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QUANTIFYING THE DERMATOGLYPHIC GROWTH PATTERNS IN CHILDREN THROUGH ADOLESCENCE

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ABSTRACT

Ultra-Scan Corporation was awarded a five year grant through the Office of Justice Programs in response to a proposal titled *Quantifying the Dermatoglyphic Growth Patterns in Children through Adolescence*. The project's objective was to research friction ridge patterns during a rapid period of growth (such as that found in children through adolescence) to determine whether a commonality of growth exists and to develop a statistically valid mathematical model for predicting this change. The project's goal was to provide the NIJ and scientific community a means for predicting the shape changes of fingerprints during this period of growth in order to significantly enhance the probability of matching an individual's adolescent/adult fingerprints to fingerprints acquired when the individual was a child.

The project's goal necessitated the capture of children's fingerprints at specific intervals. Prior to any interaction with collection subjects, a thorough Independent Review Board (IRB) application and review process was completed, as was a full design research protocol. Recruitment, Consent, Procedure, Confidentiality and Human Participant Protections protocols were developed and approved.

Subject recruitment proved to be a daunting task throughout the study. The limited availability and cooperation of subjects (children), guardians (school administrators, Scout leaders), and parents (consent) was an unexpected and constant hurdle during the recruitment process. After exploring several populations of potential collection subjects including local schools students, regional Boy Scout groups proved to be willing and available subjects for the study. Initial subject fingerprints were collected during the first one and a half years and re-collected for study during a subsequent three year period.

The collected data was thoroughly examined, categorized and analyzed in an effort to explain the observed phenomenon: growth patterns of fingerprints as measured in this study do not appear to follow a general pattern. The growth patterns are so individualistic that it is impossible to develop a single map or family of maps that accurately models minutiae pattern growth. Although individualistic patterns can be modeled, this is not a viable solution when applied to the general population.

Although the results from this study indicate that a Minutiae Growth Map (MGM: a linear, affine transformation that maps a set of a child's minutiae at one age to a set of their minutiae at a different age) does not seem feasible, the researchers employed another technique to meet the project goal of matching a child's minutiae at one age to a set of their minutiae at an older age. Funded from other resources and refined during the execution of this project, Ultra-Scan used a previously developed process to compensate for plastic distortion. Initially, this algorithm was planned to augment the automated Minutiae Extraction Matching Tool (MEMT) in order to more accurately place minutiae. Because it was originally designed to compensate for local area scaling, it was hypothesized that it would be well suited to compensating for growth patterns.

The research team modified this algorithm as a stand-alone matcher and was able to successfully match all fingerprint pairs from all of the study's collection epochs. Although this algorithm is not necessarily the MGM as originally envisioned at the project's onset, the research team nevertheless was able to meet a project goal of demonstrating a successful method for matching fingerprints of individuals after many years of growth. The results may certainly be worthy of future exploration and development.

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Variation in Minutiae Location

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EXECUTIVE SUMMARY

Ultra-Scan Corporation was awarded a five year grant through the Office of Justice Programs in response to a proposal titled *Quantifying the Dermatoglyphic Growth Patterns in Children through Adolescence*. The project's objective was to research friction ridge patterns during a rapid period of growth (such as that found in children through adolescence) to determine whether a commonality of growth exists, and to develop to a statistically valid mathematical model for predicting this change. The project's goal was to provide the NIJ and scientific community a means for predicting the shape changes of fingerprints during this period of growth in order to significantly enhance the probability of matching an individual's adolescent/adult fingerprints to fingerprints acquired when the individual was a child.

In order to successfully accomplish the technical objectives and goal, the Ultra-Scan research team divided the work plan into three sections: Administrative, Data Collection and Analysis.

1.0 Administrative

The project's goal necessitated the capture of children's fingerprints at specific intervals. Prior to any interaction with fingerprint collection subjects, the research team completed a thorough Independent Review Board (IRB) application and review process. An extensive review of IRB resources resulted in the selection of the University at Buffalo Social and Behavioral Sciences Institutional Review Board. Estimated as a two week task, IRB submittal and approval spanned nearly nine months due in large measure to the lack of biometric research protocol precedence within the IRB community. Concurrent with IRB submission and approval, the PI successfully passed an initial (and annually recurring) examination for Human Participant Protection Training through the National Cancer Institute.

The research team completed a full design research protocol, a significant administrative task that was critical to the IRB application and review process. The design research protocol included Recruitment, Consent, Procedure, Confidentiality and Human Participant Protections.

Verbal consent was obtained and recorded from each child participating in the study. A written consent form was also signed by a parent or legally authorized representative. Because researchers anticipated a wide range of reading and comprehension skills within the recruitment population, multiple (Pre-K - Grade 9+) consent forms were created.

Participant names were collected solely for the purpose of relocating individuals during the study. After each collection process, the research team stripped the subjects' names from the fingerprint images collected and replaced them with numeric codes indexed to the participant for the duration of the study only.

1.1 Recruitment

Subject recruitment proved to be a daunting task throughout the study. The limited availability and cooperation of subjects (children), guardians (school administrators, Scout leaders), and parents (consent) was an unexpected and constant hurdle during the recruitment process.

Initially, school districts located within Erie County and Niagara County (New York State) were targeted for subject recruitment because of their proximity to research team

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headquarters, the relative stability of their adolescent population (increased potential for repeat subjects), and the availability of ready collection facilities (school gyms, cafeterias). Although continued interaction with school administrators was attempted, positive reaction to the program was disappointingly sparse. A majority of those who did respond registered strong resistance to the proposed recruitment effort. Ultimately, the attempt did not result in any enrolled subjects or collected fingerprints.

In mid-2006, the research team shifted its focus to an alternate local population of potentially cooperative subjects; the Boy Scout groups of Western New York. Recruitment and outreach materials were designed to accurately address the intent, scope and impact of the research within the Scouting community. As required, materials were submitted to the Independent Review Board (IRB) for approval.

With further input from the IRB, Ultra-Scan also elected to offer scouts/parents a complimentary child's identification (ID) card. Similar to ID material distributed by local law enforcement agencies, the laminated card contained the subject's picture, fingerprints, and basic demographic information.

In late 2006, researchers were afforded the opportunity to address a wide variety of Scout leaders at numerous events and roundtable leadership assemblies. Although Scout leadership was generally positive, initial data collection efforts from individual packs and troops was disappointing. The team requested and was granted a presence at the local Scout campground facilities where a majority of the regional troop/packs participate in a four day event each summer during the months of July and August. In an attempt to complete recruitment and collect of as many child fingerprint sets as possible to ensure statistical validity, the research team directed all remaining 2007 recruiting efforts on this event.

During 11 days on-site, more than 200 additional child fingerprint data sets were collected to complete the 308-set goal necessary for the study. With recruitment and initial fingerprint collection complete, the study progressed to data re-collection.

Some clear conclusions emerged based on the lack of positive response and very limited participation of various groups:

- A basic decision timeline for many institutions is measured in months, not weeks or days. In some instances, simply having an initial inquiry placed on the docket of a group's decision makers is a glacial process.
- There is a clearly a negative parental bias with regard to the collection and retention of children's fingerprints in a database (as was necessary for this study). While many organizations are successful in promoting child ID cards that include fingerprints and demographic data, none of these entities maintain a database of the child's information.

1.2 Software Development

The research team modified existing fingerprint collection and enrollment software to allow the capture of additional demographic information necessary for the study. An interface was designed to support creation of child ID cards in a format approved by the State of New York.

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2.0 Data Collection

Data collection (fingerprints and demographics) began in December 2006 and concluded in December 2009. The research team was initially charged with collecting fingerprint images for all study participants twice annually during a five (5) year period. Once the first collection analysis was completed, the collection timeframe was modified to one collection annually to better allow for fingerprint ridge pattern growth/variation, since it was determined that the six month interval was too short to detect discernable growth. The name, age, sex, ethnicity, height, and weight of each individual were also recorded.

Initially, collection protocol defined three (3) digits of each child's hand for scanning: Middle, Index and Thumb. The research team quickly concluded that it was often awkward for small children to properly place their thumbs on the scanner platen. This process resulted in many unusable thumb scans. The collection protocol was modified to require scanning only the child's Index and Middle fingers for subsequent fingerprint collection and re-collection.

Fingerprints were scanned by a trained team member using a UPEK TouchChip single-finger capacitance scanner.

There was a noteworthy amount of approval and data capture documentation necessary for the study, a majority of which was recorded in paper form. Initial attempts to complete collection using a single interaction model (Scout/parent/team member present) quickly determined the need for a more efficient four-part procedure that allowed Scout leaders and parents to complete necessary paperwork before interaction between the subject and collection team. This updated workflow significantly streamlined the capture process and caused the least disruption at Scouting events. Subsequent annual re-collection efforts were less complicated because a child's parent/guardian did not have to be present to authorize continued collection of additional data.

As discussed in the Administration section, the annual summer Scouting event became the main site for a majority of data collections because it attracted a large population of Scouts from communities across the Western and Southwestern regions of New York State. Furthermore, it would have been be impractical for the team to continue to travel to the many individual scout troop/pack meeting locations to collect data.

After initial fingerprint collection efforts were complete, the study progressed to data re-collection. This substantial task included preserving communication links with enrolled subjects as they progressed through the ranks of the Scout organization. The research team also continued efforts to attend targeted Scouting events in order to maximize enrollee contact and streamline data re-collection.

Difficulties encountered while attempting to re-collect fingerprint images from enrolled subjects included:

- Subjects who were dispersed across a large number of individual packs in the region and were difficult to target.
- Subjects who moved up the Scout ranks to become Boy Scouts. The research team had difficulty getting information from the Scout leadership regarding these individuals since the Boy Scouts were not included in the original research study efforts.
- Subjects who dropped out of Scouting or moved out of the region.

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By the completion of the collection effort, 123 (40%) of the original enrolled study population of 308 were imaged both a second and third time in preparation for data analysis. 36 (12%) of the original enrolled study participants had moved out of the area, left scouting, or declined to continue study participation.

2.1 Data Security

The security of a child's demographic and biometric data was typically the first subject addressed by parents when presentations were made to solicit participation. All information that was collected for the project database was entered and immediately encrypted on a password protected computer. At the completion of each on-site biometric data collection effort, the data was archived on an external drive and on a secured Ultra-Scan server. The laptop, external hard drive, and Ultra-Scan server were all stored in locked, restricted areas within Ultra-Scan facilities.

Participant names and contact information (collected to relocate individuals during the study) were stored in a locked file cabinet with restricted access. After each biometric collection effort, the research team stripped the individuals' names from the fingerprint images collected and replace them with a numeric code.

Identifiable data was destroyed at the end of the project and any data analysis or reports were void of personally identifiable data. Personally identifiable data is not circulated outside of Ultra-Scan Corporation, and is not released to outside organizations such as law enforcement agencies.

3.0 Data Analysis

The originally proposed Minutiae Growth Map (MGM) was designed as a linear, affine transformation that maps a set of a child's minutiae at one age to a set of their minutiae at a different age. Hence, the accuracy of minutiae extraction and matching is critical to the success of the MGM. To maximize the accuracy of a minutia's location, the research team built a computer-aided tool for the manual extraction and matching of minutiae. The process was intended to automatically extract minutia, remove false minutiae, and add missing minutiae. Unfortunately, it was found that although the tool was adequate for Automated Fingerprint Identification Systems (AFIS), the circular error probable (CEP: a disk in which we expect half the attempts to fall within) associated with automated locations were unacceptably large for this project.

Manual extraction was instead used to allow a user to study minutiae patterns on each image and thus pick the "best" location. A Minutiae Extraction Matching Tool (MEMT) tool was developed to simultaneously display two fingerprint images of the same finger, I_o and I_1. An operator manipulated I_o and I_1 by zooming in or out and centering the focus of the images in order to locate and identify matching minutiae pairs.

Picking the "best" minutia location, however, was still subject to two types of error. The first, measurement error, has a Gaussian distribution with zero mean and a standard deviation that depends on the skill and dedication of the MEMT operator. The second source of error, which is more troublesome, is due to the distortion that occurs when the finger makes contact with the scanner platen. The team was very careful place a child's fingers on the scanner platen in a manner that minimized distortion, but distortion is

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subtle and often hard to recognize. These errors contribute random noise and biases that can corrupt the estimate of growth.

As subsequent collection periods evolved it was reasonable to ask "can we detect any growth?" The team took a statistical approach to this question. It is known that there exists a unique Delaunay triangulation for a set of points in the plane when no three points are on the same line and no four are on the same circle. The team tessellated each finger with an appropriate subset of the minutiae as permanent landmarks on the finger by constructing Delaunay triangles unique to the given finger. Delaunay triangles are an especially efficient tessellation of the fingerprint because no other minutiae other than those of the triangle are contained in any triangle's circumscribed circle. Therefore, it is an ideal basis for an interpolation scheme that would yield a family of time ordered functional descriptions from one collection period to the next. In addition, we manually determined that the triangulations between collection periods were in one-to-one correspondence.

Delaunay tessellation was employed first to detect growth between collection periods. To minimize the effects of noise, all triangles with areas less than 100 square pixels and all triangles with a minimum interior angle of less than 15° were discarded. Two measures of growth were constructed:

1) The ratio of the area of corresponding triangles
2) The difference in the length of corresponding triangle sides.

If there was no growth one would expect the ratio of triangle areas to have a mean of 1.0 and the difference in triangle sides to have a mean of 0.0. Two statistical tests of hypothesis were in order. In each case a level of significance of $\alpha = .05$ was used. That is, there is a 5% chance that one will incorrectly reject the null hypothesis (Type I error)[1]. The mean ratio of triangles with the null hypothesis: H_0 μ_r=1.0 was first tested. That is, the population mean is 1.0 indicating no growth. The alternate hypothesis, H_1 states that there has been detectable growth. Because the population standard deviation is unknown, the t-distribution to test the hypothesis is used. The test statistic is computed by $t_{test} = \frac{\bar{x}_r - \mu_r}{s_r / \sqrt{n}}$, where n is the number of triangles. In the case of side lengths, one would expect the mean to be zero if there were no growth, hence the team set up a similar test of hypothesis.

Through growth analysis from an initial sample of the first repeat fingerprint collections, it was determined that the claim of statistically significant growth could not be supported between semiannual collections. The research team concluded that the stated study interval for re-collection of fingerprint data was too frequent to be useful, and the test protocol was modified from the original six (6) months interval to a 12 month interval for repeat collection of fingerprint data. As a result of this change in collection protocol, the full year 2007 was used for completing the full study enrollment of 308 participants, and the full year 2008 was used for obtaining as many first year re-collection data sets as possible.

[1] By definition: "The probability of making a Type I error, that is, of rejecting a true null hypothesis, is called the significance level, α, of a hypothesis test" (see "Introductory Statistics, 8th edition" by Neil A. Weiss and published by Pearson/Addison Wesley, 2008).

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After a period of two collections, a first order approximation to the MGM was tested. To develop this simple MGM, it was assumed that given distortion free images of a child's fingerprint taken at an older age, the child's minutiae can be transformed to the adult's minutiae via a similarity transformation using a sequence of rigid motions and dilations. That is, if F_0 is the set of Delaunay triangles at one age and F_1 is a set from the same finger at a later age, then one should be able to estimate a lateral scale factor, a longitudinal scale factor, and a rotation angle so that a similarity transformation F_0 are, with a high degree of accuracy, congruent to those of F_1. Each pair of scale factors was assumed to be a function of the change in height and weight for the given child. To solve for the scale parameters and rotation angle, a cost function was developed that resulted in a system of seven (7) nonlinear equations in seven (7) unknowns. Newton's method was used to numerically solve for the unknowns.

For the initial attempt, 36 of the highest quality image pairs were selected from both the initial (enrollment) and first re-collection periods that were relatively free of finger placement distortion. Initial analysis was based on these 36 image pairs. Letting r_x and r_y denote the lateral and longitudinal scale factors respectively, a similarity transformation for each of he 36 pairs of images was performed from which we collected 36 pairs of ($r_x, \Delta h$), ($r_y, \Delta h$), ($r_x, \Delta w$), and ($r_y, \Delta w$),. Each of these pairs provided excellent matching agreement (see Figure 8 for example). The team hypothesized that r_x and r_y of the similarity transformations were correlated to Δh and Δw, which denote the change in height and weight respectively. If one could show that each of the transformations were highly correlated to Δh and Δw, the project would be well on its way to an MGM.

If this simple MGM proved to be sufficient first-order approximation for matching a child's minutiae to their adult minutiae, then the team would simply transform each minutia in the child's fingerprint by $(x', y') = (r_x x, r_y y)$ and match the resulting primed set to the set of minutiae taken from the adult fingerprint. The team hypothesized that if this simple MGM did not completely compensate for growth, it should at least provide a reasonable approximation. A higher order nonlinear model may be required, but one should see an indication of a growth pattern. This of course, is what the team attempted to verify with each year's subsequent re-collection.

To test this, a commercial statistical package was used to perform a multiple linear regression to determine the correlation between height and weight changes on the scale factors. A first-order approximation to an MGM assumes that one can compensate for growth by considering dilation in the *x*-direction given by r_x, and a dilation in the *y*-direction given by r_y. Since the inception of the project, the team hoped that the final MGM would be a multiple nonlinear regression model (as stated in our proposal). Assuming smooth (differentiable) nonlinear behavior, we attempted to linearize by showing that initial growth could be captured by a multiple linear regression model, whose equations for the regression plane are:

$$r_x = b_x + m_{1_x} \Delta w + m_{2_x} \Delta h$$

$$r_y = b_y + m_{1_y} \Delta w + m_{2_y} \Delta h$$

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where m_1 is the partial regression coefficient of r on Δw keeping Δh constant, m_2 is the partial regression coefficient of r on Δh keeping Δw constant, and b is a constant offset. If we keep Δh (Δw) constant, then the graph of r versus Δw (Δh) is a straight line with slope $m_1(m_2)$.

The coefficient of determination was a very low 17.3% for r_x, and an even lower 1.3% for r_y. That is, 17.3% of the lateral variation and 1.3% of the longitudinal variation can be explained by changes in height and weight. The remaining 82.7% of lateral variation and the remaining 98.7% of longitudinal variation were unexplained and thus due to chance or other factors.

What part is chance? What part is other factors? To help answer this question the team completed a simple linear regression analysis first with Δh as a predictor and then with Δw as a predictor. The resulting distribution of the pairs ($r_x, \Delta h$), ($r_y, \Delta h$), ($r_x, \Delta w$), and ($r_y, \Delta w$) clearly appeared to be randomly distributed, as can be seen on the right side of Figures 14 through 17. This was very much unexpected.. The team could not determine other parameters on which to base an MGM. The sample size was too small to consider gender or race. Finger length and width were considered, but these parameters were not collected in the initial collections, and they generally don't exist on legacy databases of fingerprinted children. In addition, the team believed that consistent accurate measurements of such parameters would be difficult to achieve, and that small errors would dominate. The near zero correlation using Δh and Δw strongly indicates that a minutiae growth pattern is individualistic, hence the team was forced to conclude that given the data analyzed, an MGM as a function of Δh and Δw did not appear feasible.

Throughout 2009 the team collected final fingerprints which were again analyzed in December 2009. This collection, together with the initial (enrollment) collection, were used to make a final effort to realize an MGM, which again was hypothesized to be based on Δh and Δw.

A linear multiple regression analysis was again employed, where the predictors were change in height and change in weight, and the response variables were r_x and r_y. As was the case with previous attempts, the multiple-correlation coefficient for the r_x prediction was 6.4% and 8% for r_y prediction. That is, 6.4% of the variation in r_x can be explained by Δh and Δw; and 8% of the variation in r_y can be explained by Δh and Δw. ***The remaining 93.6% variation for r_x and the remaining 92% variation for r_y are unexplained and thus due to chance or other factors***.

By observing the left side of Figures 14 through 17, it is clear that the distribution of the pairs ($r_x, \Delta h$), ($r_y, \Delta h$), ($r_x, \Delta w$), and ($r_y, \Delta w$) are randomly distributed; indeed, the observed distribution is the classic signature of random phenomena. With another year's growth and the final collection studied, the team again arrived at the previous conclusion: an MGM as a function of Δh and Δw as originally conceived is not feasible. Given the subject sample and using height and weight as predictors, it is

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clear that growth patterns do not follow a general pattern and are so individualistic that it is impossible to develop a single map that fits all fingers. Individualistic patterns are recognizable but cannot be applied to the population in general.

However, because the project goal was to be able to match a child's minutiae at one age to a set of their minutiae at an older age, there was another potentially viable option to consider if indeed an MGM was not feasible. The researchers employed another technique to meet this project goal. Funded through other resources and refined during the execution of this project, the team used an algorithm previously developed and based on the frequency content of the local area of a minutia to compensate for plastic distortion (a problem that often plagues minutiae based matchers). Initially, this algorithm was planned to be used to augment the automated Minutiae Extraction Matching Tool (MEMT) in order to more accurately place minutiae. The algorithm assumes that there exists an isomorphism that maps one image to another while preserving the ridge structure. Such an isomorphism is nearly impossible to find for an entire print, but it is highly applicable to the local area of each minutia. Because distortion either stretches or compresses skin, the method had to be scalable to these local areas (this type of scaling makes the method extremely appropriate for matching children at different ages). With minimum effort, the research team was able to convert the algorithm into a stand-alone fingerprint matcher that successfully matched all fingerprint pairs from this study's fingerprint collection epochs.

This algorithm was applied as a stand-alone matcher for fingerprint pairs collected during this effort. Positive results concluded that all fingerprint pairs could be matched. Although this algorithm is not the MGM as originally envisioned at the project's onset, the research team nevertheless met a project goal of demonstrating a successful method for matching fingerprints of individuals after many years of growth. The results may certainly be worthy of future exploration and development.

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I. Introduction

I.1 Statement of the Problem

With the exception of unnatural friction ridge structure changes such as deep wounds or epidermis-altering diseases, an individual's dermatoglyphic fingerprint patterns remain unchanged from birth. While friction ridge patterns expand with maturation (analogous to inflating a balloon), inadequate research has been given to Level II detail with respect to ridge endings and bifurcations. Neither Level I nor Level II detail has been studied to the extent that a predictive model for maturation may be determined.

Discussions on childhood fingerprints most often assume a linear relationship of ridge width and age/growth. This effort addressed problematic questions regarding adolescent dermatoglyphic growth distortions; whether an adolescent's fingerprint changes uniformly as the fingers grow; distortions in friction ridge patterns during growth (e.g. disproportionate horizontal vs. vertical growth); and commonality among all spatial differences due to age.

I.2 Literature Citations and Review

The research team did not find any literature that was specific to the objective and goal of this effort.

I.3 Statement of Hypothesis or Rationale for the Research

The project's objective was to research friction ridge patterns during a rapid period of growth (such as that found in children through adolescence) to determine whether a commonality of growth exists, and to develop a statistically valid mathematical model for predicting this change. The project's goal was to provide the NIJ and scientific community a means to significantly enhance the probability of matching an individual's adolescent/adult fingerprints to fingerprints acquired when the individual was a child by predicting the shape changes of fingerprints during this period of growth.

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II. Methods

II.1 Independent Review Board Submittal and Approval

The Independent Review Board (IRB) preparation and submittal required a significant amount of time at the onset of the effort. Estimated as a two week task, IRB approval spanned nearly nine months due in large measure to the lack of biometric research protocol precedence within the IRB community. Fortunately, this extended process has provided valuable experience and lessons learned that will significantly shorten the process for future biometric research protocol design and approval applications.

Prior to submittal, an extensive review of possible IRB resources resulted in the selection of the University at Buffalo Social and Behavioral Sciences Institutional Review Board. Several factors went into the selection process including the University's proximity to research team headquarters, the existence of the Center for Unified Biometric Studies at the University, and an existing relationship of the PI to the University. At designated intervals throughout the effort, the project PI submitted appropriate materials to the University at Buffalo Social and Behavioral Sciences Institutional Review Board for IRB renewal.

II.1.1 Design Research Protocol

At the start of the effort, the research team completed a full design research protocol. This significant administrative task was critical to the IRB application and review process. Initial design research (parts of which were amended as discussed later in this report) included Recruitment, Consent, Procedure, Confidentiality and Human Participant Protections protocols, and are provided below as originally written for the research protocol documentation.

II.1.1.1 Recruitment

The research team proposed contacting school districts in both Erie and Niagara counties (New York State) to gain consent for the recruitment of children as possible study enrollees. Ultra-Scan designed and distributed a written a solicitation letter explaining the research process.

II.1.1.2 Consent Process

Verbal consent was required to be obtained and recorded from children participating in the study. A written consent form to be signed by a parent or legally authorized representative was also part of the consent package.

The research team was required to ensure that children and parents understood participation was voluntary, and refusal to participate (by either parent or child) involved no penalty or loss of any benefits. The research team ensured that all parents/legally authorized representatives of participants had sufficient knowledge and subject/language comprehension to make an enlightened decision on participation.

II.1.1.3 Consent Forms

Because researchers anticipated a wide range of reading and comprehension skills within the recruitment population, multiple-level consent forms had to be created:

- Pre-K through Grade 4 (read to children)
- Grades 5 through 9
- Grades 9+

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A signed Parental Permission Form was also required for participation in the study.

II.1.1.4 Research Procedure

Ultra-Scan proposed collecting fingerprint images of 308 children, twice annually during a five (5) year period. Subsequent to school administrator and parental approval, the research team was to meet with children on school grounds, ensuring the children did not feel coerced into participation. Each subject would be asked demographic information: name, age, sex, ethnicity, height, and weight. Although the focus of this research was to explore the existence of a growth model for fingerprint patterns, demographic information would be helpful for further analysis.

During each collection period, the research team planned to scan four (4) fingers of each participant using a 500 dpi plain impression scanner. To smooth any variation in pressure or angle of finger placement on the scanner platen, the research team scanned three (3) images of each finger. An image was not be saved until it was of sufficient quality and relatively free of distortion when compared to other images of the same finger.

To preserve fingerprint uniformity, the same scanner was used during the duration of the study. An individual's data was coded with a unique numeric identifier for storage in a secure database. Names were protected and used strictly for re-identifying participants. All identifiable data was to be discarded when the effort is completed.

II.1.1.5 Confidentiality Statement

Participant names were collected solely for the purpose of relocating individuals during the study. After each collection process, the research team stripped the individuals' names from the fingerprint images collected and replaced them with numeric codes indexed to the participant for the duration of the study only.

Ultra-Scan's policy states that personally identifiable data will be used and revealed only on a need-to-know basis to officers, employees, and subcontractors of the company. Employees with access to data on a need-to-know basis will be advised in writing of the confidentiality requirements and will agree in writing to abide by these confidentiality requirements.

Upon completion of the project, identifiable data was destroyed.

II.1.1.6 Human Participant Protection Training

Concurrent with IRB submission and approval, the PI successfully passed the examination for Human Participant Protection Training offered through the National Cancer Institute and was granted the required certification. At designated intervals throughout the effort, the project PI successfully passed necessary recertification examinations associated with Human Participant Protection training.

II.2 Subject Recruitment

Subject recruitment proved to be a daunting task throughout the study. The limited availability and cooperation of subjects (children), guardians (school administrators, Scout leaders), and parents (consent) was an unexpected and constant hurdle during the recruitment process. Numerous efforts were employed to increase and expedite subject recruitment including interaction with several populations of potential subjects/parents, educating individuals about the goals and methods involved in the study, and addressing both safety and privacy concerns both verbally and through print media. Ultimately, a

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significant amount of time and resources were dedicated to recruitment efforts in order to collect the number of children's fingerprints required for the study.

Initially, school districts located within Erie County and Niagara County (New York State) were targeted for subject recruitment because of their proximity to research team headquarters, the relative stability of their adolescent population (increased potential for repeat subjects), and the availability of ready collection facilities (school gyms, cafeterias). A database of area schools was generated and solicitation letters delivered to administrators explaining the research process.

A representative from Ultra-Scan also contacted administrators by phone to ensure they understood the study goals, the research procedures, and permission process. Only after obtaining consent from school administrators would the research team engage any students to further explain the process. Students who then expressed interest would be given a consent form to complete and return to the team with the assistance and signature of a parent or legally authorized representative. It was further stressed that absolutely no coercion of any sort would be used in recruitment efforts.

Although continued interaction with school administrators was attempted, positive reaction to the program was disappointingly sparse. A majority of those who did respond registered strong resistance to the proposed recruitment effort. Ultimately, the attempt did not result in any enrolled subjects or collected fingerprints.

In mid-2006, the research team shifted its focus to an alternate local population of potentially cooperative subjects: the Boy Scout groups of Western New York. Recruitment and outreach materials were designed to accurately address the intent, scope and impact of the research within the Scouting community. As required, materials were submitted to the Independent Review Board (IRB) for approval.

With further input from the IRB, the research team also elected to offer scouts/parents a complimentary child's identification (ID) card. Similar to ID material distributed by local law enforcement agencies, the laminated card would contain the subject's picture, fingerprints, and basic demographic information. To negate perception that a complimentary card may be considered a form of coercion, the recruitment protocol was modified to ensure that any child could request and receive an ID card independent of their participation in the research study.

The research team engaged and subsequently presented the program objectives and recruitment materials to the Greater Niagara Frontier Council Assistant Scout Executive with positive results. In late 2006, researchers were afforded the opportunity to address a wide variety of Scout leaders at numerous events and roundtable leadership assemblies. Although Scout leadership was generally positive, subsequent data collection from individual packs and troops was disappointing. In spite of continued contact, less than 25% of the leadership who participated in initial presentations chose to respond. Of these, merely 60% agreed to have their group/pack enrolled and fingerprints collected. Furthermore, the effort met with vocal resistance from some Scout parents.

Additional recruitment sources were researched for populations of potential adolescent subjects. Three local educational/community organizations were engaged:

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- The Center for Unified Biometrics and Sensors (CUBS), a State University of New York research center with close ties to Ultra-Scan and with whom there was a history of joint research.
- A local girl's softball league with ties to Ultra-Scan offered the potential for access to 200 children between the ages of 12 and 16.
- The youth population from a very large local nondenominational church with ties to an Ultra-Scan employee.

Unfortunately, none of these sources yielded enough interest to enroll any new subjects.

Some clear conclusions emerged based on the lack of positive response and very limited participation of various groups:

- A basic decision timeline for many institutions is measured in months, not weeks or days. In some instances, simply the process of getting an initial inquiry placed on the docket for a yes/no determination by a group's decision makers is an extremely daunting process.
- There is a clearly a negative parental bias with regard to the collection and retention of children's fingerprints in a database (as was necessary for this study). While many organizations are successful in promoting child ID cards that include fingerprints and demographic data, none of these entities maintain a database of the child's information.

In order for the research team to maintain interest and continue a positive presence in the Scouting community (the project's major source of recruitment and collection), an additional email letter was created and an electronic flyer posted on the Scout web site. Furthermore, the team requested and was granted a presence at the local Scout campground facilities where a majority of the regional troops/packs participate in a four day event each summer during the months of July and August. In an attempt to complete recruitment and collect of as many child fingerprint sets as possible to ensure statistical validity, the research team directed all remaining 2007 recruiting efforts on this event.

During 11 days on-site, more than 200 additional child fingerprint data sets were collected to complete the 308 sets necessary for the study. Because Scouting activities were scattered throughout each day, a research team member was required to remain on-site for each 12 hour day to ensure availability during activity down times. The average enrollment time was 10 minutes per child, allowing for explanation of the research grant and data collection effort procedure; completion of the consent forms by child and parent; gathering of height & weight data (tape measure and scales); and collection of the demographics, fingerprints, and digital photo into the data collection software. The total time required to complete this process significantly impacted the ability of the team to quickly process large numbers of enrollees in short periods of time. Additionally, at least one hour was necessary for each day spent on-site to print ID cards and generate correspondence necessary for their distribution.

With recruitment and initial fingerprint collection complete, the study progressed to data re-collection. Efforts included preserving communication links with enrolled subjects as they progressed through the ranks of the Scout organization. The task was complicated by individuals who left Scouting or the geographic region, as well as Scouting leadership changes and difficulty maintaining the attention of Scout personnel. The research team

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also continued efforts to attend targeted Scouting events in order to maximize enrollee contact and streamline data recollection.

II.3 Software Development

The research team modified existing fingerprint collection and enrollment software to facilitate the capture of additional demographic information necessary for the study. An interface was designed to support creation of child ID cards in a format approved by the State of New York. This software was ready for implementation in September 2006.

II.4 Data Collection

Data collection (fingerprints and demographics) began in December 2006 and concluded in December 2009. The research team was initially charged with collecting fingerprint images for all study participants twice annually during a five (5) year period. Once the first collection analysis was completed, the collection timeframe was modified to one collection annually to better allow for fingerprint ridge pattern growth/variation, since it was determined that the six month interval was too short to detect discernable growth. The name, age, sex, ethnicity, height, and weight of each individual were also recorded.

Initially, collection protocol defined three (3) digits of each child's hand for scanning: Middle, Index and Thumb. The research team quickly concluded that it was often awkward for small children to properly place their thumbs on the scanner platen. This process resulted in many unusable thumb scans. The collection protocol was modified to require scanning only the child's Index and Middle fingers for subsequent fingerprint collection and re-collection.

Fingerprints were scanned by a trained team member using a UPEK TouchChip single-finger capacitance scanner.

There was a noteworthy amount of approval and data capture documentation necessary for the study, a majority of which was recorded in paper form. The data collection process had to be adapted accordingly to make the process as efficient as possible in order to conform to the time available during typical weekly Scout meetings that were an initial collection setting.

Most of these very active Scouting sessions were conducted in 90 minutes or less. The team quickly realized that all of the actions necessary to accurately process a minimum of ten participants would require well over an hour and would create a significant disruption. This process included reading documentation, granting participation approval, entering the demographic data into the database, collecting the biometric data, and printing the child ID card. The scenario also assumed at least one parent or guardian would be present to authorize participation. Initial attempts to complete data collection using this single interaction model quickly determined the need for a more effective and efficient procedure.

The team decided to break the process up into four segments to better accommodate the relatively brief amount of time available for personal interaction with each Scout. A new four-step streamlined process was developed:

1. Scout leaders were provided with all approval and demographic forms (in a self-addressed stamped envelope) and asked to send this documentation home with willing participants for parents to read and complete. The Scouts brought the

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completed documentation back to the Scout leader who mailed the completed paperwork to the research team.

2. The research team pre-loaded the participant's demographic data from this paperwork and subsequently contacted the Scout leader to schedule biometric information collection sessions.
3. At Scout meetings, team members accessed the individual's pre-loaded demographic record, collected four (4) fingerprints and captured a photo. This process was generally accomplished in less than two (2) minutes per child.
4. The following day, the research team would print and mail the child ID cards for the prior day's participants.

An annual summer Scouting event became the main site for a majority of data collections because it attracted a large population of Scouts from communities across the Western and Southwestern regions of New York State. Furthermore, it would have been be impractical for the team to continue to travel to the many individual scout troop/pack meeting locations to collect data.

Initial fingerprint capture of the 308-child study population was completed in December 2007. A matrix of the entire collection effort is presented in **Table 1**. A graph of the study population age breakdown is shown in **Table 2**.

When initial fingerprint collection was complete, the study focused on data re-collection. Re-collection was less complex because a child's parent/guardian did not have to be present to authorize subsequent collection of additional data. This also reduced the amount of paperwork and time necessary for document logistics and data input.

Ongoing collection efforts included preserving communication links with enrolled subjects as they progressed through the ranks of the Scout organization. The task was complicated by individuals who left Scouting or the geographic region, as well as Scouting leadership changes and difficulty maintaining the attention of Scout personnel. The research team also continued efforts to attend targeted Scouting events in order to maximize enrollee contact and streamline data re-collection.

182 (59%) of the enrolled study population of 308 were re-imaged in the 1st re-collection effort. Challenges were encountered with other enrollees:

- 47 (15%) were dispersed across a large number of individual packs in the region and were difficult to target.
- 52 (17%) moved up the Scout ranks to become Boy Scouts. The research team had difficulty receiving information from the Scouts regarding these individuals since Boy Scout groups/leaders were not included in the original research study efforts.

Re-collection efforts continued through December 2009. In addition the challenges encountered above, a full 12% of the original enrolled subject population eventually moved out of the region, dropped out of Scouting, or no longer wish to participate in the study. The research team attempted contact drop-outs to determine if they would be willing to continue participation in the study. Unfortunately, no children/parents responded to these inquiries.

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At the completion of the collection effort, 123 (40%) of the original enrolled study population of 308 were imaged both a second or third time in preparation for data analysis.

II.4.1 Data Security

The security of a child's demographic and biometric data was typically the first subject addressed by parents when presentations were made to solicit participation. At the onset of the study, the research team established and implemented a control process to manage and secure this information for the effort's duration.

All information that was collected for the project database was entered and immediately encrypted on a password protected computer. At the completion of each on-site biometric data collection effort, the data was archived on an external drive and on a secured Ultra-Scan server. The laptop, external hard drive, and Ultra-Scan server were all stored in locked, restricted areas within Ultra-Scan facilities.

Participant names and contact information (collected to relocate individuals during the study) were stored in a locked file cabinet with restricted access. After each biometric collection effort, the research team stripped the individuals' names from the fingerprint images collected and replace them with a numeric code.

Per Ultra-Scan policy relating to the security of privacy protected data, personally identifiable data is used and revealed to officers and employees of the company on a need-to-know basis. Employees agreed in writing to abide by these confidentiality requirements.

Identifiable data was destroyed at the end of the project and any data analysis or reports were void of personally identifiable data. Personally identifiable data is not circulated outside of Ultra-Scan Corporation, and is not released to outside organizations such as law enforcement agencies.

II.5 Data Analysis

The team obtained a sequence of collections that are a time series of images, which were labeled as $F = \{F_0, F_1, \ldots, F_n\}$, where the subscripts indicate the time order of collection. Thus F_0 represents the initial collection set and F_n represents the collection of images taken at the nth collection period. Within each F_i, the left and right index fingerprints of each child in the subject sample were imaged. The images for each child were denoted by $f_i^k = \{l, r\}$, where i indicates the collection period and k identifies the child in the control group, l is the image of the left index finger, and r is the image of the right index finger.

The images in F provided a basis for valid statistical data from which the team hoped to develop a Minutiae Growth Map (MGM): a linear, affine transformation that maps a set of a child's minutiae at one age to a set of their minutiae at a different age. The MGM would account for fingerprint shape changes during the rapid period of growth that children experience during adolescence. This map would be sensitive to the possibility that the pattern of growth in the horizontal direction differs from that of the vertical direction, which would not only result in spatial differences (x and y coordinates), but also variations in orientation (the angle θ) of minutiae points.

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To successfully build the MGM, the team attempted to obtain high quality images in which the fingerprint ridges were clearly visible throughout the scanned area to allow all existing minutiae within the scanned area to be easily identified, such as the fingerprint shown in **Figure 1**. Fingerprint images that include occluded areas were rejected because such areas can mask minutiae in f_i^k but not in f_j^k, $(i \neq j)$. An extreme example of poor quality is shown in **Figure 2**. It is important that for each member of the control group, f_i^k for each i, the image covers a substantial portion of the fingerprint to obtain as many minutiae as possible. The team first identified minutiae automatically, then manually removed false minutiae and added missed minutiae. The resulting minutiae for the image in Figure 1 are shown superimposed on the image in **Figure 3**. The team used minutiae to construct Delaunay triangles for each image in the time ordered sequence. An example of a tessellation using Delaunay triangulation is shown in **Figure 4**. Delaunay triangulation was an ideal basis for the study's interpolation scheme, which the team hoped would yield a family of functional descriptions, $g_i^k(x, y)$ of each image in the time sequence.

To successfully build the Minutiae Growth Map, it was obvious that the images in F must be of high quality; all images must have a sufficient set of minutiae in common for usable Delaunay triangulation; and the images should be as distortion free as possible. These guidelines were important when deciding which image pairs to analyze.

The process was intended to automatically extract minutia, remove false minutiae, and add missing minutiae. Unfortunately, it was found that although the tool was adequate for Automated Fingerprint Identification Systems (AFIS), the circular error probable (CEP: a disk in which we expect half the attempts to fall within) associated with automated locations were unacceptably large for this project.

Manual extraction was instead used to allow a user to study minutiae patterns on each image and thus pick the "best" location. A Minutiae Extraction Matching Tool (MEMT) tool was developed to simultaneously display two fingerprint images of the same finger, I_o and I_1. An operator manipulated I_o and I_1 by zooming in or out and centering the focus of the images in order to locate and identify matching minutiae pairs.

Picking the "best" minutia location, however, was still subject to two types of error. The first, measurement error, has a Gaussian distribution with zero mean and a standard deviation that depends on the skill and dedication of the MEMT operator. For example, suppose I_o and I_1 are exactly the same. If one were to compute the interconnecting distances between minutiae extracted from I_o and difference them with the corresponding interconnecting distances from I_1, the resulting differences would, in general, not be zero. Instead, as is usual with measurements, these errors have a Gaussian distribution with zero mean and a standard deviation that depends on the skill and dedication of the operator.

The second source of error is the more troublesome distortion that occurs when the finger makes contact with the scanner platen. The team was very careful to have children

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properly place their fingers on the platen to minimize distortion. Unfortunately distortion is subtle and often hard to recognize until after processing. For those images collected that included distortion, the only recourse was to work around the distorted areas.

Although manual extraction provides a reliable set of minutiae from collection epoch to collection epoch, the magnitude of relative location errors between minutiae had to be understood and compensated for during analysis. Careful attention to scanner finger placement can attenuate location errors, but cannot eliminate them. To be successful in mapping fingerprint growth, an analysis of variance experiment was initiated to separate "noise" due to finger-scanner coupling from actual growth.

However, such a study is generic to fingerprint matching in general. Automatic algorithms that match minutiae templates fall into the general class of a "point pattern matcher." One can label the inquiry and search templates by $X = \{x_i, i = 1,2,\ldots r\}$ and $Y = \{y_i, i = 1,2,\ldots s\}$ respectively, where, $x \in X$ and $y \in Y$ are points in 2-dimensional Euclidean space with an associated angular direction. Without loss of generality, assume $r \le s$, that is the cardinality of *X* is less than or equal to *Y*. For templates extracted from the same finger, $r < s$ due to a combination of missing or false minutiae - the actual number of minutiae points that can be matched is $q \le r \le s$.

When *X* and *Y* are from the same finger, the function of the matcher can be simply stated: "the matcher must determine which *x*-points go with which *y*-points". Let Π be the set of all permutations. For any permutation $\pi \in \Pi$, one can say $x_{\pi(i)}$ associates with y_i. Hence, each $\pi \in \Pi$ is a map that illustrates which *x* goes with which *y*. Given any $\pi \in \Pi$, one computes an affine transformation ϕ_π and the pure translation, b_π by minimizing, in the least squares sense, the error function:

$$e(\pi) = \sum_{i=1}^{q} \left\| \phi_\pi x_{\pi(i)} + b_\pi - y(i) \right\|.$$

The best match occurs when one finds $\pi \in \Pi$ such that $e_\pi = \min_{\pi \in \Pi} e(\pi)$, that is, the permutation that yields the smallest norm.

In a perfect world, e_π would be zero when matching two templates from the same finger. But because of the problems associated with finger-coupling discussed above, one never expects e_π to be zero for authentic matches. The transformation ϕ will rarely map correctly paired minutiae on top of each other - often the distance error is substantial. Hence the matching algorithm has to incorporate a liberal tolerance in order to achieve good matching performance. Of course this opens the door for falsely matching an impostor, i.e., when two templates that are not from the same finger.

To begin the study, the team conducted an experiment where a subject's finger was held in place during a series of scans. With a high degree of confidence, the images from scan to scan were virtually unchanged. The team hypothesized that one should repeatedly obtain the same minutiae template. However, even in this instance, automatic processing

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resulted in some false minutiae, and occasionally missed some genuine minutiae. The only observed difference between images was slight variations in gray scale levels (256 levels). Hence, one must conclude that even slight variations in gray scale due to scanner noise can result in different minutia templates (a study and analysis of this phenomenon is undoubtedly of interest to the fingerprint matching community and was documented in a white paper titled *Variation in Minutiae Location,* attached as Appendix A).

Although location errors due to noise were statistically bounded, it was reasonable to question whether there had been any growth between collection epochs before attempting to build an MGM. It was decided to use a statistical approach. Minutiae were treated as permanent landmarks on the finger from which Delaunay triangles could be constructed (an example of Delaunay triangulation is shown on the left side of **Figure 5**). A time order sequence of Delaunay triangulation was used as a basis for an interpolation scheme that yielded a family of functional descriptions, $g_i^k(x, y)$, of each image in the time sequence. Delaunay triangles are an especially efficient tessellation of the fingerprint because no other minutiae other than those of the triangle are contained in any triangle's circumscribed circle.

Delaunay tessellation was also employed to answer the question of growth. To minimize the effects of noise, all triangles with area less than 100 square pixels and all triangles with a minimum interior angle of less than 15° were discarded. The left and right side of **Figure 6** illustrates the resulting tessellation before and after pruning. Four (4) fingers from five (5) individuals taken from F_0 and F_1 were first tested. As a typical example, the matched minutiae pairs and pruned tessellation for the image "0503310930130000000056_07.bmp" is shown in Figure 5, with the F_0 image on the left and the F_1 on the right. Two measures of growth were constructed:

1) The ratio of the area of corresponding triangles
2) The difference in the length of corresponding triangle sides.

If there was no growth, then one would expect the ratio of triangle areas to have a mean of 1.0 and the difference in triangle sides to have a mean of 0.0. Two statistical tests of hypothesis were in order. In each case, a level of significance of $\alpha = .05$ was used. That is, there is a 5% chance that one will incorrectly reject the null hypothesis (Type I error). The ratio of triangles is first tested - the null hypothesis, H_0 is that the population mean is 1.0, no growth. The alternate hypothesis, H_1, which is also the claim, states that there has been detectable growth during the last four (4) months. The t-distribution is the appropriate to distribution to test the hypothesis. For example, when comparing the right index fingers of subject with id 52, - the sample mean of the area ratios is $\bar{x} = 0.9985$ with a sample standard deviation of s=0.0409, and a sample size of n=13. From a t-distribution table with 12 degrees of freedom, the critical value for right-tailed test with $\alpha = .05$ is $\mathrm{t}_c = 1.780$. The test statistic is computed by

$$\mathrm{t}_{\mathrm{test}} = \frac{\bar{x} - \mu}{s/\sqrt{n}} = \frac{0.9985 - 1}{0.049/\sqrt{13}} = -0.1281$$

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Because $t_{test} < t_c$ one cannot reject H_0, and hence there was insufficient evidence to support the claim of growth The test results for two of the subjects analyzed are shown in **Table 3** and **Table 4**. Given the short amount of time between scans, it was not surprising that there was no enough evidence to support the claim of growth.

One can compare the results shown in **Table 5** and **Table 6** with results from fingerprint images of children taken almost five (5) years apart. As the charts illustrate, there is significant evidence to support the claim of growth in Child A and Child B. Although one can clearly show statistical evidence that there has been growth (which is not at all surprising), there is insufficient data to build an MGM; two samples are not enough. Growth from the 5-year interval samples was both statistically and visually discernable, measuring 7-8 pixels (14-16 mils) on average.

Through this initial statistical sample analysis, together with a comparison of the results from early 4-month interval and existing 5-year interval data set analysis, the research team concluded that the initial 6-month study interval for re-collection of fingerprint data was too frequent to be useful. The test protocol was subsequently modified from the original 6- month interval to a 12-month interval for repeat collection of fingerprint data.

As a result of this change in collection protocol, the full year 2007 was used for completing the full study enrollment of 308 participants, and the full year 2008 was used for obtaining as many first re-collection data sets as possible. The five (5) re-collection data sets analyzed in the July 2007 report was designated as the 'original' data.

Given the time-ordered sequence of image collections as $F = \{F_0, F_1, \ldots, F_n\}$, within each F_i, one has each child's index and middle fingerprint images for both hands. The images for each child are denoted by $f_i^k = \{li, ri, lm, rm\}$, where i indicates the collection period and k identifies the child in the control group, li is the image of the left index finger, lm is the image of the left middle finger and ri and rm are defined likewise for the right hand. The set F_0 represents the initial collection, and F_1 represents the first complete re-collection effort completed in December 2008. The team compared F_0 to F_1. For these children, $F_0 = \{f_0^1, f_0^2, \ldots, f_0^N\}$ for the available 2007 images and $F_2 = \{f_2^1, f_2^2, \ldots, f_2^N\}$ for the 1st re-collection 2008 images.

F_0 and F_1 were used to test a first order approximation to the MGM. To develop this simple MGM, it was assumed that given distortion free images of a child's fingerprint taken at an older age, the child's minutiae can be transformed to the adult's minutiae via a similarity transformation using a sequence of rigid motions and dilations. In general, assume $F_i \sim F_j$, and for this particular case, assume $F_0 \sim F_1$.

Consider the transformation given by the following nonlinear equations:

$$\textbf{Eq. 1} \quad x' = r_x \cos\theta x + r_y \sin\theta y + x_0$$

$$\textbf{Eq. 2} \quad y' = -r_x \sin\theta x + r_y \cos\theta y + y_0$$

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where (x, y) is a minutia location from the child's print and (x', y') is the transformed location. It is clear that the rigid motion parameters of this model, θ, x_0 and y_0, are not dependent on growth. The angle θ is the rotation angle between the two images and x_0, y_0 is the translation difference between the two images and result from the difference in finger placement on the scanner's platen.

If the images are distortion free, however, the parameters r_x and r_y are due entirely to growth. The axes system was set so that the *y*-axis runs longitudinally up and down the finger and the *x*-axis runs across the finger as shown in **Figure 7**. As a child grows, the parameters r_x and r_y capture scales for fingers that grow differently in length than in width. During the collection process, the team endeavored to capture the fingerprint so that the *y*-axis is the longitudinal axis of the finger. Also, the rotation angle between collections was kept as close to zero as possible.

As a first attempt at an MGM, it was assumed that one could compensate for growth by considering dilation in the *x*-direction given by r_x, and a dilation in the *y*-direction given by r_y. If this simple MGM proved to be sufficient for matching a child's minutiae to their adult minutiae, then one would simply transform each minutia in the child's fingerprint by $(x', y') = (r_x x, r_y y)$ and match the resulting primed set to the set of minutiae taken from the adult fingerprint (this of course would have to be verified with future collections and the MGM augmented as needed). But initially, a 'base case' MGM was constructed.

An immediate question was "How do we determine r_x and r_y?" The answer was necessarily crude since there existed only two collection sets of images, but a trend was expected. To find the trend, a linear multiple regression analysis was employed (as explained below) to provide an initial answer, where the predictors are change in height, change in weight and the response variables are r_x and r_y.

To construct a database of predictor and response variables, it was assumed that the minutiae in each paired image from F_0 and F_1 are related by $(x', y') = (r_x x, r_y y)$. The first step was to determine the scale factors r_x and r_y for each pair in F_0 and F_1. Each pair of scale factors is associated with the change in height and weight for a given child. To compute r_x and r_y the team established a subset of paired images from F_0 and F_1 where there has been statistically significant growth to extract and pair minutiae from each of the four image pairs associated with individuals from F_0 and F_1. As stated above, two measures of growth were constructed:

1) The ratio of the area of corresponding triangles
2) The difference in the length of corresponding triangle sides.

If there was no growth, one would expect the ratio of triangle areas to have a mean of 1.0 and the difference in triangle sides to have a mean of 0.0. Two statistical tests of hypothesis were used: The null hypothesis, H_0, that there is no growth and the alternate

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hypothesis, H_1, which is the claim, that there has been growth. In each case a level of significance of $\alpha = .05$ was used. That is, there is a 5% chance that one will incorrectly reject the null hypothesis (Type I error). The t-distribution was used to test the hypothesis. The test statistic is computed by

$$\textbf{Eq. 3} \quad t_{test} = \frac{\bar{x} - \mu}{s/\sqrt{n}}$$

where μ is the hypothesized mean, $\bar{x}$ is the sample mean, s is the sample standard deviation, and n is the size of the sample. The team examined only those images whose test statistic supported the claim of significant growth at the 5% level, which was stored on the new set F_α.

Next, the minutiae for each image pair in F_α were extracted and matched. A mapping was constructed that transformed the F_0 minutiae to the F_1 minutiae for each pair. The mapping uses Equations 1 and 2 in a least mean squares error problem:

$$\textbf{Eq. 4} \quad E = \sum_{i=1}^{N} \left[\left(x_i' - r_x a x_i - r_y b y_i - x_0 \right)^2 + \left(y_i' + r_x b x_i - r_y a y_i - x_0 \right)^2 \right],$$

which is subject to the constraint equation:

$$\textbf{Eq. 5} \quad a^2 + b^2 = 1,$$

where the subscript i identifies each paired minutiae between the F_0 image and the F_1 image, and $a = \cos\theta$ and $b = \sin\theta$.

The five (5) unknown values of θ, x_0, y_0, r_x, and r_y that minimize E in Equation 4 subject to the constraint in Equation 5 must be solved, a process well suited to LaGrange's method, which minimizes the function

$$\textbf{Eq. 6} \quad u = E + \lambda(\cos^2\theta + \sin^2\theta),$$

where λ is the LaGrange multiplier. Note that Eq. 6 has (seven) 7 unknowns, so a system of seven independent simultaneous equations was sought. We can establish six (6) nonlinear equations by setting each of the following partial derivatives to zero:

$$\frac{\partial u}{\partial a} = 0, \frac{\partial u}{\partial b} = 0, \frac{\partial u}{\partial x_0} = 0, \frac{\partial u}{\partial y_0} = 0, \frac{\partial u}{\partial r_x} = 0 \text{ and } \frac{\partial u}{\partial r_y} = 0.$$

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The seventh equation comes from the constraint: $a^2 + b^2 - 1 = 0$. This provides a system of seven nonlinear equations in seven unknowns. Newton's method is used to numerically solve for the unknowns.

Let the column vector function **F** be defined by

$$\textbf{Eq. 7} \quad \mathbf{F}\left(a, b, x_o, y_0, r_x, r_y, \lambda\right) = \begin{bmatrix} \frac{\partial u}{\partial a} \\ \frac{\partial u}{\partial b} \\ \frac{\partial u}{\partial x_0} \\ \frac{\partial u}{\partial y_0} \\ \frac{\partial u}{\partial r_x} \\ \frac{\partial u}{\partial r_y} \\ a^2 + b^2 - 1 \end{bmatrix}$$

and the 7x7 Jacobian matrix, J, be given by

$$\textbf{Eq. 8} \quad \mathbf{J} = \begin{bmatrix} \frac{\partial^2 u}{\partial a^2} & \frac{\partial^2 u}{\partial a \partial b} & \frac{\partial^2 u}{\partial a \partial x_0} & \frac{\partial^2 u}{\partial a \partial y_0} & \frac{\partial^2 u}{\partial a \partial r_x} & \frac{\partial^2 u}{\partial a \partial r_y} & \frac{\partial^2 u}{\partial a \partial \lambda} \\ \frac{\partial^2 u}{\partial b \partial a} & \frac{\partial^2 u}{\partial b^2} & \frac{\partial^2 u}{\partial b \partial x_0} & \frac{\partial^2 u}{\partial b \partial y_0} & \frac{\partial^2 u}{\partial b \partial r_x} & \frac{\partial^2 u}{\partial b \partial r_y} & \frac{\partial^2 u}{\partial b \partial \lambda} \\ \frac{\partial^2 u}{\partial x_0 \partial a} & \frac{\partial^2 u}{\partial x_0 \partial b} & \frac{\partial^2 u}{\partial x_0^2} & \frac{\partial^2 u}{\partial x_0 \partial y_0} & \frac{\partial^2 u}{\partial x_0 \partial r_x} & \frac{\partial^2 u}{\partial x_0 \partial r_y} & \frac{\partial^2 u}{\partial x_0 \partial \lambda} \\ \frac{\partial^2 u}{\partial y_0 \partial a} & \frac{\partial^2 u}{\partial y_0 \partial b} & \frac{\partial^2 u}{\partial y_0 \partial x_0} & \frac{\partial^2 u}{\partial y_0^2} & \frac{\partial^2 u}{\partial y_0 \partial r_x} & \frac{\partial^2 u}{\partial y_0 \partial r_y} & \frac{\partial^2 u}{\partial y_0 \partial \lambda} \\ \frac{\partial^2 u}{\partial r_x \partial a} & \frac{\partial^2 u}{\partial r_x \partial b} & \frac{\partial^2 u}{\partial r_x \partial x_0} & \frac{\partial^2 u}{\partial r_x \partial y_0} & \frac{\partial^2 u}{\partial r_x^2} & \frac{\partial^2 u}{\partial r_x \partial r_y} & \frac{\partial^2 u}{\partial r_x \partial \lambda} \\ \frac{\partial^2 u}{\partial r_y \partial a} & \frac{\partial^2 u}{\partial r_y \partial b} & \frac{\partial^2 u}{\partial r_y \partial x_0} & \frac{\partial^2 u}{\partial r_y \partial y_0} & \frac{\partial^2 u}{\partial r_y \partial r_x} & \frac{\partial^2 u}{\partial r_y^2} & \frac{\partial^2 u}{\partial r_y \partial \lambda} \\ 2a & 2b & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

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Let

$$\textbf{Eq. 9} \quad \mathbf{x}_i = \begin{bmatrix} a_i \\ b_i \\ (x_0)_i \\ (y_0)_i \\ (r_x)_i \\ (r_y)_i \\ \lambda_i \end{bmatrix}$$

be the ith refinement to the solution, with i=0 being the initial guess, then the next refinement is computed by

$$\textbf{Eq. 10} \; \mathbf{x}_{i+1} = \mathbf{x}_i - \mathbf{J}(\mathbf{x}_i)^{-1}\mathbf{F}(\mathbf{x}_i).$$

This process is continued until $|\mathbf{F}| < \varepsilon$, for some prescribed threshold ε. An example using this transformation mapping is shown in **Figure 8**. The yellow minutiae markings on the fingerprint are the minutiae that belong to that image. The red minutiae markings are matching minutiae mapped from an image of the same finger taken a year earlier and shown in Figure 7. To better view the mapping, the right side of the figure shows the accuracy of the mapping with x's being mapped to zeros with the image of the fingerprint suppressed.

Note that if one is selective about the images under examination, then by solving Equation 6, the values for r_x, and r_y should be attributable entirely to growth between the F_0 and F_1 image pairs. By selective, it is understood that one choose only those image pairs that have a near zero rotation angle between them; that have their y-axis aligned longitudinally along the finger; and that have a reasonably large common area that is distortion free. Of the 102 image pairs in F_α, 36 of the highest quality images were selected that were relatively free of finger placement distortion. The statistical analysis is based on these 36 image pairs and presented in **Table 7**.

As previously stated, the team hoped to show that a simple, first-order approximation to an MGM could be expressed as a multiple linear regression, whose equations are:

$$\textbf{Eq. 11} \; r_x = b_x + m_{1_x}\Delta w + m_{2_x}\Delta h$$

$$\textbf{Eq. 12} \; r_y = b_y + m_{1_y}\Delta w + m_{2_y}\Delta h$$

Using the statistics from the 36 selected subjects, shown in Table 5, the team employed a commercial statistical package to perform a multiple regression analysis, resulting in the following multiple regression equations:

$$\textbf{Eq. 13} \; r_x = 1.02 + 0.00107\Delta w - 0.00047\Delta h$$

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Eq. 14 $r_y = 1.03 + 0.000297\Delta w - 0.00010\Delta h$

However, Equations 13 and 14 were essentially useless for prediction because the coefficient of determination is a very low 17.3% for the r_x prediction, and an even lower 1.3% for r_y prediction. That is, 17.3% of the variation in r_x and 1.3% of the variation in r_y can be explained by Δh and Δw. The remaining 82.7% variation for r_x and the remaining 98.7% variation for r_y are unexplained and thus due to chance or other factors. In other words, the data does not seem to indicate a direct correlation between a child's growth over time in height/weight and predictable growth exhibited by their fingerprint minutiae during that same period.

How does one explain the variation in r_x and r_y? What part is chance? What part includes other factors? To help answer this question, the team performed a simple linear regression analysis, first with Δh as a predictor and then with Δw as a predictor (results illustrated in **Figures 9** through **12**). The distribution of the pairs ($r_x, \Delta h$), ($r_y, \Delta h$), ($r_x, \Delta w$), and ($r_y, \Delta w$) clearly appear to be randomly distributed. This was very much unexpected. The team concluded that, given the data analyzed, multiple-linear regression as a function of Δh and Δw does not appear to be a suitable MGM.

As a final effort the team compared F_0 to F_3, a growth period of three (3) years - the first (enrollment) and last (2nd year) re-collection epochs. The minutiae from each image pair between F_0 and F_3 were extracted and matched. The corresponding r_x and r_y for each pairing were then computed using the least mean squares approach discussed above. As with F_0 and F_1, a linear multiple regression analysis was employed, where the predictors are change in height, change in weight and the response variables are r_x and r_y. The statistics collected for the 72 images analyzed are presented in **Table 8**.

The multiple correlation coefficient for the r_x prediction is even smaller than it was for the case discussed above - a dismal 6.4% versus 17.3%, and 8% for the r_x prediction, versus 1.3%. That is, 6.4% of the variation in r_x can be explained by Δh and Δw and 8% of the variation in r_y can be explained by Δh and Δw. *The remaining 93.6% variation for r_x and the remaining 92% variation for r_y are unexplained and thus due to chance or other factors.*

Another simple linear regression was attempted to find what might account for this unexplained variation, and to understand what part was chance and what part other factors. A simple linear regression analysis was conducted, first with Δh as a predictor and then with Δw as a predictor. F_0, F_1 results, and F_0, F_3 results are plotted and compared side-by-side in **Figures 14** through **17**.

Again, the distribution of the pairs ($r_x, \Delta h$), ($r_y, \Delta h$), ($r_x, \Delta w$), and ($r_y, \Delta w$) clearly appear to be randomly distributed for both tests. It became apparent that growth

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patterns as measured in this study do not follow a general pattern. The growth patterns are so individualistic in fact, that it is impossible to develop a single map that fits all fingers. Although individualistic patterns are recognizable, they cannot be applied to the general population.

However, another viable option was considered if indeed an MGM was ultimately not feasible. Because the project goal was to be able to match a child's minutiae at one age to a set of their minutiae at an older age, the team experimented with a new minutiae matching process whose development some years ago and its refinement over the past year were was funded from other resources. The algorithm is based on the frequency content of the local area of a minutia to compensate for plastic distortion (a problem that often plagues minutiae based matchers). Initially this algorithm was used to augment the MEMT for this project in order to more accurately place minutiae. In theory, there exists an isomorphism that maps one image to another while preserving the ridge structure. In practice, to find such an isomorphism over an entire print would almost always require localized isomorphic maps to be splined together or extended using analytic continuation. The team has found that the key to success is to combine the matching localized maps that are centered at each minutia. The matching of authentic prints provides a coherent transformation, while the transformation for impostor prints is random, and a coherent transformation can occur only by chance. Ultra-Scan's algorithm uses Fourier filtering of the local ridge structure of each minutia to produce each localized map. Although other mapping methods could also work, whichever is used must be scalable, which was the team's original intent because distortion either stretches or compresses the skin. Localized scaling is what makes it appropriate for matching children at different ages.

The algorithm was deployed as a stand-alone matcher for fingerprint pairs, and successfully matched all pairs between F_0 and F_1. The algorithm basically scores each minutia pairing separately. A distribution of authentic-pair scores versus impostor-pair scores for the pairs in F_0 and F_1 is illustrated in **Figure 13** (note that the authentic distribution is the green curve on the left). Because the plotted score distributions are for individual minutia pairs, and because all pairings are independent of each other, the probability of obtaining even two or three impostor pairings when matching two impostor prints is very small, even for the modest threshold score of 0.275 used for this report.

Ultra-Scan's plastic distortion algorithm was again used as a stand-alone matcher for collected fingerprint pairs between F_0 to F_3. Positive results concluded that all fingerprint pairs could be matched. Although this algorithm is not the MGM as originally envisioned at the project's onset, the research team nevertheless met the project goal by demonstrating a successful method for matching fingerprints of individuals after many years of growth. The results are certainly worthy of future exploration and development.

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III. Results

III.1. Statement of Results

The collected data was thoroughly examined, categorized and analyzed in an effort to explain the observed phenomenon: growth patterns of fingerprints as measured in this study do not appear to follow a general pattern. The growth patterns are so individualistic that it is impossible to develop a single Minutiae Growth Map (MGM) or family of maps that accurately models minutiae pattern growth. Although individualistic patterns can be modeled, this is not a viable solution when applied to the general population.

Although the results from this study indicate that a MGM does not seem feasible, the researchers employed another technique to attempt to meet the project goal of matching a child's minutiae at one age to a set of their minutiae at an older age. Funded from other resources and refined during the execution of this project, Ultra-Scan has developed a powerful process for compensating for plastic distortion. Initially, this algorithm was planned to be used on this project to augment the automated Minutiae Extraction Matching Tool (MEMT) in order to more accurately place minutiae. Because it was originally designed to compensate for local area scaling, it was hypothesized that it would be well suited to compensating for growth patterns.

Through modest modification of this stand-alone matcher, researchers were able to successfully match all fingerprint pairs from all of the collection epochs. Although this existing algorithm is not necessarily the MGM as originally envisioned at the project's onset, the research team nevertheless was able to meet a project goal of demonstrating a successful method for matching fingerprints of individuals after many years of growth. These results may certainly be worthy of future exploration and development.

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III.2 Tables

Collection Period	Subjects Collected		
	Initial Collection	1st Re-Collection	2nd Re-Collection
July - December 2006	26		
January - December 2007	282		
January – December 2008		182	
January - December 2009		4	123
	308	**186**	**123**

Table 1 Fingerprint Collection Matrix

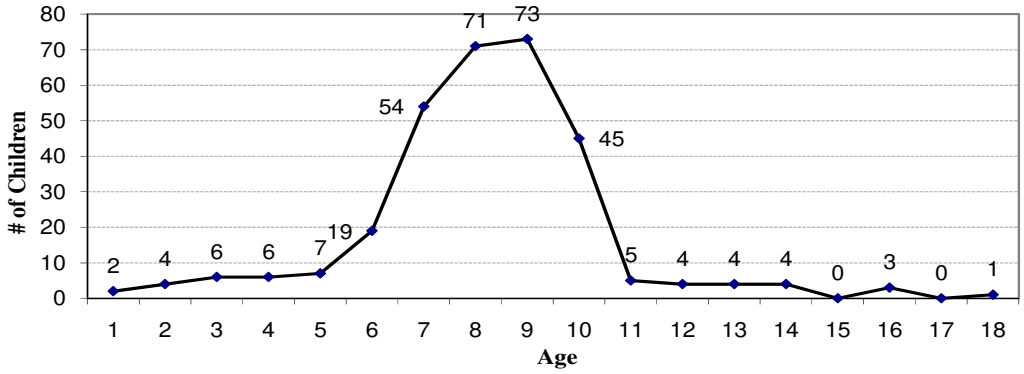

Table 2 Distribution of Age in Child Fingerprint Database

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id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
52 ri	13	0.9985	0.0409	-0.1281	1.780	cannot reject H_0
52 li	15	1.0285	0.0710	1.5553	1.761	cannot reject H_0
53 ri	7	0.9631	0.1060	-0.9217	1.943	cannot reject H_0
55 ri	16	1.0117	0.0579	0.8073	1.753	cannot reject H_0

Table 3 Test Ratio of Areas

id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
52 ri	13	0.0753	1.1968	0.2269	1.780	cannot reject H_0
52 li	15	1.0312	4.2248	0.9453	1.761	cannot reject H_0
53 ri	7	-0.0853	2.6569	-0.0850	1.943	cannot reject H_0
55 ri	16	-0.0136	2.0336	-0.0268	1.753	cannot reject H_0

Table 4 Test Difference of Side Lengths

id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
Child A	11	1.4749	0.5642	2.7920	1.812	Accept claim of growth
Child B	14	1.1326	0.2012	2.4662	1.771	Accept claim of growth

Table 5 Test Ratio of Areas for 5-year Span

id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
Child A	15	7.2413	7.0315	3.9885	1.761	Accept claim of growth
Child B	23	2.3387	2.8986	3.8687	1.717	Accept claim of growth

Table 6 Test Difference of Side Lengths for 5-year Span

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Δh (inches)	Δw (pounds)	r_x	r_y
3	8	0.9887	0.9826
7	9	1.0372	1.0950
7	9	1.0378	1.0028
10	6	1.0037	1.0067
7	36	1.0240	0.9991
7	36	1.0142	1.0317
6	24	0.9824	1.0757
6	24	1.0449	1.0022
9	-5	0.9811	1.0139
6	4	1.0291	1.0210
8	30	1.0683	1.0634
8	29	1.0840	1.0844
6	14	0.9995	1.0603
6	16	1.0169	1.0182
6	29	1.0921	0.9866
8	3	1.0109	1.0336
5	10	1.0676	1.0431
3	28	1.0261	1.0398
6	2	1.0680	1.0098
5	7	1.0110	0.9707
3	10	1.0231	1.0381
4	21	1.0476	1.0495
8	25	1.0359	1.0347
8	12	1.0372	1.0063
4	8	1.0150	1.0363
5	20	1.0400	1.0729
13	51	1.0731	1.0224
13	51	1.0656	1.0562
3	8	0.9481	1.0365
3	4	1.0497	1.0421
3	19	1.0874	0.9772
3	5	1.0054	1.1041
4	12	1.0388	1.0315
4	15	1.0596	1.0561
3	10	1.0258	1.0122
3	10	1.0593	0.9992

Table 7

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Δh (inches)	Δw (pounds)	r_x	r_y
5	14	1.0394	1.0602
5	14	1.0624	1.0950
9	29	1.0160	1.0371
9	29	1.0691	1.0354
9	30	1.0439	1.0425
6	21	1.0362	1.1003
6	28	1.0344	1.1692
6	28	1.0458	1.0969
10	70	1.0634	1.1064
10	70	1.0654	1.1243
6	94	1.1242	1.1015
6	94	1.1059	1.0678
5	19	1.0735	1.0795
5	19	1.0420	1.0575
4	29	0.9307	1.0596
5	21	1.0125	0.9862
5	21	0.9957	0.9857
10	37	1.0026	1.1224
10	37	1.0565	1.0910
7	20	1.0384	1.0319
7	66	1.0516	1.0108
7	66	1.0190	1.1414
10	63	1.0400	1.1568
9	50	1.0909	1.1005
3	48	1.0536	1.0557
3	48	1.0826	1.0622
6	14	1.0628	1.0418
1	14	1.0041	0.9794
1	14	0.9772	1.0269
5	15	0.9765	1.0798
5	15	1.0321	1.1124
5	25	0.9842	1.0810
5	25	0.9690	1.0443
3	31	0.9754	1.1465
3	31	1.0217	0.9864
11	34	1.0163	1.0640
11	34	1.0263	1.0663
8	12	1.0456	1.0524
8	12	1.0486	0.9775
7	15	1.0271	1.0691
8	23	0.9703	0.9935
6	25	1.0275	1.1018
6	25	1.0467	0.9984
6	18	1.1017	1.0437
4	18	1.0944	0.9767
5	24	1.0673	1.2121
5	24	1.1264	1.1037
4	9	0.9831	1.0786
4	10	1.0512	1.0655
4	10	1.1292	1.0018

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3	16	1.0609	1.0509
4	19	1.0327	1.1321
2	14	1.0038	1.0566
2	14	0.9170	1.0307
5	14	1.1145	1.0549
4	23	1.0429	1.0472
4	23	1.0391	1.1083
6	22	1.1018	1.0422
5	47	1.0161	1.0292
5	16	1.0859	1.0482
5	19	1.0942	1.0157
6	13	1.0240	1.0819
3	13	1.0380	1.0239
3	13	1.0799	0.9653
5	16	1.0414	1.0760
5	16	1.0702	0.9941
9	18	1.0328	1.0184
9	18	1.0032	1.0759
4	8	0.9601	1.1854
3	7	1.0247	1.0067
3	42	1.1092	1.0609
3	11	1.0393	1.1029

Table 8

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III.3 Figures

Figure 1

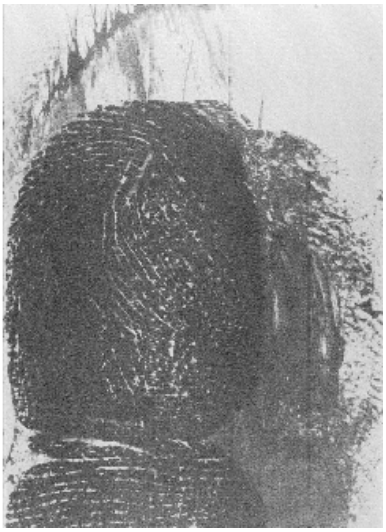

Figure 2

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Figure 3

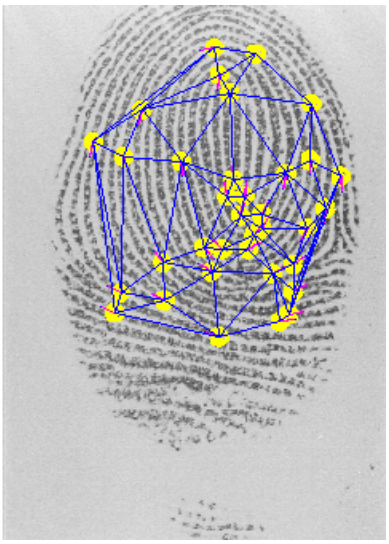

Figure 4

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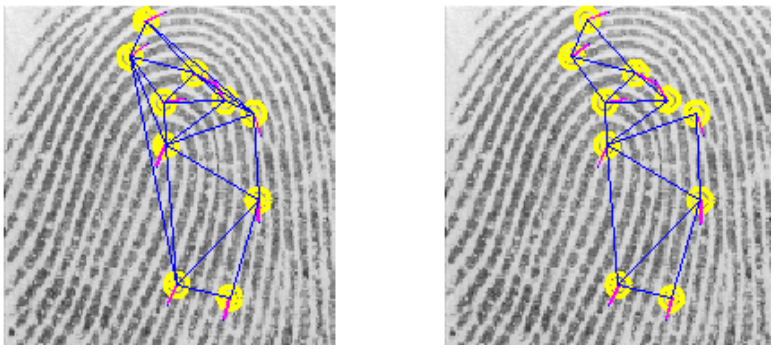

Figure 5

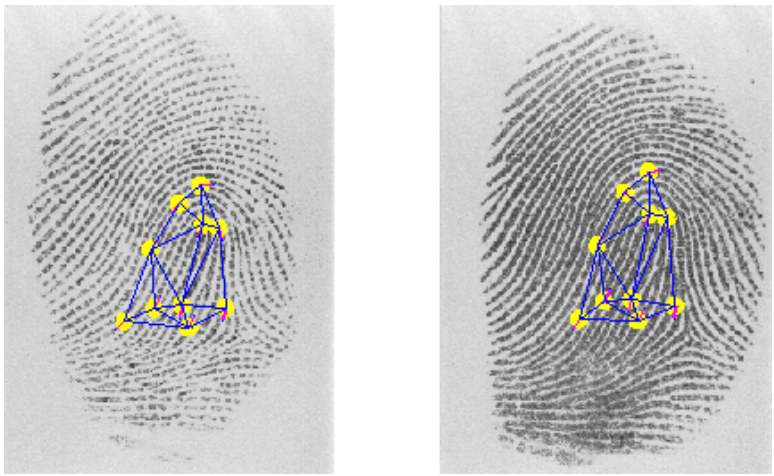

Figure 6

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Figure 7

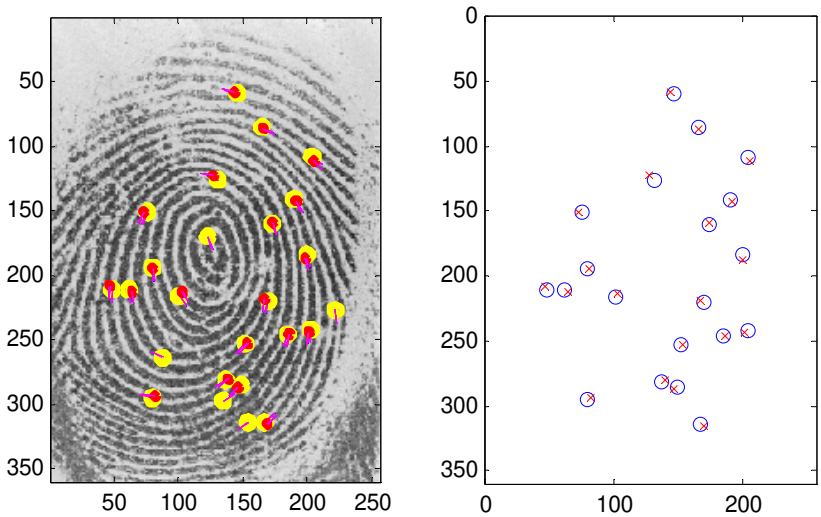

Figure 8

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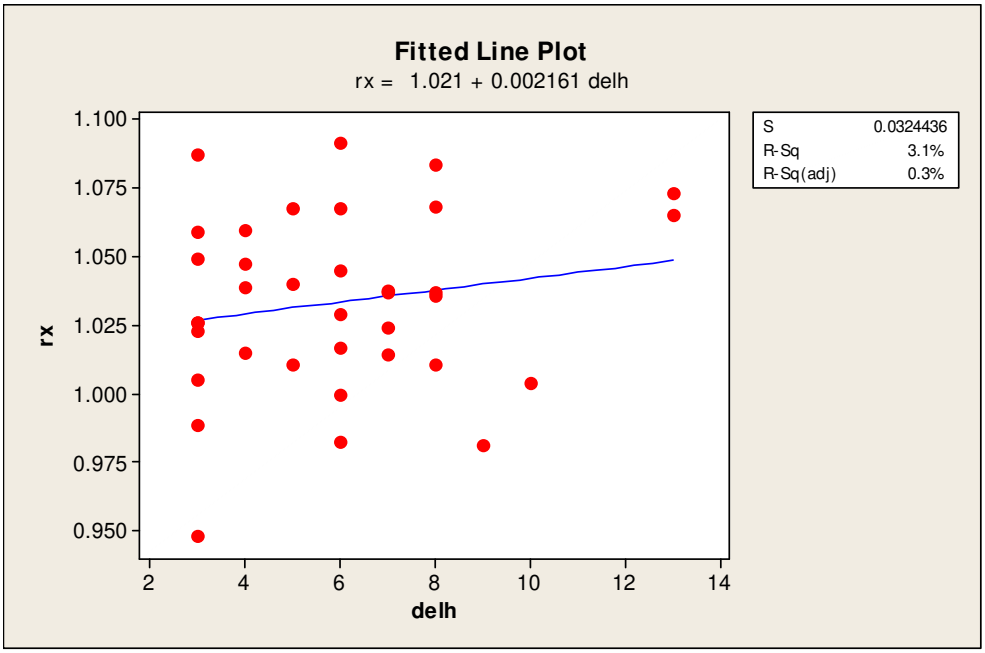

Figure 9

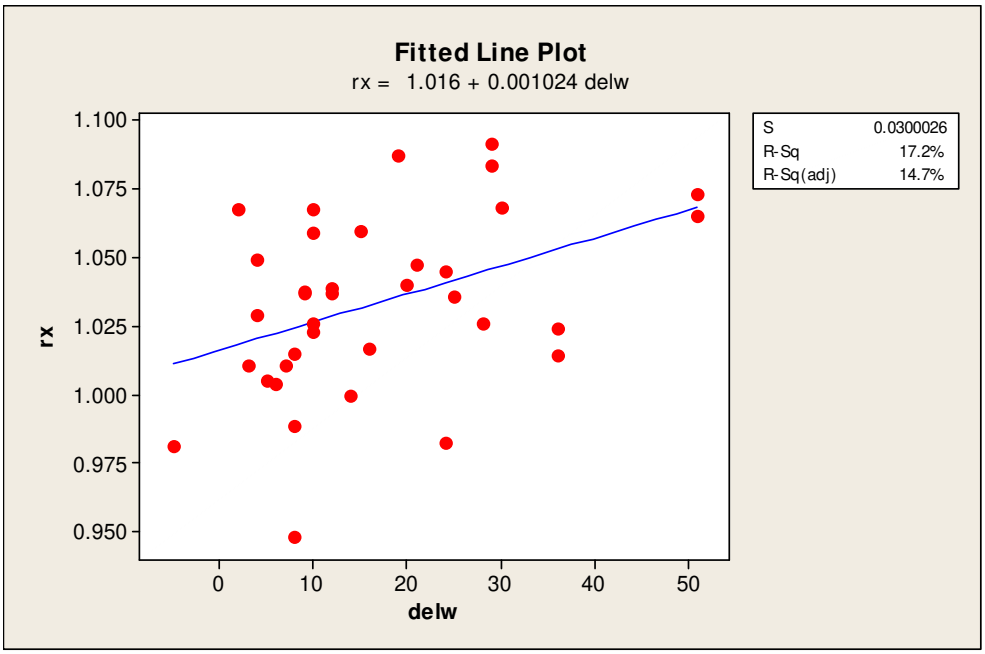

Figure 10

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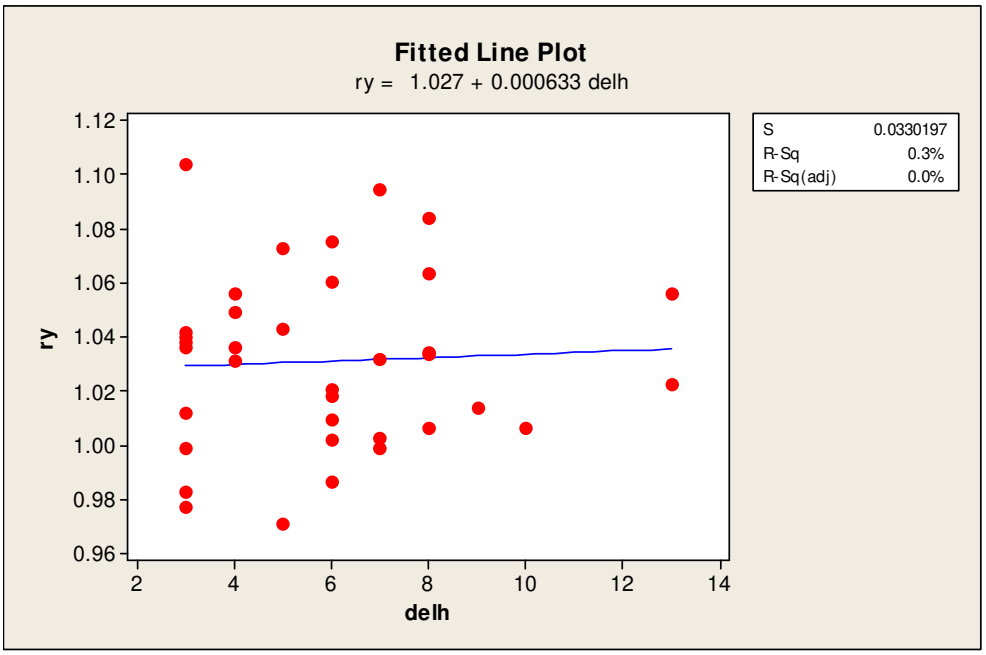

Figure 11

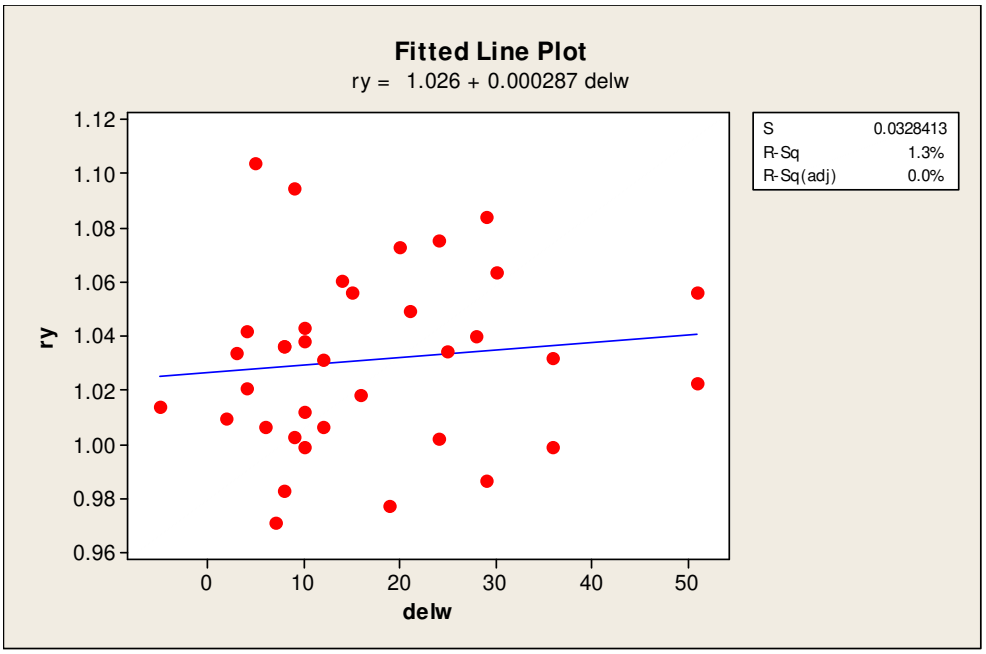

Figure 12

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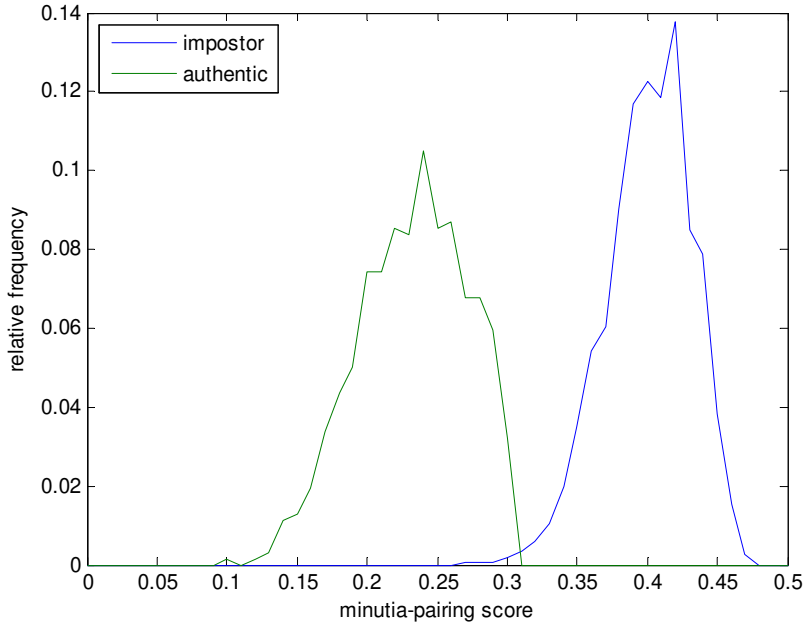

Figure 13

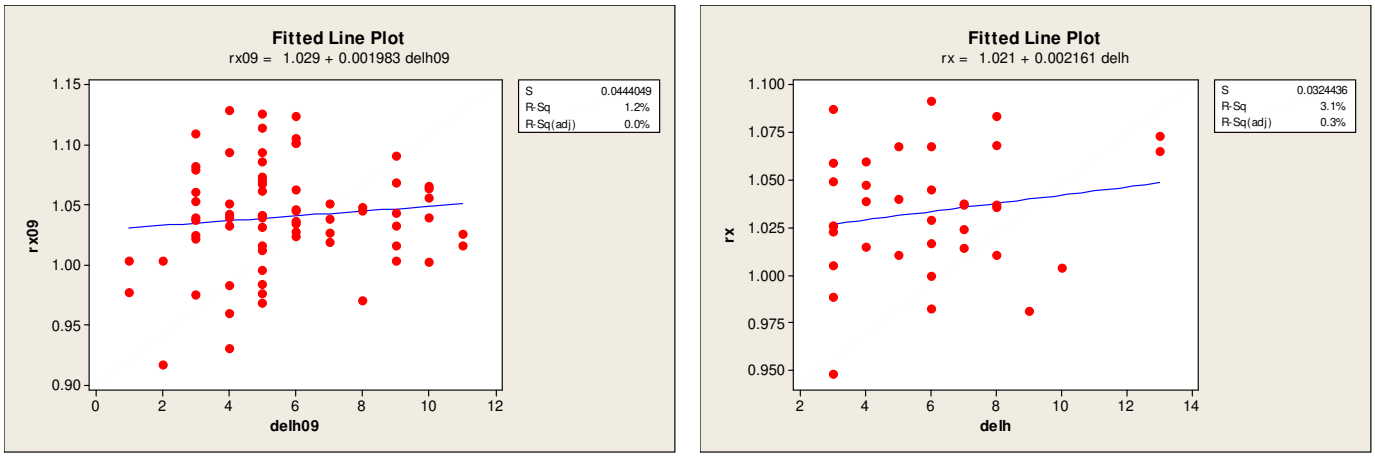

Figure 14

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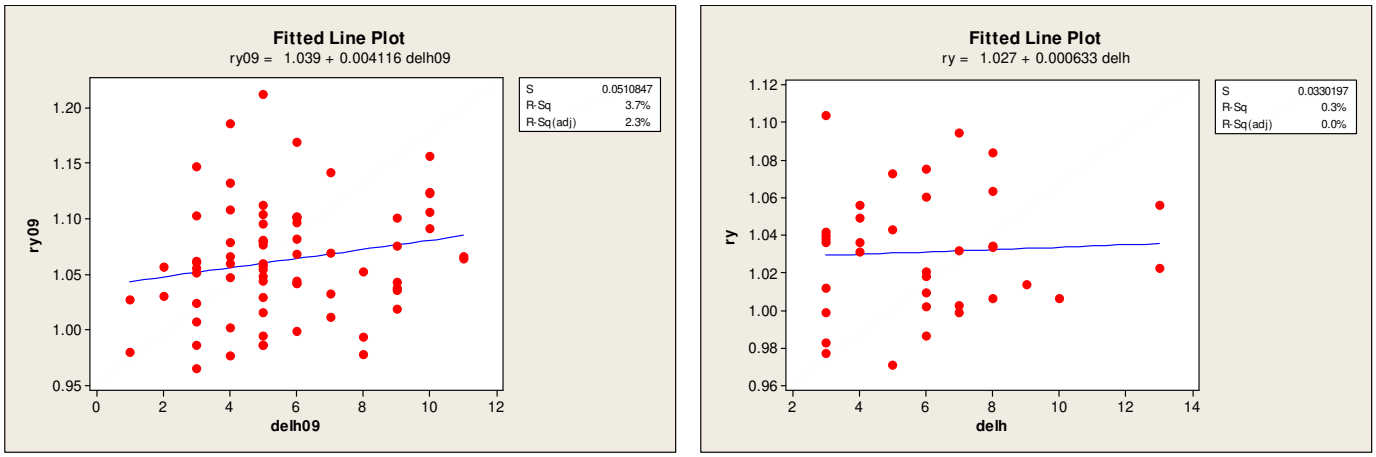

Figure 15

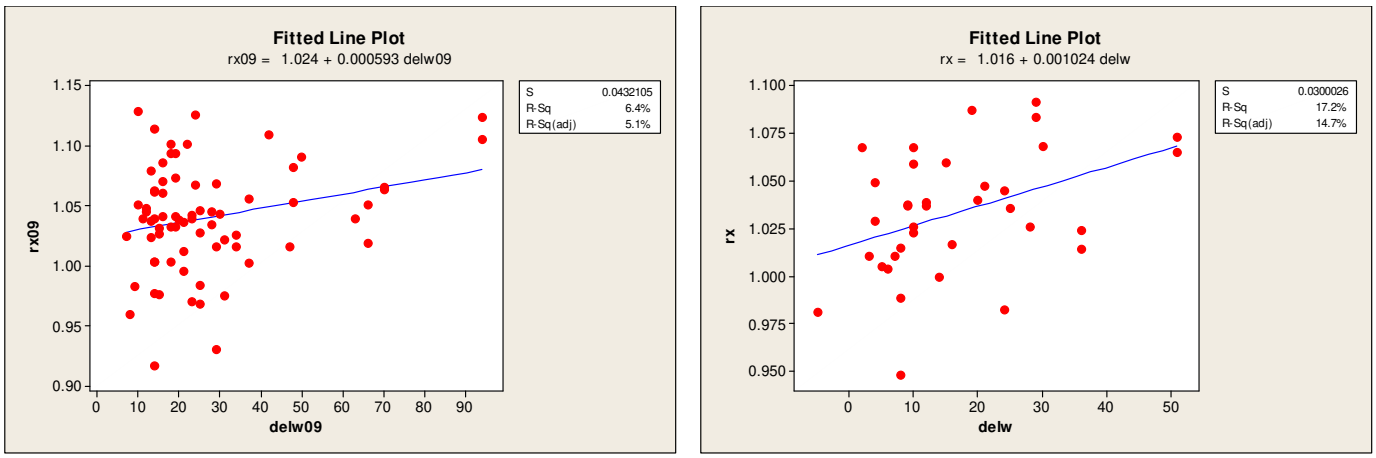

Figure 16

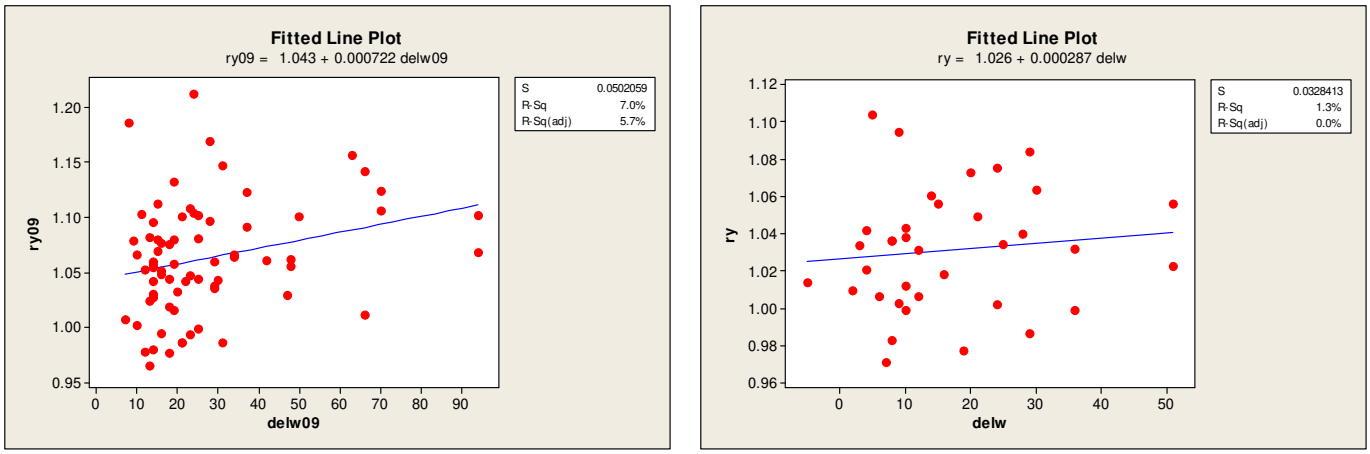

Figure 17

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IV. Conclusion

IV.1 Discussion of the Findings

The collected data was thoroughly examined, categorized and analyzed in an effort to explain the observed phenomenon: growth patterns of fingerprints as measured in this study do not appear follow a general pattern. The growth patterns are so individualistic that it is impossible to develop a single Minutiae Growth Map (MGM) or family of maps that accurately models minutiae pattern growth. Although individualistic patterns can be modeled, this is not a viable solution when applied to the general population.

The purpose of the MGM was to be able to match a child's minutiae at one age to a set of their minutiae at an older age. The researchers therefore employed another technique to meet this project goal. Funded through other resources and refined during the execution of this project, the team used a previously developed process for compensating for plastic distortion. Initially, this algorithm was planned to be used to augment the automated Minutiae Extraction Matching Tool (MEMT) in order to more accurately place minutiae. The algorithm assumes that there exists an isomorphism that maps one image to another while preserving the ridge structure. Such an isomorphism is nearly impossible to find for an entire print, but it is highly applicable to the local area of each minutia. Because distortion either stretches or compresses skin, the method had to be scalable to these local areas (this type of scaling makes the method extremely appropriate for matching children at different ages). With minimum effort, the research team was able to convert the algorithm into a stand-alone fingerprint matcher that successfully matched all fingerprint pairs from this study's fingerprint collection epochs.

Although this existing algorithm is not the MGM as originally envisioned at the project's onset, the research team nevertheless met a project goal of demonstrating a successful method for matching fingerprints of individuals after many years of growth. The results may certainly be worthy of future exploration and development.

IV.2 Implications for Policy and Procedure

The concept of collecting biometric samples (specifically fingerprints) of very young individuals in order to establish the ability to identify them from "cradle to grave" has been discussed as a desirable goal for many years. This goal is generally driven by the particular biometric application requirements. Specifically, the healthcare industry would see a significant advantage, and hence an increased adoption rate, if they could implement such a policy. However, without a reliable method to perform accurate and automated fingerprint identification of these individuals as they physically change size, collection of biometric samples would result in wasted time and energy. The pioneering work performed through this NIJ study should enable a host of applications to implement a biometric policy that the healthcare industry has been striving to achieve for several years.

IV.3 Implications for Further Research

A viable method other than a Minutiae Growth Map (MGM) was explored and was able to match a child's minutiae at one age to a set of their minutiae at an older age. The method was funded through other resources and refined during the execution of this project. Ultra-Scan originally developed this process to compensate for plastic distortion (a problem that often plagues minutiae based matchers). The algorithm assumes that there exists an isomorphism that maps one image to another while preserving the ridge structure. Such an isomorphism is nearly impossible to find for an entire print, but it is highly applicable to the local area of each minutia. Because distortion either stretches or

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compresses skin, the method had to be scalable these local areas (this type of scaling makes the method extremely appropriate for matching children at different ages). With minimum effort, the research team was able to convert the algorithm into an inchoate stand-alone fingerprint matcher that could be applied to this study's collection epochs.

This matcher was applied to the fingerprint pairs between each collection epoch and was able to match all fingerprint pairs. Although this algorithm is not the MGM the team originally envisioned, it is nevertheless a potentially powerful method for matching fingerprints of children even after many years of growth and is worthy of future exploration and development.

V. References

This report does not contain references or citations.

VI. Dissemination of Research Findings

Ultra-Scan Corporation presented on-going status and relevant findings from this study at each National Institute of Justice annual grantee's conference from 2006-2009.

A white paper based on this study titled *Variation in Minutiae Location* is scheduled to be submitted to engineering and mathematics journals for publication, and is included as Appendix A.

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APPENDIX A

Variation in Minutiae Location

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Variation in Minutiae Location

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Abstract –

INTRODUCTION

Ultra-Scan Corporation has just begun the third year of a 5-year study sponsored by the U.S. Department of Justice, National Institute of Justice (NIJ). The purpose of this study is to study the correlation between fingerprint patterns and growth in children and ultimately develop a predictive model, which we call the Minutiae Growth Map (MGM), for 2-way mapping (from younger to older and older to young) of the minutiae location, both spatial and orientation, of fingerprints captured at different points in time.

In order to determine whether commonality of growth exists and develop a predictive model of change, the orientation and spatial relationship between bifurcations and ridge endings, on x and y coordinates is currently being studied.

After the company's Design of Experiment and research protocol were approved by an Internal Review Board (IRB), Ultra-Scan began fingerprint image collection from children, once annually over a 5-year time frame.

Having collected fingerprint images from a total of 308 children over a two-year period, Ultra-Scan researchers embarked on developing processes for tracking the migration of minutiae locations. Our first attempt was to use automatic extraction algorithms. We concluded that the automatic minutia location process was too noisy for our purposes. To test this in the extreme, we took multiple images of various fingers while they were held motionless on the scanner platen. In essence, we expected the images to be duplicates and thus produce the exact same set of minutiae in exactly the same locations. Instead, we observed minutiae sets of differing sizes and those minutiae that did match often had different locations; as much as ±10 pixels.

The culprit is image-to-image fluctuation in gray scale. The fluctuations are due to slight inconsistencies in analogue hardware measurements (naturally occurring measurement errors) and slight pressure differences that the unmoving finger makes on the platen (naturally occurring process errors). What was surprising was the magnitude of the sensitivity.

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We concluded that it would be necessary to manually extract minutiae in order to achieve an accuracy that would be sensitive to effects due to growth. Manual extraction is feasible due to the small number of images that need to be processed and the time between collections.

However, even with manual extraction, there remains a random component involved in assigning a location to a minutia. This is again due to fluctuations in gray scale, but the dominant problem is nonlinear plastic distortion of the fingerprint ridges. At collection time, considerable effort is made to have distortion free images, but even minor distortion can be large enough to mask growth.

Our researchers concluded that we can know a minutia's location only statistically. There is an error ellipse within which the true location may exist for a stated statistical confidence level.

Because this is a statistical problem, we assumed underlying Gaussian distributions and designed a test of hypotheses to determine if growth could be substantiated. That is, are observed differences in minutiae locations due to growth or due to chance. From our results, it appears that two years is too short a period to determine if the measured differences are due to growth.

How long is long enough? We made an attempt to get a first-order answer to this question by using images from an unrelated database in which we have images of children taken 5 years ago. We were able to acquire current images of two of those children. The old and new images were tested resulting in sufficient evidence to support the claim of growth.

DATA COLLECTION BACKGROUND

The Design of Experiment involves the collection of fingerprint images from 308 children, aged 2 through 18, once annually over a five year time frame. Demographics collected include: age, sex, ethnicity, height, and weight.

During each collection period, four (4) fingers are scanned (1,2,6,7) from each member of the control group using a plain impression scanner.

For the purpose of the growth study, it is important that the data collected reflect changes due to growth only, and therefore, a detailed specification was created describing how to collect images so as to, as much as possible, eliminate unrelated variations. For instance, as a standard procedure, three images of each finger are taken for the purpose of smoothing out any variation of pressure or angle of finger placement on the platen surface.

Images are not saved until they are of sufficient quality and relatively free of distortion as compared to other images of the same finger. Additionally, in order to preserve uniformity, the same scanner model and make are used over the entire 5 year period of the study, collecting plain impression images.

RESEARCH OBJECTIVES / DATA ANALYSIS

The ongoing analysis of the data collected during the project is a

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combination of automated and manual processing. The minutiae of each fingerprint are first automatically processed. Because the number of prints collected during each period is relatively small, it is possible to manually verify the correctness of the minutiae found automatically. During this examination, to the best extent possible, false and questionable minutiae are removed, and obvious missing minutiae are added. A template of the resulting minutiae locations (x,y) and orientation (θ) is stored in a Minutiae Template Database. This database serves as the source for the childhood growth analysis.

In order to correlate a minutiae point between collection periods, an automated extraction algorithm is used to expedite and assist the final manual examination of minutiae pairings. Any false pairings are eliminated and missing pairings are added.

INCREMENTAL GROWTH TREND ANALYSIS

Analysis is performed on the database to allow for the identification of any anomalies in, or misconceptions about, distortions due to growth that may alter the initially conceived method of building the Minutiae Growth Map. The basic assumption is that changes in minutiae locations and orientations due to growth patterns are basically the same for the population at large. For example, boys of one ethnicity may have one map and boys of another ethnicity have a different map. In the worst case, it may ultimately be concluded that every child has his/her own map. Thus, the map building method may change with increasing data.

ESTABLISH MINUTIAE GROWTH MAP

It is safe to assume that as children grow, the distance between any given pair of minutiae changes. It cannot be assumed, however, that the change in distance between every pair is a simple scale factor. Instead, it is assumed that the Minutiae Growth Map will take the form of the following two-dimensional polynomial mapping:

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_1x_1 + a_2y_1 + a_3x_1y_1 + \ldots + a_{m-1}x_1^n + a_my_1^n \\ b_1x_1 + b_2y_1 + b_3x_1y_1 + \ldots + b_{m-1}x_1^n + b_my_1^n \end{bmatrix} \quad (1)$$

where $m_1 = \begin{bmatrix} x_1 \\ y_1 \end{bmatrix}$ is the minutia location of a child at one age and $m_2 = \begin{bmatrix} x_2 \\ y_2 \end{bmatrix}$ is the minutia location at another age. The degree of the polynomials in Equation 1 is determined during the study period and will be based on goodness of fit.

In order to use Equation 1, it is necessary to solve for the unknown polynomial coefficients $a_i, b_i, i = 1 \ldots \mathrm{N}_{ab}$. To do this, well known procedures must be followed, as described below.

Between any two collection periods, a child's finger has N minutiae in common between the two periods. It is assumed that each minutia can be mapped using the coefficients of Equation 1, so that the general matrix equation can be written:

$$\mathbf{Mx} = \mathbf{b} \quad (2)$$

where,

$$\mathbf{M} = \begin{bmatrix} x_1^1 & y_1^1 & x_1^1y_x^1 & \cdots & (x_1^1)^n & (y_1^1)^n & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & x_1^1 & y_1^1 & x_1^1y_x^1 & & (x_1^1)^n & (y_1^1)^n \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^N & y_1^N & x_1^Ny_x^N & & (x_1^N)^n & (y_1^N)^n & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & x_1^N & y_1^N & x_1^Ny_x^N & \cdots & (x_1^N)^n & (y_1^N)^n \end{bmatrix}$$

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$$\mathbf{b} = \begin{bmatrix} x_2^1 \\ y_2^1 \\ \vdots \\ x_2^N \\ y_2^N \end{bmatrix}, \text{ and } \mathbf{x} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{\mathrm{N}_{ab}} \\ b_1 \\ b_2 \\ \vdots \\ b_{\mathrm{N}_{ab}} \end{bmatrix}.$$

Note that M has N rows and N_{ab} columns. Assuming $N>N_{ab}$, the solution vector **x** is over-determined by the system of equations represented by Equation 2. This means no set of coefficients will simultaneously satisfy all the equations in 2. The best fit in a least squares sense is solved, i.e., the solution that minimizes the sum of squared errors. The error vector equation is written by

$$\mathbf{M}\mathbf{x}_{opt} - \mathbf{b} = \varepsilon \qquad (3)$$

where $\mathbf{x}_{\mathrm{opt}}$ is the "best fit" solution and it is chosen such that $\varepsilon^T \varepsilon$ is minimized. The well-known solution of the deterministic least squares problem is given by

$$\mathbf{x}_{opt} = \left[\left(\mathbf{M}^{\mathbf{T}}\mathbf{W}\mathbf{M}\right)^{-1}\mathbf{M}^{\mathbf{T}}\mathbf{W}\right]\mathbf{b} \qquad (4).$$

The weight matrix **W** is a diagonal matrix whose values represent the quality of the minutia pairings. Having solved for $\mathbf{x}_{\mathrm{opt}}$, the Minutiae Growth Map between two collection periods is thus given by the linear transformation

$$\begin{bmatrix} x_2^i \\ y_2^i \end{bmatrix} = \begin{bmatrix} x_1^i & y_1^i & x_1^i y_1^i & \cdots & (x_1^i)^n & (y_1^i)^n & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & x_1^i & y_1^i & x_1^i y_1^i & \cdots & (x_1^i)^n & (y_1^i)^n \end{bmatrix} \mathbf{x}_{opt}$$

Such a map links each of the collection periods, hence each will have its own $\mathbf{x}_{\mathrm{opt}}$. It is presumed that a polynomial, least squares fit will establish the coefficients as a function of the age interval over which the minutiae are to be transformed.

DATA COLLECTED TO DATE

To date, Ultra-Scan has enrolled 308 children in the study and collected fingerprint images. The gender demographic breakdown is 90% male and 10% female; the youngest enrollee is 1 year of age and the oldest is 18 years of age.

After Ultra-Scan's most recent recollection effort, an analysis was performed comparing the second collection to the initial data. The goal was to determine if the variation in minutiae locations could be statistically attributed to growth.

ASSESSMENT OF DATA

Ultra-Scan labels image collections as $F = \{F_0, F_1, \ldots, F_n\}$, where the subscripts indicate the time order of collection. The set F_0 represents the initial collection taken in January of 2007 and the set F_1 represents the collection of images taken at the end of April, 2007. Within each F_i, we have each child's index and middle fingerprint images for both hands. The images for each child will be denoted by $f_i^k = \{li, ri, lm, rm\}$, where i indicates the collection period and k identifies the child in the control group, li is the image of the left index finger, lm is the image of the left middle finger and ri and rm are defined likewise for the right hand. For the __ children in our database we write $F_0 = \{f_0^1, f_0^2, \ldots, f_0^{308}\}$ for the

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January images and $F_1 = \{f_1^1, f_1^2, \ldots, f_1^{308}\}$ for the April images.

The images in F, when sufficiently populated, will provide statistical data from which we will develop a Minutiae Growth Map (MGM), currently envisioned as a linear, not necessarily affine, transformation that maps a set of a child's minutiae at one age to a set of their minutiae at a different age. Hence, the accuracy of minutiae extraction and matching is critical to the success of the MGM.

Armed with the images of F_0 and F_1, we have constructed a computer-aided tool for the manual extraction and matching of minutiae. We had originally intended to first automatically extract minutiae and then remove false minutiae and add missing ones. We found that although adequate for AFIS problems, the circular error probable[1] (CEP) associated with automated locations to be unacceptably large for this project. Manual extraction allows a user to study minutiae patterns on each image and thus pick the "best" location. The tool, which we dub the Minutiae Extraction Matching Tool (MEMT), simultaneously displays two fingerprint images of the same finger, I_o and I_1. An operator manipulates I_o and I_1 by zooming in or out and centering the focus of the images in order to locate and identify matching minutiae pairs.

Despite all efforts however, locating minutiae is subject to two types of error. First, because a minutia location is an estimate it is subject to measurement error. For example, suppose I_o and I_1 .are exactly the same. If we were to compute the interconnecting distances between minutiae extracted from I_o and difference them with the corresponding interconnecting distances from I_1, the resulting differences would, in general, not be zero. Instead, as is usual with measurements, these errors appear to have a Gaussian distribution with zero mean and a standard deviation that depends on the skill and dedication of the operator. The second source of error is the more troublesome distortion that occurs when the finger makes contact with the scanner platen. We are very careful to have the children place their fingers so as to minimize distortion, but distortion is subtle and often hard to recognize until after processing. For those images collected that have distortion, the only recourse we have is to work around the distorted areas.

Future collections will include several images of the same finger with repositioning. It should be possible to then construct a mapping that attenuates distortion.

Because there is only four months between the collection of F_0 and F_1 images, it is understandable that growth patterns are inchoate and thus undetectable at this time. However, it is reasonable to ask: has there been any growth? We take a statistical approach to answer this question. We treat minutiae as permanent landmarks on the finger from which we can construct Delaunay triangles. An example of Delaunay triangulation is shown on the left side of Figure 1. We intend to use a time ordered sequence of Delaunay triangulation as a basis for an interpolation scheme that yields a family of functional descriptions, $g_i^k(x, y)$, of each image in the time sequence. Delaunay triangles are an especially efficient tessellation of the fingerprint because no other minutiae other than those of the triangle are contained in any triangle's circumscribed circle.

We also employed Delaunay tessellation to answer the question of growth. To minimize the effects of noise, we discarded all triangles with area less than 100 square pixels and all triangles with a minimum interior angle of less than 15°. The left and right side of Figure shows the resulting tessellation before and after pruning.

[1] The circular error probable (CEP) is a disk in which we expect half the attempts to fall within.

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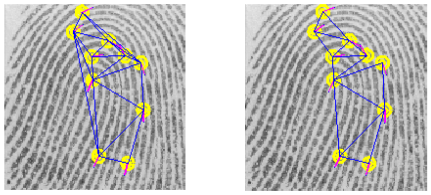

Figure 1

We used MEMT to extract and match minutiae from each of the four image pairs associated with 5 individuals from F_0 and F_1. As a typical example, the matched minutiae pairs and pruned tessellation for a sample image shown in Figure 2 with the F_0 image on the left and the F_1 on the right. We constructed two measures of growth:

1) The ratio of the area of corresponding triangles
2) The difference in the length of corresponding triangle sides.

If there was no growth, then we would expect the ratio of triangle areas to have a mean of 1.0 and the difference in triangle sides to have a mean of 0.0. Two statistical tests of hypothesis are in order. In each case we use a level of significance of $\alpha = .05$. That is, there is a 5% chance that we will incorrectly reject the null hypothesis (Type I error). We first test the ratio of triangles and our null hypothesis, H_0, is that the population mean is 1.0, no growth. The alternate hypothesis, H_1, states that there has been detectable growth over the last 4 months, which is also our claim. We use the t-distribution to test the hypothesis. For the images shown in Figure , the sample mean of the area ratios is $\bar{x} = 1.0171$ with a sample standard deviation of s=0.061, and a sample size of n=20. From a t-distribution table with 19 degrees of freedom, the critical value for right-tailed test with $\alpha = .05$ yields $t_c = 1.729$. The test statistic is computed by

$$t_{test} = \frac{\bar{x} - \mu}{s/\sqrt{n}} = \frac{1.0171 - 1}{0.061/\sqrt{20}} = 1.225$$

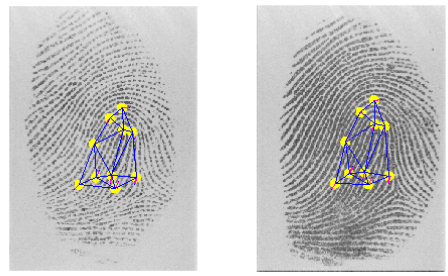

Figure 2

Because $t_{test} < t_c$ we cannot reject H_0, and hence there is insufficient evidence to support our claim of growth. For the difference of side lengths, we have $\bar{x} = 0.6488$ and $s = 2.404$. Then, with $\mu = 0$, we compute $t_{test} = 1.207$, which is less than t_c, and again we cannot reject H_0 nor support the claim of growth. The test results for the images analyzed are shown in Table 1 and Table 2. Given the

id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
52 ri	7	0.9669	0.1319	0.6198	2.015	cannot reject H_0
52 li	10	1.1892	.7091	0.8429	1.833	cannot reject H_0
53 ri	4	1.0997	0.3140	0.6348	2.353	cannot reject H_0
55 ri	12	0.8682	0.2909	-2.183	1.796	cannot reject H_0
56 lm	12	.9560	0.1677	-.8269	1.796	cannot reject H_0

Table 1 – Test Ratio of Areas

short amount of time between scans, it is not surprising that we do not have enough evidence to support the claim of growth.

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id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
52 ri	13	-0.0753	1.1968	-0.2269	1.780	cannot reject H_0
52 li	15	-1.0312	4.2248	-0.9453	1.761	cannot reject H_0
53 ri	7	0.0853	2.6569	0.0850	1.943	cannot reject H_0
55 ri	16	0.0136	2.0336	0.0268	1.753	cannot reject H_0
56 lm	17	0.2588	2.310	0.4620	1.746	cannot reject H_0

Table 2 – Test Difference of Side Lengths

A 5-YEAR COMPARISON

We can compare the results shown in Table 1 and Table 2 with results from images of children that were taken 5 years apart. In our Ultra-Scan database we have a number of children fingerprints that were scanned on November 1, 2002. e were able to obtain new images of the right index fingers for two of those children. The birth date of the first child, Phillip, is December 12, 1991, just short of his 11th birthday when first scanned. That child is now 15 years old. The birth date of the second child, Alexandra, is March 13, 1980, which means she was 13 years old when first scanned. She just recently celebrated her 18th birthday. The test results for these children are shown in Table 3 and Table 4. As we can see from these tables, there is significant evidence to support the claim of growth. Although we can clearly show statistical evidence that there has been growth, which is not at all surprising, there is insufficient data to build an MGM.

Id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
Phillip ri	11	1.4749	0.5642	2.7920	1.812	Accept claim of growth
Alexandra ri	14	1.1326	.2012	2.4662	1.771	Accept claim of growth

Table 3 – Test Ratio of Areas for 5-year Span

Id	n	$\bar{x}$	s	t_{test}	t_c	conclusion
Phillip ri	15	7.2413	7.0315	3.9885	1.761	Accept claim of growth
Alexandra ri	23	2.3387	2.8986	3.8687	1.717	Accept claim of growth

Table 4 - Test Difference of Side Lengths for 5-year Span

IMPORTANCE OF MINUTIAE LOCATION TO FINGERPRINT MATCHING

Two images of the same finger can have different numbers of minutiae: some that can be genuinely paired, some that are missing, and some that are false. This would be anathema to mapping finger growth in children. Manual extraction virtually guarantees a true set of genuine minutiae.

Although manual extraction provides a reliable set of minutiae from collection epoch to collection epoch, the magnitude of relative location errors between minutiae must be understood and compensated for in the analysis. Careful attention to finger placement on the scanner can attenuate location errors, but cannot eliminate them. So, to be successful in mapping fingerprint growth, Ultra-Scan has initiated an analysis of variance experiment so as to separate “noise” due to finger-scanner coupling from actual growth.

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This study, however, is generic to fingerprint matching in the industry. Automatic algorithms that match minutiae templates fall into the general class of a "point pattern matcher." The inquiry and search templates can be labeled by

$X = \{x_i, i = 1,2, \ldots r\}$ and

$Y = \{y_i, i = 1,2,\ldots s\}$

respectively, where $x \in X$ and $y \in Y$ are points in 2-dimenstional Euclidean space with an associated angular direction. Without loss of generality, it is assumed $r \leq s$, that is the cardinality of X is less than or equal to Y. For templates extracted from the same finger, the potential for inequality is due to a combination of missing or false minutiae, so the actual number of minutiae points that can be matched is $q \leq r \leq s$.

When X and Y are from the same finger, the function of the matcher can be simply stated: the matcher must determine which x-points go with which y-points. Let Π be the set of all permutations of combinations. For any permutation $\pi \Pi \in$, we say $x_{\pi(i)}$ associates with y_i. Hence, each $\pi \in \Pi$ is a map that tells us which x goes with which y. Given any $\pi \in \Pi$, we compute an affine transformation φ_π and the pure translation, b_π by minimizing, in the lease squares sense, the following error function:

$$e(\pi) = \sum_{i=1}^{q} \left\| \phi_\pi x_{\pi(i)} + b_\pi - y(i) \right\|$$

The best match occurs when $\pi \in \Pi$ is such that:

$$e_\pi = \min_{\pi \in \Pi} e(\pi), \text{ that is,}$$

the permutation that yields the smallest norm.

In a perfect world, e_π would be zero when matching two templates from the same finger. But because of the problems associated with finger-coupling discussed above, e_π is virtually never expected to be zero for authentic matches. The transformation ϕ will rarely map correctly paired minutiae on top of each other; often the distance error is substantial. Hence the matching algorithm has to have a liberal tolerance built in order to achieve good matching performance. Of course this opens the door for falsely matching an impostor, i.e., when comparing two templates that are not from the same finger.

AN INTERESTING OBSERVATON

Minutiae detection errors are unavoidable in automatic processing. The primary reason for error is the variation in the coupling of the finger with the scanner.

Distortion of the friction ridge surface, rotation of the finger, horizontal and vertical movement of the finger, image quality, all contribute to inaccuracies. This means that automatic image processing software can miss genuine minutiae and also generate false minutiae due to artifacts.

This is expected behavior when two images of the same finger are taken with

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the second image being taken at some future time and repositioned on the scanner. But what should we expect if we were to take multiple images of the same finger while the finger remains motionless? You might think that the images would be exact duplicates. But that is apparently not the case.

Ultra-Scan conducted an experiment where subjects' fingers were held in place while we took a series of 10 scans. With a high degree of confidence, finger placement on the scanner platen from scan to scan remained virtually unchanged. However, even in this highly controlled scenario, automatic processing resulted in varying size minutiae sets. You would also expect the minutiae that did pair to have identical locations. Again this was not the case. The observed difference between images was due to slight variations in gray scale levels (256 levels).

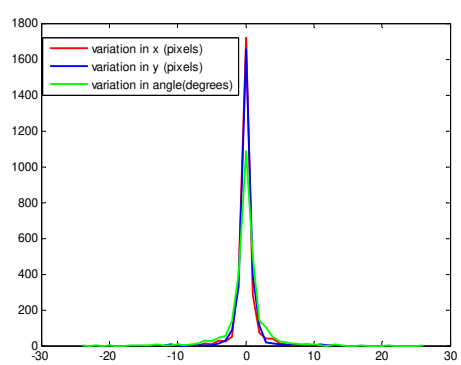

Figure 1

The histogram shown in Figure 3 shows the spread of x- and y-location variations and the variation in orientation angle. As can be seen, the mean variation is approximately zero, while the standard deviation is 1.5 pixels in x, 1.6 pixels in y and 2.8 degrees in angle. The maximum x deviation was 11 pixels in x, 13 pixels in y, and 26 degrees in angle. All caused by slight fluctuations in gray scale that result in the automatic extractor creating a slightly different ridge angle map. This in turn causes the binarization algorithm to slightly alter the topology of the local are in which a minutia exists.

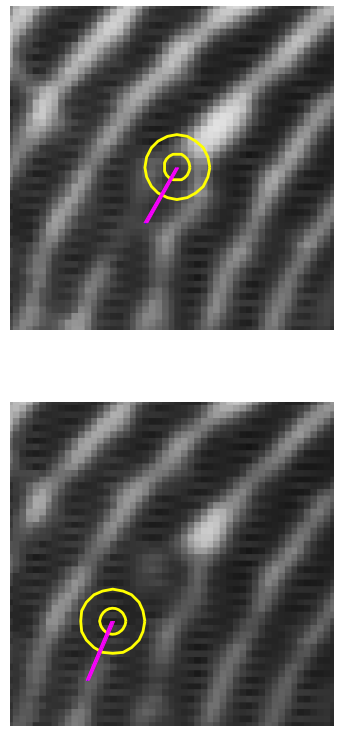

Figure 2

In Figure 5, shows the difference in gray scale between two successive scans with the finger held motionless between scans. In the top image, the minutia was captured as ridge ending, while in the bottom image it was captured as a bifurcation. As can be seen in Figure 5 below, the binarized images from which the minutiae are extracted in the automated algorithm is substantially different, all due to a few shades of gray difference.

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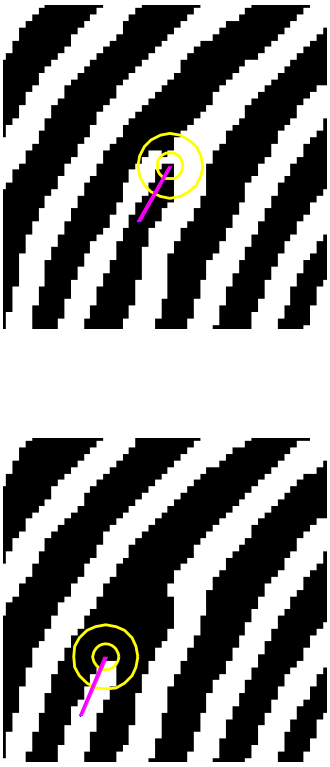

Figure 3

CONCLUSION

It is still too early to detect growth patterns. Underlying noise due to human error and gray scale fluctuations, and biases due to distortion make it impossible to detect growth at this early stage. A few samples from an unrelated database that are 5 years apart showed statistically significant growth, but there is too little data to construct a Minutiae Growth Map.

Stabilizing minutiae location from scan to scan is a daunting problem.

About the Authors

Dr. John K. Schneider, Co-Founder, CTO, and President of Ultra-Scan Corporation, enjoys a worldwide reputation as a pioneer in the use of ultrasonics for fingerprint identification. He has extensive experience in fingerprint identification, working with government agencies such as the National Institute of Standards and Technology, the Central Intelligence Agency, the Department of Defense, and the National Security Agency. Dr. Schneider's work at Ultra-Scan includes leading numerous breakthrough R&D initiatives involving multimodal biometric fusion logic, high confidence biometric match systems, and performance measurement and analysis software techniques.

Mr. Frederick Kiefer has over 20 years experience in mathematical analysis. His prior work includes the design of high speed fingerprint processing algorithms, latent match processors, and the development of fingerprint encoding and matching algorithms.