2017

Interoperability Analysis of Non-Contact Fingerprinting Devices vs. Contact-Based Fingerprinting Devices

Emily Biller

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

Biller, Emily, "Interoperability Analysis of Non-Contact Fingerprinting Devices vs. Contact-Based Fingerprinting Devices" (2017). *Graduate Theses, Dissertations, and Problem Reports*. 5210.
<https://researchrepository.wvu.edu/etd/5210>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

Interoperability Analysis of Non-Contact Fingerprinting Devices vs. Contact-Based Fingerprinting Devices

Emily Biller

Thesis submitted to the

Benjamin M. Statler College of Engineering and Mineral Resources At

West Virginia University

In partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

Jeremy Dawson, Ph.D., Chair

Donald Adjero, Ph.D.

Thirimachos Bourlai Ph.D.

Lane Department of Computer Science and Electrical Engineering

Morgantown, WV

2017

Keywords: Fingerprint Matching, Fingerprints, Contactless, Contact-Based, Ten-prints

Copyright 2017 Emily Biller

Abstract

Interoperability Analysis of Non-Contact Fingerprinting Devices vs. Contact-Based Fingerprinting Devices

Emily Biller

Fingerprints are an essential biometric identifier that have been used for centuries due to the high diversity among individuals. Contactless fingerprint systems possess advantages over conventional contact-based systems, such as increased throughput in check point screening scenarios. Increased acceptance of contactless fingerprinting technologies requires careful operational validation due to the inherent differences in their capture techniques. To leverage the maturation of contactless technologies, reliability and data interoperability with legacy fingerprint datasets must be considered. The goal of this study is to evaluate the interoperability of contactless fingerprinting devices with contact-based fingerprinting devices. To achieve this goal, the fingerprint dataset of the ManTech Non-Contact Multi-Sensor Fingerprint Collection Phase II collected by West Virginia University, has been employed.

The main objectives this study aims to achieve are:

- *Assessing the match performance of the contactless versus contact-based fingerprint devices.*
- *Statistical match performance evaluation using match score statistics.*
- *Assessing the match performance of demographic strata in comparison to the total dataset.*

Following the generation of genuine and imposter match score distributions, Receiver Operating Characteristic Curves were plotted to compare the match performance of each device. The Kullback Leibler Divergence measurements have been calculated which signify the amount of variation between match score distributions as well as the Equal Error Rates for the genuine and imposter distributions. With the help of these procedures, the interoperability of contactless devices and contact-based devices has been examined and analyzed. Results obtained from the devices, representing a 'snapshot' of capability during their development cycle, indicate that Rank1 accuracy is between 74.33 and 98.68 percent with contact based methods. The Rank 1 accuracy is between 74.66 and 97.27 percent with other contactless devices.

Table of Contents

Abstract	ii
Table of Contents	iii
List of Figures	vi
List of Tables	xxi
Chapter 1: Introduction	1
1.1 Executive Summary	2
1.2 Contactless Fingerprinting.....	4
1.3 Methods of fingerprinting	5
1.4 Hurdles in Fingerprint Identification	8
1.5 Fingerprint Recognition	9
1.6 Minutiae	11
1.7 Advantages and Disadvantages of Contact and Contactless Fingerprinting	12
1.8 Challenges involved with Contactless Fingerprint technology	14
1.9 Modulation Transfer Function.....	15
1.10 Standardization of Contactless Devices.....	16
1.11 Contactless Versus Touchless.....	18
1.12 Certification	21
1.13 Interoperability.....	21
1.14 Related Work.....	22
1.15 Problem Statement and Thesis Organization	24
Problem Statement.....	24
Thesis Organization	26
Chapter 2: Theory.....	27
Fingerprint Sensor Technology:.....	28
2.1 Integrated Biometrics Sherlock Sensor	28
2.2 Frustrated Total Internal Reflection Sensors.....	30
2.3 Structured Light Illumination.....	31
2.4 Polarized Reflected Light.....	33
2.5 Fingerprint Matching or Fingerprint Recognition.....	34
2.6 Possible Matching Errors.....	37
2.7 Biometric System Classifying Terminology.....	39
2.8 Kullback Leibler Divergence.....	41
2.9 Receiver Operating Characteristic Curves	42
2.10 NIST Fingerprint Image Quality (NFIQ)	43
Chapter 3: Data Collection & Preparation	44
3.1 Overview	45
3.2 Collection Process	45
3.3 Fingerprint Devices.....	46
3.4 Collection Site.....	49

3.5	Data Types and Organization	50
3.6	Collection Demographics.....	51
3.7	Post Processing.....	54
3.8	Fingerprint Matchers.....	55
Chapter 4: Interoperability Analysis		56
4.0	Fingerprint Image Match Score Analysis	57
4.1	Cross-Examined Genuine and Imposter Score Distributions	69
4.1.1	NBIS Cross-Examined Genuine/Imposter Distributions	69
4.1.1.1	NBIS Samples of Normal Distributions.....	69
4.1.1.2	NBIS Outliers	70
4.1.2	Neurotech Cross-Examined Genuine/Imposter Distributions.....	73
4.1.2.1	Neurotech Samples of Normal Distributions	73
4.1.2.2	Neurotech Outliers	74
4.1.3	SourceAFIS Cross-Examined Genuine/Imposter Distributions	75
4.1.3.1	SourceAFIS Samples of Normal Distributions	75
4.1.3.2	SourceAFIS Outliers	76
4.2	Gender-Based Study.....	78
4.2.1	Gender-Based Samples of Normal Distributions	78
4.2.2	Gender-Based Outliers	81
4.2.3	Gender- Based KLD Values	81
4.3	Age-Based Study.....	83
4.3.1	Age-Based Samples of Normal Distributions	83
4.3.2	Age-Based Outliers	84
4.3.3	Age-Based KLD Values.....	85
4.4	Ethnicity-Based Study.....	88
4.4.1	Ethnicity-Based Study Sample Genuine/Imposter Distributions	88
4.4.2	Ethnicity-Based Outliers	90
4.4.3	Ethnicity-Based KLD Values.....	93
4.5	Issues Faced with Devices and Matchers Which can be Observed in the Results.....	101
Chapter 5: Conclusion.....		102
5.1	Conclusions.....	103
5.2	Future Work	110
Appendix A General Study of All Data.....		111
A.1	NBIS Genuine/Imposter Score Distributions	117
A.2	Neurotech Genuine/Imposter Score Distributions	121
A.3	SourceAFIS Genuine/Imposter Score Distributions	124
A.4	NBIS Cross-Examined Genuine/Imposter Distributions	128
A.5	Neurotech Cross-Examined Genuine/Imposter Distributions.....	138
A.6	SourceAFIS Cross-Examined Genuine/Imposter Score Distributions	148
A.7	NBIS ROC Curves and Area Under Curve.....	157
A.8	Neurotech ROC Curves and Area Under Curve	163
A.9	SourceAFIS ROC Curves and Area Under Curve	168
A.10	Equal Error Rates For Each Matcher	173
Appendix B Gender Based Study		177
B.1	NBIS Genuine/Imposter Score Distributions	178
B.2	Neurotech Genuine/Imposter Score Distributions	184

B.3 SourceAFIS Genuine/Imposter Score Distributions.....	189
B.4 NBIS ROC Curves and Area Under Curve.....	194
B.5 Neurotech ROC Curves and Area Under Curve	199
B.6 SourceAFIS ROC Curves and Area Under Curve	203
B.7 Minutiae Box Plots by Device and Gender	207
B.8 Equal Error Rates For Gender Based Study	210
Appendix C Age Based Study	212
C.1 NBIS Genuine/Imposter Score Distributions	213
C.2 Neurotech Genuine/Imposter Score Distributions	229
C.3 SourceAFIS Genuine/Imposter Score Distributions.....	243
C.4 NBIS ROC Curves and Area Under Curve	258
C.5 Neurotech ROC Curves and Area Under Curve	263
C.6 SourceAFIS ROC Curves and Area Under Curve	269
C.7 Minutiae Box Plots by Age Range and Device	275
C.8 Equal Error Rates for Age Based Study.....	278
Appendix D Ethnicity Based Study	280
D.1 NBIS Genuine/Imposter Score Distributions.....	281
D.2 Neurotech Genuine/Imposter Score Distributions	299
D.3 SourceAFIS Genuine/Imposter Score Distributions	316
D.4 NBIS ROC Curves and Area Under Curve.....	334
D.5 Neurotech ROC Curves and Area Under Curve	341
D.6 SourceAFIS ROC Curves and Area Under Curve	348
D.7 Minutiae Box Plots by Ethnicity and Device.....	356

List of Figures

Figure 1.1 Blank Ten-print Card.....	6
Figure 1.2 Ten print card with fingerprints.....	7
Figure 1.3 Example of Livescan Fingerprint Capture [2].....	8
Figure 1.4: Ridge Patterns [9].....	10
Figure 1.5: (Left)Fingerprint Minutiae types [13] (Right) Fingerprint minutiae marked by location and orientation [14].....	11
Figure 1.6: Images of various finger conditions: (a) normal finger; (b) dry finger; (c) wet finger; (d) poor quality finger. [27]	13
Figure 1.7: Visualizing compatibility between (a) a touchless fingerprint from line-scan sensor using the proposed nonparametric unwrapping (b) the corresponding ink-on-paper rolled fingerprint. [31].....	15
Figure 1.8 Difference between contactless (left) and touchless (right) [1].....	18
Figure 1.9 (a) ANDI On-The-Go (OTG) [43] (b) MorphoWave or Morpho Finger-On-The-Fly (FOTF) [39] (c) TBS Touchless Ten Printer [1] (d) AIRprint Standoff Fingerprint Scanner [1] (e) TBS 3D Enroll [40] (f) IDair ONEprint [41] (g) NEC HS100-10 hybrid contactless scanner [42].....	20
Figure 2.1 Explanation of Sherlock sensor by Integrated Biometrics [50].....	29
Figure 2.2 Sherlock Sensor [51]	30
Figure 2.3 FTIR-based fingerprint sensor operation [55].....	31
Figure 2.4 Diagram of how structured light illumination sees a finger [58]	33
Figure 2.5 General block diagram for a Fingerprint Identification System. [68]	35
Figure 2.6 Typical Minutiae Matching Algorithm [64].....	37
Figure 2.7 Examples of False Non-Matches or False Rejects [69].....	38
Figure 2.8 Examples of False Matches or False Accepts [69].....	38
Figure 2.9 Representation of a typical genuine and imposter score distribution [70]	41
Figure 2.10 A Sample ROC Curve [72].....	42
Figure 3.1: Fingerprint devices (from top left): CrossMatch Guardian R2, L1/Morpho TouchPrint 5300, CrossMatch SEEK Avenger, Northrup Grumman BioSled, MorphoTrak MorphoIDent, Advanced Optical Systems (AOS) ANDI On-The-Go, MorphoTrak Finger-on-the-Fly. The IDair InnerID (on iPhone) system was not available for photograph. [2] ..	47
Figure 3.2 Sample images from a single individual for each method of capture (a) Tenprint scan of rolled print (b) Tenprint Scan of Four Finger Slap (c) Livescan rolled print image (d) Livescan Four Finger Slap image (e) ANDI OTG Right Index Finger Capture (f) Morpho FOTF Right Index Finger Segment	48
Figure 3.3 Collection laboratory and station arrangement. [2].....	49
Figure 3.4 Number of participants by month.....	51
Figure 3.5 Cumulative Participation	52
Figure 3.6 Participation Ethnicity	52
Figure 3.7 Participant Age	53
Figure 3.8 Breakdown of gender & ethnicity	53
Figure 4.1 Normalized NFIQ Score Distributions for All Devices	65
Figure 4.2 Normalized NFIQ Score Distributions for All Devices - Rolls	66
Figure 4.3 Normalized NFIQ Score Distributions for All Contact-based Devices	67

Figure 4.4 Normalized NFIQ Score Distributions for all Contactless Devices (Excluding InnerID).....	68
Figure 4.5 (Left) NBIS 10print – Crossmatch Seek Avenger (Right) NBIS ANDI Binary – FP II Guardian.....	69
Figure 4.6 NBIS BioSled - MorphoMobile	70
Figure 4.7 (Left) NBIS 10print - ANDI Greyscale (Right) NBIS ANDI Greyscale – Morpho FOTF	71
Figure 4.8 (Left) NBIS ANDI Greyscale – MorphoMobile (Right) NBIS 10print – InnerID	71
Figure 4.9 (Left) NBIS ANDI Binary – InnerID (Right) NBIS ANDI Greyscale – InnerID.....	71
Figure 4.10 (Left) NBIS BioSled – InnerID (Right) NBIS Crossmatch SEEK AVENGER – InnerID	72
Figure 4.11 (Left) NBIS FP II Guardian (Right) NBIS InnerID – L1	72
Figure 4.12 (Left) NBIS InnerID – Morpho FOTF (Right) NBIS InnerID – MorphoMobile.....	72
Figure 4.13 (Left) Neurotech 10print – Morpho FOTF (Right) Neurotech ANDI Binary - BioSled	73
Figure 4.14 Neurotech FP II Guardian - MorphoMobile.....	73
Figure 4.15 (Left) Neurotech ANDI Binary – InnerID (Right) Neurotech ANDI Greyscale - InnerID	74
Figure 4.16 (Left) Neurotech BioSled – InnerID (Right) Neurotech Crossmatch SEEK AVENGER - InnerID	74
Figure 4.17 (Left) Neurotech FP II Guardian – InnerID (Right) Neurotech InnerID – L1	75
Figure 4.18 (Left) Neurotech InnerID – Morpho FOTF (Right) Neurotech InnerID - MorphoMobile	75
Figure 4.19 (Left) SourceAFIS 10print – BioSled (Right) SourceAFIS L1 - MorphoMobile	76
Figure 4.20 SourceAFIS Morpho FOTF - MorphoMobile.....	76
Figure 4.21 (Left) SourceAFIS 10print – InnerID (Right) SourceAFIS ANDI Binary - InnerID	77
Figure 4.22 (Left) SourceAFIS ANDI Greyscale – InnerID (Right) SourceAFIS BioSled - InnerID	77
Figure 4.23 (Left) SourceAFIS Crossmatch SEEK AVENGER – InnerID (Right) SourceAFIS FP II Guardian – InnerID	77
Figure 4.24 (Left) SourceAFIS InnerID – L1 (Right) SourceAFIS InnerID – Morpho FOTF	78
Figure 4.25 SourceAFIS InnerID - MorphoMobile.....	78
Figure 4.26 (Left) NBIS ANDI Binary Male (Right) NBIS Crossmatch Seek Avenger Male	79
Figure 4.27 (Left) NBIS ANDI Greyscale Female (Right) FP II Guardian Female.....	79
Figure 4.28 (Left) Neurotech ANDI Greyscale Male (Right) Neurotech BioSled Male.....	80
Figure 4.29 (Left) Neurotech BioSled Rolls Female (Right) Neurotech Morpho FOTF Female	80
Figure 4.30 (Left) SourceAFIS Morpho FOTF Male (Right) SourceAFIS MorphoMobile Male	80
Figure 4.31 (Left) ANDI Binary Female (Right) SourceAFIS FP II Guardian Female	81
Figure 4.32 (a) Neurotech BioSled Rolls for ages 18-19 (b) SourceAFIS FP II Guardian Ages 20 – 29.....	84
(c) SourceAFIS Morpho FOTF for ages 30 - 39 (d) Neurotech ANDI Binary for Ages 40 and up	84
Figure 4.33 (Left) NBIS Crossmatch Seek Avenger Rolls for ages 40 and up (Right) NBIS BioSled Rolls for ages 40 and up.....	85
Figure 4.34 (Left) Neurotech FP II Guardian for ages 40 and up (Right) Neurotech L1 for ages 40 and up.....	85

Figure 4.35 (Left) NBIS ANDI Binary for the African Ethnicity (Right) NBIS ANDI Binary for the Middle Eastern Ethnicity	89
Figure 4.36 (Left) NBIS ANDI Greyscale for the Asian Ethnicity (Right) NBIS BioSled for the Asian Indian Ethnicity	89
Figure 4.37 (Left) Neurotech BioSled for the Other Ethnicity (Right) Neurotech FP II Guardian for the Hispanic Ethnicity	90
Figure 4.38 (Left) SourceAFIS Crossmatch Seek Avenger Rolls For the African American Ethnicity (Right) SourceAFIS MorphoMobile for the Caucasian Ethnicity.....	90
Figure 4.39 (Left) NBIS FP II Rolls For the American Indian Ethnicity (Right) NBIS Crossmatch Seek Avenger for the American Indian Ethnicity	91
Figure 4.40 (Left) NBIS Crossmatch Seek Avenger Rolls for the American Indian Ethnicity (Right) Neurotech BioSled for the American Indian Ethnicity	91
Figure 4.41 (Left) Neurotech Crossmatch Seek Avenger for the American Indian Ethnicity (Right) Neurotech Crossmatch Seek Avenger Rolls for the American Indian Ethnicity	92
Figure 4.42 (Left) SourceAFIS FP II Guardian for the American Indian Ethnicity (Right) SourceAFIS Crossmatch Seek Avenger for the American Indian Ethnicity	92
Figure 4.43 (Left) SourceAFIS Crossmatch Seek Avenger Rolls for the American Indian Ethnicity (Right) SourceAFIS MorphoMobile for the American Indian Ethnicity	93
Figure A.1.1 (Left) NBIS ANDI Binary (Right) NBIS ANDI Greyscale	117
Figure A.1.2 (Left) NBIS BioSled (Right) NBIS BioSled Rolls.....	118
Figure A.1.3 (Left) NBIS FP II Guardian (Right) NBIS FPII Guardian Rolls.....	118
Figure A.1.4 (Left) NBIS Crossmatch Seek Avenger (Right) NBIS Crossmatch Seek Avenger Rolls	118
Figure A.1.5 (Left) NBIS InnerID (Right) NBIS L1	119
Figure A.1.6 (Left) NBIS L1 Rolls (Right) NBIS Morpho FOTF.....	119
Figure A.1.7 NBIS MorphoMobile.....	119
Figure A.2.1 (Left) Neurotech ANDI Binary (Right) Neurotech ANDI Greyscale	121
Figure A.2.2 (Left) Neurotech BioSled (Right) Neurotech BioSled Rolls.....	121
Figure A.2.3 (Left) Neurotech FP II Guardian (Right) Neurotech FP II Guardian Rolls.....	122
Figure A.2.4 (Left) Neurotech Crossmatch Seek Avenger (Right) Neurotech Crossmatch Seek Avenger Rolls	122
Figure A.2.5 (Left) Neurotech InnerID (Right) Neurotech L1	122
Figure A.2.6 (Left) Neurotech Morpho FOTF (Right) Neurotech MorphoMobile.....	123
Figure A.3.1 (Left) SourceAFIS ANDI Binary (Right) SourceAFIS ANDI Greyscale.....	124
Figure A.3.2 (Left) SourceAFIS BioSled (Right) SourceAFIS BioSled Rolls.....	124
Figure A.3.3 (Left) SourceAFIS FP II Guardian (Right) SourceAFIS FP II Guardian Rolls	125
Figure A.3.4 (Left) SourceAFIS Crossmatch Seek Avenger (Right) SourceAFIS Crossmatch Seek Avenger Rolls.....	125
Figure A.3.5 (Left) SourceAFIS InnerID (Right) SourceAFIS L1	125
Figure A.3.6 (Left) SourceAFIS L1 Rolls (Right) SourceAFIS Morpho FOTF	126
Figure A.3.7 SourceAFIS MorphoMobile	126
Figure A.4.1 (Left) NBIS 10print Rolls – BioSled Rolls (Right) NBIS 10print Rolls - Crossmatch Seek Avenger Rolls.....	128
Figure A.4.2 (Left) NBIS 10print Rolls – FP II Guardian Rolls (Right) NBIS 10print Rolls – L1 Rolls	128
Figure A.4.3 (Left) NBIS 10print – ANDI Binary (Right) NBIS 10print – ANDI Greyscale ...	129

Figure A.4.4 (Left) NBIS 10print – BioSled (Right) NBIS 10print - Crossmatch Seek Avenger	129
Figure A.4.5 (Left) NBIS 10print – FP II Guardian (Right) NBIS 10print – L1	129
Figure A.4.6 (Left) NBIS 10print – Morpho FOTF (Right) NBIS 10print – MorphoMobile	130
Figure A.4.7 (Left) NBIS ANDI Binary – ANDI Greyscale (Right) NBIS ANDI Binary - BioSled	130
Figure A.4.8 (Left) NBIS ANDI Binary – Crossmatch Seek Avenger (Right) NBIS ANDI Binary – FP II Guardian	130
Figure A.4.9 (Left) NBIS ANDI Binary – L1 (Right) NBIS ANDI Binary – Morpho FOTF ...	131
Figure A.4.10 (Left) NBIS ANDI Binary – MorphoMobile (Right) NBIS ANDI Greyscale – BioSled	131
Figure A.4.11 (Left) NBIS ANDI Greyscale – Crossmatch Seek Avenger (Right) NBIS ANDI Greyscale – FP II Guardian	131
Figure A.4.12 (Left) NBIS ANDI Greyscale – L1 (Right) NBIS ANDI Greyscale – Morpho FOTF	132
Figure A.4.13 (Left) NBIS ANDI Greyscale – MorphoMobile (Right) NBIS BioSled Rolls – Crossmatch Seek Avenger Rolls	132
Figure A.4.14 (Left) NBIS BioSled Rolls – FP II Guardian Rolls (Right) NBIS BioSled Rolls – L1 Rolls	132
Figure A.4.15 (Left) NBIS BioSled – Crossmatch Seek Avenger (Right) NBIS BioSled – FP II Guardian	133
Figure A.4.16 (Left) NBIS BioSled – L1 (Right) NBIS BioSled – Morpho FOTF	133
Figure A.4.17 (Left) NBIS BioSled – MorphoMobile (Right) NBIS Crossmatch Seek Avenger Rolls – FP Guardian Rolls	133
Figure A.4.18 (Left) NBIS Crossmatch Seek Avenger Rolls – L1 Rolls (Right) NBIS Crossmatch Seek Avenger – FP II Guardian	134
Figure A.4.19 (Left) NBIS Crossmatch Seek Avenger – L1 (Right) NBIS Crossmatch Seek Avenger – Morpho FOTF	134
Figure A.4.20 (Left) NBIS Crossmatch Seek Avenger – MorphoMobile (Right) NBIS FP II Guardian Rolls – L1 Rolls	135
Figure A.4.21 (Left) NBIS FP II Guardian – L1 (Right) NBIS FP II Guardian – Morpho FOTF	135
Figure A.4.22 (Left) NBIS FP II Guardian – MorphoMobile (Right) NBIS L1 – Morpho FOTF	135
Figure A.4.23 (Left) NBIS L1 – MorphoMobile (Right) NBIS Morpho FOTF – MorphoMobile	136
Figure A.5.1 (Left) Neurotech 10print – ANDI Binary (Right) Neurotech 10print – ANDI Greyscale	138
Figure A.5.2 (Left) Neurotech 10print – BioSled (Right) Neurotech 10print – Crossmatch Seek Avenger	138
Figure A.5.3 (Left) Neurotech 10print – FP II Guardian (Right) Neurotech 10print – L1	139
Figure A.5.4 (Left) Neurotech 10print – Morpho FOTF (Right) Neurotech 10print – MorphoMobile	139
Figure A.5.5 (Left) Neurotech 10print Rolls – BioSled Rolls (Right) Neurotech 10print Rolls – Crossmatch Seek Avenger Rolls	139

Figure A.5.6 (Left) Neurotech 10print Rolls – FP II Guardian Rolls (Right) Neurotech ANDI Binary – ANDI Greyscale.....	140
Figure A.5.7 (Left) Neurotech ANDI Binary – BioSled (Right) Neurotech ANDI Binary – Crossmatch Seek Avenger	140
Figure A.5.8 (Left) Neurotech ANDI Binary – FP II Guardian (Right) Neurotech ANDI Binary – L1	140
Figure A.5.9 (Left) Neurotech ANDI Binary – Morpho FOTF (Right) Neurotech ANDI Binary – MorphoMobile	141
Figure A.5.10 (Left) Neurotech ANDI Greyscale – BioSled (Right) Neurotech ANDI Greyscale – Crossmatch Seek Avenger	141
Figure A.5.11 (Left) Neurotech ANDI Greyscale – FP II Guardian (Right) Neurotech ANDI Greyscale – L1	141
Figure A.5.12 (Left) Neurotech ANDI Greyscale – Morpho FOTF (Right) Neurotech ANDI Greyscale – MorphoMobile	142
Figure A.5.13 (Left) Neurotech BioSled – Crossmatch Seek Avenger (Right) Neurotech BioSled – FP II Guardian.....	142
Figure A.5.14 (Left) Neurotech BioSled – L1 (Right) Neurotech BioSled – Morpho FOTF	142
Figure A.5.15 (Left) Neurotech BioSled – MorphoMobile (Right) Neurotech BioSled Rolls – Crossmatch Seek Avenger Rolls.....	143
Figure A.5.16 (Left) Neurotech BioSled Rolls– FP II Guardian Rolls (Right) Neurotech Crossmatch Seek Avenger – FP II Guardian	143
Figure A.5.17 (Left) Neurotech Crossmatch Seek Avenger – L1 (Right) Neurotech Crossmatch Seek Avenger – Morpho FOTF	144
Figure A.5.18 (Left) Neurotech Crossmatch Seek Avenger – MorphoMobile (Right) Neurotech Crossmatch Seek Avenger Rolls – FP II Guardian Rolls	144
Figure A.5.19 (Left) Neurotech FP II Guardian – L1 (Right) Neurotech FP II Guardian – Morpho FOTF	144
Figure A.5.20 (Left) Neurotech FP II Guardian – MorphoMobile (Right) Neurotech L1 – Morpho FOTF	145
Figure A.5.21 (Left) Neurotech L1 – MorphoMobile (Right) Neurotech L1 Rolls – 10print Rolls	145
Figure A.5.22 (Left) Neurotech L1 Rolls – BioSled Rolls (Right) Neurotech L1 Rolls – Crossmatch Seek Avenger Rolls.....	145
Figure A.5.23 (Left) NeurotechL1 Rolls – FP II Guardian Rolls (Right) Neurotech Morpho FOTF – MorphoMobile	146
Figure A.6.1 (Left) SourceAFIS 10print – ANDI Binary (Right) SourceAFIS 10print – ANDI Greyscale.....	148
Figure A.6.2 (Left) SourceAFIS 10print – BioSled (Right) SourceAFIS 10print - Crossmatch Seek Avenger	148
Figure A.6.3 (Left) SourceAFIS 10print – FP II Guardian (Right) SourceAFIS 10print – L1 ..	149
Figure A.6.4 (Left) SourceAFIS 10print – Morpho FOTF (Right) SourceAFIS 10print – MorphoMobile	149
Figure A.6.5 (Left) SourceAFIS 10print Rolls – BioSled Rolls (Right) SourceAFIS 10print Rolls - Crossmatch Seek Avenger Rolls	149
Figure A.6.6 (Left) SourceAFIS 10print Rolls – FP II Guardian Rolls (Right) SourceAFIS 10print Rolls – L1 Rolls.....	150

Figure A.6.7 (Left) SourceAFIS ANDI Binary – ANDI Greyscale (Right) SourceAFIS ANDI Binary - BioSled	150
Figure A.6.8 (Left) SourceAFIS ANDI Binary – Crossmatch Seek Avenger (Right) SourceAFIS ANDI Binary – FP II Guardian.....	150
Figure A.6.9 (Left) SourceAFIS ANDI Binary – L1 (Right) SourceAFIS ANDI Binary – Morpho FOTF	151
Figure A.6.10 (Left) SourceAFIS ANDI Binary – MorphoMobile (Right) SourceAFIS ANDI Greyscale – BioSled.....	151
Figure A.6.11 (Left) SourceAFIS ANDI Greyscale – Crossmatch Seek Avenger (Right) SourceAFIS ANDI Greyscale – FP II Guardian.....	151
Figure A.6.12 (Left) SourceAFIS ANDI Greyscale – L1 (Right) SourceAFIS ANDI Greyscale – Morpho FOTF	152
Figure A.6.13 (Left) SourceAFIS ANDI Greyscale – MorphoMobile (Right) SourceAFIS BioSled – Crossmatch Seek Avenger	152
Figure A.6.14 (Left) SourceAFIS BioSled – FP II Guardian (Right) BioSled – L1	152
Figure A.6.15 (Left) SourceAFIS BioSled – Morpho FOTF (Right) SourceAFIS BioSled – MorphoMobile	153
Figure A.6.16 (Left) SourceAFIS BioSled Rolls – Crossmatch Seek Avenger Rolls (Right) SourceAFIS BioSled Rolls – FP II Guardian Rolls	153
Figure A.6.17 (Left) SourceAFIS BioSled Rolls – L1 Rolls (Right) SourceAFIS Crossmatch Seek Avenger – FP II Guardian	153
Figure A.6.18 (Left) SourceAFIS Crossmatch Seek Avenger– L1 (Right) SourceAFIS Crossmatch Seek Avenger – Morpho FOTF	154
Figure A.6.19 (Left) SourceAFIS Crossmatch Seek Avenger – MorphoMobile (Right) SourceAFIS Crossmatch Seek Avenger Rolls – FP II Guardian Rolls	154
Figure A.6.20 (Left) SourceAFIS Crossmatch Seek Avenger Rolls – L1 Rolls (Right) SourceAFIS FP II Guardian – L1	155
Figure A.6.21 (Left) SourceAFIS FP II Guardian – Morpho FOTF (Right) SourceAFIS FP II Guardian - MorphoMobile.....	155
Figure A.6.22 (Left) SourceAFIS FP II Guardian Rolls – L1 Rolls (Right) SourceAFIS L1 – Morpho FOTF	155
Figure A.6.23 (Left) SourceAFIS L1 – MorphoMobile (Right) SourceAFIS Morpho FOTF – MorphoMobile	156
Figure A.7.1 NBIS ROC Curves for each device	157
Figure A.7.2 Zoomed In NBIS ROC Curves for each device	158
Figure A.7.3 (Left) NBIS ANDI Binary ROC Curve (Right) NBIS ANDI Greyscale ROC Curve	159
Figure A.7.4 (Left) NBIS BioSled ROC Curve (Right) NBIS BioSled Rolls ROC Curve.....	159
Figure A.7.5 (Left) NBIS FP II Guardian ROC Curve (Right) NBIS FP II Guardian Rolls ROC Curve.....	160
Figure A.7.6 (Left) NBIS Crossmatch Seek Avenger ROC Curve (Right) NBIS Crossmatch Seek Avenger Rolls ROC Curve	160
Figure A.7.7 (Left) NBIS InnerID ROC Curve (Right) NBIS L1 Curve	161
Figure A.7.8 (Left) NBIS L1 Rolls ROC Curve (Right) NBIS Morpho FOTF ROC Curve.....	161
Figure A.7.9 NBIS MorphoMobile ROC Curve.....	162
Figure A.8.1 Neurotech ROC Curves for each Device.....	163

Figure A.8.2 Zoomed In Neurotech ROC Curves for each Device	164
Figure A.8.3 (Left) Neurotech ANDI Binary ROC Curve (Right) Neurotech ANDI Greyscale ROC Curve.....	165
Figure A.8.4 (Left) Neurotech BioSled ROC Curve (Right) Neurotech BioSled Rolls ROC Curve	165
Figure A.8.5 (Left) Neurotech FP II Guardian ROC Curve (Right) Neurotech FP II Guardian Rolls ROC Curve	166
Figure A.8.6 (Left) Neurotech Crossmatch Seek Avenger ROC Curve (Right) Neurotech Crossmatch Seek Avenger Rolls ROC Curve.....	166
Figure A.8.7 (Left) Neurotech InnerID ROC Curve (Right) Neurotech L1 ROC Curve.....	167
Figure A.8.8 (Left) Neurotech Morpho FOTF ROC Curve (Right) Neurotech MorphoMobile ROC Curve.....	167
Figure A.9.1 SourceAFIS ROC Curves For each Device.....	168
Figure A.9.2 Zoomed In SourceAFIS ROC Curves For each Device	169
Figure A.9.3 (Left) SourceAFIS ANDI Binary ROC Curve (Right) SourceAFIS ANDI Greyscale ROC Curve.....	170
Figure A.9.4 (Left) SourceAFIS BioSled ROC Curve (Right) SourceAFIS BioSled Rolls ROC Curve.....	170
Figure A.9.5 (Left) SourceAFIS FP II Guardian ROC Curve (Right) SourceAFIS FP II Guardian Rolls ROC Curve	171
Figure A.9.6 (Left) SourceAFIS Crossmatch Seek Avenger ROC Curve (Right) SourceAFIS Crossmatch Seek Avenger Rolls ROC Curve.....	171
Figure A.9.7 (Left) SourceAFIS InnerID ROC Curve (Right) SourceAFIS L1 ROC Curve.....	172
Figure A.9.8 (Left) SourceAFIS L1 Rolls ROC Curve (Right) SourceAFIS Morpho FOTF ROC Curve.....	172
Figure A.9.9 SourceAFIS MorphoMobile ROC Curve	173
Figure A Minutiae Boxplots For Each Device	176
Figure B.1.1 NBIS ANDI Binary Male (Left) Female (Right).....	179
Figure B.1.2 NBIS ANDI Greyscale Male (Left) Female (Right)	180
Figure B.1.3 NBIS BioSled Male (Left) Female (Right).....	180
Figure B.1.4 NBIS BioSled Rolls Male (Left) Female (Right)	180
Figure B.1.5 NBIS FP II Guardian Male (Left) Female (Right)	181
Figure B.1.6 NBIS FP II Guardian Rolls Male (Left) Female (Right).....	181
Figure B.1.7 NBIS Crossmatch Seek Avenger Male (Left) Female (Right).....	181
Figure B.1.8 NBIS Crossmatch Seek Avenger Rolls Male (Left) Female (Right).....	182
Figure B.1.9 NBIS InnerID Male (Left) Female (Right).....	182
Figure B.1.10 NBIS L1 Male (Left) Female (Right).....	182
Figure B.1.11 NBIS L1 Rolls Male (Left) Female (Right).....	183
Figure B.1.12 NBIS Morpho FOTF Rolls Male (Left) Female (Right)	183
Figure B.1.13 NBIS MorphoMobile Rolls Male (Left) Female (Right).....	183
Figure B.2.1 Neurotech ANDI Binary Male (Left) Female (Right)	185
Figure B.2.2 Neurotech ANDI Greyscale Male (Left) Female (Right).....	185
Figure B.2.3 Neurotech BioSled Male (Left) Female (Right)	185
Figure B.2.4 Neurotech BioSled Rolls Male (Left) Female (Right).....	186
Figure B.2.5 Neurotech FP II Guardian Male (Left) Female (Right).....	186
Figure B.2.6 Neurotech FP II Guardian Rolls Male (Left) Female (Right)	186

Figure B.2.7 Neurotech Crossmatch Seek Avenger Male (Left) Female (Right)	187
Figure B.2.8 Neurotech Crossmatch Seek Avenger Rolls Male (Left) Female (Right)	187
Figure B.2.9 Neurotech InnerID Male (Left) Female (Right)	187
Figure B.2.10 Neurotech L1 Male (Left) Female (Right)	188
Figure B.2.11 Neurotech Morpho FOTF Male (Left) Female (Right)	188
Figure B.2.12 Neurotech MorphoMobile Male (Left) Female (Right)	188
Figure B.3.1 SourceAFIS ANDI Binary Male (Left) Female (Right)	190
Figure B.3.2 SourceAFIS ANDI Greyscale Male (Left) Female (Right)	190
Figure B.3.3 SourceAFIS BioSled Male (Left) Female (Right)	190
Figure B.3.4 SourceAFIS BioSled Rolls Male (Left) Female (Right)	191
Figure B.3.5 SourceAFIS FP II Guardian Male (Left) Female (Right)	191
Figure B.3.6 SourceAFIS FP II Guardian Male (Left) Female (Right)	191
Figure B.3.7 SourceAFIS Crossmatch Seek Avenger Male (Left) Female (Right)	192
Figure B.3.8 SourceAFIS Crossmatch Seek Avenger Rolls Male (Left) Female (Right)	192
Figure B.3.9 SourceAFIS InnerID Male (Left) Female (Right)	192
Figure B.3.10 SourceAFIS L1 Male (Left) Female (Right)	193
Figure B.3.11 SourceAFIS L1 Rolls Male (Left) Female (Right)	193
Figure B.3.12 SourceAFIS Morpho FOTF Male (Left) Female (Right)	193
Figure B.3.13 SourceAFIS MorphoMobile Male (Left) Female (Right)	194
Figure B.4.1 NBIS ANDI Binary Gender ROC Curves (Left) NBIS ANDI Greyscale Gender ROC Curves (Right)	195
Figure B.4.2 NBIS BioSled Gender ROC Curves (Left) NBIS BioSled Rolls Gender ROC Curves (Right)	195
Figure B.4.3 NBIS FP II Guardian Gender ROC Curves (Left) NBIS FP II Guardian Rolls Gender ROC Curves (Right)	196
Figure B.4.4 NBIS Crossmatch Seek Avenger Gender ROC Curves (Left) NBIS Crossmatch Seek Avenger Rolls Gender ROC Curves (Right)	196
Figure B.4.5 NBIS InnerID Gender ROC Curves (Left) NBIS L1 Gender ROC Curves (Right)	197
Figure B.4.6 NBIS L1 Rolls Gender ROC Curves (Left) NBIS Morpho FOTF Gender ROC Curves (Right)	197
Figure B.4.7 NBIS MorphoMobile Gender ROC Curves	198
Figure B.5.1 Neurotech ANDI Binary Gender ROC Curves (Left) Neurotech ANDI Greyscale Gender ROC Curves (Right)	199
Figure B.5.2 Neurotech BioSled Gender ROC Curves (Left) Neurotech BioSled Rolls Gender ROC Curves (Right)	200
Figure B.5.3 Neurotech FP II Guardian Gender ROC Curves (Left) Neurotech FP II Guardian Rolls Gender ROC Curves (Right)	200
Figure B.5.4 Neurotech Crossmatch Seek Avenger Gender ROC Curves (Left) Neurotech Crossmatch Seek Avenger Rolls Gender ROC Curves (Right)	201
Figure B.5.5 Neurotech InnerID Gender ROC Curves (Left) Neurotech L1 Gender ROC Curves (Right)	201
Figure B.5.6 Neurotech Morpho FOTF Gender ROC Curves (Left) Neurotech MorphoMobile Gender ROC Curves (Right)	202
Figure B.6.1 SourceAFIS ANDI Binary Gender ROC Curves (Left) SourceAFIS ANDI Greyscale Gender ROC Curves (Right)	203

Figure B.6.2 SourceAFIS BioSled Gender ROC Curves (Left) SourceAFIS BioSled Rolls Gender ROC Curves (Right).....	204
Figure B.6.3 SourceAFIS FP II Guardian Gender ROC Curves (Left) SourceAFIS FP II Guardian Rolls Gender ROC Curves (Right)	204
Figure B.6.4 SourceAFIS Crossmatch Seek Avenger Gender ROC Curves (Left) SourceAFIS Crossmatch Seek Avenger Gender ROC Curves (Right)	205
Figure B.6.5 SourceAFIS InnerID Gender ROC Curves (Left) SourceAFIS L1 Gender ROC Curves (Right).....	205
Figure B.6.6 SourceAFIS L1 Rolls Gender ROC Curves (Left) SourceAFIS Morpho FOTF Gender ROC Curves (Right).....	206
Figure B.6.7 SourceAFIS MorphoMobile Gender ROC Curves.....	206
Figure B.7.1 Minutiae Box Plot for ANDI Binary by Gender (Left) Minutiae Box Plot for ANDI Greyscale by Gender (Right)	207
Figure B.7.2 Minutiae Box Plot for BioSled by Gender (Left) Minutiae Box Plot for BioSled Rolls by Gender (Right).....	207
Figure B.7.3 Minutiae Box Plot for FP II Guardian by Gender (Left) Minutiae Box Plot for FP II Guardian Rolls by Gender (Right).....	208
Figure B.7.4 Minutiae Box Plot for Crossmatch Seek Avenger by Gender (Left) Minutiae Box Plot for Crossmatch Seek Avenger Rolls by Gender (Right)	208
Figure B.7.5 Minutiae Box Plot for InnerID by Gender (Left) Minutiae Box Plot for L1 by Gender (Right)	209
Figure B.7.6 Minutiae Box Plot for L1 Rolls by Gender (Left) Minutiae Box Plot for Morpho FOTF by Gender (Right)	209
Figure B.7.7 Minutiae Box Plot for MorphoMobile by Gender.....	210
Figure C.1.1 NBIS ANDI Binary (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	216
Figure C.1.2 NBIS ANDI Greyscale (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	217
Figure C.1.3 NBIS BioSled (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	218
Figure C.1.4 NBIS BioSled Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	219
Figure C.1.5 NBIS FP II Guardian (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	220
Figure C.1.6 NBIS FP II Guardian Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	221
Figure C.1.7 NBIS Crossmatch Seek Avenger (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	222
Figure C.1.8 NBIS Crossmatch Seek Avenger Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	223
Figure C.1.9 NBIS InnerID (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	224
Figure C.1.10 NBIS L1 (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	225
Figure C.1.11 NBIS L1 Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	226

Figure C.1.12 NBIS Morpho FOTF (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	227
Figure C.1.13 NBIS MorphoMobile (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	228
Figure C.2.1 Neurotech ANDI Binary (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	231
Figure C.2.2 Neurotech ANDI Greyscale (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	232
Figure C.2.3 Neurotech BioSled (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	233
Figure C.2.4 Neurotech BioSled Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	234
Figure C.2.5 Neurotech FP II Guardian (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	235
Figure C.2.6 Neurotech FP II Guardian Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	236
Figure C.2.7 Neurotech Crossmatch Seek Avenger (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	237
Figure C.2.8 Neurotech Crossmatch Seek Avenger Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	238
Figure C.2.9 Neurotech InnerID (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up (Not Available)	239
Figure C.2.10 Neurotech L1 (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	240
Figure C.2.11 Neurotech Morpho FOTF (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	241
Figure C.2.12 Neurotech MorphoMobile (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	242
Figure C.3.1 SourceAFIS ANDI Binary (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	245
Figure C.3.2 SourceAFIS ANDI Greyscale (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	246
Figure C.3.3 SourceAFIS BioSled (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	247
Figure C.3.4 SourceAFIS BioSled Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	248
Figure C.3.5 SourceAFIS FP II Guardian (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	249
Figure C.3.6 SourceAFIS FP II Guardian Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	250
Figure C.3.7 SourceAFIS Crossmatch Seek Avenger (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	251
Figure C.3.8 SourceAFIS Crossmatch Seek Avenger Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	252
Figure C.3.9 SourceAFIS InnerID (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up.....	253

Figure C.3.10 SourceAFIS L1 (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	254
Figure C.3.11 SourceAFIS L1 Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	255
Figure C.3.12 SourceAFIS Morpho FOTF (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	256
Figure C.3.13 SourceAFIS MorphoMobile (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up	257
Figure C.4.1 NBIS ANDI Binary Age Demographic ROC Curves (Left) NBIS ANDI Greyscale Age Demographic ROC Curves (Right)	260
Figure C.4.2 NBIS BioSled Age Demographic ROC Curves (Left) NBIS BioSled Rolls Age Demographic ROC Curves (Right)	260
Figure C.4.3 NBIS FP II Guardian Age Demographic ROC Curves (Left) NBIS FP II Guardian Rolls Age Demographic ROC Curves (Right)	261
Figure C.4.4 NBIS Crossmatch Seek Avenger Age Demographic ROC Curves (Left) NBIS Crossmatch Seek Avenger Rolls Age Demographic ROC Curves (Right)	261
Figure C.4.5 NBIS InnerID Age Demographic ROC Curves (Left) NBIS L1 Age Demographic ROC Curves (Right)	262
Figure C.4.6 NBIS L1 Rolls Age Demographic ROC Curves (Left) NBIS Morpho FOTF Age Demographic ROC Curves (Right)	262
Figure C.4.7 NBIS MorphoMobile Age Demographic ROC Curves	263
Figure C.5.1 Neurotech ANDI Binary Age Demographic ROC Curves (Left) Neurotech ANDI Greyscale Age Demographic ROC Curves (Right)	266
Figure C.5.2 Neurotech BioSled Age Demographic ROC Curves (Left) Neurotech BioSled Rolls Age Demographic ROC Curves (Right)	266
Figure C.5.3 Neurotech FP II Guardian Age Demographic ROC Curves (Left) Neurotech FP II Guardian Rolls Age Demographic ROC Curves (Right)	267
Figure C.5.4 Neurotech Crossmatch Seek Avenger Age Demographic ROC Curves (Left) Neurotech Crossmatch Seek Avenger Rolls Age Demographic ROC Curves (Right)	267
Figure C.5.5 Neurotech L1 Age Demographic ROC Curves (Left) Neurotech Morpho FOTF Age Demographic ROC Curves (Right)	268
Figure C.5.6 Neurotech MorphoMobile Age Demographic ROC Curves	268
Figure C.6.1 SourceAFIS ANDI Binary Age Demographic ROC Curves (Left) SourceAFIS ANDI Greyscale Age Demographic ROC Curves (Right)	271
Figure C.6.2 SourceAFIS BioSled Age Demographic ROC Curves (Left) SourceAFIS BioSled Rolls Age Demographic ROC Curves (Right)	271
Figure C.6.3 SourceAFIS FP II Guardian Age Demographic ROC Curves (Left) SourceAFIS FP II Guardian Rolls Age Demographic ROC Curves (Right)	272
Figure C.6.4 SourceAFIS Crossmatch Seek Avenger Age Demographic ROC Curves (Left) SourceAFIS Crossmatch Seek Avenger Age Demographic ROC Curves (Right)	272
Figure C.6.5 SourceAFIS InnerID Age Demographic ROC Curves (Left) SourceAFIS L1 Age Demographic ROC Curves (Right)	273
Figure C.6.6 SourceAFIS L1 Rolls Age Demographic ROC Curves (Left) SourceAFIS Morpho FOTF Age Demographic ROC Curves (Right)	273
Figure C.6.7 SourceAFIS MorphoMobile Age Demographic ROC Curves	274
Figure C.7.1 (Left)AND Binary Box Plot (Right) ANDI Greyscale Box Plot	275

Figure C.7.2 (Left) BioSled Rolls Box Plot (Right) BioSled Box Plot	275
Figure C.7.3 (Left)FP II Guardian Rolls Box Plot (Right) FP II Guardian Box Plot.....	276
Figure C.7.4 (Left)Crossmatch Seek Avenger Rolls Box Plot (Right) Crossmatch Seek Avenger Box Plot	276
Figure C.7.5 (Left)InnerID Box Plot (Right) L1 Rolls Box Plot.....	277
Figure C.7.6 (Left)L1 Box Plot (Right) Morpho FOTF Box Plot	277
Figure C.7.7 MorphoMobile Box Plots	278
Figure D.1.1 NBIS ANDI Binary (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	286
Figure D.1.2 NBIS ANDI Greyscale (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	287
Figure D.1.3 NBIS BioSled (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other.....	288
Figure D.1.4 NBIS BioSled Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	289
Figure D.1.5 NBIS FP II Guardian (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	290
Figure D.1.6 NBIS FP II Guardian Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	291
Figure D.1.7 NBIS Crossmatch Seek Avenger (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	292
Figure D.1.8 Crossmatch Seek Avenger Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	293
Figure D.1.9 NBIS InnerID (a) African (b) African American (c) American Indian (Not Available due to InnerID being removed from collection midway through) (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other.....	294
Figure D.1.10 NBIS L1 (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other.....	295
Figure D.1.11 L1 Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other.....	296
Figure D.1.12 NBIS Morpho FOTF (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other.....	297
Figure D.1.13 NBIS MorphoMobile (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	298
Figure D.2.1 Neurotech ANDI Binary (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	304
Figure D.2.2 Neurotech ANDI Greyscale (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	305
Figure D.2.3 Neurotech BioSled (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	306
Figure D.2.4 Neurotech BioSled Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	307
Figure D.2.5 Neurotech FP II Guardian (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	308

Figure D.2.6 Neurotech FP II Guardian Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	309
Figure D.2.7 Neurotech Crossmatch Seek Avenger (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	310
Figure D.1.8 Neurotech Crossmatch Seek Avenger Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	311
Figure D.2.9 Neurotech InnerID (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	312
(Some Results aren't shown because of this device's low quality images and stopping operation midway through collection)	312
Figure D.2.10 Neurotech L1 (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	313
Figure D.2.11 Neurotech Morpho FOTF (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	314
(This device had trouble capturing darker complexions and the Neurotech matcher removed images that were not up to a certain quality so that is why this device could not show distributions for the ethnicities African and African American.	314
Figure D.2.12 Neurotech MorphoMobile (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	315
Figure D.3.1 SourceAFIS ANDI Binary (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	321
Figure D.3.2 SourceAFIS ANDI Greyscale (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	322
Figure D.3.3 SourceAFIS BioSled (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	323
Figure D.3.4 SourceAFIS BioSled Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	324
Figure D.3.5 SourceAFIS FP II Guardian (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	325
Figure D.3.6 SourceAFIS FP II Guardian Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	326
Figure D.3.7 SourceAFIS Crossmatch Seek Avenger (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	327
Figure D.3.8 Crossmatch Seek Avenger Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	328
Figure D.3.9 SourceAFIS InnerID (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	329
Figure D.3.10 SourceAFIS L1 (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	330

Figure D.3.11 SourceAFIS L1 Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	331
Figure D.3.12 SourceAFIS Morpho FOTF (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	332
Figure D.3.13 SourceAFIS MorphoMobile (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other	333
Figure D.4.1 NBIS ANDI Binary Ethnicity Based ROC Curves	334
Figure D.4.2 NBIS ANDI Greyscale Ethnicity Based ROC Curves	335
Figure D.4.3 NBIS BioSled Ethnicity Based ROC Curves	335
Figure D.4.4 NBIS BioSled Rolls Ethnicity Based ROC Curves	336
Figure D.4.5 NBIS FP II Guardian Ethnicity Based ROC Curves	336
Figure D.4.6 NBIS FP II Guardian Rolls Ethnicity Based ROC Curves	337
Figure D.4.7 NBIS Crossmatch Seek Avenger Ethnicity Based ROC Curves	337
Figure D.4.8 NBIS Crossmatch Seek Avenger Rolls Ethnicity Based ROC Curves	338
Figure D.4.9 NBIS InnerID Ethnicity Based ROC Curves	338
Figure D.4.10 NBIS L1 Ethnicity Based ROC Curves	339
Figure D.4.11 NBIS L1 Rolls Ethnicity Based ROC Curves	339
Figure D.4.12 NBIS Morpho FOTF Ethnicity Based ROC Curves	340
Figure D.4.13 NBIS MorphoMobile Ethnicity Based ROC Curves	340
Figure D.5.1 Neurotech ANDI Binary Ethnicity Based ROC Curves	341
Figure D.5.2 Neurotech ANDI Greyscale Ethnicity Based ROC Curves	342
Figure D.5.3 Neurotech BioSled Ethnicity Based ROC Curves	342
Figure D.5.4 Neurotech BioSled Rolls Ethnicity Based ROC Curves	343
Figure D.5.5 Neurotech FP II Guardian Ethnicity Based ROC Curves	343
Figure D.5.6 Neurotech FP II Guardian Rolls Ethnicity Based ROC Curves	344
Figure D.5.7 Neurotech Crossmatch Seek Avenger Ethnicity Based ROC Curves	344
Figure D.5.8 Neurotech Crossmatch Seek Avenger Rolls Ethnicity Based ROC Curves	345
Figure D.5.9 Neurotech InnerID Ethnicity Based ROC Curves	345
Figure D.5.10 Neurotech L1 Ethnicity Based ROC Curves	346
Figure D.5.11 Neurotech Morpho FOTF Ethnicity Based ROC Curves	346
Figure D.5.12 Neurotech MorphoMobile Ethnicity Based ROC Curves	347
Figure D.6.1 SourceAFIS ANDI Binary Ethnicity Based ROC Curves	349
Figure D.6.2 SourceAFIS ANDI Greyscale Ethnicity Based ROC Curves	349
Figure D.6.3 SourceAFIS BioSled Ethnicity Based ROC Curves	350
Figure D.6.4 SourceAFIS BioSled Rolls Ethnicity Based ROC Curves	350
Figure D.6.5 SourceAFIS FP II Guardian Ethnicity Based ROC Curves	351
Figure D.6.6 SourceAFIS FP II Guardian Rolls Ethnicity Based ROC Curves	351
Figure D.6.7 SourceAFIS Crossmatch Seek Avenger Ethnicity Based ROC Curves	352
Figure D.6.8 SourceAFIS Crossmatch Seek Avenger Rolls Ethnicity Based ROC Curves	352
Figure D.6.9 SourceAFIS InnerID Ethnicity Based ROC Curves	353
Figure D.6.10 SourceAFIS L1 Ethnicity Based ROC Curves	353
Figure D.6.11 SourceAFIS L1 Rolls Ethnicity Based ROC Curves	354
Figure D.6.12 SourceAFIS Morpho FOTF Ethnicity Based ROC Curves	354
Figure D.6.13 SourceAFIS MorphoMobile Ethnicity Based ROC Curves	355
Figure D.7.1 ANDI Binary Ethnicity Based Minutiae Box Plots	356

Figure D.7.2 ANDI Greyscale Ethnicity Based Minutiae Box Plots.....	357
Figure D.7.3 BioSled Ethnicity Based Minutiae Box Plots.....	357
Figure D.7.4 BioSled Rolls Ethnicity Based Minutiae Box Plots	358
Figure D.7.5 FP II Guardian Ethnicity Based Minutiae Box Plots.....	358
Figure D.7.6 FP II Guardian Rolls Ethnicity Based Minutiae Box Plots	359
Figure D.7.7 Crossmatch Seek Avenger Ethnicity Based Minutiae Box Plots	359
Figure D.7.8 Crossmatch Seek Avenger Rolls Ethnicity Based Minutiae Box Plots.....	360
Figure D.7.9 InnerID Ethnicity Based Minutiae Box Plots	360
Figure D.7.10 L1 Ethnicity Based Minutiae Box Plots	361
Figure D.7.11 L1 Rolls Ethnicity Based Minutiae Box Plots.....	361
Figure D.7.12 Morpho FOTF Ethnicity Based Minutiae Box Plots	362
Figure D.7.13 MorphoMobile Ethnicity Based Minutiae Box Plots	362

List of Tables

Table 1.1 Advantages and Disadvantages to Contact-Based Fingerprinting.....	14
Table 1.2: Advantages and Disadvantages to Contactless Fingerprinting.....	15
Table 1.3: Contactless Devices with the devices used in this research project highlighted in red [1].....	19
Table 3.1 Fingerprint device details [2].....	46
Table 4.1 Device Abbreviations	58
Table 4.2 ManTech Table Comparison to Thesis Results	58
Table 4.3 NBIS TMR1 Table.....	60
Blue shading = Contactless vs Contactless, Orange Shading = Contactless vs Contact-Based, Green shading = Contact vs Contact	60
Table 4.4 Neurotech TMR1 Table	61
Blue shading = Contactless vs Contactless, Orange Shading = Contactless vs Contact-Based, Green shading = Contact vs Contact.....	61
Table 4.5 SourceAFIS TMR1 Table	62
Blue shading = Contactless vs Contactless, Orange Shading = Contactless vs Contact-Based, Green shading = Contact vs Contact.....	62
Table 4.6 NBIS Rolls TMR1 Table	63
Table 4.7 Neurotech Rolls TMR1 Table.....	64
Table 4.8 SourceAFIS Rolls TMR1 Table	64
Table 4.9 NBIS Gender Based KLD Values	82
Table 4.10 Neurotech Gender Based KLD Values.....	82
Table 4.11 SourceAFIS Gender Based KLD Values.....	83
Table 4.12 NBIS Age-Based KLD Values	87
Table 4.13 Neurotech Age-Based KLD Values.....	87
Table 4.14 SourceAFIS Age-Based KLD Values.....	88
Table 4.15 African Ethnicity KLD	94
Table 4.16 African Ethnicity KLD	94
Table 4.17 African American Ethnicity KLD.....	95
Table 4.18 American Indian Ethnicity KLD.....	96
Table 4.19 Asian Ethnicity KLD	97
Table 4.20 Asian Indian Ethnicity KLD.....	98
Table 4.21 Caucasian Ethnicity KLD	99
Table 4.22 Hispanic Ethnicity KLD	99
Table 4.23 Middle Eastern Ethnicity KLD	100
Table 4.24 Other Ethnicity KLD	100
Table 5.1 TMR1 Ranges by Matcher.....	105
Table 5.2 Range of TMR1 Rates between Matchers	106
Table 5.3 Equal Error Rates for Each Matching Run	108
Table 5.4 Equal Error Rates For Each Device.....	109
Table 5.5 Equal Error Rates For Each Rolled Matching Run.....	109
Table A.1 NBIS TMR1 Table.....	113
Table A.2 Neurotech TMR1 Table	114
Table A.3 SourceAFIS TMR1 Table	115
Table A.4 NBIS Rolls TMR1 Table	116

Table A.5 Neurotech Rolls TMR1 Table.....	116
Table A.6 SourceAFIS Rolls TMR1 Table.....	116
Table A.7 NBIS Maximum and Minimum Score Values.....	117
Table A.8 Neurotech Maximum and Minimum Score Values.....	120
Table A.9 SourceAFIS Maximum and Minimum Score Values.....	123
Table A.10 NBIS Cross-Examined Maximum and Minimum Score Values.....	127
Table A.11 Neurotech Cross-Examined Maximum and Minimum Score Values.....	137
Table A.12 SourceAFIS Cross-Examined Maximum and Minimum Score Values.....	147
Table A.13 NBIS Area Under the Curve for ROC graphs.....	158
Table A.14 Neurotech Area Under the Curve for ROC graphs.....	164
Table A.15 SourceAFIS Area Under the Curve for ROC graphs.....	169
Table A.16 Equal Error Rates for Each Matching Run.....	174
Table A.17 Equal Error Rates For Each Device.....	175
Table A.18 Equal Error Rates For Each Rolled Matching Run.....	175
Table B.1 NBIS Male Genuine and Imposter KLD, Minimum and Maximum Scores.....	178
Table B.2 NBIS Female Genuine and Imposter KLD, Minimum and Maximum Scores.....	179
Table B.3 Neurotech Male Genuine and Imposter KLD, Minimum and Maximum Scores.....	184
Table B.4 Neurotech Female Genuine and Imposter KLD, Minimum and Maximum Scores ..	184
Table B.5 SourceAFIS Male Genuine and Imposter KLD, Minimum and Maximum Scores...	189
Table B.6 SourceAFIS Female Genuine and Imposter KLD, Minimum and Maximum Scores	189
Table B.7 NBIS Area Under the Curve for ROC Plots.....	194
Table B.8 Neurotech Area Under the Curve for ROC Plots.....	199
Table B.9 SourceAFIS Area Under the Curve for ROC Plots.....	203
Table B.10 NBIS Gender Based EER Values.....	210
Table B.11 Neurotech Gender Based EER Values.....	211
Table B.12 SourceAFIS Gender Based EER Values.....	211
Table C.1 NBIS 18-19 Genuine and Imposter KLD, Minimum and Maximum Scores.....	213
Table C.2 NBIS 20-29 Genuine and Imposter KLD, Minimum and Maximum Scores.....	214
Table C.3 NBIS 30-39 Genuine and Imposter KLD, Minimum and Maximum Scores.....	214
Table C.4 NBIS 40 and up Genuine and Imposter KLD, Minimum and Maximum Scores.....	215
Table C.5 Neurotech 18-19 Genuine and Imposter KLD, Minimum and Maximum Scores.....	229
Table C.6 Neurotech 20-29 Genuine and Imposter KLD, Minimum and Maximum Scores.....	229
Table C.7 NBIS 30-39 Genuine and Imposter KLD, Minimum and Maximum Scores.....	230
Table C.8 NBIS 40 and up Genuine and Imposter KLD, Minimum and Maximum Scores.....	230
Table C.9 SourceAFIS 18-19 Genuine and Imposter KLD, Minimum and Maximum Scores..	243
Table C.10 SourceAFIS 20-29 Genuine and Imposter KLD, Minimum and Maximum Scores	243
Table C.11 SourceAFIS 30-39 Genuine and Imposter KLD, Minimum and Maximum Scores	244
Table C.12 SourceAFIS 40 and up Genuine and Imposter KLD, Minimum and Maximum Scores	244
Table C.13 NBIS 18-19 Area under Curve.....	258
Table C.14 NBIS 20-29 Area under Curve.....	258
Table C.15 NBIS 30-39 Area under Curve.....	259
Table C.16 NBIS 40 and up Area under Curve.....	259
Table C.17 Neurotech 18-19 Area under Curve.....	263
Table C.18 Neurotech 20-29 Area under Curve.....	264
Table C.19 Neurotech 30-39 Area under Curve.....	264

Table C.20 Neurotech 40 and up Area under Curve.....	265
Table C.21 SourceAFIS 18-19 Area under Curve.....	269
Table C.22 SourceAFIS 20-29 Area under Curve.....	269
Table C.23 SourceAFIS 30-39 Area under Curve.....	270
Table C.24 SourceAFIS 40 and up Area under Curve.....	270
Table C.25 NBIS Equal Error Rates For Age Based Study.....	278
Table C.26 Neurotech Equal Error Rates For Age Based Study	279
Table C.27 SourceAFIS Equal Error Rates For Age Based Study	279
Table D.1 NBIS African Genuine and Imposter KLD, Maximum and Minimum Scores	281
Table D.2 NBIS African American Genuine and Imposter KLD, Maximum and Minimum Scores	282
Table D.3 NBIS American Indian Genuine and Imposter KLD, Maximum and Minimum Scores	282
Table D.4 NBIS Asian Genuine and Imposter KLD, Maximum and Minimum Scores	283
Table D.5 NBIS Asian Indian Genuine and Imposter KLD, Maximum and Minimum Scores	283
Table D.6 NBIS Caucasian Genuine and Imposter KLD, Maximum and Minimum Scores	284
Table D.7 NBIS Hispanic Genuine and Imposter KLD, Maximum and Minimum Scores	284
Table D.8 NBIS Middle Eastern Genuine and Imposter KLD, Maximum and Minimum Scores	285
Table D.9 NBIS Other Genuine and Imposter KLD, Maximum and Minimum Scores	285
Table D.10 Neurotech African Genuine and Imposter KLD, Maximum and Minimum Scores	299
Table D.11 Neurotech African American Genuine and Imposter KLD, Maximum and Minimum Scores	299
Table D.12 Neurotech American Indian Genuine and Imposter KLD, Maximum and Minimum Scores	300
Table D.13 Neurotech Asian Genuine and Imposter KLD, Maximum and Minimum Scores	300
Table D.14 Neurotech Asian Indian Genuine and Imposter KLD, Maximum and Minimum Scores	301
Table D.15 Neurotech Caucasian Genuine and Imposter KLD, Maximum and Minimum Scores	301
Table D.16 Neurotech Hispanic Genuine and Imposter KLD, Maximum and Minimum Scores	302
Table D.17 Neurotech Middle Eastern Genuine and Imposter KLD, Maximum and Minimum Scores	302
Table D.18 Neurotech Other Genuine and Imposter KLD, Maximum and Minimum Scores	303
Table D.19 SourceAFIS African Genuine and Imposter KLD, Maximum and Minimum Scores	316
Table D.20 SourceAFIS African American Genuine and Imposter KLD, Maximum and Minimum Scores	316
Table D.21 SourceAFIS American Indian Genuine and Imposter KLD, Maximum and Minimum Scores	317
Table D.22 SourceAFIS Asian Genuine and Imposter KLD, Maximum and Minimum Scores	317
Table D.23 SourceAFIS Asian Indian Genuine and Imposter KLD, Maximum and Minimum Scores	318
Table D.24 SourceAFIS Caucasian Genuine and Imposter KLD, Maximum and Minimum Scores	318

Table D.25 SourceAFIS Hispanic Genuine and Imposter KLD, Maximum and Minimum Scores	319
Table D.26 SourceAFIS Middle Eastern Genuine and Imposter KLD, Maximum and Minimum Scores	319
Table D.27 SourceAFIS Other Genuine and Imposter KLD, Maximum and Minimum Scores	320
Table D.28 NBIS Area Under Curve for Each Ethnicity	334
Table D.29 Neurotech Area Under Curve for Each Ethnicity	341
Table D.30 SourceAFIS Area Under Curve for Each Ethnicity	348

Chapter 1:

Introduction

1.1 Executive Summary

Fingerprints have been used as a biometric identifier for decades due to a high degree of uniqueness, even among large populations. Fingerprint technologies have evolved significantly since the early days of fingerprinting. Starting with wet-ink ten-print cards, to the digitizing of these cards, then livescan devices, arriving at the present situation of contactless fingerprinting devices, fingerprinting has developed consistently to become one of the most used forms of identification. The two most widely used methods of collecting fingerprints are wet-ink and livescan devices. The wet-ink technique requires the subject to cover their fingers in ink with a trained individual subsequently pressing and rolling their prints onto a ten-print card. Livescan devices omit the use of ink and other materials, requiring the user to roll and press their fingers against a platen to acquire their fingerprint information. Both of these techniques have drawbacks inherent to the contact-based nature of these methods.

Although the fingerprint scanners that are primarily used in civil, law enforcement and military applications are mature technologies, there still exists challenges in operational scenarios, including contamination from previous user, inconsistencies due to operator error, low throughput, distortion due to uncontrollable pressure used by individuals, and inability to capture prints from decomposed flesh of deceased individuals. These issues can be drastically reduced or eliminated by the use of non-contact fingerprinting devices. Contactless fingerprinting devices allow for forensics analysts to be able to capture the prints from deceased individuals without the possibility of decomposed flesh being disturbed. Contactless devices can potentially offer equal or higher quality images (compared to traditional contact-based livescan), faster capture times, less operator training, reduced likelihood of the spread of contaminants, and unattended fingerprint collection.

Contactless devices still have some issues that need to be addressed before they can be widely used. Standardization of these technologies pose one of the biggest challenges that face contactless devices. Standardizing these devices comes with a high level of difficulty due to the many ways that a print can be captured without contact. Proving that contactless devices are fully backwards compatible with the images produced by previous contact-based devices or methods is extremely crucial to the advancement of these technologies. NIST is leading efforts in standardizing these kinds of devices by creating the CRADA program, also known as the Contactless Fingerprint Capture Device Measurement Research Program, which builds upon the NIST's research in developing methodologies for measuring the image fidelity of contactless fingerprint capture devices. Another important factor in creating contactless technology is the presence of interoperability challenges, including edge detection, lack of deformation, and three-dimensional image unwrapping. Additionally, the technology involved in contactless imaging generally has a higher cost than well-established contact-based sensors.

The goal of the research described herein is to investigate the interoperability and matching performance of contact and contactless fingerprint scanners. This data used in this research project was collected in Phase 2 of a Non-Contact Fingerprint Evaluation project sponsored by ManTech International Corp. and the U.S. Dept. of Justice. The collection took place between December 2014 and April 2015 with 450 participants providing data (IRB #1309097716). Rolled-ink fingerprint cards were collected, as well as commercial and prototype contactless and contact-based fingerprint devices. For this research effort, fingerprint data was evaluated from wet-ink ten-print cards and traditional contact-based legacy fingerprint devices versus fingerprint data generated by next-generation contactless fingerprint scanners. The feasibility and performance of contactless fingerprint databases was investigated. To investigate

the matching performance and interoperability of these devices three different matching algorithms were utilized, including Neurotechnology MegaMatcher, open source NIST Biometric Image Software (NBIS) and open source fingerprint recognition toolkit by SourceAFIS. Matching runs were performed on the right index finger and thumb data from each device against themselves and all other devices, as well as the 500 dpi scans from the wet-ink fingerprint cards. Matching runs were also evaluated for genuine and imposter match score distributions. The stratifications of gender, ethnicity, and age for contactless and contact-based devices was also investigated. Based on this snapshot during the development of contactless fingerprints, Rank1 accuracy is between 74.33 and 98.68 percent with contact based methods. The Rank 1 accuracy is between 74.66 and 97.27 percent with other contactless devices.

1.2 Contactless Fingerprinting

Quickly identifying a person by waving their hand in front of a scanner could seem futuristic, but this is exactly what contactless fingerprinting devices do. Contactless fingerprinting devices can capture all fingers on one hand in one quick motion instead of the minutes that it can take on some traditional contact-based scanners or wet-ink cards. Non-contact fingerprinting is quite self-explanatory as it is capturing images of fingerprints without making contact with a device or surface. This capture can be accomplished in many ways with many different cameras and techniques. Contactless fingerprinting technology aims to speed up the process of authorizing access through high-traffic areas such as border controls, airports, and access control points.

1.3 Methods of fingerprinting

There are currently two other widely used techniques to acquire fingerprint images, wet-ink and livescan. The wet-ink method requires a subject to cover their fingers in ink with an individual/operator to aid them in pressing and rolling their prints onto a ten-print fingerprint card. This method requires materials to be replaced by the operator, and clean-up for both the subject and operator. The issues of clean-up and materials are addressed by livescan devices but these sensors still require an individual to press or roll their fingers against a platen to acquire the fingerprint information. Livescan technologies mimic the method of wet-ink ten-print cards, producing flat images of the three-dimensional finger [1]. An example of a livescan capture is shown in Figure 1.3. Both of these techniques create distortions of the three-dimensional fingerprint, whereas contactless devices create an image without any distortions due to pressure or other contact-based factors.

Figure 1.1 Blank Ten-print Card

LEAVE BLANK		CRIMINAL		(STAPLE HERE)				LEAVE BLANK			
STATE USAGE		STATE USAGE		☐		☐		☐		LEAVE BLANK	
		NIF SECOND		SUBMISSION		APPROXIMATE CLASS		AMPUTATION			
SIGNATURE OF PERSON FINGERPRINTED		SOCIAL SECURITY NO.		LAST NAME, FIRST NAME, MIDDLE NAME, SUFFIX							
ALIASES/MAIDEN LAST NAME, FIRST NAME, MIDDLE NAME, SUFFIX											
FBI NO.	STATE IDENTIFICATION NO.	DATE OF BIRTH	MM	DD	YY	SEX	RACE	HEIGHT	WEIGHT	EYES	HAIR
1. R. THUMB		2. R. INDEX		3. R. MIDDLE		4. R. RING		5. R. LITTLE			
6. L. THUMB		7. L. INDEX		8. L. MIDDLE		9. L. RING		10. L. LITTLE			
LEFT FOUR FINGERS TAKEN SIMULTANEOUSLY				L. THUMB		R. THUMB		RIGHT FOUR FINGERS TAKEN SIMULTANEOUSLY			

Figure 1.2 Ten print card with fingerprints

Figure 1.3 Example of Livescan Fingerprint Capture [2]

1.4 Hurdles in Fingerprint Identification

Fingerprint Identification has overcome numerous hurdles to get to the mature level of technology that we have now. The first standardized way to identify persons by their fingerprints was through wet-ink ten-print cards. These, as stated above are messy, and require properly trained personnel to accurately collect fingerprint images that are not smudged or blurred. These physical cards were sufficient until other agencies outside of the FBI needed them, which brought about the need for digitization of these cards into electronic fingerprint transmission files or EFTs, to easily share these files between different agencies or law enforcement offices. Digitization of these cards refers to the scanning of ten-print cards with FBI certified scanners to meet the required compliance with the FBI's EFTS IQS (Electronic Fingerprint Transmission Specification – Image Quality Specification) [3]. EFTS IQS requires a standard to be met when working with ten-print cards so that different agencies can share and utilize files. After

successful adaption of standards and digitization of ten-print cards, livescan devices were developed which acquire fingerprints digitally to eliminate the process of scanning ten-print cards in to digitize them. Livescan devices make for a much quicker transaction with less cleanup and materials than wet ink prints, but these devices still create distortions due to pressure against a flat surface. Livescan devices can employ a number of sensing mechanisms, including but not limited to: optical, capacitive, thermal, pressure-based, and ultrasound, although some of these methods do not provide images that contain the same representation of detail necessary for some latent fingerprint comparisons [4]. These devices are still being used today in the majority of establishments, but technology has advanced favorably whereby devices can be created that can acquire fingerprints without making any contact with the hand, eliminating distortion from pressure. The final hurdle to address is the issue of interoperability between devices of contact-based nature with contactless fingerprinting devices. Interoperability is the characteristic of a device or system to communicate, exchange data, and use the information that has been exchanged [5]. For this effort, interoperability is a term used to show that images of the same subject's print from contactless and contact-based devices are comparable and will produce a match.

1.5 Fingerprint Recognition

Fingerprint recognition or fingerprint authentication is the procedure of verifying a match between two fingerprints. There are three different styles of fingerprint matching: pattern-based (or Image-based) matching, correlation based matching, and minutiae matching. Pattern-based matching compares the similarities of two images, often used for determining if there are duplicates. Correlation based matching involves aligning two fingerprint images and computing the correlation for each corresponding pixel, for all possible alignments [6]. Minutiae matching

is primarily based on the comparison of features of the fingerprint minutiae pattern location and direction. The three basic fingerprint patterns that happen in fingerprint ridges are an arch, loop, and whorl, loops are sometimes classified by right or left [7]. An arch is a pattern where the ridges enter from one side of the finger, rise in the center forming an arc, and then exit the other side of the finger [8] [9]. A loop is where the ridges enter from one side of the finger, form a curve and then exit on the same side [8] [9]. A whorl is when ridges form circularly around a central point on the finger. [8] [9]

Figure 1.4: Ridge Patterns [9]

An AFIS, or Automated Fingerprint Identification System, is designed to interpret the flow of overall ridges to assign a fingerprint classification and then extract the minutiae detail [10]. The detail extracted is a subset of the total amount of information available, but enough information to search a large repository effectively [11]. AFIS systems are the primary identification tool for most law enforcement agencies in the United States and the rest of the world [10].

1.6 Minutiae

An important feature of fingerprints are minutiae. Minutiae are the major features of fingerprints that are used to compare one fingerprint to another. The different types of minutiae include core, delta, crossover or bridge, spur, ridge enclosure, island, short ridge, ridge bifurcation, and ridge ending. Minutiae are the basis upon which the matching template is formed. The precise locations of the minutiae are recorded as numerical spatial (x and y) coordinates, for each fingerprint image. The orientation of the minutiae are also recorded as vector angles which denote the direction of each minutia characteristic (shown in Figure 1.6). It is important to note that minutiae identified by human fingerprint examiners can vary from those identified by an automated system [12].

Figure 1.5: (Left) Fingerprint Minutiae types [13] (Right) Fingerprint minutiae marked by location and orientation [14]

1.7 Advantages and Disadvantages of Contact and Contactless Fingerprinting

Traditional fingerprint devices and wet-ink ten-print cards, though being implemented and used for decades, still have many disadvantages which were the motivation for the development of contactless sensors. Wet-ink ten-print cards require operators to have a moderate amount of training and even with training, the same subject's prints can come out completely different in two different collection attempts. Different operators can change the outcome as well. With the contact-based style of traditional scanners, hygiene can be a major issue [15] [16] [17]. With many hands all touching one scanner, it's practically impossible to keep the scanner clean and disinfected while still moving subjects through in a timely manner. To the same degree, oils can be left on the scanning surface, which can distort the next subject's prints [15] [16] [18] [19]. Additionally, in applications where fingerprint scanners are used, such as border controls and airports, diseases and/or viruses could potentially contaminate scanners and spread quickly with every person passing through touching this device. The next biggest issue is that the contact made and pressure used by the subject is uncontrollable [16] [20] [21] [22]. Since pressure used is uncontrollable, prints from the same person captured at two different times can look completely different [23]. Some traditional scanners cannot collect fingers that are extremely dry, wrinkly, or very scarred and worn fingers [15] [22] [24]. The elasticity of skin is also uncontrollable with temperature, hydration and genetics, changing the elasticity of each subject's skin [25] [26]. Contact-based scanners can be an inconvenience to capture images from a forensics standpoint when it comes to skin degradation. Contactless fingerprinting devices allow for forensics analysts to be able to capture the prints from deceased individuals without the possibility of decomposed flesh being disturbed. Another problem with contact-based devices is

the operator needing to invade the subject's personal space to show or help them roll their prints. Along with this issue arises the problem of training operators. Training operators for contactless devices is very minimal compared to contact-based devices. All the issues discussed above can be solved or at least improved with non-contact fingerprint devices. Additionally, contactless devices capture equal or higher quality images (compared to traditional contact-based livenesscan), with faster capture times. Some contactless devices do not require a human operator at all and they drastically reduce spread of contaminants.

Figure 1.6: Images of various finger conditions: (a) normal finger; (b) dry finger; (c) wet finger; (d) poor quality finger. [27]

Table 1.1 Advantages and Disadvantages to Contact-Based Fingerprinting

Advantages and Disadvantages to Contact-Based Fingerprinting	
Advantages	Disadvantages
Technology is cheaper than that of contactless devices	Operator Training Required
Images created have deformation, increasing the compatibility with databases already in use.	Inability to capture dry, wrinkly, worn, and scarred prints
Mature Technologies	Clean up required for each participant
	Materials Needed (Ten-prints)
	Uncontrollable Amount of Pressure
	Residue/Contamination from prior subjects
	Inability or difficulty capturing forensics data

1.8 Challenges involved with Contactless Fingerprint technology

Contactless fingerprint scanners are significantly different from contact-based scanners. Therefore, images produced by contactless devices are fundamentally different from conventional scanned wet-ink ten-print cards and livescan fingerprints, which creates the problem of recognition between devices and prints. The technology needed to produce contactless devices tends to be costly. Though contactless scanners capture true un-deformed images of the finger, it's a detriment because no existing livescan or touch-based fingerprint database is absent of this deformation, creating perhaps the biggest challenge for interoperability [20] [28]. All things equal (cost being irrelevant for comparison), in a 1-to-1 comparison, same resolution, contrast, and quality, an image from a contactless device will never have the deformation that a contact-based image will, which poses the issue of interoperability [29]. A possible fix to this problem could be a measurement/estimation of deformation due to contact [30]. Images created by contactless devices must be backwards compatible with the deformed images created by contact-based fingerprinting. Sometimes the images created by contactless

devices can be three-dimensional. If so, an algorithm must be applied that unwraps the three-dimensional image into a two-dimensional image for compatibility [20].

Figure 1.7: Visualizing compatibility between (a) a touchless fingerprint from line-scan sensor using the proposed nonparametric unwrapping (b) the corresponding ink-on-paper rolled fingerprint. [31]

Table 1.2: Advantages and Disadvantages to Contactless Fingerprinting

Advantages and Disadvantages to Contactless Fingerprinting	
Advantages	Disadvantages
Hygienically Sound	Lack of Deformation
Operator Training reduced	Cost
Ability to capture forensics data	3D Image Unwrapping
Pressure is irrelevant	Edge Detection
Ability to capture dry, wrinkled, scarred/worn fingers	
Residue obscuring images is irrelevant	
Reduces Spread of Contaminants	

1.9 Modulation Transfer Function

A major component that must be considered occurs in modern methods of fingerprinting is the modulation transfer function of the device (or scanner for wet-ink ten-print cards).

Modulation transfer function, or MTF, is used to describe the performance of a camera lens, scanning sensor, or any transfer of information from one point to another through a system in

terms of imaging performance. It is a measure of the transfer of modulation (or contrast) from the subject to the image that is produced. In other words, it measures how faithfully the lens reproduces detail from the object to the captured image. MITRE developed the MTF application to support performance analysis of fingerprint capture devices and printers for the FBI's Integrated Automated Fingerprint Identification System (IAFIS). MITRE's MTF application is used to compute the modulation transfer function of an imaging system [32]. The general modulation transfer function that applies to several contact-based devices is shown below. This equation is generated from multiplying the MTF of the Lens, CCD image sensor MTF and the Electronic processing MTF to get the MTF of the whole system [33]. Coming from the Equation 1.1, the MTF of digital wet-ink ten-print cards is solely based on the MTF of the scanner or the electronic processing MTF. Using this same equation, the MTF of contact-based scanners can be found by multiplying, the electronic processing MTF and the MTF of the CCD image sensor. The MTF of contactless fingerprinting devices would be developed with every variable of equation 1.1.

$$MTF = MTF_L \cdot MTF_{CCD} \cdot MTF_e$$

[33] Equation 1.1

1.10 Standardization of Contactless Devices

With the development of new fingerprint scanners and databases arose a need for standards for fingerprint devices and the images that they produce. Since the different devices that are available all use different techniques to capture fingerprint images, standardization is critical. Additionally, all the images produced are different, considering that some devices can create a two-dimensional image and others, a three-dimensional image. Even within the

collection of devices used to capture the data used for this research, there were many different techniques including: moving and fixed structured light illumination, digital camera images, polarized reflected light, composite digital camera images and line scanning optical cameras. Considering all these different techniques and their capability to produce different types of images, standards must be created for compatibility between all devices.

NIST headed up the effort of developing standards for these types of devices. In January of 2015, The National Institute of Standards and Technology (NIST) developed a research program for research in developing methodology for measuring the image fidelity of contactless fingerprint capturing devices. This program is called the Contactless Fingerprint Capture Device Measurement Research Program, or CRADA, and focuses on producing open testing methods, metrics, and artifacts that will support the future certification of devices for inclusion on the Government Certified Products Lists [34]. In this context, artifacts refer to an object that can be used for testing fingerprint devices, with known geometric attributes, employed for comparison with a captured image to establish fidelity and repeatability, and measure error [35]. Participants of this program are requested to provide their contactless fingerprint devices, software and non-proprietary documentation, on loan, to NIST for testing [34]. Each device must be able to sense contactless fingerprints reliably in a contactless manner and produce resulting images in a standard or open file format. NIST will test the devices with controlled artifacts and will measure/analyze properties of the images captured. [34]

Most recently in March of 2017, NIST published the “Contactless Fingerprint Devices Usability Test” [36]. This study deals with the usability of contactless and contact-based devices, looking specifically into the efficiency, effectiveness and user satisfaction of each device. This study is similar to our own, as they also look into the similarity scores for each device.

1.11 Contactless Versus Touchless

“Contactless fingerprinting” has different meanings within the biometrics industry.

“Contactless” can refer solely to the sensor of a device or the entirety of the device or system.

Contactless devices can have a varying level of contact, where the subject may have part of their hand or finger resting on a surface in order for the sensor to capture the remaining part of the hand or finger in a non-contact still manner. If the whole device is contactless, then there is absolutely no contact made with any surface or sensor. These devices can be referred to as touchless. Figure 1.9 shows the difference between contactless and touchless devices. Table 2 provides a list of current contactless technologies [1]. The three contactless devices that were used to collect the data evaluated in in this research project are touchless devices. Shown below is a table of current contactless technologies (Table 2) as well as pictures of some of these devices in Figure 1.10.

Figure 1.8 Difference between contactless (left) and touchless (right) [1]

Table 1.3: Contactless Devices with the devices used in this research project highlighted in red [1].

Device	Scanning Technique	Scanning Resolution	Touchless	Maturity Level
Advanced Optical Systems Inc. (AOS) AIRprint [37]	Polarized Reflected light	500 ppi	Yes	Pre-commercialization
Carnegie Mellon University, Handshot, LLC Handshot ID	Composite Digital Camera Images	1000 ppi	Yes	R & D
Handshot HandID	Digital Camera Images	1000 ppi	Yes	R & D
University of Massachusetts Lowell single-finger Rolled Equivalent Scanner [38]	Line Scanning Optical Camera	Single Finger: 700 ppi (Up-Sampled to 1000 dpi) 4-slap/Palm: 72 ppi	No	Prototype
General Electric Tenprint Scanner	Multi-focus Digital images combined into a 3D global finger shape	1000 ppi	Yes	Pre-commercialization
AFIS and Biometrics Consulting, Inc. Fingerprint-on-the-Move	High Resolution Digital Camera	500 ppi	Yes	Pre-commercialization
FlashScan3D Single-finger Scanner	Moving Structured Light Illumination	500 ppi	No	Commercialization
FlashScan3D Tenprint Scanner	Moving Structured Light Illumination	500 ppi	Yes	Prototype
FlashScan3D Single-finger Rolled-Equivalent Scanner	Fixed Structured Light illumination on moving finger	1000 ppi	No	R & D
FlashScan3D Full-hand Contactless 3D Scanner	Fixed Structured Light illumination on moving hand	500 ppi	No	Pre-commercialization
TBS Touchless Ten Printer (TTP) [1]	Composite Digital Camera Images with structured light for 3D modeling	1000 ppi	No	Prototype
MorphoTrak Finger-on-the-Fly [39]	Structured Light Illumination	500 ppi	Yes	Pre-commercialization
Lumidigm Contactless Fingerprint Sensor	Stereoscopic digital images using multiple color illumination to capture 3D representation	Undetermined	Yes	Prototype
TBSGuard 3D-Line [40]	Composite Digital Camera Images	500 ppi	Yes	Commercial
TST BiRD ¾ [1]	Digital Camera image with multispectral imaging for liveness detection	500 ppi	Yes	Commercial
Advanced Optical Systems Inc. (AOS) ONEprint [41]	Digital Camera Image	500 ppi	Yes	Commercial
NEC HS100-10 [42]	Digital Camera Image	600 ppi	No	Commercial
Advanced Optical Systems Inc. (AOS) ANDI-on-the-go (OTG) [43]	Digital Camera Image	500 ppi	Yes	Prototype

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 1.9 (a) ANDI On-The-Go (OTG) [43] (b) MorphoWave or Morpho Finger-On-The-Fly (FOTF) [39] (c) TBS Touchless Ten Printer [1] (d) AIRprint Standoff Fingerprint Scanner [1] (e) TBS 3D Enroll [40] (f) IDair ONEprint [41] (g) NEC HS100-10 hybrid contactless scanner [42]

1.12 Certification

Since the second contactless fingerprint collection ended, some of the contactless devices have been certified. The FBI added the Advanced Optical Systems ANDI On-The-Go to the agency's certified product list (CPL) on November 27, 2015 [44]. After meeting the Personal Identity Verification (PIV) Image quality specifications standard, the FBI also certified the Morpho (Safran) MorphoWave Desktop contactless fingerprint scanner on January 5, 2016, which is the commercial version of the Morpho Finger-on-the-fly [45].

1.13 Interoperability

Interoperability is the most important issue facing the widespread adoption of contactless fingerprinting devices, considering the databases created by these systems must be completely backward-compatible with images captured from traditional scanners. The applications of these devices requires full interoperability with legacy systems. Contactless fingerprinting technology aims to address the issues experienced with previous techniques while also providing more information and fingerprint detail. Interoperability calls for careful design of lighting, resolution, and three-dimensional shape estimation. These devices also call for independent certification, Personal Identity Verification (PIV), and testing due to the diversity in these contactless devices compared to contact-based interaction. It's important to note that interoperability could mean different things. Jain and Ross considered interoperability as a biometrics systems ability to adapt to variability in images produced by different sensor technologies [46]. Interoperability could also refer to the usability between fingerprinting devices, as described in [36].

Interoperability has been evaluated for every different method of fingerprinting device throughout history to investigate the ability of the system to work with a diverse set of

fingerprinting devices or methods. For this effort, interoperability is a term used to show that images of the same subject's print from contactless and contact-based devices are comparable and will produce a match. Interoperability could also refer to the usability between devices.

1.14 Related Work

Research in contactless fingerprint recognition has increased in recent years. However, related work is still limited. One technical report that is related to contactless fingerprinting devices belongs to the US Department of Justice and ManTech [1]. They used 13 Contactless Fingerprinting devices that were still in the research and development stage and 4 commercial livescan devices to evaluate the efforts that were being made in government, industry, and academia in pursuing contactless fingerprint collection technologies. The researchers within this study identified that, at the time, there were no prior concerted efforts to compare contact versus contactless fingerprinting. Another study that examined contactless fingerprinting devices was performed by the University of Massachusetts, this study explored methods that would allow for cross examination of 10prints, livescan and contactless devices [30].

Another study that considered the interoperability between fingerprinting devices not particularly with contactless devices but other contact-based fingerprinting devices was researched at WVU [47]. The approach they proposed reduced the match error rates between devices by several levels but each performance gain depended on the matching algorithm used. A similar study that considered the interoperability of fingerprinting devices, but once again only looked at livescan devices and ten-print cards [48]. This study looked at data from 494 participants using 4 contact-based devices. They found that match score similarity between two same subject samples were generally higher when both images were captured from the same device. They also found higher match score sensitivity due to image quality when using two

different devices.

A case study by Arun Ross and Anil Jain also considered the interoperability of biometric sensors, capacitive and optical [46]. This study showed the influence of different fingerprint sensors on match performance. They experienced an EER of 23.13% for images matched between two different sensors, while the EERs for the other cases between images from the same sensors were 6.14% and 10.39%.

NIST led the effort of developing standards for contactless devices. In January of 2015, The National Institute of Standards and Technology (NIST) developed a research program for research in developing methodology for measuring the image fidelity of contactless fingerprint capturing devices. This program is called the Contactless Fingerprint Capture Device Measurement Research Program, or CRADA, and focuses on producing open testing methods, metrics, and artifacts that will support the future certification of devices for inclusion on the Government Certified Products Lists [34].

The dataset used in the research described in this theses was compiled for the effort reported in [1]. A second technical report by ManTech evaluated interoperability among contact and contactless systems for only a selection of 200 participants of this data [2]. Some of their findings are displayed in Table 4.2 with comparison to the findings of this thesis. They used only the participants out of the first 200 subjects that had data for every device. The study here used similar methods to acquire the results for the full dataset.

Most recently in March of 2017, NIST published the “Contactless Fingerprint Devices Usability Test” [36]. This study deals with the usability of contactless and contact-based devices, looking specifically into the efficiency, effectiveness and user satisfaction of each device. This study is like that presented here, as they also evaluated the similarity scores for each device and

found at least two of the touchless devices exhibited match scores well above an imposter baseline for matches of the same subject from contact-based device images [36]. Other papers have also been referenced throughout this thesis.

1.15 Problem Statement and Thesis Organization

Problem Statement

The main goal of this research is to investigate the interoperability of contactless fingerprinting devices with the currently used livenesscan legacy fingerprinting devices and techniques. Fingerprint data will be evaluated from wet-ink ten-print cards and traditional contact-based legacy fingerprint devices versus fingerprint data generated by next-generation contactless fingerprint scanners. The feasibility and performance of contactless fingerprint databases will be explored. To investigate the matching performance and interoperability of these devices, three different matching algorithms were utilized, including: Neurotechnology MegaMatcher, open source NIST Biometric Image Software (NBIS) and open source fingerprint recognition toolkit by SourceAFIS. Matching runs were performed on the right index finger and right thumb data from each device against themselves and all other devices, as well as the 500 dpi scans from the wet-ink fingerprint cards (thumb data results are not shown as they did not involve the contactless devices). After identifying the interoperability, it is desired to discover the stratification of contactless devices to see if a person's demographics share a relationship with the match capabilities of their fingerprints. The main tasks associated with these goals are:

1. Data Collection: Guiding 450 participants through the collection on each fingerprint device as well as rolling his or her prints with wet ink ten-print cards.

2. Image Pre-processing: Isolating each fingerprint image with segmentation programs as well as extracting images that are doubles or erroneous.
3. Match Score Generation: Data from each device was ran through each matching algorithm against every other device's data to determine similarity scores as well as ran against itself to determine genuine and imposter scores.
4. Data Analysis: Kullback-Leibler divergence was performed on the similarity scores generated from the matching runs as well as producing the score distributions. Genuine and imposter match score distributions were produced. EER values were also generated from the genuine and imposter distributions.

Knowing that contactless technologies have many advantageous qualities over traditional fingerprinting methods, this work will aid in determining if contactless databases are comparable to those currently in use is critical to the advancement of contactless fingerprinting.

The contributions of this research effort are:

- It shows fingerprints collected under ideal conditions from contactless and contact-based devices can be matched against each other in a statistically meaningful way. Data collection and analysis can be employed to determine the comparative match performance of contact-based and contactless fingerprinting devices.
- This dataset enables the investigation of performance and interoperability of contactless and contact-based fingerprint devices. Few biometric dataset resources exist that cover as many devices capturing the same subject pool. This research can escalate the understanding, performance, and adoption of contactless fingerprint systems, as well as inter-device matching.

- Evaluation of demographic stratification of contactless devices.

Thesis Organization

Chapter 2 explains the art of contactless fingerprinting and the technologies that are involved in the process. Chapter 3 describes in detail the process of data collection and the process that occurred in preparation for the matching algorithms. Chapter 4 covers the interoperability analysis; this section will display the results of this research project. The conclusions section, or Chapter 5, deals with the summary of the results from the interoperability analysis.

Chapter 2: Theory

Fingerprint Sensor Technology:

2.1 Integrated Biometrics Sherlock Sensor

The Sherlock sensor is a contact-based mobile fingerprint reader designed for stand-alone or embedded module usage [49]. This compact reader is manufactured by Integrated Biometrics and is used in two devices from the CFPv2 collection, the CrossMatch SEEK Avenger and Northrop Grumman BioSled. This sensor and the Integrated Biometrics Watson sensor were the first non-optical FAP 45, appendix F fingerprint sensors [50]. This sensor captures a livescan equivalent to a ten-print card. The FBI has granted the Sherlock with PIV-071006, Mobile ID IQS FAP 45, GSA FIPS 201, and Appendix F certifications [49] [51]. This platen has the ability to capture single or dual flat prints, or single rolled prints [49]. It utilizes Integrated Biometrics' Light Emitting Sensor (LES) technology along with a thin film transistor (TFT) [49]. The LES technology, proprietary to Integrated Biometrics, employs the use of an electroluminescence film, which emits a high resolution image when an electric field is applied to the film [52]. This reader uses a hybrid method of capture, utilizing both capacitive and optical sensor technology [49].

The Sherlock enables fingerprint capture in standalone applications, smartphones, or tablets, with its ideal use being in mobile computers, hand-held devices, smartphones and tablets [51]. The Northrop Grumman BioSled used a Samsung Galaxy S5 Android Smartphone housed in rugged case that strategically positions the Sherlock fingerprint sensor for fast and easy capture [53]. The CrossMatch SEEK Avenger delivers an all in one design with large touchscreen and keyboard with Sherlock Sensor built directly into the device [54].

The LES film provides the image, the thin film transistor captures the image and a USB interface allows the customer to integrate into their device [52]. When an electric field is applied

across the LES film, and a finger is placed on the film, the EL particles suspended in the film glow beneath the finger resulting in a high resolution image of the fingerprint [50]. In the case of the Sherlock sensor, this film is laminated directly to a thin film transistor (TFT) camera [50]. The Sherlock sensor is smaller, lighter and thinner than most sensors with reduced power requirements, which makes it desirable compared to optical sensors [50]. This sensor is also not affected by bright lights or direct sunlight, allowing it to be used in severe conditions for field collection [50]. The Sherlock sensor is also spoof resistant, as the finger touching the film must be conductive, restricting users from capturing artificial silicon fingers for prints [50].

Figure 2.1 Explanation of Sherlock sensor by Integrated Biometrics [50]

Figure 2.2 Sherlock Sensor [51]

2.2 Frustrated Total Internal Reflection Sensors

Frustrated total internal reflection or FTIR, is the oldest and most used livescan technique [55]. A contact image sensor with FTIR projects high contrast images onto a linear array sensor by the Frustrated total internal reflection of the fingerprint being projected by a GRIN (GRadient INdex of refraction) lens array onto the linear array sensor [56].

The embodiment is a contact image sensor with an optically transparent platen in which light must be introduced inside the platen [56]. Light is introduced using either a flat or curved surface, which acts as a lens to help collimate the light so that it forms a flat sheet of light the length of the sensor [56] [57]. Once introduced, the light is directed inside the platen using total internal reflection (TIR) or reflections from a mirror-like surface or surfaces [56]. The reflections inside the platen allow for the light to be placed more conveniently within the device and allow for the device to be more compact [56]. The reflective surfaces or TIR surfaces can be slightly rough to partially diffuse the light beam to send more light onto the fingerprint [56].

If viewed through the transparent platen at an oblique angle, a high contrast image can be obtained [56]. The image is then focused by the GRIN lens array onto a linear sensor array [56]. Light is directed at an angle to the top interior surface of the platen, typically 45 degrees or more to a line normal to the surface of the platen, where it is reflected by total internal reflection if no fingerprint is present [56]. When light is not reflected, fingers are on the sensor, and due to frustrated total internal reflection, the light is absorbed, resulting in a dark pattern for the fingerprint ridges and bright light for the fingerprint valleys [56] [55].

Figure 2.3 FTIR-based fingerprint sensor operation [55]

2.3 Structured Light Illumination

Structured light illumination is a method to capture images in a contactless manner. To execute this system, fine-grid-structured lights from different directions are projected to the target object and the images are captured from cameras at different angles [58]. The captured images are processed to create either a three-dimensional or hybrid two-dimensional model of the target object [58]. The process of capturing an image obtains all or most of the fingerprint information at once. The multiple angles of the cameras allow for the capture of worn finger

ridges and fine features which are difficult to capture with just one camera or conventional scanners [58]. Structured Light Illumination involves at least one projection unit for projecting a structured light pattern onto a hand positioned in the scan volume on or in front of the backdrop pattern [59]. These systems also include at least one camera for capturing multiple images of the hand, these images consist of at least a portion of the hand and the backdrop pattern [59]. The embodiment of these systems further includes a processing unit for calculating three dimensional coordinates of the hand from the images using the predetermined coordinates of the backdrop pattern to align the plurality of images and mapping the three-dimensional coordinates to a two-dimensional flat surface to create a two-dimensional representation equivalent to that of a wet ink rolled fingerprint [59]. One way that the images created can be segmented to remove the background and shadows is shown in Equation 2.1, where $I_F(x, y)$ is the original image, $I_S(x, y)$ is the binary segmentation mask, t_1 and t_h are two experimentally estimated threshold values [60].

$$I_S(x, y) = \begin{cases} 1, & t_1 < I_F(x, y) < t_h \\ 0, & \text{otherwise} \end{cases} \quad \text{Eq(2.1) [60]}$$

Figure 2.4 Diagram of how structured light illumination sees a finger [58]

2.4 Polarized Reflected Light

This technique provides a contactless method of capturing a three-dimensional fingerprint using polarization rotation to get different angles of reflected light. This approach is comprised of illuminating a fingerprint and directing a reflected light from the fingerprint through an imaging system [61]. This imaging system comprises an image capture device, a liquid crystal panel (LCP) and a birefringent element wherein the LCP and the birefringent element are positioned between the fingerprint and the image capture device such that the reflected light from the fingerprint passes through the LCP and birefringent element [61]. In other words, this system can be described as a polarizer added between the imaging capturing device and the finger surface [62]. This technique captures a plurality of rotation angles of the linearly polarized images of the fingerprint to comprise each of the steps of polarizing the reflected light [61]. The polarization filters could have angles of 0, 45, and 90, although other polarization angles can be

used. [62] At least one image is captured from each of the polarization orientation states of the LCP, registering these images to create a fused image [61]. Next step is calculating a depth of structural features using a depth from focus algorithm and generating a two dimensional rolled image of the fingerprint using the calculated depth of structural features and the fused image using an algorithm to reverse the projection of the fingerprint surface on to a two-dimensional projection [61].

2.5 Fingerprint Matching or Fingerprint Recognition

Fingerprint matching refers to determining the similarity between two given fingerprint images [63]. Fingerprint matching is used by law enforcement agencies for two main reasons, establish the identity of a suspect (or victim) based on partial prints, or latents, left at a crime scene and identifying repeat offenders based on prints of all their fingers [64]. A fingerprint recognition system can be used for verification and identification. Verification compares an input fingerprint to the an “enrolled” fingerprint to see if they are from the same finger or a one-to-one match [64]. For identification, the system compares an input fingerprint with all of the prints that are enrolled in the database or gallery also known as a one-to-many match or one-to-N match [64]. Identification is used in cases to determine if a person is already known under a duplicated or false identity [64]. There are a couple different methods of fingerprint matching but minutiae based fingerprint matching is the most popular method of fingerprint matching [65] [64] [66] [67] [68].

Figure 2.5 General block diagram for a Fingerprint Identification System. [68]

Fingerprint matching can be broken down into four primary sections, sensor, feature extraction, matcher, and system database. The sensor module captures the fingerprint data of the individual [66]. Some sensors are described earlier in this chapter. Feature extraction is the process in which the acquired data is processed to extract a set of discriminatory features [66]. During this process the position and orientation of minutiae points (local ridge and valley singularities) in a fingerprint image are extracted [66]. Features extracted from a fingerprint image are generally categorized into three levels [64]. Level 1 features capture macrodetails such as friction ridge flow, pattern type, and singular points [64]. Level 2 features refer to minutiae such as ridge bifurcations and endings [64]. Level 3 features include all dimensional attributes of the ridge such as ridge path deviation, width, shape, pores, edge contour, and other details, including incipient ridges, creases, and scars [64].

The next section of recognition is the matcher, in which the features extracted during recognition are compared against the stored templates to generate matching scores [66]. The

number of matching minutiae between the input and the template fingerprint images is determined and a matching or similarity score is reported [66]. The similarity or match scores should be high for fingerprints from the same finger and low for those of different fingers [64]. The matching process can be difficult due to large intraclass variations or variations in fingerprint images of the same finger and large interclass similarity (similarity between fingerprint images from different fingers [64]. The final section of fingerprint matching is the system database module, which is used by the matcher to store the fingerprint templates of the enrolled users [66].

Minutiae based matching uses local minutiae structures to quickly find a coarse alignment between two fingerprints and then consolidate the local matching results at a global level [64]. Minutiae based algorithms typically consists of four steps shown in Figure 2.6. The algorithm starts by computing the pairwise similarity between minutiae of two fingerprints by comparing minutiae descriptors that are invariant to rotation and translation [64] [68]. The next step is to align the two fingerprints according to the most similar minutiae pair [64]. Next the algorithm establishes minutiae correspondence, minutiae that are close enough both in location and direction are deemed to be mated or corresponding minutiae [64]. The last component of the algorithm is the computation of a similarity score that reflects the degree of match between the two prints [64]. The score is computed based on number of matching minutiae, the percentage of matching minutiae in the overlapping area of two fingerprints, and the consistency of ridge count between matching minutiae [64].

Figure 2.6 Typical Minutiae Matching Algorithm [64]

2.6 Possible Matching Errors

A matcher has two main types of errors that it can make: a false match and a false non-match [64] [66]. A false match is when the matcher mistakes a match from two different fingers to be the same finger [64] [66]. A false non-match is when the matcher mistakes two prints from the same person to be from two different persons [64] [66]. A false match is normally called a false accept and a false non-match can also be called a false reject [64] [66]. Examples of false non-matches or false rejects are shown in Figure 2.7 with the images on the left creating a false non-match with the images on the right, with the corresponding images being from the same finger. Examples of false matches or false accepts are shown in Figure 2.8 with the images on the left producing a false match with the images right, the corresponding images being from different fingers.

Figure 2.7 Examples of False Non-Matches or False Rejects [69]

Each row in Figure 2.7 shows a pair of impressions from the same finger which were falsely non-matched by an algorithm

Figure 2.8 Examples of False Matches or False Accepts [69]

Each row of Figure 2.8 shows a pair of impressions of different fingers that were falsely matched by an algorithm.

2.7 Biometric System Classifying Terminology

Genuine Match

A genuine match indicates the similarity between two mate samples, i.e. a genuine match score is generated with a pair of samples from the same user and same finger.

Imposter Match

An imposter match or a false accept score, measures the similarity between two non-mate samples, i.e. an imposter match score is generated with a pair of samples from two different users or two different fingers.

Genuine Acceptance Rate (GAR)

The Genuine Acceptance Rate is defined as the probability at which a correct match or genuine match is made in a data set. It is the number of genuine matches made divided by the number of attempts. The GAR can also be described as the true match rate (TMR).

False Acceptance Rate (FAR)

The false acceptance rate or false match rate, is defined as the probability at which imposters or false accept errors are made in a data set. It is the number of false acceptances divided by the number of imposter attempts.

False Rejection Rate (FRR)

The False Rejection rate is the probability that a genuine match will be mistaken for an imposter match.

True Match Rank 1 (TMR1)

True Matches or Genuine Matches at rank 1. Rank 1 is defined as the highest similarity score in a one to many probe to gallery match.

False Match Rank 1 (FMR1)

False Matches or Imposter Matches at rank 1. Rank 1 is defined as the highest similarity score in a one to many probe to gallery match.

True Match Rank 1 Rate (TMR1 Rate)

The Rate at which a True Match Rank 1 happens within a matching run.

False Match Rank 1 Rate (FMR1 Rate)

The Rate at which a False Match Rank 1 happens within a matching run.

Equal Error Rate (EER)

The Equal Error Rate is determined from the False Acceptance Rate and the False Rejection Rate. The Equal Error Rate is where FAR and FRR cross, or their intersection point.

Figure 2.9 Representation of a typical genuine and imposter score distribution [70]

2.8 Kullback Leibler Divergence

Kullback-Leibler Divergence (KLD) is used to measure the difference between two probability distributions over the same variable x [71]. KLD is a non-symmetric measure of the difference between two probability distributions $p(x)$ and $q(x)$ [71]. Specifically, KLD is a measure of the information lost when $q(x)$ is used to approximate $p(x)$ [71]. The KL divergence of the probability distributions P , Q , and a finite set X is defined as shown in Equation 2.1.

$$D_{KL}(P||Q) = \sum_{x \in X} P(x) \log \frac{P(x)}{Q(x)} \quad \text{Eq(2.2)}$$

Typically, $p(x)$ represents the “true” distribution of data, in our case that is the genuine or imposter match distribution of the overall dataset. $Q(x)$ usually represents a theory, model, description or approximation of $p(x)$, in this case it represents the genuine or imposter match distribution of a certain demographic group.

2.9 Receiver Operating Characteristic Curves

A receiver operating characteristic curve or ROC curve is a graphical plot that illustrates genuine acceptance rate against false acceptance rate. An ROC curve is a way to represent the performance of a matching or classification system [72]. It is created by plotting the GAR vs. the FAR at various threshold settings. The closer the curve follows the left-hand border and the top boarder of the ROC space, the more accurate the test [73]. The slope of the tangent line at any given threshold, gives the likelihood ratio for that value of the test [73]. An example of an ROC curve is shown in Figure 2.9.

Figure 2.10 A Sample ROC Curve [72].

2.10 NIST Fingerprint Image Quality (NFIQ)

NFIQ stands for NIST Fingerprint Image Quality, this algorithm assigns a quality value to fingerprint images. NFIQ was developed in 2004 by NIST, it was created to produce a value from a fingerprint image which is directly predictive of the expected matching performance [74]. The values that can be assigned range from 1 to 5, 1 being the highest quality and 5 being the lowest quality. NIST is currently developing NFIQ 2.0, which would be better optimized for contactless fingerprints [75].

Chapter 3: Data Collection & Preparation

3.1 Overview

This data collection was Phase 2 of a Non-Contact Fingerprint Evaluation project sponsored by ManTech International Corp. and the U.S. Dept. of Justice (CFPv2) (IRB# 1309097716). The main goal of this research was to obtain data to enable the evaluation of contactless fingerprint devices. The target number of participants for this collection was 400. Data was collected from 450 participants while the collection took place between 12/1/2014 and 4/2/2015. In 2012, The NIJ SSBT CoE performed a biometric collection of fingerprint data from traditional scanners and contactless devices, named Contactless Fingerprint Collection; Round 1 (CFPv1). Due to the success of the CFPv1 and its value to the biometrics research community, a second collection of contact and non-contact fingerprint data has been performed (CFPv2). [2]

3.2 Collection Process

Data Collection began December 1st of 2014 and ended April 2nd of 2015. Participants were contacted via email, based on previous studies where they opted for future contact about new data collections, where a website and phone number were provided so that they could schedule an appointment or call in to make an appointment. Data collection was performed on the WVU Evansdale Campus, in an indoor laboratory space as the collection area, with all sensors and rolled-ink impressions collected in the same area. Data was collected from 450 individuals, providing two sequential sessions of fingerprints for each sensor. The collection utilized livescan and non-contact fingerprint devices provided by ManTech with the addition of wet ink ten-print cards. [2]

3.3 Fingerprint Devices

Seven different fingerprinting devices were used for data collection. Both livescan and contactless devices were used as well as rolled ink impressions on a standard 10-print card. Table 3.1 lists the devices used in this data collection and the data that was collected from each device, while Figure 3.1 shows pictures of each of these devices.

Table 3.1 Fingerprint device details [2]

Vendor	Sensor	Collection Type	Data Collected
1. CrossMatch	Guardian R2	Livescan, contact	Left & right hands, slaps & rolls
2. L1/Morpho	TouchPrint 5300	Livescan, contact	Left & right hands, slaps & rolls
3. CrossMatch	SEEK Avenger	Mobile, contact	Livescan equivalent to 10-print card
4. Northrup Grumman	BioSled	Mobile, contact	Livescan equivalent to 10-print card
5. MorphoTrak	MorphoIDent	Mobile, Contact	Left & right hands, slaps only
6. Advanced Optical Systems (AOS)	ANDI On-The-Go	Portal, contactless	4 fingers on right hands only
7. MorphoTrak	Finger-on-the-Fly	Livescan, contactless	Left & right hands, 4 fingers only
8. IDair	InnerID (on iPhone)	Mobile, contactless	Left & right hands, finger photos

Figure 3.1: Fingerprint devices (from top left): CrossMatch Guardian R2, L1/Morpho TouchPrint 5300, CrossMatch SEEK Avenger, Northrup Grumman BioSled, MorphoTrak MorphoIDent, Advanced Optical Systems (AOS) ANDI On-The-Go, MorphoTrak Finger-on-the-Fly. The IDair InnerID (on iPhone) system was not available for photograph. [2]

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.2 Sample images from a single individual for each method of capture (a) Tenprint scan of rolled print (b) Tenprint Scan of Four Finger Slap (c) Livescan rolled print image (d) Livescan Four Finger Slap image (e) ANDI OTG Right Index Finger Capture (f) Morpho FOTF Right Index Finger Segment

3.4 Collection Site

The laboratory space that housed the various collection equipment was approximately 24x24ft. The collection area used approximately 12x24ft of this space. Three different benches were used to acquire the data from the devices which were table top or mobile devices, while the ANDI OTG was a freestanding device. The first bench housed the MorphoIDent, BioSled, and InnerID devices, as well as a laptop for data transfer from these devices. The second bench was used to house the SEEK Avenger and Finger-On-The-Fly (FOTF) devices, and the control laptop for the FOTF system. The third bench housed the Guardian and Touchprint devices and their control laptop, as well as the control laptop for the ANDI On-The-Go (OTG) system. The OTG system was located in the middle of the collection area to allow space for the participant to gain a walking start before interaction with the system. A station for fingerprint impression collection was located on a nearby counter surface. A sink was available for wet ink cleanup after the fingerprint impression station. Figure 3.2 illustrates the laboratory layout for data collection. [2]

Figure 3.3 Collection laboratory and station arrangement. [2]

3.5 Data Types and Organization

Each participant provided two sequential sessions of fingerprints for each sensor. These sessions were collected within 30 – 45 minutes of each other, so they show little variation due to collection time. The wet-ink prints were only collected once and were scanned at 500 and 1000ppi. The file structure for all of the electronically collected images is as follows:

- 10 print cards
 - Subject ID_Date_WVU Collection ID
 - 500
 - .eft file x1, .bmp images x14
 - 1000
 - .eft file x1, .bmp images x14
- Andi OTG
 - Subject ID_Date_WVU Collection ID
 - Session 1 & 2 folders
 - Binary .bmp images x4
 - Grayscale .bmp images x4
- BioSled
 - Subject ID_Date_WVU Collection ID
 - Session 1 & 2 folders
 - BioSled system files x16
 - .bmp images x16
- Crossmatch SEEK avenger
 - Subject ID_Date_WVU Collection ID
 - Session 1 & 2 folders
 - .eft file x1
 - .bmp images x14
- FPII Guardian
 - Subject ID_Date_WVU Collection ID
 - Session 1 & 2 folders
 - Sensor date folder
 - .bmp images x13
- innerID
 - Subject ID_Date_WVU Collection ID
 - Session 1 & 2 folders
 - .bmp images x10
- L1 TouchPrint
 - Subject ID_Date_WVU Collection ID
 - Session 1 & 2 folders
 - .bmp images x13

Morpho FOTF
Subject ID_Date_WVU Collection ID
Session 1 & 2 folders
Unsegmented .bmp images x4
Segmented .bmp images x16
MorphoMobile
Subject ID_Date_WVU Collection ID
Session 1 & 2 folders
.bmp images x10

The syntax of each fingerprint image filename is as follows:

SubjectRID_CollectionDate_CollectionNumber_SensorName_Slap/RollIdentifier_SessionNumber_Finger/SlapIdentifier.EXT

3.6 Collection Demographics

Figures 3.3 – 3.7 provide information on cumulative participation in the data collection and a breakdown of ethnicity, age, and gender.

Figure 3.4 Number of participants by month

Figure 3.5 Cumulative Participation

Participants by Ethnicity Group (%)

Figure 3.6 Participation Ethnicity

Figure 3.7 Participant Age

Figure 3.8 Breakdown of gender & ethnicity

3.7 Post Processing

The data collected was stored on each station's laptop computer where it was then compiled onto the storage server in weekly backup operations. With all data compiled, a script was written to rename and re-order the data according to the hierarchy listed in section 3.5. Once transferred, the fingerprint images were stored in .nst files which can be opened with NISTPack's TransactionEdit software. To extract these image files, the data was split among 4 workstations and each file was exported manually from the .nst files into .bmp format. Once all the files had been exported, a Matlab script was used to recognize and rename the files according to the format listed in section 3.5.

Data was delivered to ManTech in two releases. One took place after the first 200 participants, and the second after the final total 450 was achieved. Electronic records of the ten-print cards were delivered to the FBI due to IRB restrictions on data transfer. ManTech supplied WVU with an FBI-certified flat-bed scanner (Epson Perfection V700) and Aware Accuscan card scanning software to create the electronic records. Cards were scanned at both 500 and 1000ppi, and an .eft record and individual .bmp images were created for each participant in both resolutions.

Due to an error in the software of the ANDI OTG, with some participants, fingers were recorded erroneously, causing there to be duplicate images of the same finger on one hand. To accommodate this problem, all images used for this research were ran through the fingerprint matcher to find duplicates within one hand. The duplicates were then removed from the dataset.

3.8 Fingerprint Matchers

Three matching algorithms were utilized in this research project; Neurotechnology MegaMatcher, National Institute of Standards and Technology (NIST) Biometric Image Software (NBIS), and SourceAFIS Fingerprint Recognition Toolkit. The Neurotechnology MegaMatcher comes in an SDK that is developed by Neurotechnology. It is a large-scale AFIS that was introduced back in 2005 and its used for multi-biometric identification [76]. It is compliant with rolled, flat, and latent fingerprints. NIST has recognized MegaMatcher fingerprint algorithm as MINEX compliant and suitable for use in personal identity verification (PIV) program applications [76]. The MegaMatcher software also includes fingerprint image quality determination [76]. The Neurotech MegaMatcher also claims to be tolerant to fingerprint translation, rotation, and deformation.

The next matching algorithm was developed by NIST and is called NBIS. This software is open source and available to download via NIST Biometric Open Souce Server [77]. For this research project, the NBIS.NET adaptation was used. This software has the capability to generate the NIST Fingerprint Image Quality of the images or the NFIQ score of the image. It also has the capability to deliver the number of minutia found in the image. The SourceAFIS fingerprint recognition toolkit is an open source SDK that utilizes a minutia based matching technique [78]. It incorporates some of the same components used in the NIST NBIS software.

For a more in depth report of this data collection, refer to “Evaluation of Contactless versus Contact Fingerprint Data, Phase 2” [2]

Chapter 4:

Interoperability

Analysis

4.0 Fingerprint Image Match Score Analysis

Each of the three matchers (NIST NBIS, Neurotech MegaMatcher, and SourceAFIS) were used to produce genuine and imposter scores as well as the matching scores between devices. These groups were then broken down into demographic strata to compare the results. Each of the matchers works similarly as a probe image is matched against the set of images in the gallery. To generate the genuine scores, a probe image is matched against a gallery which consist of other images from the same subject. To generate imposter scores, a probe image is matched against a gallery which consist of images from all the other subjects within the dataset. In both cases, the probe image is not included in the gallery. Each matching run resulted in a genuine and imposter match score list in the form of a comma separated variable (csv) file. These files were then imported into Matlab to generate the imposter and match score distributions as well as the KLD scores and ROC Curves. The Neurotech and SourceAFIS matchers output only the match scores, but the NIST NBIS matcher was also used to acquire the minutiae counts and NFIQ scores for each image, these results were used to create the minutia box plots that are shown in Appendix A and the NIFQ score Distributions(shown in Figures 4.1 – 4.4). Table 4.2 shows the results of the ManTech Study Compared to ours. Tables 4.3 – 4.8 show the number of rank 1 true and false matches as well as the rate rank 1 rates for each matching run. The outliers and some of the normal genuine and imposter distributions are shown, all graphs/results can be viewed in Appendix A. The results to the demographic strata tests are shown in Appendix B, C and D. Appendix B deals with the gender-based study, Appendix C shows the age-based study and Appendix D displays the ethnicity-based study. Table 4.1 shows the abbreviations used in results tables in this chapter and chapter 5.

Table 4.1 Device Abbreviations

Code	Definition
10p	Ten Print Card (Scanned at 1000 & 500 dpi)
IID	InnerID (iPhone App)
MFF	Safran Morpho Finger on the Fly
CSA	CrossMatch SEEK Avenger
BIO	Northrup Grumman BioSled
ANDI BIN	ANDI On the Go (OTG) Binary Images
ANDI GRY	ANDI On the Go (OTG) Greyscale Images
L1	L-1 Scanner
CG2	CrossMatch Guardian 2
SMM	Safran Morpho Mobile MorphoIDent

Table 4.2 ManTech Table Comparison to Thesis Results

Probe	Gallery	ManTech	NBIS	Neurotech	SourceAFIS
CG2 R	CG2 R	100	100	100	100
MFF	MFF	99.8	100	100	100
CSA R	CG2 R	97.8	97.75	99.5	97.75
CSA	CG2 R	95	98.1	99.61	98.01
SMM	CG2 R	96.5	95.63	99.4	95.63
L1 R	CG2 R	97	98.74	99.09	98.74
L1	CG2 R	96.7	97.47	99.19	97.47
BioSled R	CG2 R	96.3	95.11	98.4	95.11
BioSled	CG2 R	94.2	95.35	97.2	95.35
ANDI GRY	CG2 R	76	74.33	97.19	74.33
ANDI BIN	CG2 R	83.6	86.66	97.02	86.65
MFF	CG2 R	92.4	93.22	98.68	93.21
CG2 R	MFF	92	93.22	98.68	93.21
CSA	MFF	87.2	95.93	98.69	95.93
ANDI GRY	MFF	79.5	74.66	97.27	74.66
ANDI BIN	MFF	83.2	85.10	94.89	83.86
IID	MFF	2	.32	1.94	.32

Table 4.2 shows that our results compared to those obtained in the ManTech study detailed in [2]. The values highlighted in red represent the TMR1 accuracies that increased when the full dataset was considered in the interoperability assessment. ManTech used the FP II Guardian Rolls (CG2 R) as the baseline comparison to compare all the other devices to. Most of the results presented here indicate a higher accuracy. This is noteworthy since, typically, when more data is added, overall rank 1 accuracy is expected to decline. This could have been caused

by ManTech using only the participants that had data for all devices, as some subjects that didn't have data for every device could have produced higher results than those that had data for every device. Another possibility of why this occurred is that by the time second part of the collection was happening the operators would have had more experience and training and been able to better use each of the devices.

Table 4.3 NBIS TMR1 Table

Blue shading = Contactless vs Contactless, Orange Shading = Contactless vs Contact-Based,
Green shading = Contact vs Contact

NBIS	Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
Blue shading	ANDI BIN - ANDI BIN	830	830	0	100	0
	ANDI BIN - ANDI GRY	830	829	1	99.88	0.12
	ANDI BIN - IID	316	5	311	1.58	98.42
	ANDI BIN - MFF	812	691	121	85.1	14.9
	ANDI GRY - ANDI GRY	831	831	0	100	0
	ANDI GRY - IID	316	5	311	1.58	98.42
	ANDI GRY - MFF	813	607	206	74.66	25.34
	IID - IID	319	319	0	100	0
	IID - MFF	315	1	314	0.32	99.68
	MFF - MFF	1734	1734	0	100	0
Orange shading	10p - ANDI BIN	381	296	85	77.69	22.31
	10p - ANDI GRY	381	260	121	68.24	31.76
	10p - IID	144	3	141	2.08	97.92
	10p - MFF	395	336	59	85.06	14.94
	ANDI BIN - BIO	767	656	111	85.53	14.47
	ANDI BIN - CSA	753	679	74	90.17	9.83
	ANDI BIN - CG2	811	738	73	91	9
	ANDI BIN - L1	820	721	99	87.93	12.07
	ANDI BIN - SMM	800	700	100	87.5	12.5
	ANDI GRY - BIO	768	540	228	70.31	29.69
	ANDI GRY - CSA	754	584	170	77.45	22.55
	ANDI GRY - CG2	812	623	189	76.72	23.28
	ANDI GRY - L1	821	614	207	74.79	25.21
	ANDI GRY - SMM	801	580	221	72.41	27.59
	BIO - IID	297	6	291	2.02	97.98
	BIO - MFF	785	709	76	90.32	9.68
Orange shading	CSA - IID	289	7	282	2.42	97.58
	CSA - MFF	762	731	31	95.93	4.07
	CG2 - IID	306	3	303	0.98	99.02
	CG2 - MFF	847	809	38	95.51	4.49
	IID - L1	315	0	315	0	100
	IID - SMM	313	1	312	0.32	99.68
	L1 - MFF	861	821	40	95.35	4.65
	MFF - SMM	1666	1458	208	87.52	12.48
Green shading	10p - 10p	405	405	0	100	0
	10p - BIO	375	330	45	88	12
	10p - CSA	369	337	32	91.33	8.67
	10p - CG2	398	364	34	91.46	8.54
	10p - L1	401	368	33	91.77	8.23
	10p - SMM	388	339	49	87.37	12.63
	BIO - BIO	806	806	0	100	0
	BIO - CSA	738	709	29	96.07	3.93
	BIO - CG2	792	758	34	95.71	4.29
	BIO - L1	801	769	32	96	4
	BIO - SMM	778	746	32	95.89	4.11
	CSA - CSA	784	784	0	100	0
	CSA - CG2	771	763	8	98.96	1.04
	CSA - L1	778	770	8	98.97	1.03
	CSA - SMM	758	753	5	99.34	0.66
	CG2 - CG2	870	870	0	100	0
	CG2 - L1	860	846	14	98.37	1.63
	CG2 - SMM	838	817	21	97.49	2.51
	L1 - L1	883	883	0	100	0
	L1 - SMM	849	832	17	98	2
	SMM - SMM	859	859	0	100	0

Table 4.4 Neurotech TMR1 Table

Blue shading = Contactless vs Contactless, Orange Shading = Contactless vs Contact-Based,
Green shading = Contact vs Contact

Neurotech	Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
Blue shading	ANDI BIN - ANDI BIN	825	825	0	100	0
	ANDI BIN - ANDI GRY	804	802	2	99.75	0.25
	ANDI BIN - IID	319	9	310	2.82	97.18
	ANDI BIN - MFF	822	780	42	94.89	5.11
	ANDI GRY - ANDI GRY	796	796	0	100	0
	ANDI GRY - IID	287	5	282	1.74	98.26
	ANDI GRY - MFF	768	747	21	97.27	2.73
	IID - IID	273	273	0	100	0
	IID - MFF	309	6	303	1.94	98.06
	MFF - MFF	1626	1626	0	100	0
Orange Shading	10p - ANDI BIN	381	372	9	97.64	2.36
	10p - ANDI GRY	355	347	8	97.75	2.25
	10p - MFF	396	381	15	96.21	3.79
	ANDI BIN - BIO	778	730	48	93.83	6.17
	ANDI BIN - CSA	764	732	32	95.81	4.19
	ANDI BIN - CG2	822	788	34	95.86	4.14
	ANDI BIN - L1	832	794	38	95.43	4.57
	ANDI BIN - SMM	810	770	40	95.06	4.94
	ANDI GRY - BIO	735	694	41	94.42	5.58
	ANDI GRY - CSA	721	698	23	96.81	3.19
	ANDI GRY - CG2	783	756	27	96.55	3.45
	ANDI GRY - L1	790	767	23	97.09	2.91
	ANDI GRY - SMM	767	739	28	96.35	3.65
	BIO - IID	297	5	292	1.68	98.32
	BIO - MFF	785	758	27	96.56	3.44
	CSA - IID	287	6	281	2.09	97.91
	CSA - MFF	762	752	10	98.69	1.31
	CG2 - IID	304	3	301	0.99	99.01
Green shading	CG2 - MFF	847	831	16	98.11	1.89
	IID - L1	311	4	307	1.29	98.71
	IID - SMM	307	2	305	0.65	99.35
	L1 - MFF	861	847	14	98.37	1.63
	MFF - SMM	1662	1638	24	98.56	1.44
	10p - 10p	388	388	0	100	0
	10p - BIO	376	362	14	96.28	3.72
	10p - CSA	370	367	3	99.19	0.81
	10p - CG2	399	396	3	99.25	0.75
	10p - L1	402	400	2	99.5	0.5
	10p - SMM	389	380	9	97.69	2.31
	BIO - BIO	802	802	0	100	0
	BIO - CSA	738	717	21	97.15	2.85
	BIO - CG2	792	770	22	97.22	2.78
	BIO - L1	801	780	21	97.38	2.62
	BIO - SMM	778	756	22	97.17	2.83
	CSA - CSA	783	783	0	100	0
	CSA - CG2	771	767	4	99.48	0.52
	CSA - L1	778	776	2	99.74	0.26
	CSA - SMM	758	757	1	99.87	0.13
	CG2 - CG2	867	867	0	100	0
	CG2 - L1	860	849	11	98.72	1.28
	CG2 - SMM	838	828	10	98.81	1.19
	L1 - L1	883	883	0	100	0
	L1 - SMM	849	843	6	99.29	0.71
	SMM - SMM	855	855	0	100	0

Table 4.5 SourceAFIS TMR1 Table

Blue shading = Contactless vs Contactless, Orange Shading = Contactless vs Contact-Based,
Green shading = Contact vs Contact

SourceAFIS Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
ANDI BIN - ANDI BIN	830	830	0	100	0
ANDI BIN - ANDI GRY	830	829	1	99.88	0.12
ANDI BIN - IID	321	5	311	1.56	96.88
ANDI BIN - MFF	824	691	121	83.86	14.68
ANDI GRY - ANDI GRY	831	831	0	100	0
ANDI GRY - IID	316	5	311	1.58	98.42
ANDI GRY - MFF	813	607	206	74.66	25.34
IID - IID	319	319	0	100	0
IID - MFF	315	1	314	0.32	99.68
MFF - MFF	1734	1734	0	100	0
10p - ANDI BIN	380	296	85	77.89	22.37
10p - ANDI GRY	381	260	121	68.24	31.76
10p - IID	144	3	141	2.08	97.92
10p - MFF	395	336	59	85.06	14.94
ANDI BIN - BIO	778	656	111	84.32	14.27
ANDI BIN - CSA	764	679	74	88.87	9.69
ANDI BIN - CG2	822	738	73	89.78	8.88
ANDI BIN - L1	832	721	99	86.66	11.9
ANDI BIN - SMM	800	700	100	87.5	12.5
ANDI GRY - BIO	768	540	228	70.31	29.69
ANDI GRY - CSA	754	584	170	77.45	22.55
ANDI GRY - CG2	812	623	189	76.72	23.28
ANDI GRY - L1	821	614	207	74.79	25.21
ANDI GRY - SMM	801	580	221	72.41	27.59
BIO - IID	297	6	291	2.02	97.98
BIO - MFF	785	709	76	90.32	9.68
CSA - IID	289	7	282	2.42	97.58
CSA - MFF	762	731	31	95.93	4.07
CG2 - IID	306	3	303	0.98	99.02
CG2 - MFF	847	809	38	95.51	4.49
IID - L1	315	0	315	0	100
IID - SMM	313	1	312	0.32	99.68
L1 - MFF	861	821	40	95.35	4.65
MFF - SMM	1666	1458	208	87.52	12.48
10p - 10p	406	405	0	99.75	0
10p - BIO	375	330	45	88	12
10p - CSA	369	337	32	91.33	8.67
10p - CG2	398	364	34	91.46	8.54
10p - L1	401	368	33	91.77	8.23
10p - SMM	388	339	49	87.37	12.63
BIO - BIO	806	806	0	100	0
BIO - CSA	738	709	29	96.07	3.93
BIO - CG2	792	758	34	95.71	4.29
BIO - L1	801	769	32	96	4
BIO - SMM	778	746	32	95.89	4.11
CSA - CSA	784	784	0	100	0
CSA - CG2	771	763	8	98.96	1.04
CSA - L1	778	770	8	98.97	1.03
CSA - SMM	758	753	5	99.34	0.66
CG2 - CG2	870	870	0	100	0
CG2 - L1	860	846	14	98.37	1.63
CG2 - SMM	838	817	21	97.49	2.51
L1 - L1	883	883	0	100	0
L1 - SMM	849	832	17	98	2
SMM - SMM	859	859	0	100	0

The Total column in Tables 4.3 - 4.5 shows the total number of rank 1 matches acquired. The TMR1 and FMR1 columns denote the number of True Match Rank 1 and False Match Rank 1 matches out of the total number of matches. The True Match Rank 1 Rate is the number of TMR1 Matches divided by the total number of matches. The TMR1 values that are highest, or share the highest value of the three matchers, are denoted in red. The blue shading in Tables 4.3 - 4.5, denote the matches between contactless devices, the orange denotes matches between contactless and contact-based devices and the green is for contact-based devices only. The total number of matches may vary within the Neurotech TMR1 Table 4.4 compared to the NBIS and SourceAFIS totals. This is because the Neurotech matcher removed images of bad quality from the gallery, which led to fewer matches. This is most likely why the Neurotech matcher produced the best TMR1 accuracy for almost every test. The matching algorithms used were not optimized for use with images obtained from contactless methods of capture, this may account for the lower matching accuracies when contactless methods of capture were involved. The TMR1 accuracy Ranges between matchers can better viewed in Table 5.2.

Table 4.6 NBIS Rolls TMR1 Table

<i>NBIS Rolls</i>	<i>Match</i>	<i>Total</i>	<i>TMR1</i>	<i>FMR1</i>	<i>TMR1 Rate</i>	<i>FMR1 Rate</i>
	<i>10p R - 10p R</i>	<i>417</i>	<i>417</i>	<i>0</i>	<i>100.00</i>	<i>0.00</i>
	<i>10p R - BIO R</i>	<i>389</i>	<i>342</i>	<i>47</i>	<i>87.92</i>	<i>12.08</i>
	<i>10p R - CSA R</i>	<i>383</i>	<i>349</i>	<i>34</i>	<i>91.12</i>	<i>8.88</i>
	<i>10p R - CG2 R</i>	<i>412</i>	<i>369</i>	<i>43</i>	<i>89.56</i>	<i>10.44</i>
	<i>10p R - L1 R</i>	<i>415</i>	<i>372</i>	<i>43</i>	<i>89.64</i>	<i>10.36</i>
	<i>BIO R - BIO R</i>	<i>828</i>	<i>828</i>	<i>0</i>	<i>100.00</i>	<i>0.00</i>
	<i>BIO R - CSA R</i>	<i>765</i>	<i>735</i>	<i>30</i>	<i>96.08</i>	<i>3.92</i>
	<i>BIO R - CG2 R</i>	<i>818</i>	<i>778</i>	<i>40</i>	<i>95.11</i>	<i>4.89</i>
	<i>BIO R - L1 R</i>	<i>824</i>	<i>785</i>	<i>39</i>	<i>95.27</i>	<i>4.73</i>
	<i>CSA R - CSA R</i>	<i>811</i>	<i>811</i>	<i>0</i>	<i>100.00</i>	<i>0.00</i>
	<i>CSA R - CG2 R</i>	<i>799</i>	<i>781</i>	<i>18</i>	<i>97.75</i>	<i>2.25</i>
	<i>CSA R - L1 R</i>	<i>809</i>	<i>795</i>	<i>14</i>	<i>98.27</i>	<i>1.73</i>
	<i>CG2 R - CG2 R</i>	<i>877</i>	<i>877</i>	<i>0</i>	<i>100.00</i>	<i>0.00</i>
	<i>CG2 R - L1 R</i>	<i>871</i>	<i>860</i>	<i>11</i>	<i>98.74</i>	<i>1.26</i>
	<i>L1 R - L1 R</i>	<i>893</i>	<i>893</i>	<i>0</i>	<i>100.00</i>	<i>0.00</i>

Table 4.7 Neurotech Rolls TMR1 Table

<i>Neurotech Rolls</i>	<i>Match</i>	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
	<i>10p R - 10p R</i>	360	360	0	100.00	0.00
	<i>10p R - BIO R</i>	390	375	15	96.15	3.85
	<i>10p R - CSA R</i>	383	377	6	98.43	1.57
	<i>10p R - CG2 R</i>	411	404	7	98.30	1.70
	<i>BIO R - BIO R</i>	815	815	0	100.00	0.00
	<i>BIO R - CSA R</i>	757	743	14	98.15	1.85
	<i>BIO R - CG2 R</i>	810	797	13	98.40	1.60
	<i>CSA R - CSA R</i>	804	804	0	100.00	0.00
	<i>CSA R - CG2 R</i>	796	792	4	99.50	0.50
	<i>CG2 R - CG2 R</i>	862	862	0	100.00	0.00
	<i>L1 R - 10p R</i>	828	807	21	97.46	2.54
	<i>L1 R - BIO R</i>	835	819	16	98.08	1.92
	<i>L1 R - CSA R</i>	820	811	9	98.90	1.10
	<i>L1 R - CG2 R</i>	878	870	8	99.09	0.91

Table 4.8 SourceAFIS Rolls TMR1 Table

<i>SourceAFIS Rolls</i>	<i>Match</i>	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
	<i>10p R - 10p R</i>	418	417	0	99.76	0.00
	<i>10p R - BIO R</i>	389	342	47	87.92	12.08
	<i>10p R - CSA R</i>	383	349	34	91.12	8.88
	<i>10p R - CG2 R</i>	411	369	43	89.78	10.46
	<i>10p R - L1 R</i>	415	372	43	89.64	10.36
	<i>BIO R - BIO R</i>	828	828	0	100.00	0.00
	<i>BIO R - CSA R</i>	765	735	30	96.08	3.92
	<i>BIO R - CG2 R</i>	818	778	40	95.11	4.89
	<i>BIO R - L1 R</i>	824	785	39	95.27	4.73
	<i>CSA R - CSA R</i>	811	811	0	100.00	0.00
	<i>CSA R - CG2 R</i>	799	781	18	97.75	2.25
	<i>CSA R - L1 R</i>	809	795	14	98.27	1.73
	<i>CG2 R - CG2 R</i>	877	877	0	100.00	0.00
	<i>CG2 R - L1 R</i>	871	860	11	98.74	1.26
	<i>L1 R - L1 R</i>	893	893	0	100.00	0.00

The TMR1 Accuracy shown in Tables 4.6 - 4.8 are relatively high compared to the other TMR1 accuracy tables. These high values are because all tests are between rolled prints images that were produced on contact-based devices. The values that are highest, or share the highest value of the three matchers, are denoted in red. The total number of matches may vary within the Neurotech TMR1 Rolls Table compared to the NBIS and SourceAFIS totals. Again, this is because the Neurotech matcher removed images of bad quality from the gallery, which led to fewer matches being performed. Again, this is most likely why the Neurotech matcher produced the best TMR1 accuracy for almost every rolls test.

Figure 4.1 Normalized NFIQ Score Distributions for All Devices

Figure 4.2 Normalized NFIQ Score Distributions for All Devices - Rolls

Figure 4.3 Normalized NFIQ Score Distributions for All Contact-based Devices

Figure 4.4 Normalized NFIQ Score Distributions for all Contactless Devices (Excluding InnerID)

These NFIQ scores were output from the NBIS matching algorithm. NFIQ is explained in Section 2.10. The same number of images was not produced by each device. One device that stands out is the Morpho FOTF, which had almost double that of the other devices. The ten-print NFIQ distributions seem lower than most, this could be due to low operator experience in collecting ten-print cards.

Figure 4.1 shows all the devices distributions together, while Figures 4.3 – 4.4 show these same distributions displayed by method of capture. Figure 4.2 shows the distributions for rolled images only and the devices that acquired them. For the contact-based devices, these distributions agree with the rest of the results, as they show that devices with better image quality

distributions produced better results than those with poor image NFIQ distributions. The NFIQ algorithm is not optimized for contactless images, that is why these results do not really agree with the rest of the results

4.1 Cross-Examined Genuine and Imposter Score Distributions

4.1.1 NBIS Cross-Examined Genuine/Imposter Distributions

4.1.1.1 NBIS Samples of Normal Distributions

The genuine/imposter distributions shown in Figures 4.5 – 4.6 are sample genuine/imposter match score distributions obtained using the NBIS matcher. They have been chosen to illustrate the typical genuine/imposter score distributions of each type of device used in this study, as well as the ten-print cards. The rest of the distributions have been provided in Appendix A.

Figure 4.5 (Left) NBIS 10print – Crossmatch Seek Avenger (Right) NBIS ANDI Binary – FP II Guardian

Figure 4.6 NBIS BioSled - MorphoMobile

4.1.1.2 NBIS Outliers

Due to the InnerID running into technical problems during the collection, it was removed from the collection midway through. While still in operation, the InnerID produced low quality images, this statement is proven with the genuine/imposter distributions shown below. Each test shown in Figures 4.8(Right) – 4.18 involved the InnerID device. The genuine/imposter distributions shown in Figures 4.7 – 4.8 (left) show outliers that do not involve the InnerID device. The reason these differ slightly from the typical genuine/imposter distribution is due to the match involving the ANDI Greyscale images. Considering the TMR1 scores involving the ANDI greyscale images, they do not perform as well as most of the other matches with these three match scenarios achieving TMR1 accuracy of 68.24, 74.66, and 72.41, respectively for this particular matcher.

Figure 4.7 (Left) NBIS 10print - ANDI Greyscale (Right) NBIS ANDI Greyscale – Morpho FOTF

Figure 4.8 (Left) NBIS ANDI Greyscale – MorphoMobile (Right) NBIS 10print – InnerID

Figure 4.9 (Left) NBIS ANDI Binary – InnerID (Right) NBIS ANDI Greyscale – InnerID

Figure 4.10 (Left) NBIS BioSled – InnerID (Right) NBIS Crossmatch SEEK AVENGER – InnerID

Figure 4.11 (Left) NBIS FP II Guardian (Right) NBIS InnerID – L1

Figure 4.12 (Left) NBIS InnerID – Morpho FOTF (Right) NBIS InnerID – MorphoMobile

4.1.2 Neurotech Cross-Examined Genuine/Imposter Distributions

4.1.2.1 Neurotech Samples of Normal Distributions

The genuine/imposter distributions shown in Figures 4.13 – 4.14 are sample genuine/imposter match score distributions obtained using the Neurotech matcher. They have been chosen to illustrate the typical genuine/imposter score distributions of each type of device used in this study, as well as the ten-print cards. The rest of the distributions have been provided in Appendix A.

Figure 4.13 (Left) Neurotech 10print – Morpho FOTF (Right) Neurotech ANDI Binary – BioSled

Figure 4.14 Neurotech FP II Guardian - MorphoMobile

4.1.2.2 Neurotech Outliers

As described in section 4.1.1.1.

Figure 4.15 (Left) Neurotech ANDI Binary – InnerID(Right) Neurotech ANDI Greyscale - InnerID

Figure 4.16 (Left) Neurotech BioSled – InnerID (Right) Neurotech Crossmatch SEEK AVENGER - InnerID

Figure 4.17 (Left) Neurotech FP II Guardian – InnerID (Right) Neurotech InnerID – L1

Figure 4.18 (Left) Neurotech InnerID – Morpho FOTF (Right) Neurotech InnerID - MorphoMobile

4.1.3 SourceAFIS Cross-Examined Genuine/Imposter Distributions

4.1.3.1 SourceAFIS Samples of Normal Distributions

The genuine/imposter distributions shown in Figures 4.19 – 4.20 are sample genuine/imposter match score distributions obtained using the SourceAFIS matcher. They have been chosen to illustrate the typical genuine/imposter score distributions of each type of device used in this study, as well as the ten-print cards. The rest of the distributions have been provided in Appendix A.

Figure 4.19 (Left) SourceAFIS 10print – BioSled (Right) SourceAFIS L1 - MorphoMobile

Figure 4.20 SourceAFIS Morpho FOTF - MorphoMobile

4.1.3.2 SourceAFIS Outliers

As described in section 4.1.1.1.

Figure 4.21 (Left) SourceAFIS 10print – InnerID (Right) SourceAFIS ANDI Binary - InnerID

Figure 4.22 (Left) SourceAFIS ANDI Greyscale – InnerID (Right) SourceAFIS BioSled - InnerID

Figure 4.23 (Left) SourceAFIS Crossmatch SEEK AVENGER – InnerID (Right) SourceAFIS FP II Guardian – InnerID

Figure 4.24 (Left) SourceAFIS InnerID – L1 (Right) SourceAFIS InnerID – Morpho FOTF

Figure 4.25 SourceAFIS InnerID - MorphoMobile

The full set of results for the general study can be seen in Appendix A.

4.2 Gender-Based Study

4.2.1 Gender-Based Samples of Normal Distributions

The genuine/imposter distributions shown in Figures 4.26 – 4.31 are sample genuine/imposter match score distributions obtained using the each of the three matching algorithms for male and female strata. They have been chosen to illustrate the typical genuine/imposter score distributions of each type of device and gender used in this study. Figures 4.26, 4.28, and 4.30 represent male genuine/imposter distributions for each of the

matchers and Figures 4.27, 4.29, and 4.31 represent female genuine/imposter distributions for each matcher. There are no noticeable trends shown within the distributions. The rest of the distributions have been provided in Appendix B.

Figure 4.26 (Left) NBIS ANDI Binary Male (Right) NBIS Crossmatch Seek Avenger Male

Figure 4.27 (Left) NBIS ANDI Greyscale Female (Right) FP II Guardian Female

Figure 4.28 (Left) Neurotech ANDI Greyscale Male (Right) Neurotech BioSled Male

Figure 4.29 (Left) Neurotech BioSled Rolls Female (Right) Neurotech Morpho FOTF Female

Figure 4.30 (Left) SourceAFIS Morpho FOTF Male (Right) SourceAFIS MorphoMobile Male

Figure 4.31(Left) ANDI Binary Female (Right) SourceAFIS FP II Guardian Female

4.2.2 Gender-Based Outliers

There were not any outliers based on the genuine/imposter distributions for this matcher using these stratifications.

4.2.3 Gender- Based KLD Values

The values shown in Tables 4.9 – 4.11 show the Kullback Leibler Divergence measures of the genuine and imposter distributions for both genders on each matcher. The genuine KLD values produced for males showed little variation with the genuine average being 0.0245 and an imposter KLD average of 1.0595. For females the values varied showed more but still were relatively low with a genuine KLD average of 0.0417 and an imposter KLD average of 3.8321.

These values reveal the similarity to the original dataset and show little to no performance variation between genders. The outlying values for Tables 4.9 – 4.11 show no trend as they don't show the same variations across all three matcher algorithms results. The KLD values for this study were inconclusive as they showed little to no variation from the general study of the whole dataset.

Table 4.9 NBIS Gender Based KLD Values

NBIS KLD Values		Male		Female	
<i>Device</i>		Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>		0.0282	1.6236	0.0316	0.7008
<i>ANDI GRY</i>		0.0373	0.0893	0.0214	0.2379
<i>BioSled</i>		0.0328	0.0836	0.0434	3.8267
<i>BioSled Rolls</i>		0.0327	0.4227	0.0176	5.4024
<i>CG2</i>		0.0272	0.1348	0.0356	7.8629
<i>CG2 Rolls</i>		0.0163	0.9924	0.0388	2.2804
<i>CSA</i>		0.0148	1.0866	0.1378	0.3865
<i>CSA Rolls</i>		0.0217	6.4243	0.0614	3.5796
<i>L1</i>		0.0219	0.1464	0.0221	9.0137
<i>L1 Rolls</i>		0.0155	0.2235	0.0394	6.0952
<i>MFF</i>		0.0543	0.5960	0.0169	1.1263
<i>MorphoMobile</i>		0.0248	0.1028	0.0461	1.7152

Table 4.10 Neurotech Gender Based KLD Values

Neurotech KLD Values		Male		Female	
<i>Device</i>		Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>		0.0073	5.9406	0.0102	3.1744
<i>ANDI GRY</i>		0.0044	0.1447	0.0041	0.2866
<i>BioSled</i>		0.0148	0.0063	0.0251	0.3071
<i>BioSled Rolls</i>		0.0080	0.0110	0.0073	0.0299
<i>CG2</i>		0.0041	0.0099	0.0094	0.0807
<i>CG2 Rolls</i>		0.0051	0.0052	0.0103	0.0210
<i>CSA</i>		0.0363	5.0927	0.0641	0.6460
<i>CSA Rolls</i>		0.0046	0.8327	0.0309	1.2743
<i>L1</i>		0.0052	0.0005	0.0054	0.0032
<i>MFF</i>		0.0087	2.2364	0.0218	0.6446
<i>MorphoMobile</i>		0.0144	0.0235	0.0116	0.2484

Table 4.11 SourceAFIS Gender Based KLD Values

SourceAFIS KLD Values		Male		Female	
<i>Device</i>		Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>		0.0328	0.0849	0.0309	2.5337
<i>ANDI GRY</i>		0.0269	2.5543	0.0737	0.1235
<i>BioSled</i>		0.0359	1.0288	0.1505	6.9133
<i>BioSled Rolls</i>		0.0265	0.0113	0.0275	42.0973
<i>CG2</i>		0.0491	0.0202	0.0228	1.4555
<i>CG2 Rolls</i>		0.0255	0.3119	0.0294	16.7425
<i>CSA</i>		0.0516	1.8634	0.1705	0.4403
<i>CSA Rolls</i>		0.0204	1.6716	0.0719	0.1603
<i>L1</i>		0.0511	0.0240	0.0621	6.6097
<i>L1 Rolls</i>		0.0202	1.2847	0.0205	1.6524
<i>MFF</i>		0.0313	1.9772	0.0492	0.0939
<i>MorphoMobile</i>		0.0440	0.0222	0.0364	6.4280

4.3 Age-Based Study

4.3.1 Age-Based Samples of Normal Distributions

The genuine/imposter distributions shown in Figure 4.32 are sample genuine/imposter match score distributions obtained using the NBIS matcher for male and female strata. They have been chosen to illustrate the typical genuine/imposter score distributions of each type of device and age range used in this study. This study is biased as a large majority of the subjects were between the ages of 20-29. There are no noticeable trends shown within the distributions. The rest of the distributions have been provided in Appendix C.

(a)

(b)

(c)

(d)

Figure 4.32 (a) Neurotech BioSled Rolls for ages 18-19 (b) SourceAFIS FP II Guardian Ages 20 – 29
(c) SourceAFIS Morpho FOTF for ages 30 - 39 (d) Neurotech ANDI Binary for Ages 40 and up

4.3.2 Age-Based Outliers

Figures 4.33 – 4.34 show the outlying distributions from the age-based study. These figures show a slight trend considering each of them are from the age range of 40 years and older, this is most likely caused by older subjects' hands being more worn and wrinkled than those of younger subjects, causing devices to produce lower quality images.

Figure 4.33 (Left) NBIS Crossmatch Seek Avenger Rolls for ages 40 and up (Right) NBIS BioSled Rolls for ages 40 and up

Figure 4.34 (Left) Neurotech FP II Guardian for ages 40 and up (Right) Neurotech L1 for ages 40 and up

4.3.3 Age-Based KLD Values

The values shown in Tables 4.12 – 4.14 show the Kullback Leibler Divergence measures of the genuine and imposter distributions for the different age ranges on each matcher. The genuine KLD values produced for each age range showed little variation with the genuine KLD averages ranging from 0.0207 to 0.0807 and the imposter KLD averages ranging between 1.604 to 2.7602 between age ranges and matchers. The imposter KLD values show slightly more variation which is likely caused by each one to many match having many more imposter

matchers as it does genuine matches. These values reveal the similarity to the general study of the complete dataset and show little to no performance variation across age ranges.

Table 4.12 NBIS Age-Based KLD Values

NBIS KLD Values	18-19		20-29		30-39		40 and up	
<i>Device</i>	Gen	Imp	Gen	Imp	Gen	Imp	Gen	Imp
<i>ANDI BIN</i>	0.0838	0.8833	0.0114	0.1265	0.0489	1.0251	0.1035	0.9506
<i>ANDI GRY</i>	0.0343	0.6518	0.0131	0.2460	0.0730	0.8623	0.1147	0.9976
<i>BioSled</i>	0.0408	1.9944	0.0065	0.0128	0.0554	1.9477	0.0398	1.6229
<i>BioSled Rolls</i>	0.0437	3.4163	0.0136	0.6659	0.0471	1.4452	0.0861	2.5945
<i>CG2</i>	0.1168	3.1837	0.0132	0.0120	0.0786	1.2275	0.0984	2.7650
<i>CG2 Rolls</i>	0.0633	2.1104	0.0071	0.0106	0.0552	0.9662	0.0985	1.6706
<i>CSA</i>	0.0394	1.7727	0.1228	0.8538	0.2237	3.2299	0.0485	5.4184
<i>CSA Rolls</i>	0.0348	4.3977	0.0452	7.4043	0.0762	3.0186	0.0991	3.9052
<i>L1</i>	0.0604	3.4227	0.0092	0.0190	0.0559	4.0166	0.0718	2.9361
<i>L1 Rolls</i>	0.0529	2.4702	0.0258	0.0337	0.1650	2.7238	0.0499	4.7252
<i>MFF</i>	0.0320	1.8875	0.0137	0.1676	0.1250	1.0947	0.0436	1.1245
<i>MorphoMobile</i>	0.0427	0.8768	0.0373	3.5694	0.1000	0.7262	0.1182	0.6724

Table 4.13 Neurotech Age-Based KLD Values

Neurotech	18-19		20-29		30-39		40 and up	
<i>Device</i>	Gen	Imp	Gen	Imp	Gen	Imp	Gen	Imp
<i>ANDI BIN</i>	0.0230	3.6518	0.0022	0.1658	0.0150	3.4460	0.0232	3.8684
<i>ANDI GRY</i>	0.0174	1.2327	0.0029	0.9697	0.0101	0.6944	0.0334	3.1249
<i>BioSled</i>	0.0138	0.4548	0.0033	0.0120	0.0300	0.9620	0.0140	1.2292
<i>BioSled Rolls</i>	0.0167	0.0106	0.0073	0.0012	0.0434	0.0183	0.0079	0.0277
<i>CG2</i>	0.0118	0.1391	0.0036	0.0090	0.0170	0.2309	0.0388	0.3270
<i>CG2 Rolls</i>	0.0109	0.0156	0.0028	0.0015	0.0324	0.0102	0.0178	0.0164
<i>CSA</i>	0.0617	2.1182	0.0153	5.0395	0.1189	1.4025	0.0193	5.4521
<i>CSA Rolls</i>	0.0115	4.1534	0.0377	9.8309	0.0207	6.1675	0.0175	9.6163
<i>L1</i>	0.0203	0.0037	0.0034	0.0002	0.0362	0.0039	0.0289	0.0048
<i>MFF</i>	0.0224	2.8592	0.0059	0.9825	0.0252	1.9548	0.0292	2.4726
<i>MorphoMobile</i>	0.0139	0.1080	0.0044	0.4012	0.0191	0.3839	0.0229	0.4160

Table 4.14 SourceAFIS Age-Based KLD Values

SourceAFIS KLD Values	18-19		20-29		30-39		40 and up	
<i>Device</i>	Gen	Imp	Gen	Imp	Gen	Imp	Gen	Imp
<i>ANDI BIN</i>	0.0360	1.1649	0.0139	3.7860	0.0889	5.4711	0.0760	2.7526
<i>ANDI GRY</i>	0.0584	6.9912	0.0255	3.2567	0.1356	0.9623	0.1072	1.7703
<i>BioSled</i>	0.0944	3.9879	0.0158	0.4477	0.0872	18.7870	0.1062	1.6458
<i>BioSled Rolls</i>	0.0369	4.3084	0.0112	0.0946	0.0423	2.1651	0.0501	1.8843
<i>CG2</i>	0.1343	4.4908	0.0367	1.2740	0.1037	4.5059	0.1089	5.8069
<i>CG2 Rolls</i>	0.0708	8.6481	0.0122	0.0198	0.0461	2.9185	0.0882	2.1999
<i>CSA</i>	0.0368	2.3131	0.0331	1.6879	0.3016	1.0281	0.1147	1.4563
<i>CSA Rolls</i>	0.0461	1.8668	0.0927	0.6877	0.0652	3.2166	0.0540	2.0094
<i>L1</i>	0.0755	3.0207	0.0149	0.4659	0.1115	2.5975	0.0675	3.1641
<i>L1 Rolls</i>	0.1159	4.8319	0.0119	1.3526	0.0743	2.5510	0.0675	1.5156
<i>MFF</i>	0.0866	1.1763	0.0243	1.9716	0.1043	0.9298	0.0611	2.3292
<i>MorphoMobile</i>	0.1229	4.1186	0.0235	10.5725	0.1931	5.1173	0.1420	14.1331

4.4 Ethnicity-Based Study

4.4.1 Ethnicity-Based Study Sample Genuine/Imposter Distributions

The genuine/imposter distributions shown in Figures 4.35 – 4.38 are sample genuine/imposter match score distributions obtained using the each of the three matching algorithms for each possible ethnicity from this collection. They have been chosen to illustrate the typical genuine/imposter score distributions of each type of device and ethnicity used in this study. This study is biased as a large majority of the subjects were of the Caucasian ethnicity. The ethnicities of “Other Pacific Islander” and “Unknown” data were not used in this study as they did not have enough results to provide distributions or analysis. There are no noticeable trends shown within the distributions. The rest of the distributions have been provided in Appendix D.

Figure 4.35 (Left) NBIS ANDI Binary for the African Ethnicity (Right) NBIS ANDI Binary for the Middle Eastern Ethnicity

Figure 4.36 (Left) NBIS ANDI Greyscale for the Asian Ethnicity (Right) NBIS BioSled for the Asian Indian Ethnicity

Figure 4.37 (Left) Neurotech BioSled for the Other Ethnicity (Right) Neurotech FP II Guardian for the Hispanic Ethnicity

Figure 4.38 (Left) SourceAFIS Crossmatch Seek Avenger Rolls For the African American Ethnicity (Right) SourceAFIS MorphoMobile for the Caucasian Ethnicity

4.4.2 Ethnicity-Based Outliers

The outliers that were produced for this study all involved the American Indian Ethnicity. Considering Figure 3.5, these graphs are most likely caused by the low number of subjects identified as American Indian. The large variation in these graphs also had an effect on the KLD values for this ethnicity, shown in Table 4.18.

Figure 4.39 (Left) NBIS FP II Rolls For the American Indian Ethnicity (Right) NBIS Crossmatch Seek Avenger for the American Indian Ethnicity

Figure 4.40 (Left) NBIS Crossmatch Seek Avenger Rolls for the American Indian Ethnicity (Right) Neurotech BioSled for the American Indian Ethnicity

Figure 4.41 (Left) Neurotech Crossmatch Seek Avenger for the American Indian Ethnicity (Right) Neurotech Crossmatch Seek Avenger Rolls for the American Indian Ethnicity

Figure 4.42 (Left) SourceAFIS FP II Guardian for the American Indian Ethnicity (Right) SourceAFIS Crossmatch Seek Avenger for the American Indian Ethnicity

Figure 4.43 (Left) SourceAFIS Crossmatch Seek Avenger Rolls for the American Indian Ethnicity (Right) SourceAFIS MorphoMobile for the American Indian Ethnicity

4.4.3 Ethnicity-Based KLD Values

The KLD values for the ethnicities involved in this study showed little variation with averages ranging from 0.0655 to 1.2355 for genuine distributions and 2.0559 to 3.7915 for the imposter distributions. Table 4.15 shows the averages KLD values among devices for each ethnicity. Tables 4.16 – 4.24 show the KLD values produced by each matcher and device by ethnicity. These values reveal the similarity to the original dataset and show little to no performance variation across ethnicities. The only genuine outlier and highest KLD value, the American Indian ethnicity averaged a value of 1.2355, the main reason for this variation is because this ethnicity occupied a very small subset of the data as well as the distributions shown in Figures 4.39 – 4.43.

Table 4.15 African Ethnicity KLD

Average KLD Value per Ethnicity		
	Genuine	Imposter
African	0.1489	2.6386
African American	0.0940	2.1271
American Indian	1.2355	2.8202
Asian	0.0736	2.3542
Asian Indian	0.0849	3.7915
Caucasian	0.1290	2.7291
Hispanic	0.1761	2.9911
Middle Eastern	0.1090	2.2396
Other	0.0655	2.0559

Table 4.16 African Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
<i>Device</i>	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>	0.0783	3.7148	0.0097	11.8608	0.2958	2.7067
<i>ANDI GRY</i>	0.0510	1.7698	0.0311	2.5344	0.4007	1.5936
<i>BioSled</i>	1.1091	1.3129	0.1777	1.294	0.4054	2.0859
<i>BioSled Rolls</i>	0.0779	1.8666	0.0744	0.0389	0.0877	1.3681
<i>CG2</i>	0.2033	1.9118	0.0442	0.382	0.1495	3.1481
<i>CG2 Rolls</i>	0.0749	1.6157	0.0462	0.0045	0.1186	1.4545
<i>CSA</i>	0.0744	1.1948	0.074	8.7876	0.1544	1.8807
<i>CSA Rolls</i>	0.1097	4.4832	0.0204	11.2825	0.0627	1.3722
<i>L1</i>	0.1288	2.8118	0.158	0.0027	0.1761	1.9177
<i>L1 Rolls</i>	0.1106	3.7102			0.0652	2.1790
<i>MFF</i>	0.1435	2.3449			0.0991	3.9406
<i>SMM</i>	0.0581	0.4241	0.0151	0.4388	0.1763	2.2796

As stated earlier the Neurotech matcher removed images of bad quality and that is why there are blank spots in this table as there were not enough results to process the KLD values. There are no genuine outlying values and the outlying values of the imposters are most likely caused by the fact that for every match there are more imposter matches than there are genuine

matches, so imposter values should show more variation. These KLD values are inconclusive as they show little to no performance variation.

Table 4.17 African American Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
<i>Device</i>	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>	0.0958	2.1134	0.0149	5.2858	0.1160	1.6159
<i>ANDI GRY</i>	0.0829	0.8404	0.012	2.4253	0.1484	1.7079
<i>BioSled</i>	0.0744	1.6203	0.019	0.9989	0.1706	2.0052
<i>BioSled Rolls</i>	0.0757	1.9739	0.0172	0.0317	0.0599	1.8500
<i>CG2</i>	0.1037	1.4777	0.0316	0.0974	0.2349	0.4904
<i>CG2 Rolls</i>	0.0621	0.9826	0.0208	0.0052	0.0525	1.0825
<i>CSA</i>	0.1006	1.3257	0.0186	5.251	0.2122	1.8233
<i>CSA Rolls</i>	0.0769	3.1626	0.0244	9.1188	0.1688	1.5454
<i>L1</i>	0.1638	3.5862	0.0152	0.0029	0.1865	3.9513
<i>L1 Rolls</i>	0.1393	2.2078			0.0430	1.5083
<i>MFF</i>	0.0915	1.0985			0.0971	6.1422
<i>SMM</i>	0.1340	0.5541	0.0405	0.3605	0.2903	4.0777

As stated above the Neurotech matcher removed images of bad quality and that is why there are blank spots in this table as there were not enough results to process the KLD values. There are no genuine outlying values and the outlying values of the imposters are most likely caused by the fact that for every match there are more imposter matches than there are genuine matches, so imposter values will show more variation. These KLD values are inconclusive as they show little to no performance variation.

Table 4.18 American Indian Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
<i>Device</i>	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>	0.1323	3.4101	0.008	10.1086	0.1132	4.7527
<i>ANDI GRY</i>	0.4058	2.3173	0.0299	2.9429	0.2532	1.3756
<i>BioSled</i>	0.2299	1.6737	0.2007	0.9628	1.6077	1.8946
<i>BioSled Rolls</i>	0.1608	1.8898	0.3719	0.0142	0.1340	1.8281
<i>CG2</i>	0.1522	1.6136	0.1273	0.4346	11.5257	3.1644
<i>CG2 Rolls</i>	16.2262	1.5360	0.0367	0.0117	0.2110	1.2978
<i>CSA</i>	0.6285	3.3994	0.3452	7.3243	1.4274	2.5726
<i>CSA Rolls</i>	0.4880	7.7471	0.256	13.0463	1.1587	1.6133
<i>L1</i>	0.0855	2.4008	0.042	0.0021	0.3275	2.1223
<i>L1 Rolls</i>	1.0198	3.2321			0.3340	1.8069
<i>MFF</i>	0.1508	2.7805	0.0272	4.5010	0.2095	1.8234
<i>SMM</i>	0.7334	0.5920	0.4359	0.405	3.6469	2.1081

As stated above the Neurotech matcher removed images of bad quality and that is why there are blank spots in this table as there were not enough results to process the KLD values. The outlying values for genuine matches show variation for the FP II Guardian and this is most likely caused from there being such a small number of subjects identifying as American Indian that participated in this collection as shown in Figures 3.6 and 3.8 point out.

Table 4.19 Asian Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
<i>Device</i>	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>	0.0840	0.9661	0.0171	3.073	0.0840	4.7585
<i>ANDI GRY</i>	0.1544	0.7247	0.0139	0.7672	0.1145	5.1985
<i>BioSled</i>	0.0697	2.2829	0.0071	0.7864	0.1331	2.9401
<i>BioSled Rolls</i>	0.0348	1.6884	0.0343	0.023	0.0268	1.5402
<i>CG2</i>	0.0359	3.6145	0.0219	0.29	0.1013	4.2584
<i>CG2 Rolls</i>	0.0609	1.0781	0.0156	0.0118	0.0552	2.3071
<i>CSA</i>	0.1235	0.7760	0.0267	4.9202	0.2142	1.0064
<i>CSA Rolls</i>	0.0646	3.4451	0.0184	5.9803	0.0797	4.0234
<i>L1</i>	0.0797	4.1767	0.0476	0.0046	0.2285	3.3654
<i>L1 Rolls</i>	0.0824	3.1502			0.0987	1.2757
<i>MFF</i>	0.0782	1.1225	0.0438	3.1822	0.1283	2.5673
<i>SMM</i>	0.0992	0.8352	0.0219	0.1911	0.0760	6.0662

As stated above the Neurotech matcher removed images of bad quality and that is why there are blank spots in this table as there were not enough results to process the KLD values. There are no genuine outlying values and the outlying values of the imposters are most likely caused by the fact that for every match there are more imposter matches than there are genuine matches, so imposter values will show more variation. These KLD values are inconclusive as they show little to no performance variation.

Table 4.20 Asian Indian Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
<i>Device</i>	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>	0.1264	1.1123	0.0179	3.4657	0.0501	3.6349
<i>ANDI GRY</i>	0.1199	0.6402	0.0115	1.506	0.1811	1.6904
<i>BioSled</i>	0.0495	1.6303	0.029	0.6308	0.1587	3.2662
<i>BioSled Rolls</i>	0.0640	1.1785	0.0062	0.0119	0.0287	59.8285
<i>CG2</i>	0.0854	3.7023	0.0242	0.1915	0.1493	2.9030
<i>CG2 Rolls</i>	0.0377	0.7534	0.0166	0.0147	0.0658	3.8008
<i>CSA</i>	0.1555	4.0159	0.0206	2.4215	0.2086	1.0524
<i>CSA Rolls</i>	0.1786	4.2146	0.0805	4.7043	0.1789	1.6509
<i>L1</i>	0.0133	4.0681	0.0309	0.0042	0.1051	2.0692
<i>L1 Rolls</i>	0.0592	2.9283			0.0603	2.1540
<i>MFF</i>	0.1142	1.1213	0.0325	2.7939	0.0915	0.9591
<i>SMM</i>	0.1598	0.7430	0.0186	0.1396	0.2404	7.7016

For Tables 4.20 through 4.22 as already stated, the Neurotech matcher removed images of bad quality and that is why there are blank spots in this table as there were not enough results to process the KLD values. There are no genuine outlying values and the outlying values of the imposters are most likely caused by the fact that for every match there are more imposter matches than there are genuine matches, so imposter values will show more variation. These KLD values are inconclusive as they show little to no performance variation.

Table 4.21 Caucasian Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>Device</i>						
<i>ANDI BIN</i>	0.0451	1.2735	0.0054	4.9975	0.0217	4.9814
<i>ANDI GRY</i>	0.0177	0.2685	0.0051	0.1466	0.0348	5.4394
<i>BioSled</i>	0.0126	0.0685	0.0086	0.1891	0.0809	0.5678
<i>BioSled Rolls</i>	0.0147	0.4063	0.0042	0.0155	0.0195	0.3038
<i>CG2</i>	0.0188	0.5531	0.0066	0.1977	0.0453	1.9521
<i>CG2 Rolls</i>	0.0203	1.6604	0.0187	0.0238	0.0223	6.5154
<i>CSA</i>	0.0130	0.7696	0.0305	5.8025	0.0317	0.6262
<i>CSA Rolls</i>	0.0114	10.4262	0.0049	0.8022	0.0125	1.1713
<i>L1</i>	0.0191	0.1701	0.009	0.0005	0.0174	1.1054
<i>L1 Rolls</i>	0.0127	0.2256			0.0356	2.1613
<i>MFF</i>	0.0133	2.6603	0.3185	16.0444	0.0555	0.4224
<i>SMM</i>	0.0220	1.7941	3.4609	8.4185	0.0440	13.3578

Table 4.22 Hispanic Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>Device</i>						
<i>ANDI BIN</i>	0.1275	3.9449	0.0159	3.4466	0.0701	1.9296
<i>ANDI GRY</i>	0.1196	0.5169	0.0162	0.5137	0.0884	1.1892
<i>BioSled</i>	0.0451	1.8945	0.0298	0.0173	0.1920	1.8107
<i>BioSled Rolls</i>	0.0863	0.2200	0.0167	0.0226	0.0685	0.1880
<i>CG2</i>	0.0451	1.5253	0.0383	0.1664	0.0971	6.6522
<i>CG2 Rolls</i>	0.0720	2.0993	0.0163	0.016	0.0714	3.2236
<i>CSA</i>	0.1817	1.2669	0.0166	2.2627	0.1413	2.8328
<i>CSA Rolls</i>	0.0300	3.1587	0.0163	4.6099	0.0894	2.3991
<i>L1</i>	0.0292	3.6985	0.024	0.0034	0.1326	2.5505
<i>L1 Rolls</i>	0.0485	2.9663			0.0691	2.0646
<i>MFF</i>	0.1302	1.1028	0.3185	16.0444	0.1329	3.5195
<i>SMM</i>	0.0447	0.7097	3.4609	8.4185	0.0796	17.7029

Table 4.23 Middle Eastern Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
<i>Device</i>	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>	0.1897	0.9501	0.0567	2.7733	0.1821	1.6499
<i>ANDI GRY</i>	0.1799	0.4859	0.0509	1.7713	0.2166	3.6323
<i>BioSled</i>	0.0942	1.3721	0.0299	0.7524	0.2231	2.9841
<i>BioSled Rolls</i>	0.0573	2.0614	0.0219	0.0228	0.1069	2.4911
<i>CG2</i>	0.0991	3.0393	0.0211	0.2659	0.1805	3.7760
<i>CG2 Rolls</i>	0.0197	1.0196	0.0274	0.0091	0.0553	1.8371
<i>CSA</i>	0.2012	3.0568	0.1126	3.3431	0.2585	1.2818
<i>CSA Rolls</i>	0.1629	3.0872	0.0375	7.193	0.1423	1.1311
<i>L1</i>	0.0284	1.2655	0.0399	0.0036	0.1101	3.7773
<i>L1 Rolls</i>	0.0442	2.7705			0.0589	1.3476
<i>MFF</i>	0.1744	1.1906	0.0636	1.9447	0.1368	1.1941
<i>SMM</i>	0.1195	0.6415	0.0162	0.1793	0.2942	14.0849

Table 4.24 Other Ethnicity KLD

	NBIS		Neurotech		SourceAFIS	
<i>Device</i>	Genuine	Imposter	Genuine	Imposter	Genuine	Imposter
<i>ANDI BIN</i>	0.1411	1.1652	0.0309	2.9675	0.0872	1.1178
<i>ANDI GRY</i>	0.1260	0.9902	0.0302	0.4649	0.1441	1.4404
<i>BioSled</i>	0.0306	0.8462	0.0166	1.2776	0.0888	2.9397
<i>BioSled Rolls</i>	0.0979	2.8849	0.0145	0.0199	0.1010	1.4833
<i>CG2</i>	0.0582	3.5313	0.0203	0.2719	0.0951	3.8648
<i>CG2 Rolls</i>	0.1028	1.0031	0.0222	0.0103	0.0355	1.9505
<i>CSA</i>	0.0718	0.5612	0.0237	3.0206	0.0519	0.8744
<i>CSA Rolls</i>	0.0518	3.2520	0.0349	4.8668	0.0609	0.9662
<i>L1</i>	0.0657	3.3504	0.0379	0.0041	0.0997	2.0550
<i>L1 Rolls</i>	0.0783	3.0633			0.0847	4.0564
<i>MFF</i>	0.0935	1.3848	0.0556	2.8755	0.0638	1.3916
<i>SMM</i>	0.0762	0.6609	0.0192	0.2111	0.0784	11.1336

For Tables 4.23 through 4.24 as previously stated, the Neurotech matcher removed images of bad quality and that is why there are blank spots in this table as there were not enough results to process the KLD values. There are no genuine outlying values and the outlying values

of the imposters are most likely caused by the fact that for every match there are more imposter matches than there are genuine matches, so imposter values will show more variation. These KLD values are inconclusive as they show little to no performance variation.

4.5 Issues Faced with Devices and Matchers Which can be Observed in the Results

The L1 rolled images sometimes caused complications from the matchers, so in some cases there are no results from this specific category. Neurotech's Matcher removed images that were of bad quality, and this resulted in some tests having fewer images, or non at all. This became more of an issue once the data was subdivided into demographic strata. Another obstacle that was faced, involved the Morpho Finger-On-The-Fly, this device tended not to allow for capture of subjects that had a darker complexion, which once again only became an issue once the data was broken into demographic strata. The InnerID was removed from the collection midway through when it stopped working. The images that were produced are low in quality, and stand out among the other results.

Chapter 5:

Conclusion

5.1 Conclusions

The main goal of this research effort was to investigate the interoperability of contactless fingerprinting devices with the currently used livescan legacy fingerprinting devices and techniques. This goal was accomplished through performing these tasks; data collection, image pre-processing, match score generation and data analysis. The collection of data was achieved as 450 participant's data was collected and each participant was guided through the collection successfully. Our pre-processing involved doing segmentation of the images that involved more than one print and extraction was performed on duplicates and erroneously captured prints. Pre-processing also involved developing the matching programs from the software development kits, the programs were each able to run all of the data through to produce match score csv files. Succession of the goal of Data Analysis is shown in all of the results tables, these tables include TMR1 rates, EER values, and genuine/imposter distributions were also produced. The goal of investigation into stratification of contactless devices to see if a person's demographics share a relationship with the capabilities of their fingerprints, was examined and was inconclusive. It is important to note that this dataset is biased as a large amount of the subjects were between the ages of 20 to 29 and of the Caucasian ethnicity. With the similarity shown by the Kullback Leibler Divergence measurements, from this small data set, there was little to no performance variation across demographics. Other statistical analysis could have displayed these results differently and have been more conclusive, such as using the Weighted Hamming Distance instead of the KLD. If this dataset were larger, a larger variation could be experienced, possibly showing devices that favored certain demographics or conversely worked unfavorably with certain demographics.

These Results are to be taken as a snapshot of the technology in terms of the interoperability with legacy based methods. Based on this snapshot during the development of contactless fingerprints Rank1 accuracy is between 74.33 and 98.68 percent with contact based methods. The contactless fingerprint Rank 1 accuracy is between 74.66 and 97.27 percent with other contactless devices. We think the lower values may be because incompatibility with the matchers, low quality images, and lack of deformation. The results shown depict the accuracy of contactless devices in comparison to the current widely used contact-based fingerprinting technology. Table 5.1 shows the TMR1 Ranges for each device type combination. Table 5.2 displays the ranges of TMR1 accuracy across all the matchers. The Equal Error Rates can be found in Tables 5.3 through 5.5 for all matching runs with each matcher.

Due to the growing number of contactless devices that are currently available, interoperability between contactless devices and contact-based devices is more significant now than it has ever been however, without the availability of a larger dataset, it cannot be conclusively proven that contact-based devices and non-contact devices are completely compatible and interoperable

Table 5.1 TMR1 Ranges by Matcher

	Device	TMR1 Range
<i>NBIS</i>	10print – Contact	87.37 – 91.77
	10print – Contactless W/O InnerID	68.24 – 85.06
	10print – Contactless W InnerID	2.08 – 85.08
	Contact – Contact	95.71 - 100
	Contactless – Contactless W/O InnerID	74.66 - 100
	Contactless – Contactless W Inner	0.32 - 100
	Contact – Contactless W/O Inner ID	70.31 – 95.93
	Contact – Contactless W InnerID	0 – 95.93
	Contact Rolls – Contact Rolls	87.92 - 100
<i>Neurotech</i>	10print – Contact	96.28 – 99.5
	10print – Contactless W/O InnerID	
	10print – Contactless W InnerID	96.21 – 97.75
	Contact – Contact	97.15 - 100
	Contactless – Contactless W/O InnerID	94.89 – 100
	Contactless – Contactless Inner	1.74 – 100
	Contact – Contactless W/O Inner ID	93.83 – 98.69
	Contact – Contactless W InnerID	0.65 – 98.69
	Contact Rolls – Contact Rolls	96.15 - 100
<i>SourceAFIS</i>	10print – Contact	87.37 – 91.77
	10print – Contactless W/O InnerID	68.24 – 85.06
	10print – Contactless W InnerID	2.08 – 85.06
	Contact – Contact	95.71 - 100
	Contactless – Contactless W/O InnerID	74.66 - 100
	Contactless – Contactless W InnerID	0.32 - 100
	Contact – Contactless W/O Inner ID	70.31 – 95.93
	Contact – Contactless W InnerID	0 – 95.93
	Contact Rolls – Contact Rolls	87.92 - 100

Table 5.2 Range of TMR1 Rates between Matchers

Range of TMR1 Rates between matchers			
10p - 10p	99.75 – 100	BIOSLED - CSA	96.07 – 97.15
10p - ANDI BIN	77.69 – 97.64	BIOSLED - CG2	95.71 – 97.22
10p - ANDI GRY	68.24 – 97.75	BIOSLED - INNERID	1.68 – 2.02
10p - BIOSLED	88 – 96.28	BIOSLED - L1	96 -97.38
10p - CSA	91.33 – 99.19	BIOSLED - SMM	95.89 – 97.17
10p - CG2	91.46 – 99.25	BIOSLED - MFF	90.32 – 96.56
10p - INNERID	2.08 – 2.08	CSA - CSA	100 - 100
10p - L1	91.77 – 99.5	CSA - CG2	98.96 – 99.48
10p - SMM	87.37 – 97.69	CSA - INNERID	2.09 – 2.42
10p - MFF	85.06 – 96.21	CSA - L1	98.97 – 99.74
ANDI BIN - ANDI BIN	100 – 100	CSA - SMM	99.34 – 99.87
ANDI BIN - ANDI GRY	99.75 – 99.88	CSA - MFF	95.93 – 98.69
ANDI BIN - BIOSLED	84.32 – 93.83	CG2 - CG2	100 – 100
ANDI BIN - CSA	88.87 – 95.81	CG2 - INNERID	0.98 – 0.99
ANDI BIN - CG2	89.78 – 95.86	CG2 - L1	98.37 – 98.72
ANDI BIN - INNERID	1.56 – 2.82	CG2 - SMM	97.49 – 98.81
ANDI BIN - L1	86.66 – 95.43	CG2 - MFF	95.51 – 98.11
ANDI BIN - SMM	87.5 – 95.06	INNERID - INNERID	100 – 100
ANDI BIN - MFF	83.86 – 94.89	INNERID - L1	0 – 1.29
ANDI GRY - ANDI GRY	100 – 100	INNERID - SMM	0.32 – 0.65
ANDI GRY - BIOSLED	70.31 – 94.42	INNERID - MFF	0.32 – 1.94
ANDI GRY - CSA	77.45 – 96.81	L1 - L1	100 – 100
ANDI GRY - CG2	76.72 – 96.55	L1 - SMM	98 – 99.29
ANDI GRY - INNERID	1.58 – 1.74	L1 - MFF	95.35 – 98.37
ANDI GRY - L1	74.79 – 97.09	SMM - SMM	100 – 100
ANDI GRY - SMM	72.41 – 96.35	MFF - SMM	87.52 - 98.56
ANDI GRY - MFF	74.66 – 97.27	MFF - MFF	100 – 100
BIOSLED - BIOSLED	100 – 100		

Tables 5.1 – 5.2 show the summarized TMR1 Accuracy for each of the matching runs and collection methods. The InnerID produced very low match accuracy with both contact and contactless devices. As expected, the matching accuracy generally was highest when a device was matched against its same type. The ANDI OTG binary images produced higher accuracy results than that of the ANDI OTG greyscale images. The matching accuracy between ten-print card images and contactless devices was lower than that with contact-based devices, this most likely is caused by the fact there was only one image for each subject for this dataset compared to at least two sessions of images for every other device. It could also have to do with the modulation transfer of the ten-print images from the scanner. The matching accuracy was better for the ANDI OTG Binary images when it was against the contact-based devices than against the

Morpho FOTF, the way these devices translate their images into an image that is usable with contact-based images may be different causing different features to be extracted from similar images. The ANDI Greyscale images performed the worst in terms of match accuracy amongst the contactless devices (excluding the InnerID), this may have been caused because the feature extraction process for the matchers used may be different for greyscale images. The Morpho FOTF performed best out of the contactless devices against contact-based methods, may have occurred due to the Morpho FOTF collecting double the amount of images compared to most the other devices.

It is important to note that, if this dataset was much larger, the results of this analysis could improve and be more conclusive and the statistical variations could be reduced.

Table 5.3 Equal Error Rates for Each Matching Run

Match	NBIS EER	Neurotech EER	SourceAFIS EER
10p-10p	0.0000	0.0000	0.0000
10p-ANDI BIN	0.1207	0.0411	0.1500
10p-ANDI GRY	0.1495	0.0309	0.2401
10p-BIO	0.0778	0.0316	0.1034
10p-CSA	0.0587	0.0123	0.0660
10p-CG2	0.0558	0.0107	0.0911
10p-L1	0.0561	0.0100	0.0748
10p-MFF	0.0980	0.0269	0.1829
10p-SMM	0.0806	0.0273	0.1111
10p-IID	0.4660		0.4861
ANDI BIN-ANDI BIN	0.0231	0.0171	0.0309
ANDI BIN-ANDI GRY	0.0401	0.0171	0.0782
ANDI BIN-BIO	0.0997	0.0479	0.1105
ANDI BIN-CSA	0.0723	0.0280	0.0782
ANDI BIN-CG2	0.0769	0.0328	0.0899
ANDI BIN-L1	0.0878	0.0335	0.0996
ANDI BIN-MFF	0.1048	0.0377	0.1641
ANDI BIN-SMM	0.0919	0.0370	0.0859
ANDI BIN-IID	0.4714	0.4298	0.4767
ANDI GRY-ANDI GRY	0.0345	0.0166	0.0612
ANDI GRY-BIO	0.1549	0.0491	0.1698
ANDI GRY-CSA	0.1178	0.0281	0.1420
ANDI GRY-CG2	0.1155	0.0352	0.1487
ANDI GRY-L1	0.1249	0.0304	0.1640
ANDI GRY-MFF	0.1302	0.0260	0.2232
ANDI GRY-SMM	0.1366	0.0357	0.1523
ANDI GRY-IID	0.4727	0.4841	0.4667
BIO-BIO	0.0256	0.0151	0.0238
BIO-CSA	0.0378	0.0227	0.0359
BIO-CG2	0.0483	0.0229	0.0387
BIO-L1	0.0452	0.0238	0.0392
BIO-MFF	0.0950	0.0251	0.1007
BIO-SMM	0.0466	0.0232	0.0438
BIO-IID	0.4622	0.4342	0.4748
CSA-CSA	0.0049	0.0013	0.0020
CSA-CG2	0.0154	0.0059	0.0137
CSA-L1	0.0181	0.0032	0.0107
CSA-MFF	0.0645	0.0134	0.0706
CSA-SMM	0.0219	0.0053	0.0166
CSA-IID	0.4490	0.4507	0.4798
CG2-CG2	0.0172	0.0161	0.0189
CG2-L1	0.0217	0.0129	0.0192
CG2-MFF	0.0566	0.0159	0.0785
CG2-SMM	0.0339	0.0114	0.0299
CG2-IID	0.4700	0.4572	0.4886
L1-L1	0.0134	0.0112	0.0112
L1-MFF	0.0622	0.0129	0.0877
L1-SMM	0.0291	0.0089	0.0265
MFF-MFF	0.0111	0.0078	0.0295
MFF-SMM	0.0837	0.0166	0.0970
SMM-SMM	0.0175	0.0070	0.0108
IID-L1	0.4477	0.4446	0.4817
IID-MFF	0.4816	0.4601	0.4960
IID-SMM	0.4778	0.4591	0.4810
IID-IID	0.1392	0.0678	0.1654

Table 5.4 Equal Error Rates For Each Device

EER VALUES FOR THE GENUINE/IMPOSTER RUNS OF EACH DEVICE			
MATCH	NBIS	Neurotech	SourceAFIS
Andi Binary	0.0429	0.0346	0.0587
Andi Greyscale	0.0594	0.0336	0.1159
BioSled	0.0506	0.0307	0.0479
BioSled Rolls	0.0398	0.0201	0.0744
CG2	0.0342	0.0298	0.0376
CG2 Rolls	0.0137	0.0070	0.0194
CSA	0.0088	0.0027	0.0027
CSA Rolls	0.0251	0.0076	0.0363
InnerID	0.2308	0.1239	0.2770
L1	0.0267	0.0223	0.0222
Morpho FOTF	0.0145	0.0123	0.0405
MorphoMobile	0.0326	0.0141	0.0164

Table 5.5 Equal Error Rates For Each Rolled Matching Run

EER VALUES FOR EACH ROLLS MATCHING RUN			
MATCH	NBIS	Neurotech	SourceAFIS
10p Rolls-10p Rolls	0.0024	0.0000	0.0000
10p Rolls-BIO Rolls	0.0848	0.0232	0.1567
10p Rolls-CSA Rolls	0.0678	0.0136	0.1381
10p Rolls-CG2 Rolls	0.0753	0.0099	0.1254
10p Rolls-L1 Rolls	0.0755	0.0127	0.1300
BIO Rolls-BIO Rolls	0.0206	0.0099	0.0430
BIO Rolls-CSA Rolls	0.0462	0.0149	0.0707
BIO Rolls-CG2 Rolls	0.0452	0.0127	0.0662
BIO Rolls-L1 Rolls	0.0469	0.0142	0.0856
CSA Rolls-CSA Rolls	0.0130	0.0038	0.0174
CSA Rolls-CG2 Rolls	0.0230	0.0038	0.0396
CSA Rolls-L1 Rolls	0.0244	0.0056	0.0529
CG2 Rolls-CG2 Rolls	0.0080	0.0035	0.0096
CG2 Rolls-L1 Rolls	0.0245	0.0058	0.0456
L1 Rolls-L1 Rolls	0.0162		0.0259

Tables 5.3 – 5.5 depict the equal error rates of each matching run. The lower the EER, the higher the accuracy of the matching run. The EER values highlighted in red indicate the InnerID values which, as previously discussed, produced the lowest matching accuracy obtained in this study, also produced highest EER values (~0.4). The overall average cross-examined Equal Error Rate was 0.1240, the values above this average are denoted in yellow, the values below the

average are denoted in black. The overall average EER value was 0.0463 among all the devices for Table 5.4 values above this average are denoted in yellow.

5.2 Future Work

All the conclusions that have been listed above are based on the match score values that have been obtained from only 3 different contactless fingerprinting devices, more devices should be explored to get a better range of results. A larger dataset would also aid in the research on contactless devices. A larger dataset consisting of thousands of subjects would yield more conclusive results. Further study could also include using the match score distributions for the left-hand fingers to check for similarities in match performance. Different statistical analysis could be performed on the data that could better display the results. Future work could also include using the current versions of the devices used in this study and comparing the data produced with our data. A comparison could be performed on the data from this collection and the data from the phase 1 collection for the recurring subjects. Further Study could also include running the data on a different matching algorithm than the three already used. A larger dataset with more contactless devices would make the biggest impact to contactless fingerprinting research community. Another study could be done with less bias towards age ranges and ethnicities, with there being a larger variety of age ranges and ethnicities data being collected. If this study were to be done again, the two sessions could be spanned over a few weeks to create more variation between sessions.

Appendix A

General Study of

All Data

This Appendix shows the results from the general study using all of the data without being divided up into any demographic strata. The TMR1 Tables included in this section, show the TMR1 Results from every matching run that was performed. The genuine and imposter distributions for each matching run are shown in this section as well as the distributions each device ran against itself. The Receiver Operating Characteristic Curves or ROC Curves are shown for each of the devices used in this collection, a table of values is shown to identify the area under the curve for each ROC curve. All of the results stated above are shown for each of the three matchers used. The EER values are shown for each matcher for all matching runs. At the end of this appendix there are box plots that represent the number of minutiae found in images from each device, this data came from the NBIS matcher.

Table A.1 NBIS TMR1 Table

<i>NBIS</i>	<i>Match</i>	<i>Total</i>	<i>TMR1</i>	<i>FMR1</i>	<i>TMR1 Rate</i>	<i>FMR1 Rate</i>
	10p - 10p	405	405	0	100.00	0.00
	10p - ANDI BIN	381	296	85	77.69	22.31
	10p - ANDI GRY	381	260	121	68.24	31.76
	10p - BIO	375	330	45	88.00	12.00
	10p - CSA	369	337	32	91.33	8.67
	10p - CG2	398	364	34	91.46	8.54
	10p - IID	144	3	141	2.08	97.92
	10p - L1	401	368	33	91.77	8.23
	10p - SMM	388	339	49	87.37	12.63
	10p - MFF	395	336	59	85.06	14.94
	ANDI BIN - ANDI BIN	830	830	0	100.00	0.00
	ANDI BIN - ANDI GRY	830	829	1	99.88	0.12
	ANDI BIN - BIO	767	656	111	85.53	14.47
	ANDI BIN - CSA	753	679	74	90.17	9.83
	ANDI BIN - CG2	811	738	73	91.00	9.00
	ANDI BIN - IID	316	5	311	1.58	98.42
	ANDI BIN - L1	820	721	99	87.93	12.07
	ANDI BIN - SMM	800	700	100	87.50	12.50
	ANDI BIN - MFF	812	691	121	85.10	14.90
	ANDI GRY - ANDI GRY	831	831	0	100.00	0.00
	ANDI GRY - BIO	768	540	228	70.31	29.69
	ANDI GRY - CSA	754	584	170	77.45	22.55
	ANDI GRY - CG2	812	623	189	76.72	23.28
	ANDI GRY - IID	316	5	311	1.58	98.42
	ANDI GRY - L1	821	614	207	74.79	25.21
	ANDI GRY - SMM	801	580	221	72.41	27.59
	ANDI GRY - MFF	813	607	206	74.66	25.34
	BIO - BIO	806	806	0	100.00	0.00
	BIO - CSA	738	709	29	96.07	3.93
	BIO - CG2	792	758	34	95.71	4.29
	BIO - IID	297	6	291	2.02	97.98
	BIO - L1	801	769	32	96.00	4.00
	BIO - SMM	778	746	32	95.89	4.11
	BIO - MFF	785	709	76	90.32	9.68
	CSA - CSA	784	784	0	100.00	0.00
	CSA - CG2	771	763	8	98.96	1.04
	CSA - IID	289	7	282	2.42	97.58
	CSA - L1	778	770	8	98.97	1.03
	CSA - SMM	758	753	5	99.34	0.66
	CSA - MFF	762	731	31	95.93	4.07
	CG2 - CG2	870	870	0	100.00	0.00
	CG2 - IID	306	3	303	0.98	99.02
	CG2 - L1	860	846	14	98.37	1.63
	CG2 - SMM	838	817	21	97.49	2.51
	CG2 - MFF	847	809	38	95.51	4.49
	IID - IID	319	319	0	100.00	0.00
	IID - L1	315	0	315	0.00	100.00
	IID - SMM	313	1	312	0.32	99.68
	IID - MFF	315	1	314	0.32	99.68
	L1 - L1	883	883	0	100.00	0.00
	L1 - SMM	849	832	17	98.00	2.00
	L1 - MFF	861	821	40	95.35	4.65
	SMM - SMM	859	859	0	100.00	0.00
	MFF - SMM	1666	1458	208	87.52	12.48
	MFF - MFF	1734	1734	0	100.00	0.00

Table A.2 Neurotech TMR1 Table

Neurotech	Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
	10p - 10p	388	388	0	100.00	0.00
	10p - ANDI BIN	381	372	9	97.64	2.36
	10p - ANDI GRY	355	347	8	97.75	2.25
	10p - BIO	376	362	14	96.28	3.72
	10p - CSA	370	367	3	99.19	0.81
	10p - CG2	399	396	3	99.25	0.75
	10p - L1	402	400	2	99.50	0.50
	10p - SMM	389	380	9	97.69	2.31
	10p - MFF	396	381	15	96.21	3.79
	ANDI BIN - ANDI BIN	825	825	0	100.00	0.00
	ANDI BIN - ANDI GRY	804	802	2	99.75	0.25
	ANDI BIN - BIO	778	730	48	93.83	6.17
	ANDI BIN - CSA	764	732	32	95.81	4.19
	ANDI BIN - CG2	822	788	34	95.86	4.14
	ANDI BIN - IID	319	9	310	2.82	97.18
	ANDI BIN - L1	832	794	38	95.43	4.57
	ANDI BIN - SMM	810	770	40	95.06	4.94
	ANDI BIN - MFF	822	780	42	94.89	5.11
	ANDI GRY - ANDI GRY	796	796	0	100.00	0.00
	ANDI GRY - BIO	735	694	41	94.42	5.58
	ANDI GRY - CSA	721	698	23	96.81	3.19
	ANDI GRY - CG2	783	756	27	96.55	3.45
	ANDI GRY - IID	287	5	282	1.74	98.26
	ANDI GRY - L1	790	767	23	97.09	2.91
	ANDI GRY - SMM	767	739	28	96.35	3.65
	ANDI GRY - MFF	768	747	21	97.27	2.73
	BIO - BIO	802	802	0	100.00	0.00
	BIO - CSA	738	717	21	97.15	2.85
	BIO - CG2	792	770	22	97.22	2.78
	BIO - IID	297	5	292	1.68	98.32
	BIO - L1	801	780	21	97.38	2.62
	BIO - SMM	778	756	22	97.17	2.83
	BIO - MFF	785	758	27	96.56	3.44
	CSA - CSA	783	783	0	100.00	0.00
	CSA - CG2	771	767	4	99.48	0.52
	CSA - IID	287	6	281	2.09	97.91
	CSA - L1	778	776	2	99.74	0.26
	CSA - SMM	758	757	1	99.87	0.13
	CSA - MFF	762	752	10	98.69	1.31
	CG2 - CG2	867	867	0	100.00	0.00
	CG2 - IID	304	3	301	0.99	99.01
	CG2 - L1	860	849	11	98.72	1.28
	CG2 - SMM	838	828	10	98.81	1.19
	CG2 - MFF	847	831	16	98.11	1.89
	IID - IID	273	273	0	100.00	0.00
	IID - L1	311	4	307	1.29	98.71
	IID - SMM	307	2	305	0.65	99.35
	IID - MFF	309	6	303	1.94	98.06
	L1 - L1	883	883	0	100.00	0.00
	L1 - SMM	849	843	6	99.29	0.71
	L1 - MFF	861	847	14	98.37	1.63
	SMM - SMM	855	855	0	100.00	0.00
	MFF - SMM	1662	1638	24	98.56	1.44
	MFF - MFF	1626	1626	0	100.00	0.00

Table A.3 SourceAFIS TMR1 Table

SourceAFIS	Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
	10p - 10p	406	405	0	99.75	0.00
	10p - ANDI BIN	380	296	85	77.89	22.37
	10p - ANDI GRY	381	260	121	68.24	31.76
	10p - BIO	375	330	45	88.00	12.00
	10p - CSA	369	337	32	91.33	8.67
	10p - CG2	398	364	34	91.46	8.54
	10p - IID	144	3	141	2.08	97.92
	10p - L1	401	368	33	91.77	8.23
	10p - SMM	388	339	49	87.37	12.63
	10p - MFF	395	336	59	85.06	14.94
	ANDI BIN - ANDI BIN	830	830	0	100.00	0.00
	ANDI BIN - ANDI GRY	830	829	1	99.88	0.12
	ANDI BIN - BIO	778	656	111	84.32	14.27
	ANDI BIN - CSA	764	679	74	88.87	9.69
	ANDI BIN - CG2	822	738	73	89.78	8.88
	ANDI BIN - IID	321	5	311	1.56	96.88
	ANDI BIN - L1	832	721	99	86.66	11.90
	ANDI BIN - SMM	800	700	100	87.50	12.50
	ANDI BIN - MFF	824	691	121	83.86	14.68
	ANDI GRY - ANDI GRY	831	831	0	100.00	0.00
	ANDI GRY - BIO	768	540	228	70.31	29.69
	ANDI GRY - CSA	754	584	170	77.45	22.55
	ANDI GRY - CG2	812	623	189	76.72	23.28
	ANDI GRY - IID	316	5	311	1.58	98.42
	ANDI GRY - L1	821	614	207	74.79	25.21
	ANDI GRY - SMM	801	580	221	72.41	27.59
	ANDI GRY - MFF	813	607	206	74.66	25.34
	BIO - BIO	806	806	0	100.00	0.00
	BIO - CSA	738	709	29	96.07	3.93
	BIO - CG2	792	758	34	95.71	4.29
	BIO - IID	297	6	291	2.02	97.98
	BIO - L1	801	769	32	96.00	4.00
	BIO - SMM	778	746	32	95.89	4.11
	BIO - MFF	785	709	76	90.32	9.68
	CSA - CSA	784	784	0	100.00	0.00
	CSA - CG2	771	763	8	98.96	1.04
	CSA - IID	289	7	282	2.42	97.58
	CSA - L1	778	770	8	98.97	1.03
	CSA - SMM	758	753	5	99.34	0.66
	CSA - MFF	762	731	31	95.93	4.07
	CG2 - CG2	870	870	0	100.00	0.00
	CG2 - IID	306	3	303	0.98	99.02
	CG2 - L1	860	846	14	98.37	1.63
	CG2 - SMM	838	817	21	97.49	2.51
	CG2 - MFF	847	809	38	95.51	4.49
	IID - IID	319	319	0	100.00	0.00
	IID - L1	315	0	315	0.00	100.00
	IID - SMM	313	1	312	0.32	99.68
	IID - MFF	315	1	314	0.32	99.68
	L1 - L1	883	883	0	100.00	0.00
	L1 - SMM	849	832	17	98.00	2.00
	L1 - MFF	861	821	40	95.35	4.65
	SMM - SMM	859	859	0	100.00	0.00
	MFF - SMM	1666	1458	208	87.52	12.48
	MFF - MFF	1734	1734	0	100.00	0.00

Table A.4 NBIS Rolls TMR1 Table

NBIS Rolls	Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
	10p R - 10p R	417	417	0	100.00	0.00
	10p R - BIO R	389	342	47	87.92	12.08
	10p R - CSA R	383	349	34	91.12	8.88
	10p R - CG2 R	412	369	43	89.56	10.44
	10p R - L1 R	415	372	43	89.64	10.36
	BIO R - BIO R	828	828	0	100.00	0.00
	BIO R - CSA R	765	735	30	96.08	3.92
	BIO R - CG2 R	818	778	40	95.11	4.89
	BIO R - L1 R	824	785	39	95.27	4.73
	CSA R - CSA R	811	811	0	100.00	0.00
	CSA R - CG2 R	799	781	18	97.75	2.25
	CSA R - L1 R	809	795	14	98.27	1.73
	CG2 R - CG2 R	877	877	0	100.00	0.00
	CG2 R - L1 R	871	860	11	98.74	1.26
	L1 R - L1 R	893	893	0	100.00	0.00

Table A.5 Neurotech Rolls TMR1 Table

Neurotech Rolls	Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
	10p R - 10p R	360	360	0	100.00	0.00
	10p R - BIO R	390	375	15	96.15	3.85
	10p R - CSA R	383	377	6	98.43	1.57
	10p R - CG2 R	411	404	7	98.30	1.70
	BIO R - BIO R	815	815	0	100.00	0.00
	BIO R - CSA R	757	743	14	98.15	1.85
	BIO R - CG2 R	810	797	13	98.40	1.60
	CSA R - CSA R	804	804	0	100.00	0.00
	CSA R - CG2 R	796	792	4	99.50	0.50
	CG2 R - CG2 R	862	862	0	100.00	0.00
	L1 R - 10p R	828	807	21	97.46	2.54
	L1 R - BIO R	835	819	16	98.08	1.92
	L1 R - CSA R	820	811	9	98.90	1.10
	L1 R - CG2 R	878	870	8	99.09	0.91

Table A.6 SourceAFIS Rolls TMR1 Table

SourceAFIS Rolls	Match	Total	TMR1	FMR1	TMR1 Rate	FMR1 Rate
	10p R - 10p R	418	417	0	99.76	0.00
	10p R - BIO R	389	342	47	87.92	12.08
	10p R - CSA R	383	349	34	91.12	8.88
	10p R - CG2 R	411	369	43	89.78	10.46
	10p R - L1 R	415	372	43	89.64	10.36
	BIO R - BIO R	828	828	0	100.00	0.00
	BIO R - CSA R	765	735	30	96.08	3.92
	BIO R - CG2 R	818	778	40	95.11	4.89
	BIO R - L1 R	824	785	39	95.27	4.73
	CSA R - CSA R	811	811	0	100.00	0.00
	CSA R - CG2 R	799	781	18	97.75	2.25
	CSA R - L1 R	809	795	14	98.27	1.73
	CG2 R - CG2 R	877	877	0	100.00	0.00
	CG2 R - L1 R	871	860	11	98.74	1.26
	L1 R - L1 R	893	893	0	100.00	0.00

Table A.7 NBIS Maximum and Minimum Score Values

NBIS				
<i>Sensor</i>	Genuine Maximum Score	Genuine Minimum Score	Imposter Maximum Score	Imposter Minimum Score
<i>ANDI BIN</i>	319	4	44	0
<i>ANDI GRY</i>	358	8	70	0
<i>BioSled</i>	304	4	245	0
<i>BIO Rolls</i>	317	5	184	0
<i>CG2</i>	358	4	159	0
<i>CG2 Rolls</i>	452	4	262	0
<i>CSA</i>	499	8	63	0
<i>CSA Rolls</i>	506	4	31	0
<i>InnerID</i>	176	7	62	4
<i>L1</i>	328	4	137	0
<i>L1 Rolls</i>	449	0	143	0
<i>MFF</i>	360	5	48	0
<i>MorphoMobile</i>	278	3	201	0

A.1 NBIS Genuine/Imposter Score Distributions

Figure A.1.1 (Left) NBIS ANDI Binary (Right) NBIS ANDI Greyscale

Figure A.1.2 (Left) NBIS BioSled (Right) NBIS BioSled Rolls

Figure A.1.3 (Left) NBIS FP II Guardian (Right) NBIS FPII Guardian Rolls

Figure A.1.4 (Left) NBIS Crossmatch Seek Avenger (Right) NBIS Crossmatch Seek Avenger Rolls

Figure A.1.5 (Left) NBIS InnerID (Right) NBIS L1

Figure A.1.6 (Left) NBIS L1 Rolls (Right) NBIS Morpho FOTF

Figure A.1.7 NBIS MorphoMobile

Table A.8 Neurotech Maximum and Minimum Score Values

Neurotech				
<i>Sensor</i>	Genuine Maximum Score	Genuine Minimum Score	Imposter Maximum Score	Imposter Minimum Score
<i>ANDI BIN</i>	986	0	41	0
<i>ANDI GRY</i>	1003	3	45	0
<i>BioSled</i>	951	0	539	0
<i>BIO Rolls</i>	993	0	656	0
<i>CG2</i>	1000	1	641	0
<i>CG2 Rolls</i>	1188	2	658	0
<i>CSA</i>	1267	1	58	0
<i>CSA Rolls</i>	1682	0	26	0
<i>InnerID</i>	508	2	35	0
<i>L1</i>	925	0	681	0
<i>L1 Rolls</i>				
<i>MFF</i>	952	2	58	0
<i>MorphoMobile</i>	705	1	465	0

A.2 Neurotech Genuine/Imposter Score Distributions

Figure A.2.1 (Left) Neurotech ANDI Binary (Right) Neurotech ANDI Greyscale

Figure A.2.2 (Left) Neurotech BioSled (Right) Neurotech BioSled Rolls

Figure A.2.3 (Left) Neurotech FP II Guardian (Right) Neurotech FP II Guardian Rolls

Figure A.2.4 (Left) Neurotech Crossmatch Seek Avenger (Right) Neurotech Crossmatch Seek Avenger Rolls

Figure A.2.5 (Left) Neurotech InnerID (Right) Neurotech L1

Figure A.2.6 (Left) Neurotech Morpho FOTF (Right) Neurotech MorphoMobile

Table A.9 SourceAFIS Maximum and Minimum Score Values

SourceAFIS				
<i>Sensor</i>	Genuine Maximum Score	Genuine Minimum Score	Imposter Maximum Score	Imposter Minimum Score
<i>ANDI BIN</i>	258.72	10.45	41.22	2.40
<i>ANDI GRY</i>	227.51	8.98	35.99	1.05
<i>BioSled</i>	248.36	9.96	141.30	1.13
<i>BIO Rolls</i>	331.39	4.48	219.31	1.02
<i>CG2</i>	248.38	10.82	120.65	2.58
<i>CG2 Rolls</i>	364.86	11.06	214.73	1.02
<i>CSA</i>	284.96	13.24	35.92	2.56
<i>CSA Rolls</i>	517.80	9.01	35.01	1.03
<i>InnerID</i>	148.15	8.88	32.62	3.67
<i>L1</i>	288.08	9.57	89.70	1.21
<i>L1 Rolls</i>	341.77	0	35.18	0.00
<i>MFF</i>	289.72	9.18	36.04	1.02
<i>MorphoMobile</i>	172.81	9.08	99.94	4.47

A.3 SourceAFIS Genuine/Imposter Score Distributions

Figure A.3.1 (Left) SourceAFIS ANDI Binary (Right) SourceAFIS ANDI Greyscale

Figure A.3.2 (Left) SourceAFIS BioSled (Right) SourceAFIS BioSled Rolls

Figure A.3.3 (Left) SourceAFIS FP II Guardian (Right) SourceAFIS FP II Guardian Rolls

Figure A.3.4 (Left) SourceAFIS Crossmatch Seek Avenger (Right) SourceAFIS Crossmatch Seek Avenger Rolls

Figure A.3.5 (Left) SourceAFIS InnerID (Right) SourceAFIS L1

Figure A.3.6 (Left) SourceAFIS L1 Rolls (Right) SourceAFIS Morpho FOTF

Figure A.3.7 SourceAFIS MorphoMobile

Table A.10 NBIS Cross-Examined Maximum and Minimum Score Values

NBIS	Devices	Max Genuine	Min Genuine	Max Imposter	Min Imposter
	10p R - BIO R	316	0	140	0
	10p R - CSA R	261	0	36	0
	10p R - CG2 R	308	0	57	0
	10p R - L1 R	322	0	115	0
	10p - ANDI BIN	167	4	50	0
	10p - ANDI GRY	163	4	69	0
	10p - BIO	232	3	180	0
	10p - CSA	272	4	48	0
	10p - CG2	303	4	47	0
	10p - L1	266	3	125	0
	10p - MFF	164	4	64	0
	10p - SMM	235	3	96	0
	10p - IID	30	4	47	0
	ANDI BIN - ANDI GRY	293	5	70	0
	ANDI BIN - BIO	191	3	130	0
	ANDI BIN - CSA	168	0	39	0
	ANDI BIN - CG2	169	3	97	0
	ANDI BIN - L1	172	3	51	0
	ANDI BIN - MFF	169	3	57	0
	ANDI BIN - SMM	158	0	74	0
	ANDI BIN - IID	24	3	52	0
	ANDI GRY - BIO	146	3	89	0
	ANDI GRY - CSA	181	3	50	0
	ANDI GRY - CG2	212	3	95	0
	ANDI GRY - L1	185	3	59	0
	ANDI GRY - MFF	149	3	62	0
	ANDI GRY - SMM	148	0	61	0
	ANDI GRY - IID	45	4	61	3
	BIO R - CSA R	444	4	232	0
	BIO R - CG2 R	416	3	220	0
	BIO R - L1 R	453	0	193	0
	BIO - CSA	316	3	236	0
	BIO - CG2	336	0	185	0
	BIO - L1	285	3	175	0
	BIO - MFF	185	0	101	0
	BIO - SMM	280	3	215	0
	BIO - IID	27	3	45	0
	CSA R - CG2 R	443	4	82	0
	CSA R - L1 R	447	0	112	0
	CSA - CG2	291	3	164	0
	CSA - L1	349	3	105	0
	CSA - MFF	205	0	49	0
	CSA - SMM	258	3	134	0
	CSA - IID	23	3	40	0
	CG2 R - L1 R	436	0	209	0
	CG2 - L1	353	3	142	0
	CG2 - MFF	209	0	86	0
	CG2 - SMM	256	0	126	0
	CG2 - IID	24	3	38	0
	L1 - MFF	188	3	88	0
	L1 - SMM	277	0	176	0
	MFF - SMM	159	0	80	0
	IID - L1	27	3	39	0
	IID - MFF	38	3	48	0
	IID - SMM	23	0	33	0

A.4 NBIS Cross-Examined Genuine/Imposter Distributions

Figure A.4.3 (Left) NBIS 10print – ANDI Binary (Right) NBIS 10print – ANDI Greyscale

Figure A.4.4 (Left) NBIS 10print – BioSled (Right) NBIS 10print - Crossmatch Seek Avenger

Figure A.4.5 (Left) NBIS 10print – FP II Guardian (Right) NBIS 10print – L1

Figure A.4.6 (Left) NBIS 10print – Morpho FOTF (Right) NBIS 10print – MorphoMobile

Figure A.4.7 (Left) NBIS ANDI Binary – ANDI Greyscale (Right) NBIS ANDI Binary - BioSled

Figure A.4.8 (Left) NBIS ANDI Binary – Crossmatch Seek Avenger (Right) NBIS ANDI Binary – FP II Guardian

Figure A.4.9 (Left) NBIS ANDI Binary – L1 (Right) NBIS ANDI Binary – Morpho FOTF

Figure A.4.10 (Left) NBIS ANDI Binary – MorphoMobile (Right) NBIS ANDI Greyscale – BioSled

Figure A.4.11 (Left) NBIS ANDI Greyscale – Crossmatch Seek Avenger (Right) NBIS ANDI Greyscale – FP II Guardian

Figure A.4.12 (Left) NBIS ANDI Greyscale – L1 (Right) NBIS ANDI Greyscale – Morpho FOTF

Figure A.4.13 (Left) NBIS ANDI Greyscale – MorphoMobile (Right) NBIS BioSled Rolls – Crossmatch Seek Avenger Rolls

Figure A.4.14 (Left) NBIS BioSled Rolls – FP II Guardian Rolls (Right) NBIS BioSled Rolls – L1 Rolls

Figure A.4.15 (Left) NBIS BioSled – Crossmatch Seek Avenger (Right) NBIS BioSled – FP II Guardian

Figure A.4.16 (Left) NBIS BioSled – L1 (Right) NBIS BioSled – Morpho FOTF

Figure A.4.17 (Left) NBIS BioSled – MorphoMobile (Right) NBIS Crossmatch Seek Avenger Rolls – FP Guardian Rolls

Figure A.4.18 (Left) NBIS Crossmatch Seek Avenger Rolls – L1 Rolls (Right) NBIS Crossmatch Seek Avenger – FP II Guardian

Figure A.4.19 (Left) NBIS Crossmatch Seek Avenger – L1 (Right) NBIS Crossmatch Seek Avenger – Morpho FOTF

Figure A.4.20 (Left) NBIS Crossmatch Seek Avenger – MorphoMobile (Right) NBIS FP II Guardian Rolls – L1 Rolls

Figure A.4.21 (Left) NBIS FP II Guardian – L1 (Right) NBIS FP II Guardian – Morpho FOTF

Figure A.4.22 (Left) NBIS FP II Guardian – MorphoMobile (Right) NBIS L1 – Morpho FOTF

Figure A.4.23 (Left) NBIS L1 – MorphoMobile (Right) NBIS Morpho FOTF – MorphoMobile

Table A.11 Neurotech Cross-Examined Maximum and Minimum Score Values

Neurotech	Device	Max Genuine	Min Genuine	Max Imposter	Min Imposter
	10p - ANDI BIN	2274	3	54	1
	10p - ANDI GRY	414	2	44	0
	10p - BIO	15133	1	3380	1
	10p - CSA	12502	4	67	1
	10p - CG2	22403	3	268	1
	10p - L1	16829	7	3710	1
	10p - SMM	8661	4	590	1
	10p - MFF	1338	3	169	1
	10p R - BIO R	5013	3	1077	1
	10p R - CSA R	5407	3	39	1
	10p R - CG2 R	5966	2	141	1
ANDI BIN - ANDI GRY		825	2	43	0
ANDI BIN - BIO		3771	3	1265	1
ANDI BIN - CSA		2535	2	58	1
ANDI BIN - CG2		2690	2	717	1
ANDI BIN - L1		2613	1	230	1
ANDI BIN - SMM		2254	2	557	1
ANDI BIN - MFF		1021	3	96	1
ANDI BIN - IID		30	1	36	1
ANDI GRY - BIO		447	0	351	0
ANDI GRY - CSA		455	1	45	0
ANDI GRY - CG2		447	1	247	0
ANDI GRY - L1		423	0	153	0
ANDI GRY - SMM		410	0	169	0
ANDI GRY - MFF		413	2	74	2
ANDI GRY - IID		21	0	30	0
BIO - CSA		24719	5	18663	1
BIO - CG2		23638	2	6572	1
BIO - L1		23100	2	5679	1
BIO - SMM		15269	4	6152	1
BIO - MFF		1616	3	748	1
BIO R - CSA R		14386	1	4758	1
BIO R - CG2 R		10015	2	2978	1
BIO - IID		36	1	39	1
CSA - CG2		22034	1	4443	1
CSA - IID		30	1	46	1
CSA - L1		19946	4	2776	1
CSA - SMM		14426	3	896	1
CSA - MFF		1388	3	165	1
CSA R - CG2 R		9281	3	135	1
CG2 - IID		29	1	38	1
CG2 - L1		25511	3	5504	1
CG2 - SMM		19192	2	2237	1
CG2 - MFF		1273	3	504	1
IID - L1		30	1	39	1
IID - SMM		30	1	39	1
IID - MFF		30	1	33	1
L1 - SMM		18846	3	4406	1
L1 - MFF		1516	3	224	1
L1 R - 10p R		5042	2	1282	1
L1 R - BIO R		9172	2	2597	1
L1 R - CSA R		7047	1	416	1
L1 R - CG2 R		12847	1	3455	1
MFF - SMM		1305	3	183	1

A.5 Neurotech Cross-Examined Genuine/Imposter Distributions

Figure A.5.1 (Left) Neurotech 10print – ANDI Binary (Right) Neurotech 10print – ANDI Greyscale

Figure A.5.2 (Left) Neurotech 10print – BioSled (Right) Neurotech 10print – Crossmatch Seek Avenger

Figure A.5.3 (Left) Neurotech 10print – FP II Guardian (Right) Neurotech 10print – L1

Figure A.5.4 (Left) Neurotech 10print – Morpho FOTF (Right) Neurotech 10print – MorphoMobile

Figure A.5.5 (Left) Neurotech 10print Rolls – BioSled Rolls (Right) Neurotech 10print Rolls – Crossmatch Seek Avenger Rolls

Figure A.5.6 (Left) Neurotech 10print Rolls – FP II Guardian Rolls (Right) Neurotech ANDI Binary – ANDI Greyscale

Figure A.5.7 (Left) Neurotech ANDI Binary – BioSled (Right) Neurotech ANDI Binary – Crossmatch Seek Avenger

Figure A.5.8 (Left) Neurotech ANDI Binary – FP II Guardian (Right) Neurotech ANDI Binary – L1

Figure A.5.9 (Left) Neurotech ANDI Binary – Morpho FOTF (Right) Neurotech ANDI Binary – MorphoMobile

Figure A.5.10 (Left) Neurotech ANDI Greyscale – BioSled (Right) Neurotech ANDI Greyscale – Crossmatch Seek Avenger

Figure A.5.11 (Left) Neurotech ANDI Greyscale – FP II Guardian (Right) Neurotech ANDI Greyscale – L1

Figure A.5.12 (Left) Neurotech ANDI Greyscale – Morpho FOTF (Right) Neurotech ANDI Greyscale – MorphoMobile

Figure A.5.13 (Left) Neurotech BioSled – Crossmatch Seek Avenger (Right) Neurotech BioSled – FP II Guardian

Figure A.5.14 (Left) Neurotech BioSled – L1 (Right) Neurotech BioSled – Morpho FOTF

Figure A.5.15 (Left) Neurotech BioSled – MorphoMobile (Right) Neurotech BioSled Rolls – Crossmatch Seek Avenger Rolls

Figure A.5.16 (Left) Neurotech BioSled Rolls– FP II Guardian Rolls (Right) Neurotech Crossmatch Seek Avenger – FP II Guardian

Figure A.5.17 (Left) Neurotech Crossmatch Seek Avenger – L1 (Right) Neurotech Crossmatch Seek Avenger – Morpho FOTF

Figure A.5.18 (Left) Neurotech Crossmatch Seek Avenger – MorphoMobile (Right) Neurotech Crossmatch Seek Avenger Rolls – FP II Guardian Rolls

Figure A.5.19 (Left) Neurotech FP II Guardian – L1 (Right) Neurotech FP II Guardian – Morpho FOTF

Figure A.5.20 (Left) Neurotech FP II Guardian – MorphoMobile (Right) Neurotech L1 – Morpho FOTF

Figure A.5.21 (Left) Neurotech L1 – MorphoMobile (Right) Neurotech L1 Rolls – 10print Rolls

Figure A.5.22 (Left) Neurotech L1 Rolls – BioSled Rolls (Right) Neurotech L1 Rolls – Crossmatch Seek Avenger Rolls

Figure A.5.23 (Left) NeurotechL1 Rolls – FP II Guardian Rolls (Right) Neurotech Morpho FOTF – MorphoMobile

Table A.12 SourceAFIS Cross-Examined Maximum and Minimum Score Values

<i>SourceAFIS</i>	<i>Devices</i>	Max Genuine	Min Genuine	Max Imposter	Min Imposter
	<i>10p - ANDI BIN</i>	146.27	9.67	36.36	1.15
	<i>10p - ANDI GRY</i>	115.10	8.67	35.21	1.07
	<i>10p - BIO</i>	211.68	10.67	120.76	1.17
	<i>10p - CSA</i>	225.33	11.04	34.61	3.05
	<i>10p - CG2</i>	231.38	9.41	62.39	1.08
	<i>10p - L1</i>	220.90	9.87	167.78	1.11
	<i>10p - MFF</i>	170.37	9.91	53.03	1.09
	<i>10p - SMM</i>	159.79	9.27	64.65	1.15
	<i>10p R - BIO R</i>	270.40	9.61	171.60	1.02
	<i>10p R - CSA R</i>	303.44	8.89	31.84	1.02
	<i>10p R - CG2 R</i>	293.25	10.30	43.02	1.02
	<i>10p R - L1 R</i>	287.39	0.00	129.25	0.00
	<i>10p - IID</i>	18.53	8.89	27.94	3.57
<i>ANDI BIN</i>	<i>- ANDI GRY</i>	240.88	9.91	39.50	1.10
	<i>ANDI BIN - BIO</i>	154.24	5.62	106.18	1.10
	<i>ANDI BIN - CSA</i>	171.76	10.15	37.91	1.15
	<i>ANDI BIN - CG2</i>	150.54	6.38	94.26	1.13
	<i>ANDI BIN - L1</i>	173.52	9.67	72.75	1.09
	<i>ANDI BIN - SMM</i>	134.80	8.75	55.83	1.11
	<i>ANDI BIN - MFF</i>	189.75	8.95	40.86	1.03
	<i>ANDI BIN - IID</i>	26.25	9.05	31.50	3.44
	<i>ANDI GRY - BIO</i>	129.40	8.41	71.34	1.10
	<i>ANDI GRY - CSA</i>	149.24	8.14	36.20	1.07
	<i>ANDI GRY - CG2</i>	150.66	9.05	56.88	1.02
	<i>ANDI GRY - L1</i>	152.41	6.91	68.78	1.07
	<i>ANDI GRY - SMM</i>	124.64	8.39	42.48	1.13
	<i>ANDI GRY - MFF</i>	183.14	6.75	43.43	1.02
	<i>ANDI GRY - IID</i>	20.43	8.91	30.22	1.06
	<i>BIO - CSA</i>	267.14	9.94	128.17	1.26
	<i>BIO - CG2</i>	270.79	9.70	189.73	1.20
	<i>BIO - L1</i>	242.63	10.50	133.19	1.12
	<i>BIO - SMM</i>	194.05	10.56	97.40	1.17
	<i>BIO - MFF</i>	202.00	9.27	109.29	1.06
	<i>BIO R - CSA R</i>	348.05	8.90	275.02	1.02
	<i>BIO R - CG2 R</i>	333.19	9.90	247.35	1.02
	<i>BIO R - L1 R</i>	330.59	0.00	231.09	0.00
	<i>BIO - IID</i>	23.30	8.39	33.73	1.24
	<i>CSA - CG2</i>	288.52	11.27	119.39	1.17
	<i>CSA - L1</i>	259.76	11.95	132.76	2.63
	<i>CSA - SMM</i>	193.06	11.02	92.33	2.41
	<i>CSA - MFF</i>	233.11	9.80	63.35	1.10
	<i>CSA R - CG2 R</i>	348.13	9.48	85.60	1.02
	<i>CSA R - L1 R</i>	320.97	0.00	176.75	0.00
	<i>CSA - IID</i>	20.85	7.65	29.83	1.94
	<i>CG2 - L1</i>	237.47	10.68	148.12	3.37
	<i>CG2 - SMM</i>	183.25	9.81	136.43	1.23
	<i>CG2 - MFF</i>	200.67	9.01	77.90	1.10
	<i>CG2 R - L1 R</i>	325.06	0.00	214.50	0.00
	<i>CG2 - IID</i>	22.40	4.50	29.22	1.08
	<i>L1 - SMM</i>	194.19	10.46	111.26	1.14
	<i>L1 - MFF</i>	182.92	7.64	79.59	1.09
	<i>MFF - SMM</i>	136.34	8.34	56.30	1.06
	<i>IID - L1</i>	21.33	9.07	35.39	1.11
	<i>IID - SMM</i>	19.90	7.89	29.47	1.09
	<i>IID - MFF</i>	23.68	7.88	31.36	1.04

A.6 SourceAFIS Cross-Examined Genuine/Imposter Score

Distributions

Figure A.6.1 (Left) SourceAFIS 10print – ANDI Binary (Right) SourceAFIS 10print – ANDI Greyscale

Figure A.6.2 (Left) SourceAFIS 10print – BioSled (Right) SourceAFIS 10print - Crossmatch Seek Avenger

Figure A.6.3 (Left) SourceAFIS 10print – FP II Guardian (Right) SourceAFIS 10print – L1

Figure A.6.4 (Left) SourceAFIS 10print – Morpho FOTF (Right) SourceAFIS 10print – MorphoMobile

Figure A.6.5 (Left) SourceAFIS 10print Rolls – BioSled Rolls (Right) SourceAFIS 10print Rolls - Crossmatch Seek Avenger Rolls

Figure A.6.6 (Left) SourceAFIS 10print Rolls – FP II Guardian Rolls (Right) SourceAFIS 10print Rolls – L1 Rolls

Figure A.6.7 (Left) SourceAFIS ANDI Binary – ANDI Greyscale (Right) SourceAFIS ANDI Binary – BioSled

Figure A.6.8 (Left) SourceAFIS ANDI Binary – Crossmatch Seek Avenger (Right) SourceAFIS ANDI Binary – FP II Guardian

Figure A.6.9 (Left) SourceAFIS ANDI Binary – L1 (Right) SourceAFIS ANDI Binary – Morpho FOTF

Figure A.6.10 (Left) SourceAFIS ANDI Binary – MorphoMobile (Right) SourceAFIS ANDI Greyscale – BioSled

Figure A.6.11 (Left) SourceAFIS ANDI Greyscale – Crossmatch Seek Avenger (Right) SourceAFIS ANDI Greyscale – FP II Guardian

Figure A.6.12 (Left) SourceAFIS ANDI Greyscale – L1 (Right) SourceAFIS ANDI Greyscale – Morpho FOTF

Figure A.6.13 (Left) SourceAFIS ANDI Greyscale – MorphoMobile (Right) SourceAFIS BioSled – Crossmatch Seek Avenger

Figure A.6.14 (Left) SourceAFIS BioSled – FP II Guardian (Right) BioSled – L1

Figure A.6.15 (Left) SourceAFIS BioSled – Morpho FOTF (Right) SourceAFIS BioSled – MorphoMobile

Figure A.6.16 (Left) SourceAFIS BioSled Rolls – Crossmatch Seek Avenger Rolls (Right) SourceAFIS BioSled Rolls – FP II Guardian Rolls

Figure A.6.17 (Left) SourceAFIS BioSled Rolls – L1 Rolls (Right) SourceAFIS Crossmatch Seek Avenger – FP II Guardian

Figure A.6.18 (Left) SourceAFIS Crossmatch Seek Avenger– L1 (Right) SourceAFIS Crossmatch Seek Avenger – Morpho FOTF

Figure A.6.19 (Left) SourceAFIS Crossmatch Seek Avenger – MorphoMobile (Right) SourceAFIS Crossmatch Seek Avenger Rolls – FP II Guardian Rolls

Figure A.6.20 (Left) SourceAFIS Crossmatch Seek Avenger Rolls – L1 Rolls (Right) SourceAFIS FP II Guardian – L1

Figure A.6.21 (Left) SourceAFIS FP II Guardian – Morpho FOTF (Right) SourceAFIS FP II Guardian – MorphoMobile

Figure A.6.22 (Left) SourceAFIS FP II Guardian Rolls – L1 Rolls (Right) SourceAFIS L1 – Morpho FOTF

Figure A.6.23 (Left) SourceAFIS L1 – MorphoMobile (Right) SourceAFIS Morpho FOTF – MorphoMobile

A.7 NBIS ROC Curves and Area Under Curve

Figure A.7.1 NBIS ROC Curves for each device

Figure A.7.2 Zoomed In NBIS ROC Curves for each device

Table A.13 NBIS Area Under the Curve for ROC graphs.

NBIS	Device	Area Under Curve
	<i>ANDI BIN</i>	0.981396
	<i>ANDI GRY</i>	0.979449
	<i>BioSled</i>	0.982126
	<i>BioSled Rolls</i>	0.982929
	<i>CG2</i>	0.979025
	<i>CG2 Rolls</i>	0.992307
	<i>CSA</i>	0.998439
	<i>CSA Rolls</i>	0.987915
	<i>InnerID</i>	0.856881
	<i>L1</i>	0.982475
	<i>L1 Rolls</i>	0.979738
	<i>MFF</i>	0.993983
	<i>MorphoMobile</i>	0.99231

Figure A.7.3 (Left) NBIS ANDI Binary ROC Curve (Right) NBIS ANDI Greyscale ROC Curve

Figure A.7.4 (Left) NBIS BioSled ROC Curve (Right) NBIS BioSled Rolls ROC Curve

Figure A.7.5 (Left) NBIS FP II Guardian ROC Curve (Right) NBIS FP II Guardian Rolls ROC Curve

Figure A.7.6 (Left) NBIS Crossmatch Seek Avenger ROC Curve (Right) NBIS Crossmatch Seek Avenger Rolls ROC Curve

Figure A.7.7 (Left) NBIS InnerID ROC Curve (Right) NBIS L1 Curve

Figure A.7.8 (Left) NBIS L1 Rolls ROC Curve (Right) NBIS Morpho FOTF ROC Curve

Figure A.7.9 NBIS MorphoMobile ROC Curve

A.8 Neurotech ROC Curves and Area Under Curve

Figure A.8.1 Neurotech ROC Curves for each Device

Figure A.8.2 Zoomed In Neurotech ROC Curves for each Device

Table A.14 Neurotech Area Under the Curve for ROC graphs.

Neurotech Device	Area Under Curve
<i>ANDI BIN</i>	0.98037
<i>ANDI GRY</i>	0.982468
<i>BioSled</i>	0.981787
<i>BioSled Rolls</i>	0.988932
<i>CG2</i>	0.982212
<i>CG2 Rolls</i>	0.996949
<i>CSA</i>	0.997675
<i>CSA Rolls</i>	0.99515
<i>InnerID</i>	0.93257
<i>L1</i>	0.987632
<i>MFF</i>	0.99526
<i>MorphoMobile</i>	0.992997

Figure A.8.3 (Left) Neurotech ANDI Binary ROC Curve (Right) Neurotech ANDI Greyscale ROC Curve

Figure A.8.4 (Left) Neurotech BioSled ROC Curve (Right) Neurotech BioSled Rolls ROC Curve

Figure A.8.5 (Left) Neurotech FP II Guardian ROC Curve (Right) Neurotech FP II Guardian Rolls ROC Curve

Figure A.8.6 (Left) Neurotech Crossmatch Seek Avenger ROC Curve (Right) Neurotech Crossmatch Seek Avenger Rolls ROC Curve

Figure A.8.7 (Left) Neurotech InnerID ROC Curve (Right) Neurotech L1 ROC Curve

Figure A.8.8 (Left) Neurotech Morpho FOTF ROC Curve (Right) Neurotech MorphoMobile ROC Curve

A.9 SourceAFIS ROC Curves and Area Under Curve

Figure A.9.1 SourceAFIS ROC Curves For each Device

Figure A.9.2 Zoomed In SourceAFIS ROC Curves For each Device

Table A.15 SourceAFIS Area Under the Curve for ROC graphs.

SourceAFIS	Device	Area Under Curve
	<i>ANDI BIN</i>	0.966689
	<i>ANDI GRY</i>	0.936297
	<i>BioSled</i>	0.974903
	<i>BioSled Rolls</i>	0.955877
	<i>CG2</i>	0.978741
	<i>CG2 Rolls</i>	0.988263
	<i>CSA</i>	0.999
	<i>CSA Rolls</i>	0.97992
	<i>InnerID</i>	0.79834
	<i>L1</i>	0.98811
	<i>L1 Rolls</i>	0.970133
	<i>MFF</i>	0.98041
	<i>MorphoMobile</i>	0.989864

Figure A.9.3 (Left) SourceAFIS ANDI Binary ROC Curve (Right) SourceAFIS ANDI Greyscale ROC Curve

Figure A.9.4 (Left) SourceAFIS BioSled ROC Curve (Right) SourceAFIS BioSled Rolls ROC Curve

Figure A. 9.5(Left) SourceAFIS FP II Guardian ROC Curve (Right) SourceAFIS FP II Guardian Rolls ROC Curve

Figure A.9.6 (Left) SourceAFIS Crossmatch Seek Avenger ROC Curve (Right) SourceAFIS Crossmatch Seek Avenger Rolls ROC Curve

Figure A.9.7 (Left) SourceAFIS InnerID ROC Curve (Right) SourceAFIS L1 ROC Curve

Figure A.9.8 (Left) SourceAFIS L1 Rolls ROC Curve (Right) SourceAFIS Morpho FOTF ROC Curve

Figure A.9.9 SourceAFIS MorphoMobile ROC Curve

A.10 Equal Error Rates For Each Matcher

Table A.16 Equal Error Rates for Each Matching Run

<i>Match</i>	<i>NBIS EER Value</i>	<i>SourceAFIS EER</i>	<i>Neurotech EER</i>
<i>10p-10p</i>	0.0000	0.0000	0.0000
<i>10p-ANDI BIN</i>	0.1207	0.1500	0.0411
<i>10p-ANDI GRY</i>	0.1495	0.2401	0.0309
<i>10p-BIO</i>	0.0778	0.1034	0.0316
<i>10p-CSA</i>	0.0587	0.0660	0.0123
<i>10p-CG2</i>	0.0558	0.0911	0.0107
<i>10p-L1</i>	0.0561	0.0748	0.0100
<i>10p-MFF</i>	0.0980	0.1829	0.0269
<i>10p-SMM</i>	0.0806	0.1111	0.0273
<i>10p-IID</i>	0.4660	0.4861	
<i>ANDI BIN-ANDI BIN</i>	0.0231	0.0309	0.0171
<i>ANDI BIN-ANDI GRY</i>	0.0401	0.0782	0.0171
<i>ANDI BIN-BIO</i>	0.0997	0.1105	0.0479
<i>ANDI BIN-CSA</i>	0.0723	0.0782	0.0280
<i>ANDI BIN-CG2</i>	0.0769	0.0899	0.0328
<i>ANDI BIN-L1</i>	0.0878	0.0996	0.0335
<i>ANDI BIN-MFF</i>	0.1048	0.1641	0.0377
<i>ANDI BIN-SMM</i>	0.0919	0.0859	0.0370
<i>ANDI BIN-IID</i>	0.4714	0.4767	0.4298
<i>ANDI GRY-ANDI GRY</i>	0.0345	0.0612	0.0166
<i>ANDI GRY-BIO</i>	0.1549	0.1698	0.0491
<i>ANDI GRY-CSA</i>	0.1178	0.1420	0.0281
<i>ANDI GRY-CG2</i>	0.1155	0.1487	0.0352
<i>ANDI GRY-L1</i>	0.1249	0.1640	0.0304
<i>ANDI GRY-MFF</i>	0.1302	0.2232	0.0260
<i>ANDI GRY-SMM</i>	0.1366	0.1523	0.0357
<i>ANDI GRY-IID</i>	0.4727	0.4667	0.4841
<i>BIO-BIO</i>	0.0256	0.0238	0.0151
<i>BIO-CSA</i>	0.0378	0.0359	0.0227
<i>BIO-CG2</i>	0.0483	0.0387	0.0229
<i>BIO-L1</i>	0.0452	0.0392	0.0238
<i>BIO-MFF</i>	0.0950	0.1007	0.0251
<i>BIO-SMM</i>	0.0466	0.0438	0.0232
<i>BIO-IID</i>	0.4622	0.4748	0.4342
<i>CSA-CSA</i>	0.0049	0.0020	0.0013
<i>CSA-CG2</i>	0.0154	0.0137	0.0059
<i>CSA-L1</i>	0.0181	0.0107	0.0032
<i>CSA-MFF</i>	0.0645	0.0706	0.0134
<i>CSA-SMM</i>	0.0219	0.0166	0.0053
<i>CSA-IID</i>	0.4490	0.4798	0.4507
<i>CG2-CG2</i>	0.0172	0.0189	0.0161
<i>CG2-L1</i>	0.0217	0.0192	0.0129
<i>CG2-MFF</i>	0.0566	0.0785	0.0159
<i>CG2-SMM</i>	0.0339	0.0299	0.0114
<i>CG2-IID</i>	0.4700	0.4886	0.4572
<i>L1-L1</i>	0.0134	0.0112	0.0112
<i>L1-MFF</i>	0.0622	0.0877	0.0129
<i>L1-SMM</i>	0.0291	0.0265	0.0089
<i>MFF-MFF</i>	0.0111	0.0295	0.0078
<i>MFF-SMM</i>	0.0837	0.0970	0.0166
<i>SMM-SMM</i>	0.0175	0.0108	0.0070
<i>IID-L1</i>	0.4477	0.4817	0.4446
<i>IID-MFF</i>	0.4816	0.4960	0.4601
<i>IID-SMM</i>	0.4778	0.4810	0.4591
<i>IID-IID</i>	0.1392	0.1654	0.0678

Table A.17 Equal Error Rates For Each Device

EER VALUES FOR THE GENUINE/IMPOSTER RUNS OF EACH DEVICE			
MATCH	NBIS	Neurotech	SourceAFIS
Andi Binary	0.0429	0.0346	0.0587
Andi Greyscale	0.0594	0.0336	0.1159
BioSled	0.0506	0.0307	0.0479
BioSled Rolls	0.0398	0.0201	0.0744
CG2	0.0342	0.0298	0.0376
CG2 Rolls	0.0137	0.0070	0.0194
CSA	0.0088	0.0027	0.0027
CSA Rolls	0.0251	0.0076	0.0363
InnerID	0.2308	0.1239	0.2770
L1	0.0267	0.0223	0.0222
Morpho FOTF	0.0145	0.0123	0.0405
MorphoMobile	0.0326	0.0141	0.0164

Table A.18 Equal Error Rates For Each Rolled Matching Run

EER VALUES FOR EACH ROLLS MATCHING RUN			
MATCH	NBIS	Neurotech	SourceAFIS
10p Rolls-10p Rolls	0.0024	0.0000	0.0000
10p Rolls-BIO Rolls	0.0848	0.0232	0.1567
10p Rolls-CSA Rolls	0.0678	0.0136	0.1381
10p Rolls-CG2 Rolls	0.0753	0.0099	0.1254
10p Rolls-L1 Rolls	0.0755	0.0127	0.1300
BIO Rolls-BIO Rolls	0.0206	0.0099	0.0430
BIO Rolls-CSA Rolls	0.0462	0.0149	0.0707
BIO Rolls-CG2 Rolls	0.0452	0.0127	0.0662
BIO Rolls-L1 Rolls	0.0469	0.0142	0.0856
CSA Rolls-CSA Rolls	0.0130	0.0038	0.0174
CSA Rolls-CG2 Rolls	0.0230	0.0038	0.0396
CSA Rolls-L1 Rolls	0.0244	0.0056	0.0529
CG2 Rolls-CG2 Rolls	0.0080	0.0035	0.0096
CG2 Rolls-L1 Rolls	0.0245	0.0058	0.0456
L1 Rolls-L1 Rolls	0.0162		0.0259

Figure A Minutiae Boxplots For Each Device

Appendix B

Gender Based Study

This appendix shows all of the results from the Gender Based Demographic Study. The genuine and imposter distributions for each matching run and gender are shown in this section. The Receiver Operating Characteristic Curves or ROC Curves are shown for each of the devices used in this collection, a table of values is shown to identify the area under the curve for each ROC curve. All of the results stated above are shown for each of the three matchers used. At the end of this appendix there are box plots that represent the number of minutiae found in images from each device, this data came from the NBIS matcher.

B.1 NBIS Genuine/Imposter Score Distributions

Table B.1 NBIS Male Genuine and Imposter KLD, Minimum and Maximum Scores

<i>NBIS Male Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0282	1.6236	319	4	34	0
<i>ANDI GRY</i>	0.0373	0.0893	322	8	70	0
<i>BioSled</i>	0.0328	0.0836	298	4	245	0
<i>BioSled Rolls</i>	0.0327	0.4227	285	5	184	0
<i>CG2</i>	0.0272	0.1348	358	4	159	0
<i>CG2 Rolls</i>	0.0163	0.9924	452	4	262	0
<i>CSA</i>	0.0148	1.0866	499	17	48	0
<i>CSA Rolls</i>	0.0217	6.4243	506	5	30	0
<i>InnerID</i>	0.0411	0.2325	176	11	62	4
<i>L1</i>	0.0219	0.1464	328	4	137	0
<i>L1 Rolls</i>	0.0155	0.2235	449	5	143	0
<i>MFF</i>	0.0543	0.5960	323	5	48	0
<i>MorphoMobile</i>	0.0248	0.1028	278	3	201	0

Table B.2 NBIS Female Genuine and Imposter KLD, Minimum and Maximum Scores

NBIS Female Device	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0316	0.7008	275	6	44	0
<i>ANDI GRY</i>	0.0214	0.2379	358	9	62	3
<i>BioSled</i>	0.0434	3.8267	304	10	57	0
<i>BioSled Rolls</i>	0.0176	5.4024	317	6	30	0
<i>CG2</i>	0.0356	7.8629	310	4	50	0
<i>CG2 Rolls</i>	0.0388	2.2804	367	13	36	0
<i>CSA</i>	0.1378	0.3865	280	8	63	0
<i>CSA Rolls</i>	0.0614	3.5796	356	4	31	0
<i>InnerID</i>	0.2519	0.1381	132	7	60	4
<i>L1</i>	0.0221	9.0137	297	4	52	0
<i>L1 Rolls</i>	0.0394	6.0952	384	0	31	0
<i>MFF</i>	0.0169	1.1263	360	8	47	3
<i>MorphoMobile</i>	0.0461	1.7152	235	8	38	0

Figure B.1.1 NBIS ANDI Binary Male (Left) Female (Right)

Figure B.1.2 NBIS ANDI Greyscale Male (Left) Female (Right)

Figure B.1.3 NBIS BioSled Male (Left) Female (Right)

Figure B.1.4 NBIS BioSled Rolls Male (Left) Female (Right)

Figure B.1.5 NBIS FP II Guardian Male (Left) Female (Right)

Figure B.1.6 NBIS FP II Guardian Rolls Male (Left) Female (Right)

Figure B.1.7 NBIS Crossmatch Seek Avenger Male (Left) Female (Right)

Figure B.1.8 NBIS Crossmatch Seek Avenger Rolls Male (Left) Female (Right)

Figure B.1.9 NBIS InnerID Male (Left) Female (Right)

Figure B.1.10 NBIS L1 Male (Left) Female (Right)

Figure B.1.11 NBIS L1 Rolls Male (Left) Female (Right)

Figure B.1.12 NBIS Morpho FOTF Rolls Male (Left) Female (Right)

Figure B.1.13 NBIS MorphoMobile Rolls Male (Left) Female (Right)

B.2 Neurotech Genuine/Imposter Score Distributions

Table B.3 Neurotech Male Genuine and Imposter KLD, Minimum and Maximum Scores

Neurotech Male Device	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0073	5.9406	986	0	35	0
<i>ANDI GRY</i>	0.0044	0.1447	971	3	45	0
<i>BioSled</i>	0.0148	0.0063	951	0	539	0
<i>BioSled Rolls</i>	0.0080	0.0110	968	0	656	0
<i>CG2</i>	0.0041	0.0099	1000	1	641	0
<i>CG2 Rolls</i>	0.0051	0.0052	1188	2	658	0
<i>CSA</i>	0.0363	5.0927	1267	201	49	0
<i>CSA Rolls</i>	0.0046	0.8327	1682	0	26	0
<i>InnerID</i>	0.0135	0.3826	508	3	35	0
<i>L1</i>	0.0052	0.0005	925	0	681	0
<i>MFF</i>	0.0087	2.2364	952	2	34	0
<i>MorphoMobile</i>	0.0144	0.0235	681	3	465	0

Table B.4 Neurotech Female Genuine and Imposter KLD, Minimum and Maximum Scores

Neurotech Female Device	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0102	3.1744	868	1	41	0
<i>ANDI GRY</i>	0.0041	0.2866	1003	3	45	0
<i>BioSled</i>	0.0251	0.3071	906	5	45	0
<i>BioSled Rolls</i>	0.0073	0.0299	993	3	30	0
<i>CG2</i>	0.0094	0.0807	939	1	218	0
<i>CG2 Rolls</i>	0.0103	0.0210	1102	175	29	0
<i>CSA</i>	0.0641	0.6460	859	1	58	0
<i>CSA Rolls</i>	0.0309	1.2743	1035	1	26	0
<i>InnerID</i>	0.0516	2.4966	384	2	30	0
<i>L1</i>	0.0054	0.0032	913	2	48	0
<i>MFF</i>	0.0218	0.6446	836	4	58	0
<i>MorphoMobile</i>	0.0116	0.2484	705	1	48	0

Figure B.2.1 Neurotech ANDI Binary Male (Left) Female (Right)

Figure B.2.2 Neurotech ANDI Greyscale Male (Left) Female (Right)

Figure B.2.3 Neurotech BioSled Male (Left) Female (Right)

Figure B.2.4 Neurotech BioSled Rolls Male (Left) Female (Right)

Figure B.2.5 Neurotech FP II Guardian Male (Left) Female (Right)

Figure B.2.6 Neurotech FP II Guardian Rolls Male (Left) Female (Right)

Figure B.2.7 Neurotech Crossmatch Seek Avenger Male (Left) Female (Right)

Figure B.2.8 Neurotech Crossmatch Seek Avenger Rolls Male (Left) Female (Right)

Figure B.2.9 Neurotech InnerID Male (Left) Female (Right)

Figure B.2.10 Neurotech L1 Male (Left) Female (Right)

Figure B.2.11 Neurotech Morpho FOTF Male (Left) Female (Right)

Figure B.2.12 Neurotech MorphoMobile Male (Left) Female (Right)

B.3 SourceAFIS Genuine/Imposter Score Distributions

Table B.5 SourceAFIS Male Genuine and Imposter KLD, Minimum and Maximum Scores

SourceAFIS Male Device	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0328	0.0849	258.72	11.14	41.22	2.40
<i>ANDI GRY</i>	0.0269	2.5543	227.51	8.98	34.60	4.43
<i>BioSled</i>	0.0359	1.0288	248.36	9.96	141.30	3.65
<i>BioSled Rolls</i>	0.0265	0.0113	329.20	4.48	219.31	1.02
<i>CG2</i>	0.0491	0.0202	248.38	10.82	120.65	2.58
<i>CG2 Rolls</i>	0.0255	0.3119	364.86	11.92	214.73	2.37
<i>CSA</i>	0.0516	1.8634	284.96	33.32	33.18	2.56
<i>CSA Rolls</i>	0.0204	1.6716	517.80	9.01	29.68	5.29
<i>InnerID</i>	0.2466	0.0653	148.15	9.77	32.62	3.67
<i>L1</i>	0.0511	0.0240	288.08	10.70	89.70	1.21
<i>L1 Rolls</i>	0.0202	1.2847	341.77	9.87	35.18	1.02
<i>MFF</i>	0.0313	1.9772	289.72	9.97	33.23	1.02
<i>MorphoMobile</i>	0.0440	0.0222	172.81	10.15	99.94	4.51

Table B.6 SourceAFIS Female Genuine and Imposter KLD, Minimum and Maximum Scores

SourceAFIS Female Device	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0309	2.5337	222.20	10.45	35.35	2.87
<i>ANDI GRY</i>	0.0737	0.1235	181.90	9.50	35.99	1.05
<i>BioSled</i>	0.1505	6.9133	210.80	10.65	37.64	1.13
<i>BioSled Rolls</i>	0.0275	42.0973	331.39	10.26	38.51	1.02
<i>CG2</i>	0.0228	1.4555	230.58	11.39	86.49	3.61
<i>CG2 Rolls</i>	0.0294	16.7425	356.58	11.06	36.67	1.02
<i>CSA</i>	0.1705	0.4403	209.85	13.24	35.92	2.98
<i>CSA Rolls</i>	0.0719	0.1603	319.62	10.27	35.01	1.03
<i>InnerID</i>	0.2600	2.0087	116.29	8.88	31.22	5.57
<i>L1</i>	0.0621	6.6097	239.31	9.57	33.07	3.16
<i>L1 Rolls</i>	0.0205	1.6524	323.08	0.00	32.98	0.00
<i>MFF</i>	0.0492	0.0939	235.71	9.18	36.04	1.02
<i>MorphoMobile</i>	0.0364	6.4280	168.69	9.08	33.70	4.47

Figure B.3.1 SourceAFIS ANDI Binary Male (Left) Female (Right)

Figure B.3.2 SourceAFIS ANDI Greyscale Male (Left) Female (Right)

Figure B.3.3 SourceAFIS BioSled Male (Left) Female (Right)

Figure B.3.4 SourceAFIS BioSled Rolls Male (Left) Female (Right)

Figure B.3.5 SourceAFIS FP II Guardian Male (Left) Female (Right)

Figure B.3.6 SourceAFIS FP II Guardian Male (Left) Female (Right)

Figure B.3.7 SourceAFIS Crossmatch Seek Avenger Male (Left) Female (Right)

Figure B.3.8 SourceAFIS Crossmatch Seek Avenger Rolls Male (Left) Female (Right)

Figure B.3.9 SourceAFIS InnerID Male (Left) Female (Right)

Figure B.3.10 SourceAFIS L1 Male (Left) Female (Right)

Figure B.3.11 SourceAFIS L1 Rolls Male (Left) Female (Right)

Figure B.3.12 SourceAFIS Morpho FOTF Male (Left) Female (Right)

Figure B.3.13 SourceAFIS MorphoMobile Male (Left) Female (Right)

B.4 NBIS ROC Curves and Area Under Curve

Table B.7 NBIS Area Under the Curve for ROC Plots

NBIS	Device	Male Area Under Curve	Female Area Under Curve
	<i>ANDI BIN</i>	0.9826	0.9773
	<i>ANDI GRY</i>	0.9784	0.9808
	<i>BioSled</i>	0.9731	0.9958
	<i>BioSled Rolls</i>	0.9783	0.9891
	<i>CG2</i>	0.9821	0.9752
	<i>CG2 Rolls</i>	0.9872	0.9996
	<i>CSA</i>	0.9998	0.9967
	<i>CSA Rolls</i>	0.9893	0.9861
	<i>InnerID</i>	0.8745	0.8440
	<i>L1</i>	0.9815	0.9836
	<i>MFF</i>	0.9854	0.9739
	<i>MorphoMobile</i>	0.9932	0.9953

Figure B.4.1 NBIS ANDI Binary Gender ROC Curves (Left) NBIS ANDI Greyscale Gender ROC Curves (Right)

Figure B.4.2 NBIS BioSled Gender ROC Curves (Left) NBIS BioSled Rolls Gender ROC Curves (Right)

Figure B.4.3 NBIS FP II Guardian Gender ROC Curves (Left) NBIS FP II Guardian Rolls Gender ROC Curves (Right)

Figure B.4.4 NBIS Crossmatch Seek Avenger Gender ROC Curves (Left) NBIS Crossmatch Seek Avenger Rolls Gender ROC Curves (Right)

Figure B.4.5 NBIS InnerID Gender ROC Curves (Left) NBIS L1 Gender ROC Curves (Right)

Figure B.4.6 NBIS L1 Rolls Gender ROC Curves (Left) NBIS Morpho FOTF Gender ROC Curves (Right)

Figure B.4.7 NBIS MorphoMobile Gender ROC Curves

B.5 Neurotech ROC Curves and Area Under Curve

Table B.8 Neurotech Area Under the Curve for ROC Plots

Neurotech Device	Male Area Under Curve	Female Area Under Curve
<i>ANDI BIN</i>	0.9851	0.9715
<i>ANDI GRY</i>	0.9880	0.9752
<i>BioSled</i>	0.9682	0.9986
<i>BioSled Rolls</i>	0.9823	0.9965
<i>CG2</i>	0.9817	0.9828
<i>CG2 Rolls</i>	0.9950	1.0000
<i>CSA</i>	1.0000	0.9950
<i>CSA Rolls</i>	0.9953	0.9946
<i>InnerID</i>	0.9422	0.9089
<i>L1</i>	0.9853	0.9904
<i>MFF</i>	0.9940	0.9971
<i>MorphoMobile</i>	0.9948	0.9911

Figure B.5.1 Neurotech ANDI Binary Gender ROC Curves (Left) Neurotech ANDI Greyscale Gender ROC Curves (Right)

Figure B.5.2 Neurotech BioSled Gender ROC Curves (Left) Neurotech BioSled Rolls Gender ROC Curves (Right)

Figure B.5.3 Neurotech FP II Guardian Gender ROC Curves (Left) Neurotech FP II Guardian Rolls Gender ROC Curves (Right)

Figure B.5.4 Neurotech Crossmatch Seek Avenger Gender ROC Curves (Left) Neurotech Crossmatch Seek Avenger Rolls Gender ROC Curves (Right)

Figure B.5.5 Neurotech InnerID Gender ROC Curves (Left) Neurotech L1 Gender ROC Curves (Right)

Figure B.5.6 Neurotech Morpho FOTF Gender ROC Curves (Left) Neurotech MorphoMobile Gender ROC Curves (Right)

B.6 SourceAFIS ROC Curves and Area Under Curve

Table B.9 SourceAFIS Area Under the Curve for ROC Plots

SourceAFIS Device	Male Area Under Curve	Female Area Under Curve
<i>ANDI BIN</i>	0.9760	0.9554
<i>ANDI GRY</i>	0.9389	0.9340
<i>BioSled</i>	0.9609	0.9927
<i>BioSled Rolls</i>	0.9584	0.9526
<i>CG2</i>	0.9779	0.9798
<i>CG2 Rolls</i>	0.9892	0.9872
<i>CSA</i>	1.0000	0.9978
<i>CSA Rolls</i>	0.9849	0.9742
<i>InnerID</i>	0.8209	0.7635
<i>L1</i>	0.9897	0.9863
<i>L1 Rolls</i>	0.9758	0.9634
<i>MFF</i>	0.9857	0.9745
<i>MorphoMobile</i>	0.9902	0.9895

Figure B.6.1 SourceAFIS ANDI Binary Gender ROC Curves (Left) SourceAFIS ANDI Greyscale Gender ROC Curves (Right)

Figure B.6.2 SourceAFIS BioSled Gender ROC Curves (Left) SourceAFIS BioSled Rolls Gender ROC Curves (Right)

Figure B.6.3 SourceAFIS FP II Guardian Gender ROC Curves (Left) SourceAFIS FP II Guardian Rolls Gender ROC Curves (Right)

Figure B.6.4 SourceAFIS Crossmatch Seek Avenger Gender ROC Curves (Left) SourceAFIS Crossmatch Seek Avenger Gender ROC Curves (Right)

Figure B.6.5 SourceAFIS InnerID Gender ROC Curves (Left) SourceAFIS L1 Gender ROC Curves (Right)

Figure B.6.6 SourceAFIS L1 Rolls Gender ROC Curves (Left) SourceAFIS Morpho FOTF Gender ROC Curves (Right)

Figure B.6.7 SourceAFIS MorphoMobile Gender ROC Curves

B.7 Minutiae Box Plots by Device and Gender

Figure B.7.1 Minutiae Box Plot for ANDI Binary by Gender (Left) Minutiae Box Plot for ANDI Greyscale by Gender (Right)

Figure B.7.2 Minutiae Box Plot for BioSled by Gender (Left) Minutiae Box Plot for BioSled Rolls by Gender (Right)

Figure B.7.3 Minutiae Box Plot for FP II Guardian by Gender (Left) Minutiae Box Plot for FP II Guardian Rolls by Gender (Right)

Figure B.7.4 Minutiae Box Plot for Crossmatch Seek Avenger by Gender (Left) Minutiae Box Plot for Crossmatch Seek Avenger Rolls by Gender (Right)

Figure B.7.5 Minutiae Box Plot for InnerID by Gender (Left) Minutiae Box Plot for L1 by Gender (Right)

Figure B.7.6 Minutiae Box Plot for L1 Rolls by Gender (Left) Minutiae Box Plot for Morpho FOTF by Gender (Right)

Figure B.7.7 Minutiae Box Plot for MorphoMobile by Gender

B.8 Equal Error Rates For Gender Based Study

Table B.10 NBIS Gender Based EER Values

<i>NBIS</i>	<i>EER Value</i>	
Device	Male	Female
<i>ANDI BIN</i>	0.0310	0.0561
<i>ANDI GRY</i>	0.0607	0.0577
<i>BioSled</i>	0.0696	0.0222
<i>BioSled Rolls</i>	0.0480	0.0262
<i>CG2</i>	0.0335	0.0350
<i>CG2 Rolls</i>	0.0210	0.0125
<i>CSA</i>	0.0050	0.0139
<i>CSA Rolls</i>	0.0192	0.0314
<i>InnerID</i>	0.2125	0.2412
<i>L1</i>	0.0276	0.0244
<i>MFF</i>	0.0176	0.0113
<i>MorphoMobile</i>	0.0219	0.0433

Table B.11 Neurotech Gender Based EER Values

<i>Neurotech</i>	<i>EER Value</i>	
Device	Male	Female
<i>ANDI BIN</i>	0.0268	0.0441
<i>ANDI GRY</i>	0.0193	0.0501
<i>BioSled</i>	0.0518	0.0056
<i>BioSled Rolls</i>	0.0281	0.0108
<i>CG2</i>	0.0294	0.0303
<i>CG2 Rolls</i>	0.0128	0.0000
<i>CSA</i>	0.0000	0.0057
<i>CSA Rolls</i>	0.0048	0.0107
<i>InnerID</i>	0.1138	0.1620
<i>L1</i>	0.0245	0.0196
<i>MFF</i>	0.0154	0.0082
<i>MorphoMobile</i>	0.0132	0.0152

Table B.12 SourceAFIS Gender Based EER Values

<i>SourceAFIS</i>	<i>EER Value</i>	
Device	Male	Female
<i>ANDI BIN</i>	0.0446	0.0757
<i>ANDI GRY</i>	0.1049	0.1210
<i>BioSled</i>	0.0783	0.0139
<i>BioSled Rolls</i>	0.0708	0.0785
<i>CG2</i>	0.0356	0.0400
<i>CG2 Rolls</i>	0.0210	0.0175
<i>CSA</i>	0.0000	0.0056
<i>CSA Rolls</i>	0.0264	0.0471
<i>InnerID</i>	0.2500	0.3197
<i>L1</i>	0.0224	0.0220
<i>MFF</i>	0.0346	0.0470
<i>MorphoMobile</i>	0.0175	0.0175

Appendix C

Age Based Study

This appendix shows all of the results from the Age Based Demographic Study. The data was broken into 4 categories, ages 18-19, 20-29, 30-39, and 40 and over. The largest group is made up of age 20 to 29 year old subjects due to the environment where the collection was held. The age breakdowns can be seen in Figure 3.6. The results that can be seen in this section include: genuine and imposter distributions, Kullback Leibler Divergence measures, maximum and minimum match scores, ROC Curves, area under the curve, and Equal Error Rates for each matching run. All of the results stated above are shown for each of the three matchers used. At the end of this appendix there are box plots that represent the number of minutiae found in images from each device, this data came from the NBIS matcher.

C.1 NBIS Genuine/Imposter Score Distributions

Table C.1 NBIS 18-19 Genuine and Imposter KLD, Minimum and Maximum Scores

NBIS 18-19						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0838	0.8833	241	8	36	3
<i>ANDI GRY</i>	0.0343	0.6518	332	16	40	4
<i>BioSled</i>	0.0408	1.9944	298	11	47	0
<i>BioSled Rolls</i>	0.0437	3.4163	277	20	27	0
<i>CG2</i>	0.1168	3.1837	246	4	40	0
<i>CG2 Rolls</i>	0.0633	2.1104	359	31	22	0
<i>CSA</i>	0.0394	1.7727	499	30	46	0
<i>CSA Rolls</i>	0.0348	4.3977	506	10	28	3
<i>InnerID</i>	0.6693	1.1118	118	10	49	5
<i>L1</i>	0.0604	3.4227	297	16	47	0
<i>L1 Rolls</i>	0.0529	2.4702	449	0	28	0
<i>MFF</i>	0.0320	1.8875	310	24	51	3
<i>MorphoMobile</i>	0.0427	0.8768	278	11	35	0

Table C.2 NBIS 20-29 Genuine and Imposter KLD, Minimum and Maximum Scores

NBIS 20-29							
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter	Genuine KLD
<i>ANDI BIN</i>	0.0114	0.1265	319	5	44	0	0.45367
<i>ANDI GRY</i>	0.0131	0.2460	358	8	64	0	0.325301
<i>BioSled</i>	0.0065	0.0128	304	4	245	0	10.166853
<i>BioSled Rolls</i>	0.0136	0.6659	317	5	184	0	2.039956
<i>CG2</i>	0.0132	0.0120	358	4	159	0	20.75243
<i>CG2 Rolls</i>	0.0071	0.0106	452	4	262	0	0.031799
<i>CSA</i>	0.1228	0.8538	289	17	61	0	0.615569
<i>CSA Rolls</i>	0.0452	7.4043	435	4	32	0	0.566192
<i>InnerID</i>	0.0688	0.7238	176	7	73	4	0.687748
<i>L1</i>	0.0092	0.0190	328	4	137	0	0.546715
<i>L1 Rolls</i>	0.0258	0.0337	422	4	143	0	0.084613
<i>MFF</i>	0.0137	0.1676	360	5	48	0	0.330587
<i>MorphoMobile</i>	0.0373	3.5694	261	3	44	0	0.550937

Table C.3 NBIS 30-39 Genuine and Imposter KLD, Minimum and Maximum Scores

NBIS 30-39							
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter	Genuine KLD
<i>ANDI BIN</i>	0.0489	1.0251	275	6	27	3	0.397235
<i>ANDI GRY</i>	0.0730	0.8623	281	10	48	3	0.404862
<i>BioSled</i>	0.0554	1.9477	267	9	27	0	0.374085
<i>BioSled Rolls</i>	0.0471	1.4452	289	27	21	3	0.570223
<i>CG2</i>	0.0786	1.2275	259	8	29	3	0.334276
<i>CG2 Rolls</i>	0.0552	0.9662	336	29	22	3	0.392907
<i>CSA</i>	0.2237	3.2299	244	8	34	0	0.321009
<i>CSA Rolls</i>	0.0762	3.0186	292	36	22	3	0.57702
<i>InnerID</i>	0.6002	2.8443	29	14	27	10	1.470773
<i>L1</i>	0.0559	4.0166	222	54	24	0	0.468441
<i>L1 Rolls</i>	0.1650	2.7238	221	4	23	3	0.640702
<i>MFF</i>	0.1250	1.0947	262	8	43	3	0.471992
<i>MorphoMobile</i>	0.1000	0.7262	200	7	28	0	0.463784

Table C.4 NBIS 40 and up Genuine and Imposter KLD, Minimum and Maximum Scores

NBIS 40 and up							
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter	Genuine KLD
<i>ANDI BIN</i>	0.1035	0.9506	225	14	41	3	0.310583
<i>ANDI GRY</i>	0.1147	0.9976	251	22	48	6	0.384789
<i>BioSled</i>	0.0398	1.6229	241	19	27	0	0.42708
<i>BioSled Rolls</i>	0.0861	2.5945	170	9	18	0	0.831423
<i>CG2</i>	0.0984	2.7650	209	5	23	0	0.494974
<i>CG2 Rolls</i>	0.0985	1.6706	327	7	25	4	0.293415
<i>CSA</i>	0.0485	5.4184	242	23	23	0	0.586351
<i>CSA Rolls</i>	0.0991	3.9052	337	5	20	3	0.616656
<i>InnerID</i>	0.6008	1.7907	30	17	32	10	1.62096
<i>L1</i>	0.0718	2.9361	180	14	22	0	0.497768
<i>L1 Rolls</i>	0.0499	4.7252	235	7	23	3	0.569319
<i>MFF</i>	0.0436	1.1245	272	18	41	4	0.571957
<i>MorphoMobile</i>	0.1182	0.6724	137	11	25	0	0.644492

(a)

(b)

(c)

(d)

Figure C.1.1 NBIS ANDI Binary (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.2 NBIS ANDI Greyscale (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.3 NBIS BioSled (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.4 NBIS BioSled Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.5 NBIS FP II Guardian (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.6 NBIS FP II Guardian Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.7 NBIS Crossmatch Seek Avenger (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.8 NBIS Crossmatch Seek Avenger Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.9 NBIS InnerID (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.10 NBIS L1 (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.11 NBIS L1 Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.12 NBIS Morpho FOTF (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.1.13 NBIS MorphoMobile (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

C.2 Neurotech Genuine/Imposter Score Distributions

Table C.5 Neurotech 18-19 Genuine and Imposter KLD, Minimum and Maximum Scores

Neurotech 18-19						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0230	3.6518	809	4	26	0
<i>ANDI GRY</i>	0.0174	1.2327	863	9	36	0
<i>BioSled</i>	0.0138	0.4548	860	107	36	0
<i>BioSled Rolls</i>	0.0167	0.0106	914	212	20	0
<i>CG2</i>	0.0118	0.1391	927	4	31	0
<i>CG2 Rolls</i>	0.0109	0.0156	1018	230	20	0
<i>CSA</i>	0.0617	2.1182	1267	267	35	0
<i>CSA Rolls</i>	0.0115	4.1534	1682	86	26	0
<i>L1</i>	0.0203	0.0037	913	224	37	0
<i>MFF</i>	0.0224	2.8592	836	148	31	0
<i>MorphoMobile</i>	0.0139	0.1080	681	1	39	0

Table C.6 Neurotech 20-29 Genuine and Imposter KLD, Minimum and Maximum Scores

Neurotech 20-29						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0022	0.1658	986	1	41	0
<i>ANDI GRY</i>	0.0029	0.9697	1003	3	45	0
<i>BioSled</i>	0.0033	0.0120	951	0	539	0
<i>BioSled Rolls</i>	0.0073	0.0012	968	0	656	0
<i>CG2</i>	0.0036	0.0090	1000	1	641	0
<i>CG2 Rolls</i>	0.0028	0.0015	1188	2	658	0
<i>CSA</i>	0.0153	5.0395	863	241	49	0
<i>CSA Rolls</i>	0.0377	9.8309	1035	0	29	0
<i>L1</i>	0.0034	0.0002	925	0	681	0
<i>MFF</i>	0.0059	0.9825	952	3	58	1
<i>MorphoMobile</i>	0.0044	0.4012	705	4	44	0

Table C.7 NBIS 30-39 Genuine and Imposter KLD, Minimum and Maximum Scores

Neurotech 30-39						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0150	3.4460	842	2	21	0
<i>ANDI GRY</i>	0.0101	0.6944	903	6	41	1
<i>BioSled</i>	0.0300	0.9620	742	3	33	0
<i>BioSled Rolls</i>	0.0434	0.0183	993	181	18	0
<i>CG2</i>	0.0170	0.2309	875	141	27	0
<i>CG2 Rolls</i>	0.0324	0.0102	1072	229	18	0
<i>CSA</i>	0.1189	1.4025	793	1	41	0
<i>CSA Rolls</i>	0.0207	6.1675	760	219	17	0
<i>L1</i>	0.0362	0.0039	891	164	23	0
<i>MFF</i>	0.0252	1.9548	801	4	33	1
<i>MorphoMobile</i>	0.0191	0.3839	595	3	30	0

Table C.8 NBIS 40 and up Genuine and Imposter KLD, Minimum and Maximum Scores

Neurotech 40 and up						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0232	3.8684	749	132	25	0
<i>ANDI GRY</i>	0.0334	3.1249	820	61	32	1
<i>BioSled</i>	0.0140	1.2292	768	126	21	0
<i>BioSled Rolls</i>	0.0079	0.0277	762	3	24	0
<i>CG2</i>	0.0388	0.3270	748	1	29	0
<i>CG2 Rolls</i>	0.0178	0.0164	1072	216	10	0
<i>CSA</i>	0.0193	5.4521	749	201	18	0
<i>CSA Rolls</i>	0.0175	9.6163	891	73	12	0
<i>L1</i>	0.0289	0.0048	759	342	29	0
<i>MFF</i>	0.0292	2.4726	671	208	25	2
<i>MorphoMobile</i>	0.0229	0.4160	555	139	22	0

(a)

(b)

(c)

(d)

Figure C.2.1 Neurotech ANDI Binary (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.2 Neurotech ANDI Greyscale (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.3 Neurotech BioSled (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.4 Neurotech BioSled Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.5 Neurotech FP II Guardian (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.6 Neurotech FP II Guardian Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.7 Neurotech Crossmatch Seek Avenger (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.8 Neurotech Crossmatch Seek Avenger Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

Figure C.2.9 Neurotech InnerID (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up (Not Available)

(a)

(b)

(c)

(d)

Figure C.2.10 Neurotech L1 (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.11 Neurotech Morpho FOTF (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.2.12 Neurotech MorphoMobile (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

C.3 SourceAFIS Genuine/Imposter Score Distributions

Table C.9 SourceAFIS 18-19 Genuine and Imposter KLD, Minimum and Maximum Scores

SourceAFIS 18-19						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0360	1.1649	259.7252	11.85273	30.19959	5.878553
<i>ANDI GRY</i>	0.0584	6.9912	216.3056	10.55984	38.68415	6.92837
<i>BioSled</i>	0.0944	3.9879	214.9599	13.20869	31.48004	6.289892
<i>BioSled Rolls</i>	0.0369	4.3084	305.3576	10.55244	26.79964	5.206804
<i>CG2</i>	0.1343	4.4908	190.5806	9.11262	35.63965	5.668835
<i>CG2 Rolls</i>	0.0708	8.6481	322.159	10.87964	34.52416	4.572073
<i>CSA</i>	0.0368	2.3131	261.0499	21.84235	32.15683	6.654526
<i>CSA Rolls</i>	0.0461	1.8668	518.3488	11.35223	29.48184	6.068511
<i>InnerID</i>	1.3770	3.9396	117.0034	9.712775	19.33523	7.380855
<i>L1</i>	0.0755	3.0207	238.0814	23.20657	29.80924	7.061163
<i>L1 Rolls</i>	0.1159	4.8319	291.972	0	30.03865	0
<i>MFF</i>	0.0866	1.1763	252.8406	10.53184	30.18343	5.116627
<i>MorphoMobile</i>	0.1229	4.1186	156.4674	9.806087	31.98695	6.877412

Table C.10 SourceAFIS 20-29 Genuine and Imposter KLD, Minimum and Maximum Scores

SourceAFIS 20-29						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0139	3.7860	258.9763	11.24244	37.96463	1.1505
<i>ANDI GRY</i>	0.0255	3.2567	227.3911	8.953438	41.80738	1.068082
<i>BioSled</i>	0.0158	0.4477	247.8092	10.44588	140.6996	2.44783
<i>BioSled Rolls</i>	0.0112	0.0946	336.4065	9.458447	214.1273	1.01918
<i>CG2</i>	0.0367	1.2740	244.6543	8.773584	155.1426	2.002312
<i>CG2 Rolls</i>	0.0122	0.0198	364.865	11.4828	214.8845	1.072709
<i>CSA</i>	0.0331	1.6879	285.5363	25.56576	37.04658	3.415862
<i>CSA Rolls</i>	0.0927	0.6877	336.2823	8.577291	34.38301	1.021923
<i>InnerID</i>	0.0795	0.7772	148.194	9.427563	31.8045	3.630311
<i>L1</i>	0.0149	0.4659	287.0937	9.631104	89.61704	2.009291
<i>L1 Rolls</i>	0.0119	1.3526	341.7931	9.870334	35.23992	1.0158
<i>MFF</i>	0.0243	1.9716	290.2585	8.428964	39.19853	1.0158
<i>MorphoMobile</i>	0.0235	10.5725	172.8451	11.19441	33.69872	1.265244

Table C.11 SourceAFIS 30-39 Genuine and Imposter KLD, Minimum and Maximum Scores

SourceAFIS 30-39						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0889	5.4711	198.5667	12.04636	25.95447	4.662342
<i>ANDI GRY</i>	0.1356	0.9623	147.5204	10.5444	27.5129	4.930195
<i>BioSled</i>	0.0872	18.7870	213.4055	13.12	25.72716	4.65225
<i>BioSled Rolls</i>	0.0423	2.1651	284.5245	11.3334	25.43212	6.607458
<i>CG2</i>	0.1037	4.5059	210.5107	12.60935	30.83772	6.081194
<i>CG2 Rolls</i>	0.0461	2.9185	293.6561	8.773874	28.32818	3.84902
<i>CSA</i>	0.3016	1.0281	171.7189	11.71629	27.61703	5.962965
<i>CSA Rolls</i>	0.0652	3.2166	257.2393	51.99955	28.55286	7.618226
<i>InnerID</i>	1.3632	1.9192	15.35044	10.02823	17.53011	10.17242
<i>L1</i>	0.1115	2.5975	183.8853	45.33661	26.11816	7.516325
<i>L1 Rolls</i>	0.0743	2.5510	244.6956	12.48463	29.49694	5.333611
<i>MFF</i>	0.1043	0.9298	195.1617	11.24871	29.006	5.155389
<i>MorphoMobile</i>	0.1931	5.1173	104.4118	12.4216	29.11408	6.372153

Table C.12 SourceAFIS 40 and up Genuine and Imposter KLD, Minimum and Maximum Scores

SourceAFIS 40 and up						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0760	2.7526	209.7784	11.5091	24.01522	6.774823
<i>ANDI GRY</i>	0.1072	1.7703	150.2118	10.76227	24.582	8.93766
<i>BioSled</i>	0.1062	1.6458	172.6986	29.25277	25.50017	9.102567
<i>BioSled Rolls</i>	0.0501	1.8843	251.6365	11.20195	24.24384	6.865717
<i>CG2</i>	0.1089	5.8069	190.3472	12.61516	23.62895	6.888422
<i>CG2 Rolls</i>	0.0882	2.1999	263.4852	10.74035	24.87952	5.531532
<i>CSA</i>	0.1147	1.4563	159.6051	25.41742	22.98182	8.734149
<i>CSA Rolls</i>	0.0540	2.0094	264.1351	12.81646	28.26393	6.489259
<i>InnerID</i>	1.3822	2.4455	14.55067	11.29338	16.08005	10.46509
<i>L1</i>	0.0675	3.1641	193.4362	28.72438	24.41692	7.669943
<i>L1 Rolls</i>	0.0675	1.5156	205.0054	11.37656	24.54967	4.833644
<i>MFF</i>	0.0611	2.3292	190.9	9.912061	23.76718	5.180087
<i>MorphoMobile</i>	0.1420	14.1331	102.6575	12.29423	22.09316	3.040535

(a)

(b)

(c)

(d)

Figure C.3.1 SourceAFIS ANDI Binary (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.2 SourceAFIS ANDI Greyscale (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.3 SourceAFIS BioSled (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.4 SourceAFIS BioSled Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.5 SourceAFIS FP II Guardian (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.6 SourceAFIS FP II Guardian Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.7 SourceAFIS Crossmatch Seek Avenger (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.8 SourceAFIS Crossmatch Seek Avenger Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.9 SourceAFIS InnerID (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.10 SourceAFIS L1 (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.11 SourceAFIS L1 Rolls (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

Figure C.3.12 SourceAFIS Morpho FOTF (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

(a)

(b)

(c)

(d)

Figure C.3.13 SourceAFIS MorphoMobile (a) Ages 18-19 (b) Ages 20-29 (c) Ages 30-39 (d) Ages 40 and up

C.4 NBIS ROC Curves and Area Under Curve

Table C.13 NBIS 18-19 Area under Curve

NBIS 18-19	
Device	Area Under Curve
ANDI BIN	0.988839
ANDI GRY	0.99552
BioSled	0.994623
BioSled Rolls	0.999971
CG2	0.972421
CG2 Rolls	1
CSA	0.999838
CSA Rolls	0.996351
InnerID	0.87304
L1	0.998894
L1 Rolls	0.983324
MFF	0.99998
MorphoMobile	0.996163

Table C.14 NBIS 20-29 Area under Curve

NBIS 20-29	
Device	Area Under Curve
ANDI BIN	0.986152
ANDI GRY	0.980966
BioSled	0.977594
BioSled Rolls	0.97685
CG2	0.982419
CG2 Rolls	0.991015
CSA	0.999744
CSA Rolls	0.987361
InnerID	0.870499
L1	0.976552
L1 Rolls	0.979743
MFF	0.993658
MorphoMobile	0.992372

Table C.15 NBIS 30-39 Area under Curve

NBIS 30-39	
Device	Area Under Curve
ANDI BIN	0.960701
ANDI GRY	0.954972
BioSled	0.992645
BioSled Rolls	1
CG2	0.991879
CG2 Rolls	1
CSA	0.987423
CSA Rolls	1
InnerID	0.57375
L1	1
L1 Rolls	0.976454
MFF	0.984673
MorphoMobile	0.983952

Table C.16 NBIS 40 and up Area under Curve

NBIS 40 and up	
Device	Area Under Curve
ANDI BIN	0.990047
ANDI GRY	0.97675
BioSled	0.999112
BioSled Rolls	0.989228
CG2	0.922401
CG2 Rolls	0.964758
CSA	0.999952
CSA Rolls	0.948507
InnerID	0.791667
L1	0.999047
L1 Rolls	0.970189
MFF	0.999351
MorphoMobile	0.994694

Figure C.4.1 NBIS ANDI Binary Age Demographic ROC Curves (Left) NBIS ANDI Greyscale Age Demographic ROC Curves (Right)

Figure C.4.2 NBIS BioSled Age Demographic ROC Curves (Left) NBIS BioSled Rolls Age Demographic ROC Curves (Right)

Figure C.4.3 NBIS FP II Guardian Age Demographic ROC Curves (Left) NBIS FP II Guardian Rolls Age Demographic ROC Curves (Right)

Figure C.4.4 NBIS Crossmatch Seek Avenger Age Demographic ROC Curves (Left) NBIS Crossmatch Seek Avenger Rolls Age Demographic ROC Curves (Right)

Figure C.4.5 NBIS InnerID Age Demographic ROC Curves (Left) NBIS L1 Age Demographic ROC Curves (Right)

Figure C.4.6 NBIS L1 Rolls Age Demographic ROC Curves (Left) NBIS Morpho FOTF Age Demographic ROC Curves (Right)

Figure C.4.7 NBIS MorphoMobile Age Demographic ROC Curves

C.5 Neurotech ROC Curves and Area Under Curve

Table C.17 Neurotech 18-19 Area under Curve

Neurotech 18-19	
Device	Area Under Curve
ANDI BIN	0.989207
ANDI GRY	0.988166
BioSled	1
BioSled Rolls	1
CG2	0.993148
CG2 Rolls	1
CSA	1
CSA Rolls	1
L1	1
MFF	1
MorphoMobile	0.972874

Table C.18 Neurotech 20-29 Area under Curve

Neurotech 20-29	
Device	Area Under Curve
ANDI BIN	0.984873
ANDI GRY	0.98276
BioSled	0.976493
BioSled Rolls	0.985896
CG2	0.982915
CG2 Rolls	0.99611
CSA	1
CSA Rolls	0.993444
L1	0.983861
MFF	0.995235
MorphoMobile	0.997851

Table C.19 Neurotech 30-39 Area under Curve

Neurotech 30-39	
Device	Area Under Curve
ANDI BIN	0.963432
ANDI GRY	0.966645
BioSled	0.988278
BioSled Rolls	1
CG2	1
CG2 Rolls	1
CSA	0.973109
CSA Rolls	1
L1	1
MFF	0.991565
MorphoMobile	0.981169

Table C.20 Neurotech 40 and up Area under Curve

Neurotech 40 and up	
Device	Area Under Curve
ANDI BIN	1
ANDI GRY	1
BioSled	1
BioSled Rolls	0.976248
CG2	0.904583
CG2 Rolls	1
CSA	1
CSA Rolls	1
L1	1
MFF	1
MorphoMobile	1

Figure C.5.1 Neurotech ANDI Binary Age Demographic ROC Curves (Left) Neurotech ANDI Greyscale Age Demographic ROC Curves (Right)

Figure C.5.2 Neurotech BioSled Age Demographic ROC Curves (Left) Neurotech BioSled Rolls Age Demographic ROC Curves (Right)

Figure C.5.3 Neurotech FP II Guardian Age Demographic ROC Curves (Left) Neurotech FP II Guardian Rolls Age Demographic ROC Curves (Right)

Figure C.5.4 Neurotech Crossmatch Seek Avenger Age Demographic ROC Curves (Left) Neurotech Crossmatch Seek Avenger Rolls Age Demographic ROC Curves (Right)

Figure C.5.5 Neurotech L1 Age Demographic ROC Curves (Left) Neurotech Morpho FOTF Age Demographic ROC Curves (Right)

Figure C.5.6 Neurotech MorphoMobile Age Demographic ROC Curves

C.6 SourceAFIS ROC Curves and Area Under Curve

Table C.21 SourceAFIS 18-19 Area under Curve

SourceAFIS 18-19	
Device	Area Under Curve
ANDI BIN	0.964563
ANDI GRY	0.920342
BioSled	0.98982
BioSled Rolls	0.980301
CG2	0.974147
CG2 Rolls	0.991968
CSA	0.999921
CSA Rolls	0.957505
InnerID	0.844872
L1	0.999979
L1 Rolls	0.983741
MFF	0.986496
MorphoMobile	0.983584

Table C.22 SourceAFIS 20-29 Area under Curve

SourceAFIS 20-29	
Device	Area Under Curve
ANDI BIN	0.983914
ANDI GRY	0.953698
BioSled	0.969801
BioSled Rolls	0.952522
CG2	0.981794
CG2 Rolls	0.990839
CSA	0.999998
CSA Rolls	0.984035
InnerID	0.783963
L1	0.980878
L1 Rolls	0.973318
MFF	0.987444
MorphoMobile	0.993096

Table C.23 SourceAFIS 30-39 Area under Curve

SourceAFIS 30-39	
Device	Area Under Curve
ANDI BIN	0.960774
ANDI GRY	0.892799
BioSled	0.990629
BioSled Rolls	0.988284
CG2	0.985936
CG2 Rolls	0.986558
CSA	0.980732
CSA Rolls	1
InnerID	0.5375
L1	1
L1 Rolls	0.987974
MFF	0.980062
MorphoMobile	0.980289

Table C.24 SourceAFIS 40 and up Area under Curve

SourceAFIS 40 and up	
Device	Area Under Curve
ANDI BIN	0.93168
ANDI GRY	0.858469
BioSled	1
BioSled Rolls	0.857277
CG2	0.951094
CG2 Rolls	0.883476
CSA	1
CSA Rolls	0.974026
InnerID	0.631944
L1	1
L1 Rolls	0.931319
MFF	0.92585
MorphoMobile	0.973707

Figure C.6.1 SourceAFIS ANDI Binary Age Demographic ROC Curves (Left) SourceAFIS ANDI Greyscale Age Demographic ROC Curves (Right)

Figure C.6.2 SourceAFIS BioSled Age Demographic ROC Curves (Left) SourceAFIS BioSled Rolls Age Demographic ROC Curves (Right)

Figure C.6.3 SourceAFIS FP II Guardian Age Demographic ROC Curves (Left) SourceAFIS FP II Guardian Rolls Age Demographic ROC Curves (Right)

Figure C.6.4 SourceAFIS Crossmatch Seek Avenger Age Demographic ROC Curves (Left) SourceAFIS Crossmatch Seek Avenger Age Demographic ROC Curves (Right)

Figure C.6.5 SourceAFIS InnerID Age Demographic ROC Curves (Left) SourceAFIS L1 Age Demographic ROC Curves (Right)

Figure C.6.6 SourceAFIS L1 Rolls Age Demographic ROC Curves (Left) SourceAFIS Morpho FOTF Age Demographic ROC Curves (Right)

Figure C.6.7 SourceAFIS MorphoMobile Age Demographic ROC Curves

C.7 Minutiae Box Plots by Age Range and Device

Figure C.7.1 (Left) AND Binary Box Plot (Right) ANDI Greyscale Box Plot

Figure C.7.2 (Left) BioSled Rolls Box Plot (Right) BioSled Box Plot

Figure C.7.3 (Left)FP II Guardian Rolls Box Plot (Right) FP II Guardian Box Plot

Figure C.7.4 (Left)Crossmatch Seek Avenger Rolls Box Plot (Right) Crossmatch Seek Avenger Box Plot

Figure C.7.5 (Left)InnerID Box Plot (Right) L1 Rolls Box Plot

Figure C.7.6 (Left)L1 Box Plot (Right) Morpho FOTF Box Plot

Figure C.7.7 MorphoMobile Box Plots

C.8 Equal Error Rates for Age Based Study

Table C.25 NBIS Equal Error Rates For Age Based Study

<i>NBIS</i>	<i>EER Value</i>			
Device	18-19	20-29	30-39	40 and up
<i>ANDI BIN</i>	0.0357	0.0334	0.0909	0.0794
<i>ANDI GRY</i>	0.0357	0.0533	0.0909	0.1000
<i>BioSled</i>	0.0306	0.0602	0.0263	0.0137
<i>BioSled Rolls</i>	0.0014	0.0508	0.0000	0.0526
<i>CG2</i>	0.0333	0.0313	0.0270	0.1000
<i>CG2 Rolls</i>	0.0000	0.0157	0.0000	0.0476
<i>CSA</i>	0.0086	0.0055	0.0313	0.0016
<i>CSA Rolls</i>	0.0357	0.0175	0.0000	0.0971
<i>InnerID</i>	0.2028	0.2148	0.5000	0.3333
<i>L1</i>	0.0164	0.0302	0.0000	0.0198
<i>L1 Rolls</i>	0.0251	0.0329	0.0263	0.0435
<i>MFF</i>	0.0027	0.0159	0.0278	0.0131
<i>MorphoMobile</i>	0.0328	0.0246	0.0590	0.0435

Table C.26 Neurotech Equal Error Rates For Age Based Study

<i>Neurotech</i>	<i>EER Value</i>			
Device	18-19	20-29	30-39	40 and up
<i>ANDI BIN</i>	0.0360	0.0235	0.0923	0.0000
<i>ANDI GRY</i>	0.0367	0.0278	0.0678	0.0000
<i>BioSled</i>	0.0000	0.0396	0.0267	0.0000
<i>BioSled Rolls</i>	0.0000	0.0246	0.0000	0.0571
<i>CG2</i>	0.0336	0.0282	0.0000	0.1053
<i>CG2 Rolls</i>	0.0000	0.0095	0.0000	0.0000
<i>CSA</i>	0.0000	0.0000	0.0317	0.0000
<i>CSA Rolls</i>	0.0000	0.0106	0.0000	0.0000
<i>L1</i>	0.0000	0.0303	0.0000	0.0000
<i>MFF</i>	0.0000	0.0136	0.0159	0.0000
<i>MorphoMobile</i>	0.0331	0.0097	0.0308	0.0000

Table C.27 SourceAFIS Equal Error Rates For Age Based Study

<i>SourceAFIS</i>	<i>EER Value</i>			
Device	18-19	20-29	30-39	40 and up
<i>ANDI BIN</i>	0.0982	0.0419	0.1061	0.1000
<i>ANDI GRY</i>	0.1184	0.0920	0.1667	0.2444
<i>BioSled</i>	0.0351	0.0569	0.0263	0.0000
<i>BioSled Rolls</i>	0.0345	0.0870	0.0263	0.2105
<i>CG2</i>	0.0333	0.0313	N/A	0.1434
<i>CG2 Rolls</i>	0.0085	0.0188	N/A	0.1429
<i>CSA</i>	0.0052	0.0007	0.0313	0.0000
<i>CSA Rolls</i>	0.0714	0.0316	0.0000	0.0909
<i>InnerID</i>	0.2059	0.3045	0.4375	0.3333
<i>L1</i>	0.0024	0.0272	0.0000	0.0000
<i>L1 Rolls</i>	0.0164	0.0449	0.0395	0.1444
<i>MFF</i>	0.0325	0.0283	0.0532	0.1148
<i>MorphoMobile</i>	0.0164	0.0146	0.0303	N/A

Appendix D

Ethnicity Based Study

This section is made up of the results derived from dividing the data into categories by ethnicity. The results that can be seen in this section include Genuine/Imposter Distributions for each device, Kullback Leibler Divergence measurements, minimum and maximum scores for each matching run, ROC Curves, and Area under the curve measurements. Each of these results were produced with each of the three matchers. The ethnicity categories of “Other Pacific Islander” and “Unknown” were too small to produce any distributions or any other results analysis. At the end of this appendix there are Minutiae Box Plots that are categorized by device, this data was obtained from the NBIS matching algorithm.

D.1 NBIS Genuine/Imposter Score Distributions

Table D.1 NBIS African Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS African						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0783	3.7148	214	61	11	3
<i>ANDI GRY</i>	0.0510	1.7698	240	40	22	4
<i>BioSled</i>	1.1091	1.3129	209	6	30	4
<i>BioSled Rolls</i>	0.0779	1.8666	208	80	13	4
<i>CG2</i>	0.2033	1.9118	202	92	16	5
<i>CG2 Rolls</i>	0.0749	1.6157	240	142	13	3
<i>CSA</i>	0.0744	1.1948	194	84	35	4
<i>CSA Rolls</i>	0.1097	4.4832	187	83	11	3
<i>L1</i>	0.1288	2.8118	227	49	18	3
<i>L1 Rolls</i>	0.1106	3.7102	341	92	13	3
<i>MFF</i>	0.1435	2.3449	143	6	14	4
<i>SMM</i>	0.0581	0.4241	178	37	13	4

Table D.2 NBIS African American Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS African American						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0958	2.1134	319	29	21	3
<i>ANDI GRY</i>	0.0829	0.8404	278	15	37	4
<i>BioSled</i>	0.0744	1.6203	223	7	37	3
<i>BioSled Rolls</i>	0.0757	1.9739	199	30	18	3
<i>CG2</i>	0.1037	1.4777	260	4	34	3
<i>CG2 Rolls</i>	0.0621	0.9826	276	68	17	3
<i>CSA</i>	0.1006	1.3257	183	30	36	3
<i>CSA Rolls</i>	0.0769	3.1626	236	45	20	3
<i>L1</i>	0.1638	3.5862	239	29	28	0
<i>L1 Rolls</i>	0.1393	2.2078	234	31	19	3
<i>MFF</i>	0.0915	1.0985	216	12	36	3
<i>SMM</i>	0.1340	0.5541	139	40	22	0

Table D.3 NBIS American Indian Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS American Indian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1323	3.4101	148	60	9	4
<i>ANDI GRY</i>	0.4058	2.3173	179	84	19	7
<i>BioSled</i>	0.2299	1.6737	235	200	17	8
<i>BioSled Rolls</i>	0.1608	1.8898	225	52	12	8
<i>CG2</i>	0.1522	1.6136	177	110	17	3
<i>CG2 Rolls</i>	16.2262	1.5360	239	4	15	3
<i>CSA</i>	0.6285	3.3994	185	185	12	6
<i>CSA Rolls</i>	0.4880	7.7471	83	80	10	7
<i>L1</i>	0.0855	2.4008	154	98	13	5
<i>L1 Rolls</i>	1.0198	3.2321	156	64	18	3
<i>MFF</i>	0.1508	2.7805	131	39	19	8
<i>SMM</i>	0.7334	0.5920				

Table D.4 NBIS Asian Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS Asian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0840	0.9661	279	6	37	3
<i>ANDI GRY</i>	0.1544	0.7247	219	12	41	3
<i>BioSled</i>	0.0697	2.2829	210	9	34	0
<i>BioSled Rolls</i>	0.0348	1.6884	294	11	27	3
<i>CG2</i>	0.0359	3.6145	335	6	31	0
<i>CG2 Rolls</i>	0.0609	1.0781	452	5	25	3
<i>CSA</i>	0.1235	0.7760	248	33	38	3
<i>CSA Rolls</i>	0.0646	3.4451	292	24	29	3
<i>L1</i>	0.0797	4.1767	292	64	34	0
<i>L1 Rolls</i>	0.0824	3.1502	271	65	20	3
<i>MFF</i>	0.0782	1.1225	323	10	40	3
<i>SMM</i>	0.0992	0.8352	200	7	28	0

Table D.5 NBIS Asian Indian Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS Asian Indian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1264	1.1123	226	14	27	3
<i>ANDI GRY</i>	0.1199	0.6402	315	12	45	4
<i>BioSled</i>	0.0495	1.6303	304	8	27	0
<i>BioSled Rolls</i>	0.0640	1.1785	262	5	25	3
<i>CG2</i>	0.0854	3.7023	294	20	27	0
<i>CG2 Rolls</i>	0.0377	0.7534	352	68	36	3
<i>CSA</i>	0.1555	4.0159	271	26	30	0
<i>CSA Rolls</i>	0.1786	4.2146	303	4	28	3
<i>L1</i>	0.0133	4.0681	289	29	30	0
<i>L1 Rolls</i>	0.0592	2.9283	340	47	23	3
<i>MFF</i>	0.1142	1.1213	316	5	37	3
<i>SMM</i>	0.1598	0.7430	220	6	28	0

Table D.6 NBIS Caucasian Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS Caucasian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0451	1.2735	265	4	41	0
<i>ANDI GRY</i>	0.0177	0.2685	358	8	62	3
<i>BioSled</i>	0.0126	0.0685	298	4	245	0
<i>BioSled Rolls</i>	0.0147	0.4063	317	5	172	0
<i>CG2</i>	0.0188	0.5531	358	4	131	0
<i>CG2 Rolls</i>	0.0203	1.6604	442	7	29	0
<i>CSA</i>	0.0130	0.7696	499	23	54	0
<i>CSA Rolls</i>	0.0114	10.4262	506	5	29	0
<i>L1</i>	0.0191	0.1701	328	6	137	0
<i>L1 Rolls</i>	0.0127	0.2256	449	0	143	0
<i>MFF</i>	0.0133	2.6603	360	8	51	0
<i>SMM</i>	0.0220	1.7941	278	8	37	0

Table D.7 NBIS Hispanic Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS Hispanic						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1275	3.9449	230	7	29	0
<i>ANDI GRY</i>	0.1196	0.5169	254	10	47	3
<i>BioSled</i>	0.0451	1.8945	250	11	71	0
<i>BioSled Rolls</i>	0.0863	0.2200	232	5	143	3
<i>CG2</i>	0.0451	1.5253	275	45	46	3
<i>CG2 Rolls</i>	0.0720	2.0993	302	28	27	0
<i>CSA</i>	0.1817	1.2669	223	17	61	0
<i>CSA Rolls</i>	0.0300	3.1587	394	24	24	3
<i>L1</i>	0.0292	3.6985	277	43	46	0
<i>L1 Rolls</i>	0.0485	2.9663	329	49	27	3
<i>MFF</i>	0.1302	1.1028	245	19	36	3
<i>SMM</i>	0.0447	0.7097	233	24	31	0

Table D.8 NBIS Middle Eastern Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS Middle Eastern						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1897	0.9501	275	6	32	3
<i>ANDI GRY</i>	0.1799	0.4859	282	10	49	4
<i>BioSled</i>	0.0942	1.3721	238	10	35	0
<i>BioSled Rolls</i>	0.0573	2.0614	289	25	19	3
<i>CG2</i>	0.0991	3.0393	275	8	45	0
<i>CG2 Rolls</i>	0.0197	1.0196	379	13	20	3
<i>CSA</i>	0.2012	3.0568	244	8	33	0
<i>CSA Rolls</i>	0.1629	3.0872	265	5	19	3
<i>L1</i>	0.0284	1.2655	285	33	33	3
<i>L1 Rolls</i>	0.0442	2.7705	311	30	23	3
<i>MFF</i>	0.1744	1.1906	262	9	42	3
<i>SMM</i>	0.1195	0.6415	177	12	25	0

Table D.9 NBIS Other Genuine and Imposter KLD, Maximum and Minimum Scores

NBIS Other						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1411	1.1652	213	9	29	3
<i>ANDI GRY</i>	0.1260	0.9902	213	21	37	3
<i>BioSled</i>	0.0306	0.8462	286	7	36	3
<i>BioSled Rolls</i>	0.0979	2.8849	265	11	23	3
<i>CG2</i>	0.0582	3.5313	303	25	33	0
<i>CG2 Rolls</i>	0.1028	1.0031	313	16	23	3
<i>CSA</i>	0.0718	0.5612	259	77	52	3
<i>CSA Rolls</i>	0.0518	3.2520	435	45	26	3
<i>L1</i>	0.0657	3.3504	299	4	29	0
<i>L1 Rolls</i>	0.0783	3.0633	404	4	21	3
<i>MFF</i>	0.0935	1.3848	283	28	33	3
<i>SMM</i>	0.0762	0.6609	261	3	26	0

Figure D.1.1 NBIS ANDI Binary (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.2 NBIS ANDI Greyscale (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.3 NBIS BioSled (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.4 NBIS BioSled Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.5 NBIS FP II Guardian (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.6 NBIS FP II Guardian Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.7 NBIS Crossmatch Seek Avenger (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.8 Crossmatch Seek Avenger Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

Figure D.1.9 NBIS InnerID (a) African (b) African American (c) American Indian (Not Available due to InnerID being removed from collection midway through) (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.10 NBIS L1 (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.11 L1 Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.12 NBIS Morpho FOTF (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.13 NBIS MorphoMobile (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

D.2 Neurotech Genuine/Imposter Score Distributions

Table D.10 Neurotech African Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech African						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0097	11.8608	813	324	4	0
<i>ANDI GRY</i>	0.0311	2.5344	863	156	16	1
<i>BioSled</i>	0.1777	1.294	714	3	16	0
<i>BioSled Rolls</i>	0.0744	0.0389	647	333	8	0
<i>CG2</i>	0.0442	0.382	754	383	9	0
<i>CG2 Rolls</i>	0.0462	0.0045	977	498	6	0
<i>CSA</i>	0.074	8.7876	701	465	7	0
<i>CSA Rolls</i>	0.0204	11.2825	795	362	7	0
<i>L1</i>	0.158	0.0027	848	323	12	0
<i>SMM</i>	0.0151	0.4388	527	231	9	0

Table D.11 Neurotech African American Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech African American						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0149	5.2858	838	132	14	0
<i>ANDI GRY</i>	0.012	2.4253	754	61	30	0
<i>BioSled</i>	0.019	0.9989	744	1	21	0
<i>BioSled Rolls</i>	0.0172	0.0317	740	187	10	0
<i>CG2</i>	0.0316	0.0974	848	1	193	0
<i>CG2 Rolls</i>	0.0208	0.0052	897	322	11	0
<i>CSA</i>	0.0186	5.251	737	359	16	0
<i>CSA Rolls</i>	0.0244	9.1188	720	224	10	0
<i>L1</i>	0.0152	0.0029	757	217	19	0
<i>SMM</i>	0.0405	0.3605	579	286	23	0

Table D.12 Neurotech American Indian Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech American Indian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.008	10.1086	666	321	6	1
<i>ANDI GRY</i>	0.0299	2.9429	798	464	10	7
<i>BioSled</i>	0.2007	0.9628	501	486	7	4
<i>BioSled Rolls</i>	0.3719	0.0142	679	254	4	2
<i>CG2</i>	0.1273	0.4346	680	360	17	1
<i>CG2 Rolls</i>	0.0367	0.0117	848	143	24	1
<i>CSA</i>	0.3452	7.3243	587	587	12	5
<i>CSA Rolls</i>	0.256	13.0463	339	339	4	2
<i>L1</i>	0.042	0.0021	618	307	11	1
<i>MFF</i>	0.0272	4.5010	610	228	20	2
<i>SMM</i>	0.4359	0.405	301	227	14	1

Table D.13 Neurotech Asian Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech Asian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0171	3.073	842	4	24	0
<i>ANDI GRY</i>	0.0139	0.7672	867	9	33	1
<i>BioSled</i>	0.0071	0.7864	763	3	25	0
<i>BioSled Rolls</i>	0.0343	0.023	942	180	21	0
<i>CG2</i>	0.0219	0.29	935	2	21	0
<i>CG2 Rolls</i>	0.0156	0.0118	1102	2	22	0
<i>CSA</i>	0.0267	4.9202	735	325	27	0
<i>CSA Rolls</i>	0.0184	5.9803	700	179	19	0
<i>L1</i>	0.0476	0.0046	863	287	27	0
<i>MFF</i>	0.0438	3.1822	827	4	28	0
<i>SMM</i>	0.0219	0.1911	672	3	27	0

Table D.14 Neurotech Asian Indian Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech Asian Indian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0179	3.4657	810	55	40	0
<i>ANDI GRY</i>	0.0115	1.506	971	58	36	0
<i>BioSled</i>	0.029	0.6308	811	0	33	0
<i>BioSled</i>			924	1	28	0
<i>Rolls</i>	0.0062	0.0119				
<i>CG2</i>	0.0242	0.1915	939	159	30	0
<i>CG2 Rolls</i>	0.0166	0.0147	1072	314	29	0
<i>CSA</i>	0.0206	2.4215	835	275	35	0
<i>CSA Rolls</i>	0.0805	4.7043	888	1	26	0
<i>L1</i>	0.0309	0.0042	893	141	33	0
<i>MFF</i>	0.0325	2.7939	848	2	33	0
<i>SMM</i>	0.0186	0.1396	648	5	31	0

Table D.15 Neurotech Caucasian Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech Caucasian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0054	4.9975	986	0	38	0
<i>ANDI GRY</i>	0.0051	0.1466	1003	3	45	0
<i>BioSled</i>	0.0086	0.1891	951	0	518	0
<i>BioSled</i>			968	0	601	0
<i>Rolls</i>	0.0042	0.0155				
<i>CG2</i>	0.0066	0.1977	1000	1	400	0
<i>CG2 Rolls</i>	0.0187	0.0238	1188	230	28	0
<i>CSA</i>	0.0305	5.8025	1267	201	45	0
<i>CSA Rolls</i>	0.0049	0.8022	1682	0	26	0
<i>L1</i>	0.009	0.0005	913	1	681	0
<i>MFF</i>	0.0230	1.3482	863	4	39	0
<i>SMM</i>	0.0078	0.2404	691	1	48	0

Table D.16 Neurotech Hispanic Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech Hispanic						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0159	3.4466	975	1	21	0
<i>ANDI GRY</i>	0.0162	0.5137	915	3	41	0
<i>BioSled</i>	0.0298	0.0173	747	1	397	0
<i>BioSled</i>			835	1	520	0
<i>Rolls</i>	0.0167	0.0226				
<i>CG2</i>	0.0383	0.1664	908	239	34	0
<i>CG2 Rolls</i>	0.0163	0.016	1018	174	28	0
<i>CSA</i>	0.0166	2.2627	804	254	34	0
<i>CSA Rolls</i>	0.0163	4.6099	946	142	17	0
<i>L1</i>	0.024	0.0034	863	164	28	0
<i>MFF</i>	0.0232	2.8467	813	201	27	0
<i>SMM</i>	0.0307	0.1323	647	187	44	0

Table D.17 Neurotech Middle Eastern Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech Middle Eastern						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0567	2.7733	847	2	26	0
<i>ANDI GRY</i>	0.0509	1.7713	903	6	27	1
<i>BioSled</i>	0.0299	0.7524	854	109	29	0
<i>BioSled</i>			993	180	17	0
<i>Rolls</i>	0.0219	0.0228				
<i>CG2</i>	0.0211	0.2659	875	141	19	0
<i>CG2 Rolls</i>	0.0274	0.0091	1000	308	20	0
<i>CSA</i>	0.1126	3.3431	808	1	19	0
<i>CSA Rolls</i>	0.0375	7.193	863	148	12	0
<i>L1</i>	0.0399	0.0036	891	288	19	0
<i>MFF</i>	0.0636	1.9447	727	7	28	1
<i>SMM</i>	0.0162	0.1793	542	122	35	0

Table D.18 Neurotech Other Genuine and Imposter KLD, Maximum and Minimum Scores

Neurotech Other						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0309	2.9675	774	2	22	0
<i>ANDI GRY</i>	0.0302	0.4649	767	17	37	1
<i>BioSled</i>	0.0166	1.2776	906	2	27	0
<i>BioSled Rolls</i>	0.0145	0.0199	965	107	23	0
<i>CG2</i>	0.0203	0.2719	925	228	31	0
<i>CG2 Rolls</i>	0.0222	0.0103	1002	175	21	0
<i>CSA</i>	0.0237	3.0206	852	383	30	0
<i>CSA Rolls</i>	0.0349	4.8668	905	191	20	0
<i>L1</i>	0.0379	0.0041	925	0	28	0
<i>MFF</i>	0.0556	2.8755	952	165	32	0
<i>SMM</i>	0.0192	0.2111	705	4	34	0

Figure D.2.1 Neurotech ANDI Binary (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.2 Neurotech ANDI Greyscale (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.3 Neurotech BioSled (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.4 Neurotech BioSled Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.5 Neurotech FP II Guardian (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.6 Neurotech FP II Guardian Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.7 Neurotech Crossmatch Seek Avenger (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.1.8 Neurotech Crossmatch Seek Avenger Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.9 Neurotech InnerID (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

(Some Results aren't shown because of this device's low quality images and stopping operation midway through collection)

Figure D.2.10 Neurotech L1 (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.2.11 Neurotech Morpho FOTF (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

(This device had trouble capturing darker complexions and the Neurotech matcher removed images that were not up to a certain quality so that is why this device could not show distributions for the ethnicities African and African American.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

Figure D.2.12 Neurotech MorphoMobile (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

D.3 SourceAFIS Genuine/Imposter Score Distributions

Table D.19 SourceAFIS African Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS African						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.2958	2.7067	259.1137	26.29867	19.56224	9.071217
<i>ANDI GRY</i>	0.4007	1.5936	219.8125	13.64682	19.78427	10.34025
<i>BioSled</i>	0.4054	2.0859	116.7156	18.48837	23.66089	8.728425
<i>BioSled Rolls</i>	0.0877	1.3681	232.7462	90.15849	18.7267	9.510126
<i>CG2</i>	0.1495	3.1481	126.3058	52.07077	19.61867	8.699016
<i>CG2 Rolls</i>	0.1186	1.4545	284.1035	136.0848	18.56935	8.164021
<i>CSA</i>	0.1544	1.8807	145.7916	83.77911	25.81906	9.968618
<i>CSA Rolls</i>	0.0627	1.3722	331.1613	140.573	21.13575	9.915087
<i>L1</i>	0.1761	1.9177	191.7825	55.52259	20.45505	9.566579
<i>L1 Rolls</i>	0.0652	2.1790	324.0332	98.4247	18.31746	8.345504
<i>MFF</i>	0.0991	3.9406	137.2591	11.3185	17.39243	6.982936
<i>SMM</i>	0.1763	2.2796	115.0201	38.36327	22.87316	9.75632

Table D.20 SourceAFIS African American Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS African American						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1160	1.6159	238.8023	33.84354	26.73114	6.897929
<i>ANDI GRY</i>	0.1484	1.7079	152.3309	12.71153	26.36873	8.367515
<i>BioSled</i>	0.1706	2.0052	198.0786	9.413997	22.15639	9.434989
<i>BioSled Rolls</i>	0.0599	1.8500	274.1496	30.08374	26.01874	7.327523
<i>CG2</i>	0.2349	0.4904	167.3741	11.76633	56.35846	8.749595
<i>CG2 Rolls</i>	0.0525	1.0825	305.1128	58.29882	25.08028	8.702084
<i>CSA</i>	0.2122	1.8233	136.6192	33.32489	20.97421	9.594802
<i>CSA Rolls</i>	0.1688	1.5454	275.242	16.3768	21.24726	9.086631
<i>L1</i>	0.1865	3.9513	213.8614	46.14794	23.99998	8.074486
<i>L1 Rolls</i>	0.0430	1.5083	324.7177	10.10076	23.43524	6.591611
<i>MFF</i>	0.0971	6.1422	170.7587	11.29338	24.38368	2.894054
<i>SMM</i>	0.2903	4.0777	100.2059	29.83898	19.79535	8.270656

Table D.21 SourceAFIS American Indian Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS American Indian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1132	4.7527	142.8334	64.82221	16.79907	9.212389
<i>ANDI GRY</i>	0.2532	1.3756	122.2119	32.08049	17.0113	11.38951
<i>BioSled</i>	1.6077	1.8946	129.9908	129.2516	15.70051	12.04497
<i>BioSled Rolls</i>	0.1340	1.8281	274.3735	92.58033	19.93548	11.77341
<i>CG2</i>	11.5257	3.1644	131.4841	90.385	16.02594	10.15785
<i>CG2 Rolls</i>	0.2110	1.2978	318.4995	13.73975	15.39719	10.69792
<i>CSA</i>	1.4274	2.5726	140.2756	139.9248	15.67848	12.68303
<i>CSA Rolls</i>	1.1587	1.6133	133.718	133.6721	18.78525	12.4854
<i>L1</i>	0.3275	2.1223	178.5928	147.2782	17.46229	10.76368
<i>L1 Rolls</i>	0.3340	1.8069	169.3093	20.85485	17.94952	9.443677
<i>MFF</i>	0.2095	1.8234	71.79872	41.32655	17.834	11.50585

Table D.22 SourceAFIS Asian Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS Asian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0840	4.7585	194.8807	11.06559	22.97893	5.939764
<i>ANDI GRY</i>	0.1145	5.1985	174.2071	12.11068	22.63984	4.346674
<i>BioSled</i>	0.1331	2.9401	163.281	13.01383	24.57107	7.623753
<i>BioSled Rolls</i>	0.0268	1.5402	298.9304	11.42592	26.4133	7.951399
<i>CG2</i>	0.1013	4.2584	201.406	10.05764	25.60952	7.072711
<i>CG2 Rolls</i>	0.0552	2.3071	288.6129	10.53184	27.77499	6.210144
<i>CSA</i>	0.2142	1.0064	151.9046	40.32472	26.87905	6.870134
<i>CSA Rolls</i>	0.0797	4.0234	256.5767	12.10818	32.35595	6.524864
<i>L1</i>	0.2285	3.3654	172.7331	11.1369	26.66762	6.883381
<i>L1 Rolls</i>	0.0987	1.2757	247.3902	55.72922	26.01221	5.831905
<i>MFF</i>	0.1283	2.5673	252.5184	9.009671	32.68176	5.042907
<i>SMM</i>	0.0760	6.0662	159.7176	12.4216	21.77014	7.413802

Table D.23 SourceAFIS Asian Indian Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS Asian Indian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0501	3.6349	238.4998	13.34194	25.44888	5.948489
<i>ANDI GRY</i>	0.1811	1.6904	163.7371	10.82603	33.1993	4.561862
<i>BioSled</i>	0.1587	3.2662	213.3672	11.49542	32.63971	6.999399
<i>BioSled Rolls</i>	0.0287	59.8285	303.5761	11.1294	30.26171	2.765737
<i>CG2</i>	0.1493	2.9030	229.8958	15.6628	32.53723	7.979208
<i>CG2 Rolls</i>	0.0658	3.8008	335.2613	50.97131	33.62403	4.382007
<i>CSA</i>	0.2086	1.0524	213.7571	25.56576	28.16516	6.971332
<i>CSA Rolls</i>	0.1789	1.6509	278.3809	11.35834	27.82566	6.459023
<i>L1</i>	0.1051	2.0692	245.6121	18.29633	35.7662	6.872118
<i>L1 Rolls</i>	0.0603	2.1540	275.835	11.6884	25.35682	3.819754
<i>MFF</i>	0.0915	0.9591	236.7135	10.92929	29.63063	3.892233
<i>SMM</i>	0.2404	7.7016	150.498	10.04467	28.08446	5.794656

Table D.24 SourceAFIS Caucasian Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS Caucasian						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0217	4.9814	258.8593	9.766249	33.64554	2.022266
<i>ANDI GRY</i>	0.0348	5.4394	222.0455	9.902842	40.35332	4.321751
<i>BioSled</i>	0.0809	0.5678	216.0775	10.76042	133.0017	3.549333
<i>BioSled Rolls</i>	0.0195	0.3038	332.5888	10.61221	214.1114	3.359193
<i>CG2</i>	0.0453	1.9521	229.018	9.126302	150.8312	4.068837
<i>CG2 Rolls</i>	0.0223	6.5154	365.2294	10.53184	37.59151	1.0158
<i>CSA</i>	0.0317	0.6262	261.1282	25.35305	32.90313	4.415732
<i>CSA Rolls</i>	0.0125	1.1713	518.2886	11.45706	36.75151	1.035972
<i>L1</i>	0.0174	1.1054	280.5571	12.77533	89.70628	3.698551
<i>L1 Rolls</i>	0.0356	2.1613	324.1864	0	38.23815	0
<i>MFF</i>	0.0555	0.4224	254.9791	9.659011	36.71928	1.0158
<i>SMM</i>	0.0440	13.3578	166.9086	9.806087	34.43536	1.19943

Table D.25 SourceAFIS Hispanic Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS Hispanic						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0701	1.9296	233.7107	12.51677	29.45402	5.533568
<i>ANDI GRY</i>	0.0884	1.1892	226.3276	10.56398	28.44455	6.006702
<i>BioSled</i>	0.1920	1.8107	163.2991	11.87605	49.03751	6.748479
<i>BioSled</i>			264.4757	10.53184	179.3929	5.404606
<i>Rolls</i>	0.0685	0.1880				
<i>CG2</i>	0.0971	6.6522	179.4396	33.96733	32.02315	4.746463
<i>CG2 Rolls</i>	0.0714	3.2236	310.4168	11.92265	27.33675	4.081307
<i>CSA</i>	0.1413	2.8328	166.0101	40.81303	32.3677	6.931957
<i>CSA Rolls</i>	0.0894	2.3991	318.4915	13.7747	29.25764	6.812571
<i>L1</i>	0.1326	2.5505	227.5417	54.56351	27.07703	7.757417
<i>L1 Rolls</i>	0.0691	2.0646	284.7716	12.18746	28.70368	5.735529
<i>MFF</i>	0.1329	3.5195	242.7262	10.3637	35.07605	4.917602
<i>SMM</i>	0.0796	17.7029	152.8738	24.03162	32.02045	4.576688

Table D.26 SourceAFIS Middle Eastern Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS Middle Eastern						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.1821	1.6499	218.4843	12.04636	27.98296	6.334945
<i>ANDI GRY</i>	0.2166	3.6323	187.8634	11.47555	26.27157	3.627262
<i>BioSled</i>	0.2231	2.9841	168.724	14.43362	26.5876	8.149198
<i>BioSled</i>			327.6002	9.770303	25.53419	7.505122
<i>Rolls</i>	0.1069	2.4911				
<i>CG2</i>	0.1805	3.7760	210.9301	11.47672	27.88251	6.963401
<i>CG2 Rolls</i>	0.0553	1.8371	308.9363	10.13526	21.98601	6.707691
<i>CSA</i>	0.2585	1.2818	216.3997	11.83961	25.29209	6.895127
<i>CSA Rolls</i>	0.1423	1.1311	275.2286	10.59432	24.75159	7.287093
<i>L1</i>	0.1101	3.7773	229.4577	34.61526	23.36124	7.078579
<i>L1 Rolls</i>	0.0589	1.3476	300.8031	10.3993	25.04766	6.524864
<i>MFF</i>	0.1368	1.1941	222.0757	10.66438	26.32177	5.368564
<i>SMM</i>	0.2942	14.0849	115.637	10.43807	27.00021	4.776016

Table D.27 SourceAFIS Other Genuine and Imposter KLD, Maximum and Minimum Scores

SourceAFIS Other						
<i>Device</i>	Genuine KLD	Imposter KLD	Max Genuine	Min Genuine	Max Imposter	Min Imposter
<i>ANDI BIN</i>	0.0872	1.1178	216.2899	12.81646	30.53337	5.857705
<i>ANDI GRY</i>	0.1441	1.4404	175.0319	11.39268	26.73659	7.282349
<i>BioSled</i>	0.0888	2.9397	248.3664	13.89209	28.31911	7.980638
<i>BioSled Rolls</i>	0.1010	1.4833	320.201	11.56863	26.92059	8.289468
<i>CG2</i>	0.0951	3.8648	244.837	38.79229	24.80103	7.655017
<i>CG2 Rolls</i>	0.0355	1.9505	363.1709	12.8476	28.51096	6.200431
<i>CSA</i>	0.0519	0.8744	279.6029	52.56234	28.43942	6.117246
<i>CSA Rolls</i>	0.0609	0.9662	317.2518	86.21761	27.25427	5.039689
<i>L1</i>	0.0997	2.0550	243.2939	6.561505	26.2432	8.264335
<i>L1 Rolls</i>	0.0847	4.0564	339.6964	10.20002	30.91195	6.258831
<i>MFF</i>	0.0638	1.3916	291.2537	10.16441	30.48556	2.927113
<i>SMM</i>	0.0784	11.1336	171.836	10.90741	25.3558	3.236016

Figure D.3.1 SourceAFIS ANDI Binary (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.2 SourceAFIS ANDI Greyscale (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.3 SourceAFIS BioSled (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.4 SourceAFIS BioSled Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.5 SourceAFIS FP II Guardian (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.6 SourceAFIS FP II Guardian Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.7 SourceAFIS Crossmatch Seek Avenger (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.8 Crossmatch Seek Avenger Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.9 SourceAFIS InnerID (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

This Device was removed from the collection midway through when it stopped working. What images were produced are low quality, i.e. the reason for the outlying distributions.

Figure D.3.10 SourceAFIS L1 (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.11 SourceAFIS L1 Rolls (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.12 SourceAFIS Morpho FOTF (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

Figure D.3.13 SourceAFIS MorphoMobile (a) African (b) African American (c) American Indian (d) Asian (e) Asian Indian (f) Caucasian (g) Hispanic (h) Middle Eastern (i) Other

D.4 NBIS ROC Curves and Area Under Curve

Table D.28 NBIS Area Under Curve for Each Ethnicity

	NBIS Area Under the Curve								
	African	African American	American Indian	Asian	Asian Indian	Caucasian	Hispanic	Middle Eastern	Other
<i>ANDI BIN</i>	1.0000	1.0000	1.0000	0.9807	0.9987	0.9751	0.9845	0.9748	0.9889
<i>ANDI GRY</i>	1.0000	0.9844	1.0000	0.9834	0.9883	0.9742	0.9833	0.9777	0.9958
<i>BioSled</i>	0.8410	0.9549	1.0000	0.9918	0.9907	0.9816	0.9784	0.9930	0.9807
<i>BioSled Rolls</i>	1.0000	1.0000	1.0000	0.9905	0.9688	0.9870	0.9258	1.0000	0.9961
<i>CG2</i>	1.0000	0.8477	1.0000	0.9736	0.9999	0.9795	1.0000	0.9869	0.9998
<i>CG2 Rolls</i>	1.0000	1.0000	0.7500	0.9443	1.0000	0.9979	1.0000	0.9994	0.9995
<i>CSA</i>	1.0000	0.9995	1.0000	1.0000	1.0000	0.9999	0.9963	0.9830	1.0000
<i>CSA Rolls</i>	1.0000	1.0000	1.0000	0.9999	0.9763	0.9900	1.0000	0.9416	1.0000
<i>IID</i>	1.0000	0.8413	1.0000	0.8823	0.8592	0.8676	0.8478	0.9444	0.8100
<i>L1</i>	1.0000	1.0000	1.0000	1.0000	1.0000	0.9950	1.0000	1.0000	0.8407
<i>L1 Rolls</i>	1.0000	1.0000	1.0000	1.0000	1.0000	0.9867	1.0000	1.0000	0.8445
<i>MFF</i>	0.8683	0.9956	1.0000	0.9972	0.9795	0.9965	0.9998	0.9934	1.0000
<i>SMM</i>	1.0000	1.0000	1.0000	0.9835	0.9873	0.9955	0.9999	0.9979	0.9664

Figure D.4.1 NBIS ANDI Binary Ethnicity Based ROC Curves

Figure D.4.2 NBIS ANDI Greyscale Ethnicity Based ROC Curves

Figure D.4.3 NBIS BioSled Ethnicity Based ROC Curves

Figure D.4.4 NBIS BioSled Rolls Ethnicity Based ROC Curves

Figure D.4.5 NBIS FP II Guardian Ethnicity Based ROC Curves

Figure D.4.6 NBIS FP II Guardian Rolls Ethnicity Based ROC Curves

Figure D.4.7 NBIS Crossmatch Seek Avenger Ethnicity Based ROC Curves

Figure D.4.8 NBIS Crossmatch Seek Avenger Rolls Ethnicity Based ROC Curves

Figure D.4.9 NBIS InnerID Ethnicity Based ROC Curves

Figure D.4.10 NBIS L1 Ethnicity Based ROC Curves

Figure D.4.11 NBIS L1 Rolls Ethnicity Based ROC Curves

Figure D.4.12 NBIS Morpho FOTF Ethnicity Based ROC Curves

Figure D.4.13 NBIS MorphoMobile Ethnicity Based ROC Curves

D.5 Neurotech ROC Curves and Area Under Curve

Table D.29 Neurotech Area Under Curve for Each Ethnicity

Neurotech Area Under Curve									
	<i>African</i>	<i>African American</i>	<i>American Indian</i>	<i>Asian</i>	<i>Asian Indian</i>	<i>Caucasian</i>	<i>Hispanic</i>	<i>Middle Eastern</i>	<i>Other</i>
ANDI BIN	1.0000	1.0000	1.0000	0.9886	1.0000	0.9746	0.9753	0.9768	0.9815
ANDI GRY	1.0000	1.0000	1.0000	0.9896	1.0000	0.9749	0.9768	0.9816	0.9985
BioSled	0.9011	0.9388	1.0000	0.9851	0.9789	0.9912	0.9408	1.0000	0.9756
BioSled Rolls	1.0000	1.0000	1.0000	1.0000	0.9825	0.9894	0.9602	1.0000	1.0000
CG2	1.0000	0.8573	1.0000	0.9410	1.0000	0.9870	1.0000	1.0000	1.0000
CG2 Rolls	1.0000	1.0000	1.0000	0.9574	1.0000	1.0000	1.0000	1.0000	1.0000
CSA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9665	1.0000
CSA Rolls	1.0000	1.0000	1.0000	1.0000	0.9797	0.9947	1.0000	1.0000	1.0000
IID	1.0000	0.7963	1.0000	1.0000	0.9728	0.9225	0.9288	0.9180	0.9493
L1	1.0000	1.0000	1.0000	1.0000	1.0000	0.9939	1.0000	1.0000	0.8938
MFF			1.0000	0.9934	0.9798	0.9987	1.0000	0.9949	1.0000
SMM	1.0000	1.0000	1.0000	0.9819	0.9940	0.9922	1.0000	1.0000	0.9875

Figure D.5.1 Neurotech ANDI Binary Ethnicity Based ROC Curves

Figure D.5.2 Neurotech ANDI Greyscale Ethnicity Based ROC Curves

Figure D.5.3 Neurotech BioSled Ethnicity Based ROC Curves

Figure D.5.4 Neurotech BioSled Rolls Ethnicity Based ROC Curves

Figure D.5.5 Neurotech FP II Guardian Ethnicity Based ROC Curves

Figure D.5.6 Neurotech FP II Guardian Rolls Ethnicity Based ROC Curves

Figure D.5.7 Neurotech Crossmatch Seek Avenger Ethnicity Based ROC Curves

Figure D.5.8 Neurotech Crossmatch Seek Avenger Rolls Ethnicity Based ROC Curves

Figure D.5.9 Neurotech InnerID Ethnicity Based ROC Curves

Figure D.5.10 Neurotech L1 Ethnicity Based ROC Curves

Figure D.5.11 Neurotech Morpho FOTF Ethnicity Based ROC Curves

Figure D.5.12 Neurotech MorphoMobile Ethnicity Based ROC Curves

D.6 SourceAFIS ROC Curves and Area Under Curve

Table D.30 SourceAFIS Area Under Curve for Each Ethnicity

SourceAFIS Area Under Curve									
	<i>African</i>	<i>African American</i>	<i>American Indian</i>	<i>Asian</i>	<i>Asian Indian</i>	<i>Caucasian</i>	<i>Hispanic</i>	<i>Middle Eastern</i>	<i>Other</i>
ANDI BIN	1.0000	1.0000	1.0000	0.9690	0.9930	0.9540	0.9864	0.9669	0.9843
ANDI GRY	0.9075	0.9728	1.0000	0.9578	0.9749	0.9174	0.9667	0.9571	0.9567
BioSled	0.9960	0.9357	1.0000	0.9748	0.9707	0.9798	0.9419	0.9966	0.9921
BioSled Rolls	1.0000	1.0000	1.0000	0.9530	0.9663	0.9630	0.9131	0.9384	0.9442
CG2	1.0000	0.9158	1.0000	0.9362	0.9981	0.9804	1.0000	0.9767	1.0000
CG2 Rolls	1.0000	1.0000	0.9653	0.9242	1.0000	0.9904	0.9904	0.9393	0.9938
CSA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9770	1.0000
CSA Rolls	1.0000	0.9977	1.0000	0.9801	0.9870	0.9841	0.9965	0.9720	1.0000
IID	0.5313	0.7225	1.0000	0.7682	0.7171	0.8074	0.7880	0.9064	0.7400
L1	1.0000	1.0000	1.0000	0.9862	0.9995	0.9978	1.0000	1.0000	0.8552
L1 Rolls	1.0000	0.9714	1.0000	1.0000	0.9924	0.9693	0.9845	0.9742	0.8898
MFF	0.8896	0.9759	1.0000	0.9826	0.9698	0.9807	0.9837	0.9839	0.9782
SMM	1.0000	1.0000	1.0000	0.9799	0.9816	0.9881	0.9999	0.9675	0.9705

Figure D.6.1 SourceAFIS ANDI Binary Ethnicity Based ROC Curves

Figure D.6.2 SourceAFIS ANDI Greyscale Ethnicity Based ROC Curves

Figure D.6.3 SourceAFIS BioSled Ethnicity Based ROC Curves

Figure D.6.4 SourceAFIS BioSled Rolls Ethnicity Based ROC Curves

Figure D.6.5 SourceAFIS FP II Guardian Ethnicity Based ROC Curves

Figure D.6.6 SourceAFIS FP II Guardian Rolls Ethnicity Based ROC Curves

Figure D.6.7 SourceAFIS Crossmatch Seek Avenger Ethnicity Based ROC Curves

Figure D.6.8 SourceAFIS Crossmatch Seek Avenger Rolls Ethnicity Based ROC Curves

Figure D.6.9 SourceAFIS InnerID Ethnicity Based ROC Curves

Figure D.6.10 SourceAFIS L1 Ethnicity Based ROC Curves

Figure D.6.11 SourceAFIS L1 Rolls Ethnicity Based ROC Curves

Figure D.6.12 SourceAFIS Morpho FOTF Ethnicity Based ROC Curves

Figure D.6.13 SourceAFIS MorphoMobile Ethnicity Based ROC Curves

D.7 Minutiae Box Plots by Ethnicity and Device

Figure D.7.1 ANDI Binary Ethnicity Based Minutiae Box Plots

Figure D.7.2 ANDI Greyscale Ethnicity Based Minutiae Box Plots

Figure D.7.3 BioSled Ethnicity Based Minutiae Box Plots

Figure D.7.4 BioSled Rolls Ethnicity Based Minutiae Box Plots

Figure D.7.5 FP II Guardian Ethnicity Based Minutiae Box Plots

Figure D.7.6 FP II Guardian Rolls Ethnicity Based Minutiae Box Plots

Figure D.7.7 Crossmatch Seek Avenger Ethnicity Based Minutiae Box Plots

Figure D.7.8 Crossmatch Seek Avenger Rolls Ethnicity Based Minutiae Box Plots

Figure D.7.9 InnerID Ethnicity Based Minutiae Box Plots

Figure D.7.10 L1 Ethnicity Based Minutiae Box Plots

Figure D.7.11 L1 Rolls Ethnicity Based Minutiae Box Plots

Figure D.7.12 Morpho FOTF Ethnicity Based Minutiae Box Plots

Figure D.7.13 MorphoMobile Ethnicity Based Minutiae Box Plots

References

- [1] P. Wiggins and L. Ericson, "Contactless Fingerprint Technologies Assessment (Version 2)," ncjrs.gov, 2014.
- [2] L. Ericson and S. Shine, "Evaluation of Contactless versus Contact Fingerprint Data, Phase 2 (Version 1.1)," ncjrs.gov.
- [3] "FBI-Certified Scanning and Digitization of Fingerprint Cards," [Online]. Available: <http://www.aware.com/biometrics/accuscan/>. [Accessed 24 October 2016].
- [4] K. R. Moses, P. Higgins, M. McCabe, S. Prabhakar and S. Swann, "Automated Fingerprint Identification System (AFIS)," in *Fingerprint Sourcebook*, Rockville, MD, National Institute of Justice/NCJRS, 2010.
- [5] "Wikipedia," Wikipedia, [Online]. Available: <https://en.wikipedia.org/wiki/Interoperability>. [Accessed 17 January 2017].
- [6] Understanding Biometrics, Griaule Biometrics, 2008.
- [7] N. Nain, B. Bhadviya, B. Gautam, D. Kumar and D. B. M, "A Fast Fingerprint Classification Algorithm by Tracing Ridge-Flow Patterns," in *Signal Image Technology and Internet Based Systems, 2008. SITIS '08. IEEE Conference on Signal Image Technology and Internet Based Systems*, 2008.
- [8] "Fingerprint Recognition," Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Fingerprint_recognition. [Accessed 24 October 2016].
- [9] P. Reid, *Biometrics for Network Security* (Prentice Hall Series in Computer Networking and Distributed), Upper Saddle River, NJ: Prentice Hall PTR, 2003.
- [10] P. T. Higgins, K. M. Higgins, L. K. Fox and P. Komarinski, *Automated Fingerprint Identification Systems (AFIS)*, Burlington, MA: Elsevier Academic Press, 2005.
- [11] National Science and Technology Council (NSTC) Committee on Technology, Committee on Homeland and National Security, Subcommittee on Biometrics, "Fingerprint Recognition," in *Introduction to Biometrics*, Biometrics.gov, 2006.
- [12] A. A. Paulino, A. K. Jain and J. Feng, "Latent Fingerprint Matching: Fusion of Manually Marked and Derived Minutiae," in *2010 23rd SIBGRAPI - Conference on Graphics, Patterns and Images*, 2010.
- [13] "Fingerprint Feature Extraction," Syahrul, 13 April 2012. [Online]. Available: <http://syhrl.blogspot.com/2012/04/036-fyp-minutiae.html>. [Accessed 24 October 2016].
- [14] J. Zhou, F. Chen, N. Wu and C. Wu, "Crease detection from fingerprint images and its applications in elderly people," *Pattern Recognition*, vol. 42, no. 5, pp. 896-906, May 2009.

- [15] Y. Wang, L. G. Hassebrook and D. L. Lau, "Data Acquisition and Processing of 3-D Fingerprints," University of Kentucky, Lexington, KY, 2009.
- [16] Y. Wang, Q. Hao, A. Fatehpuria, L. G. Hassebrook and D. L. Lau, "Quality and Matching Performance Analysis of Three-dimensional Unraveled Fingerprints," University of Kentucky, Lexington, KY, 2010.
- [17] A. Kumar and C. Kwong, "Towards Contactless, Low-Cost and Accurate 3D Fingerprint Identification," in *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2013.
- [18] Y. Wang, D. L. Lau and L. G. Hassebrook, "Fit-sphere Unwrapping and Performance Analysis of 3D Fingerprints," University of Kentucky, Lexington, KY, 2010.
- [19] Y. Wang, Q. Hao, A. Fatehpuria, L. G. Hassebrook and D. L. Lau, "Data Acquisition and Quality Analysis of 3-Dimensional Fingerprints," University of Kentucky, Lexington, KY.
- [20] Q. Zhao, A. Jain and G. Abramovich, "3D to 2D Fingerprints: Unrolling and Distortion Correction," *Biometrics (IJCB)*, no. 11-13, 2011.
- [21] H. C. Lee and R. E. Gaensslen, Eds., *Advances in Fingerprint Technology*, 2nd Edition ed., Boca Raton, FL: CRC Press, 2001.
- [22] N. K. Ratha and V. Govindaraju, Eds., *Advances in Biometrics Sensors, Algorithms and Systems*, London: Springer-Verlag , 2008.
- [23] S. Mil'shtein and C. Buzawa, "Wireless Communication Supported by Contactless Fingerprints," in *Technologies for Homeland Security (HST), 2016 IEEE Symposium on Technologies for Homeland Security (HST)*, 2016.
- [24] T. Dunstone and N. Yager, Eds., *Biometric System and Data Analysis Design, Evaluation, and Data Mining*, New York, NY: Springer Science + Business Media, LLC, 2009.
- [25] G. Parziale and Y. Chen, *Handbook of Remote Biometrics*, M. Tistarelli, S. Z. Li and R. Chellappa, Eds., London: Springer London, 2009.
- [26] C. R. Blomeke, S. K. Modi and S. J. Elliot, "Investigating The Relationship Between Fingerprint Image Quality and Skin Characteristics," Purdue University, West Lafayette, IN.
- [27] X. Xia and L. O'Gorman, "Innovations In Fingerprint Capture Devices," *Pattern Recognition*, vol. 36, pp. 361-369, 2003.
- [28] W. Zhou, J. Hu, I. Petersen, S. Wang and M. Bennamoun, "A Benchmark 3D Fingerprint Database," in *2014 11th International Conference on Fuzzy Systems and Knowledge Discovery*, 2014.
- [29] A. Pillai and S. Mil'shtein, "Can Contactless Fingerprints be Compared to Existing Database?," in *Homeland Security (HST), 2012 IEEE Conference on Technologies for , 2012.*

- [30] A. Ross, S. C. Dass and A. K. Jain, "Estimating Fingerprint Deformation," in *International Conference on Biometric Authentication (ICBA)*, Hong Kong, 2004.
- [31] Y. Chen, G. Parziale, E. Diaz-Santana and A. K. Jain, "3D Touchless Fingerprints: Compatibility with Legacy Rolled Images," in *Biometric Consortium Conference, 2006 Biometrics Symposium: Special Session on Research at the Biometric Consortium Conference*, Baltimore, MD, 2006.
- [32] N. B. Nill, D. J. Braunegg and B. R. Paine, "Computer Program to Determine the Sine Wave Modulation Transfer Function (MTF) of Imaging Devices," The MITRE Corporation, Bedford, MA, 1996.
- [33] M. E. Bravo-Zanoguera, J. Rivera-Castillo, M. Vera-Perez and M. A. Reyna Carranza, "Use of the Modulation Transfer Function to Measure Quality of Digital Cameras," in *Proceedings of the 16th IEEE International Conference on Electronics, Communications and Computers (CONIELECOMP 2006)*, 2006.
- [34] "CRADA Program: Contactless Fingerprint Capture Device Measurement," NIST, 26 January 2015. [Online]. Available: <https://www.nist.gov/itl/iad/image-group/crada-program-contactless-fingerprint-capture-device-measurement>. [Accessed 24 October 2016].
- [35] S. Orandi, M. Garriss, B. Wing, E. Tabassi, P. Grother, C. Watson, R. Michaels and M. Theofanos, "NIST Fingerprint Testing and Standards," biometrics.nist.gov, 2013.
- [36] S. Furman, B. Stanton, M. Theofanos, J. M. Libert and J. Grantham, "nist.gov," National Institute of Standards and Technology, March 2017. [Online]. Available: <http://nvlpubs.nist.gov/nistpubs/ir/2017/NIST.IR.8171.pdf>.
- [37] C. Centamore, "AIRprint - Rapid, Long Range Fingerprinting Technology," Advanced Optical Systems, Inc. , 26 November 2012. [Online]. Available: <http://www.aos-inc.com/index.php/products/biometrics-new/airprint-new>. [Accessed 24 October 2016].
- [38] P. Wiggins and L. Ericson, "University of Massachusetts Lowell 3D Contactless Fingerprint Scanner: Technology Evaluation (Version 2)," ncjrs.com, Fairmont, WV, 2014.
- [39] Safran Morpho MorphoTrak, "MorphoTrak Finger-On-The-Fly Specs sheet," MorphoTrak.com, Alexandria, VA, 2014.
- [40] TBS, "TBS Touchless Fingerprinting 3D Enroll Technical Datasheet," Touchless Biometrics Systems, Switzerland.
- [41] IDair, "ONEprint Touchless Fingerprint System Technical Datasheet," idairco.com, Huntsville, AL.
- [42] NEC, "Multi-modal Identification Solution Contactless Hybrid Fingerprint Scanner Technical Datasheet," au.nec.com.
- [43] Advanced Optical Systems, INC. AOS, "ANDI OTG Automated Non-Contact Distance Identity Technical Datasheet," Advanced Optical Systems, Inc., Huntsville, AL, 2014.

- [44] "ANDI OTG Recieves FBI Certification," ANDI OTG, 30 November 2015. [Online]. Available: <http://www.andiotg.com/single-post/2015/11/30/ANDI-OTG-Receive-FBI-Certification>. [Accessed 24 October 2016].
- [45] "FBI Certifies MorphoWave Desktop Contactless Fingerprint Scanner," Safran Morpho, 5 January 2016. [Online]. Available: http://www.morpho.com/en/media/20160105_fbi-certifies-morphowave-desktop-contactless-fingerprint-scanner. [Accessed 24 October 2016].
- [46] A. Ross and A. Jain, "Biometric Sensor Interoperability: A Case Study in Fingerprints," in *ECCV Workshop on Biometric Authentication (BioAW)*, Prague, Czech Republic, 2004.
- [47] E. Marasco, L. Lugini, B. Cukic and B. Thirimachos, "Minimizing the Impact of Low Interoperability between Optical Fingerprints Sensors," in *Biometrics: Theory, Applications and Systems (BTAS)*, Arlington, VA, 2013.
- [48] L. Lugini, E. Marasco, B. Cukic and I. Gashi, "Interoperability in fingerprint recognition: A large-scale empirical study," in *Dependable Systems and Networks Workshop*, Budapest, Hungary, 2013.
- [49] "Sherlock," Neurotechnology, [Online]. Available: <http://www.neurotechnology.com/fingerprint-scanner-integrated-biometrics-sherlock.html>. [Accessed 24 October 2016].
- [50] Integrated Biometrics, "The Differences and benefits of "LES" fingerprint sensor technology vs. Optical based FAP 45, FBI appendix "F" certified fingerprint sensors.," Integrated Biometrics LLC, Spartanburg, SC.
- [51] Integrated Biometrics, "Sherlock Technical Datasheet," Integrated Biometrics.
- [52] S. Thies, Interviewee, *Interview with Stephen Thies, CEO Integrated Biometrics*. [Interview]. 19 November 2013.
- [53] Northrop Grumman, "Northrop Grumman BioSled Technical Datasheet," Northrop Grumman, 2016.
- [54] CrossMatch, "CrossMatch SEEK Avenger Rugged Multimodal Handheld Technical Datasheet," Cross Match Technologies Inc., 2014.
- [55] D. Maltoni, "Fingerprint Sensing," in *Handbook of Fingerprint Recognition*, Springer, 2009, pp. 57 - 95.
- [56] K. Antonelli, G. Vanderkooy, T. Vlaar and G. Immega, "Fingerprint Image Optical Input Apparatus". United States Patent US6259108 B1, 10 July 2001.
- [57] S. J. Borza, "Imaging Device, Especially for Optical Fingerprinting". US Patent US6429927 B1, 6 August 2002.
- [58] F. Chen, "3D fingerprint and palm print data model and capture devices using multi structured lights and cameras". United States of America Patent US 7609865 B2, 27 October 2009.

- [59] L. G. Hassebrook, D. L. Lau and H. G. Dietz, "System and method for 3D imaging using structured light illumination". United States of America Patent US8224064 B1, 17 Jul 2012.
- [60] R. D. Labati, A. Genovese, V. Piuri and F. Scotti, "Fast 3-D Fingertip Reconstruction Using a Single Two-View Structured Light Acquisition," in *Biometric Measurements and Systems for Security and Medical Applications (BIOMS) 2011 IEEE Workshop*, 2011.
- [61] G. Abramovich, K. George Harding, Q. Hu, S. Manickam, M. Ganesh and C. Allen Nafis, "Method and system for contactless fingerprint detection and verification". United States of America Patent US8406487 B2, 26 March 2013.
- [62] N. Engheta, E. Pugh, S.-S. Lin and K. Yemelyanov, "Polarization and Reflection Based Non-Contact Latent Fingerprint Imaging and Lifting". United States of America Patent US20070280513 A1, 6 December 2007.
- [63] S. Prabhakar and A. K. Jain, "Fingerprint Matching," in *Automatic Fingerprint Recognition Systems*, N. Ratha and R. Bolle, Eds., New York, NY: Springer Science & Media, 2004.
- [64] A. K. Jain, J. Feng and K. Nandakumar, "Fingerprint Matching," *Computer*, vol. 43, no. 2, February 2010.
- [65] M. Adhiyaman and D. Ezhilmaran, "Fingerprint Matching and Similarity Checking System using Minutia Based Technique," in *2015 IEEE International Conference on Engineering and Technology (ICETECH)*, Coimbatore, TN, India, 2015.
- [66] A. K. Jain, A. Ross and S. Prabhakar, "An Introduction to Biometric Recognition," *IEEE Transactions on Circuits and Systems For Video Technology*, vol. 14, no. 1, pp. 4-20, January 2004.
- [67] R. Cappelli, M. Ferrara and D. Maltoni, "Minutiae-Based Fingerprint Matching," in *Cross Disciplinary Biometric Systems*, J. Kacprzyk and L. C. Jain, Eds., Berlin, NY: Springer, 2012.
- [68] A. Saleh, A. Bahaa and A. Wahdan, "Fingerprint Recognition," in *Advanced Biometric Technologies*, G. Chetty and J. Yang, Eds., InTech, 2011, pp. 201-224.
- [69] "Fingerprint Matching," in *Handbook of Fingerprint Recognition*, Second ed., London, Springer-Verlag, 2009, pp. 167-233.
- [70] C. Ntantogian, S. Malliaros and C. Xenakis, "Gaithashing: A two-factor authentication scheme based on gait features," *Computers & Security*, April 2015.
- [71] "KL-Divergence," [Online]. Available: <http://web.engr.illinois.edu/~hanj/cs412/bk3/KL-divergence.pdf>. [Accessed 18 January 2017].
- [72] M. E. Schuckers, *Computational Methods in Biometric Authentication*, Springer, 2010.
- [73] "Plotting and Interpretating an ROC Curve," [Online]. Available: <http://gim.unmc.edu/dxtests/roc2.htm>. [Accessed 20 February 2017].

- [74] NIST, "Biometric Quality Homepage," NIST, [Online]. Available: <https://www.nist.gov/programs-projects/biometric-quality-homepage>. [Accessed 17 April 2017].
- [75] NIST, "Development of NFIQ 2.0," NIST, 28 April 2016. [Online]. Available: <https://www.nist.gov/services-resources/software/development-nfiq-20>. [Accessed 26 April 2017].
- [76] Neurotechnology, "www.neurotechnology.com," Neurotechnology, 2016. [Online]. Available: <http://www.neurotechnology.com/megamatcher.html>. [Accessed 9 November 2016].
- [77] NIST, "NIST Biometric Image Software nbis," NIST , [Online]. Available: <https://www.nist.gov/services-resources/software/nist-biometric-image-software-nbis>. [Accessed 23 March 2017].
- [78] "SourceAFIS," [Online]. Available: <http://www.sourceafis.org/blog/>. [Accessed 23 March 2017].
- [79] P. Komarinski, P. T. Higgins, K. M. Higgins and L. K. Fox, Automated Fingerprint Identification Systems (AFIS), Burlington, MA: Elsevier Academic Press, 2005.
- [80] Safran Morpho, "MorphoWave Desktop Safran Identity & Security," Safran Morpho, [Online]. Available: <http://www.morpho.com/en/public-security/smart-borders/automated-solutions/acquisition-devices/morphowave-desktop>. [Accessed 24 October 2016].
- [81] L. Ericson and S. Shine, "Evaluation of Contactless versus Contact Fingerprint Data, Phase 2 (Version 1.1)," ncjrs.gov.