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Examination of Pressure Induced Microstructural Changes in Fingerprint Pores

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Abstract

Background: Fingerprints' permanence, individuality, and complex ridge patterns have made them a mainstay of forensic science for a long time. While traditional fingerprint analysis focuses on minutiae and ridge flow, modern forensic processes now look at Level 3 features, which are microscopic properties including pore size, shape, and distribution. Particularly in forensic situations when latent prints may be affected, the impact of outside variables like pressure on these micro-features is crucial. Understanding how applied pressure varies can improve the accuracy of fingerprint recognition and interpretation morphology of pores.

Methods: This study focuses on the deformation of fingerprint pores under varying levels of applied pressure and its implications for latent print analysis. A total of 30 fingerprint samples, collected from male and female participants of Alakh Prakash Goyal University, Shimla, were examined under three distinct pressure conditions: light, medium, and heavy. Using stereomicroscopy and ImageJ software, the morphological changes in pore structure were observed and analyzed. To measure pore deformation and evaluate feature stability, statistical methods such as ANOVA and t-tests were used.

Results: Significant deformation was seen in medium and high pressure situations, and the study showed detectable variations in pore area and shape across the three pressure levels. Because pore morphology is susceptible to external pressure, the statistical analysis shows that these micro-features are not completely stable under different stressors.

Conclusion: The findings aim to enhance the reliability of fingerprint comparison by distinguishing between natural micro-features and pressure-induced alterations. This study advances forensic identification techniques, especially in difficult situations where conventional traits can be jeopardized.

Keywords: Digital Image Processing, Poroscopy, Pore Deformation, Applied Pressure, Effect of Pressure, Fingerprint, Level 3 Features, and Forensic Significance.

Background

Fingerprint analysis is a cornerstone of forensic identification, owing to the uniqueness and permanence of friction ridge patterns formed on the fingers, palms, and soles of individuals [1]. These patterns are categorized into three hierarchical levels: Level 1 (overall ridge flow and pattern types), Level 2 (minutiae points such as ridge endings and bifurcations), and Level 3 (microscopic characteristics such as sweat pores and ridge edges) [2]. Poroscopy, or the study of sweat pores, was introduced by Locard in 1912 and is one of the most significant third-level features for individualization. For fingerprints that have been partially or completely obliterated, it is especially helpful [3,4].

Sweat pores vary in shape, size, number, and placement across individuals, making them reliable biometric markers [5]. Studies have demonstrated that while pore characteristics can remain constant over time, external factors such as temperature, surface roughness, or deposition pressure can alter how they appear [6]. Raising pressure during fingerprint deposition may alter ridge structures in addition to possibly altering pore diameters and spatial arrangements [7, 8]. Despite advances in digital tools such as ImageJ and MATLAB that allow precise measurement of pore features, most previous studies have been conducted under controlled conditions, with limited exploration of how pressure variations affect pore morphology [9,10].Given that latent prints at crime scenes are deposited under uncontrolled conditions, understanding how pressure affects pore features is essential for improving the reliability of forensic fingerprint analysis.

This study aims to investigate the microstructural deformation of fingerprint pores under varying pressure conditions. By collecting fingerprint impressions subjected to light, medium, and heavy pressure, and analyzing them using stereomicroscopy and ImageJ software, the research seeks to quantify changes in pore shape, area,and angle. The results should improve the accuracy of latent fingerprint analysis and aid in the creation of pressure-aware biometric identification systems by advancing our knowledge of how pressure affects pore morphology.

Materials and Methods

An oil-based black inkless pad (Clear Mark®) was used in this investigation to take fingerprint impressions, transparent adhesive fingerprint-lifting tape, and standard clean glass microscope slides (75 mm x 25 mm) for sample mounting. The main tools were a RallyTech SM-6620 Zoom Stereomicroscope with a magnification range of 7x to 45x for microscopic examination of fingerprint pore structures and a 108-megapixel AI camera smartphone (Tecno Pova 6 Neo 5G) for taking pictures.The open-source program ImageJ, version 1.53t (Java 8.1.8), was used for picture analysis. Permanent markers, cotton, tissue paper, lint-free wipes, disposable gloves, and 70% ethanol were among the other consumables.

Study Design and Ethical Considerations

This study was conducted in April 2025 at Alakh Prakash Goyal University, Shimla, Himachal Pradesh, India, with prior ethical approval. Informed oral consent was obtained from all 30 healthy participants (15 males and 15 females), aged 18–25 years, selected through convenience sampling. Individuals with finger injuries or dermatological conditions (e.g., eczema, psoriasis) were excluded. The study aimed to assess pressure-induced changes in third-level fingerprint features, including pore shape, area, and angle. Data collection occurred under natural laboratory conditions (average temperature: 20.5 °C; humidity: ~48%) without artificial environmental control.

Sample Collection and Preparation

For uniformity, participants were told to use their right thumb. In order to replicate real-life forensic deposition, the fingerprint surface was kept untreated (unwashed and undisinfected) to preserve natural skin conditions and secretion patterns. Three distinct pressure levels were used to capture each fingerprint: Low pressure: very little contact that resembles a light touch. Medium pressure: force similar to that of natural writing. High pressure: a purposeful, hard press.

These subjective pressure thresholds were modified from earlier research (Oklevski et al., 2019; Kaur and Garg, 2021). Following the application of ink, impressions were created on sticky tape and promptly moved to microscope slides with labels. Participant ID, gender, and pressure level were designated by labels (e.g., S1-L-M for Sample 1, Low Pressure, Male). Slides were cleaned prior to mounting using 70% ethanol and lint-free wipes. Care was taken to prevent air bubbles and misalignment during mounting, ensuring optimal pore clarity **(Fig 1).**

Imaging and Region of Interest (ROI) Selection

Microscopic imaging was performed at 45x magnification. The center of each fingerprint pattern (core) was identified, or, in its absence, the first ridge bifurcation was located. From this point, three ridges were counted downward, and a fixed ROI (500x500µm) was defined using ImageJ software, oriented parallel to the ridge flow. This area typically encompassed ~25 ridge lines. Four pores located along a single ridge within this ROI were selected for analysis **(Fig 2).**

Feature Analysis

Pore Shape: Pore shape was quantified by calculating the circularity index using ImageJ. Images were converted to 8-bit grayscale and thresholded for contrast enhancement. The elliptical and freehand tools were used to trace the pores manually. Shape categorization was based on circularity values: Near 1.0: Round 0.7- 0.89: Oval, <0.7: Distorted

Pore Area: Following Gupta et al. (2007), pore area was measured using a best-fit circle drawn around the pore touching at least three points. Binary images were created to enhance pore boundary visibility, and four distinct pores per image were analyzed **(Fig 3).**

Pore Angle: Pore orientation was measured by drawing intersecting lines across each pore in ImageJ using the "angle between lines" tool. The angle between the major axis of the pore and the ridge direction was calculated to determine any deformation associated with pressure variation **(Fig 4).**

Statistical Analysis

Descriptive statistics were computed for all pore parameters. One-way analysis of variance (ANOVA) was used to evaluate significant differences in pore characteristics across different pressure levels. Paired t-tests were employed for post-hoc comparisons. All analyses were performed to determine the influence of pressure on third-level fingerprint features and to assess their forensic stability and reliability.

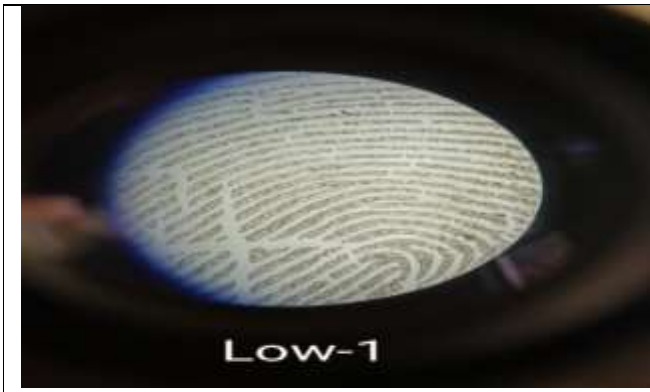
(a)

(b)

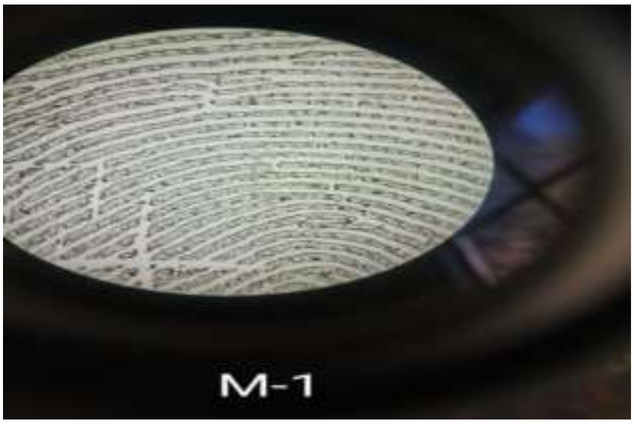
(c)

(d)

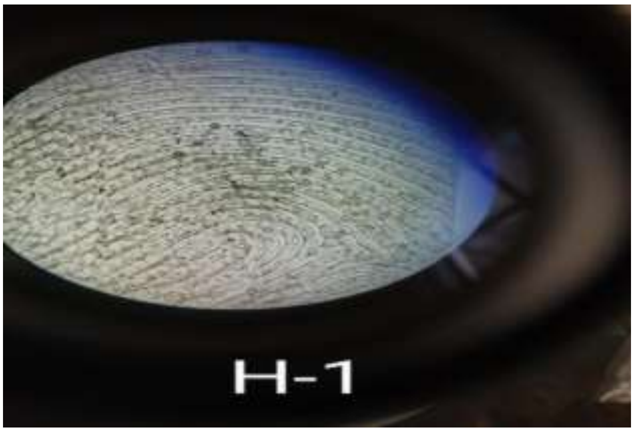
Fig 1 Sample Collection a).Application of ink on the thumb b).Deposition of thumbprint on adhesive tape at varying pressure conditions c).Collection of fingerprints deposited under different pressure on adhesive tape d). Code assigned as S1LM, S1MM, S1HM.



(a)



(b)



(c)

Fig 2 Microscopic images of fingerprints a). Fingerprint recorded on sticky side of adhesive tape at low pressure **b).**Fingerprint recorded on sticky side of adhesive tape at medium pressure **c).** Fingerprint recorded on sticky side of adhesive tape at high pressure (captured at x40 magnification using 108 MP smartphone).

Fig 3 Binary image of fingerprint pore measuring pore area using ImageJ Software.

Fig 4 Binary image of fingerprint pore measuring pore angle using ImageJ Software.

Result

Pore Shape Variation Under Varying Pressure Conditions

To assess the reproducibility and variation in fingerprint pore shape under different mechanical pressures, a total of 90 fingerprint samples (30 each under low, medium, and high pressure) were examined. Four distinct pores were selected from each sample, resulting in 120 pores per pressure category. Pore circularity—a unitless measure ranging from 0 (highly elongated) to 1 (perfectly circular)—was used as the primary morphological parameter. The mean circularity values recorded were 0.753 under low pressure, 0.825 under medium pressure, and 0.631 under high pressure, indicating a progressive elongation of pore shape with increasing pressure.

One-Way ANOVA Analysis Across Pressure Levels: A one-way analysis of variance (ANOVA) was conducted to evaluate the influence of pressure on pore circularity. The results revealed statistically significant differences among all three pressure levels: **Low pressure:** $F = 286.63$, $p = 9.84 \times 10^{-43}$, **Medium pressure:** $F = 263.48$, $p = 2.16 \times 10^{-40}$, **High pressure:** $F = 326.35$, $p = 1.62 \times 10^{-46}$. These results confirm that mechanical pressure significantly affects pore morphology, with the greatest shape distortion observed under high pressure **(Table1,2,3).**

Table 1: ANOVA Results for Low Pressure Fingerprint Samples

Source of Variation	**SS**	**df**	**MS**	**F**	**p-value**	**F_{crit}**
Between Groups	183.021	1	183.021	286.63	9.84×10^{-43}	3.8808
Within Groups	151.969	238	0.639			
Total	**334.990**	**239**				

Table 2: ANOVA Results for Medium Pressure Fingerprint Samples

Source of Variation	SS	df	MS	F	p-value	F_{crit}
Between Groups	168.357	1	168.357	263.48	2.16×10^{-40}	3.8808
Within Groups	152.075	238	0.639			
Total	**320.432**	**239**				

Table 3: ANOVA Results for High Pressure Fingerprint Samples

Source of Variation	SS	df	MS	F	p-value	F_{crit}
Between Groups	209.513	1	209.513	326.35	1.62×10^{-46}	3.8808
Within Groups	152.796	238	0.642			
Total	**362.309**	**239**				

Pairwise Comparison Using t-Tests: Subsequent t-tests were conducted to identify statistically significant differences between individual pressure pairs. The results showed the following: **Low vs. Medium pressure:** $t = -4.24$, $p = 3.14 \times 10^{-5}$, **Medium vs. High pressure:** $t = 10.48$, $p = 2.22 \times 10^{-21}$**,** **Low vs. High pressure:** $t = 6.69$, $p = 1.62 \times 10^{-10}$**.** Each pairwise comparison yielded statistically significant differences in circularity **(Tables 4, 5, 6)** , indicating that pore shape deforms distinctly between pressure conditions.

Gender-Based Differences in Pore Shape: An additional ANOVA was conducted to evaluate the influence of gender on pore circularity across all pressure levels. No statistically significant gender-based differences were found in any condition:**Low pressure:** F = 0.0748, $p = 0.7849$, **Medium pressure:** F = 0.7961, $p = 0.3741$**, High pressure:** F = 1.9853, $p = 0.1615$**.** Although males exhibited slightly higher average circularity values under medium and high pressure, these differences were not statistically significant. Therefore, gender was not a contributing factor to pore shape variability under mechanical pressure **(Tables 7,8,9).**

Table 4: T-Test for Low vs. Medium Pressure (Two-Sample Assuming Equal Variances)

Parameter	Variable 1 (Low Pressure)	Variable 2 (Medium Pressure)
Mean	0.753475	0.824903
Variance	0.016549	0.017434
Observations	120	120
Pooled Variance	0.016992	
Hypothesized Mean Difference	0	
Degrees of Freedom (df)	238	
t Statistic	–4.24446	
$P(T \leq t)$ one-tail	1.57×10^{-5}	
t Critical one-tail	1.651281	
$P(T \leq t)$ two-tail	3.14×10^{-5}	
t Critical two-tail	1.969981	

Table 5: T-Test for Medium vs. High Pressure (Two-Sample Assuming Equal Variances)

Parameter	Variable 1 (Medium Pressure)	Variable 2 (High Pressure)
Mean	0.824903	0.631342
Variance	0.017434	0.023492
Observations	120	120
Pooled Variance	0.020463	
Hypothesized Mean Difference	0	
Degrees of Freedom (df)	238	
t Statistic	10.48108	
P(T ≤ t) one-tail	1.11×10^{-21}	
t Critical one-tail	1.651281	
P(T ≤ t) two-tail	2.22×10^{-21}	
t Critical two-tail	1.969981	

Table 6: T-Test for Low vs. High Pressure (Two-Sample Assuming Equal Variances)

Parameter	**Variable 1 (Low Pressure)**	**Variable 2 (High Pressure)**
Mean	0.753475	0.631342
Variance	0.016549	0.023492
Observations	120	120
Pooled Variance	0.020021	
Hypothesized Mean Difference	0	
Degrees of Freedom (df)	238	
t Statistic	6.686084	
P(T ≤ t) one-tail	8.09×10^{-11}	
t Critical one-tail	1.651281	
P(T ≤ t) two-tail	1.62×10^{-10}	
t Critical two-tail	1.969981	

Table 7 Result for ANOVA for Low Pressure Gender Comparison

	Count	**Sum**	**Average**	**Variance**
Female	60	45.015	0.75025	0.022368
Male	60	45.402	0.75670	0.010990

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.001248	1	0.001248	0.07483	0.784908	3.92148
Within Groups	1.968090	118	0.016679			
Total	1.969338	119				

Table 8 Result for ANOVA for Medium Pressure Gender Comparison

	Count	Sum	Average	Variance
Female	60	48.8483	0.814138	0.024660
Male	60	50.1400	0.835667	0.010269

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.013904	1	0.013904	0.79614	0.37407	3.92148
Within Groups	2.060787	118	0.017464			
Total	2.074691	119				

Table 9 Result for ANOVA for High Pressure Gender Comparison

	Count	Sum	Average	Variance
Female	60	36.609	0.61015	0.022923
Male	60	38.916	0.64860	0.021759

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.044352	1	0.044352	1.98526	0.16147	3.92148
Within Groups	2.636202	118	0.022341			
Total	2.680554	119				

Pore Area

Fingerprint pore areas were measured under three pressure conditions (low, medium, and high) using ImageJ software. For each group, mean pore area, standard deviation, and coefficient of variation (CV%) were calculated to analyze the influence of pressure on pore size (Table 10). A one-way ANOVA comparing pore area across pressure levels showed no significant difference ($F = 1.20$, $p = 0.303$), indicating pressure does not significantly affect pore area despite minor mean differences (low: 252.95 µm, medium: 332.21 µm, high: 282.60 µm) (Table 11). However, a two-way ANOVA considering pressure and gender revealed significant effects of gender ($F = 20.78$, $p < 0.05$), pressure ($F = 4.71$, $p = 0.0098$), and their interaction ($F = 4.39$, $p < 0.0001$), suggesting pressure impacts pore area differently in males and females **(Table12).**

Table 10 Mean Area and Variability of Fingerprint Pores at Different Pressure Levels

Pressure Level	Count	Mean Area (µm)	Variance
Low	119	252.95	98,644.54
Medium	119	332.21	231,543.5
High	119	282.60	147,632.4

Table 11 One Way ANOVA for Pore Area across Pressure Levels

Source	SS	df	MS	F	P-value	F crit
Between Groups	381,699.2	2	190,849.6	1.198	0.303	3.021
Within Groups	56,382,810	354	159,273.5			
Total	56,764,509	356				

Table 12 Two Way ANOVA for Pore Area by Gender and Pressure

Source	SS	df	MS	F	P-value
Gender	32,809,732	39	841,275.2	20.78	< 0.05
Pressure	381,601.2	2	190,800.6	4.71	0.0098
Interaction	13,860,094	78	177,693.5	4.39	< 0.0001
Within	9,714,237	240	40,475.99		
Total	56,765,664	359			

Pore Angle

In this study, pore angles were measured under three different pressure conditions—low, medium, and high—using ImageJ software. Four representative pores from each fingerprint sample were selected, and two internal angles per pore were recorded. The average angles for each pressure condition are summarized in **(Table 13).** A one-way ANOVA was conducted to evaluate whether pressure significantly influenced pore angle. The results revealed no statistically significant difference across the three pressure conditions ($F = 0.391$, $p = 0.677$), as shown in **(Table 14).** These findings suggest that pore angle remains relatively stable under different pressure applications and may have limited value in pressure-induced fingerprint deformation assessments. To evaluate potential gender-based differences, independent sample t-tests were conducted for each pressure group. Although female participants exhibited higher average angles under low (111.24° vs. 96.90°) and high pressure (115.70° vs. 97.33°), and a slightly lower average under medium pressure (97.94° vs. 99.22°), none of the differences reached statistical significance ($p > 0.05$). Detailed results are presented in **(Tables 15 to 17).** Therefore, gender appears to have no significant effect on pore angle under varying pressure conditions.

Table 13: Mean pore angles and standard deviation under different pressure conditions (N = 60 pores per group)

Pressure Leve l	Mean Angle (°)	Standard Deviation
Low	104.07	± 48.74
Medium	98.58	± 52.44
High	106.51	± 49.62

Table 14: One way ANOVA comparing pore angle under low, medium, and high pressure conditions

Source of Variation	**SS**	**df**	**MS**	**F**	***p*-value**	**F_{crit}**
Between Groups	1980.16	2	990.08	0.391	0.677	3.047
Within Groups	447790.40	177	2529.89			
Total	449770.56	179				

Table 15: Independent t- test comparing pore angle under low pressure (male vs. female)

Group	**Mean (°)**	**Variance**	**N**
Male	96.90	2130.40	30
Female	111.24	2595.65	30
Statistic		**Value**	
t-statistic		-1.143	
Df		58	
p-value (two-tail)		0.258	
t-critical (0.05)		2.002	

Table 16: Independent t- test comparing pore angle under medium pressure (female vs. male)

Group	**Mean (°)**	**Variance**	**N**
Female	97.94	2164.62	30
Male	99.22	3432.20	30
Statistic		**Value**	
t-statistic		-0.094	
df		58	
p-value (two-tail)		0.925	
t-critical (0.05)		2.002	

Table 17 : Independent t- test comparing pore angle under high pressure (female vs. male)

Group	Mean (°)	Variance	N
Female	115.70	2147.26	30
Male	97.33	2689.04	30
Statistic		**Value**	
t-statistic		1.447	
df		58	
p-value (two-tail)		0.153	
t-critical (0.05)		2.002	

Discussion

This study examined the effects of varying pressure levels on fingerprint pore features—circularity, area, and angle—providing new insights into third-level fingerprint deformations under mechanical stress. The findings revealed that **pore circularity is significantly influenced by pressure**, with low-pressure prints retaining a more circular shape and high-pressure prints showing noticeable distortion. These results align with Delican et al. (2021), who emphasized the vulnerability of third-level features to distortion during fingerprint acquisition. While **pore area** did not show significant differences in the one-way ANOVA, the **two-way ANOVA revealed a notable interaction between pressure and gender**, suggesting individual physiological traits may influence how pore dimensions respond to applied force. This supports earlier findings by Ibragimov and Segundo (2023) regarding the variability in pore-based biometric traits. In contrast, **pore angle remained stable across all conditions**, with no significant effects from pressure or gender. This suggests limited forensic utility for angle measurements in pressure-related analyses, consistent with the observations of Oklevski et al. (2019).

These results underscore the importance of **standardizing pressure during fingerprint collection**, especially in forensic settings where uncontrolled pressure could compromise pore detail accuracy. As Barnett and Berger (2020) highlighted, environmental and physical variables can affect fingerprint quality. Lastly, understanding these effects can aid the development of **more robust biometric algorithms**, capable of accommodating pressure-induced variability, as recommended by Ibragimov and Segundo (2023).

Conclusion

This study provides evidence that pressure significantly affects fingerprint pore morphology, particularly circularity, and that such deformations could impact the accuracy of forensic identification and biometric systems. While pore area and angle were less sensitive to pressure, interaction effects suggest a role for individual physiological factors. The findings underscore the importance of adopting standardized fingerprint collection procedures that limit pressure variability. Such protocols are crucial not only for forensic reliability but also for improving the robustness of biometric authentication systems.

Limitations and Future Directions

This study, while informative, had certain limitations. The sample size was restricted to 30 individuals, limiting generalizability. Pressure was applied manually, which may have introduced inconsistency. Only three pore features—circularity, area, and angle—were analyzed, with others like pore count and spacing excluded. The study was limited to the right thumb, and environmental factors such as humidity and skin moisture were not controlled. Future research should include a larger, more diverse population and use digital pressure sensors for accuracy. Expanding analysis to additional pore features and multiple fingers, along with controlled environmental conditions, will enhance the reliability of findings and support the advancement of forensic and biometric fingerprint applications.

Abbreviations

ANOVA: Analysis of Variance; S.D.: Standard Deviation; ; ID: Identification; µm: Micrometer; °C: Degrees Celsius; Et al.: And others; %: Percent; PPI: Pixels Per Inch; mm: Milimeter; vs.: Versus; e.g.: Exempli gratia (for example).

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