Wet Fingerprint Recognition: Challenges and Opportunities

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Abstract

Many fingers wrinkle or shrivel when immersed in water. When used for biometric identification, the recognition rate for wrinkled fingers degrades. The impact of wrinkling has so far not been well-understood. In this study, we present an investigation of how the finger-skin expansion due to wrinkling impacts the quality of scanned fingerprints and characterize the qualitative changes that affect recognition. We also introduce the ***Wet and Wrinkled Finger (WWF)*** *database that we will make available to other researchers. In this database of 300 fingers, 185 are visibly wrinkled after immersion; multiple images of dry and immersed fingerprints were acquired.*

In this paper, we present baseline recognition rates on WWF using two algorithms – a commercial fingerprint recognition algorithm and the publicly available Bozorth3 matcher. Specifically, we show a degradation in accuracy with both algorithms when comparing Dry-finger to Dry-finger verification with Dry-finger to Wet-finger verification. We analyze performance on a per-finger basis and note a difference in accuracy amongst fingers, and as consequence make recommendations about which fingers to use in environments where fingers are apt to be wet. Additionally, we propose an implementation of a classifier that can decide if the incoming query is wrinkled.

1. Introduction

Fingerprint recognition is a well analyzed problem with many successful methods having an equal error rate (EER) that is less than 5% even on challenging datasets like those used in the Fingerprint Verification Competition (FVC) 2002, 2004 and 2006 [11][4] which includes non-ideal or perturbed prints. Performing well in challenging conditions without compromising the performance from ideal dry conditions is vital for a biometric system to operate in uncontrolled operating conditions. One of the domains that has only been lightly explored is fingerprint recognition in the maritime domain where in which hands may be subject to prolonged exposure to water, and fingertips become wrinkled or shriveled. Applications include access control, forensics, and security. Fakourfar et al.[8] had shown a degradation in the performance on a small number of subjects on a particular commercial matching algorithm. In this paper, we try to make a more detailed analysis of the problem of recognition on wrinkled fingertips and propose possible directions to take it forward.

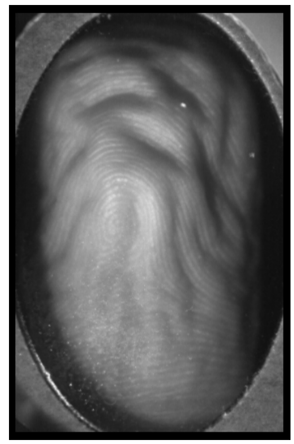


Figure 1: An image acquired with a Lumidigm sensor of a wrinkled finger after soaking in water; the finger is not pressed on the platen and is in the air a short distance from the platen.

Even the process of wrinking is not fully understood, though there are a few theories on the origin of wrinkles, and [19] surveys them concisely. Some claim that wrinkling occurs due to expansion on the outer layer of the skin (*Stratum Corneum*)[2] or contraction of myo-epithelial cells in the absence of sebaceous glands in glabrous skin [15]. Recent studies [18][17] have suggested that vasoconstriction may be the cause as it decreases the turgor (finger pulp pressure) and effectively shrinks the volume to produce skin wrinkles. See Figure 1 for an image of highly wrinkled finger in air. There are a number of challenges in performing recognition of waterlogged fingers. First, widely used sensors based on capacitive imaging or based on frustrated total internal reflectance (FTIR) are unreliable without drying when the fingers are wet or very damp. Even after drying the physical changes persist for 10-15 minutes. So, an appropriate sensor, such as a multispectral sensor, must be used. Along with visible large scale wrinkling, there is a non-isometric deformation to the surface of the skin. That is, there may be expansion of the surface in some locations and contraction in others and as a consequence, the distances between fingerprint features such as minutiae and corepoints may change. When a wet fingerprint is imaged in air, the surface topography has changed with wrinkling. One hope is that when a wrinkled fingerprint is pressed onto a sensor's platten, the fingerprint would flatten and effectively restore the geometry. Unfortunately, there is a different distribution of feature locations when a wet fingerprint is pressed on the platen than a dry one. This can be viewed as an aggravation of the plastic or elastic distortion that occurs when the finger is pressed on a sensor platen [5],[14]. We do not tackle the problem where the finger is moist from sweat as this mostly affects image quality with FTIR and capacitive sensors. This situation might be a concern for Level 3 features which include pores that are imaged with high resolution (1000 dpi) sensors[9].

Because there are no publicly available datasets of wrinkled, waterlogged fingerprints and because the only prior study had very few prints [8], we acquired our own dataset. In this paper we introduce the **Wet and Wrinkled Finger (WWF)** database to examine the phenomenon of wrinkling, and we will make this database available to other researchers upon publication. In this paper, we present qualitative observations and a quantitative evaluation to form a baseline for future work. To our knowledge, such a database of fingerprints does not exist. We use a commercial algorithm and the publicly available Bozorth3 algorithm for minutiae point extraction, matching and scoring. Since we do not envision scenarios where users would be enrolled with wet fingers, we concentrate on comparisons where one of the fingerprints is dry. As a baseline, we consider performance when both fingerprints are dry and compare this to situations where one fingerprint is dry and one is wet. Because we segregate the most wrinkled prints and use only them for experiments, wet and wrinkled are used interchangeably. Our aim is to improve existing techniques in fingerprint recognition by using a model that is aware that the wrinkles are present in a particular finger.

2. Related Work

Fakourfar et al.[8] studied the performance of the fingerprint recognition systems with wet fingerprints. Their database was constructed by soaking the right hand in a glove filled with cold water for about 30 minutes. This process does not guarantee the appearance of wrinkles, either because the person cannot wrinkle despite long exposure or because 30 minutes was insufficient for skin expansion to set in. On communication with the authors, we learned that the subjects soaked for a fixed amount of time, and the amount of wrinkling was not documented. So, their evaluation included mildly wrinkled fingers as well as wrinkled fingers. In the WWF database, we promote wrinkling by maintaining a warm water bath using a heating system and fixing the pH to 8.1 by using baking soda. These are optimal conditions for diffusion of water into the outer layer of the skin. And, if in spite of these measures, the finger fails to wrinkle, we have annotated the dataset to allow selection of images exhibiting high degrees of wrinkling before performance testing.

There has been work in the field of medicine to use wrinkling of finger tips as a screening test for normal nerve function [3, 1, 17]. They discuss various conditions to promote wrinkling. We used these observations to obtain excellent conditions for inducing fingertip wrinkling in order to collect the WWF Database as discussed in Section 3.

Yin et al. [19] present a mechanical model of wrinkling including factors like wrinkle-to-wrinkle distance (wavelength), wrinkle depth and critical wrinkling stress/strain with varying geometry and material parameters. This gives valuable insight into the physiology of wrinkling of a finger by characterizing the wrinkling using analytical equations over the above factors. This work is a sample of the body of work that represents how thin sheets could be used to model wrinkles in human skin, textiles and for example an apple's skin.

Ross et al. [12] have given a deformable thin plate spline based model to estimate a measure called the *average deformation*. This average deformation is used to pre-distort the minutiae points in the template image. If wrinkling artifacts are viewed as an extended form of this nonlinear change, they can be similarly modeled. However, this is possible only when template fingerprints are also wet fingerprints so that the average deformation can be estimated. In relation to the deformation modeling, Cappelli et al.[5] considered the slipping force applied after touching the sensor that is non-orthogonal and were able to model the distortion in the minutiae distribution. They model it as three regions that have different properties. One challenge for the model is the automatic derivation of the model parameters.

3. The WWF Database

To study the effect of immersion in water and wrinkling of fingerprints, we constructed the Wet and Wrinkled Finger (WWF) database. We collected data from 30 people for all ten fingers using a multispectral fingerprint scanner from Lumidigm (Venus series). We treat 300 fingers as separate identities. Multispectral sensors are effective for our application because they are designed to function when the fingers are wet with dripping water, and they can acquire an image when the finger is not in contact with the platen. This is possible because the multispectral sensor is able to acquire subsurface features as well as surface feature even under poor conditions; this contrasts with frustrated total Internal reflection sensors that require sufficient moisture along the ridges, air gaps in the valleys, and a clean dry platen [13].

For each finger, the database contains two types of images: a *pressed* image and an *air* image. A *pressed* image is a regular scan of a finger that is pressed against the platen. The *air* image is an image of a fingertip that is not pressed on the sensor platen and lies just above it. The sensor produces a grayscale composite image from the multispectral signal, a raw RGB image to visually inspect the fingerprint, and a quality image. In total there were 3600 acquisitions because each of the 300 fingers has four modes (Dry-Air, Dry-Pressed, Wet-Air and Wet-Pressed) and each of the four modes has 3 repetitions for samples. Inspection of 300 *air* images revealed wrinkling in 185 images, and the corresponding fingers have been labeled as having exhibited wrinkling. The database will be available for researchers to download at http://vision.ucsd.edu/WWF.

To stimulate finger wrinkling, we soaked both hands of thirty subjects for 30 minutes in warm water maintained at $40\,^{\circ}$C and at a basic pH of 8.1 as this promotes wrinkling [19]. Using the Lumidigm sensor, we captured three sets of images – a binary fingerprint image and a raw RGB image before and after soaking. The stored RGB bitmap images is 352×544 pixels. Rather than acquiring three successive images of each finger, we acquired all fingers and repeated this three times.

To offset the disadvantage of having a limited number of subjects we captured fingerprints from all ten fingers. The experiments in the subsequent sections have treated each finger as a separate identity to be recognized. While there may be correlations amongst fingers coming from the same hand as found for twins [10], this is acceptable because the objective for us is to prove the degradation in match scores when we perform the same experiments for two different conditions, Dry and Wet.

After acquisition we subjectively labeled each image as being of a wrinkled finger or a non-wrinkled finger. 185 fingers out of the 300 fingers are visibly wrinkled. We have also observed that about 10 out of the 30 people do not wrinkle enough in spite of soaking the hand in water for an hour. There are also a couple of instances of damaged skin because of heavy work.

4. Evaluating Accuracy for Wet and Dry Fingerprints

To assess the impact of immersion and wrinkling on fingerprint recognition, we used two systems, a commercially and a publicly available system. Each of these systems has two stages: minutia detection and matching/scoring. Of the 300 fingers in the database, 185 exhibited visible wrinkling in the *air* images, and we used these 185 images in the experiments reported in this section.

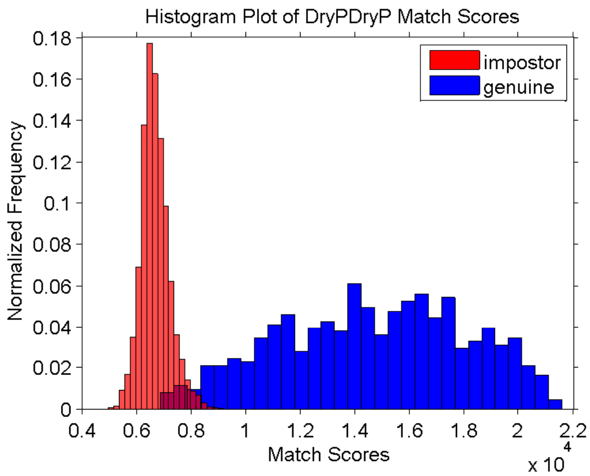
The publicly available, open source system is the National Institute of Standards and Technology (NIST) Biometric Image Software (NBIS) release 3.1.1, and we use the minutiae detector (called MINDTCT) and the matcher (called Bozorth3) [16]. Because of agreements with the vendor, we cannot reveal the name of the commercial detector.

The Bozorth3 algorithm [16] uses a rotation- and translation-invariant matching method. The essence of the approach involves building a list of pairs of minutiae from an image. Each pair is described by the distance between the minutiae and the two angles between the line segment formed by the two minutiae and the minutae's orientation returned by the detector. Pairs of line segments between the probe and gallery images are considered compatible if the difference of distances is within a threshold and if the orientation difference are also within a limit. *Compatible* line segment pairs are stored in the list. The method uses pairs of minutiae instead of individual minutia points in order to construct translation and rotation invariants. Bozorth3 then traverses the list and clusters all *linked* pairs. The length of the longest chain is the score. The notion of linking of two line-segments seems to be close to the method of maximum matched pair support (MPS) [7] although a graph-based terminology is used.

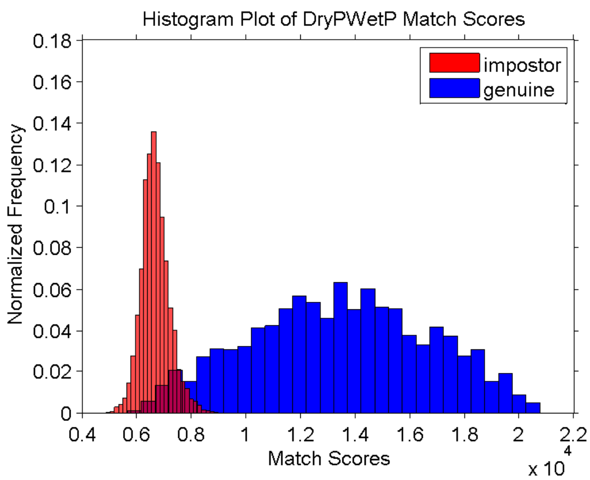
We evaluate the impact of immersion in a verification task in which a system is given two fingerprints and must decide if they are from the same or different fingers. The performance is judged by *genuine* and *impostor* scores. Genuine scores indicate the level of agreement between different samples of the same finger. Impostor scores are obtained by matching samples from different fingers. In the following analysis, all possible genuine scores for the 185 fingers are computed. Because there are so many potential impostor pairs, we randomly sampled the impostor set. The Receiver Operating Characteristic (ROC) curve is presented, and the Equal Error Rate (EER) is provided.

4.1. Commercial Algorithm Performance

Figure 2 shows histograms of match scores for the commercial algorithm; Figure 2a shows the case where both the gallery and probe are dry whereas Fig. 2b shows the case where the gallery is dry and the probe is wet. Notice that the overlap region, where there is potential for error depending upon match threshold, is larger for the wet fingerprints. This is born out in the ROC curve shown in Figure 3. The equal error rates (EER) are respectively 2.29% and 4.12%, nearly a doubling of the error rate for wrinkled fingerprints.



(a) DryPressed-DryPressed



(b) DryPressed-WetPressed

Figure 2: Histogram plot of match scores with the Commercial Algorithm for both minutiae and matching. Notice the greater overlap and shifted mean in the case of fig 2b.

4.2. NIST NBIS Algorithm Performance

Figure 4 shows histograms of match scores when the MINDTCT and Bozorth3 algorithms are used; Figure 4a shows the case where both the gallery and probe are dry whereas Fig. 4b shows the case where the gallery is dry and the probe is wet. The ROC curve provided in Figure 5 reinforces the observation about confusion in wet finger matches. The EER are respectively 2.29% and 3.23% showing the NBIS performs better on the wet fingerprints than the commercial system, but there remains a marked decrease in performance for wrinkled fingers.

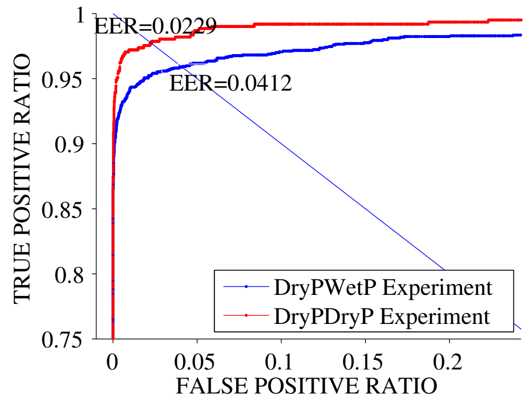


Figure 3: ROC curves – Commercial algorithm for minutiae detection & matching.

5. Physical effects on the fingers

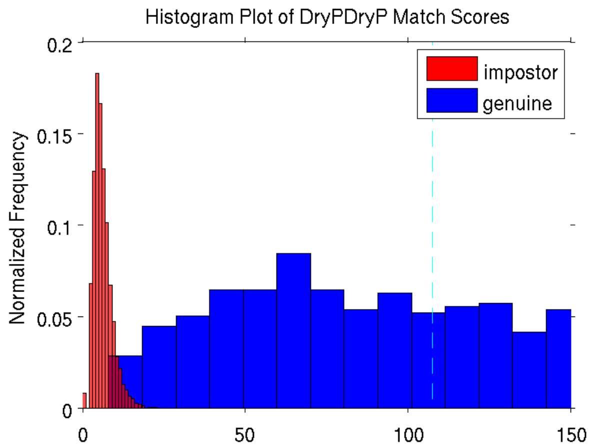
In the previous sections, we have seen that wet/wrinkled fingerprints yield lower recognition rates than dry ones. While the presence of wrinkles is a visible phenomena in these images, are the wrinkles themselves the cause of the degradation in pressed images, or are there other physical effects at play? In this section, we consider some of the effects that might be leading to decreased performance in pressed images and present qualitative observations from this study.

The change in fingerprints when they are immersed is driven by skin expansion. On analyzing *air* images such as the one shown in Figure 1, we found that the presence of wrinkles post-soaking correlates with certain effects in the pressed fingerprint. These effects do not occur for every wet fingerprint, but they occur often enough to be noteworthy.

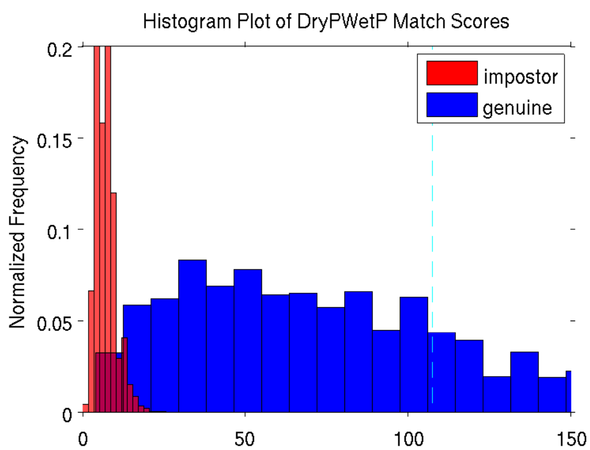
1. **Clumping of skin causes u-shaped artifacts** – Figure 6 shows this effect in which clumping leads to a spurious light U-shaped curve in the image that is transversal to the fingerprint ridge. In turn, this leads to spurious minutiae. In our analysis, the commercial algorithm was fairly robust when these clumping do not occur near a core or delta point.

2. **Cuts already present become more prominent.** – Figure 7 presents *air* images of a wet and dry finger with small surface cuts, and the cuts are more prominent in the wet image. These lead to spurious minutiae which may lead to lower scores depending on the matching method used.

3. **Thickening of ridges** – The ridges become thicker and the label of the minutae type (bifurcation vs ending) returned by the minutiae detector might change. Some-



(a) DryPressed-DryPressed



(b) DryPressed-WetPressed

Figure 4: Histogram plot of match scores with NIST NBIS system (MINDTCT and Bozorth3). Notice the greater overlap in the case of fig 4b.

times, there is a significant shift in the location of the minutiae.

4. **Moving apart of minutiae** – The non-linear distortion of the skin is due to the surface profile change and subsequent pressing on the platen. This leads to regions of the print where the minutae move closer together while in other regions the minutiae move further apart.

6. Fingers to use

We have found that the error rate varies by finger, and this leads to a natural question. Which finger is most affected by wet conditions and which one is least affected? To answer this we looked at ROC performance on a finger-

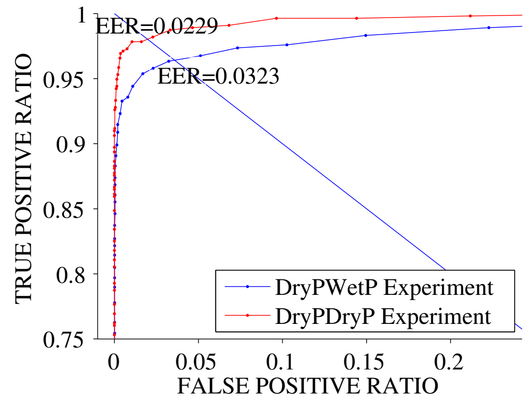
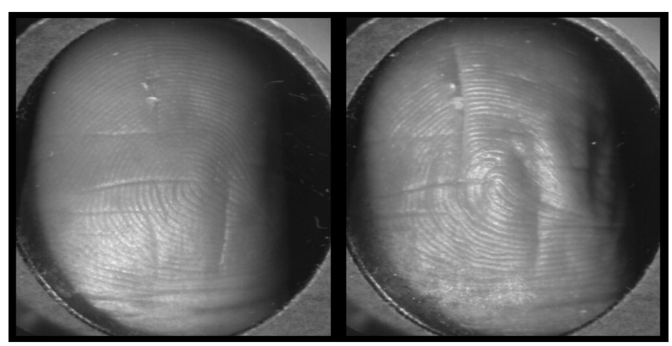


Figure 5: ROC curves for the NIST NBIS system.

(a) Dry

(b) Wet

Figure 6: Skin gets clumped in certain places and may lead to misfiring of the minutiae detector. Here, we see an example of a u-shaped curve, which is the downward sloping white curve in the circled region of the Wet image.



(a) Dry (b) Wet

Figure 7: Cuts already present become more prominent on soaking and expansion

by-finger basis. 300 fingers irrespective of highly wrinkled or not are tested on Mindtct (minutiae detection) and the

Table 1: EERs of Dry-Dry match and Dry-Wet match for each of the fingers. The error rate is given in percentage.

	Dry-Dry Match	Dry-Wet Match
Thumb	1.27	0.84
Fore	0.12	2.65
Middle	1.06	2.72
Ring	1.64	3.3
Little	3.49	4.69

Bozorth3 (matching), both available from NIST. This lets us conclude, on the whole, which finger may be beneficial in terms of performance w.r.t ROCs. For each of the fingers, the impostor scores are subsampled to select around 3500 scores for both Dry-Dry match and Dry-Wet match. The number of genuine scores are 180 and 540 for Dry-Dry and Dry-Wet respectively.

The Dry-Wet EER degrades from the Dry-Dry EER for all fingers except the thumb where the rate is slightly higher as shown in Table 1. Ring finger and little finger have the highest error rates in wet condition. This supports the conclusion, consistent with [8] that the ring finger is among the bad choices. It also shows the thumb to be the best choice. The ROC curves are shown in Figure 8. Apart from the finger-wise ROC analysis, we investigated the shift in genuine matchscores for every finger that was enrolled after it got wet i.e. Shift = Dry-Dry score − Dry-Wet score. On average, all shifts were positive and indicated a reduction in match scores when fingers got wet. We found that the average reduction in scores for ring finger and fore finger (commonly used in recognition) was higher than for other fingers and thumb was relatively better than the others.

7. Future work - Handling wrinkles

Future work should include the following two directions. The first is to simply to determine when a fingerprint is excessively wrinkled and potentially not report an answer. In essence, this would serve as part of a fingerprint image quality measure. The second would be to actually improve recognition accuracy when fingerprints are wrinkled.

To address the first challenge, we have done some promising experiments for classifying wrinkled versus nonwrinkled fingerprints. We took as input the raw RGB *air*images rather than the pressed images and made a decision using a linear SVM [6]. The feature vector consists of the standard deviation of 10 subbands (3-level decomposition) of discrete wavelet transformed image (Haar wavelet). This method attempts to capture the essential difference between wrinkled and unwrinkled air images through a wavelet representation. The frequencies present in wrinkled fingers are different because of the low-frequency folds on top of the high frequency ridge-valley patterns. The *air* images of the highly wrinkled fingers are used for positive (wet) and negative (dry) training samples. A separate set is used for evaluation of the classifier. In total, the 555 images each of wrinkled and unwrinkled air images were used. When tested, this simple classifier was accurate 84.25% of the time.

8. Conclusion

In this paper, we consider the challenge of recognizing fingerprints that have become so wet as to have wrinkled. We have introduced a new database, the Wet and Wrinkled Fingerprint (WWF) database, and this database has been used in subsequent performance analysis of existing fingerprint software systems. We found an increase in verification error rates for both the commercial algorithm and publicly available NIST NBIS algorithm when a gallery image is dry and a probe image is wet. We also found that the effect of wrinkling depends on the finger; wrinkling of the thumb seems to affect recognition less than the other fingers with respect to ROC performance and in terms of shift in histogram scores. We have put forth possible approaches to take this problem forward and make biometric technology more robust in less constrained settings.

Acknowledgements

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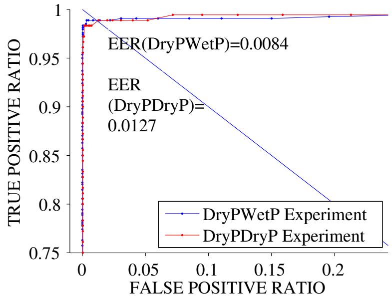
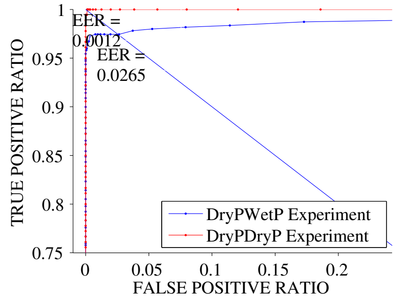
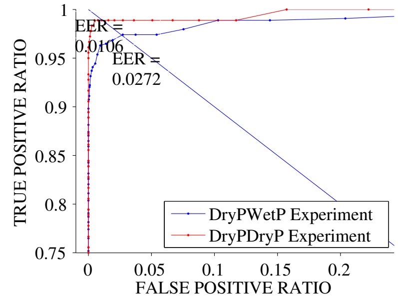


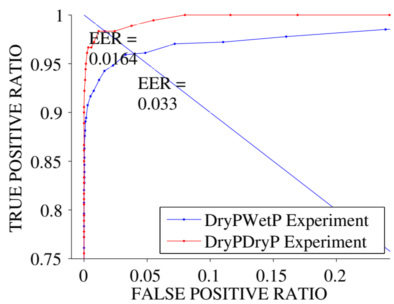
(a) Thumb



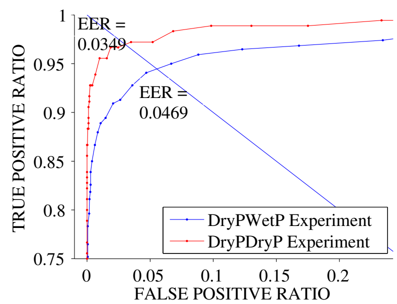
(b) Fore Finger



(c) Middle Finger



(d) Ring Finger



(e) Little Finger

Figure 8: Finger-wise ROC plot on how the dry-finger to dry-finger match for each finger changes compared to dry-finger to wet-finger match in EER.

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