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PAPER

CRIMINALISTICS

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Introducing a Semi-Automatic Method to Simulate Large Numbers of Forensic Fingermarks for Research on Fingerprint Identification

ABSTRACT: Statistical research on fingerprint identification and the testing of automated fingerprint identification system (AFIS) performances require large numbers of forensic fingermarks. These fingermarks are rarely available. This study presents a semi-automatic method to create simulated fingermarks in large quantities that model minutiae features or images of forensic fingermarks. This method takes into account several aspects contributing to the variability of forensic fingermarks such as the number of minutiae, the finger region, and the elastic deformation of the skin. To investigate the applicability of the simulated fingermarks, fingermarks have been simulated with 5–12 minutiae originating from different finger regions for six fingers. An AFIS matching algorithm was used to obtain similarity scores for comparisons between the minutiae configurations of fingerprints and the minutiae configurations of simulated and forensic fingermarks. The results showed similar scores for both types of fingermarks suggesting that the simulated fingermarks are good substitutes for forensic fingermarks.

KEYWORDS: forensic science, fingerprint, fingermark, simulated fingermarks, skin deformation, likelihood ratio, identification, individualization

Recently, several studies have been performed that focus on the statistical foundation of fingerprint identification (1–3). These studies underline the need for statistical modeling of forensic fingermarks. Large databases consisting of forensic fingermarks with corresponding fingerprints are needed in research to successfully model the different aspects contributing to the variability of fingermarks observed in forensic casework. Unfortunately, these large databases are rarely available for research, and creating these databases is very labor intensive. In general, the largest fingermark/fingerprint database available is the NIST Special Database 27, which consists of fingermark and fingerprint images and their minutiae data for 258 forensic cases (4).

Fingerprints are (controlled) friction ridge impressions that cover a large part of the ridge details of the fingertip. In the forensic field, fingerprints are captured as rolled or flat impressions and are used as reference material. Forensic fingermarks are (uncontrolled) friction ridge impressions left on an object at a crime scene. These impressions represent a fraction of the ridges present on the surface of a finger. They can originate from every region of a finger, depending on the part of the finger being in contact with the object. Furthermore, variability in fingermarks is caused by among other nonlinear distortions observed in ridge details resulting from elastic skin deformations, the type of surface where the mark is left on, the amount of pressure applied during contact with the object, and the development technique used to visualize the mark (5). Little research has been carried out on the variability in fingermarks induced by these aspects because of the lack of large forensic fingermark/fingerprint databases. The few studies that have been performed are all on the topic of elastic skin deformation for a finger. In 1999, Ashbaugh (6) described the existence of distortion in fingermarks because of elastic deformation of the skin. In 2009, Maceo (7) analyzed the skin flexibility for fingers exerting different forces to a surface.

Simulated fingermarks provide a practical solution to study some aspects of forensic fingermarks at a larger scale. Two major questions arise with the use of these marks for research. First, do simulated fingermarks model forensic fingermarks realistically? Little research has been performed on defining the variations in forensic fingermarks. As there are many aspects in fingermarks involved, the answer is currently no. The second question is which aspects of forensic fingermarks should these fingermarks simulate? These aspects should be studied and chosen according to their relevance to the application they are used for.

Several groups have implemented distortion models to simulate forensic fingermarks from flat fingerprints. These models are however not based on actual forensic fingermarks and are currently not validated. Maltoni and Cappelli (8,9) and Bazen and Gerez (10) described models to implement distortions on flat fingerprints to create simulated fingermark images. Neumann et al. (1,2) described a model to implement distortions on fingerprints to create simulated minutiae configurations.

In this study, a semi-automatic method is presented to create simulated fingermarks that model forensic fingermarks. In addition, it introduces a way to produce these fingermarks in large quantities. The fingermarks simulate either the minutiae features or the images of fingermarks. The simulated minutiae features can be used for different applications among others for statistical research on fingerprint identification and for testing performances of matching

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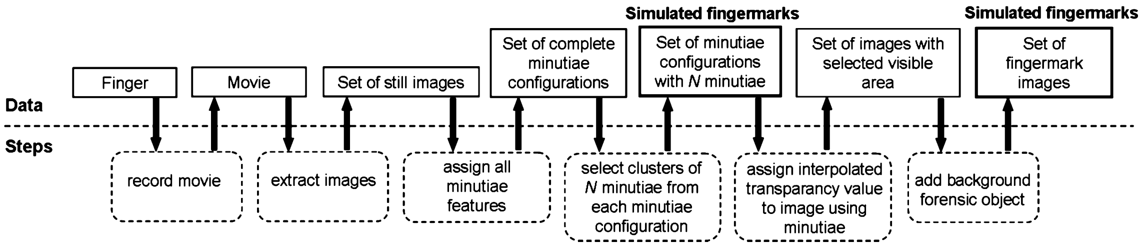

FIG. 1—*Schematic flow to create simulated fingermarks.*

algorithms of automated fingerprint identification systems (AFIS). The simulated images can be used for testing performances of feature extraction and matching AFIS algorithms. The method focuses on creating simulated fingermarks by simulating local clusters of minutiae with a specific number of minutiae. Based on these clusters of minutiae, simulated fingermark images can be created. The method takes into account several aspects contributing to the variability of forensic fingermarks such as the number of minutiae, the finger region, and the distortions in ridge details resulting from elastic deformation of the skin. Other aspects such as the image quality and the variability in manual minutiae assignment are currently not considered in the method. To be able to acquire a large amount of data efficiently, a way to optimize the data processing procedure is presented. In addition, two experiments are presented to study the applicability of simulated fingermarks for forensic research purposes. This study focuses on fingermarks with 5–12 minutiae as these fingermarks are used for statistical research in fingerprint identification.

Description of the Method to Create Simulated Fingermarks

The method presented in this study provides a way to create simulated fingermarks on the level of minutiae features and on the level of images. It is based on creating local clusters of minutiae from the complete minutiae configuration of a flat fingerprint. Figure 1 shows the schematic flow of this method, starting from the finger and ending with the simulated fingermark image.

Step 1: The Recording of a Movie

The first step consists of recording a movie while a finger performs a predefined motion sequence on the sensor of a livescan device. In this study, each movie had a duration of approximately 30 sec and was recorded using the software SnagIt® with a frame rate of four frames per second (http://www.techsmith.com/snagit.html). An ACCO 1394 livescan device (Smiths Heimann Biometrics, Jena, Germany) was used for the recordings. At the start of the procedure, the finger was placed flat on the center of the glass plate of the livescan device. In this position, a low amount of distortion is caused because of the pressure applied when the finger makes contact with the sensor. The donor was instructed to maintain a constant moderate pressure on the device from the start to the end of the procedure to minimize extreme distortions. Next, the donor was asked to move the finger in a sequence of eight different directions to obtain images with a wide variety of distortions caused by these movements. This sequence was chosen to include possible distortions that could occur in forensic fingermarks because of a criminal activity. This method focuses only on distortions that could occur in fingermarks left on flat surfaces. Each finger movement started in the flat position. With this approach, images were created with gradually increasing and decreasing degrees of distortion particular for the movement type. From the center of the sensor, the finger was displaced slowly by sliding the finger in a certain direction on the sensor. First, the finger was displaced horizontally toward the right and then the left end of the plate. Next, it was displaced vertically to the upper and then the lower end of the plate. Hereafter, the finger made a rotation clockwise and then anti-clockwise while moving on the plate. At last, a small rotation clockwise and anti-clockwise was made while leaving the core region of the finger in place.

Step 2: Extraction of Still Images

Still images were automatically extracted from the movies using the open source software VirtualDub (http://virtualdub.org/), starting at the image where the finger rests flat on the sensor and ending where the finger finishes the last rotation. The number of extracted still images depends on the length of the movie and on the speed of the movement of the finger. The images were stored as 8-bit grayscale bitmap files with a resolution of 500 dots per inch. Figure 2 shows still images extracted from a movie for different movements of the finger. The region that is distorted depends on the direction of the force applied, for example, for loop patterns, large distortions are observed in the region above the core of the pattern when the finger is moved to the upper end of the plate. In the core region itself, little or no distortion is observed as this region touches the sensor plate tightly. For this study, all possible distortion types were included, as there is no information about distortions that occur in forensic fingermarks.

Step 3: The Assignment of the Minutiae

The procedure to assign minutiae manually for a large number of images is very labor intensive. Therefore, a procedure was developed in this study to facilitate this process. First, image registration was applied to the movie images to align the images in the movie sequence with a reference image, in this case the first image in the movie sequence. Figure 3 shows the registration process as applied to a movie image in this study.

FIG. 2—*Still images representing different types of distortion. The arrows show the directions of the applied forces.*

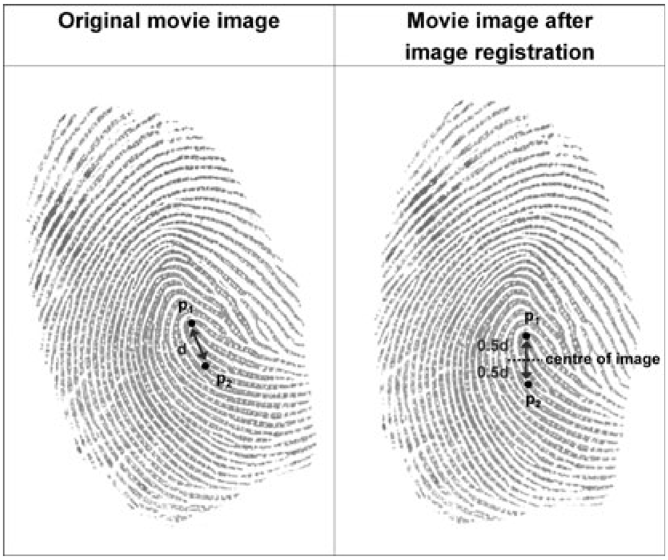

FIG. 3—*Illustration of the registration process applied to a movie image.*

This image registration is based on the assignment of two defined points in the fingerprint image area, p_1 and p_2. For each movie, two minutiae were chosen as the defined points. These two minutiae should be present in every image in the sequence to ensure a consistent alignment of the images. In the example (Fig. 3), two minutiae were chosen near the core region of the fingerprint. The distance between these two minutiae is denoted with d. The aim is to rotate and translate the image so that p_1 is at $0.5d$ above the center of the image and p_2 is at $0.5d$ below the center of the image. The images in the sequence will have the same orientation when the same two minutiae are chosen, and the same procedure is followed in every image.

After registration, a feature extraction algorithm was used to automatically assign minutiae in the movie images. Using this algorithm, large sets of data can be processed in a very short time. Depending on the performance of the algorithm and the quality of the images, it can result in a considerable amount of false and/or missed minutiae. A software tool was created to display the automatically assigned minutiae on the images and to provide editing facilities for a manual correction of these minutiae. This tool automatically detects minutiae that are wrongly assigned and minutiae that are missed in an image by comparing the minutiae assigned in the current image with the minutiae assigned in the previous image. Some tolerance in the location and the angle of a minutia caused by elastic skin deformation is allowed. The largest differences were observed in the outer area of the fingerprint and the smallest differences in the core region of the print. Hereafter, the operator can manually remove falsely assigned minutiae and add minutiae that were not detected.

Step 4: Simulating Fingermarks in Terms of Minutiae Features

Forensic fingermarks originate from different regions of a finger and vary in size. These aspects should be considered when creating a large database of simulated fingermarks for statistical research. With this method, fingermarks are simulated representing local clusters of nearest neighboring minutiae with a predefined number of minutiae at specific regions of a movie image. A software tool was created to select a cluster of minutiae automatically from the complete minutiae configuration assigned on the image extracted from the movie. The procedure starts with selecting the number of minutiae for the simulated fingermarks and subsequently selecting the region where the clusters of minutiae should be created from the complete minutiae configuration in the images. The software tool provides two different options for region selection.

The first option consists of selecting a specific region in the images. Six different regions were defined in this tool: the core, delta, top, bottom, radial, and ulnar region. The possibility to create fingermarks at the core and delta regions depends on the general pattern of the fingerprint. For fingerprints with arches, the center of the minutiae configuration of the image is determined and used as the core region as arches do not have a core or a delta. In a complete minutiae configuration, the options to produce marks from the top, bottom, radial, and ulnar region can be defined automatically based on the median of the minutiae coordinates. Figure 4 shows a flat fingerprint image with four examples of local clusters of four minutiae each created in different regions. A random minutia is chosen as starting point in the selected region. The tool calculates the distances from the defined starting point to all minutiae in the print. A cluster of N minutiae is created by selecting the $N - 1$ nearest minutiae to the starting point. Figure 5 illustrates two local clusters of eight minutiae, one at the core region and one at the radial region of the flat fingerprint. The coordinates and the angle of each minutia are written among other features in a file describing the biometric features of the fingermark. This file has the same format as files created by the AFIS feature extraction algorithm.

The second option for region selection consists of selecting randomly a fingerprint region in the images. Two approaches were defined for this option. The first approach consists of creating *one* mark for each movie image at a random region, hereafter called the single random mark approach. The starting point is a random minutia in the complete minutiae configuration. The second approach consists of creating a *set* of marks for each movie image at all possible regions, hereafter called the multiple random marks approach. In this approach, all available minutiae are considered successively as the starting point to create all possible clusters of minutiae in an image. The minutiae clusters that were created more

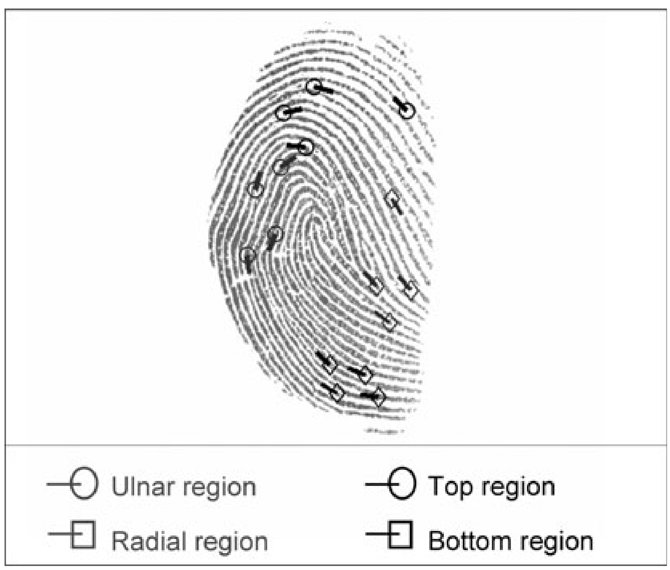

FIG. 4—*Flat fingerprint image for a left index finger with local clusters of four minutiae, each created in four different regions.*

FIG. 5—*Flat fingerprint image for a left index finger with local clusters of eight minutiae for (a) the core region and (b) the radial region. The red minutia is the starting point.*

than once were automatically removed. This approach provides a way to create automatically a large number of marks in different regions from a small set of movie images; however, minutiae clusters in the set are partially dependent on each other.

Step 5: Simulating Fingermarks in Terms of Images

A simulated fingermark image can be created by combining a fingermark image with a defined number of minutiae and an image of a background observed in casework. The minutiae clusters created in step 4 of this procedure are used to create these simulated fingermark images. Figure 6 shows an example of a simulated fingermark created with eight minutiae. Images were created by first defining the area in the image where the mark will be made, for example, the area of the selected eight minutiae (Fig. 6*a*). Hereafter, interpolated transparency was applied to the image; the area of the image surrounding the fingerprint area of the minutiae set is made transparent using linear interpolation. This results in an image where only the area of the eight minutiae is visible (Fig. 6*b*). To create a more realistic fingermark image, a background similar to backgrounds of forensic fingermarks was added (Fig. 6*c*). Figure 7 illustrates three fingermark images with different forensic backgrounds. In the forensic identification field, fingerprint experts can use these images to test their ability to assign minutiae.

Investigating the Applicability of Simulated Fingermarks

Two experiments were performed to study the use of simulated marks as substitutes for forensic fingermarks. These experiments will determine whether simulated fingermarks can be used for statistical research on forensic identification and performance tests for

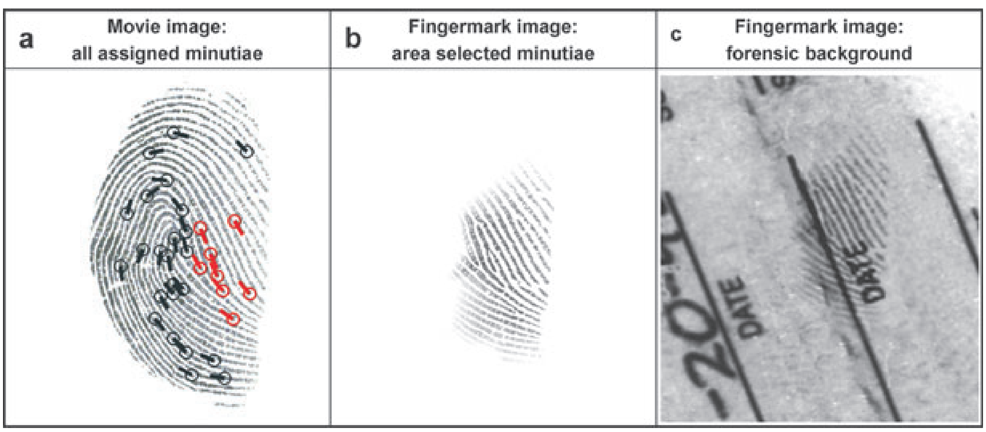

FIG. 6—*Illustration of the process to create a fingermark image with eight minutiae (shown in red).*

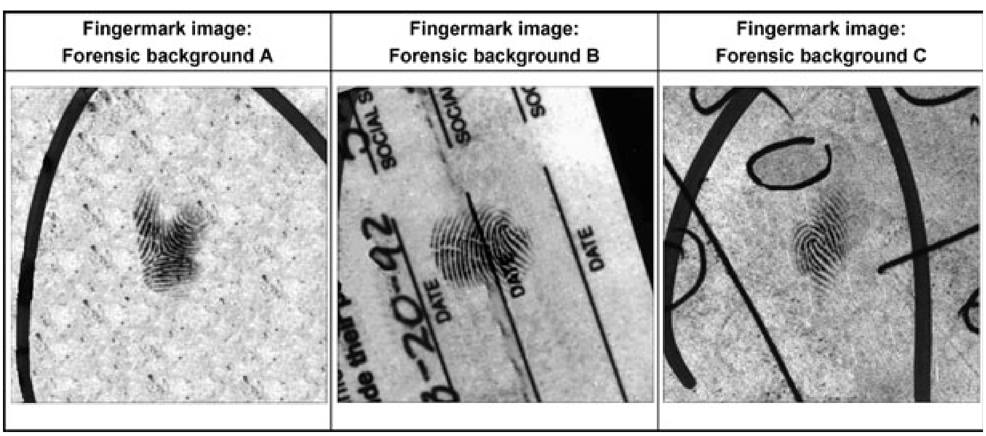

FIG. 7—*Three simulated fingermark images with different forensic backgrounds.*

AFIS systems. In both areas, comparison scores reported by AFIS matching algorithms play an important role. The two experiments focus on the comparison of simulated fingermarks with fingerprints using a modified research AFIS algorithm. In general, AFIS matching algorithms quantify the degree of similarity between the position and the orientation of the two minutia configurations in a mark and a print and report a score for each comparison; a high degree of similarity gives a high score.

The first experiment aims to study the effect of the partial dependency of marks for the multiple random marks approach on score distributions. As discussed earlier, the multiple random marks approach yields more simulated marks than the single random mark approach. However, these marks have a partial dependency that can affect the score distributions resulting from the comparisons between mark and prints. This experiment focuses on the similarity between the score distributions obtained for fingermarks created with the multiple marks approach and the random single mark approach. The second experiment aims to study the similarity between simulated fingermarks and forensic fingermarks. The results of this study can indicate whether the simulated marks are good substitutes for forensic fingermarks and focuses on the similarity between the score distributions obtained for simulated and forensic fingermarks.

Experiment 1—The Single Random Mark Approach Versus the Multiple Random Marks Approach

This experiment studies the effect of the partial dependency of marks by studying the similarity between score distributions obtained for the multiple random marks and the single random mark approach. These score distributions were determined by comparing fingermarks with fingerprints from the same finger. Simulated fingermarks were created from movies of six fingers from separate donors. These fingers were chosen so that various fingers and general patterns were represented in the data set. Detailed information on these fingers and the number of still images extracted from each movie is shown in Table 1.

TABLE 1—*Detailed information on the movie images used to create simulated fingermarks.*

Finger	Type finger	General pattern	Number of still images
1	Left index	Radial loop	276
2	Left index	Radial loop	143
3	Left thumb	Ulnar loop	98
4	Left middle	Tented arch	145
5	Right index	Whorl	91
6	Right middle	Ulnar loop	114

TABLE 2—*Number of created simulated and forensic fingermarks.*

# Minutiae	# Simulated marks (random approach)	# Simulated marks (multiple approach)	# Forensic marks (multiple approach)
5	867	24,650	1411
6	867	25,058	1316
7	867	24,876	1237
8	867	25,015	1131
9	867	25,036	969
10	867	24,994	807
11	867	24,658	541
12	867	24,443	174

For the single random mark and the multiple random marks approaches, eight sets of fingermarks were created consisting of minutiae clusters for 5–12 minutiae. As showed in Table 2, the multiple random marks approach produced approximately 28 times more simulated fingermarks than the single random mark approach in all eight sets. Fingerprint images were captured using a Smiths Heimann Biometrics ACCO 1394 livescan device following a rolling procedure where the fingers were rolled from side to side on the glass plate of the livescan sensor. The police use this rolling procedure to capture inked fingerprints on paper. The quality of these fingerprint images is equivalent to the good quality fingerprint images in the existing Dutch Police fingerprint database. A fingerprint examiner assigned manually the minutiae features in the prints. For each finger, the marks were compared with their corresponding rolled fingerprints. The scores resulting from these comparisons were plotted in a distribution called the true score distribution. The true score distributions for both approaches were compared in terms of shape and score range.

For both approaches, similar score distributions are observed for marks with 5–12 minutiae. Figure 8 illustrates the distributions of the resulting scores for both approaches for marks with 7 and 12 minutiae. For the AFIS algorithm used in this study, the score distributions always consist of two peaks. The first peak consists of early out scores determined in the first stage of the matching procedure. These early out scores are scores obtained for pairs of marks and prints that have a lower degree of similarity than a defined threshold and are not taken into account in the complete matching procedure. This threshold score changes with the number of minutiae in the mark. The second peak consists of the remaining scores obtained in the second stage of the matching procedure where a more sophisticated comparison is performed. The mean score, the shape, and the width of the distributions are similar. The distribution for the multiple random marks approach is smoother because of the larger number of marks in the set. The logarithmic plots (Fig. 8*a2*,*b2*) show that the distribution for the multiple random marks approach is determined for a larger score range than for the single random mark approach. Figure 9 shows box plots of the scores obtained for fingermarks with 5–12 minutiae. As expected, the scores are higher for marks with a higher number of minutiae. This feature is a build-in property of the AFIS algorithm. The score intervals and the sizes of the boxes that represent 50% of the data are similar for both approaches, indicating that the partial dependence of marks does not have an affect on the score distributions. The multiple random marks approach however gives more extreme values because of the larger sample size. These results suggest that the decision on which approach to choose in a certain study solely depends on the number of marks needed.

Experiment 2—Simulated Fingermarks Versus Forensic Fingermarks

This experiment studies the similarity between score distributions obtained for simulated fingermarks and forensic fingermarks with 5–12 minutiae. The experiment consists of two parts. In experiment 2a, the similarity in score distributions resulting from the comparison of fingermarks and fingerprints originating from the same source (true score distributions) is investigated. In experiment 2b, the similarity in score distributions resulting from the comparison of fingermarks and fingerprints originating from different sources (false score distributions) is investigated. As in experiment 1, this experiment focuses on comparing the distributions in terms of shape and score range.

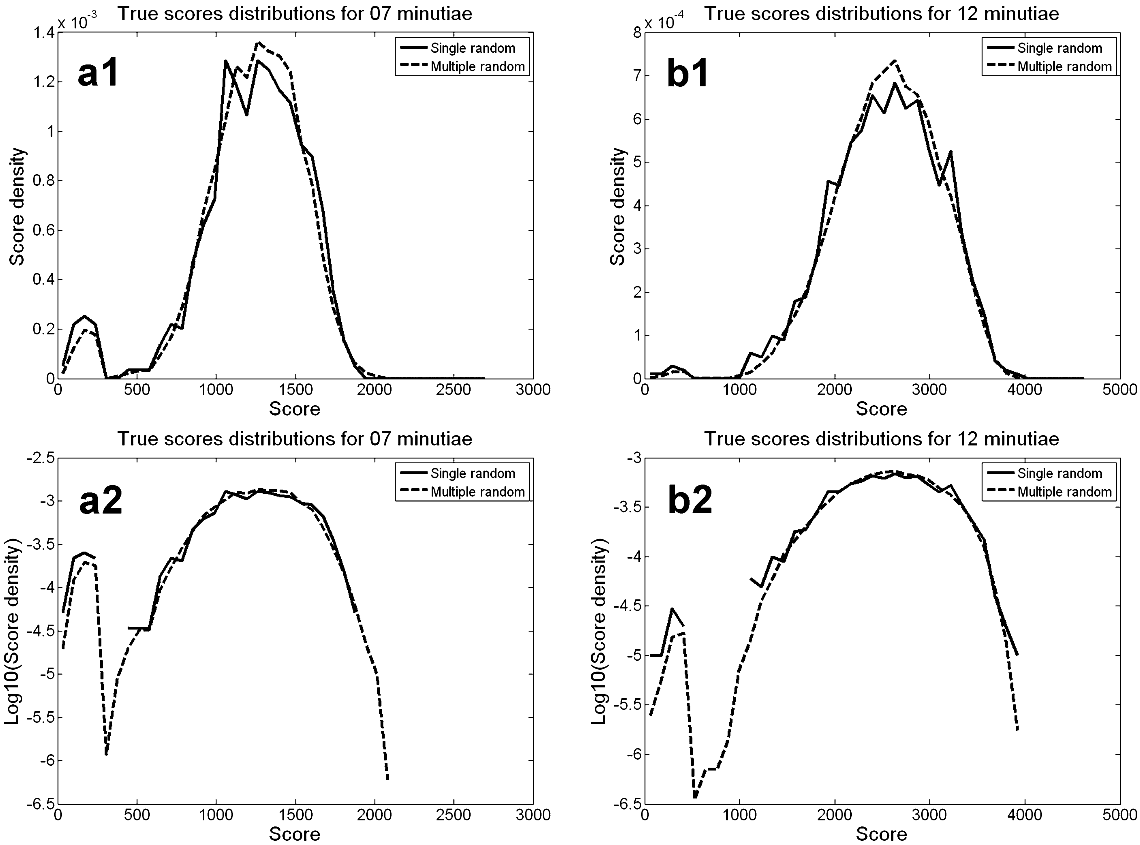

FIG. 8—*True score distributions for fingermarks with (a) 7 and (b) 12 minutiae created from six fingers for the single random mark and the multiple random marks approaches.*

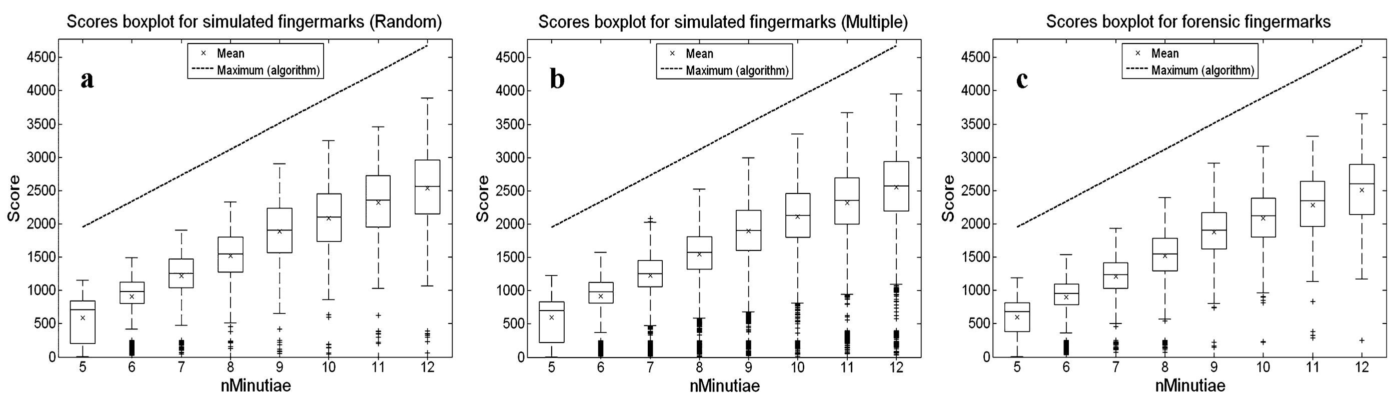

FIG. 9—*Box plots of scores for simulated and forensic fingermarks (5–12 minutiae): (a) simulated fingermarks, single random mark approach, (b) simulated fingermarks, multiple random marks approach, and (c) forensic fingermarks, multiple random marks approach.*

In experiment 2a, the true score distributions for forensic fingermarks were based on a set of 58 forensic fingermarks images and their corresponding fingerprint images. These images were obtained from forensic cases in which a fingerprint examiner reported a positive identification. Three fingerprint experts analyzed these marks independently and were asked to manually assign 12 minutiae on each mark as they would assign in the current Dutch identification procedure. These 174 minutiae sets (3 experts $\times$ 58 marks) constitute one set of forensic fingermarks. Seven more sets of forensic fingermarks were created from these 174 minutiae sets consisting of minutiae clusters with 5–11 minutiae. Table 2 shows the number of forensic marks produced for the eight sets of fingermarks. The multiple marks approach was chosen to obtain more data in the distributions. The fingerprints were captured by the police with ink on paper following the same rolling procedure as described in the previous experiment and were later scanned. A fingerprint examiner manually assigned the minutiae features in the prints. For each finger, the forensic fingermarks were compared with their corresponding fingerprints resulting in a set of true scores for forensic fingermarks. To create true score distributions for simulated fingermarks, the eight sets of simulated fingermarks in experiment 1 were compared with their corresponding fingerprints.

The forensic and the simulated fingermarks have similar true score distributions for marks with 5–12 minutiae. Figure 10 illustrates the true score distributions for simulated and forensic fingermarks with 7 and 12 minutiae. The mean scores, shape, and the width of the distributions are similar. The shape of the distributions becomes less smooth when the number of minutiae in the marks increases. This is expected, as there are fewer marks in the sets with a high number of minutiae (see Table 2). The scores obtained for the forensic fingermarks with 5–12 minutiae are shown in Fig. 9*c*. The box plot shows increasing scores as the number of minutiae in the marks increases. The mean scores for forensic (Fig. 9*c*) and simulated marks (Fig. 9*b*) are similar. With the simulated marks approach, larger number of marks can be used to assess the distributions for a larger score range (Fig. 10*a2*,*b2*). The score range for the forensic marks with a higher number of minutiae is slightly smaller and less outliers are observed. Both findings can be explained by the movie images having smaller and larger distortions than forensic marks. The second finding can also be explained by the set of forensic marks having a smaller number of marks.

In experiment 2b, false score distributions were created for the same eight sets of forensic and simulated fingermarks as in experiment 2a consisting of minutiae clusters of 5–12 minutiae. For this study, the forensic fingermarks created in experiment 2a and the simulated fingermarks created in experiment 1 using the single random mark approach were compared with a set of 10,000 fingerprints from the Dutch Police fingerprint database. The single random mark approach was chosen for the simulated fingermarks as a very large number of marks are not needed to determine a continuous false score distribution.

The forensic and the simulated fingermarks have similar false score distributions for marks with 5–12 minutiae. Figure 11 shows the distributions for the resulting false scores for simulated and forensic fingermarks with 7 and 12 minutiae. The shape and the score range of both distributions are similar, even for marks with a small number of minutiae.

Discussion

Currently, large databases of pairs of forensic fingermarks and fingerprints are rarely available for research. In this study, a semi-automatic method is presented to simulate large numbers of fingermarks for a selected number of fingers. These fingermarks simulate either the minutiae features or the images of forensic fingermarks. Sets of simulated fingermarks can be created with a specific number of minutiae, type of ridge distortions, and region of the finger. The results show similar true and false score distributions for simulated and forensic fingermarks suggesting that the simulated fingermarks are good substitutes for forensic fingermarks for research purposes.

During the gathering of the movie data, several aspects were observed that influence the extent of the distortions and the quality of the movies. The extent of the distortions in the ridge details is very dependent on the general pattern of the finger and the elasticity of the skin. Fingers having a firm skin and fingers having an arch as the general pattern have less distortion. On the other hand, fingers having whorls and loops have more distortion. The quality of the movies was influenced by the following factors. First, fingers moving too fast on the livescan sensor caused blurred images of the ridge patterns. This was observed mainly for fingers producing

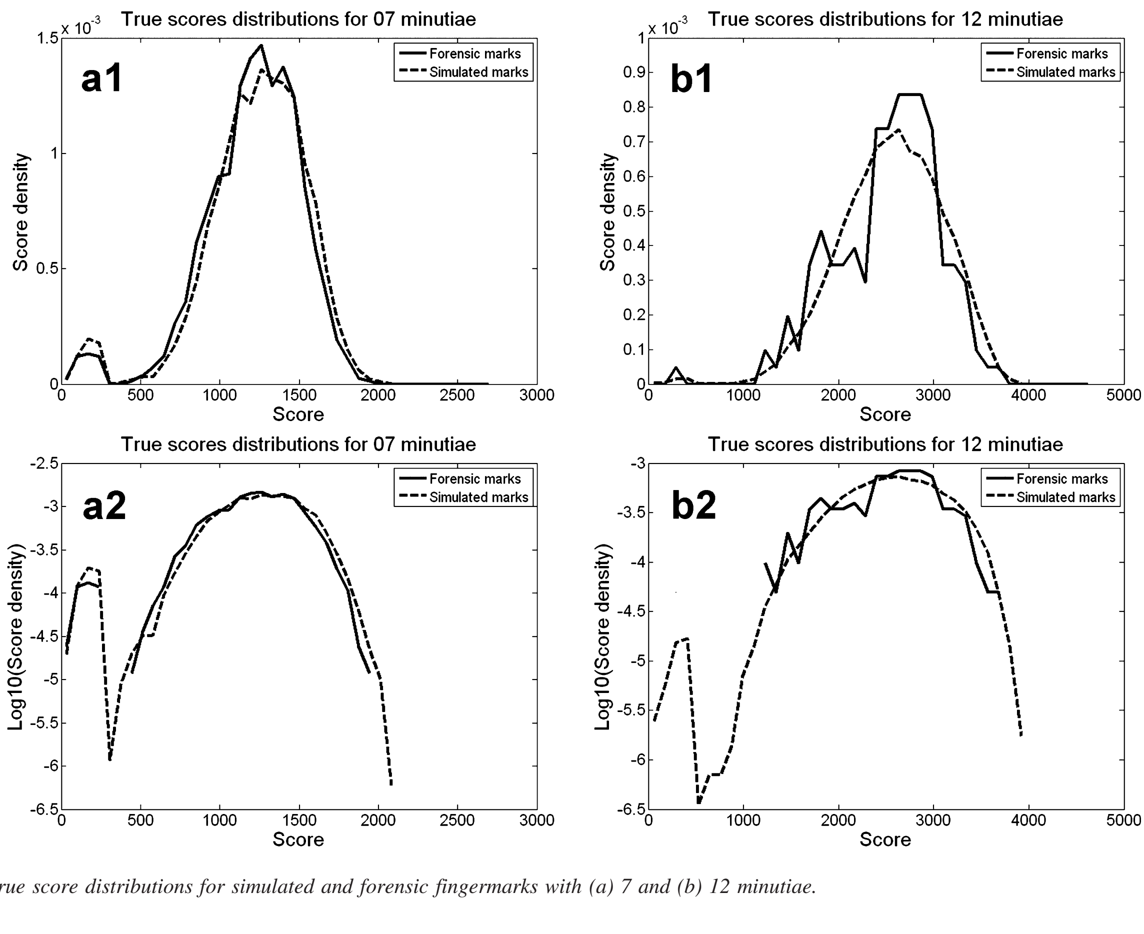

FIG. 10—*True score distributions for simulated and forensic fingermarks with (a) 7 and (b) 12 minutiae.*

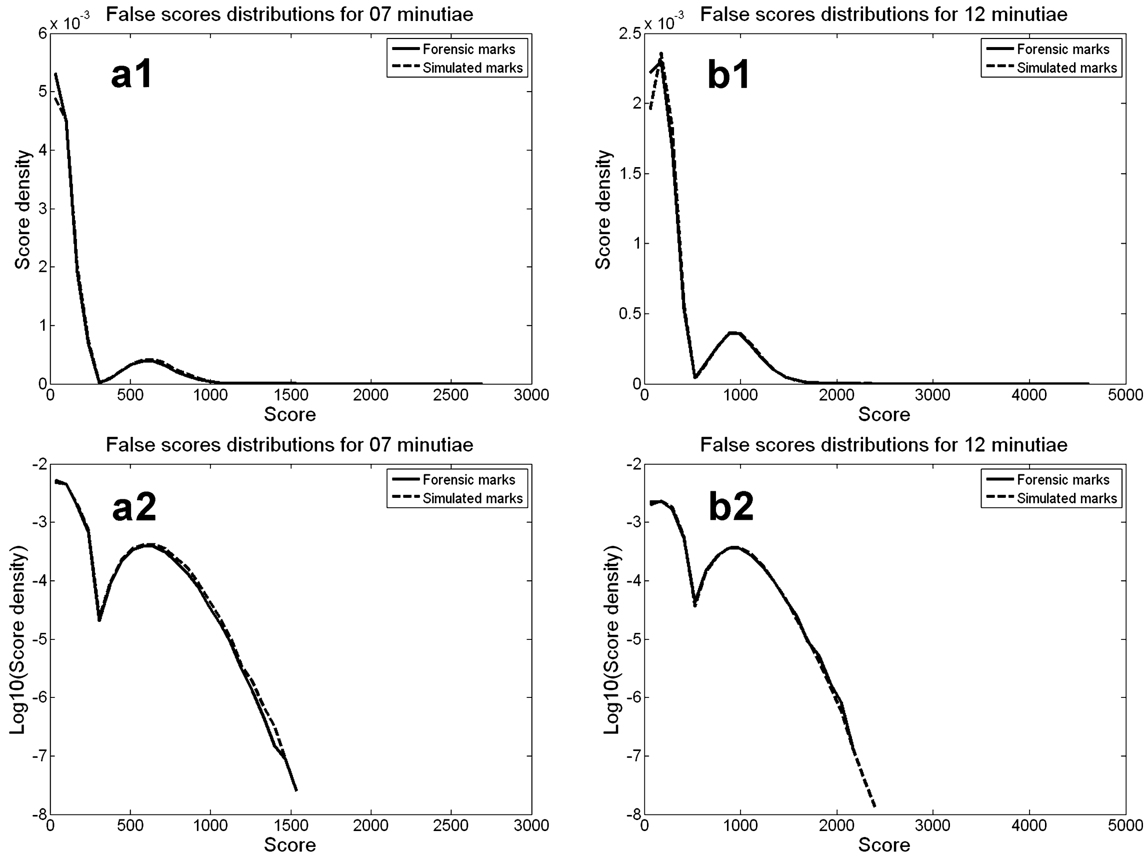

FIG. 11—*False score distributions for simulated and forensic fingermarks with (a) 7 and (b) 12 minutiae.*

less secretion (dry fingers), as they were more difficult to displace on the glass plate and for donors who had difficulty making slow movements of the finger. In general, most donors had difficulty with displacing the middle and ring fingers. Finally, fingers producing more secretions (fatty fingers) left traces of residue on the glass plate. These traces of residue were captured in the images and had to be removed from the sensor between recordings to minimize wrongly automatically assigned minutiae.

For statistical research such as the calculation of likelihood ratios (LRs) in fingerprint identification, this method provides a way to create large sets of fingermarks. The LR framework in general has been described by Aitken and Taroni (11). In the forensic field, several studies have been performed on this topic already for forensic identifications (1–3). In these studies, the calculation of the LR provides the evidential value of the link between a questioned fingermark and a fingerprint by estimating the ratio of the probability densities of observing the similarity score given two scenarios. The evidential value in these studies is based on the comparison of the minutiae features, but currently disregards third level details. The first scenario describes that the fingermark and the fingerprint originate from the same finger (within-source variability). The analysis of the within-source variability focuses on the effect of distortions in the location and the orientation of minutiae in fingermarks from one source, including the distances between the minutiae (12). Large numbers of comparisons need to be performed between fingerprints and fingermarks from the same finger to study the within-source variability and to derive reliable score distributions. With the method described, large numbers of marks can be created to derive score distributions for a specific finger. The second scenario describes that the fingermark originates from another finger than the fingerprint (between-source variability). The analysis of the between-source variability focuses primarily on the variation in marks caused by differences in minutiae configurations between different fingers. The results in this study show that simulated fingermarks can be used to study the between-source variability as well.

The simulated fingermarks can in the future also be used to quantify the extent of the distortions in terms of shifts of minutiae. Recently Maceo (7) described the concepts in fingermark distortion such as the skin flexibility of a finger in combination with the different stresses that are applied to a surface. The focus of the study by Maceo (7) was to raise the awareness of fingerprint examiners on the phenomenon of distortion and to start investigating how to recognize types of skin deformation observed in these marks. The method proposed in the current study provides a tool to produce simulated fingermarks for specific types of distortions, for example, for finger movements that shift to the right or to the left. In future studies, one can create statistical models of the extent of this distortion in terms of shifts of minutiae on a large scale based on simulated fingermarks.

The simulated fingermarks can be used in performance tests for feature extraction and feature matching algorithms in AFIS systems. In order for the tests to be relevant, large databases of fingerprints and fingermarks are needed to simulate the size of the database used in actual casework. In a future study, we will illustrate the advantages of using simulated fingermarks over forensic fingermarks in performance tests.

In future, the method can be expanded by incorporating more features playing a role in fingerprint identification, for example, the quality of the images and the assignment of third level details.

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