Reproducibility of Automated Bullet Matching Scores Using High-Resolution 3D LEA Scans

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Outline

Introduction

3D Scanning Process

Study Design
  Gauge R&R Background
  Bullet Context
  Results

Conclusions
Automated Matching Algorithms

Multiple algorithms have been proposed based on 3D imaging of bullet LEAs:

- Chu et al. (2010): cross-correlation function
- Chu et al. (2013): consecutively matching striae
- Hare, Hofmann, Carriquiry (2017): random forest using multiple features
Automated Matching Algorithm

Step 1: 3D scan
Automated Matching Algorithm

Step 1: 3D scan

Step 2: Horizontal crosscut
Automated Matching Algorithm

Step 1: 3D scan

Step 2: Horizontal crosscut

Step 3: Curvature removal
Automated Matching Algorithm

Step 1: 3D scan

Step 2: Horizontal crosscut

Step 3: Curvature removal

Step 4: Extracted signature
Automated Matching Algorithm

Signatures are compared to one another, and pairwise features are extracted from aligned pairs of signatures.
This entire process is dependent on the scan data that is captured:

- Which operator scanned the LEA
- Which microscope was used
Variability in Scan Data
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Introduced Variability in Scanning
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Same bullet, same operator, different machines:
Introduced Variability in Scanning

Different bullets, same operator, same machine:
Stages of Impact

We want to consider variability introduced in:

- The extracted 2D signature
- Random forest scores (or other pairwise similarity metrics).
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Introduced Variability in Scanning

- How similar are striation patterns for two different bullets?
- Are there differences in scans due to operator?
- Are there differences in scans due to machine?
- For the same operator and machine:
  - How similar will repetitions of the same bullet be?
There are multiple ways we can think about repetitions:
▶ Immediate recapture
▶ Restaging on different days
We focus on restaging for our repetitions.
Restaging helps us answer the forensic question of interest.

- A firearms examiner should be able to come back to the same evidence at a later date and reach the same conclusion.
  - Data collected under the same conditions (operator, machine) should be consistent regardless of timing.
- Multiple firearms examiners should be able to independently look at evidence and reach the same conclusion.
  - Data collected under different conditions should be consistent.
Also known as **Gauge R&R studies**, these are studies typically used in industrial engineering to evaluate a measurement method or measurement tool.
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- **How repeatable** are measurements of the same object taken under the same environmental conditions?
  - Repeat measurements using the same tool, same operator
- **How reproducible** are measurements of the same object taken under different environmental conditions?
  - Repeat measurements using different tools, different operators
Traditionally, parts would be similar objects (e.g. steel punches). Here, we consider *parts* to be repetitions of specific *barrel-lands*.

- The **pattern** is the barrel-land.
- The **impression** is the corresponding bullet.
Repeated scans were captured for three barrels.

- Bullets: *three* bullets fired through each barrel
- Operators: *five* operators
- Machines: *two* confocal light microscopes (same brand)
- Restaging repetitions: at least *three* for each operator-bullet-machine combination

This results in **90** repetitions of each barrel-land, **30** scans originating from each of the 3 bullets.
Co-aligned signatures give us an initial visual of variability (Hamby set barrel):
Co-aligned signatures give us an initial visual of variability (Hamby set barrel):
Gauge R&R: Signatures

Barrel Orange Land 3

Signature Height

Relative X Location

Operator ID
- Operator A
- Operator B
- Operator C
- Operator D
- Operator E
Gauge R&R: Signatures

Barrel Orange Land 3

Signature Height vs. Relative X Location

Machine ID
- Snax1
- Snax2
Much of the variability structure appears to be from bullet:
Gauge R&R: Signatures

Another example, from a different barrel type (Houston barrel):
Another example, from a different barrel type (Houston barrel):
Gauge R&R: Signatures

![Graph showing signature analysis](image)

- **Operator ID**
  - Operator A
  - Operator B
  - Operator C
  - Operator D
  - Operator E

**Barrel Pink Land 6**

- **Signature Height**
- **Relative X Location**
Gauge R&R: Signatures

Barrel Pink Land 6

Signature Height

Relative X Location

Machine ID
- SneoX1
- SneoX2
Gauge R&R: Signatures

Much of the variability structure appears to be from bullet:

Barrel Pink Land 6

Bullet ID
- Bullet 1
- Bullet 2
- Bullet 3

Signature Height

Relative X Location
Gauge R&R: Signatures

Distinct structure on the bullet:
Pairwise comparisons model

We want to quantify the impact these differences could have on automated pairwise comparisons. We compare each signature originating from the same barrel-land to each other and investigate variability in pairwise matching scores.
Pairwise comparisons model

With our pilot study data, we can fit a mixed-effects model for all same-source comparisons:
That is, scores which compare two signatures that originate from the same barrel-land.

\[ s_{p,p'} = \text{Random Forest score comparing Signature } p, \text{ Signature } p' \]
\[ = \mu_{BL} + \beta I[\text{Same Bullet (within source)}] + \omega I[\text{Same Operator}] \]
\[ + \eta I[\text{Same Machine}] + \beta \omega I[\text{Same Bullet and Operator}] \]
\[ + \beta \eta I[\text{Same Bullet and Machine}] \]
\[ + \eta \omega I[\text{Same Machine and Operator}] \]
\[ + \epsilon \]
Pairwise comparisons results

- Individual bullet characteristics are the most significant contribution to variability in pairwise matching scores.
- After accounting for individual land differences, the remaining random effects for Barrel Orange (Hamby set) are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same bullet</td>
<td>$\sigma_\beta$</td>
<td>0.097</td>
</tr>
<tr>
<td>Same operator</td>
<td>$\sigma_\omega$</td>
<td>0.004</td>
</tr>
<tr>
<td>Same machine</td>
<td>$\sigma_\eta$</td>
<td>0.001</td>
</tr>
<tr>
<td>Bullet-operator interaction</td>
<td>$\sigma_{\beta\omega}$</td>
<td>0.013</td>
</tr>
<tr>
<td>Bullet-machine interaction</td>
<td>$\sigma_{\beta\eta}$</td>
<td>0.001</td>
</tr>
<tr>
<td>Machine-operator interaction</td>
<td>$\sigma_{\eta\omega}$</td>
<td>0.002</td>
</tr>
<tr>
<td>Residual error</td>
<td>$\sigma$</td>
<td>0.163</td>
</tr>
</tbody>
</table>
Pairwise comparisons results

- Individual bullet characteristics are the most significant contribution to variability in pairwise matching scores.
- After accounting for individual land differences, the remaining random effects for Barrel Pink (Houston set) are:

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<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same bullet</td>
<td>( \sigma_\beta )</td>
<td>0.019</td>
</tr>
<tr>
<td>Same operator</td>
<td>( \sigma_\omega )</td>
<td>0.006</td>
</tr>
<tr>
<td>Same machine</td>
<td>( \sigma_\eta )</td>
<td>0.010</td>
</tr>
<tr>
<td>Bullet-operator interaction</td>
<td>( \sigma_{\beta\omega} )</td>
<td>0.004</td>
</tr>
<tr>
<td>Bullet-machine interaction</td>
<td>( \sigma_{\beta\eta} )</td>
<td>0.003</td>
</tr>
<tr>
<td>Machine-operator interaction</td>
<td>( \sigma_{\eta\omega} )</td>
<td>0.006</td>
</tr>
<tr>
<td>Residual error</td>
<td>( \sigma )</td>
<td>0.151</td>
</tr>
</tbody>
</table>
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- After accounting for variability due to bullet characteristics, operator-related differences account for minimal variability
- Inherent relationship between operators and breakoff and other bullet characteristics
- Machine effect is larger for Houston barrel than Hamby set barrel
- Bullet effect is larger for Hamby barrel - tank rash
- Detailed protocols are crucial to reducing variability in extracted signatures
Acknowledgments

- We would like to thank the efforts of the Iowa State University Roy J. Carver High Resolution Microscopy Lab in scanning the variability pilot study data and providing the scans to us.
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