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Quantifying the limits of fingerprint variability

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ABSTRACT

The comparison and identification of fingerprints are made difficult by fingerprint variability arising from distortion. This study seeks to quantify both the limits of fingerprint variability when subject to heavy distortion, and the variability observed in repeated inked planar impressions. A total of 30 fingers were studied: 10 right slant loops, 10 plain whorls, and 10 plain arches. Fingers were video recorded performing several distortion movements under heavy deposition pressure: left, right, up, and down translation of the finger, clockwise and counter-clockwise torque of the finger, and planar impressions. Fingerprint templates, containing 'true' minutiae locations, were created for each finger using 10 repeated inked planar impressions. A minimal amount of variability, 0.18 mm globally, was observed for minutiae in repeated inked planar impressions. When subject to heavy distortion minutiae can be displaced by upwards of 3 mm and their orientation altered by as much as 30° in relation to their template positions. Minutiae displacements of 1 mm and 10° changes in orientation are readily observed. The results of this study will allow fingerprint examiners to identify and understand the degree of variability that can be reasonably expected throughout the various regions of fingerprints.

1. Introduction

Fingerprints are one of the most widely used identification features in both the biometric and forensic fields. However, the comparison and identification of fingerprints is made difficult by variability arising from distortions. The purpose of this study is to quantify and characterize the limits of fingerprint variability when subjected to heavy distortions. The motivation for this study arises from concerns raised by The National Academy of Science 2009 report, *Strengthening Forensic Science in The United States: A Path Forward*, on fingerprint variability and distortion. The report states:

> the impression left by a given finger will differ every time, because of inevitable variations in pressure, which change the degree of contact between each part of the ridge structure and the impression medium. None of these variabilities—of features across a population of fingers or of repeated impressions left by the same finger has been characterized, quantified, or compared [1].

The report later states, "examiners can too easily explain a 'difference' as an 'acceptable distortion' in order to make an identification" [1]. These statements will be addressed by quantifying and characterizing variability in both the repeated impressions of the same finger and across a population of fingers subjected to various distortions. In addition to this data, distortion maps will be created to enable examiners to explicitly describe 'differences' throughout a fingerprint and identify areas affected the most by distortions.

Fingerprint comparisons are often facilitated with automated matching systems (AFIS). These systems implement various types of algorithms that make the systems robust to distortion and increase their minutiae matching abilities [2–6]. While AFIS systems are equipped with these distortion algorithms, an examiner still has to compare the distorted latent impressions with known standards 1:1. The examiner has to be able to explain what are reasonable distortions both in their examinations and in a court of law. Of particular interest is the testimony of Peter Swann and his misidentification of Shirley McKie's fingerprint [7]. Swann (and John Berry) explained the distortion observed in the print as resulting from a 66° rotation of the finger's tip, and Berry also identified a 40° change in the orientation of a bifurcation due to this rotation. The results of this study can be applied directly to instances like this to identify the unlikeness of theses occurrences in a realistically distorted fingerprint.

There have been several studies since the NAS report that go beyond minutiae matching algorithms and focus specifically on distortion in fingerprints. Maceo [8] presented a qualitative study

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of distortion in the two index fingers (a loop and a whorl) of an individual. The study characterized visible effects of distortion and noted the potential for variability is greatest in areas of parallel flowing ridges. Maceo also determined the distance a finger could be moved distally (2.9 mm loop, 3.0 mm whorl), proximally (0.7 mm loop, 2.1 mm whorl), left (1.0 mm loop, 0.7 mm whorl), and right (1.3 mm loop, 0.6 mm whorl) before a gross slip of the finger occurred. The fingers could also be rotated up to 26.7° (loop) and 30° (whorl) before slipping occurred. However, there is still a need to quantitatively measure the effects of the distortions on minutiae themselves.

Sheets et al. [9] proposed a geometric morphometric (GM) analysis method, employing Procrustes distance and canonical variates analysis (CVA) plots, to study distortion in rolled impressions by pressure and various substrates. The study showed the variability in most minutiae locations to be less than 0.5 mm (approximate width of a friction ridge) for rolled impressions. However, this technique cannot be applied to study deformation between individuals, as the Procrustes distances requires a homologous set of landmarks (minutiae) across a population of fingerprints.

Kalka and Hicklin [10] proposed a method that firsts aligns minutiae pairs with an affine transformation then quantifies the non-linear deformation between minutiae pairs with a thin plate spline (TPS) algorithm. Minutiae pairs can then be classified as true or erroneous correspondences based on a Euclidean metric that measures the residual distance between affine registered pairs and a post TPS bending energy metric. A residual distance greater than 20, or a bending energy value greater than 0.2 were found to indicate an erroneous correspondence. While effective at identifying erroneous pairings the method is difficult to represent visually and is not something that can be utilized by the examiner in 1:1 comparisons.

To quantify and characterize variability template 'images' are necessary. Template images contain the 'true' location of minutiae throughout the fingerprint. In this study, true locations are determined with inked planar impressions of each finger. Inked planar impressions contain minimal amounts of distortion, making them suitable for template generation. The minutiae locations are defined in relation to the core area of the fingerprint. This is based on the close contact region as observed in the center of the contacting area of the finger by [2]. Minutiae and features in this area remain static due to high pressure, and provide a fixed reference point. The location of each minutiae can then be averaged across repeated impressions of a finger to calculate their true locations for a template image.

2. Methods

A total of 30 fingers from 27 subjects were analyzed in this study. The fingers consisted of 10 right slant loops, 10 plain whorls, and 10 plain arches. The subjects were between the ages of 18 and 30 and consisted of 16 males and 11 females. A single finger was used from each subject except in the case of arches. Only 7 individuals with plain arch pattern types were readily available in the accessible population, so three fingers were used from a male subject and two fingers from a female subject. The 30 fingers studied consisted of 21 index fingers, 5 thumbs, 2 middle fingers, and 2 ring fingers.

2.1. Distortion videos

Each finger was video recorded performing distortion movements on a fixed piece of glass. The glass was fixed in the center of a 15.5″ × 36″ piece of oak plywood as part of a 2 × 4 Basics shelf links kit. The glass and subject's finger were wiped clean with a Kim Wipe® before the videos were recorded. Each subject then placed their finger down on the piece of glass with heavy deposition pressure and performed seven movements: left, right, up, and down translation, clockwise and counter-clockwise torque, and planar glass impressions. Each movement was performed up to but not beyond the point of gross slippage, and repeated 7 times. Videos were recorded with a Nikon® D7100™ camera, equipped with a Nikkor® 60 mm f/2.8D lens. A six inch ruler was placed next to the fingers to later set a scale for minutiae marking.

2.2. Inked planar impressions

Each finger was then photographed before recording inked planar impressions. Photos were taken to ensure ending ridges were recorded as ending ridges and bifurcations as bifurcations in the inked impressions. The subject's finger was then rolled in Evident® black fingerprint ink and 10 quality planar impressions were recorded on white cardstock. The finger was lightly re-inked between each impression. The inked impressions were scanned onto an external hard drive at 1000 ppi; the same ruler used for the distortion videos was included in the scanned image of the inked planars.

2.3. Finger template generation

The scanned image of the inked planar impressions for each finger was opened in ImageJ [11], and using the ruler the scale was set to mm for the image. A minutiae or feature from the core area was selected for each finger to serve as the origin. All minutiae present in each of the 10 impressions were then marked manually by a single individual and their x and y coordinates recorded. To ensure consistent marking, the minutiae set was marked for the first impression, and this image was used to mark the remaining 9 impressions. The origin coordinates were then subtracted from those of the entire set to position them in relation to this central feature. The average minutiae locations were calculated for the 10 impressions to represent the 'true' location of each minutiae in the finger template. The locations of each minutiae were also converted to polar coordinates for versatility in data processing and visualization.

2.4. Distorted images and image processing

Images from the distortion videos were isolated on the camera itself. The video was paused at the peak of each distortion movement, and the frame at the pause point was saved for each movement and all repetitions. Each set of distortion images was opened in ImageJ, and the scale set in the same manner as the inked planars. Each image was then split into its red, green, and blue color channels, and contrast limited adaptive histogram equalization (CLAHE) was performed on each color channel. A maximum slope of 3.00 and box size of 31 were found to be the best CLAHE settings for optimum image and contrast enhancement. The channels were then recombined and each image converted to grayscale (Fig. 1).

A horizontal flip of the distorted images was performed in ImageJ to orientate the images as they would appear as latent prints or inked impressions. The minutiae present in the 5 clearest images were marked in the same manner as the inked planars, and the x and y coordinates recorded. Due to the various movements and the heavy deposition pressure some minutiae fell outside the contacting region or became too blurry to mark accurately. These minutiae were not used for the variability calculations.

2.5. Calculating degree of variability

Variability in minutiae location was measured with the Euclidean distance between the distorted minutiae locations