Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 11s (2025)
https://www.jneonatalsurg.com

OPEN ACCESS

Ink on Paper: A Study of Line Quality and Fluid Dynamics in Handwritten Documents

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Cite this paper as: Shukla Rudrank, M C Janaki, (2025) Ink on Paper: A Study of Line Quality and Fluid Dynamics in Handwritten Documents. *Journal of Neonatal Surgery*, 14 (11s), 104-112.

ABSTRACT

Handwriting and document analysis is a major area of forensic science. The present research attempts to study the line quality of handwritten documents, which is useful for comparing and analyzing questioned documents. This study examines the differences in line quality produced by 0.5mm ballpoint pens, commonly used in daily life. The objective is to determine whether any differences exist between different pens of the same tip caliber. For this study, a stereomicroscope was used to capture images of handwritten documents collected by the researcher. Specialized software was then used to measure line quality. The results indicate that even when using pens of the same caliber, the line quality varied depending on the pen. This variation was observed not only in standard writing but also in scribbling motions such as vertical and horizontal strokes, where differences in line quality were also evident. Furthermore, the study applied Fick's time-dependent diffusion law of fluid dynamics to determine the age of ink. Combining line quality data with Fick's law of diffusion provided valuable insights. It was found that handwriting produced with pens of the same caliber exhibited disparities, and if such writing was added at a later time, diffusion analysis could help detect alterations or additions to the original writing. These findings highlight the practical application of fluid dynamics laws in handwriting analysis and the detection of alterations in questioned documents.

Keywords: *Line Quality; Image Analysis; Fluid Dynamics; Age identification; Justice.*

1. INTRODUCTION

Documents are evidence of our amenability with society's necessities, and of the circumstances of our communication with others fellow individuals in society. Dependency over the document is grown day by day over the centuries as the transactions between the individuals as increased and the demand of the document also. In such a condition the understanding of the document and analysing the document, written or printed content, analysis of ink, have evolved it as a science of identification(1–3).

Handwriting is as old as human evolution with improvisation, as human evolved the writing skills were also get refined. The handwriting plays a vital role in questioned document analysis where initially the documents were handwritten only before to the invention of machines. So, it is very significant to recognize the handwriting as significance in the questioned document analysis (4–6).

Questioned document is one which was in question about the identity of author, content, age etc, the analysis of questioned document provides insight for understanding of such questions. The questioned document can be divided into handwritten and printed, the handwritten documents were been encountered in more controversy(7). Handwriting analysis is one of the significant part of the document analysis where the analysis depends on various characteristics to define persons and to identify (8–10). Handwriting analysis is more important when there is any doubt on authors identity and thus many examinations will be conducted to find the author or owner of the handwriting. Among such class characteristics the analysis of line quality gains importance in handwritten document which will reveal the vital information about the author. Line quality analysis is one of the area where the impact of writing instrument that is pen has a significant role in producing handwriting (11,12). In the modern era the line quality can be analysed in both manual as well as digitally the establishment of author is also possible(13). The modern technology as brought in many techniques for analysis of handwriting examination in digitally but the quality of such analysis is still has some drawbacks (14–16). Hence application of mechanical/mathematical models in analysis of writing can be infused for additional accuracy and reliability(17).

Fluid dynamics contributes majorly in forensic handwriting analysis to understand ink flow, deposition, and diffusion on paper. Ink, rather, is transferred from a pen to a writing surface partly due to capillary action, viscosity and surface tension principles, which, in their turn, combine to influence stroke consistency and ink spread(18–20). Significant application of Fick's diffusion law for estimating ink aging. By studying the spread of ink particles over time, forensic experts can tell whether words were added at a later date and detect possible alterations or forgeries. In addition to the varying line quality, or stroke width, and ink diffusion rates would readily distinguish one pen from another, even if both pens had the same line of calibre, thus providing very useful evidence in questioned document examiners(21–25). Therefore, the combination of fluid mechanics and mathematic models with forensic science helps provide more accurate handwriting examination with respect to authenticating or detecting tampering and determining the relative timings of handwritten entries on documents(26–28).

Based on the literature review conducted, research investigating the quality of lines in handwritten documents remains limited, especially in how the principles of fluid dynamics can be applied to their analysis. Previous studies have ventured to define diffusion and mechanisms of deposition somewhat; however, scarce have been those studies that have integrated fluid mechanics in line quality assessment based on images. Thus, more so, this study is an attempt to attempt into the gap by formally investigating line quality in handwritten documents, employing advanced image analysis methods. The present study aims to improve forensic handwriting examination by coupling microscopic imaging, digital processing, and fluid dynamics modelling to present evidence for handwriting features and possible document alterations.

2. RESEARCH METHOD

The current research employs a comparative qualitative method to examine the quality of handwritten text written with two 0.5mm ballpoint pens from different manufacturers. The main aim is to find out if differences occur in the line quality even with the same tip calibers when written by the same writer with the same text content. controlled horizontal scribbling strokes were also captured and analysed for additional investigation of ink deposition and stroke consistency.

Data Acquisition and imaging:

The handwriting samples were generated under controlled conditions, maintaining consistent pressure and writing speed. For accurate line quality evaluation, a stereomicroscope with camera mounted with optical zoom system was utilized. Initially written material was imaged at 33% zoom ration at 10x magnification. Whereas, scribbled strokes were imaged at 39% zoom ratio to increase the resolution of fine structural differences. The images were capture and processed to determine major parameters, such as consistency of stroke width, ink flow, discontinuities. Comparison analysis was also done to measure the difference between the two brands of pens.

Application of Fick’s Diffusion Model for Ink Aging:

To complement the line quality assessment, Fick’s time-dependent diffusion equation was used to explore the dynamics of ink diffusion with respect to time. Ink spreading from the initial stroke was measured to determine diffusion coefficient (D) for one of the samples. The diffusion-based method allowed relative aging of the ink and detection of possible changes or additions to the document. The diffusion coefficient was determined through experimental measurement of the ink spreading, making it possible to estimate temporal properties of the handwriting.

Hypothesis:

Based on the stated problem, the research assumes the following Null Hypotheis (H_O):

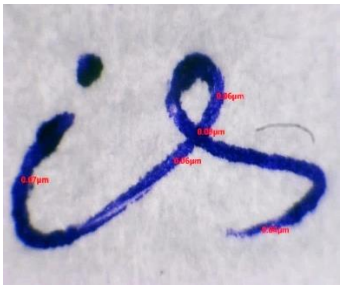
“Line quality is different for various ballpoint pens of the same tip calibre, even when written by the same writer under the same conditions”.

Microscopic image analysis and diffusion model results present forensic information for discrimination of writing tools and authentication of document authenticity. The incorporation of fluid dynamics theories into forensic document examination improves the accuracy of ink age determination and modification detection.

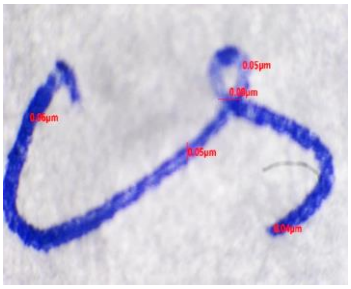
3. RESULTS AND DISCUSSION

Image Analysis:

The images were analysed using the software provided by the image capturing stereomicroscope and the for the purpose of study some writings were selected looking upon the features like circular motion, overlapping, start & ending stroke, were chosen and analysed were discussed below.



Sample A



Sample B

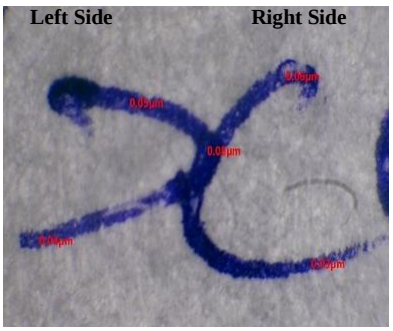
Figure 1: Analysis of the Letters 'I' and 'S' for Line Quality at 10× Magnification with 33% Zoom

Table – 1: Data of line quality differences between pens for the letter 'I & S'

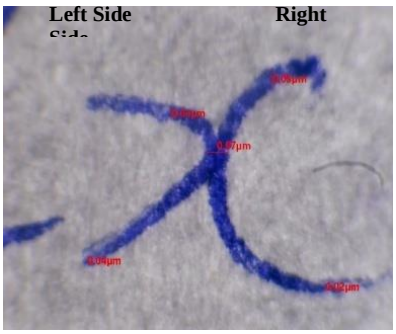
Sl. No	Name	Sample A		Sample B	
		Measurement	Length	Measurement	Length
1	L1	(72 - 63)	09	(82 - 74)	08
2	L2	(79 - 73)	06	(87 - 82)	05
3	L3	(61 - 54)	07	(31 - 25)	06
4	L4	(96 - 92)	04	(67 - 62)	05
5	L5	(63 - 60)	03	(98 - 94)	04

Unit: Micrometre

In the above figure the letter 'I & S' is chosen for study where the circular motion, overlapping and strokes were studied. The above Table infers that L1 – overlapping of the line among both the writing the difference is .01µm, whereas with respect to the L2 – circular motion, L3 – Width before overlapping the table indicates the difference of .01µm where the Sample A ballpoint pen is having higher score than that of Sample B ballpoint pen. But when it is referred to the L4 & L5 – starting and ending stroke respectively the result is overturned where sample B ballpoint pen strokes scored higher score than that of sample A the difference is .01µm only. The above numbers provide the width of the line quality written by .5mm ballpoint pen where the difference is found even though the difference is not much huge but still the line quality among the two pen in above writing is found by .01µm respectively.



Sample A



Sample B

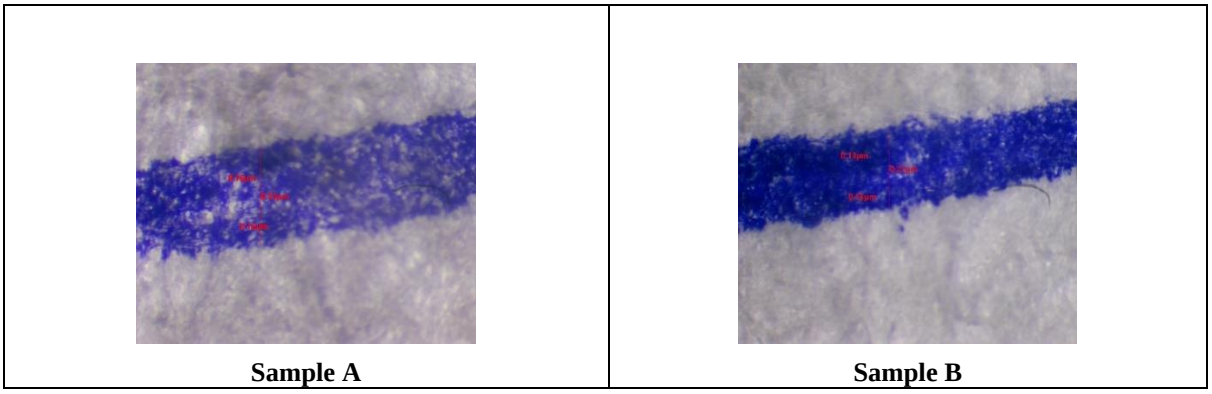
Figure 2: Analysis of the Letter 'X' for Line Quality at 10× Magnification with 33% Zoom

Table – 2: Data of line quality differences between pens for the letter 'X'

Sl. No	Name	Sample A		Sample B	
		Measurement	Length	Measurement	Length
1	L1	(70 - 62)	08	(65 - 58)	07
2	L2	(46 - 41)	05	(51 - 47)	04
3	L3	(55 - 51)	04	(66 - 62)	04
4	L4	(93 - 87)	06	(81 - 76)	05
5	L5	(60 - 57)	03	(98 - 96)	02

Unit: Micrometre

The Image infers the analysis of letter 'X' where the overlapping and strokes were studied. The above Table clearly indicates the measurement of line quality where L1 – overlapping of line number shows that Sample A as higher score than that of Sample B with the difference of .01µm. Whereas L2 & L3 – Left side start & end stroke analysis of image as not found much difference more or less the line quality is same. Comparatively on the L4 & L5 Right side start & end stroke L4 – starting stroke as .02µm difference but L5 – ending stroke as only .01µm difference respectively. The above numbers give an understanding that the Sample A as superiority over the Sample B written line quality.



Sample A **Sample B**

Figures 3: Analysis of Horizontal Scribbling for Line Quality at 10× Magnification with 39% Zoom

Table – 3: Data of line quality differences between pens for horizontal scribes

Sl. No	Name	Sample A		Sample B	
		Measurement	Length	Measurement	Length
Horizontal Measurement					
1	L1	(46, 13)	33	(56, 29)	27
2	L2	(34, 16)	18	(37, 24)	13
3	L3	(38, 22)	16	(40, 25)	15

Unit: Micrometre

The above picture indicates the measurement of the line quality in horizontal and vertically scribbled writing using the .5mm ballpoint pen. Where L1 – is the total line width for both Sample A & B for this analysis of line quality the zoom ration was increased to 39% where it is clearly indicates that the difference between two sample is .06µm. Whereas, L2 & L3 – speaks about the intersection or dividing line in the line. Where L2 is upper section and L3 is lower section respectively. The measurement clearly states that the difference between the two samples for upper section i.e. L2 is .05µm and with respect to lower section i.e. L3 is .01µm respectively. The difference for upper section is observed more than that of lower section. The division in the line occurs in the centre most region of the ballpoint which contacts the paper it is very clear that comparatively Sample A has got more wider line than that of Sample B even though the pen is of .5mm.

Hypothesis Testing

Table – 4: Analysis for Association of line quality between the pens.

Test Types	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	91.000[a]	72	.065
Likelihood Ratio	47.960	72	.987
Linear-by-Linear Association	11.767	1	.001

The above Table indicates the association between the line quality of two different pen of .5mm tip written by the same author. Where it is clear that the value of Chi-Square is 91.0 with *df* of 72. The *p-value* is .06 which is greater than the alpha value i.e., .05 which indicates that the result is in-significant. Generally, in this condition statistical inference predicts that the null hypothesis be accepted i.e., "Line quality is different for various ballpoint pens of the same tip calibre, even when written by the same writer under the same conditions".

Analysis of Ink applying Fluid Dynamics – Fick's Second Law:

Ink diffusion over time is an essential study in identifying the age of handwriting and the possibility of forgery(29). Fick's Second Law of Diffusion is referred to as a formula used in forensic studies to describe the way in which ink particles disperse with time. Sample A and B data has been utilised for analysis applying Gaussian solution for ink diffusion.

Basic formula for calculation of Fick's time-dependent equation:

$$C(x,t) = \frac{C_0}{\sqrt{4\pi Dt}}\, exp\left(-\frac{x^2}{4Dt}\right)$$

Before starting the calculation first, we have to find the observation value for the equation like, C_0 = 1.0 as normalized value, $x = 0.5mm\ calibre\ of\ pen$, t = 3600 seconds, let's find the value for D and calculate the equation to find the diffusion of ink.

Table – 5: Calculation of the Diffusion Coefficient – D in the formula

Sample A	Sample B
Equation: $x_{diff} = \sqrt{4Dt}$ Rearrange the formula for D: $D = \frac{x_{diff}^2}{4t}$ *Observation value* t = 3600s (1 hour), ink radius is x_{diff} = 33mm $D = \frac{(33)^2}{4 \times 3600}$ $D = \frac{1089}{14400}$ $\mathbf{D \approx 0.0756\ m^2/s}$	**Equation:** $x_{diff} = \sqrt{4Dt}$ Rearrange the formula for D: $D = \frac{x_{diff}^2}{4t}$ *Observation value* t = 3600s (1 hour), ink radius is x_{diff} = 27mm $D = \frac{(27)^2}{4 \times 3600}$ $D = \frac{729}{14400}$ $\mathbf{D \approx 0.0506\ m^2/s}$

Table – 6: Calculating the Denominator of formula

Sample A	Sample B
Equation: $\sqrt{4\pi Dt}$ *Observation value* D $\approx 0.0756\ m^2/s$ t = 3600s (1 hour), First, calculate the term inside the square root: $4\pi Dt = 4 \times 3.1416 \times (0.0756) \times (3600)$ $= 4 \times 3.1416 \times 272.16$ $= 3420.72$ Now, take the square root: $\sqrt{3420.72} \approx 58.48$ Thus, the denominator is: $\boldsymbol{\sqrt{4\pi Dt} \approx 58.48}$	**Equation:** $\sqrt{4\pi Dt}$ *Observation value* D $\approx 0.0506\ m^2/s$ t = 3600s (1 hour), First, calculate the term inside the square root: $4\pi Dt = 4 \times 3.1416 \times (0.0506) \times (3600)$ $= 4 \times 3.1416 \times 182.16$ $= 2289.09$ Now, take the square root: $\sqrt{2289.09} \approx 47.84$ Thus, the denominator is: $\boldsymbol{\sqrt{4\pi Dt} \approx 47.84}$

Table – 7 Calculating the Exponential Term of formula

Sample A	Sample B
Equation: $-\frac{x^2}{4Dt}$ *Observation value* *x = 0.5* D $\approx 0.0756\ m^2/s$ t = 3600s (1 hour), $\frac{(0.5)^2}{4 \times (0.0756) \times 3600}$ $\frac{0.25}{1088.64}$ ≈ -0.0002296 $\boldsymbol{e^{-0.00023} \approx 0.9997}$	**Equation:** $-\frac{x^2}{4Dt}$ *Observation value* *x = 0.5* D $\approx 0.0506\ m^2/s$ t = 3600s (1 hour), $\frac{(0.5)^2}{4 \times (0.0506) \times 3600}$ $\frac{0.25}{728.64}$ ≈ -0.0343 $\boldsymbol{e^{-0.0343} \approx 0.9663}$

Table – 8: Calculating the diffusion of ink samples

Sample A	Sample B
Equation: $C(x,t) = \frac{C_0}{\sqrt{4\pi Dt}}\ exp\ \left(-\frac{x^2}{4Dt}\right)$ $C(0.5,3600) = \frac{1.0}{\sqrt{58.48}} \times 0.9997$ $C(0.5,3600) = \frac{1.0}{7.65} \times 0.9997$ $= 0.1307 \times 0.9997$ ≈ 0.13 **Final value obtained is:** $\mathbf{C\ (0.5, 3600)\ \approx 0.13}$	**Equation:** $C(x,t) = \frac{C_0}{\sqrt{4\pi Dt}}\ exp\ \left(-\frac{x^2}{4Dt}\right)$ $C(0.5,3600) = \frac{1.0}{\sqrt{47.84}} \times 0.9663$ $C(0.5,3600) = \frac{1.0}{6.951} \times 0.9659$ $= 0.1446 \times 0.9663$ ≈ 0.1397 **Final value obtained is:** $\mathbf{C\ (0.5, 3600)\ \approx 0.14}$
This means that after 1 hour, the ink concentration at 0.5 mm from the source has reduced to 0.13% of its initial value, showing diffusion in progress.	This means that after 1 hour, the ink concentration at 0.5 mm from the source has reduced to 0.14% of its initial value, showing diffusion in progress.

Overall Interpretation of Fick's law result:

Ink Diffusion Variation:

The slight deviation in concentration values indicates that even with inks of the same type or calibre, Diffusion properties differ. Many factors influence the rate diffusion, including ink composition, viscosity, paper absorbency, etc.

Line Quality Implications:

- The more Concentrated the sample B, the slower the Diffusion, and this higher Concentration $C(0.5,3600)=0.14$) implies more Concentration within one localized area.
- Where $C(0.5,3600)=0.13$ in Sample A implies that the ink spreads more promptly into the other area, thereby giving lesser and more disperse darkness.
- This could influence a handwriting analysis, some ink might appear darker or lighter because of their behaviour in terms of diffusion.
- The differences in $C(0.5,3600)$ highlight the cruciality of fluid dynamics in forensic handwriting analysis.

The knowledge of ink diffusion behaviour provides insight into line quality determination, forgery detection, and document authentication in forensic science.

Major Findings:

The study describes that the line quality in handwritten documents varies according to the type of pen used, taking into consideration that the tip of the pen is same. Image analysis and diffusion studies allowed the following key observational findings:

- Different pens produced noticeable differences in stroke width, ink deposition etc, highlighting the impact of pen characteristics on handwriting appearance(30,31).
- Estimation of Ink Aging: Since diffusion continues over time, monitoring the ink spread would allow the estimation of the age of handwritten text-a critical process in forensic document examination(26–28,32–34).
- Alteration Detection: A new stroke showing a reduction in diffusion drastically lower than that of a prior stroke could signify a possible forgery or tampering(35–38).

4. CONCLUSION

Handwriting analysis is important due to the pivotal role it plays in considering authorship in forensic questioned document examination. In this case, both class characteristics and individual characteristics work together to indicate if a handwriting sample is authentic. The authenticity of the handwriting depends not only on the writer but also on the pen with which the writer wrote. Even a change in pens may make a difference in the quality of the line, which seems to emerge as an important variable in forensic handwriting authentication. Moreover, the combined consideration of fluid dynamics and the diffusion analysis was expected to considerably enhance the confidence of the methodology in dealing with authorship verification and in addressing questions of alterations with questioned document analysis.

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