of the lifts and whether the lifts remained successful during this period.

The effects of temperature and humidity were also explored. These tests were carried out to investigate both the storage conditions during the setting process and after the lift had been set and tested. During the setting process, heat, cold and humidity were investigated.

For the effects of heat on the setting times, both heating the cast and heating the components were tested. To heat the cast, the oven was preheated to 100°C, once the oven reached temperature, a cast containing a coat of Vaseline was placed inside and was left for 30 minutes to ensure it was heated to the desired temperature. Once heated, the Vaseline was redistributed using a small artist paintbrush to ensure full coverage. The Provil and conductive paint were then combined and applied to the cast as detailed in section 3.2.6 and allowed to set. For heating the components, the Provil parts and conductive paint were weighed into a metal tray and placed on a hotplate with a second metal tray covering them. The parts were heated using the hotplate being left for 20 minutes, temperatures investigated were 100°C, 50°C and 25°C. Once the time had passed the parts were combined and placed in the lubricated cast as detailed in section 3.2.6. for each test, once the material had been set, the lifts were removed and tested.

For the cold tests, a lubricated cast was placed into a large chiller. Whilst the temperature of the chiller fluctuated slightly, the temperature remained between 4°C and 6.5°C. The cast was left at the temperature for 30 minutes, following which the components of the Provil and conductive paint were brought in, combined, and applied as detailed in section 3.2.6. The material was then left to set for one hour to ensure it had set, after which it was removed and tested. The tests done in the chiller were using a chilled cast with room temperature components and using a chilled cast and chilled components (left in the chiller for 5 minutes).

To investigate humidity, a small steam chamber was used. The components were combined and applied as described in section 3.2.6 and the cast was placed directly into the steam chamber. This was then left for 24 hours to allow the steam to fully dissipate before removing the cast. The lift was then removed and tested.

All of these conditions were also tested for the longer-term storage of the lifts. The effects of heat were tested through the use of the oven. A lift confirmed to successfully unlock the device was placed into the oven set at 25°C and left for 3 weeks. During this period, the lift was tested several times on the same device to determine if the lift was still successful after being subjected to the temperature for a period of time.

For the cold test, a lift that had been confirmed to unlock the device was left in the chiller for 3 weeks at 4°C – 6.5°C. Throughout this time the lift was tested on the device to see if it was still successful over this period.

For humidity testing, the steam chamber previously mentioned was used to place a successful lift in a moist environment for 3 days. To do this boiling water was placed into the box and the lift was placed inside. As the water cooled and the steam became less, a second box was filled with the boiling water and the frame and lift were moved to this freshly boiled water and again enclosed. This was continuously done for two days to determine if moisture were to deteriorate the material.

3.3 – Applicability of technique

3.3.1 - Grading

To fully assess the quality of the various cast and lifts being produced, a grading system was developed (section 2.2.1.1) to track the quality and progress of techniques.

The grading systems developed were based on the grading system detailed within section 1.2.4 by (Rajan et al., 2018). The grading systems used for this study assess the clarity of the fingerprints and how many ridges and characteristics can be viewed and identified, the durability of the material used to determine the life span of the lifts and the flexibility of the materials to ensure the best material is found that does not become too fragile or brittle.

3.3.2 – Results and Discussion for Casting

Both the Provil and Xantopren casting methods produced successful casts that provided clear copies of ridges within the fingerprint (figure 3.3). All of the casts showed a degree of flexibility which aided with the removal of lifts. However, it was found that some of the materials used to create the lifts did not work as easily with either the Provil or the Xantopren. This meant that there was some trial and error to determine which materials worked best with which cast type. It was found that the Provil was not suited for Provil-based conductive silicone. When the conductive silicone was first investigated, the conductive paint was applied to Provil which was then dispensed into a Provil cast. Even with a layer of lubricant, it was found that the Provil bonded to itself too well and a clear lift could not be achieved. This led to Xantopren being used with the conductive paint, this was much easier to pull away from the Provil, with the use of lubricant, and captured good detail, however, a good level of conductivity could not be achieved with this material. As a result, the materials were alternated, and a cast was made from the Xantopren and the Provil was used with the conductive paint to form the lift.

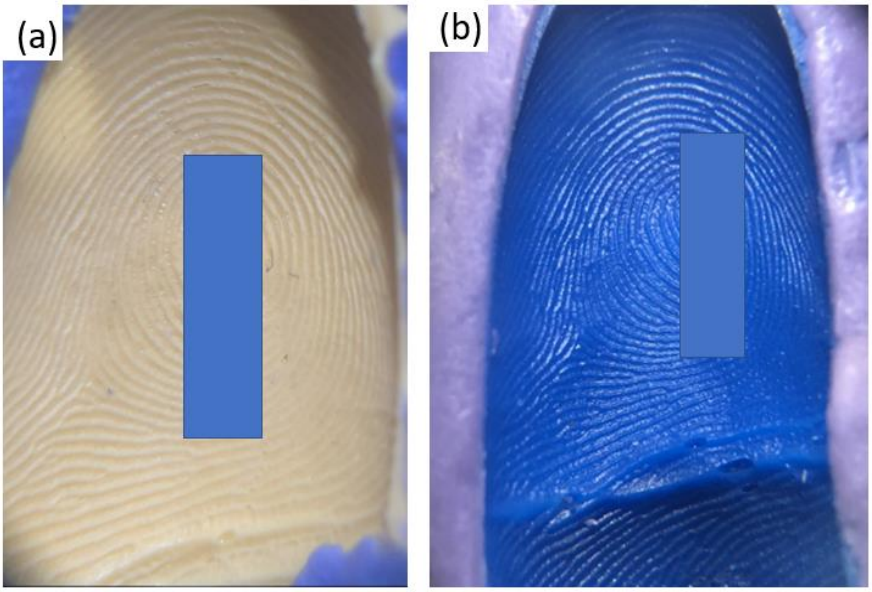

Figure 3.3 - Side-by-side comparison of the quality produced by the (a) Provil and (b) Xantopren casts

As discussed within section 3.2.1.1, the application technique was considered to be very important. Any error with Provil overlap resulted in gaps and/or air bubbles as seen in figure 3.4.

Figure 3.4(a) shows a cast from Provil that has many pockets that obscure ridge detail. Both the larger pockets and the lines of small pockets have resulted from the overlap of the Provil not being close enough during the application. As a result, this cast would only be assigned a clarity grade of 1 as details are visible but there are enough gaps which overlap ridges and minutiae making this cast unusable. Many of the early casts received low grades and were destroyed. Further development of the technique led to a higher grade being achieved, an example of this quality can be seen in figure 3.4(b). By getting the overlap of the Provil closer, little to no gaps and bubbles can be observed. This cast would receive a clarity grading of 5 as the cast is completely intact and all of the ridges and details are clear. Casts such as this are more likely to lead to a positive match if characteristics were assessed and a positive identification leads to the unlocking of a device.

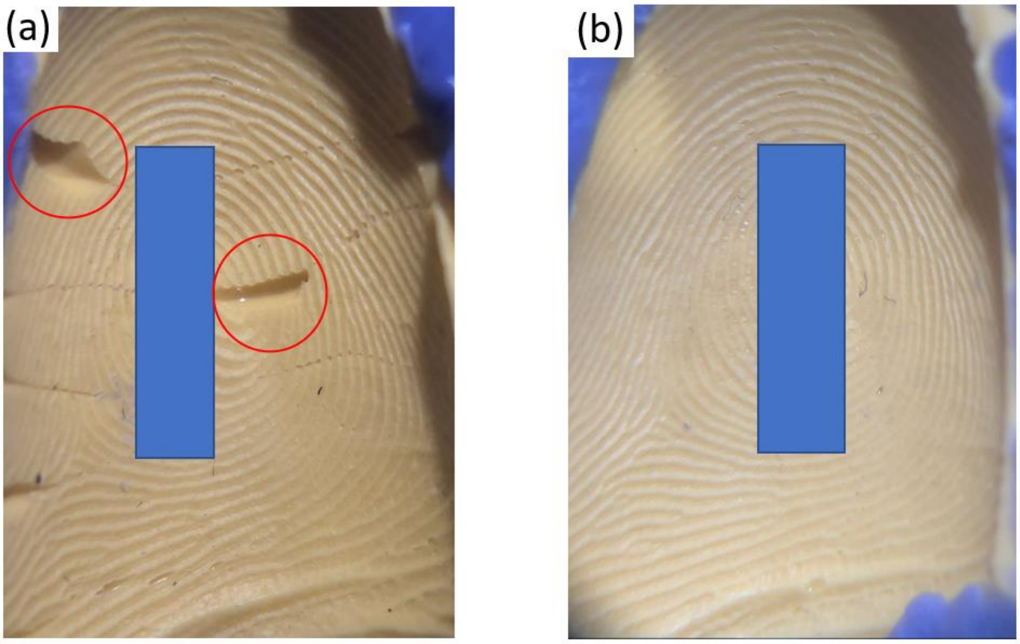

Figure 3.4 - Photographs showing (a) a bad Provil cast, with bubbles and gaps as shown by the red circles and (b) a good Provil cast

As the Xantopren cast was made by placing the finger into an amount of the mixture (section 3.2.1.2), this meant the issue of air bubble formation was not as present. The movement of the finger when placed in the shot glass helped ensure that any bubbles created by the mixing were worked away from the finger and to the surface. There were not many cases in which bubbles occurred to a degree that compromised the clarity of the cast and so became the main casts that were used. Xantopren cast such as the one shown in figure 3.5 would receive a clarity grading of 5 as no air pockets are obscuring the details of the ridges.

Figure 3.5 - Photograph showing the quality of a Xantopren cast

Overall, the Provil was a much quicker and easier cast to produce however the lack of detail and the frequency at which casts were unusable due to bubbles meant that this was not the preferred casting method and was not continued. The Xantopren, whilst being a more complex method, provided great amounts of detail within the cast and were more consistent and so became the method of casting for the remainder of the study.

3.3.3 – Testing

Once the best techniques for casting had been determined, the materials for creating the lifts and the testing of the lifts were explored. To do this several materials that were known to have a level of conductance were placed into the casts produced. When using each of the materials discussed within this section, various qualities were required for a successful lift. Firstly, it was documented how user friendly a material was, if it could be placed in the cast and removed from the cast with little difficulty. The ease of handling once set was also important to ensure the material was not too delicate to be used. There was also the consideration of how much detail this material could capture and how easy it was to capture this detail and then the level of success when attempting to unlock the devices. A later consideration included the storage and length of life of the materials tested, this was so the material chosen could provide the longest working lift with little to no time limits.

3.3.3.1 – Gelatine

A series of 3D gelatine moulds were first created. The ratios of gelatine:water used were as follows:

- 1:5
- 0.5:5
- 0.25:5

Results obtained from ratios of 1:5 and 0.5:5 are shown in figure 3.6. However, due to the fragility of the 0.25:5, a photograph was not possible to capture as the lift was not recoverable from the cast.

Upon examination of the quality of the lifts, the gelatine was concluded to be a good medium for capturing all of the ridges within the fingerprint as the liquid form of the mixture allows for the gaps to be filled. The usability of the lifts depended on the ratio of gelatine to water. The ratio that was best to use was 1:5 as this had a good firmness and could be easily handled. 0.5:5 was still a good consistency to hold but was considerably softer, however, the 0.25:5 was too soft and fell apart quickly when picked up and so was considered unrecoverable and unusable.

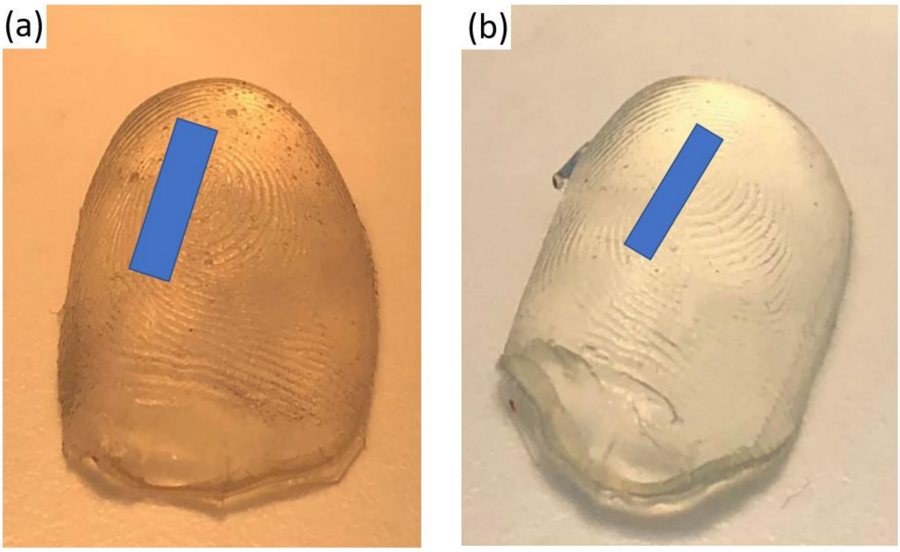

Figure 3.6 - Gelatine lifts of ratios (a) 1:5 and (b) 0.5:5

The 1:5 and 0.5:5 samples were subjected to biometric testing. Although these were registered by the sensor as the finger being present, they were not successful in unlocking the device.

The storage of the gelatine lifts was also found to be an important factor in how well the gelatine worked as a conductive material for biometric fingerprint identification. The first trial of using the gelatine using these ratios was left in glass jars placed within a lockbox, these lifts were then left overnight. When tested after 24 hours, the gelatine became dehydrated, causing the lifts to shrivel and become solid making these unusable, figure 3.7 (a). When the storage method changed to using plastic bags, the same ratios were tried again to see if this storage method would retain moisture, allowing the lifts to remain soft. This worked for several days; however, the lifts eventually mouldy inside of the bags (figure 3.7 (b)). The firmer lifts retained some of the ridge details, but the lower ratio lifts completely deteriorated. The difficulty with storage meant that the gelatine was no longer considered to be a suitable material for conductive fingermark recovery. If this were used further then other storage such as cold storage would need to be considered to prolong the life of the lifts.

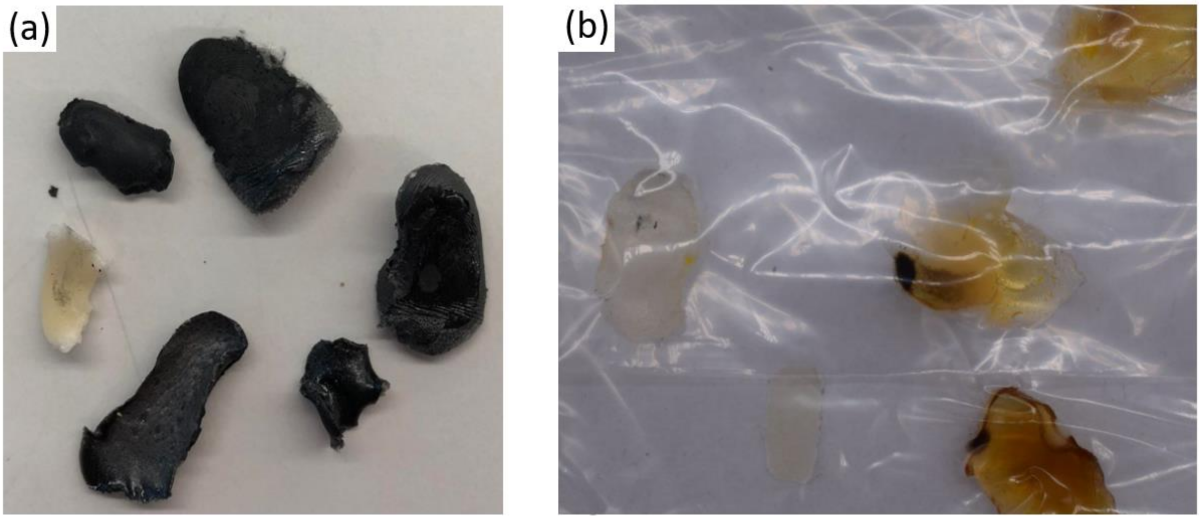

Figure 3.7 - Gelatine lifts becoming (a) dehydrated and (b) mouldy

3.3.3.2 – Conductive paint

Various types of conductive paint are commercially available, as summarised within section 3.2.3.

The effectiveness of these paints was investigated. Each of the paints was initially tested with a single thin layer over a Provil cast, as summarised within section 3.2.3. When applying the paint with the brush, the 'Wire glue' did not stick well to the side of the cast where pooling of the paint at the bottom of the cast occurred. The lift produced from the wire glue did not register as a finger being present when tested on the fingerprint sensor. While the paint did capture the ridges, the difficulty in getting the paint to cover all of the ridges as well as not being registered meant this was not a viable option for continuing the testing.

The Bare conductive tube and Bare conductive paint were both the same brand; however, these have been considered separately in this research due to these possessing different consistencies. The material within the pot had a much thicker consistency which made it much easier to create a thin coating over the surface of the cast whereas the tube was slightly thinner. It was the pot of 'Bare conductive' that was determined to be the best paint to continue with the tests required and was also more cost-effective.

When layering the paint, there were no spoons or spatulas available that were small enough to be able to provide an exact measurement of the paint used. Weighing the paint was also ineffective as a measurement as there will always be a little product left behind on the weigh boat, so would not be an accurate measurement of how much paint was used. As a result, the technique followed was to paint a layer of paint thin enough to just cover the area of the cast, this was done for each layer that was painted onto the cast. When trying to determine how many layers were required, initially one, two and three layers were tested allowed to dry completely and then peeled. It was found that the single layer was the most difficult to remove from the cast without causing damage due to how delicate the material was (figure 3.8 (a)). Two layers did crack when removed but could be carefully handled without falling apart (figure 3.8 (a)). Three layers was found to be the most durable and so later testing used three layers as a minimum (figure 3.8 b – c). Early tests also involved combining the paint with a few drops of ethanol, methanol, and water, for each of these tests the mixture was combined and then placed into the cast. In all cases, the setting and consistency of the paint was affected in a way that made the lifts unusable, instead of creating a layer across the surface of the cast the material collected in the bottom and did not capture the ridges or dry as expected.

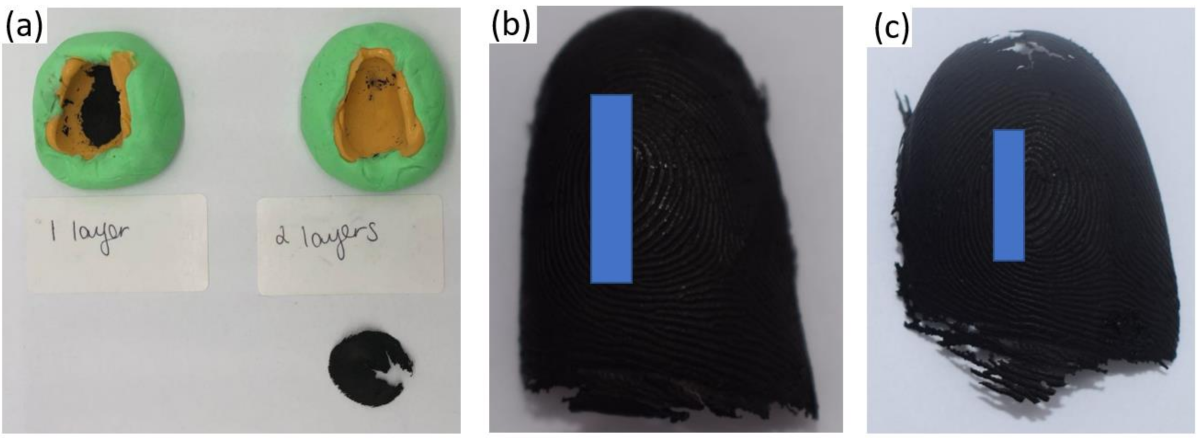

Figure 3.8 - Conductive paint lifts showing (a) an unusable lift, (b) a clear but unsuccessful lift and (c) a clear and successful lift

When further testing on the layers of paint was done, drying time was taken into consideration. For this, there were two sets of tests done. Each of these tests included a cast with three, four and five layers. The first test involved allowing the layers to become completely dry before painting the next and leaving the casts to dry overnight before lifting. The second test was only leaving the casts to dry to the touch before adding the next layer, and again lifting the paint once it was just dry enough to come out. For all of these lifts, the amount of time left to dry, and the number of layers did not seem to have a significant effect on the success or the handling of the lifts.

All of the paint layering lifts attempted were good at capturing all of the details however they were consistently unsuccessful at unlocking the device although they did register. All of the paints were first carried out on the Provil casts; however, later tests involved the use of the Xantopren casts. When this cast was used there were two that were successful at unlocking after following the same technique. Once the Xantopren cast had been determined as being more reliable than the Provil, the main issue to solve with the paint lifts was the fragility that led to the lifts cracking and falling apart either during the removal or after being handled too much.

The use of lubricants, as detailed in section 3.2.3, was investigated to determine if this would allow easier removal of the lifts and to keep them as one piece. The hairspray and Vaseline had similar results when tested. Both of these lubricants created an even layer across the cast, as the hairspray was more liquid once sprayed it was allowed to drip a little whereas the Vaseline did not need this. Overall, the use of lubricants was not necessary for the paint lifts, while it did ease the removal slightly, the difference was not significant enough to warrant the use of the materials. Additionally, when the lifts were removed there was a layer of grease on the surface of the lift which may have affected the quality and usability of these. This layer of grease could not easily be cleaned off due to the fragility of the paint making it harder to use.

3.3.3.3 – Conductive silicone

There was a considerable amount of trial and error when it came to developing the method and technique for creating a clear and effective conductive silicone lift. The process of this development included determining what materials were best to combine with the paint and through testing, it was discovered that certain silicones did not work with the material in the cast and so this was also something that needed to be assessed.

3.3.2.3.1 – Xantopren

When trying the Xantopren as a conductive silicone all of the ratios tried were unsuccessful and did not register on the fingerprint sensor. The several ratios tested had different amounts of the conductive paint present, in all of the ratios, this amount of paint was not enough to create a conductive material that would register on the phone. When trying the ratios, the main factor affected in the lifts was softness and flexibility, and while the lifts were not conductive most of the details were captured with clarity. When the Xantopren was first used, no lubricant was used as well as trying a thin layer of Vaseline and hairspray. Whilst the lifts were not particularly difficult to remove without the layer of lubricant, they did come away easier with the use of lubricant.

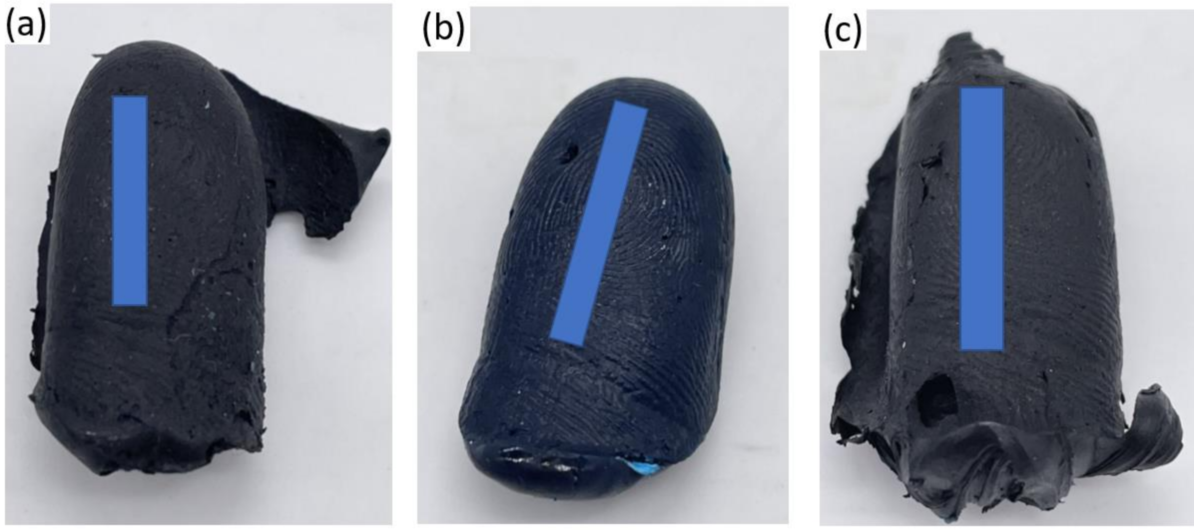

Figure 3.9 - Xantopren and Conductive paint lifts in ratios of (a) 10:3:1, (b) 13:0.5:0.5 and (c) 13:4:1

3.3.2.3.2 – Provil

When the Xantopren was found to be unsuccessful, Provil was combined with the conductive paint to see if it would create the conductivity required. The first uses of the Provil were placed into the Provil casts, one with a layer of Vaseline, one with hairspray and one with nothing. With all three of these test casts, the Provil bonded too well with the Provil of the cast and so when it was removed it tore and became unusable. These sections of materials were enough to test on the phone sensor to show that it provided the conductivity required for the phone to register the presence of a finger. As a result, the Xantopren and the Provil were swapped, and a cast was made from the Xantopren so a lift could be made from the Provil.

This was first done by weighing equal parts of paint and Provil and mixing them with a metal spatula and then this spatula was used to apply the combination into the Xantopren cast. The issue encountered with this method of application was the metal spatula created holes in the Provil and led to the presence of air bubbles within the lift which resulted in a loss of detail. The use of a larger spatula was briefly tried however this caused the lifts to be thicker and harder to handle during the testing on the sensor. This issue led to the use of disposable syringes intended to mimic the dispensing method used with the Provil and the gun and nozzle. To do this, the parts were weighed out into a weigh boat and once combined the metal spatula was used to push the mixture into the syringe. This allowed the mixture to be pushed out helping to remove bubbles present. The spatula was then gently used to spread the Provil up the sides of the cast. This was much more effective at creating a clear lift in which characteristics of the fingerprint could be seen.

The use of lubricants, as described in sections 3.2.3 and 3.2.4 assessed Vaseline, hairspray, coconut oil and glycerine. It was found that both the coconut oil and the glycerine created a pool of lubricant at the base of the cast instead of an even layer across the surface. This meant that the side of the cast bonded and was difficult to separate. The base of the cast could be removed but picked up little of the detail required. The hairspray was more effective allowing the Provil to be removed from the Xantopren, however, in many cases, there was still some material left in the cast making this method more unreliable. Vaseline was the lubricant of choice as the application was much easier, and cleaner and the quantity of material was easier to control. This lubricant allowed the easiest removal of lifts and the greatest amount of detail out of the methods investigated.

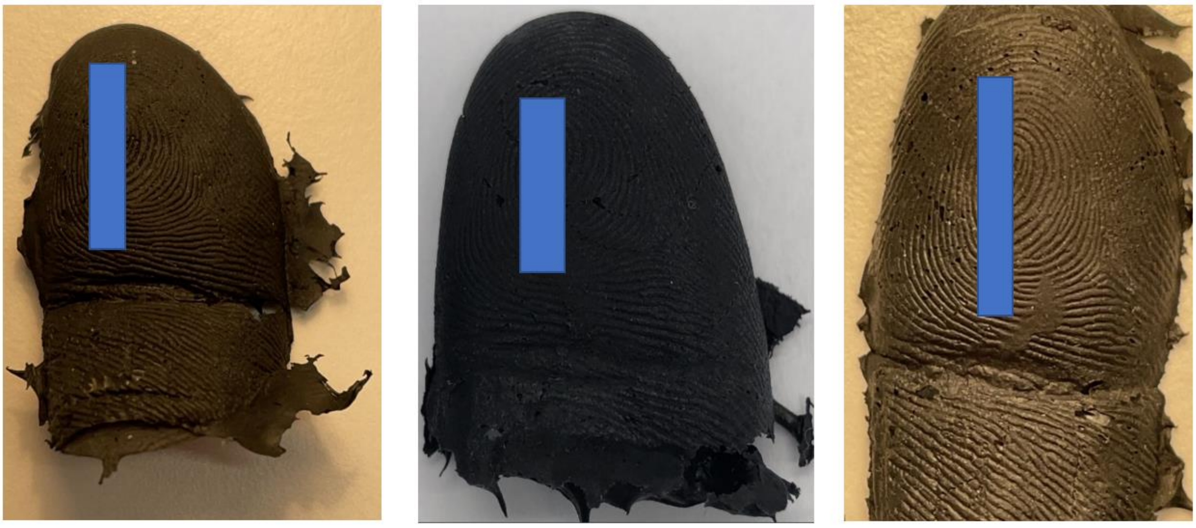

Figure 3.10 - Series of Provil and conductive paint lifts

The durability and flexibility of the lifts produced was assessed with various different storage, thickness and ratios tests carried out. The thicker lifts created by the large spatula were found to be dense and not very flexible, this made it difficult for the lift to fully cover the fingerprint sensor during testing so reduced the likelihood of a successful unlocking. The syringe method allowed the lifts to be made much thinner creating more flexibility, as a result the lift could be flattened against the sensor giving a positive ID and unlocking the device. From here the issue was discovered that regardless of the thickness, the lifts would begin to harden and lose this flexibility if left out of a plastic bag and begin to break apart. To address this the dried lifts were steamed to see if the extra moisture would regain some flexibility. This however was a temporary fix and so the ratios were explored.

Previously a 1:1 ratio was used, so it was investigated as to what the lowest quantity of conductive paint was required for the conductive properties needed. The paint was able to be reduced to half the amount of Provil before it was not recognised by the device. When a longevity test was carried out to determine if this made a difference to the life of the lift outside of a bag, it did not make a significant difference. As a result, some of the activator was also removed, giving the ratio described in section 3.2.4.2 of 1:0.5:0.5. This gave a positive identification on the sensor and when a longevity test was carried out the lifts worked for over 10 weeks whether in a tray or bag, meaning a cut off period for these lifts has not yet been found.

3.4 – Final version of technique

The investigation into techniques as detailed above resulted in a final working version of a technique found to successfully unlock secured devices with consistency. This final technique is detailed as a step-by-step account, summarised below:

To make the cast:

- In a weigh boat, weigh out 8.5 g of the Xantopren base (blue) and 0.65 g of the Xantopren activator (red)
- Using a large spatula, combine the two parts until a homogenous colour can be observed
- Transfer the mixture into a shot glass
- Place the required finger into the shot glass and move the finger side to side for a few seconds to remove air bubbles
- Remain still until the material is set
- Once set, carefully remove the finger and shot glass from the Xantopren
- Using a sharp scalpel or scissors, cut the cast in half (either side of the nail bed avoiding damage to the ridge pattern) and remove excess material
- Using the add-i-gum putty, measure equal parts base (purple) and activator (white) and combine until a homogenous colour can be observed
- Mould the putty around the cast, building walls and a flat surface around the Xantopren.

To make the Conductive lift:

- Using a small artists paintbrush apply a thin layer of Vaseline (in solid form) to the cast. This should cover the fingerprint detail and the surrounding area to prevent any sticking
- To separate out the activator and base of the Provil, cut a weigh boat in half and place it between the nozzles of the two parts. Dispense some so that it falls into two separate weigh boats

- In a single weigh boat, weigh out 1 g of the Provil base (yellow), 0.5 g of the activator (white) and 0.5 g of the conductive paint
- Using a small metal spatula, combine all three components until a homogenous colour can be observed
- Using a spatula push this mixture into a disposable syringe
- Push the mixture through the syringe and into the lubricated cast
- Use the spatula to spread the mixture up the sides of the cast. Lift should be made thin enough that it can easily bend
- Allow cast to set (approx.5 min)
- When dry to the touch use spatula and tweezers to carefully pull the lifts away from the cast
- Press lift gently onto piece of tissue to remove any residue from the paint and Vaseline
- Line the lift up against the fingerprint sensor and gently press the lift flat against the sensor
- If unsuccessful, try adjusting the positioning before again pressing the lift flat against the sensor

3.5 – Presenting the fingerprints

As the methods proposed within this paper were intended to be used for both biometric purposes and the comparison of ridge characteristics the presentation of the fingerprints was also explored. As the photographs throughout chapter 3 have demonstrated, the dark colour of the conductive paint causes a reduction in the visibility of the ridges and difficulty in capturing these for evidential purposes. The uses of powders and ink could create more of a contrast of the ridges to allow for this analysis and comparison.

Firstly, different lighting was used for several of the lifts, gelatine, paint, and silicone. The types of lights that were used was a light box designed to bounce a white light around a confined space allowing for even lighting across a whole sample as shown in figure 3.11 (a). Secondly, a table lamp was used at an angle opposite to that of the camera. This meant that shadows were caused within the 3D ridges of the samples creating a contrast as seen in figure 3.11 (b). This was effective for some lifts but not for all of them. As this was not reliable and still needed adjustments in the contrast of the image, powdering the fingerprints was investigated.

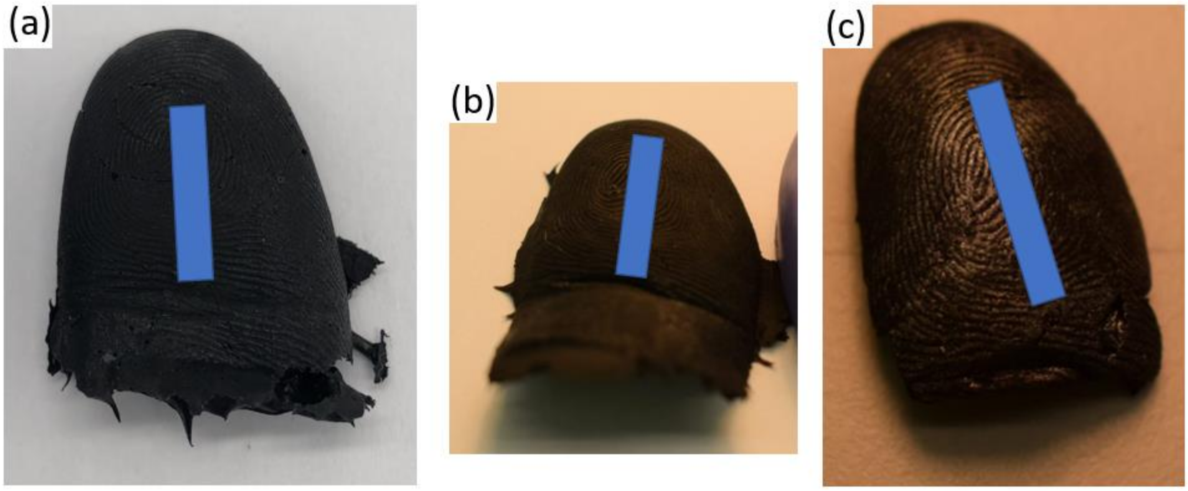

Figure 3.11 - Provil lifts presented using (a) a lightbox, (b) lighting from angled lamp and (c) silver powder with alternative lighting

When powdering, a silver and white powder were first tested in conjunction with the alternative lighting to determine if this would highlight the ridges enough for the image to show the details. As figure 3.11 (c) shows this did work to a degree, however, the curve of the lifts meant that even with both the powder and alternate lighting, not all of the ridges and details could be identified from the image.

This led to attempting to lift the powder from the Provil using J-Lar tape. This was done similarly to how a person's fingerprints would be taken using an ink pad. The lift was powdered gently with a black magnetic powder. The lift was then rolled over a piece of JLar tape laid sticky side up. This was then placed onto a piece of acetate using a roller. Due to the rigidity of the lifts, there were some sections missed and so multiple lifts were done and then overlayed with the intention that these gaps could be filled in.

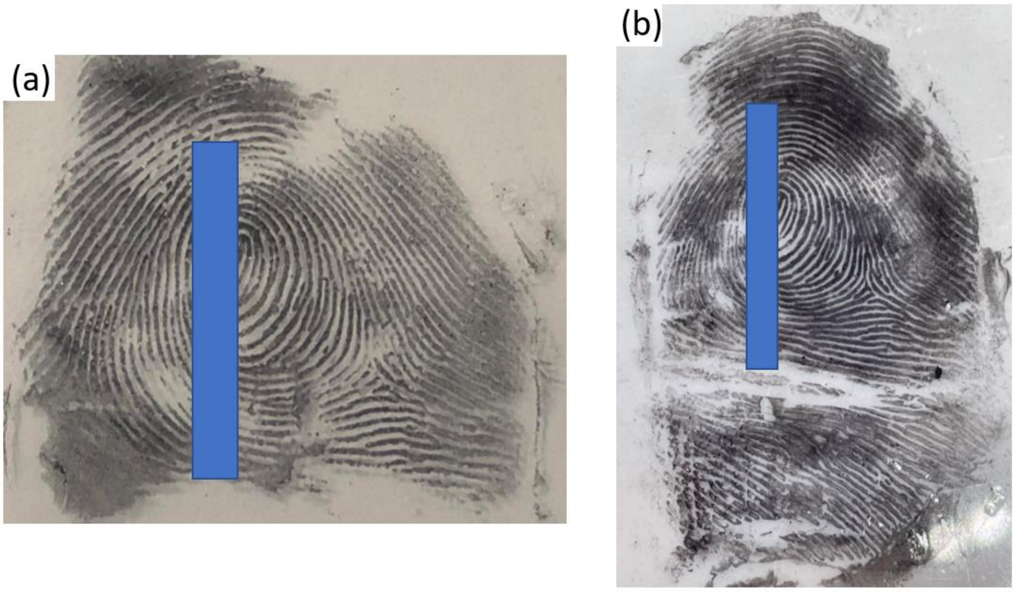

Figure 3.12 - Powder and J-Lar lifts with (a) one layer (b) overlay of two powdered lifts

Inking the fingerprint was also done in the same way a person would be fingerprinted, by holding the lift over the finger and rolling it over the ink pad and then the paper. This method encountered the same issue as the tape lifts as some gaps occurred as the lift did not flatten fully against the paper as a finger would be seen in figure 3.13. In this case, however, overlaying was not as possible as with the J-Lar and acetate.

Figure 3.13 - Inking of Provil lift

The results produced from inking and powdering the conductive lifts provided a great amount of detail and many ridge characteristics could be identified when analysing the patterns. Due to this, a comparison was conducted between the powdered lifts as shown in figure 3.12(a) and an inked print taken from the finger itself (figure 3.14 (b)). The resulting comparison can be seen in figure 3.14.

As figure 3.14 displays, there are several identifiable features present in the powdered lift on the left-hand image. Initial examination clearly shows the similarities in the flow of the ridge pattern and level 1 characteristics as discussed within chapter 2. Many of the identified minutiae such as the bifurcations and ridge endings correspond clearly to those identified on the right-hand image. Many of these matching minutiae appear around the core and the delta of the fingerprint with 22 characteristics being identified as matching on both analysed fingerprints. This is significant evidence to indicate that these fingerprints have been recovered from the same person.

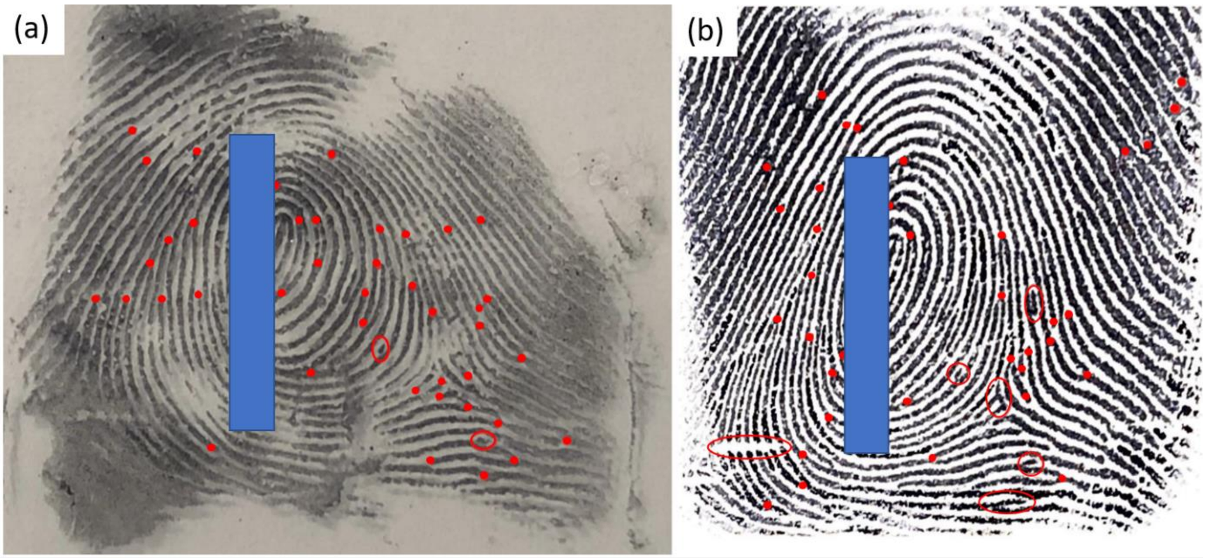

Figure 3.14 - Characteristic comparison of (a) the powdered lift from Provil and (b) inked print from the finger

When carrying out the powdering, the conductive lifts were successful at unlocking the required device both before and after the powder had been applied and cleaned off. This has shown the success of having these lifts be used for both biometric purposes as well as for standard comparisons of ridge characteristics.

3.6 - Conclusion

Through all of the experimenting discussed within chapter 3, it was found that some of the methods tried were impractical especially with considerations of the possible uses within real life crime scene scenarios.

The considerations when exploring the casting included the quality of fingerprint producible and the compatibility of casting materials and lifting materials, primarily the conductive silicone. As discussed within section 3.3.2, both the Provil and Xantropen casts produced a good amount of detail within the casts however the chances of air pockets were lower when using the Xantopren and produced slightly more detail than the Provil. When using the conductive paint alone, successful lifts could not be produced using the Provil casts however when tried with a Xantopren cast, the device could be unlocked. Additionally, the Xantopren was better suited for the use of the conductive silicone as the lifts were easier to remove and held enough detail to successfully unlock the device tested. As a result, it can be determined that the Xantopren was a more reliable material for the process of casting.

When deciding the best material for the lifts, the gelatine was tested as it has been found that the material does conduct, however this material was unsuccessful in unlocking the devices. Additionally, the storage of these lifts were problematic as mentioned within section 3.3.3.1, due to the nature of the material and the fact that it would either go mouldy or dry out. Whilst the conductive paint alone did succeed in unlocking the devices during later tests, using the Xantopren casts, this again was impractical due to the fragility of the material when dry and would mean that the storage would again create difficulties.

The conductive silicone was the material that could consistently unlock the device once the technique had been developed. This was found to be most successful when using the Xantopren cast and a syringe for application with Vaseline being the most effective lubricant used in solid form. It was found that the primary consideration when creating the lifts is the thickness. Early attempts of the conductive silicone were unsuccessful due to the thickness not allowing the conduction of current. This meant that later trials were done by making the lifts as thin possible without compromising the quality of the lift.

To determine if the lifts provided better longevity than that of the conductive paint, several setting and storage tests were carried out as detailed within section 3.2.5. The results of which showed that whilst temperature can greatly affect the setting of the silicone material, the storage in these same conditions did not have an effect. When setting the Provil and conductive paint in hot conditions, the setting time was greatly reduced and resulted in unusable lifts as the material set as soon as it was subjected to the heat. The colder temperatures had the opposite effect of lengthening the setting time, from 3-5 minutes to considerably longer. Humidity did not seem to have a considerable effect on the quality or time for setting. The storage tests as detailed within section 3.2.5 used lifts that were already found to unlock devices and then were subjected to the temperatures as before. In every test the flexibility of the material was not affected and when tried on the device, the lifts succeeded to unlock the device as easily as before the treatments.

Chapter 4

Applicability of conductive fingermark recovery in biometric security

4.1 – Introduction

The results within chapter 3 highlight the development of a technique which is successful in unlocking devices and captures good ridge detail. However, this was only tested on one primary device. To further determine the applicability of this technique additional biometrically secured devices were tested. This included various makes and models of phones and considered the differences between phone, tablets, and laptops/computers as well as operating systems.

For this section, the ethical guidelines required that all participants remain anonymous and provide signed forms of consent allowing both fingerprints and electronic devices to be temporarily used. To provide anonymity to the participants involved, each person was given a participant number and the contact information for these participants was written in a password protected document. These participants were allowed to withdraw from the study at any time to have the data and casts destroyed.

4.2 - Method

The participant numbers and the devices that were tested with each fingerprint can be seen in table 4.1 along with whether the device could be unlocked with the techniques described in section 3.4. The participants were chosen to try and allow as many different devices as possible to be tested with a relatively even number of phones using both Android and Apple's Operating Systems (iOS).

Table 4.1 - Table of participants, the devices tested for each participant and the success of the testing

Participant Number	Devices tested	Successful Unlock	Clarity Grade
0	iPhone 8 Plus, PC Scanner	iPhone 8 Plus: Yes PC Scanner: Yes	5
1	iPhone 6, iPad Air 2	iPhone 6: Yes iPad Air 2: Yes	4
2	iPad Air 2	iPad Air 2: No	4
3	Samsung Galaxy S22 Ultra	Samsung Galaxy S22 Ultra: Yes	5
4	OPPO X3 Lite	OPPO X3 Lite: No	4
5	Samsung Galaxy S7	Samsung Galaxy S7: Yes	4
6	iPhone 6, 8 Plus	iPhone 6: Yes 8 Plus: Yes	4
7	PC Scanner	PC Scanner: Yes	5
8	iPhone 7	iPhone 7: Yes	5
10	iPhone SE	iPhone SE: No	4
11	iPhone SE	iPhone SE: No	4
12	PC Scanner	PC Scanner: Yes	4
13	Samsung Galaxy S21 Ultra	Samsung Galaxy S21 Ultra: Yes	5
14	Samsung A71	Samsung A71: No	4

Each participant was invited to do a casting of a finger, the method for which can be found within section 3.4. This method was followed as described; however it was noted that curing time varied slightly between different participants. This is thought to be due to difference in body temperature and sebum production.

The Provil and conductive paint lift was then prepared, and the participant was invited back to test the lift on the devices as seen in table 4.1. When testing the lifts, both the researcher and owner of the phone attempted to unlock the device. This was because the owner would know the orientation usually used for unlocking the device and the researcher had become accustomed to the best techniques to flatten the lift against the sensor. The lifts were tried several times in a single session with each participant, with slightly varying time allowances, and the results collected and graded as seen within table 4.1.

4.3 – Results and discussion

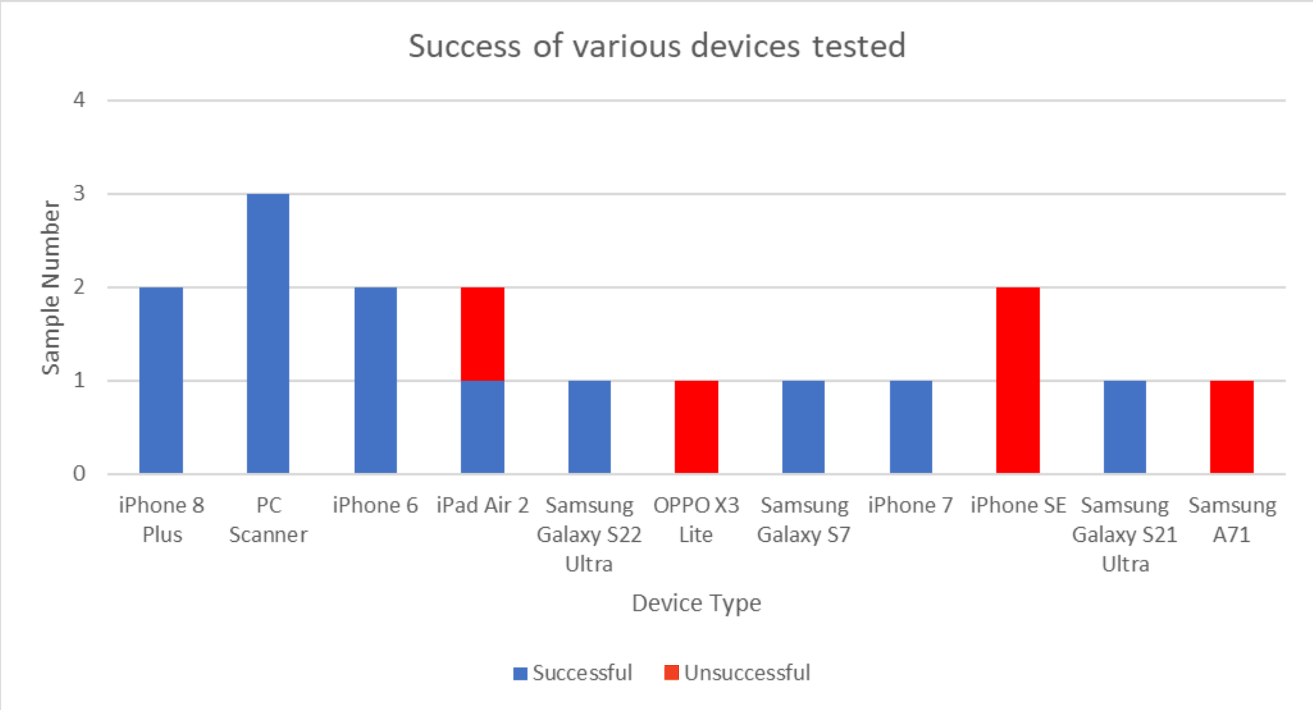

Figure 4.1 - Graph of devices tested and the number of successful and unsuccessful attempts

As shown in figure 4.1, there is a higher ratio of successful unlocking's compared to those which were unsuccessful. Some devices such as OPPO X3 lite, Samsung A71 and iPhone SE, were all unsuccessful at unlocking the devices attempted. This may signify that the developed technique is not applicable to these devices or other factors were contributing the failed attempts with these cases. In the case of the iPad air 2 device, two different devices were used in this study. In the case of participant 1, the device was unlocked with ease, however this was not successful with participant 2. This difference may indicate either a difference with the devices such as damage, different software versions affecting the success of the technique or inherent factors of the participants fingermark. Previous research (Wilson et al., 2012; Daftardar, 2021) has shown that the projection of friction ridges on a finger are affected by the individuals age, handwashing habits and type of work carried out. It has been found (Smart Eye Technology, 2020; Daftardar, 2021), for example that an individual handling bricks on a regular basis would produce poor fingermarks due to the abrasion of friction ridges with this material. Equally, a decrease in collagen production as a person ages, results in decrease of friction ridge projection (Wilson et al., 2012; Reilly and Lozano, 2021) as discussed in section 1.1.2.

These factors were not considered during the ethical approval stage of the research and could therefore not be investigated in detail. However, it was noted that there was greater difficulty in unlocking devices from those older participants compared to younger participants. This observation is thought to contribute to the overall success rate of the technique and should therefore be researched in the future.

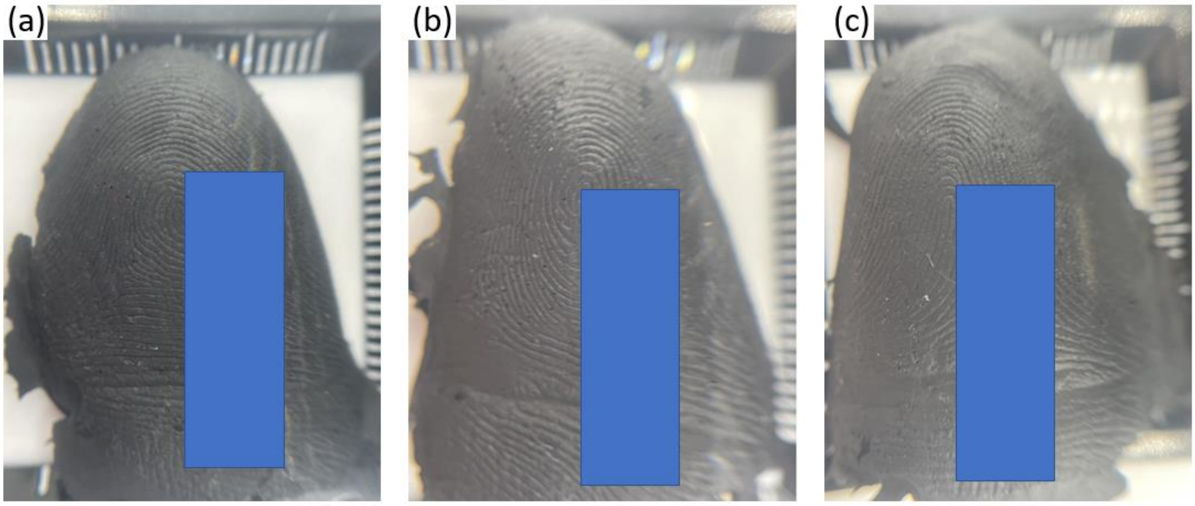

Figure 4.2 - Lifts created from casts of those aged <30

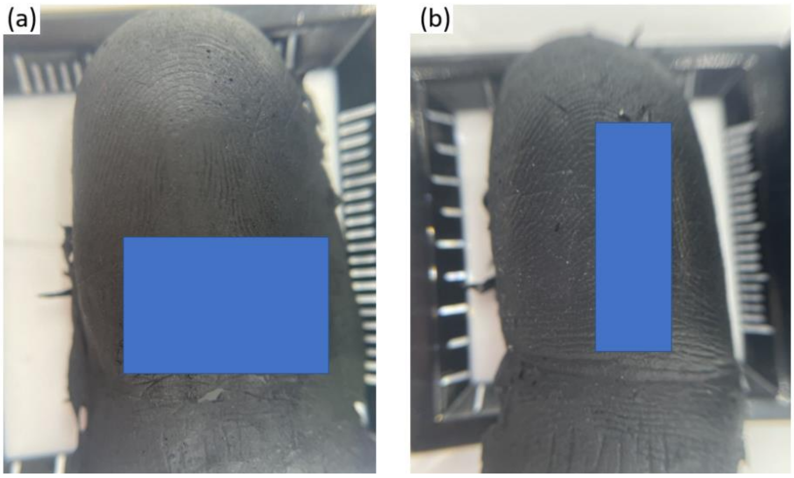

Figure 4.3 - Lifts created from casts of those aged >30

As shown by figures 4.2 and 4.3, there is a significant difference in the quality of the lifts produced. As previously stated, age was not a focus and so an estimation of over and under 30 years was made and as displayed the over 30 fingerprints lacked detail in comparison to the under 30s. This could be a result of age and the decrease of collagen production (section 1.1.2) or there is the possibility of some participants being involved in more laborious jobs or hobbies that have decreased the detail present.

Grading of all fingermarks was carried out for both successful and unsuccessful attempts. These results are shown in table 4.1. As at this stage the technique had been fully developed, there were few issues with quality when producing the lifts required. As a result, most of the lifts created received a higher grade than those made at the beginning of the study. Full details of how the grading changed throughout the study can be found within appendix B. It was found that overall, that in the successful lifts both during the development of the technique and the testing of participants, it was the lifts given a grade of 4 or 5 that were more successful and easier to unlock with than lifts with a lower grading. As this grading of clarity directly refers to the quality of the lifts and the number of ridges visible, this was to be expected that a lower grade has less ridges and therefore is less likely to be successful. The technique used throughout testing each participant has been consistent for both the casting and making the lift. As a result, the clarity of the ridge details within the lift will likely be due to characteristics on the fingertips of the participants. The success of the unlocking will then be affected by this level of detail if the device itself is not having an impact.

To investigate if operating systems contributed to overall success rate, the above data (table 4.1) was grouped into the following: IOS, Android and Windows. The results of which are shown in figure 4.4.

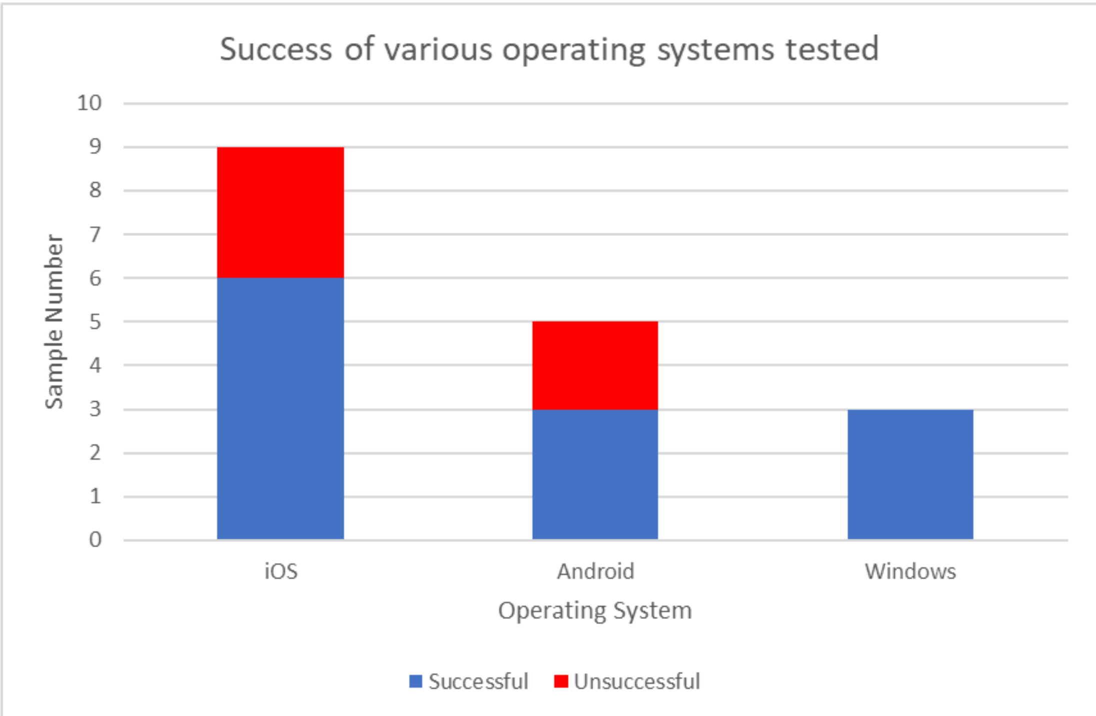

Figure 4.4 - Graph of operating systems tested and the number of successful and unsuccessful attempts

Figure 4.4 shows that the windows operating system was successful for all attempts. In this case, the same fingerprint sensor (section 2.4.3) was used for various different participants. This consistency may impact the success rate obtained for this operating system. Different iOS and Android devices were used as these were the personal devices of the participants. A ratio of 2:1 was obtained for iOS devices whereas a ratio of 3:2 was obtained for Android devices. This highlights that there was very little difference between the success of the developed technique for unlocking devices from different operating systems. However, this is a small data set and future research would need to be conducted to increase sample numbers thereby allowing for a more meaningful comparison to be made. This comparison has been hindered and will be hindered in the future as there is very little information made available to the public in relation to the algorithms used for each operating system. As summarised in section 2.4.2, information regarding fingerprint sensors was obtained primarily from forums or non-peer reviewed sources, including unpublished journal articles. This difficulty in obtaining data may be due to multiple reasons such as companies protecting own technology, competition in the market, data and security breaches, etc. However, it is important to consider if there is any bias within the fingerprint technology used in these operating systems.

Facial recognition is another biometric feature which was produced outside of the control of both Android and iOS (Leslie, 2020), but applied in both operating systems. It is known that there is a great deal of bias in the algorithms used for facial recognition. Studies (Leslie, 2020; Perkowitz, 2021) have shown that participants used for developing these algorithms were primarily middle-aged white males. Meaning that there is gender and racial bias in this technology. This may also be a factor when considering the usability of the developed technique as age, for example, may be an inherent bias within the technology of fingerprint recognition.

4.4 – Conclusion

The grading process has shown that overall, a higher grade, and a higher level of detail will lead to a more likely successful lift. As discussed within this chapter, the technique had been fully developed at the point of involving participants and remained consistent throughout. This suggests that the participants fingerprints or the device itself had an effect on the success of the testing. Characteristics such as those relating to the degradation of a person's fingerprints (e.g., age, manual labour) may have a detrimental effect on how the technique developed may be used. In the case of the iPad Air, in which one device worked and the other could not be unlocked, it could be suggested that the quality of the fingerprints themselves had an effect on the success as the same make and model of device was used.

There are several factors that were difficult to control or were an unknown factor during the testing of the participants that may have contributed to the success of the lifts. Firstly, there was a notable effect caused by phone cases and thick screen protectors that some of the phones had. The participants were not expected to remove screen protectors but were asked to remove thick cases, however some of the participants had cases that were difficult to get on and off or it would have damaged to screen protector. In these cases, there may have been a reduced chance of success as it was found that this thickness prevented the lift from covering the fingerprint sensor. This could have had an effect on how well the sensor could recognise the fingerprint and so was more difficult to unlock the devices in these cases. Additionally, the quality and age of the phone could not be determined or compared easily. As detailed within section 2.4.2, the age of the phone could be estimated by using the release date however it is known that phones can be sold as ‘brand new’ months or years after being first released. There is also the question of how many owners had possession of the phone prior to the participants and how well the phone was kept in this time. The quality of the fingerprint sensor may have deteriorated over time and if mistreated the phone may have had considerable scratches that were not noticeable. This is possibly an area for further research in the future to determine if this does have a significant impact on the usability of the technique detailed within this paper and to what extent these factors may have an effect.

In terms of the testing, there were additional factors involving time allowances that may have reduced the chances of a successful unlocking, as mentioned within section 4.3. The involvement of many of the participants required working around multiples schedules and often limited time was available for the testing. To combat this, the casting and testing were carried out on separate occasions, however this did not make a significant difference to the time available for some of the participants. It is thought that in these cases, had more time been available more attempts could be done with different angles and a successful unlock may have been reached. This could also be related to the experience of the researcher and improving the technique used for testing, as experience is gained, less time may be required for a successful unlocking to be achieved.

Chapter 5

Recovery of conductive fingermarks from exhibits

5.1 - Introduction

In order to determine the real-world applications of the developed technique (chapter 3), a series of tests were conducted upon several exhibits showing 3D form. This was done through various materials that can be found in everyday life, the intent behind this was to mimic the possible samples that may be found within a crime scene. For this testing the primary device (iPhone 8 Plus) was again used for the attempts at unlocking a biometrically secured device.

5.2 – Plasticine and modelling dough

Both a modelling dough and plasticine were tested, due to the mouldable properties of these materials, it was thought that the casts may also be useful for mimicking other items such as chewing gum and putty.

The use of these materials utilised different techniques to see how it worked best and where the limits of the material lie.

5.2.1 – Plasticine

The plasticine is a solid material that requires a certain amount of heat in order to become malleable. When freshly pulled out of the packet, the deposition of a fingermark was not possible as the material was too hard. The soften the plasticine, several temperatures were used. Firstly, the plasticine was rolled into a ball shape and placed into an oven set at 25°C ≥ T ≥ 50°C. Secondly, the material was kneaded between the palms of hands at body temperature.

When using the plasticine for the deposition of a fingermark, it was found that no matter the temperature on the oven the ball made remained solid and a clear fingermark was not possible to be made. This was thought to be due to the volume of plasticine used. This process heated the external layer of the material, however the core remained hard. Instead, the use of body heat and moving the plasticine through kneading the material was much more effective at softening the product. As a result, a clear fingermark was made into the material given a grade of 4, as figure 5.1 shows, ready for recovery.

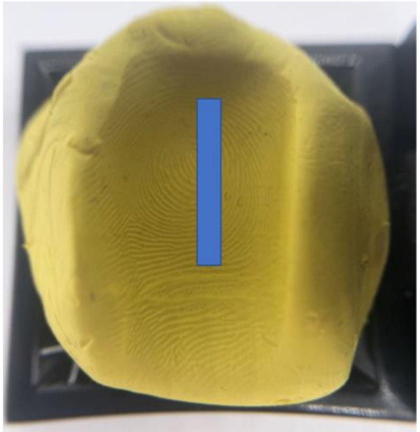

Figure 5.1 - Fingermark deposited on to plasticine

Figure 5.1 shows a good level of detail is captured from the fingermark, with no deformation in the form of cracking, voids, etc. observed on the impression. Once the fingermark had been deposited, the same technique detailed within section 3.4 was used. These results can be seen in figure 5.2.

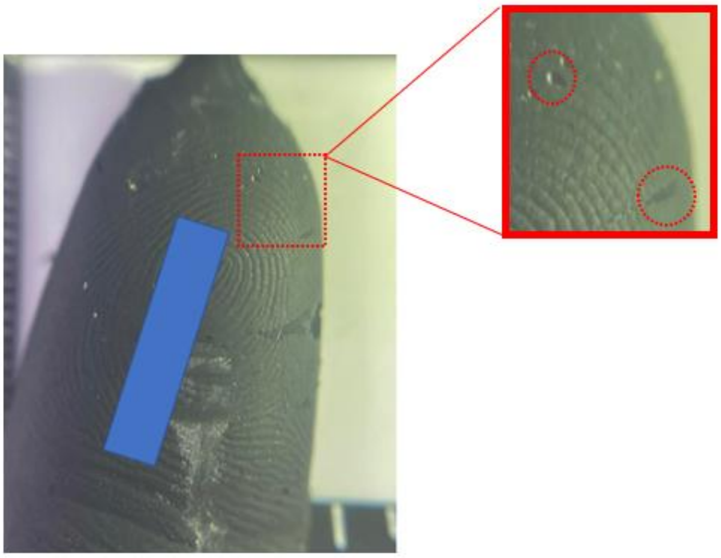

Figure 5.2 - Provil and conductive paint lift from plasticine.
Where figure insert highlights pockets within lift

The recovery of the sample in plasticine produced a good level of detail with many ridges and characteristics visible. This lift was determined to be a grade 4 due to the minor pockets highlighted within the figure insert (figure 5.2). Despite these minor pockets, when tried on the fingerprint sensor, this lift was able to successfully unlock the device. This demonstrates that minor imperfections within the cast do not affect the usability of this proposed technique.

5.2.2 – Modelling dough

The modelling dough used was similar to an unbranded Play Doh. This material was much softer and more malleable than the plasticine. There was not much kneading required to get the material ready for the deposition of a fingermark. This meant that this material was ideal for capturing a good quality fingermark for recovering.

To determine how temperature may affect fingermark deposition on the modelling dough, the material was firstly placed into an oven in ball shape at a temperature range of 25°C ≥ T ≥ 50°C. Secondly, the material was kneaded between the palms of hands at body temperature. .

After removal of the dough ball from the oven, a slight colour change was observed. This is thought to be associated with a drying of the material (discussed later within this section). A poor-quality fingermark was also produced using this method, where minute cracks were observed on the surface which is again thought to be link with loss of moisture.

There was also testing involving time left out of the airtight container to determine if this would have an effect. For this test, a piece of modelling dough was rolled into a ball and left in weigh boats, one was left for 30 minutes, another for 3 hours and one had the fingerprint deposited and then it was left for 24 hours. Another piece was used as a control and was freshly marked and recovered. The results obtained can be seen in figure 5.3.

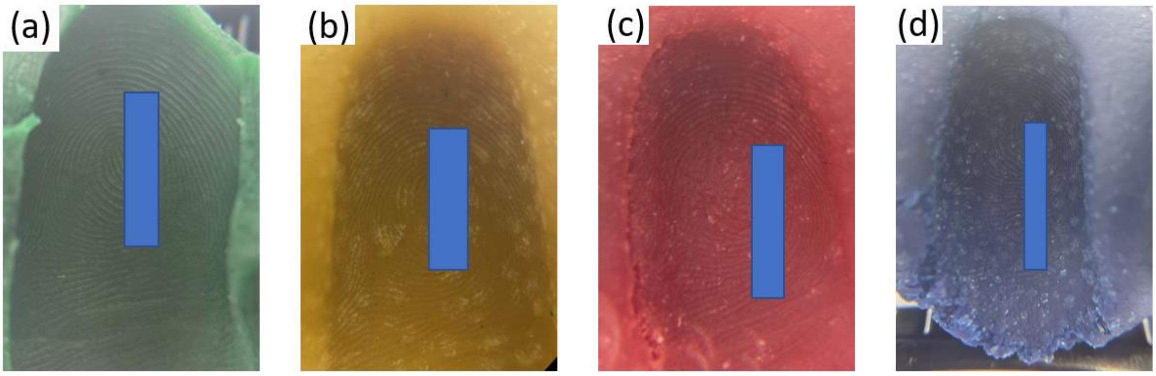

Figure 5.3 - Fingermarks deposited on to playdoh when (a) fresh, (b) dried after deposition (24 hours), (c) left 30 minutes before deposition and (d) left 3 hours before deposition

Good quality fingermarks were produced when the impression was made directly after kneading being given grades of 4 (figure 5.3 a – b). However, an increase in time between kneading and the creation of an impression, led to a decrease in the quality of the fingermark produced leading to a grade of only 2 for these samples (figure 5.3 (c – d)). This is thought to be due to loss of moisture from the sample causing a decrease in the malleability of the material. This loss of moisture appears to manifest as the appearance of dots on the surface of the playdough, as also observed in sample 4.2 (b).

Once the fingermarks had been deposited, the same technique detailed within section 3.4 was used. These results can be seen in figure 5.4.

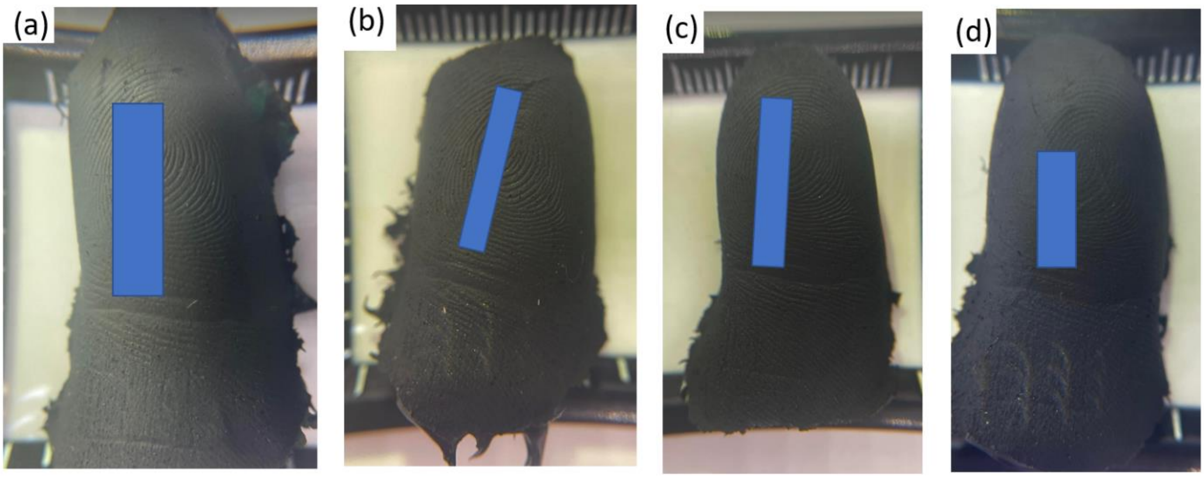

Figure 5.4 - Provil and conductive paint lifts from playdoh when (a) fresh, (b) dried after deposition (24 hours), (c) left 30 minutes before deposition and (d) left 3 hours before deposition

As can be seen within figure 5.4, the lifts produced from the playdoh did hold some good detail. In all of the lifts the overall flow of ridges can be seen with level 1 characteristics being identified. The samples left out before the deposition of the fingermarks (figure 5.4 (c) and (d)) showed considerably less detail than the fresh samples. Samples (a) and (b) were given grade 4 as they both had a lot of detail but some slight thinning to some ridges. Sample (c) was given a grade 3 and sample (d) a grade 1. When tested on the device, the lifts displayed in figure 5.4 (a) and (b) were successful at unlocking the phone whereas the samples shown in figure 5.4 (c) and (d) did not succeed in the unlocking of the device. These results demonstrate that the impression should be of grade 4 or above in order for the developed technique to be usable in practice.

5.3 – Wax

The wax used was from unscented white candles and came in a completely solid form. As a result, the method involved melting the wax before a fingerprint could be deposited which, if done too soon, could result in burns and so the use of the wax required safety precautions. This involved allowing the wax to cool for approximately one minute before depositing the fingerprint.

To do this, a beaker was used to melt down candles on a hotplate set to 80°C. Once melted, the wax was poured into a small metal tin and allowed to cool slightly. As the wax changed from clear to white, the chosen finger was slowly and carefully pushed into the wax and removed, after which the wax was left to solidify, as seen in figure 5.5.

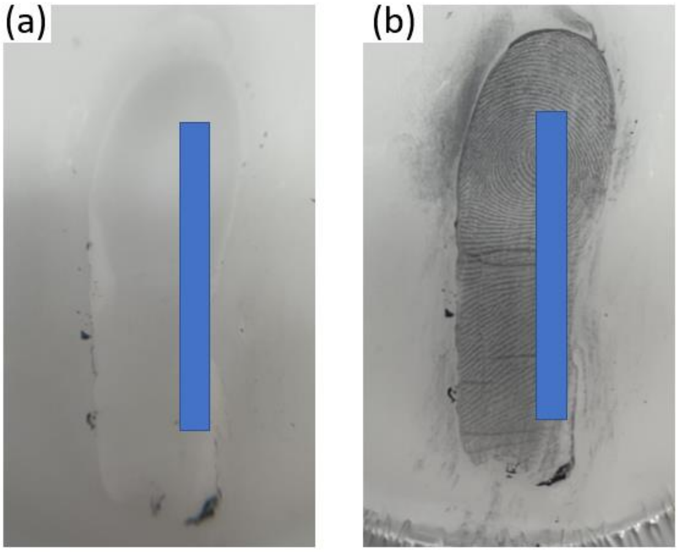

Figure 5.5: Images showing fingermark deposition in wax with (a) the absence of physical developer and (b) with the presence of black magnetic powder.

The use of the wax produced a very clear copy of the fingermark (figure 5.5 (a)) where this was given a grade of 5. However, ridge detail could not be captured using photography, but this detail was observed under ambient lighting at different angles. In order to photograph the fingermark, black magnetic powder was used to highlight the ridges. Once the wax was solid, the procedure for applying the Provil and conductive paint followed that detailed within section 3.4.

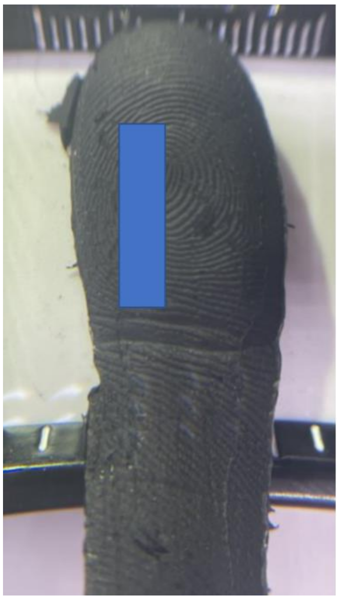

Figure 5.6 - Provil and conductive paint lift from wax

Figure 5.6 shows that the recovered lift from the wax also held as much detail as the sample itself being given a grade 5 for the clarity and details identifiable. When this lift was tested on the fingerprint sensor, the device was successfully unlocked.

5.4 – Clay

Oven cured polymer clay brand FIMO was used for the clay. Both cured and uncured samples were used for the recovery of the deposited fingermarks.

The method used closely resembled that used for the plasticine and playdoh (section 4.2.1), by kneading the clay to soften and then rolling the clay to a ball and creating the fingerprint impression. Two samples were then placed into the oven following the instructions provided for the product (100°C for 30 minutes) and two samples were left in the soft uncured state, these results can be seen in figure 5.7.

The fingermarks deposited into the clay held a good amount of detail with the overall pattern and some minutiae visible (figure 5.7 a-b), curing the clay did not seem to have a considerable effect on the detail of the fingermarks and assigned grading with both being assigned a grade of 4.

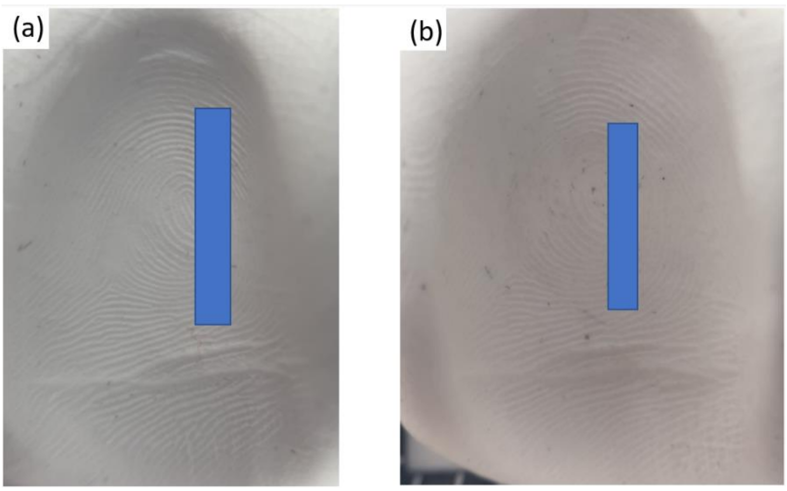

Figure 5.7 - Fingermarks deposited in to (a) uncured clay and (b) cured clay

The fingermarks were then recovered using the Provil and conductive paint method described within section 3.4. The unbaked clay did not require any lubrication however due to the porous nature of the clay when cured, a thin layer of Vaseline was used.

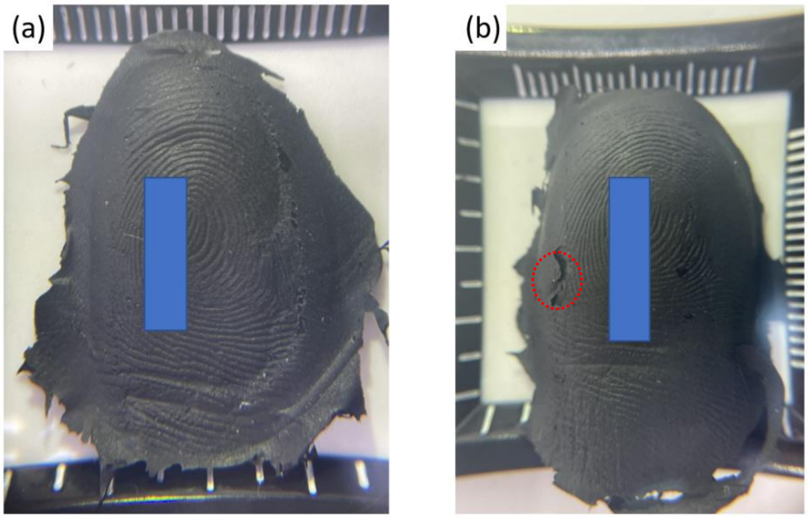

Figure 5.8 - Provil and conductive paint lifts from (a) uncured clay and (b) cured clay where the red circle highlights pockets within lift.

As figure 5.8 displays, the lifts produced from the clay samples showed much detail. The grading associated with each sample remained unchanged and assigned as a grade 4. Some minor pockets were observed within the cured sample, as highlighted by the red circle in figure 5.8 (b). This is thought to be due to the increased porosity occurring within the cured clay. However, upon testing, these pockets did not affect the usability of the proposed method as when tested on the device both samples successfully unlocked the biometric sensor.

5.5 – Paint

When testing the paint, several techniques were assessed to see under what conditions paint may be recoverable. This was done using both acrylic paint and anti-climb paint. Acrylic paint is a water-based paint that will dry as the water evaporates leaving a plastic feel to the material as the polymers fuse (artincontext, 2021). Anti-climb paint is a petroleum gel-based paint designed to remain wet and slippery indefinitely with a greasy feel to it (Insight Security, 2022). When assessing these paints, primary and secondary transfer were explored with a thin layer of each paint applied to a piece of acetate.

5.5.1 – Acrylic Paint

In the case of the acrylic paint, the finger was placed into the paint immediately as the thin layer would dry quickly. Additionally, to this, a large bead of acrylic paint was used to determine if a 3D impression could be made. This bead of paint was allowed to partially dry, when the outer layers had formed a skin, but the centre was still soft and malleable. When the paint had reached this point, the finger was gently pushed into the material and allowed to fully dry.

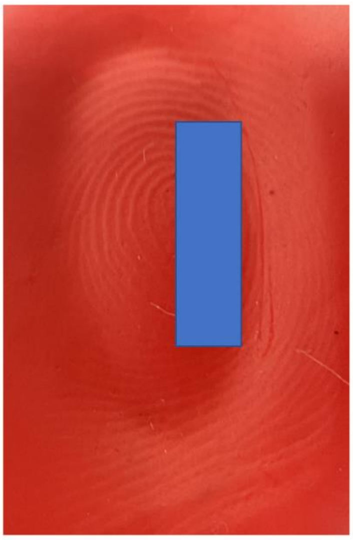

Figure 5.9 - Fingermark deposited in acrylic paint

It was difficult to successfully deposit a fingermark in the acrylic paint, due to multiple factors such as drying time and movement of the exhibit. The samples shown in figure 5.9 used the larger bead of paint which needed to dry to the right amount which was hard to accomplish. The resulting fingermark as shown did not produce much detail, whilst the overall flow is visible, the identification of any minutiae was difficult, thus was assigned a grade of 2.

For all the samples, the Provil and conductive paint was applied following the method detailed within section 3.4. The results obtained can be seen in figure 5.10.

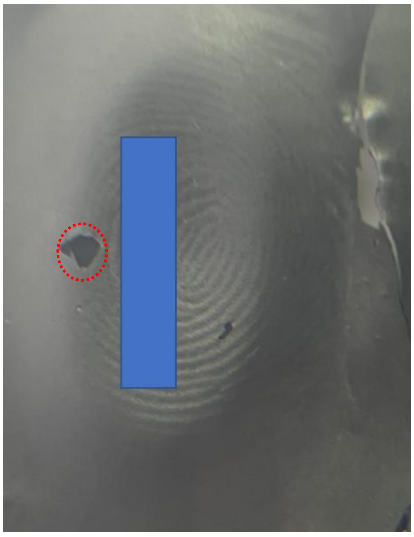

Figure 5.10 - Provil and conductive paint lift from acrylic paint where the red circle highlights pockets within the lift

As shown in figure 5.10, the recovery of the acrylic paint did have a slight pocket, however as this was to the edge of the fingermark it did not interfere with the analysis. The lift, much like the sample, did not have a great amount of detail and so was given a grade 2. When tested on the sensor, this lift could not successfully unlock the device.

5.5.2 – Anti climb Paint

Previous research (Davatwal, 2022) has shown that tackiness of anti-climb paint reduces over time, therefore the material was applied to an acetate sheet and left for a few hours until tackiness decreased. The finger was rolled across the paint (primary) and then over a fresh piece of acetate (secondary). Before the recovery using the conductive silicone, the anti-climb paint was firstly treated using cyanoacrylate ester fuming, a newly proposed method (Davatwal, 2022) in order to harden the paint. These results are shown in figure 4.11. The anti-climb paint did successfully show some level 3 characteristics with the secondary transfer being considerably more detailed compared to the primary transfer as seen in figure 4.11. This resulted in a grade of 3 being assigned to the primary transfer whereas a grade of 4 was assigned to the secondary transfer.

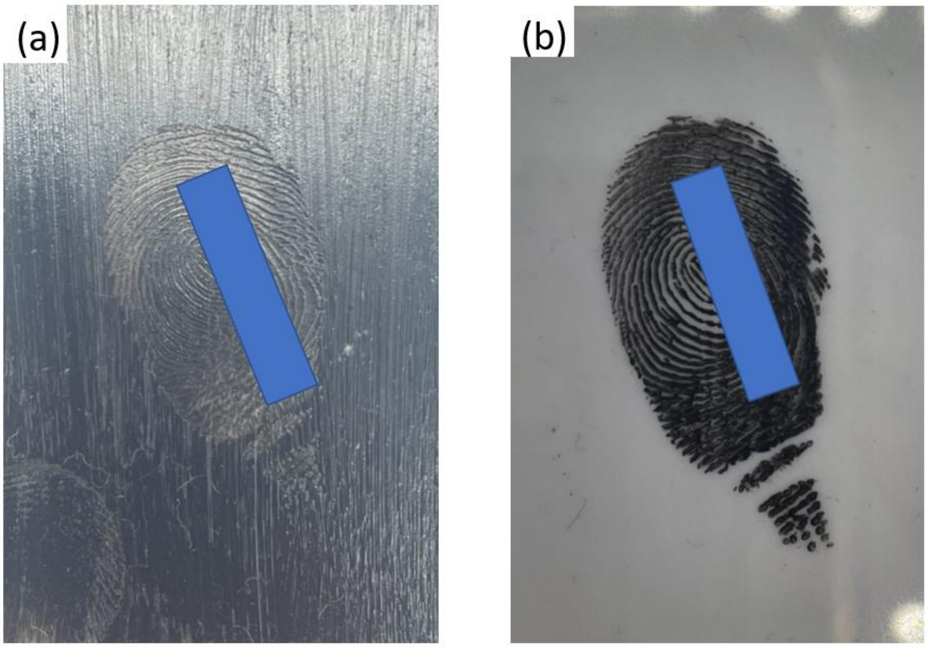

Figure 5.11 - Fingermark deposited in anti-climb paint using (a) primary and (b) secondary transfer

For all the samples, the Provil and conductive paint was applied following the method detailed within section 3.4.

The lifts obtained for these samples showed a good resemblance to the anti-climb paint deposits shown in figure 5.11. However, more detail was obtained on the secondary transfer compared to the primary transfer. The grading for the casts remained consistent with that previously assigned, where a grade 3 was given to the primary transfer and the secondary transfer was given a grade 4. When tested on the fingerprint sensor, the primary transfer did not successfully unlock the device, however the secondary transfer was successful in unlocking the device. Similarly to previous findings, the success of this technique is linked to the grading of the fingermark and cast obtained.

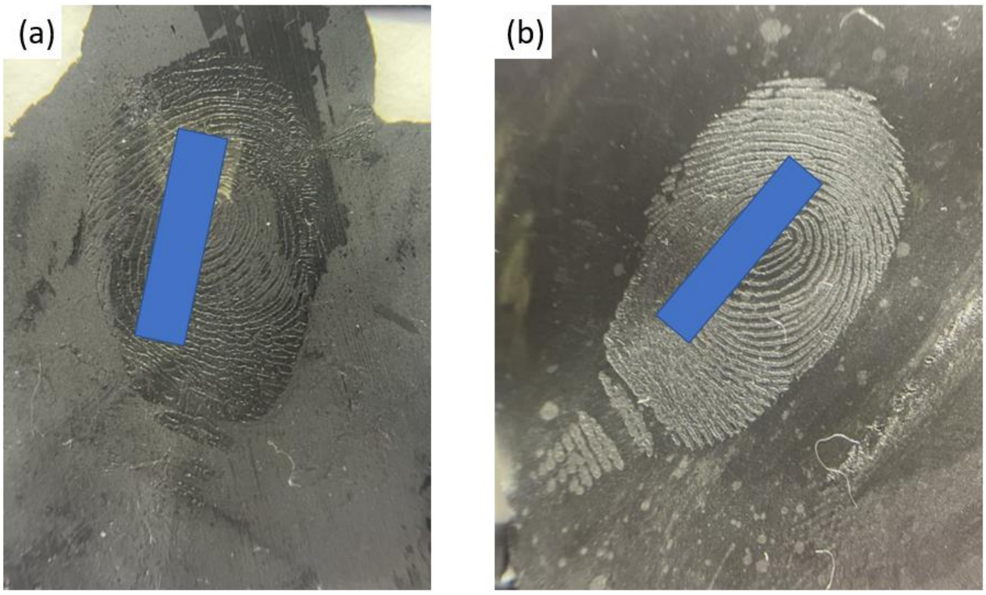

Figure 5.12 - Provil and conductive paint lifts from anti-climb paint using (a) primary and (b) secondary transfer

5.6 - Conclusion

Overall, the technique that has been developed and discussed within this paper is successful across various surfaces, including those which have been previously considered to be problematic within practice such as paint in various forms. The success of the technique appears to be linked to the grade of the deposited fingermark, where a grade below four seemed to be unsuccessful in unlocking the mobile device. However, for many of the samples detailed within this section, the technique does not cause any damage to the sample. The cases in which it has been damaged has been due to the metal spatula and tweezers knocking the sample during the lifting and the soft nature of some of the samples. It is envisioned that this damage would decrease with increased experience of the researcher. Therefore, the technique can be considered to be non-destructive.

Materials researched within this chapter were primarily based upon 3D impressions, however the success obtained using the paint exhibits, particularly the anti-climb paint, demonstrate that the method may be applicable to 2D fingermarks. Future work could further investigate this possibility.

Chapter 6

Conclusion

The field of fingerprinting was developed throughout the 19th and 20th centuries with the first uses in Scotland yard being introduced by Sir Edward Henry when he wrote the '*Classification and Uses of Fingerprint'* detailing methods for developing and recovering fingermarks (Henry, 1913; Huynh and Halámek, 2016). This is a system that is still used today, displaying that these techniques work well but have not been developed further (Orthmann and Hess, 2012). The use of fingerprinting within the criminal justice system has become a vital type of evidence. According to studies detailed by Schweitzer and Nuñez (2018), Kadane and Koehler (2018) and Garrett and Mitchell (2013) alongside DNA, fingerprints are one of the most highly regarded forms of evidence used in court.

These existing techniques primarily use physical and chemical developers as discussed throughout section 1.2.2. These methods have been developed to be very good at recovering fingermarks from surfaces such as bottles and other hard surfaces using physical developers and porous surfaces such as paper and card using chemical developers(Hawthorne, 2009a). This success has led researchers to investigate the limits of these physical and chemical developers to ascertain their applicability to various different exhibit surfaces and conditions, such as wet surfaces. This has allowed for the development of numerous methods and techniques for the recovery of fingermarks. However, as discussed throughout this paper, while there are studies working to improve fingerprinting, this has been stalled at technology with few studies addressing how the collection and use of fingerprints may be applied within the modern world of technology.

The studies that have looked into this area have been published as non-peer-reviewed articles, such as work by Cao and Jain (2016) Levalle (2020). This can be considered to be a rare occurrence within research, where high confidence (value) is placed by the scientific community in the peer review process. This can also be associated with the verification stage employed within forensic practice. The lack of peer-review in this area of research may be due to commercial interests, where technological advancements are heavily guarded. Equally, little information is released regarding any faults, bugs or security vulnerabilities within these operating systems in order to avoid the loss of consumer confidence. Research into remediating these vulnerabilities is also conducted primarily by individual companies such as Apple and Windows who use both internal and external consulting agencies to investigate issues within their software. This information is used solely by these companies for the improvement of products and is not released in the public domain. Equally funding within this area of research is very limited which impacts any potential advancement within the forensic field.

This research has begun to explore the many uses and techniques that could be developed surrounding not only analysis but also further uses of fingermarks recovered from a scene.

When developing the methodology for this research, importance was placed upon the use of materials and processes currently used within forensic practice to mimic, as closely as possible, those processes currently accepted within the field. Therefore, the use of powders and casting silicones were applied and developed in a way that would allow fingerprint evidence to provide so much more to an investigation.

Although companies withhold much of the information surrounding the development and mechanisms of fingerprint sensors within electronic devices, it is known that the sensors utilise the types of scanners described within section 1.3.2. As discussed within this paper, the most commonly used is the capacitive scanner, the type that has been the focus of this study, which requires a level of capacitance or current from the body. The uses of such devices have become an integral part of the modern-day world and technology that is a part of people's everyday life. However, the forensic field is not currently equipped to use this type of evidence. Being able to use evidence collected from a crime scene that would allow investigators to access electronic devices, that would otherwise be locked due the need of a fingerprint, could be beneficial to investigations.

The development of the technique proposed has shown that the most effective material to create a working lift is the conductive silicone as discussed throughout chapter 3. This material allows for the capture of a good level of detail and durability which means the material has a long shelf life of usability with minimal issues surrounding storage and handling. The longevity proved to be better with the conductive silicone over the gelatine for example, which showed a higher degree of degradation and was extremely delicate to handle. This was also observed for conductive paint lifts. The only issue encountered with the silicone is that the thickness contributed to the effectiveness of the lifts. When measured with vernier callipers, the lifts under 2 mm thick worked better (successful unlocking and registering of fingerprint) compared to those thicker than 2 mm.

The additional testing explored within chapter 4 displays that this technique developed can be applied to multiple phones and individuals. Whilst there were some unsuccessful attempts, there are many factors that are suggested within the chapter as to why this may be. The possibility of damage to the device or the effects of the participant's fingerprint quality may have had a large effect on how well the lifts were able to unlock the devices. The overall success of this testing shows that the methods and materials proposed within this research are applicable to multiple devices and operating systems.

The testing within chapter 5 also demonstrates the possible uses and successes of the techniques developed throughout this paper. As shown, there were various surfaces that could adequately capture the details of a fingerprint allowing for a good recovery using the conductive silicone. As a result, many of the surfaces could be used to successfully unlock the primary device. This again shows that the technique has real-world applications and can be used on materials that can be commonly found within a crime scene.

The future applications for such a technique could be further explored through research focussing more on the factors that can affect the success of the methods described throughout this paper. The possible effects of the conditions of a person's hand, the quality of the fingerprint sensor or the thickness of the silicone lifts could be explored further for a better identification of exactly where the limitations are. The testing done has already shown that there are certain materials that are difficult to recover successful lifts, however, further research and development of the technique may mean that more surfaces can be successfully recovered to unlock a device. Additionally, the device types and operating systems could also be further investigated by gathering a larger data pool to look into more device makes and models as well as the update on the device. There are also other operating systems that could be tested, in particular the computer systems that may be used in conjunction with the computer scanner detailed within section 2.5 such as Apple or Linux as well as Windows.

Other possible future applications may involve adapting the technique to be used for 2D fingermarks as well as further development of the 3D technique. For example, 3D printing may be used through the use of a scanned image of the fingermark. This can be used to then either create a cast such as the one detailed within section 3.2.1 and then using the existing technique to create the lift or if the conductive paint could be added to the material, then this may be used to print the lift itself. The success of the anti-climb paint suggests that there are possible 2D applications that may allow for latent fingermarks to be recovered as well as the plastic fingermarks. Additionally, there are also post-mortem applications that should be considered in future research (Plante, 2022).

The use of impedance spectroscopy may aid in determining the level of electrical conductance that the lifts are able to produce. '*Electrochemical impedance spectroscopy (EIS) is a rapid, non-destructive, and easily automated technique to investigate the electric properties of a great variety of materials*' (Nossol et al., 2021). The use of such equipment may allow for determining the conductivity of the materials used and how an increase may be achieved. As discussed, the thickness affects the success of the lifts and so impedance spectroscopy could help determine the ideal thickness for the lifts to allow the level of capacitance required to activate the phone sensors.

Overall, there has been a lack of development within the area of fingerprinting and the processes discussed within this paper could have important implications for the field as a whole and how fingerprints can be used throughout investigations. It is thought that the technique can be developed to work consistently across many surfaces and device types and potentially contribute to standard procedures being developed which could revolutionise the field.

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Appendices

Appendix A

Table A1 - Xantopren user instructions (amounts followed highlighted in yellow) (Kulzer, 2022b)

Technical Information
Silicon based precision condensation curing impression material.

Instructions for use GB

Optosil®/ Xantopren®	EN ISO 4823	Colours	Dosage*2			Mixing-time	Working-time*1	Time in mouth
			BASE	Activator universal Plus				
				Liquid	Paste	s	min : s	min : s
Optosil® Comfort®	Type 0	yellow	**1** spoon (10.7 g/9.5 ml)	**6–8** drops (0.14 g/0.13 ml)	**6–8** graduations (0.32 g/0.29 ml)	30	1:00	4:00
Optosil® P Plus	Type 0	yellow	**1** spoon (14.4 g/9.5 ml)	**4–6** drops (0.09 g/0.09 ml)	**4–6** graduations (0.21 g/0.19 ml)	30	1:00	4:00
Xantopren® H green	Type 1	green	**6** graduations (11.0 g/8.8 ml)	**12** drops (0.27 g/0.26 ml)	**12** graduations (0.65 g/0.59 ml)	30	1:00	4:00
Xantopren® M mucosa	Type 2	orange	**12** graduations (9.0 g/7.6 ml)	**12** drops (0.27 g/0.26 ml)	**12** graduations (0.65 g/0.59 ml)	30	1:30	4:00
Xantopren® L*4 blue	Type 3	blue	**12** graduations*3 (8.6 g/7.6 ml)	**12** drops (0.27 g/0.26 ml)	**12** graduations (0.65 g/0.59 ml)	30	1:30	4:00
Xantopren® VL*4 Plus	Type 3	blue	**12** graduations*3 (8.5 g/7.6 ml)	**12** drops (0.27 g/0.26 ml)	**12** graduations (0.65 g/0.59 ml)	30	1:30	4:00

*1 At room temperature of 23°C (73°F), 50 % rel. humidity.
Higher temperatures shorten, lower temperatures prolong these times.
*2 1 graduation = 1.3 cm (applies to mixing pad available)
*3 Bottom ring on mixing dish is equivalent to 7.6 ml
*4 When using the dispenser: 1 stroke (4.5 g / 4.0 ml) + 6 drops (0.14 g / 0.13 ml)
The stated dosage should be observed.

Type 0 = putty consistency
Type 1 = heavy bodied consistency
Type 2 = medium bodied consistency
Type 3 = light bodied consistency

Appendix B

Table B1 – Details of paints lifts created the grades given to each sample

Paint lift number	Paint lift description	Paint lift date	Clarity grading	Durability grading	Flexibility grading				Successful unlock?
					1	2	3	4	
1	Bare conductive' pot single layer fully dried	24/11/2021	2	0	1	2	-	-	No
2	Bare conductive' tube single layer fully dried	24/11/2021	2	0	1	2	-	-	No
3	Wire glue' single layer fully dried	24/11/2021	2	0	1	-	-	-	No
4	Bare conductive' pot 3 layers fully dried	08/12/2021	3	0	1	2	3	3	No
5	Bare conductive' + 'Wire glue' 3 layers fully dried	08/12/2021	4	0	1	2	-	-	No
6	Conductive paint test 1 (3 layers not fully dry)	19/01/2022	3	0	1	2	3	-	No
7	Conductive paint test 2 (4 layers not fully dry)	19/01/2022	4	0	1	2	3	4	No
8	Conductive paint test 3 (5 layers not fully dry)	19/01/2022	3	0	1	2	3	4	No
9	Conductive paint test 4 (3 layers fully dried)	19/01/2022	4	0	1	2	3	4	No
10	Conductive paint test 5 (4 layers fully dried)	19/01/2022	4	0	1	2	3	4	No
11	Conductive paint test 6 (5 layers fully dried)	19/01/2022	4	0	1	2	3	-	No
12	Conductive paint test 7 (cast dipped in Vaseline)	19/01/2022	2	0	1	2	3	-	No
13	3 layers conductive paint on Xantopren cast	20/01/2022	5	3	1	2	3	-	Yes

Table B2 - Details of gelatine lifts created the grades given to each sample

Gelatine lift number	Gelatine lift description	Gelatine lift date	Clarity grading	Durability grading	Flexibility grading				Successful unlock?
					1	2	3	4	
1	Gelatine lift (ended shrivelled)	02/12/2021	4	0	1	-	-	-	No
2	Gelatine lift G:W 1:5	14/12/2021	4	0	1	2	3	-	No
3	Gelatine lift G:W 0.5:5	14/12/2021	4	0	1	2	3	-	No
4	Gelatine lift G:W 0.25:5	14/12/2021	4	0	1	2	3	-	No

Table B3 - Details of conductive silicone lifts created the grades given to each sample

Provil lift number	Provil lift description	Provil lift date	Clarity grading	Durability grading	Flexibility grading				Successful unlock?
					1	2	3	4	
1	Provil + 'Bare conductive' lifted from wax	14/12/2021	1	0	1	2	3	4	No
2	Provil + 'Bare conductive' lifted from plasticine	14/12/2022	1	0	1	2	3	4	No
3	Provil + 'Bare conductive' on Provil with Vaseline	15/12/2021	2	0	1	2	3	4	No
4	Xantropen test 1	15/12/2022	2	0	1	2	3	4	No
5	Xantropen test 2	15/12/2023	2	0	1	2	3	4	No
6	Xantropen test 3	15/12/2024	1	0	1	2	3	4	No
7	Provil + conductive paint on Xantropen cast w/ hairspray	20/01/2022	2	0	1	2	3	4	No
8	Provil + conductive paint on Xantropen cast w/ Vaseline	20/01/2023	3	0	1	2	3	4	No
9	Provil + conductive paint on Xantropen cast w/ Vaseline applied with syringe	20/01/2024	5	4	1	2	3	4	Yes
10	Provil + conductive paint over glycerine	01/02/2022	1	0	1	2	3	-	No
11	Provil + conductive paint over coconut oil	01/03/2022	3	0	1	2	3	-	No
12	Provil+ paint 1:0.25 on Vaseline	01/03/2022	3	0	1	2	3	-	No
13	Provil+ paint 1:0.5 on Vaseline	01/03/2022	4	0	1	2	3	-	No
14	Provil base:activator:paint 1:0.5:0.5	01/03/2022	4	0	1	2	3	4	No
15	Provil + paint 1:0.5 in humidifier	01/03/2022	4	0	1	2	3	-	No

16	Thin layer Provil + paint Test 1	03/03/2022	5	4	1	2	3	-	Yes
17	Thin layer Provil + paint Test 2	03/03/2022	5	4	1	2	3	4	Yes
18	Thin layer Provil + paint Test 3	03/03/2022	5	4	1	2	3	-	Yes
19	Thin layer Provil + paint Test 4	03/03/2022	5	4	1	2	3	4	Yes
20	Thin layer Provil + paint Test 5	03/03/2022	5	4	1	2	3	4	Yes
21	Thin layer Provil + paint Test 6	03/03/2022	5	4	1	2	3	3	Yes
22	Participant 1 Provil + paint on Xantropen	08/03/2022	3	0	1	2	3	4	No
23	Participant 1 Provil + paint on wax	08/03/2022	4	0	1	2	3	4	No
24	Provil + paint 1:0.5 on plasticine	09/03/2022	3	0	1	2	3	-	No
25	Provil + paint on wax	15/03/2022	5	3	1	2	3	-	Yes
26	Provil + paint on play doh	15/03/2022	3	2	1	2	3	-	No
27	Provil + paint longevity test 1:0.5:0.5	23/03/2022	5	5	1	2	3	4	Yes
28	Participant 1 Provil + paint on Xantropen Test 2 1:0.5:0.5	30/03/2022	3	5	1	2	3	4	Yes
29	Participant 2 Provil + paint on Xantropen 1:0.5:0.5	30/03/2022	4	0	1	2	3	4	No
30	Participant 3 Provil + paint on Xantropen 1:0.5:0.5	14/04/2022	4	0	1	2	3	4	No
31	Participant 3 Provil + paint on Xantropen 1:0.5:0.5 cast 2	14/04/2022	4	1	1	2	3	4	Yes
32	Participant 4 Provil + paint on Xantropen 1:0.5:0.5	27/04/2022	3	1	1	2	3	4	No
33	Participant 5 Provil + paint on Xantropen 1:0.5:0.5	04/05/2022	4	1	1	2	3	4	No
34	Participant 1 lift off new cast	04/05/2022	4	0	1	2	3	4	No

35	Provil + paint on thin layer acrylic paint	24/05/2022	2	0	1	2	3	4	No
36	Provil + paint on dried playdoh	24/05/2022	4	0	1	2	3	4	No
37	Provil + paint on playdoh 30 min before print	24/05/2022	2	0	1	2	3	4	No
38	Provil + paint on play doh 3 hr before print	24/05/2022	1	0	1	2	3	4	No
39	Provil + paint on fresh playdoh	24/05/2022	4	0	1	2	3	4	No
40	Provil + paint on melted soap	24/05/2022	3	0	1	2	3	4	No
41	Provil + paint on washed soap	24/05/2022	2	0	1	2	3	4	No
42	Provil + paint on wax	24/05/2022	4	0	1	2	3	4	No
43	Provil + paint components heated in water bath	31/05/2022	3	0	1	2	3	4	No
44	Participant 6 Provil + paint set with pressure	01/06/2022	4	0	1	2	3	4	No
45	Participant 8 Provil + paint set with pressure	28/06/2022	4	0	1	2	3	4	No
46	Provil + paint on cast heated to 100C	29/06/2022	1	0	1	2	3	4	No
47	Provil + paint on chilled cast	07/07/2022	3	0	1	2	3	4	No
48	Provil + paint set with pressure	07/07/2022	4	0	1	2	3	4	No
49	Provil + paint set with pressure of paint can	07/07/2022	3	0	1	2	3	4	No
50	New paint pot tested with Provil	13/07/2022	3	5	1	2	3	4	Yes
51	Provil + paint cast & components chilled	13/07/2022	4	5	1	2	3	4	Yes
52	Provil + paint only cast chilled	13/07/2022	4	5	1	2	3	4	Yes
53	Provil + paint only cast chilled set with pressure	13/07/2022	4	3	1	2	3	4	Yes
54	Participant 1 New paint	26/07/2022	4	5	1	2	3	4	Yes
55	Participant 3 New paint	26/07/2022	5	5	1	2	3	4	Yes

56	Participant 4 New paint	26/07/2022	4	0	1	2	3	4	No
57	Participant 5 New paint	26/07/2022	4	5	1	2	3	4	Yes
58	Participant 6 New paint	26/07/2022	4	5	1	2	3	4	Yes
59	Participant 7 New paint	26/07/2022	5	5	1	2	3	4	Yes
60	Participant 8 New paint	26/07/2022	5	5	1	2	3	4	Yes
61	Provil + paint storage test (hot)	26/07/2022	5	5	1	2	3	4	Yes
62	Provil + paint storage test (cold)	26/07/2022	5	5	1	2	3	4	Yes
63	Provil + paint storage test (humid)	26/07/2022	5	5	1	2	3	4	Yes
64	Provil + paint on gum	02/08/2022	5	0	1	2	3	4	No
65	Provil + paint on wax	02/08/2022	5	5	1	2	3	4	Yes
66	Provil + paint on acrylic paint (blob)	02/08/2022	2	0	1	2	3	4	No
67	Provil + paint on unbaked clay	02/08/2022	4	5	1	2	3	4	Yes
68	Provil + paint on playdoh left for 30 min	02/08/2022	3	0	1	2	3	4	No
69	Provil + paint on playdoh left for 3 hours	02/08/2022	1	0	1	2	3	4	No
70	Provil + paint on fresh playdoh	02/08/2022	4	5	1	2	3	4	Yes
71	Provil + paint on dried playdoh	02/08/2022	4	5	1	2	3	4	Yes
72	Provil + paint on plasticine	02/08/2022	4	5	1	2	3	4	Yes
73	Participant 11	04/08/2022	4	0	1	2	3	4	No
74	Participant 12	04/08/2022	4	5	1	2	3	4	Yes
75	Participant 13	04/08/2022	5	5	1	2	3	4	Yes
76	Participant 14	11/08/2022	4	0	1	2	3	4	No

77	Provil + paint on anti-climb paint (primary)	11/08/2022	3	0	1	2	3	4	No
78	Provil + paint on anti-climb paint (secondary)	11/08/2022	4	5	1	2	3	4	Yes
79	Provil + paint on baked clay	11/08/2022	4	5	1	2	3	4	Yes
80	Participant 10	30/08/2022	4	0	1	2	3	4	No