Damage invariant and high security acquisition of the internal fingerprint using optical coherence tomography

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***Abstract*—Fingerprints are widely used for biometric authentication, identification, and access control. However, most current acquisition devices obtain fingerprints from the surface of the skin and are thus inherently restricted by the surface 2D representation they offer. Using an emerging fingerprint acquisition technology – optical coherence tomography – to access an internal fingerprint under the skin surface, this paper serves to address two limitations of conventional scanners: fingertip skin damage (owing to eczema, in this case) and presentation attacks. The surface fingerprint was very poorly affected by severe damage, with minutiae detection accuracy diminished from 88.7% to 4.7%. The internal fingerprint was far less affected by severe damage, with minutiae detection accuracy decreased from 81.3% to 40.5%. The internal fingerprint showed improved recovery when eczema abated, with minutiae extraction accuracy improvements of 35.6% for the internal fingerprint yet only 0.6% for the surface fingerprint. Furthermore, the difference between the internal fingerprint of real and fake fingers is distinct and an analysis of the orientation certainty level allowed for fully automated and entirely accurate presentation attack detection.**

***Index Terms*—Biometrics, Fingerprints, Spoof-detection, Security, Optical Coherence Tomography.**

I. Introduction

Fingerprint acquisition technologies are well-established and they fulfill their role adequately by providing a representation of the ridge-valley structure of the surface skin which is known as the stratum corneum. Regardless of any advances in this field, this approach to fingerprint acquisition by scanning the surface skin only is restricted by the input data (the condition of the human fingerprint itself) and the representation afforded (a 2D image). Although multispectral fingerprint acquisition [1] has improved upon the former of these two limitations, it still results in a 2D representation of the fingerprint.

Optical coherence tomography [2] (OCT) is an emerging technology that uses near-infrared light to image optically scattering media (such as semi-transparent biological media) in 3D by measuring the internal reflections from under the surface. Owing to the 3D and penetrative data it provides, it is well-suited to solving issues associated with current fingerprint acquisition technologies. It can provide a 3D representation that is entirely invariant to poor moisture conditions. Moreover, the 3D data generated by an OCT scan represents a real volumetric quantity, whereas other 3D fingerprint imaging modalities provide a superficial 3D representation that is a reconstruction from either multiple 2D images or through a structured lighting approach [3]. The penetrative capability of OCT allows for contactless and non-invasive access to the internal structure of the skin. Although OCT is primarily used in ophthalmology and dermatology, its viability for fingerprint acquisition is clear [4]–[15].

Many claims can be made regarding the utility and functionality of OCT within the domain of security (specifically in biometric authentication) because the internal fingerprint, represented in 3D, is intrinsically well-suited to solve problems related to current fingerprint acquisition technology. That said, the research presented in this paper will demonstrate this utility through a two-fold analysis in the form of case studies, as follows:

1) Case study 1: damaged fingerprints; and
2) Case study 2: presentation attack detection.

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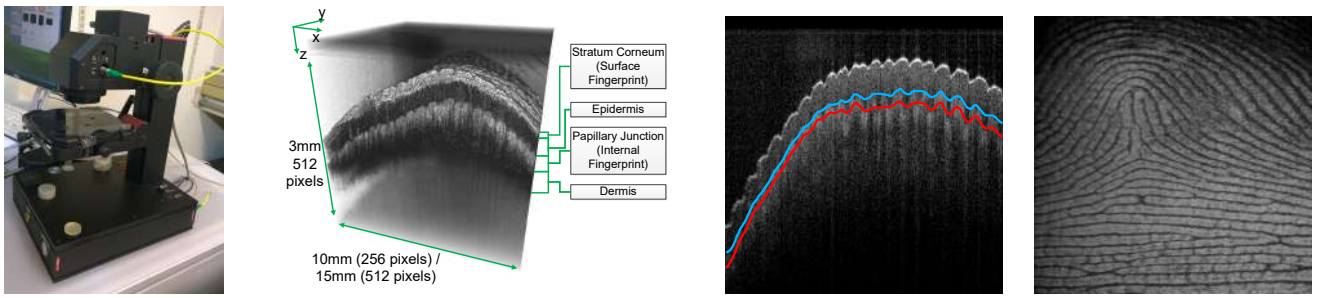

(a) Thorlabs OCS1300 scanner (b) 3D OCT scan (c) Constituent slice example (b-scan) (d) Extracted internal fingerprint

Figure 1: OCT scan and internal fingerprint example. (a) is the scanner used in this research. (b) shows the 3D OCT scan with resolution constraints. (c) shows a constituent slice (i.e. a b-scan), and shows the region containing the internal fingerprint – that which is extracted for the fingerprint image in (d).

The algorithms presented by Darlow and Connan [12] are used to detect and extract internal and surface fingerprints from OCT scans for both case studies. The remainder of this paper is structured as per the above-mentioned two-fold analysis. Section II analyses the fingerprint skin under differing severities of damage owing to eczema. Section III provides an algorithm for presentation attack detection and gives results regarding its performance. Section IV concludes this work and suggests future avenues of research.

II. Case study 1: eczema

Eczema is a medical condition that causes excessive skin dryness. It most often occurs on the face, hands, wrists, feet, and the back of the knees; and causes the skin to appear very dry and scaly. The origin thereof is unknown. Nevertheless, since it can affect the fingertips, it can obscure the fingerprint.

Skin consists of three layers: the epidermis, the dermis, and a fat layer. The papillary junction is the junction between the dermis and epidermis, and is highlighted as the undulating (blue) line in Fig. 1(c). Skin cell regeneration begins in the lower epidermis and propagates toward the stratum corneum (surface layer). However, it is possible for the skin to become diseased or damaged on a temporary or permanent basis [16]. This can have a negative effect on the structure of the fingerprint, and thus on fingerprint verification.

Eczema is the most common skin disease encountered by dermatologists [17]. The word ‘eczema’ is derived from the Greek word meaning ’to boil forth or to effervesce’ [18]. It is an inflammatory non-infectious relapsing skin disease that can be accentuated by irritants, allergens, or stress. Hand or fingertip eczema can cause employment issues for affected people. Acute eczema is associated with marked erythema, superficial papules and crusts. Chronic eczema is indicated by faint erythema, infiltration and scaling [19]. Fingerprint images taken from fingers damaged by skin diseases exhibit poorer quality fingerprints, thus making fingerprint enhancement and minutiae extraction a greater challenge.

Fingerprint acquisition and recognition can be affected by dry skin and skin diseases [17], [19]. Moreover, the fluctuating severity of eczema causes short-term changes in the fingerprint which may have a detrimental impact on a fingerprint recognition system. Some earlier works have looked at the effect of eczema on the external fingerprint using conventional scanners [17], [19]–[21]. Lee *et al.* [19] performed an extensive study that looks at the changes in fingerprints caused by hand dermatitis.

Available research in this domain has focused on the effect of skin diseases on the surface (external) fingerprint, but this research intends to provide insight into the consistency and persistence of the two skin layers that result in the structure of the surface and internal fingerprints: the stratum corneum and papillary junction (see Fig. 1), respectively. This case study is not meant as an exhaustive assessment of the internal fingerprint under the condition of eczema, but rather as to provide insight into the capacity of OCT fingerprint acquisition when the fingertip skin is damaged. It is **paramount to note** that the data available for this avenue of research is rare. In point of fact, to encounter the data used in this analysis was fortuitous. OCT scans of a fingerprint were taken before eczema symptoms began (for a separate research endeavour), during a severe bout of eczema, and after the eczema had abated enough for the skin to recover somewhat.

Section II-A and II-B detail the approach taken and results yielded, respectively.

TABLE I: Availability of OCT scans of the fingerprints

Finger	Availability before	Availability when severe	Availability when slight
Right thumb	yes	yes	yes
Left thumb	no	yes	yes
Right ring	no	no	yes

A. Approach

The availability of ‘before’ and ‘after’ OCT scans of fingers affected by eczema is exclusively owing to good fortune as

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the onset of eczema cannot be planned. Multiple data capture sessions were carried out and the fingerprints studied herein began to exhibit eczema between these sessions. Three fingers from a single individual were affected by eczema of differing severity at different times. This, along with misalignment of the OCT scanner during some data capture sessions, resulted in different availability of scans for these fingers. Table I details the availability.

Using these rare fingerprint scans, the surface and internal fingerprints can be studied under different damage extremities. The technique by Darlow and Connan [12] is used to extract the fingerprints. For details on this, and for information regarding the Thorlabs OCS1300SS OCT scanner used herein and shown in Fig. 1 (a), the reader is referred to the above-mentioned work [12].

A qualitative analysis of the surface and internal skin layers that contribute to the fingerprint structure serves to reveal much regarding the effect of eczema. These fingerprints are displayed and analysed in Section II-B, which follows. Extending this assessment is an investigation of the minutiae extracted from the fingerprints. To do so, the National Institute of Standards and Technology (NIST – www.nist.gov) provides a fingerprint minutiae viewer tool. The relevant minutiae were manually checked for correctness. The accuracy/correctness of minutiae is the percentage of minutiae that are correctly determined.

B. Results

Table II gives the minutiae analysis, while Figures 2, 3, and 4 show the extracted fingerprints for the right thumb, left thumb, and right ring, respectively. The levels of severity are determined by the level of dryness and erosion evident on the skin during the time of scanning.

Fig. 2 shows the right thumb and gives the most thorough understanding of the consistency of the internal fingerprint when eczema is present. When the surface skin exhibits peak severity in terms of damage, the internal fingerprint still has continuous ridge-valley structure and minutiae extraction performs relatively well, with minutiae extraction accuracy of 12.8% on the surface and 97.4% on the internal (Table II). This consistency is carried through when eczema abates somewhat, although the surface skin still shows the prolonged damage effect. The deeper erosion 'cracks' are even evident in the internal fingerprint, albeit to a lesser degree.

Fig. 3 shows the left thumb and contains the most damaged fingerprint (the surface at peak severity). In this case the internal fingerprint is also eroded and damaged, although the ridge-valley structure is stronger. When the severity of the eczema reduced, both surface and internal fingerprints recovered, although the deeper cracks and damage are still clearly evident on the surface fingerprint, while the internal fingerprint has improved structure and minutiae extraction performs comparatively well (Table II).

Although the ring finger, exhibited in Fig. 4, may seem to present severe eczema, this was not the case. Instead, the damage done owing to eczema was previously very severe and the fingerprint was not fully recovered when this data was captured. The structure of the internal fingerprint, however, still persists. This pervasive damage resulted in 1.0% minutiae extraction correctness for the surface fingerprint and 61.5% correctness for the internal fingerprint.

TABLE II: Analysis of extracted minutiae.

Finger	Severity	Total	Correct	False	Uncertain
Right thumb; **Surface**	Before ezema	62	55	3	4
Right thumb; **Internal**	Before ezema	64	52	8	4
Right thumb; **Surface**	Severe ezema	78	10	61	7
Right thumb; **Internal**	Severe ezema	39	38	0	1
Right thumb; **Surface**	Reduced ezema	84	11	67	6
Right thumb; **Internal**	Reduced ezema	33	31	1	1
Left thumb; **Surface**	Severe ezema	137	0	132	5
Left thumb; **Internal**	Severe ezema	87	13	69	5
Left thumb; **Surface**	Reduced ezema	97	3	89	5
Left thumb; **Internal**	Reduced ezema	45	34	7	4
Right ring; **Surface**	Reduced ezema	100	1	95	4
Right ring; **Internal**	Reduced ezema	39	24	10	5

The average minutiae extraction accuracy from the surface and internal fingerprints before eczema was 88.7% and 81.3%, respectively. At peak severity the average minutiae extraction accuracy decreased to 4.7% and 40.5% for surface and internal fingerprints, respectively. When the effect owing to eczema diminished minutiae extraction accuracy improved to 76.1% for the internal fingerprints but remained low at 5.3% for the surface fingerprints. Thus, although the internal fingerprint is inevitably negatively affected by damage, it is markedly more robust and recovers more swiftly than the surface fingerprint.

The following section is the second case study of this research and intends to provide a means of presentation attack detection that is grounded in the fundamental biological structure of the skin.

III. Case study 2: presentation attack detection

It should be noted that the research presented in this case study is not as an attempt to disclose a new presentation attack detection algorithm or scheme universal to all fingerprints. Instead, and owing to the valuable 3D penetrative perspective afforded by OCT technology, a simplistic approach can be formulated and undertaken. The presence of the internal fingerprint in real fingertip skin, and its complete lack of existence in fingerprint fakes, is the critical assumption made in the

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Figure 2: Right thumb with all instances of eczema severities.

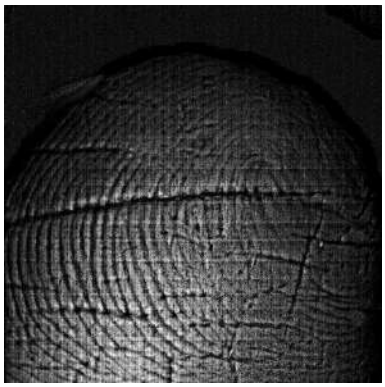
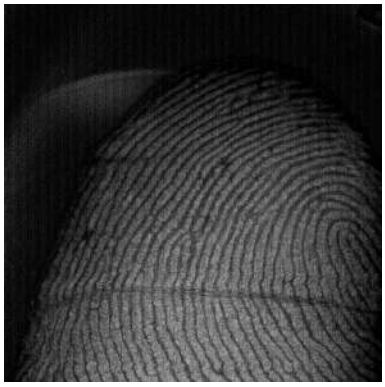
Layer	Before Eczema	Peak Severity	Reduced Severity
Surface			
Internal			

Figure 3: Left thumb at peak and reduced severities.

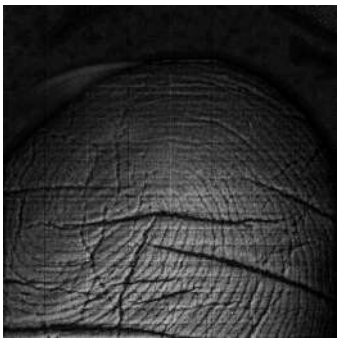
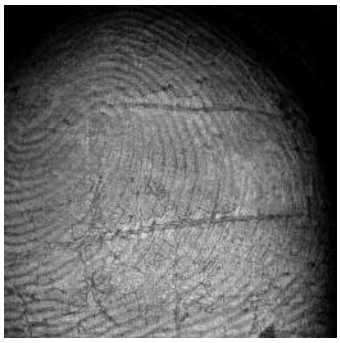
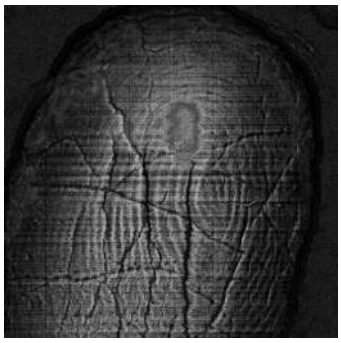
Layer	Peak Severity	Reduced Severity
Surface		
Internal		

Figure 4: Right ring at reduced severities.

Layer	Reduced Severity
Surface	
Internal	

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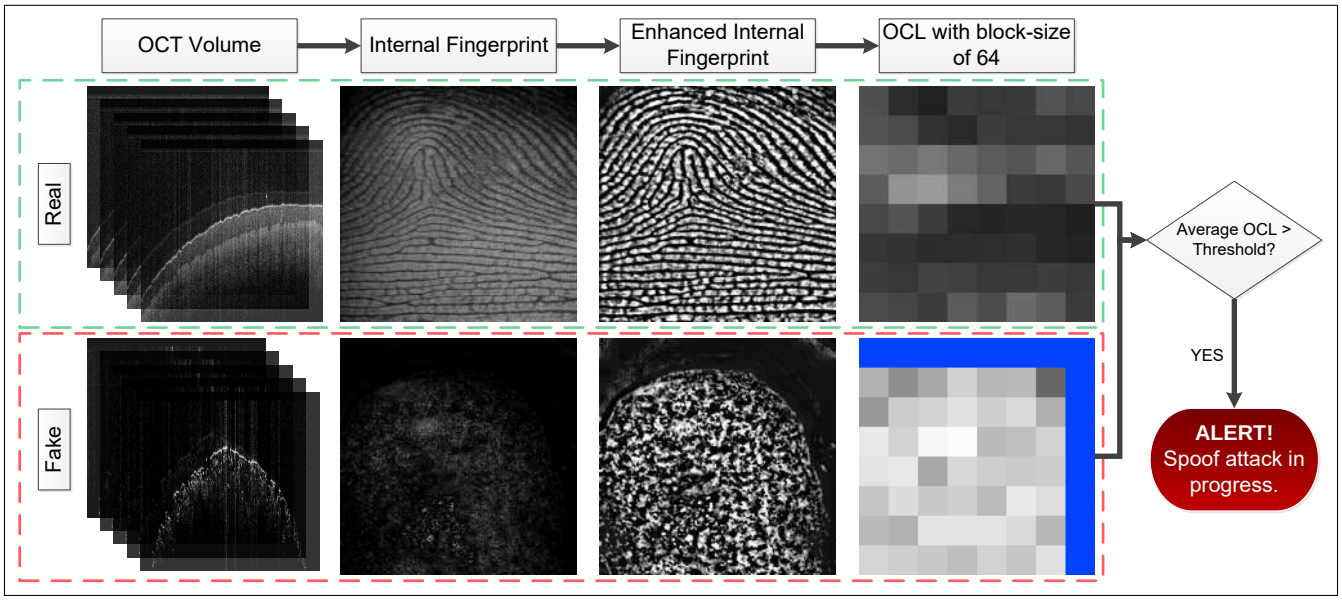

Figure 5: Presentation attack detection flowchart. The internal fingerprint is extracted and enhanced. The OCL score is calculated using a block-size of 64 (the blue region represents the masked out region that does not contribute). The average OCL score over the entire fingerprint is used to detect a presentation attack.

approach presented herein. The presentation attack detection approach is disclosed in Section III-A.

Cheng and Larin [22] used the repetitive and inhomogeneous characteristics of real fingertip skin to perform autocorrelation signal analysis on 1D OCT depth signals, shown as the columns of b-scans in Fig. 1(c). Nasiri-Avanaki *et al.*[23] used *en-face* (i.e. along the plane of the fingerprint) OCT to identify an additional layer of sellotape on the skin. Meissner *et al.*[24] argued the insufficiency of fake detection on 2D surface scans and manually detected fake fingers on a dataset of OCT scans. Although the above-mentioned research endeavours show the viability and efficacy of OCT in this domain, they never presented these techniques as repeatable automated approaches.

Earlier work has seen Darlow *et al.* [25] produce an automated spoof-detection scheme using OCT and an analysis of the 1D signals. These are the columns of an image slice (b-scan) that constitute a 3D volume – see Fig. 1(b) and (c). Although the results of their research were promising, it is not necessary to analyse the depth-structure characteristics of OCT scans. Alternatively, the assumption of the presence of the internal fingerprint presented in this paper is strong and, as Section III-B shows, yields good performance for presentation attack-detection. The following section details the strategy developed and followed in this research.

A. Approach

The process followed to detect a presentation attack is illustrated in Fig. 5. The internal fingerprint components are extracted according to [12]. The internal fingerprint can be thought of as a flattened region of 3D space (on the Z-axis as shown in Fig. 1) beneath the surface of the skin. Consequently, the extracted result for real fingerprints is the intended internal fingerprint, while the extracted result for a fake fingerprint is anomalous and has no ridge-valley structure. This is shown in Fig. 5.

The reason for the stark difference in what results as the extracted internal fingerprint, between real and fake fingerprints, is that fake fingers/fingerprints have not yet been constructed with internal structure or detail to mimic the internal fingerprint. **This is the strong underlying assumption that makes OCT a practical tool for presentation attack detection**. A quality analysis of this internal fingerprint flattened region – using the average orientation certainty level (OCL) [26] to evaluate ridge-valley structure – is enough to determine whether a fake finger was presented to the OCT scanner.

To test the performance of this approach, three artificial fingers were created from three different volunteers, and one fingerprint layer fake was created from one of the same volunteers. Molds were made with the LifeCasting Silicone LifeForm from MouldLife [27]. A gelatin mixture was prepared and used to create the fakes. Although it would be ideal to test fingerprint fakes using various materials, a deviation in construction material is not a deviation in the prior assumptions and goals (to create a replica surface fingerprint) and thus will still not provide the necessary additional internal structural reflectivity to reproduce the internal fingerprint. Moreover, mimicking the relative reflectivity of the internal structure of human skin is non-trivial.

For comparison, the fakes were scanned using four conventional commercially available surface flat scanners to test if they could fool the built-in liveness detection systems: the Watson Mini (Integrated Biometrics), Realscan G1 (Suprema),

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FS88 (Futronic), and Hamster Plus (Secugen). Multiple OCT scans (at varying resolutions as per Darlow *et al.* [25]) were also taken using the commercially available Thorlabs OCS1300SS swept source OCT scanner shown in Fig. 1(a). This resulted in twenty OCT scans. The same number of OCT scans from real fingers were also analysed for comparison. The reader is referred to Darlow and Connan [12] for more detail on this scanner. After the addition of moisture (in some cases) all of the surface flat scanners were fooled. The results regarding the internal fingerprint quality analysis approach, presented herein, is given in the following section.

B. Results

Fig. 6 gives the statistics of the measured OCL scores. The extending arms of these box plots define the lowest and highest measured values. The lowest OCL score of the assessed fakes was 0.8141, while the highest OCL score of the real fingers was 0.4559. These are significantly separate, considering the OCL score ranges from 0 (best) to 1 (worst).

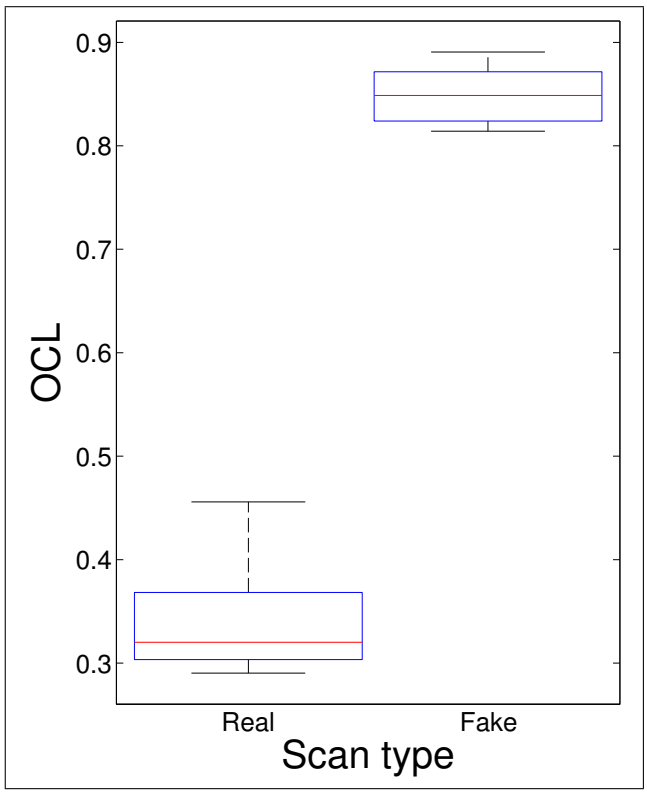

Figure 6: OCL results for real and fake fingerprint scans. The center of the boxes (i.e. the red lines) represent the median values, the top and bottom of the boxes represent the interquartile range, and the extending whiskers are the extrema values.

The measured values are entirely separable. That is, the **OCL score of the internal fingerprint is a distinguishing feature for spoof-detection**. Moreover, it shows that the automatic assessment of the internal fingerprint is a useful tool in detecting presentation attacks.

High and low security OCL score thresholds of ± 0.46 and ± 0.81, respectively, will distinguish internal fingerprints from fake fingerprints for a system implementing this approach.

Fig. 5 gives qualitative examples of the measured OCL scores, highlighting the contrast between real and fake fingers in the assessment of the internal fingerprint quality. Furthermore, this figure gives example OCT scans (b-scans are shown), exemplifying the differences in reflectivity as measured by the OCT scanner.

IV. Conclusions

OCT provides promising solutions to problems associated with fingerprint acquisition. The scanning procedure is unaffected by moisture, although the effect of moisture conditions on the performance of the internal fingerprint must still be researched in future work. OCT produces a real 3D perspective of the fingerprint that is naturally suited to the emerging domain of contactless and accurate 3D fingerprint identification [3]. Configurations of OCT technology can also yield higher resolution fingerprint images than the current standard of 500 dots per inch [15]. Furthermore, the existence of the internal fingerprint and access to it by OCT are foundational components to solutions addressing issues with current fingerprint acquisition technology.

This research sought to address two problems in the form of case studies: fingerprint damage (from eczema, in this case) and presentation attacks. These are directly related to the limitations of 2D superficial representation provided by most commercial surface flat scanners.

For the first of these case studies, OCT, being 3D and penetrative to the internal fingerprint, was used to image fingerprints that had incurred damage owing to eczema. The internal and surface fingerprints – at varying degrees of eczema severity – were compared to fingerprints obtained prior to any onset of eczema. This data comparison is a purely fortuitous outcome and was as a product of a previous study where the undamaged fingerprints were scanned. The occurrence and availability of the rare data is important to note as this is the first study attempting to show the internal fingerprint under varying conditions of real-world damage.

The persistence and quality of the internal fingerprint is evidently better than that of the surface fingerprint, whether considering minutiae detection accuracy (using the NIST software) or a qualitative analysis. Moreover, even though the internal skin is affected by severe eczema damage, it healed better than the surface skin when eczema abated.

The second case study proposed a presentation attack detection scheme based upon the fundamental assumption that only real fingers/fingerprints have an internal reflective structure that embodies the internal fingerprint. The 3D subsurface region was extracted as an internal fingerprint 'component' [12]. It results in an actual fingerprint when the presented finger is real, but is entirely spurious when a fake is presented.

A comparison of the quality of the internal component, using the average orientation certainty level, showed ideal statistical separation between real and fake fingers. Although

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other types of fakes must be constructed and tested as future work, the important assumption – the lack of an internal fingerprint in fakes – will hold true unless construction is improved to fool even the penetrative perspective of skin that OCT gives. Nevertheless, this must be investigated as future work and improved solutions to attack detection should be forged.

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