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Article

Computational Analysis of Dimensional Stability in Reproduced Signatures Using Fiji (ImageJ): A Multi-Device, Multi-Generation Study and Its Forensic Implications

Anurag Srivastava[1*], Kavita Sharma[2]

[1]Shri Vaishnav Vidyapeeth Vishwavidyalaya, Indore, India, E-mail: forensicanu@gmail.com
[2]Medicaps University, Indore, India, E-mail: kavita.sharma@medicaps.ac.in

Abstract: The present study investigates the effect of successive reproduction on the dimensional characteristics of handwritten signature samples using a computational image analysis approach. Samples were reproduced up to five generations (G1-G5) using laser multifunction printers (MFPs), inkjet MFPs and single-function (SF) photocopiers, and were compared with original control specimens. Dimensional measurements, specifically height and width, were extracted using Fiji (ImageJ), an open-source digital image processing software, to support precision and reproducibility in measurement acquisition. Statistical analysis was performed using one-way analysis of variance (ANOVA), Dunnett's post hoc test and correlation analysis, with significance set at $p <= 0.05$. The results indicated that no statistically significant differences were observed in either height or width measurements across all devices and generations ($p > 0.05$). Minor fluctuations in variability were observed in later generations; however, these remained statistically non-significant. Correlation analysis further revealed no meaningful relationship between height and width variations, indicating independent and random dimensional changes. The findings demonstrate that computational measurement using Fiji provides reliable dimensional extraction, while modern reproduction technologies preserve geometric features with high fidelity. From a forensic and computational perspective, dimensional parameters are stable but possess limited discriminative power for detecting reproduction or forgery. The study highlights the importance of integrating digital image analysis tools into forensic workflows and recommends future incorporation of pixel-level and feature-based computational methods for enhanced document examination.
Keywords: Fiji (ImageJ); computational forensics; digital image analysis; forensic document examination; reproduced signatures; dimensional analysis.

1. INTRODUCTION

Documents are central to administrative, legal and investigative processes because they record information and support authentication, transaction and identity-related decisions. A document may contain printed text, seals, logos, handwriting and signatures. Among these elements, handwritten signatures remain one of the most widely accepted methods of personal authentication because they are simple to execute and may retain individualistic features of the writer [1,2].

A signature is not merely a graphical mark; it reflects neuromuscular coordination, habitual writing behavior and individual variation. These features are considered during forensic document examination to assess authorship, genuineness or possible simulation. The forensic comparison of signatures relies on the combined evaluation of class characteristics and individual characteristics, since no two individuals are expected to reproduce all handwriting features in exactly the same manner [2-7].

In forensic investigations, questioned documents are not always available in their original form for examination. Reproduced documents, including photocopies and scanned-and-printed copies, are frequently encountered when the originals are retained in secure custody, unavailable, misplaced, or reproduced for dissemination across multiple locations. Modern reproduction devices, including laser MFPs, inkjet MFPs and SF photocopiers, are capable of producing high-quality copies; however, the evidential value of such copies remains a practical concern for investigators and forensic document examiners [8-15].

Previous studies have examined several aspects of reproduced or photocopied documents, including line quality, handwriting features, signature forgery detection, and comparisons between original and reproduced documents [9-13]. At the same time, computational approaches have increasingly contributed to handwriting and document examination through digital feature extraction, interactive tools and image-based analysis frameworks [16-19]. Nevertheless, limited attention has been directed toward the quantitative dimensional stability of reproduced signatures across successive generations of reproduction.

Accurate assessment of dimensional stability is important because signature comparison requires natural proportions to be preserved as far as possible. If reproduction introduces measurable distortion in height or width, the interpretation of similarities or differences may be affected. The present study therefore evaluates the dimensional consistency of handwritten signatures across five successive reproduction generations using different categories of reproduction devices. By combining statistical testing with Fiji (ImageJ)-based computational image measurement, the study assesses whether reproduced signatures retain dimensional integrity and considers the forensic and computational implications of the findings.

2. STATEMENT OF THE PROBLEM

The increasing acceptance and circulation of reproduced documents has created a practical challenge in forensic document examination. Investigators may need to submit reproduced copies for examination when the original document is unavailable, but uncertainty remains regarding whether inherited signature features remain sufficiently stable for forensic interpretation. In particular, dimensional features such as height and width may be assumed to be preserved when reproduction is performed at the original scale (100%) without enlargement or reduction, but this assumption requires empirical validation across device types and successive reproduction generations. This study addresses this problem by testing whether reproduced signatures show statistically significant dimensional variation when reproduced through laser MFPs, inkjet MFPs and single-function photocopiers up to five generations.

3. MATERIALS AND METHODS

3.1 Sample Collection and Reproduction Protocol

A total of 110 reproduced signature samples were generated from an original control signature for the purpose of evaluating dimensional consistency across successive reproduction generations. Reproductions were obtained up to five generations (G1-G5) using 22 different document reproduction machines selected from three categories: laser MFPs, inkjet MFPs and SF photocopiers. Each reproduced copy served as the source document for the subsequent generation, thereby establishing a controlled sequential reproduction chain.

3.2 Image Acquisition

All original and reproduced signature samples were digitized using an HP Deskjet 3545 scanner at a resolution of 300 dpi. Images were preserved in a lossless TIFF format to minimize compression-related artefacts and maintain image integrity during analysis. To reduce external variability, uniform orientation, standardized scanning conditions and minimal background noise were maintained throughout the image acquisition process.

3.3 Measurement Using Fiji (ImageJ)

Dimensional analysis was performed using Fiji (ImageJ), a Java-based open-source image processing and analysis software that supports scientific image analysis and reproducible measurement workflows [20, 21]. Fiji was selected because it provides pixel-level measurement tools, calibration capability and compatibility with computational image analysis procedures.

Each scanned signature image was imported into Fiji and subjected to a standardized processing workflow. The region of interest (ROI) corresponding to the signature area was selected and isolated for analysis. Images were converted to 8-bit grayscale and then to binary format to facilitate thresholding and feature extraction. Manual thresholding was applied to reduce background noise and enhance edge clarity, thereby improving the visibility of signature boundaries.

Scale calibration was performed using a known reference scale before dimensional measurement. Height and width were measured as the maximum vertical and horizontal extents of each signature, respectively. Measurements were digitally recorded and exported to Microsoft Excel for statistical analysis. To improve reliability, each measurement was repeated three times and the mean value was used for analysis.

3.4 Computational Significance of Fiji-Based Analysis

The use of Fiji enabled standardized computational analysis with reduced observer dependency. The software provided pixel-level precision, reproducibility of measurements and reduced subjective bias associated with manual dimensional estimation. The digital workflow also supports integration with computational forensic methodologies, including automated feature extraction and artificial intelligence-based document examination frameworks [16-21].

3.5 Statistical Analysis

Statistical analysis was conducted to evaluate dimensional variations across device categories and reproduction generations. One-way ANOVA was used to assess differences in height and width measurements among machine groups across successive generations. Dunnett's post hoc test was then applied to compare each machine category directly with the control group. Correlation analysis was performed to examine the relationship between variations in height and width measurements. Statistical significance was evaluated at $p <= 0.05$. The analysis was designed to test whether reproduced signatures showed statistically significant dimensional changes when compared with the control.

4. Results and Discussion

4.1 Dimensional Stability Across Generations

ANOVA results for height and width are illustrated in Fig. 1. Height p-values ranged from 0.183 to 0.465, while width p-values ranged from 0.416 to 0.951. All values were greater than 0.05, indicating that no statistically significant differences existed across device categories or generations. These findings confirm that signature dimensions remained stable up to five generations of reproduction.

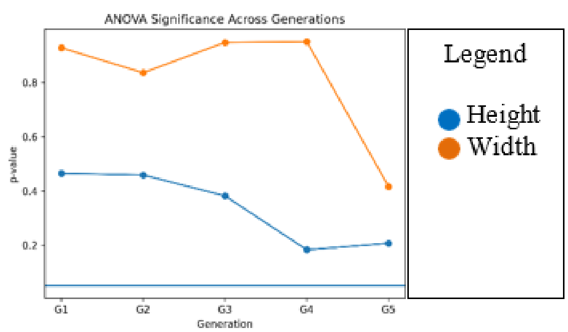

Figure 1. ANOVA p-values for height and width across five generations (G1-G5).

4.2 Variability Analysis

The F-values shown in Fig. 2 indicate slight increases in height variability in later generations, particularly G4 and G5, while width remained comparatively stable with minimal fluctuation. However, all observed variations were statistically non-significant. This indicates that the variability was random rather than systematic and that no device category introduced measurable dimensional distortion.

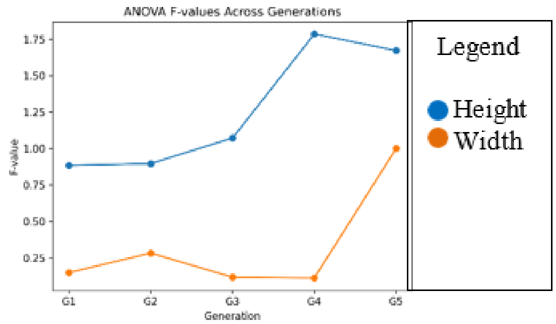

Figure 2. ANOVA F-values for height and width across generations.

4.3 Device-Wise Comparison with Control

Dunnett's test results showed that all comparisons between device groups and the control yielded p-values greater than 0.05. Mean differences were small and inconsistent in direction. A relatively larger deviation was observed for inkjet MFP in G5 for width (mean difference = -0.17083), but this remained statistically non-significant ($p = 0.169$). These findings support the interpretation that no device category introduced significant dimensional distortion when compared with the control.

4.4 Correlation Between Height and Width

Correlation analysis, presented in Fig. 3, revealed weak relationships between height and width, with correlation coefficients ranging from -0.033 to 0.302. All correlations were statistically non-significant, indicating that height and width variations were independent and that no proportional scaling effect occurred during reproduction.

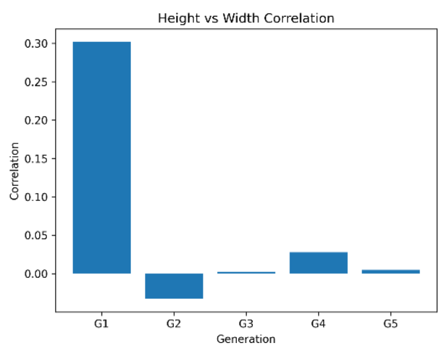

Figure 3. Correlation between height and width measurements across five generations (G1-G5).

4.5 Forensic and Computational Implications

The findings establish that dimensional features such as height and width are stable but non-diagnostic. Reproduction did not introduce detectable geometric distortion, and the computational workflow enhanced measurement reliability but did not increase the discriminative power of dimensional parameters alone. Therefore, forensic examination of reproduced signatures should not rely exclusively on height and width. Greater interpretive value may be obtained by integrating dimensional findings with line quality, stroke dynamics, pixel-level characteristics, texture analysis and other qualitative features previously considered in studies on photocopied and reproduced documents [10-16].

4.6 Contribution to Computational Forensics

This study contributes to computational forensics by demonstrating a reproducible digital measurement workflow for the assessment of signature dimensions in reproduced documents. The use of Fiji provides a practical and accessible platform for standardized image measurement and offers a basis for future integration with automated feature extraction, machine learning and deep learning-based handwritten signature analysis. The findings also provide empirical support for cautious forensic use of high-quality reproduced signatures when original documents are unavailable, while emphasizing that dimensional analysis must be interpreted as one component of a broader document examination process.

5. CONCLUSION

The widespread use of reproduced documents in administrative and legal contexts necessitates a clear understanding of their forensic reliability. The present study demonstrated that dimensional characteristics of handwritten signatures, specifically height and width, remained statistically stable across successive reproduction generations (G1-G5) and across different device categories. The absence of statistically significant variation indicated that modern reproduction technologies preserved geometric features with a high degree of fidelity.

The use of Fiji (ImageJ) as a computational measurement tool further supported precision and reproducibility in dimensional analysis, indicating that the observed stability was not influenced by measurement bias. The study therefore contributes to both forensic science and computational forensics by presenting a standardized, accessible and reproducible workflow for quantitative examination of reproduced signatures.

However, dimensional parameters were found to be robust rather than diagnostically decisive. Height and width alone showed limited discriminative value for identifying reproduction or forgery. This limitation indicates that dimensional analysis should be considered as a supportive measurement rather than a standalone basis for forensic conclusion. Qualitative and micro-level features, including line quality, stroke dynamics, edge characteristics, pixel-level texture and toner or ink distribution, remain important for more complete interpretation.

The main uniqueness of the study lies in its multi-device and multi-generation design combined with Fiji-based computational image analysis. The findings support the cautious use of high-quality first-generation reproduced copies in forensic examination when original documents are unavailable, provided that conclusions are framed carefully and supported by additional features. Future research should expand the sample base, include more device models and scanning conditions, and integrate automated feature extraction, texture analysis and machine learning methods to improve the diagnostic capability of reproduced document examination.

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Ethics approval and consent to participate

Informed consent was obtained from all participants whose signature samples were used in this study.

Consent for publication

Informed consent was obtained from the participants for the use of the signature samples for research and publication purposes.

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Authors' contributions

AS designed the methodology, conducted the experiments, performed the statistical analysis, and drafted the manuscript. KS contributed to the study design, assisted with data interpretation, and critically revised the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

List of Abbreviations

Abbreviation	Definition
MFP	Multifunction printer
SF	Single function
ROI	Region of interest
ANOVA	Analysis of variance

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