Forensic Identification using Palatal Rugae and Image Processing Techniques

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ABSTRACT

The rapid advancement of technology has enabled innovative approaches to longstanding scientific challenges, including the reliable identification of individuals. Identity verification plays a critical role across multiple domains, such as legal investigations, medical records, and forensic science. Despite significant progress, the task of establishing a consistent and tamper-proof method of personal identification remains a complex and open-ended problem.

In the present work, the focus is placed on palatal rugae, which are irregular, asymmetric ridges of the mucous membrane located laterally from the incisive papilla and along the anterior part of the palatal raphe. These structures are uniquely advantageous because of their protected anatomical location inside the oral cavity, granting them remarkable stability even under extreme conditions such as high temperatures, trauma, or decomposition. Their distinct patterns and resistance to alteration make palatal rugae an excellent candidate for forensic identification.

To explore their utility, this study employs image processing techniques for the extraction and analysis of palatal rugae patterns. Using computational tools, images of palatal rugae are captured, processed, and compared to differentiate between individuals. The approach emphasizes accuracy and reproducibility, minimizing human error in manual assessment. Data collection and validation have been conducted in close collaboration with dental experts, ensuring both scientific reliability and clinical precision.

The findings highlight that palatal rugae, when analyzed with modern image processing methods, provide a robust and non-invasive biometric marker for individual identification. This work contributes to forensic science by offering a technologically driven solution that integrates dentistry, biometrics, and computer vision. It underscores the significance of interdisciplinary collaboration and opens avenues for the development of efficient and reliable identity verification systems.

KEYWORDS: Palatal Rugae, Forensic Identification, Image Processing, Biometric Marker, Dental Forensics, Individual Identification, Pattern Recognition

How to Cite: Amos R, Dr. R. Kamalraj, (2025) Forensic Identification using Palatal Rugae and Image Processing Techniques, Vol.8, No.18s, 257-262.

INTRODUCTION

In an era dominated by simulation and globalization, the identity of an individual often becomes a crucial question, especially in cases of mass disasters and mass casualties. Forensic science has long sought reliable markers to establish personal identity, with methods such as dental records, fingerprints, and DNA comparisons being the most widely used. These techniques have proven to be highly effective; however, they cannot always be applied universally. In situations such as extreme trauma, fire accidents, or advanced decomposition, traditional methods may fail to yield conclusive results. This creates a need for alternative and complementary approaches in forensic identification **[7].**

One such method is **palatal rugoscopy**, the study of palatal rugae—the irregular ridges located on the anterior part of the palatal mucosa. Palatal rugae are unique to each individual, highly resistant to trauma, and stable even under conditions of extreme heat or decomposition. Due to these characteristics, palatal rugae have often been equated with fingerprints in terms of their uniqueness and reliability **[5].** Their application in forensic odontology is growing, though in India, this branch still remains in its early developmental stages.

Palatal Rugae as a Forensic Marker: Palatal rugae exhibit characteristics that make them suitable as a biomarker for identity verification are a) **Uniqueness:** No two individuals, even identical twins, share the same rugae pattern. b) **Stability:** Once formed in early life, rugae remain largely unchanged throughout adulthood, except in cases of significant trauma or orthodontic treatment. c) **Resistance:** Their intraoral location protects them from decomposition, mechanical trauma, or environmental effects such as high temperatures. These attributes make palatal rugoscopy particularly valuable in challenging scenarios, such as when individuals are edentulous (lacking teeth), when fingerprints are unavailable, or in cases involving severely burned or decomposed bodies **[9].** The development of digital storage systems allows large volumes of palatal rugae data to be preserved and retrieved quickly, making this technique both practical and efficient.

Variations in data samples: Recent comparative studies between **western Indian and northern Indian populations** have shown significant differences in rugae shapes and distributions **[8].** Key findings include: **Gender differences:** The number and shape of palatal rugae differ significantly between males and females. In western Indian groups, males predominantly exhibited **wavy-shaped rugae**, while females had **straight-shaped rugae [3]**. In northern Indian populations, males also showed a predominance of wavy patterns, whereas females displayed more **curved-shaped rugae**. **Population differences:** These variations across different geographic regions highlight the importance of population-specific databases for forensic identification **[10].**

Thus, Palatal rugae serve as a unique, reliable, and trauma-resistant biological marker that holds great promise for forensic identification. Their role is particularly vital in cases where conventional techniques fail due to environmental or biological limitations. The demonstrated differences in rugae patterns across genders and regional populations underscore the importance of creating comprehensive reference databases. By integrating palatal rugoscopy with modern technological tools, forensic science can move towards more effective, accessible, and accurate methods of human identification.

PROBLEM STATEMENT

Accurate identification of individuals is a critical challenge in forensic and medico-legal investigations, particularly in cases where conventional methods such as fingerprints, dental records. **Palatal rugae**, due to their unique and stable patterns, offer a promising alternative for personal identification, comparable to fingerprints. However, manual analysis of palatal rugae is time-consuming, subjective, and prone to errors.

The specific problem addressed in this study is the **development and implementation of image processing techniques to enhance, analyze, and extract the unique patterns of palatal rugae**. By applying these techniques to data samples from different individuals, the system aims to recognize and classify rugae patterns accurately, thereby establishing a reliable, non-invasive biometric method for individual identification.

BACKGROUND

The present study was undertaken to examine and record **palatal rugae patterns** with respect to various biometric characteristics, including shape, size, direction, number, and position, within a cross-section of the population in Uttar Pradesh. Additionally, the individuality of rugae patterns and their correlation with the sex of individuals were evaluated. Establishing the identity of a person is a fundamental objective in forensic science and legal investigations **[2].** While conventional methods such as fingerprints, dental records, and DNA analysis are widely used, these approaches may not always be feasible, especially in cases involving severe trauma, decomposition, or mass disasters. Consequently, alternative methods that are reliable, non-invasive, and easily accessible are of significant interest.

Dental identification relies on the principle that no two individuals possess identical dentition. Similarly, **palatal rugae**, the irregular and asymmetric ridges of the mucous membrane extending laterally from the incisive papilla and along the anterior part of the palatal raphe, exhibit unique patterns for each individual. Their anatomical location within the oral cavity offers remarkable stability, protecting them from environmental damage, high temperatures, and physical trauma **[3].** These characteristics make palatal rugae a valuable tool for human identification in forensic investigations.

The uniqueness of palatal rugae has led researchers to consider their use in forensic applications analogous to fingerprints. When combined with other biometric methods, palatal rugae patterns can enhance the accuracy of identification. The current literature indicates that this approach is cost-effective, simple, and reliable, making it an attractive alternative or complementary method for forensic use **[6].** Although minor changes in rugae may occur due to factors such as tooth loss, orthodontic interventions, persistent pressure, or habits like thumb-sucking, the overall pattern remains largely stable over an individual’s lifetime.

Palatal rugae have been studied in various populations globally, demonstrating both uniqueness and ethnic specificity. For example, **Thomas and Kotze (1983) [11],** analyzed rugae patterns in six South African populations to examine interracial differences. Their findings confirmed that rugae patterns were unique not only to each individual but also to specific ethnic groups, suggesting their potential application in genetic research and population studies [1]. Such research underlines the dual significance of palatal rugae: they can serve as reliable personal identifiers while also providing insights into population-level genetic diversity.

A notable aspect of the present study is its focus on populations from western and northern India, which, according to literature reviews, had not been extensively studied prior to this work. This contributes to a broader understanding of regional and gender-based variations in palatal rugae. Observing these patterns across different geographic and demographic groups provides valuable data for forensic identification databases. Moreover, the low cost and simplicity of rugae analysis, combined with its scientific reliability, strengthen its practical applicability in real-world scenarios.

Overall, the uniqueness, stability, and resistance to environmental and traumatic influences make palatal rugae a promising biomarker for forensic identification. Their analysis can supplement traditional methods, particularly in situations where fingerprints, dental records, or DNA are unavailable or compromised. By documenting rugae patterns across previously unstudied populations, this study contributes to the creation of a more comprehensive understanding of human biometric diversity, supporting both forensic applications and broader anthropological and genetic research.

1. A) Data Samples:
The study included 200 subjects aged between 18 and 25 years. Maxillary impressions were obtained using elastomeric impression material, and dental stone was used to create precise models of the upper arches. The palatal rugae patterns were carefully traced and subsequently analyzed using a digital camera for accurate documentation. All sample collection and model preparation were conducted under the supervision and guidance of a qualified dentist to ensure clinical accuracy. To maintain clarity and facilitate analysis, each sample was assigned a unique numerical code, enabling easy identification and differentiation of individual subjects. **Reading image in the workspace of MATLAB**: In this step, we store the path to our image dataset into a variable then we created a function to load folders containing image into arrays.

IMPLEMENTATION

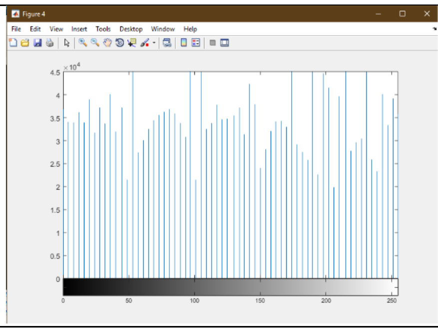
Image Enhancement and Processing of Palatal Rugae Patterns: *The* ***image enhancement process*** *plays a crucial role in digital image analysis, as it improves the visibility of features and prepares images for further processing or display. Enhanced images allow researchers to identify key structures more accurately, reduce noise, and improve contrast, ultimately facilitating better analysis of biometric features such as palatal rugae patterns. In the present study, several sequential steps were undertaken to enhance and filter the acquired palatal rugae images.*

Histogram Equalization: One of the primary techniques applied was **histogram equalization**, a widely used method to improve the contrast of digital images. An image histogram represents the distribution of pixel intensity values, with the x-axis indicating gray level intensities and the y-axis representing the frequency of each intensity value. In the initial images, the histogram often showed a high frequency of pixels in the lower intensity range, indicating that the images were predominantly dark. By applying the **histeq function**, the intensity distribution of the image was equalized, resulting in an enhanced image with a more balanced range of pixel intensities. This process effectively spreads out the most frequent intensity values across the entire range, improving visibility of rugae structures and highlighting subtle variations. The histogram of the enhanced image demonstrates a more uniform distribution of pixel intensities, making the patterns easier to observe and analyze *(Table 1).* Histogram equalization not only improves contrast but also facilitates subsequent processing steps by providing a clearer representation of key image features. **Manual Segmentation and Cropping:** Following enhancement, **manual segmentation** was employed to isolate regions of interest in the palatal rugae images. Image segmentation is a fundamental step in digital image processing, used to partition an image into meaningful regions based on pixel characteristics such as intensity, color, or shape. In this study, segmentation was performed according to the classification system proposed by Thomas and Kotze, while rugae shapes were recorded following the methodology of Kapali et al. After identifying the regions of interest, **cropping** was performed using the MATLAB **imcrop function**. This interactive tool allows precise selection of the desired area within the image by creating a movable and resizable rectangle over the displayed image. The imcrop tool blocks the MATLAB command line until the crop operation is completed, ensuring accuracy in selecting only the relevant portion of the image. Cropping eliminates background noise and irrelevant regions, thereby reducing computational complexity and enhancing the accuracy of subsequent analyses.

Conversion to Binary Image: The final step involved converting the grayscale images into **binary (black and white) images** using the MATLAB **imbinarize function**. This function automatically selects a threshold value to separate the foreground (rugae) from the background. Pixels above the threshold are set to 1 (white), while pixels below the threshold are set to 0 (black). By default, imbinarize employs **Otsu's method**, which minimizes intra-class variance and optimizes the threshold for clear separation of object and background. Binary conversion simplifies the analysis of palatal rugae patterns by reducing the image to two intensity levels, thereby highlighting the contours and shapes of rugae more distinctly. This process is crucial for quantitative measurements, pattern recognition, and classification, as it provides a clear, noise-reduced representation suitable for further computational processing or database storage.

The sequence of image enhancement, manual segmentation, cropping, and binary conversion forms a robust workflow for preparing palatal rugae images for detailed analysis. Histogram equalization ensures optimal contrast, segmentation isolates relevant structures, cropping removes irrelevant regions, and binarization simplifies the image for pattern recognition. By applying these techniques, the unique morphological characteristics of palatal rugae can be reliably extracted, analyzed, and utilized for biometric identification.

This workflow demonstrates the **effectiveness of image processing techniques** in forensic odontology, providing a low-cost, efficient, and reproducible method to enhance the visibility of palatal rugae patterns and support accurate individual identification. Furthermore, this methodology establishes a standardized framework for future studies aiming to automate rugae pattern analysis and integrate it into forensic databases.

Data Sample		***Histogram Equalization Process***	

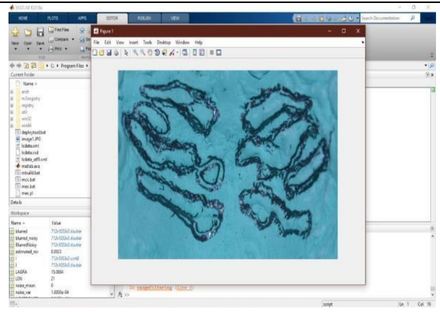
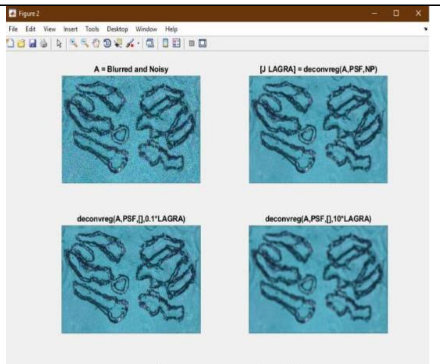
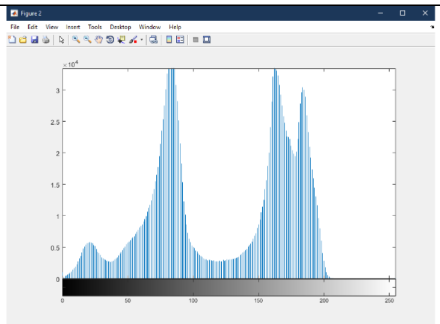
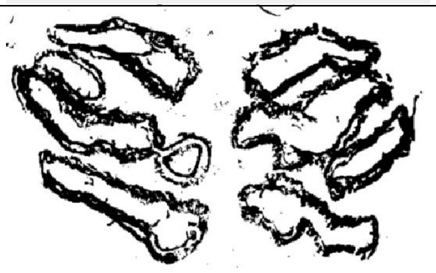
Reading Image into the Workspace of MATLAB		***Regularized Filter Processing***	
Histogram of sample image		***Image Enhancement***	

Table 1: Illustration of various stages of sample analysis

ALGORITHM TO CALCULATE THE AREA OF PALATAL RUGAE PATTERN

Input: Binary (black and white) image of the **Region of Interest (ROI)**, i.e., the palatal rugae pattern.
Output: Area of the ROI measured as the number of palatal rugae pixels.
Steps:

1. **Invert the binary image:**
The binary image is inverted so that black pixels are converted to white, and white pixels are converted to black. This is performed using the operation:
BW=~BWBW = \sim BWBW=~BW
where BW represents the original binary image.
2. **Determine image dimensions:**
Compute the number of rows and columns in the binary image using the size function:
[r,c]=size(BW)[r, c] = \text{size}(BW)[r,c]=size(BW)
where r and c represent the total rows and columns, respectively.
3. **Initialize pixel counters:**
Set counters for black and white pixels to zero (or 1, depending on implementation).
4. **Iterate through each pixel:**
Use nested loops to traverse the entire image:

```
5.     for i = 1:r
6.       for j = 1:c
7.         if BW(i,j) == 0
8.           BlackPixelCount = BlackPixelCount + 1;
9.         else
10.          WhitePixelCount = WhitePixelCount + 1;
11.        end
12.      end
13.    end
```

In this loop, each pixel is checked: if the pixel value is 0 (black), the black pixel counter is incremented; otherwise, the white pixel counter is incremented.

Calculate the area of the palatal rugae pattern:
The area is obtained as the total count of white pixels (representing the rugae pattern) in the binary image:

Area of Palatal Rugae Pattern=WhitePixelCount\text{Area of Palatal Rugae Pattern} = \text{WhitePixelCount}Area of Palatal Rugae Pattern=WhitePixelCount

This algorithm provides a simple yet effective method to quantify the area of palatal rugae from a binary image. The computed area can be used for comparative analysis, biometric classification, or further statistical studies on the uniqueness of rugae patterns.

The entire image processing workflow begins with importing the original RGB image into the workspace. The RGB image is first converted to grayscale to simplify analysis while preserving essential structural information. To enhance the quality of the grayscale image, a median filter is applied, effectively reducing noise and improving the visibility of the palatal rugae patterns.

Next, the imcrop function along with the interactive Crop Image tool is utilized to select the Region of Interest (ROI). The tool offers several functionalities, such as "Copy Position" and "Crop Image," from which the Crop Image option is used to isolate the relevant portion of the image. The resulting cropped image is then displayed and converted into a binary image, representing the palatal rugae pattern as black and white pixels. Following this, the binary image is inverted, and the white pixels are counted to determine the area of the palatal rugae pattern. This process is repeated for each sample, and the output is displayed through a Python console window, which also allows for user input and interaction during analysis. The calculated area values differ across individual samples, demonstrating the distinctiveness of palatal rugae patterns for each subject. These variations confirm that palatal rugae can serve as a reliable biometric marker, highlighting the uniqueness of each individual and supporting their use in forensic identification and comparative analysis.

SUMMARY

In the present study, palatal rugae**,** the unique ridges present in the upper jaw of the human mouth, were investigated as a potential biometric marker for individual identification**.** The study was conducted under the supervision of a dental expert to ensure accurate understanding of dental features related to palatal rugae, and the sample collection process was performed by a qualified dentist**.** A total of 200 samples were initially collected, out of which the 80 most representative samples were selected for detailed computational and algorithmic analysis. The participants belonged to the 18–25 years age group, providing a uniform population subset for the study.

The computational analysis involved several pre-processing stages using image processing techniques to identify and enhance the shapes present in the palatal rugae. The workflow began with importing the selected sample images into MATLAB for shape recognition and intensity analysis. Histogram equalization was applied to enhance the contrast of pixel intensities, providing a clearer representation of the rugae patterns. To further improve image quality, median filtering was performed, reducing noise while preserving the edges and contours of the rugae shapes, as documented in Tables 1f and 1g.

After initial enhancement, the region of interest (ROI) was isolated using MATLAB's crop function. Subsequently, Otsu's thresholding method was applied to convert the grayscale cropped images **into** binary (black and white) images**,** which simplified the detection and analysis of rugae shapes. Following binarization, the total area of the palatal rugae shapes within each sample was computed using a specifically designed algorithm (Table 1j). This quantification enabled the identification of unique patterns in each individual sample.

The next stage involved comparative analysis across all selected samples to determine similarities or differences in rugae patterns. This analysis was implemented using Python**,** which provided a flexible environment for data handling and computation. The calculated areas for all samples**,** summarized in Table 1, demonstrate that each sample possesses a distinct area**,** confirming the uniqueness of every individual's palatal rugae.

The findings indicate that palatal rugae can serve as a reliable and distinct biometric marker**,** as the area and shape patterns are unique across individuals. Moreover, the data suggests that rugae patterns can potentially be grouped based on age and gender, since variations in shape and area may correlate with demographic characteristics. This highlights the broader applicability of palatal rugae analysis in forensic identification, human biometric studies, and population-based research.

Overall, this study establishes a systematic methodology for the acquisition, processing, and analysis of palatal rugae using digital imaging, image enhancement, and computational algorithms. The workflow—from sample collection to area computation—demonstrates a reproducible and accurate approach for identifying individual uniqueness based on palatal rugae patterns. By combining image processing techniques with algorithmic analysis, this research provides a robust framework for utilizing palatal rugae in human identification**,** thereby contributing to the development of cost-effective and reliable forensic tools.

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