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A Dento-Technical Model for the Analysis and Classification of Palatal Rugae

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Abstract
Identification of the persons is a key necessity of forensic science, dentistry, and medico-legal investigation. The traditional methods of identification including fingerprints, dental records, and DNA samples are quite valid but, the methods are not consistently useful in situations involving severe trauma, fire incidents, or severe decomposition. The irregular ridges present on the anterior part of the hard palate are termed as palatal rugae, which are unique, stable and are resistant to postmortem alterations; hence, they make a useful biometric identifier in human identification. It is a dento-technical model of grasping and examining palatal rugae by using a mixture of dental images and computer technologies. The suggested strategy integrates standardized image capture of the dentures, preprocessing of the images, and automated techniques of classifying the images to facilitate better visualization, measurement, and interpretation of rugae patterns. The system reduces the number of manual actions required and biases of the observers and enhances the accuracy and reproducibility by using both traditional machine learning and deep learning classifiers. The system provides increased accuracy and repeatability by combining two classifier methods, namely, traditional machine learning (feature-based morphometric analysis) and deep learning architecture (automated pattern recognition).The paper has shown that the combination of digital image processing and dento-technical analysis is a stable and scalable platform of palatal rugae analysis. The suggested model assists in applying forensic odontology, clinical dentistry, and dental education and thus helps in the development of technology-driven and objective systems of identification.

Keywords: *Palatal Rugae, Forensic Odontology, Dental Imaging, Image Processing, Biometric Identification, Automated Classification.*

1. Introduction
The identification of an individual is one of the major necessities of a forensic science study, dental science and medico-legal study. The traditional means of identification like fingerprints, dental records and DNA profiling are well embraced due to their reliability and accuracy. Nevertheless, they cannot always be used in a situation where there is severe trauma, fire, mass disaster, or high-level postmortem decomposition, whereby the biological evidence may be lost or rendered useless. These shortcomings will prompt the need to look into other and additional biometric markers that remain stable, unique, and not susceptible to postmortem modifications. Diagnosis, treatment planning, disease progression, and forensic identification are some of the roles played by dental imaging in the current dentistry. The usual types of imaging are; intraoral photos, periapical radiographs, bitewing radiographs, panoramic radiographs (OPG), and cone-beam computed tomography (CBCT). As the digital dental records continue rapidly expanding, dental images have grown exponentially, and their analysis is time consuming, subjective and susceptible to inter-observer variation. Therefore, automatic methods of dental images analysis have become more significant in clinical and forensic studies. Dental image classification is the act of classifying dental images into pre-existing categories as in healthy and diseased teeth, caries stage, periodontal disease and tooth morphology and the existence of restoration or implants. They would need a standardized dental image database in order to detect and classify dental conditions such as caries, periapical lesions, bone loss, and impacted teeth. Regulatory image acquisition protocols provide

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consistency in image resolution, orientation, illumination, contrast and scale, and this will decrease variation due to differences in imaging equipment, operators and clinical settings. Automated classification methods also contribute to the reliability of the diagnosis process enabling objective and reproducible analysis. The palatal rugae are one of the numerous anatomical characteristics that have been studied in forensic odontology because of their uniqueness, stability, and post-mortem resistance. Palatal rugae are uneven, irregular, ridges of mucosa which are situated in the anterior part of the hard palate which extends laterally off of the incisive papilla. Their intra oral site is safeguarded and therefore is mostly unaffected by the environmental conditions, traumas, or decomposition, which makes them an excellent biometric identifier of a person. In the cases where dentition is lacking or damaged severely, unlike teeth, palatal rugae still can be utilized. The analysis of palatal rugae as done by the use of dental casts, photographs, and tracing by hand is well-known but is subjective and non-standardized. The accuracy and reproducibility of the results may be affected by the variations in the observation, methods of measurement, and the recording procedures. New possibilities to improve the visualization, measurement and interpretation of palatal rugae patterns in a more objective way are offered by the recent developments in dental imaging and image processing methods. The current research in this regard suggests a dento-technical model of studying and analysing palatal rugae through combining standardized dental imaging with digital image processing and computational analysis. The suggested strategy is expected to minimize the number of people working manually and to decrease the observer bias and increase the measurement accuracy, reproducibility, and scalability. This piece of work has been used in the formulation of objective, technology-oriented systems of forensic identification, clinical dentistry, and dental education.

2. Background

Human identification is a major necessity in forensic science and forensic odontology. The most common structure that is utilized in this purpose is dental structures based on their durability, individuality and resistance to alteration after death. Of these structures, palatal rugae, which are irregular ridges of mucosal ridges on the anterior portion of the hard palate have been identified as a good biometric measure. Their safe intramuscular status and low exposure to environmental and mechanical factors make them highly useful in trauma cases, fire cases, or cases of high degree of decomposition [1], [2]. Every individual has distinct morphological features of palatal rugae and they do not change significantly in the course of life. Initial research findings have determined their forensic usefulness through proving their uniqueness and consistency with time [1], [3]. Besides forensic identification, palatal rugae are also significant in clinical dentistry, and they help in the process of mastication, speech articulation, orthodontic evaluation and prosthodontic planning [2]. They are also anatomically stable and may be used as reference landmark of assessing dental treatment. Although palatal rugae analysis has been shown to have clinical and forensic value, it has been historically based on manual techniques that include dental casts, photographs and visual tracing. These methods although effective are lengthy in time and can be biased and unstandardized by the observer. It has given rise to a demand of organized and replicable solutions that combine dental expertise and technical aids in order to achieve precision and dependability.

3. Related Work

The uniqueness and forensic value of palatal rugae has been confirmed by a lot of research. According to English et al., the rugae patterns are not the same in any two individuals, which validates their effectiveness in identifying an individual [3]. These findings were also supported by population-based investigations. According to Kapali et al., differences in rugae pattern between Australian Aborigines and Caucasians were different, which suggested that ethnicity had an effect on the morphology of the rugae [6]. In the same vein, Hermosa et al. also have found great morphological diversity of the palatal rugae in a Peruvian population, showing that they can be used in population-specific forensic databases [4].

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The reliability of the palatal rugae in the establishment of identity has also been established by studies in the region. According to the results of Indira et al. there is high consistency and reproducibility of the patterns of rugae in an Indian population even when assessed over a period of time [5]. Stability of palatal rugae patterns was also proven by Shukla et al., where they highlighted that the patterns are resistant to age related and treatment induced changes [8]. All these studies offer support to the forensic strength of palatal rugae as an anatomical feature. New trends in dental studies have focused on computerized and three dimensional methods of better analysis and reporting. It is demonstrated that studies with digital models of the dentures, three dimensional imaging and craniofacial measurements have shown better precision and objectivity over conventional methods [9–11]. Also, there has been emerging possibilities of automated pattern recognition and classification of tasks by the increasing use of artificial intelligence and machine learning in forensic sciences [1235]. Nevertheless, the vast majority of these studies are performed in dental age estimation, cranio-facial reconstructions, or DNA analysis as opposed to much more comprehensive palatal rugae examination.

4. Research Gap

Though palatal rugae have received extensive research with regard to forensics and clinical implications, the current studies are mostly based on the analysis of these features through manual or semi digital means. No standardized dento-technical systems have been developed that combine traditional dental cast examination and digital image processing of pre-systematic rugae examination. More so, although there is recent research that points to high-level digital and computational methods in forensic dentistry, its use in palatal rugae is scattered and uncoordinated. This discrepancy promotes the need to develop a standardized dento-technical model that integrates the standardization of imaging, structured analysis, and objective interpretation to increase precision, reproducibility, and scalability of palatal rugae assessment.

5. Methodology for Model Development

The proposed dento-technical model adheres to a systematic methodological approach that combines the traditional dental cast analysis with the digital image processing in order to get objective and reproducible evaluation of palatal rugae. The workflow includes dataset preparation, image and surface processing, rugae classification, model combining, and validation.

5.1. Dataset Description and Data Collection

The data set in this research was the maxillary dental cast and related computerized images of 16 participants, who were chosen to have a limited sample that could be used as a controlled clinical group to conduct a pre- and post-treatment analysis. The sample size is adequate compared with the similar exploratory forensic odontology researches that have concentrated on morphmetric rugae analysis [5], [8]. To meet medico-legal and research ethics, ethical approval was provided before data collection and all samples were anonymized. Physical casts of the maxillary impressions were obtained by using the standard dental impression materials poured into them. Consistency was achieved by obtaining the digital images of the palatal area with the aid of high-resolution intraoral photography with the help of standardized illumination, and orientation. Since there is no publicly accessible and generally accepted open-access dataset in existence specifically on palatal rugae morphology, an institutional dataset was offered to this study. The method is in line with the past palatal rugae studies, which use institution-specific clinical data [1], [4], [5]. Although the sample size is limited to 16 participants, the sample is chosen as a controlled clinical group, which means that longitudinal analysis of variations in the pre- and post-treatment can be developed with high precision. Data augmentation techniques, which had been used to augment the diversity of the training set, such as rotation, horizontal flipping, and scaling, were used to compensate the limited dataset size in the computational phase to prevent the risk of model overfitting. To help carry out the computational assessment, the data was divided into training, validation, and testing sets according to the conventional norms. In order to increase data diversity and reduce overfitting, the digital images

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were augmented using rotation, horizontal flipping and scaling.

5.2. Image and Surface Processing

Preprocessing of all digital images was done to enhance the visualization, as well as, accuracy of palatal rugae measurement. Noise reduction and surface smoothing methods were done to suppress the artifacts that are caused during image acquisition. Contrast enhancement was done to enhance the definition of edge of rugae and then segmentation was done to isolate palatal rugae area with respect to other organs. All this was done to guarantee consistency in samples and minimize variability based on acquisition conditions. The morphometric parameters of rugae length, spacing and orientation were well extracted using the preprocessing pipeline and allowed a comparability of physical and digital measures.

5.3. Classification of Rugae and Integration of Models.

The palatal rugae was classified by employing universally accepted systems that is, the systems offered by Lysell and Thomas and Kotze, that classify the rugae according to their shape, length, direction and ways of unification patterns. These coded categories were used uniformly to the physical casts and the computer images so as to ensure continuity in diagnostics. In order to move away the manual observation method and develop an automated system, the digital analysis pipeline involves the use of Convolutional Neural Networks (CNNs) to perform the automated segmentation of the rugae region in the case of intraoral photographs. This deep learning model will guarantee accurate separation of mucosal ridges amongst the palatal tissues. After segmentation, morphometric measures, such as, rugae length, shape and direction, were then obtained and then fed into conventional machine learning classifiers, in the case of Support Vector Machines (SVM) or Random Forest, to guarantee objective pattern recognition. The suggested dento-technical model is therefore the one that involves physical cast analysis and digital representations, which enables parallel analysis of the samples. This bi-mode integration helps to cross-check the results of manual tracing and digital measurements which is needed to support objectivity and reduce observer bias in forensic and clinical environments.

5.4. Cast Analysis and Measurements

The methodology of Kapali et al. [6] was used to trace the pre- and post-expansion maxillary casts using a 0.3-mm graphite pencil. The secondary and medial endpoints of the first, second and third palatal rugae were located and marked. To quantitatively measure linear distances between consecutive rugae, linear distances were measured and recorded. Fig. 1 represents how the intermedial and interlateral rugae distances are identified and measured of the maxillary cast. The systematic recording of the rugae measurements was provided in figure 2 to be subjected to further statistical analysis.

Figure 1 Identification of Medial and Lateral Endpoints on Maxillary Palatal Casts

Figure 1 Illustrates the tracing points on the first, second, and third palatal rugae used for linear measurement of inter-rugae distances.

Figure 2 Documentation of Palatal Rugae Measurements for Pre- and Post-Expansion Analysis

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Figure 2 Shows the recorded measurements and mapping of palatal rugae distances, ready for statistical analysis. Statistical comparison showed that medial and lateral rugae measurements were significantly different between pre- and post-expansion stages where p-values were less than the significant level.

6. Experimental Results and Validation

In this section, the results of the quantitative research conducted on the proposed dento-technical model in the form of the experimental research are presented. The aim was to determine the morphometric variations in palatal rugae and to confirm the reproducibility and reliability of measures of their combined cast-based analysis and digital analysis.

6.1. Quantitative Analysis of Palatal Rugae

The experimental study involved 16 samples of maxillary. Linear measures were made between the medial and lateral endpoints of first, second and third palate rugae of both pre and post expansion stages. Rugae dimensional variation parameters were described using descriptive statistical parameters such as minimum, maximum, mean, and standard deviation. Table 1 provides a summary of the quantitative and metric change which has been witnessed in the pre-expansion phase. The values suggest the relatively uniform distance between the rugae, as a number of ranges and low values of standard deviation exist in all parameters measured.

Table 1 Quantitative and Metric Changes in Palatal Rugae Before Expansion

Pre				
No. of Samples	Min	Max	Mean	SD
16	0.4	1.81	0.94	0.165
16	2	2.88	2.45	0.228
16	2	3.71	3.38	0.183

Table 1 Summarizes pre-expansion measurements of medial and lateral endpoints of the first, second, and third palatal rugae. Includes minimum, maximum, mean, and standard deviation values for 16 samples.
In order to administer a visual representation of the distribution of the pre-expansion rugae measurements, Figure 3 demonstrates a comparative bar graph of mean values at the three measured rugae positions.

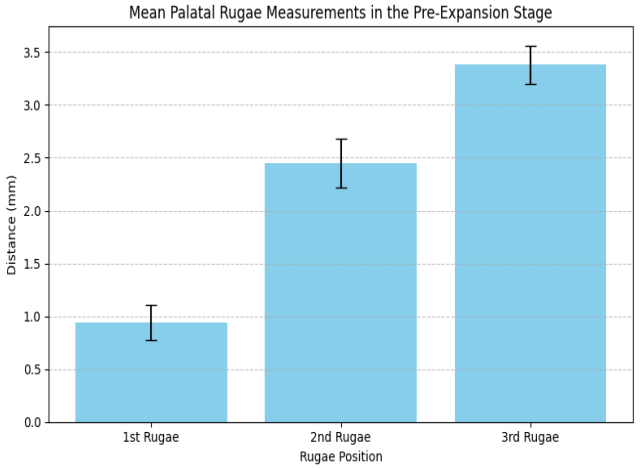

Figure 3 Mean Measurements of Palatal Rugae at Pre-Expansion Stage

Figure 3 gives the Comparative bar graph showing the average distances between medial and lateral endpoints of the first, second, and third palatal rugae before expansion.

6.2. Post-Expansion Analysis and Comparative Evaluation

Table 2 shows the quantitative measures of the post-expansion state. The significant growth in the mean values and measurement ranges was detected, which means morphological change of palatal rugae after expansion.

Table 2 Quantitative and Metric Changes in Palatal Rugae After Expansion

Post				
No. of Samples	Min	Max	Mean	SD
16	0.3	1.3	0.76	0.27
16	4.9	5.5	5.27	0.148
16	5.3	6.6	6.03	0.311

Table 2 Summarizes post-expansion measurements, showing the dimensional changes of palatal rugae after treatment. Includes minimum, maximum, mean, and standard deviation values for 16 samples. Direct

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comparison between pre- and post-expansion means is represented in Figure 4, and it shows the extent of dimensional change throughout the range of measured rugae. The graphical presentation enables easier analysis of variations that are caused by treatment.

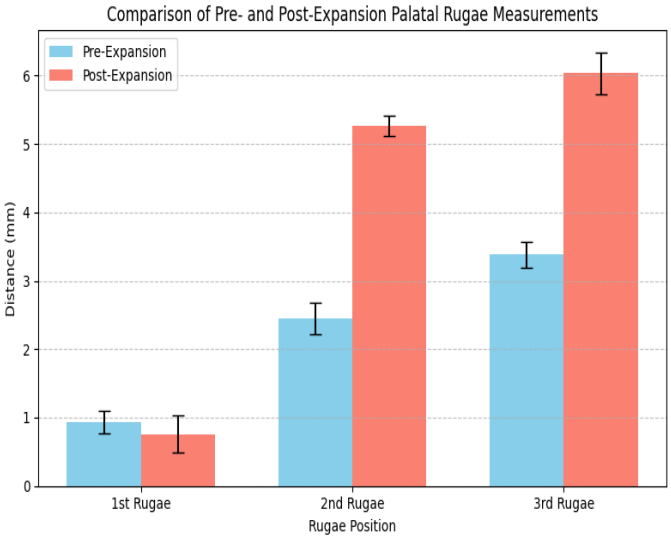

Figure 4 Comparative Analysis of Pre- and Post-Expansion Palatal Rugae

Bar graph in Figure 4 illustrates the dimensional changes of palatal rugae after expansion, highlighting differences in medial and lateral measurements across the three rugae positions.

6.3. Statistical Validation and Observations

The morphometric changes observed between pre- and post-expansion stages were validated using paired t-tests to compare the linear distances between the medial and lateral rugae endpoints1. Statistical significance was confirmed for all measured positions, as the obtained p-values were $p < 0.05$, indicating that the dimensional changes in the palatal rugae were not the result of random variation2. The high consistency and reliability of the measurements are further evidenced by the low standard deviation values maintained across both experimental stages3.Furthermore, the reproducibility of the proposed dento-technical framework is supported by the high degree of agreement between the digitally processed values and the manually traced cast measurements4. These results demonstrate that the model provides an accurate and objective methodology for the analysis of palatal rugae5. By integrating traditional dental techniques with digital processing, the model effectively minimizes observer bias and improves measurement precision, reinforcing its utility in both clinical orthodontics and forensic odontology

On the whole, the results of the experiment show that the suggested model is accurate and objective when it comes to the analysis of palatal rugae. The combination of the traditional dental technique with digital processing improves the accuracy of measurements and reduces the bias based on the observer reducing the applicability of the technique in forensic odontology and clinical examination.

7. Applications of The Proposed Model

The suggested dento-technical paradigm of palatal rugae examination proves widespread as far as forensic, clinical, and educational fields are concerned. The model using the combination of conventional cast-based techniques with digital image processing guarantees the objective, repeatable, and scalable evaluation of palatal rugae. The palatal rugae in forensic identification Palatal rugae are unique and stable and the model can be used in a reliable biometric identification method especially when fingerprints are not available, dental records are destroyed or contaminated or no DNA is available. It provides the opportunity to make quick and objective comparisons between pre- and postmortem dental records and helps find out the mass disasters and medico-legal evaluations. The model is used in clinical dentistry to aid accurate assessment of palatal morphology to aid treatment planning, to assess the result of expansion, and to determine the stability of post-treatment. Computerized classification eliminates subjectivity and makes it possible to quantify rugae variations over time. In the case of dental education and research, the system provides a common platform of teaching palatal rugae analysis which involves integration of digital technology and old dental facts. The morphometric studies, cross-population comparisons and longitudinal evaluation can be utilized by the researchers, which will result in the creation of trustworthy data to be used in further

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studies. Also, the combination of machine learning and digital image processing opens up a path to technology-based biometric and possible supplementing or substituting traditional approaches in forensics. On the whole, standardized methodology will guarantee uniform acquisition, processing and interpretation of the rugae data reducing inter-observer variability and human error and it facilitates large-scale studies. The model, being a hybrid of conventional and computational dental methods, presents an all-purpose tool in both practical and research-oriented applications.

Conclusion

The proposed paper presents a dento-technical model of combining the traditional method of dental cast inspection with the digital processing of images to give a subjective, accurate, and repeatable analysis of palatal rugae. Experimental findings have shown that the model is a stable metric of morphometric changes of rugae before and after orthodontic expansion. Moreover, the system is much compatible to manual tracing processes and has managed to reduce the bias of the observers. The model suggested can be used in the fields of forensic identification, clinical dentistry, and dental education to enable the development of a standardized, technology-intensive practices that will result in increased reproducibility and scalability. The model, which combines computational analysis and conventional dental skills, enhances the level of measurement and opens up new possibilities of population-specific research, biometric systems and medico-legal practices.

Limitations and Future Work

Although the model offers a solid platform to be studied, some limitations have to be identified, to inform further developments.

- **Sample Size:** The present research involved a sample of 16 clinical samples. Although it is adequate to conduct the exploratory morphometric analysis, a larger and more varied dataset is needed to improve the strength and validity of the deep learning elements.
- **Dimensionality:** The current approach to 2D digital imaging restricts the model to measure rugae height and volume.

Further investigation should be aimed at:

- Expanding data to encompass more diverse groups of people, thus increasing the usefulness and validity of the system.
- The use of three-dimensional (3D) imaging techniques to obtain a more detailed morphological profile, with both vertical and volumetric information.
- Use of superior predictive modelling based on machine learning to enhance diagnostic and identifications attributes of the system even more.
- Overall, the paper confirms the palatal rugae as a reliable and measurable biometric identification in a standardized paradigm of dento-technological approach, which harmonizes the disciplines of forensic science, clinical dentistry, and technological advancement.

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