Enabling Fingerprint Presentation Attacks: Fake Fingerprint Fabrication Techniques and Recognition Performance

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Abstract
Fake fingerprint representation pose a severe threat for fingerprint based authentication systems. Despite advances in presentation attack detection technologies, which are often integrated directly into the fingerprint scanner devices, many fingerprint scanners are still susceptible to presentation attacks using physical fake fingerprint representation. In this work we evaluate five different commercial-off-the-shelf fingerprint scanners based on different sensing technologies, including optical, optical multispectral, passive capacitive, active capacitive and thermal regarding their susceptibility to presentation attacks using fake fingerprint representations. Several different materials to create the fake representation are tested and evaluated, including wax, cast, latex, silicone, different types of glue, window colours, modelling clay, etc. The quantitative evaluation includes assessing the fingerprint quality of the samples captured from the fake representations as well as comparison experiments where the achieved matching scores of the fake representations against the corresponding real fingerprints indicate the effectiveness of the fake representations. Our results confirmed that all except one of the tested devices are susceptible to at least one type/material of fake fingerprint representations.

Index Terms
Fingerprint Recognition, Presentation Attacks, Fake Fingerprint Fabrication, Presentation Attack Evaluation

I. INTRODUCTION

In our modern world there is an ever growing need to identify individuals, especially for personal authentication, e.g. to unlock a smart phone, to authorize a banking transaction or to withdraw some money from an automated teller machine. Biometric recognition systems provide a convenient way to perform this necessary authentication step without having to hassle with keys, smart cards or having to remember complicated passwords and thus, have the potential to provide some extra security as well. According to the ISO/IEC standard TR24741:2018, biometric recognition is defined as “the automated recognition of individuals based on their biological and behavioural characteristics.” [1]. The most commonly used biological traits include fingerprints, face, iris and voice. For each of those traits, a special device to capture samples of the particular trait is needed, commonly denoted as biometric capturing device or formerly as biometric scanner. Most modern fingerprint scanners are based on optical or capacitive technology and can be built as small as a one cent coin, enabling the integration of fingerprint recognition technology in a great variety of different devices, from door locks over laptop computer to smartphones. Capturing a fingerprint small is a quick and reliable process which enjoys a high users’ acceptance. All those advantages lead to the widespread utilisation of fingerprint recognition and made fingerprints the predominant biometric trait.

Despite those advantages, fingerprint recognition technology is far from being perfect. In contrast to passwords and tokens, a biometric trait can neither be changed nor revoked. Thus the legitimate users of a biometric recognition system are put in a dangerous situation, if biometric data gets compromised or is abused. Researchers found several different vulnerabilities of biometric recognition systems in general and fingerprint systems in particular. These attack possibilities or vulnerabilities can be grouped into eight different attack points [2]: (1) presentation attack, (2) biometric signal replication, (3) feature modification, (4) replacing features, (5) overriding the matcher, (6) replacing templates, (7) modifying data through the channel and (8) altering the decision. Except the first one, the presentation attack, all remaining 7 attack possibilities refer to alterations in digital signals or digitally stored information, while the first one refers to a “physical” or sensor-level attack to the biometric capturing device by presenting a “spoof” or “fake” representation which is a reproduction of a genuine biometric trait. These remaining 7 attack possibilities can be prevented by employing encryption and device authentication on the transmission channels as well as template protection for the database. The presentation attack however, is a direct physical attack against the sensor and one of the most important attack possibilities [3, 4] as the attack target (the sensor) is available, it is easy to implement without further knowledge about the internals of the biometric recognition system and since there exist several well
documented and easy to realise methods for fake fingerprint production which do not require any particular prior knowledge and are not cost expensive. In the following we will focus on this particular attack, the presentation attack in the scope of fingerprint recognition.

As fingerprint systems are regarded as highly reliable and are often used to secure confidential and important information, a successful presentation attack (i.e. the biometric recognition system does not detect the attack and the fake representation qualifies the fake as genuine sample of the corresponding subject) poses a severe threat to fingerprint recognition systems. By launching a successful presentation attack, an adversary can gain unauthorised access to a system by “impersonating” a genuine user and then access the confidential data. Several different methods of generating fake fingerprint representation (also denoted as spoofing artefact) have been reported, most of them using materials like gelatine, wax, wood glue, moldable plastics, clay, dental impression paste and silicone. A detailed review on those materials is given in Section III. Due to the high risk originating from successful presentation attacks, researchers and industry implemented ways to detect and/or prevent presentation attacks in order to secure their biometric systems. Those systems can either be implemented in hardware or software and are denoted as presentation attack detection (PAD) systems. PAD systems are out of the scope of this work.

The rest of this paper is organised as follows: Section III provides a short overview on fingerprint recognition and the fingerprint features used to identify an individual. Furthermore it summarised the different types of fingerprint capturing devices. Section III gives a literature review on different fingerprint presentation attack methods and different fake fingerprint fabrication materials. In Section IV the fabrication of different types of fake fingerprint representations is described and an experimental evaluation of several commercial-off-the-shelf (COTS) fingerprint capturing devices and using the fake fingerprint representations is conducted. Finally, Section V concludes this paper.

II. FINGERPRINT RECOGNITION

A typical biometric recognition system consists of the following modules/stages: acquisition of the sample, pre-processing, feature extraction, comparison, final decision [5]. It works in two phases. The first one is the enrolment, where one or multiple samples of each subject are captured, pre-processed and the extracted features are stored as biometric templates in a database. The second one is the verification/identification, where a new biometric sample is captured, again pre-processed and the extracted features are compared against the templates of the corresponding subject (verification) or against all templates in the database (identification) to arrive at the final decision (genuine or impostor in case of verification and a rank of candidate matches in identification). In fingerprint recognition systems, typically three to five samples are captured in order to derive a template that is independent of variations in placement, deformation and rotation of the fingertip.

The skin on the inside of a finger is covered with a pattern of ridges and valleys. These ridges are not continuous but can either end, fork or form an island. These ridge patterns are believed to be unique for each person and relatively stable over time. According to Maltoni et al. [5] a fingerprint refers to “a flowing pattern consisting of ridges and valleys on the fingertip of an individual”. Figure I shows a typical impression of a fingerprint with some of the main features named and highlighted. Most fingerprint recognition systems rely on specific characteristics in the pattern of the ridges, which can be separated in three different levels:

1) Global level (see figure 2): Macro details such as the pattern or type of ridges and valleys are detected. Ridges exhibit several regions where they resemble a distinct shape, usually classified into deltas, loops and whorls.

2) Local level (see figure 3): Minutiae points, which are the major feature to describe fingerprints, describe different anomalies in the ridge structure, like ridge endings and bifurcations. A minutiae point is represented by its location (x and y coordinate), the ridge direction (angle θ) and the type of anomaly (ending or bifurcation).

3) Very fine level (see figure 4): Small details such as incipient ridges and sweat pores can be detected if the capturing devices has a sufficient resolution (1000 dpi at least) and utilised as well. Pores can be further classified into open or closed, depending on their position on the ridges. Currently, those level 3 features are much harder to forge than level 1 and level 2 features.

A typical fingerprint contains about one hundred minutiae points. The area that is captured by usual fingerprint sensors contains about 30-50 minutiae points. For a positive identification that stands in European courts, at least 12 minutiae have to be unambiguously identified in a fingerprint, while most commercial fingerprint recognition systems are able to perform a successful positive match with a minimum of 8 minutiae.

A. Fingerprint Sensing Technologies

Prior to extracting the fingerprint features necessary to perform the biometric recognition, a sample of the fingerprint has to be captured. Such a sample can be acquired using different technologies of capturing devices based on the optical properties of the skin surface, electrical properties of the skin, thermal properties of the ridges and air gaps of the valleys or ultrasonic reflectance properties of the skin [5]. The first COTS fingerprint capturing devices appeared on the marked in the 1980s and were mainly based on optical sensing technology. Nowadays there is a shift towards capacitive technology and more recently to ultrasonic devices, especially in recent smartphones as these sensors are small enough to be built into virtually any appliance, while optical devices are still predominant in high-security applications. Most of the fingerprint capturing devices have a...
resolution of 500 dpi at least. Some fingerprint capturing devices are shown in Figure 5. Each of those different technologies is described in the following.

a) **Optical devices:** are the most widely used ones, followed by capacitive devices. The finger is placed on a glass surface, which is essentially a transparent prism. An optical fingerprint capturing device contains some kind of light source to illuminate the fingertip surface (usually based on light emitting diodes) and a camera to capture the image. Most optical devices use the total internal reflection (TIR) principle. The fingertip is placed directly on the glass plate with the ridges directly touching the glass plate. The surface is illuminated by the internal light source through one side of the prism. The light entering the prism is reflected at the valleys and absorbed at the ridges, creating a contrast between ridges and valleys. The reflected light is projected on the camera through a system of lenses and captured by the camera. Optical devices are sensitive to spoofs that are composed of materials exhibiting the same light reflectance as human skin. A special kind of optical devices are multispectral capturing devices which utilise more than one light source or a light source capable of emitting different wavelengths of light.
Figure 4. Level 3 fingerprint details - pores, line shapes, incipient ridges, creases, wrats and scars. Image taken from [6].

Figure 5. Fingerprint capturing devices, from middle left clockwise: Lumidigm Venus V311 (optical multispectral), Lumidigm Mercury M311 (optical multispectral), Integrated Biometrics Columbo (active capacitive), Integrated Biometrics Curve (active capacitive), Next Biometrics NB-3010-U (thermal), Upek Eikon II Swipe (capacitive swipe), Suprema Realscan G1 (optical), DigitalPersona URU5160 (optical), Zvetco Verifi PS000 (capacitive), DigitalPerson Eikon 710 Touch (capacitive)
This should improve the resistance to presentation attacks. More recently also contactless optical fingerprint capturing devices entered the market. Those devices essentially consist of an image sensor and an auxiliary light source. They do not require direct contact between the fingertip and the sensor, which eliminates hygienic issues at the one hand and problems with dirt and soiling of the sensor surface on the other hand.

b) Electric field devices: also called solid state devices or active capacitive sensors. These devices consist of an array of pixels able to measure differences in the electric field. They create an electric field between the sensor surface and the finger surface. Due to variations in the conductive layer of the skin, which is located beneath the skin surface, there are variations in the electric field of the ridges and valleys, which are then measured and translated into a digital representation (i.e. an output image). Those sensors have kind of a metal or conductive point (usually a bar at the bottom of the sensor surface) which has to be touched in order for the sensor to create the electric field.

c) Capacitive devices: also known as passive capacitive sensors. As the name suggests, those devices exploit the fact that there is a difference in the capacity between the ridges and valleys of the fingertip as the ridges directly touch the sensor surface, while there is a small air gap between the sensor surface and the valleys. This difference in the capacitance values is measured. The finger surface acts as one electrode of a capacitor with the sensor surface as the second electrode. The whole sensor surface consists of capacitance sensitive “pixels”. Capacitive sensors can be built very small and even integrated into smart cards. They are more vulnerable to gelatin based fake fingerprint representations.

d) Thermal devices: are based on a combination of silicon and a pyroelectric material, which measures differences in temperature and converts these into a digital output signal. When the fingertip is placed at the sensor, the ridges directly touch the sensor surface, changing the sensor surface temperature, while the valleys are isolated by a small air gap between the skin and the sensor surface, hence the temperature remains constant where the valleys are located. This creates the necessary difference in temperatures between ridges and valleys which can then be measures. A disadvantage is that after some time the image disappears as the sensor reaches a thermal equilibrium, i.e. there is a constant temperature all over the sensor surface. In order to reduce production costs and device dimensions (smaller sensor area), the first thermal devices were built as so called swipe sensors, i.e. sensor surface does not cover the whole fingertip area but only a small bar with the same width as the width of the fingertip but only a few pixels in height. The finger is slid over the sensor surface (in a swiping motion) and the sensor generates the output image by stitching together small image patches of the different regions of the fingertip during the sliding process. In general, swipe sensors are considered as less user-friendly due to the necessary swiping motion. Thermal sensors are rarely used nowadays.

e) Ultrasound devices: These devices exploit the difference in the acoustic impedance between the skin of the ridges and the air of the valleys (the ridges directly touch the sensor surface). The sensor itself is an acoustic transmitter, which transmits an acoustic signal towards the fingertip surface and captures the signal which is received. The frequency range of those devices is from about 20 kHz to several GHz. Higher frequencies correspond to higher resolution of the resulting images. Ultrasound devices used to be more expensive than other fingerprint capturing devices but with the advent of new fabrication technologies and in-screen sensing solutions for smartphones, those devices became more popular.

III. LITERATURE REVIEW ON FINGERPRINT PRESENTATION ATTACKS

There are several possibilities to launch a presentation attack or to spoof a fingerprint scanner. All of them have in common that someone wants to trick the system, either in order to gain illegitimate access to it or to impersonate another person for various reasons (e.g. to have a shared personality). For a presentation attack to be successful, not only the spoofing detection
of the fingerprint scanner has to be circumvented/tricked, but also during the matching process, the match score has to be high enough to allow access to be granted. Besides creating a spoofing artefact, other options include: forcing the legitimate user to present his finger to the scanner device, presenting a cadaver finger to the device or use the latent imprint left on the scanner device. As we focus on physical fake fingerprint representation (spoofing artefacts), the aforementioned other possibilities are out of scope of this work.

Creating a physical fake fingerprint representation usually involves two steps: creation of the mould (negative imprint) and creating of the cast. At first, either the legitimate user presses his finger on the mould material (cooperative duplication), or some kind of latent representation is used for that (non-cooperative duplication). Afterwards, depending on the mould it needs some time to cure. Afterwards the cast material is filled in the mould, let there to cure and removed afterwards, resulting in the final fake fingerprint representation. Table I listing common mould and cast materials and techniques. Besides the mould-cast method, there are also some materials for which no mould is needed, i.e. the genuine fingerprint is directly applied on the cast material. These materials are listed in Tab. II. In the following, the cooperative and non-cooperative duplication are described in more detail.

A. Cooperative Duplication

The first variant of creating an artificial (fake) fingerprint is cooperative duplication. This involves the active participation of the live subject (fingerprint donor). The finger of the subject is at first pressed on the surface of the mould material, usually some kind of cast, dental impression material, plaster or modelling clay. Once the negative impression of the finger is fixed on it, the finger is removed and depending on the material, the mould is cured in an oven or at room temperature for some time. The actual spoof (cast) is then created by filling the mould with some liquid material (e.g. silicone, latex, gelatin or glue) and left in the mould until it has hardened. Once removed, the fake fingerprint (spoof) is created. Usually spoofs created by cooperative duplication are of higher quality than the ones created by non-cooperative duplication.

B. Non-Cooperative Duplication

There are several ways to create a fake fingerprint without the cooperation of the genuine subject. The first one are latent fingerprints, left on a surface by the subject. These latent prints can be lifted with powder and then covered with Scotch tape to lift the print. This print can directly be used as a fake fingerprint representation. Another method is to use a PCB (printed circuit board) to enhance the quality of the fake fingerprint. At first the fingerprint is placed on a transparency and brushed with black powder. Afterwards a digital photograph of the fingerprint is taken to create a mask, which is then placed on the PCB and etched using UV light. This PCB imprint now serves as a mould which can now be filled with some liquid material in the same way as the moulds in cooperative duplication. Another ways of non-cooperative duplication are fingerprint reactivation, where a latent print on the sensor itself is reactivated, e.g. by breathing or placing a water-filled plastic bag on the sensor surface in order to fool the sensor. Using a cadaver fingerprint and fingerprint synthesis (creating a synthetic fingerprint based on a biometric template) can also be utilized to acquire a fake fingerprint in an non-cooperative way.

In the rest of this work we focus on cooperative duplication only. All of the tested moulds and cast materials involve cooperative duplication.

IV. EXPERIMENTAL EVALUATION

In the following the evaluation methodology and experimental protocol for fabricating and testing the spoofed fingerprint representations are described. Afterwards the fabrication of the different moulds is described in detail, followed by the fabrication of the different casts. Finally, the evaluation results in terms of fingerprint quality as well as matching scores are given and discussed.

A. Evaluation Protocol and Methodology

During our experiments we utilised five COTS fingerprint scanner devices to cover most of the available sensing technologies, including optical, thermal as well as capacitive:

- Lumidigm Venus V311 (optical, multispectral) [21]
- Suprema RealScan G1 (optical) [22]
- Next Biometrics NB-3010-U (thermal) [23]
- Integrated Biometrics Columbo (active capacitive) [24]
- Zvetco Verifi P5000 (passive capacitive) [25]

To evaluate the effectiveness of the fabricated spoof fingerprints, we used a two step protocol. At first we fabricated a small number of moulds and casts for each type of material. The casts were presented to the fingerprint scanners and the result in terms of fingerprint quality, evaluated using Neurotechnology VeriFinger’s (Version 10.0) [26] built-in fingerprint quality assessment was recorded. If the scanner did not react at all while presenting the spoofed representation or if it detected it as a spoof, there is no quality value recorded.
Afterwards, the five best working materials/spoof types in terms of fingerprint quality were selected for the production of a larger number of spoofed fingerprints from 15 different subjects. These spoofs were presented to the fingerprint scanners and enrolled in the database (the respective template was created and stored). Afterwards, genuine impressions of the subjects’ fingers were enrolled as well. By comparing the templates created from the spoofed representation to the ones created from the genuine subject’s real finger (bona fide), a quantification of the spoofed representations effectiveness can be done based on the matching scores.

B. Fabrication of the Moulds

Several different types of moulds were created tested which are described in the following:

a) Cast: : For creating this mould, modelling cast from Knauf was used. The cast was first mixed with tap water. Then it was let for curing about 6 min. After that the finger was put and pressed into the clay for about 3 min. Then it was let for curing about 30 min until it hardened. As an alternative, it was first let for curing 10 min instead of 6 min, which creates a flat impression of the fingerprint instead of a deep one. An example image can be seen in Fig. 4.

b) Candle wax: : Wax was heated in a small glass bowl on an electric cooking plate at first (1 min on level 5, then about an additional minute on level 2 until it was completely molten). Afterwards we let it cool down in the glass bowl for about 5 min, then the finger is pressed into the semi hardened wax. Some candle wax moulds are depicted in Fig. 8.

c) Acrylic: : The acrylic was put in a small glass bowl as well and let there for curing about 2h. Afterwards the finger was pressed into the acrylic for about 1 min to create the imprint. With the acrylic we were not able to produce good imprints as either it sticked to the finger or it was to dry to create a good impression - too many friction ridges and no smooth surface. Hence, this type of mould was not used during the subsequent tests.

d) Silicone: : Same procedure as with the acrylic. Silicone was put into a small glass bowl and cured for about 2h. Afterwards the finger was pressed into it. Again, no good impression due to friction ridges and non-smooth surface. This type of mould was not used during the subsequent tests.

e) Hair wax: : The wax was prepared in a bowl and mixed with window colour (otherwise it would be transparent) and the finger was pressed into it immediately after pouring it into the bowl. Due to the high moisture of the hair wax, no good impression was possible and the window colour did not cure/dry properly. This type of mould was not used during the subsequent tests.

f) Play-Doh (putty): : At first some Play-Doh was prepared and spread on a surface. Afterwards the finger is pressed into the clay to create the impression. By applying varying pressure, the depth of the imprint can be varied (from flat to deep).

g) Siligum: : Siligum is a dental cast material. To create the mould, a round block of Siligum was formed, the finger was pressed into the mould and then the mould was left at room temperature for an hour to cure and harden. Example Siligum moulds are shown in Fig. 6.

h) Fimo: : Fimo is a modelling clay which is available in different variants. Some cure at room temperature, some need to be put in the oven for curing. We used the latter one. At first the finger was pressed into a block of Fimo, using the thumb of the other hand to increase the pressure. Afterwards, the block was put in the oven at 110°C for 30 min and then left at room temperature for another 2 hours to cure. Several Fimo moulds are depicted in Fig. 10. The Fimo moulds were easier to produce and worked better than the cast and wax ones, thus we decided for Fimo and Cernit moulds to produce the majority of the casts.

i) Cernit: : Cernit is basically the same type of modelling clay as Fimo, just a different manufacturer. Again to create the mould, the finger was pressed into a block of Cernit, with the thumb of the other hand to apply additional pressure. Then the block was put in the oven for 30 min at 110°C and left at room temperature for another 2 hours to cure. A few Cernit moulds can be seen in Fig. 11. For most subsequent casts (except for the initial tests), either Fimo or Cernit moulds have been used.

C. Fabrication of the Casts

The casts were created by pouring the cast material into one of the moulds. For most types of casts, either the cast moulds or the Cernit/Fimo moulds were used. Fig. 12 shows examples of all the different casts that were used during the experiments. Each attempt (cast/mould combination) has a number, which is later used in subsection IV-D and IV-E to identify the results. The different cast materials and their fabrication are described in the following:

a) Candle Wax: : (Attempt #1) At first the candle wax is poured in a small glass bowl and heated on the electric cooking plate, same as for the mould, at first 1 min on level 5, then an additional minute on level 2 until it is completely melted. Afterwards it is cooled down for 5 min and then poured into the cast mould, left there for about 30 min to cool down and cure. Finally the cast is carefully removed from the mould. Fig. 13 shows some example images of the candle wax mould. It can be seen that some parts of the cast mould still stick to the candle wax cast. The candle wax cast is rather hard and inflexible, making it difficult to apply it to the fingerprint capturing devices without breaking it. It worked with the Lumidigm scanner, but all other scanners showed no reaction at all.

The first approach with candle wax did not work well with the tested fingerprint capturing devices. Hence we did a second try by mixing the liquid candle wax with graphite powder to increase the contrast and conductivity. Again, the cast is rather
Figure 7.  Mould made from cast

Figure 8.  Mould made from candle wax

Figure 9.  Mould made from Siligum
Figure 10. Mould made from Fimo

Figure 11. Mould made from Cernit

Figure 12. Overview of the casts
solid and does not work for most fingerprint readers. Example images of this second approach are depicted in Fig. 14. This approach made the results worse as now none of the fingerprint scanners showed any reaction.

The third attempt (Attempt #2) was to spread graphite powder inside the cast mould and then pouring the liquid candle wax into the mould in order to overcome the difficulties with removing the cast from the mould. However, this did not improve the situation, the cast was still difficult to remove from the mould and the results were comparable to the second attempt with the graphite powder mixture. Again, these casts only worked with the Lumidigm scanner.

The last attempt (Attempt #3 and #4) was to use the Play-Doh mould instead of the cast one. The liquid candle wax was poured into the Play-Doh mould and left there to cure for about 30min. Afterwards the cast was removed from the mould. This time, the removal procedure was much easier than with the cast mould and also the results with the fingerprint capturing devices were more promising, at least with the Lumidigm sensor. Fig. 15 shows some examples of this kind of cast. Again, this attempt only worked with the Lumidigm scanner while all others still showed no reaction at all.

b) Play-Doh:: The Play-Doh putty was put into the cast mould, left there for about 1 minute and then removed. Unfortunately none of the fingerprint capturing devices showed any reaction when the cast was presented to the sensor. None of the tested fingerprint scanners showed any reaction when the Play-Doh casts were presented to the scanner. Some Play-Doh casts are shown in Fig. 16.

c) Plasticine:: (Attempt #5) Red plasticine putty was put into the cast mould. The cast worked for the Lumidigm scanner but did not work for the other tested devices. Another problem with this type of cast is that it wears off over time and with each use due to the pressure that needs to be applied while presenting the cast to the fingerprint reader. Fig. 17 depicts some example images. The plasticine casts worked with the Lumidigm scanner. The RealScan scanner detected them as spoofed.
fingerprints. All other scanners showed no reaction at all.

The second variant (Attempt #6) of the plasticine cast was to mix plasticine with graphite powder in order to increase the conductivity for the capacitive sensors. These casts are shown in Fig. 18 and worked for the passive capacitive fingerprint reader but not for the active capacitive one.

d) Window Colour:: (Attempt #7 and #29) Red window colour was used in combination with the candle wax mould. It was poured into the mould and left there for 5 days to cure. Interestingly this type of cast worked with the thermal fingerprint scanner but with none of the other fingerprint scanners. A problem with this type of cast is again that it is a rather soft material which wears off rather quickly due to the pressure applied while presenting it to the fingerprint scanner. Some examples of this cast can be seen in Fig. 19.

The second attempt (Attempt #8) was to additionally apply graphite powder to the mould prior to pouring the window colour into the mould. Examples of this cast are depicted in Fig. 20. This approach significantly improved the results over the first one and the cast worked with all of the tested fingerprint capturing devices.

e) Fimo (Modelling Clay): (Attempt #16) The modelling clay was put into the cast mould to create a flat and a normal cast. The first attempt was to use the Fimo cast prior to curing which only worked with the Lumidigm scanner. The flat ones worked better than the normal, thick ones. The second attempt was to use the Fimo casts after curing in the oven for 30 min at 110°C and then further curing for 2h at room temperature. These casts worked worse than the ones prior to curing, again they only worked with the Lumidigm scanner. Several examples of different Fimo casts can be seen in Fig. 21.

f) Silicone:: (Attempt #9) Silicone was poured into the cast mould and left there 5 days for curing. Fig. 22 shows some examples of the silicone casts. The problem with this cast is that it develops many small air bubbles which impact the cast

Figure 16. Play-Doh casts

Figure 17. Plasticine casts

Figure 18. Plasticine casts with graphite powder
quality. This cast did work with none of the tested fingerprint capturing devices.

g) Silicone (Pour):: (Attempt #17) This is a different type of silicone but the casts were done in the same way as the silicone ones using the cast mould, the wax mould and the Play-Doh mould. The silicone (pour) casts are depicted in Fig. 23 and Fig. 24. They worked with the Lumidigm and the thermal fingerprint scanner. After applying a small layer of graphite, it worked with the passive capacitive scanner as well. Example images of the graphite powder layer applied casts can be seen in Fig. 25.

h) Siligum:: (Attempt #18 and #25) Siligum is a dental modelling material. It was pressed into the cast mould and the left there for about half an hour to cure. Removal of the cast from the mould was easy and without any residuals of the mould on the cast. Some example images are shown in Fig. 26. This type of cast worked with the Lumidigm scanner, but none of the other tested devices showed any reaction.

i) Formable Art Eraser:: (Attempt #19) A special kind of eraser that can be formed. Again it was used in combination with the cast mould by pressing a piece of the formable art eraser into the mould and removing the cast from the mould after a few minutes. Fig. 27 shows some example images. Again this type of cast only worked with the Lumidigm scanner, while the active capacitive and the thermal ones showed no reaction and the passive capacitive one detected it as a spoofed fingerprint. Applying an additional, small layer of graphite powder did not improve the results.

j) “Uhu” Glue:: (Attempt #20) For this attempt, some glue from the brand “Uhu” was poured into the cast mould and let there over night to cure. Otherwise it was removed from the mould to obtain the cast. Again, a problem with this time of cast are the many air bubbles enclosed in the cast, lowering the fingerprint sample quality. The cast worked with the two optical fingerprint scanners as well as with the thermal one. Fig. 28 depicts an example of this type of cast as well as the captured
Figure 22. Silicone casts

Figure 23. Silicone (pour) casts, cast mould

Figure 24. Silicone (pour) casts, left: wax mould, right: Play-Doh mould

Figure 25. Silicone (pour) casts with graphite powder
k) Wood Glue: (Attempt #10) The first attempt was to pour a small amount of wood glue into the candle wax mould in order to create a thin (3-4 mm) cast. The wood glue was left in the mould for 24h to cure. A second attempt was to use thicker layer (about 20 mm) which needed a few days to cure. The thick cast did not work at all, the thin one worked with the Lumidigm scanner. Fig. 29 shows some examples of the thin one. One problem with this type of cast are the small air bubbles enclosed in the cast.

The third attempt (Attempt #11) was to use an even thinner layer of wood glue (less than 1 mm), again in combination with the candle wax mould. Some example images of these casts are depicted in Fig. 30. For those casts to work it is necessary to put them onto the finger, otherwise the fingerprint scanners do not detect the cast. The extra thin version worked with the Lumidigm and the thermal scanner. By applying a thin layer of graphite powder (as depicted in Fig. 31), it worked with the active capacitive and the passive capacitive scanner as well.

l) Acrylic: (Attempt #12) The acrylic was put into the cast mould and left there 24h for curing. Fig. 32 shows some example images. As it can be seen, the structures on the cast are rather coarse and there are some holes, making the surface non homogeneous. These casts worked with the Lumidigm scanner and the RealScan detected them as spoofed fingerprints. All other scanners showed no reaction at all.

m) Sealing Wax: (Attempt #13) The sealing wax was heated in the same way as the candle wax and poured into the cast mould while it was still liquid. After curing it was removed from the mould. Examples of this cast can be seen in Fig. 33. They again only worked with the Lumidigm scanner, the RealScan scanner showed that the “finger is too dirty”, all other devices showed no reaction at all.
Figure 29. Wood glue (thin) casts

Figure 30. Wood glue (extra thin) casts

Figure 31. Wood glue (extra thin) casts with graphite powder

Figure 32. Acrylic casts
n) **Construction Adhesive::** (Attempt #14) The construction adhesive was poured into the candle wax mould and left there about an hour for curing. Again, a problem with this type of mould are the small air bubbles enclosed in it, as it can be seen in Fig. 33. These casts worked with the Lumidigm scanner. However, the transparent areas of the cast were not detected by the scanner. This was improved by putting a finger behind the cast. The RealScan device detected it as a spoofed finger, the passive capacitive scanner as bad object, the active capacitive one showed no reaction and with the thermal one it worked as well.

The second attempt (Attempt #14) was to use an extra thin construction adhesive cast as depicted in Fig. 35. These casts worked with the Lumidigm, the passive capacitive and the thermal scanner while the active capacitive one showed no reaction.

   a) **Sellotape with Graphite Powder::** (Attempt #21 and #26) For this type of cast, no mould was necessary. The finger was put on a piece of sellotape which was then applied with a thin layer of graphite powder. Fig. 34 depicts some example image of this cast. After applying a second layer of sellotape and covering the back of the tape with the palm of the hand or some towel, it worked with the Lumidigm scanner but none of the other fingerprint scanners showed a reaction.

   p) **Gelatine with Cornflour and Food Colouring::** (Attempt #22) A thin plate of gelatine was applied with some cornflour and food colouring. Then the finger was placed on the plate and the imprint was created. Again, no mould is needed. This cast worked with all fingerprint scanners except the Lumidigm one. Fig. 36 shows some example images.

   q) **“Blu Tack”::** (Attempt #23) Blu Tack is kind of an adhesive tape by Scotch. Again, the finger was just pressed into the piece of Blu Tack, no mould is needed. An example of this cast can be seen in Fig. 37. This type of cast only worked for the Lumidigm scanner again, while all others showed no reaction at all.
Figure 36. Sellotape with graphite powder casts

Figure 37. Gelatine with cornflour and food colouring casts

r) Modelling Clay “Eberhard”: (Attempt #24) The Eberhard modelling clay was pressed into the cast mould to create the cast. Afterwards it was directly applied to the different fingerprint scanners. An example of this cast is depicted in Fig. 39. It worked with the two optical scanners (Lumidigm and RealScan) while all others did not show any reaction.

s) Sellotape with Wax and Graphite Powder: (Attempt #26) The finger was again put on a piece of sellotape which was then applied with a thin layer of graphite powder. Instead of applying a second layer of tape, a small layer of candle wax was applied on the backside. Fig. 40 shows an example of this variant of cast. This variant of the sellotape cast worked with the Lumidigm scanner, while all other scanners showed no reaction again.

t) Uhu Glue with Green Food Colouring: (Attempt #28) The Uhu glue was mixed with green food colouring and then poured into the Fimo mould and left there a few hours for curing. Afterwards the casts were removed and presented to the different fingerprint scanners. The problem with this kind of cast is again that there are many air bubbles enclosed in the cast. None of them showed any reaction. Some example images of these casts are shown in Fig. 41.

u) Natural Latex: (Attempt #30) The natural latex was poured into the cast mould and left there for about 24h to cure. Afterwards it was removed from the mould. Fig. 42 shows some example images. These casts worked for all fingerprint scanners except the thermal one.

D. Spoofed Fingerprint Quality

Table III lists the fingerprint quality values for the different presentation attack (spoofing artefact) attempts and the five tested fingerprint scanners. The quality is evaluated using Verifinger’s built in fingerprint quality measure, which quantifies the quality as integer values from 0 to 100, with 0 indicating the lowest possible quality and 100 indicating the best possible one.

Figure 38. Natural latex casts
Figure 39. Natural latex casts

Figure 40. Sellotape casts with wax and graphite powder

Figure 41. Uhu glue casts with green food colouring

Figure 42. Natural latex casts
A “-” indicates that no template could be extracted, hence there is no quality value. As the table reveals, most spoofing attempts worked for the Lumidigm V311 scanner, followed by the NB-3010-U and the Verifi P5000 and IB Columbo while only two of the attempts worked with the Realscan G1. Most of the working attempts achieved rather high quality values (>50) which indicated a good quality of the artificial fingerprint artefacts. The overall best performing attempt was #30, corresponding to the natural latex casts. Attempt #8, #15, #17 and #21 also worked well for some of the fingerprint scanners. Hence, we decided to include only those five attempts in the matching performance experiments which are described in the next subsection.

### Table III

Fingerprint quality results of the different fingerprint spoofs (different casts). The quality values are in the range from 0-100, where 0 corresponds to the lowest quality and 100 to the highest possible quality. The first column indicates the attempt number, which is mentioned for each attempt in subsection IV-B. “-” means that there was either no reaction at all or the template could not be created due to low quality or spoof detected. The best working type of cast is highlighted in **bold**.

| Attempt # | Fingerprint Quality (range: 0-100) |
|-----------|-------------------------------------|
|           | Lumidigm V311 | Realscan G1 | IB Columbo | Verifi P5000 | NB-3010-U |
| 1         | 70 - 85       | -           | -          | -            | -          |
| 2         | 60            | -           | -          | -            | -          |
| 3         | 80 - 86       | -           | -          | -            | -          |
| 4         | 65            | -           | -          | -            | -          |
| 5         | 75            | -           | -          | -            | -          |
| 6         | 50            | -           | -          | -            | -          |
| 7         | -             | -           | -          | -            | 40 - 69    |
| 8         | 80 - 93       | -           | 69 - 74    | 60 - 91      | -          |
| 9         | -             | -           | -          | -            | -          |
| 10        | 42 - 61       | -           | -          | -            | -          |
| 11        | 40 - 90       | -           | 80         | 70           | 40 - 50    |
| 12        | 50 - 65       | -           | 60         | 65           | -          |
| 13        | 96            | -           | -          | -            | -          |
| 14        | 60 - 71       | -           | -          | -            | 44 - 50    |
| 15        | 42 - 97       | -           | 65         | 80 - 85      | -          |
| 16        | 60 - 80       | -           | -          | -            | -          |
| 17        | 80 - 92       | -           | 54         | 50           | -          |
| 18        | 56 - 62       | -           | -          | -            | -          |
| 19        | 45 - 59       | -           | -          | -            | -          |
| 20        | 72            | 73          | -          | -            | 65 - 75    |
| 21        | 85 - 99       | -           | 73 - 81    | -            | -          |
| 22        | -             | -           | 60         | 49 - 59      | 66 - 75    |
| 23        | 74            | -           | -          | -            | -          |
| 24        | 86            | 79          | -          | -            | -          |
| 25        | 74 - 79       | -           | -          | -            | 53         |
| 26        | 68            | -           | -          | 48           | -          |
| 27        | 90            | -           | -          | -            | -          |
| 28        | -             | -           | -          | -            | -          |
| 29        | 94            | -           | -          | -            | -          |
| 30        | 70 - 100      | 67 - 95     | 66 - 85    | 75 - 83      | 70 - 73    |

### E. Spoofed Fingerprint Matching Performance

Fake fingerprint samples from about 15 different subjects have been created using the window colour (Attempt #8), the extra thin construction adhesive (Attempt #15), the silicone (pour) (Attempt #17), the Sellotape with graphite powder (Attempt #21) and the natural latex (Attempt #30) as those attempts achieved the highest fingerprint quality values among the tested fingerprint scanners. Based on those spoofed fingerprint samples, a matching experiment has been conducted, which is summarised as matching score values using Neurotechnology Verifinger fingerprint matcher in Table IV. The matching scores range from 0 to about 2000, where 0 means no match and higher numbers indicate higher similarity. “-” means that no match was found. Typical genuine matches (original sample vs. original sample) are in the range of 50 - 500. The best performing match scores per fingerprint scanner are highlighted in **bold**. The selected user IDs represent the best and worst user in terms of matching score per scanner and spoofing attempt. As it can be seen, all of the listed scores (except for user ID 1, Attempt #21) achieved match scores higher than 50, i.e. they would have been accepted as genuine user in a real system (given that the that match threshold is set at an usual level).
Table IV

MATCHING RESULTS (NEUROTECHNOLOGY VERIFINGER) FOR THE SELECTED BEST PERFORMING SPOOFING ATTEMPTS. - MEANS THAT THERE WAS NO MATCH FOUND. BEST MATCHING SCORES PER FINGERPRINT SCANNER ARE HIGHLIGHTED **BOLD**.

| Attempt # | User ID | Lumidigm V311 | Realscan G1 | IB Columbo | Verifi P5000 | NB-3010-U |
|-----------|---------|---------------|-------------|------------|--------------|------------|
| 8         | 1       | 202           | -           | -          | 186          | -          |
| 8         | 2       | 83            | -           | -          | 186          | -          |
| 15        | 1       | 110           | -           | -          | -            | 91         |
| 17        | 1       | 117           | **146**     | -          | -            | 152        |
| 17        | 2       | 64            | 96          | -          | -            | 166        |
| 21        | 1       | -             | -           | -          | -            | -          |
| 21        | 2       | 72            | -           | -          | -            | -          |
| 30        | 1       | 188           | -           | -          | 159          | 154        |
| 30        | 2       | 121           | -           | -          | 99           | 232        |
| 30        | 3       | 126           | -           | -          | -            | -          |
| 30        | 3       | 76            | -           | -          | -            | -          |

F. Results Summary and Discussion

It turned out, that especially the multispectral Lumidigm V311 fingerprint scanner, which should be more resistant to presentation attacks than the others, was the easiest one to spoof, followed by the thermal scanner NB-3010-U from Next Biometrics, but the manufacturer did not claim any increased spoofing resistance for this scanner. The passive capacitive sensor Verifi P5000 was harder to spoof than the others, mainly due to its capacitive principle. The active capacitive one, the Integrated Biometrics Columbo was even harder than the passive capacitive one, again due to its capturing principle requiring an active electrical field between the object on the sensor surface and the sensor surface itself. Surprisingly, none of the fabricated spoofs was able to achieve valid match scores if compared against the bona fide samples. Hence, even though the scanner itself accepted the spoofs, we were not able to successfully fool the whole system as we would have been rejected during the matching step. However, active capacitive scanners are rarely used in practical applications due to their higher costs compared to the passive capacitive ones. The Suprema RealScan G1, which is another optical sensor, was hard to spoof as well but we still able to capture some of the spoofing attempts and even successfully match them against bona fide samples despite the integrated spoofing detection built into this device according to the manufacturer.

Regarding the types of spoofing materials, the most promising one was a cast or Fimo/Cernit mould in combination with natural latex casts combined with a thin layer of graphite powder (especially to spoof the capacitive sensors). The even simpler Sellotape approach in combination with some graphite powder also turned out to work really well. The other 3 well performing approaches are basically just replacing the cast material by either silicone (pour), construction adhesive or window colour while still maintaining the Fimo/Cernit mould for creating the casts.

V. Conclusion

Several different types of fake fingerprint representations have been produced and evaluated using five common commercial-off-the-shelf fingerprint scanner devices. The evaluation based on the fingerprint sample image quality as well as the matching scores between the fake representations and the real fingerprint samples revealed that all but one of the tested fingerprint scanners are susceptible to presentation attacks using the tested materials (successful template creation and matching). The only fingerprint scanner we were not able to spoof is the Integrated Biometrics Columbo, using an active capacitive sensing technique. Regarding the different materials to create the fake representations, natural latex, silicone (pour) and window colours turned out to work best in terms of successful template creation (circumventing the presentation attack detection mechanisms of the scanner devices) and matching. Hence, it is confirmed once more that presentation attacks using cheap materials and simple methods to create the fake representations still pose a severe threat to fingerprint recognition.

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| Reference                      | Method                  | Mould Material        | Artefact Material                  | Sensor Type                                      |
|-------------------------------|-------------------------|-----------------------|------------------------------------|-------------------------------------------------|
| Van der Putte and Keuning [7] | cooperative, non-cooperative | Plaster, Printed circuit board | Silicone cement | n/a                                             |
| Schuckers [8]                 | cooperative             | Dental impression material, Play-Doh | Clay | Desktop: capacitive, optical                    |
| Matsumoto [9]                 | cooperative, non-cooperative | Moulding plastic, Gelatine | Silicone + conductive ink | Desktop: optical, capacitive                     |
| Stén, Kaseva and Virtanen [10]| cooperative, non-cooperative | Hot glue, Printed circuit board | Grease + Breath, Gelatine | Desktop: Capacitive                              |
| Galbally et al. [11]          | cooperative             | Modeling putty, Modeling silicone | Modeling silicone | Desktop: optical, thermal swipe                 |
| Barral and Tria [12]          | cooperative             | Wax, Silicone, FIMO paste | Glycerine | Desktop: optical, capacitive touch, capacitive swipe, thermal swipe |
| Espinoza and Champod [3]      | cooperative, non-cooperative | Utile plast, Siligum | Latex, White glue | Desktop: multispectral                          |
| Espinoza, Champod and Margot [4]| cooperative, non-cooperative | Utile plast, Siligum, Printed acetate sheet | Latex, White glue | Desktop: optical                               |
| Rattani and Ross [13]         | cooperative             | Wax, Play-Doh, Plaster | Gelatine, Silicone, Wood glue, Ecoflex, Latex | Desktop: optical                               |
| Cao and Jain [14]             | non-cooperative         | Conductive ink, Latex, Wood glue | Latex, Wood glue | Smartphone: Touch                              |
| Gonzalo et al. [15]           | cooperative             | BluTack, Candle wax, Hot glue, Plasticine, Play-Doh, Siligum, Stamp wax, Unbranded silicon | Alginate, Art glue, Art glue + graphite, BluTack, Body wax + conductive paint, Candle wax (+ conductive ink), Facemask, Gelatine powder (+ conductive ink), Gelatine powder + glycerine, Gelatine sheet + (graphite/water), Plasticine (+ conductive ink), Play-Doh | Smartphone: Swipe, Touch                        |
| Kanich, Drahansky and Mézl [16]| cooperative, semi-cooperative | Printed circuit board | Fimo standard, Fimo Air, Kera, Hobby Mass, Magic putty, WePAM, Mamut glue, Acrylic sealant, Herkules glue, Oyumare, Play-Doh, Vegetable play-doh, Premo, Tropicalgin, Glass colors, Cernit, Gel wax, Kato, Siligum, Latex, Wax sheets | Desktop: optical, multispectral, pressure sensitive |
| Reference                  | Method                  | Artefact Material                                      | Sensor Type                                      |
|---------------------------|-------------------------|--------------------------------------------------------|-------------------------------------------------|
| Goicoechea-Tellería et al. | cooperative, non-cooperative | Play-Doh, Gelatine, Clay, Wood glue, Conductive ink, Latex, Latex + Graphite, Silicone, Silicone + graphite | Desktop: Thermal, Capacitive, Optical Smartphone: Swipe, Touch |
| Marcialis et al. [18] (LivDet09) | cooperative | Play-Doh, Silicone, Gelatine | Desktop: optical |
| Yambay et al. [19] (LivDet11) | cooperative | Play-Doh, Silicone, Gelatine, Wood glue | Desktop: optical |
| Orrù et al. [20] (LivDet19) | cooperative | Mix1, Mix2, Liquid Ecoflex, Ecoflex, Body double, Gelatine, Latex, Wood glue | Desktop: optical, thermal swipe |