Bitemark analysis comparing the use of digital scans and 3D resin casts

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The authors declare that they have no conflict of interest.

KEYWORDS

Bitemarks,
3D analysis,
Intraoral scanner,
Computer-assisted Method,
3D printer

J Forensic Odontostomatol 2024. Aug;(42): 2-76:86
ISSN :2219-6749
DOI:doi.org/10.5281/zenodo.13474602

ABSTRACT

Although dental patterns are unique, the use of bitemark analysis in personal identification remains controversial. To accurately reproduce and compare three-dimensional models of bitemarks and dental arches, intraoral three-dimensional scans, commonly utilized in clinical dental practice for precise and stable digital impressions, are recommended. This study aims to compare two different techniques for bitemark analysis: a digital method based on the superimposition of digital scans of dental patterns and lesions, and a visual method based on the physical superimposition of impressions and resin casts produced by 3D printing.

A sample of 12 volunteers (6 males and 6 females) with a mean age of 26 years was collected as biters. Each subject was asked to bite on custom supports made from semi-rigid water bottles covered with imprintable dental wax. The dental arches and bitemarks were then recorded using an intraoral scanner and dental impressions. Scan superimposition analysis was conducted using CloudCompare software, while resin casts were printed using a 3D printer and physically superimposed on the bitemark impressions by a blind operator, who was not involved in sample collection, bite test execution, prior cast acquisition, or CloudCompare analysis. Both superimposition techniques relied on the selection of 10 corresponding landmarks (on canines and central and lateral incisors of the upper and lower arches) between the dental arches and impressions.

The digital superimposition showed an average concordance of 92.5% for the upper arch landmarks and 85% for the lower arch landmarks, with an overall average concordance of 88.8% for both arches combined. In contrast, the visual analysis of resin casts showed an average concordance of 77.5% for the upper arch and 76.7% for the lower arch, with an overall average of 77.1% for both arches combined. In the analysis performed using CloudCompare, the maxillary arch demonstrated the best superimposition, with 4 landmarks (R0, R1, R2, R5) consistently overlapping. The digital analysis outperformed the visual analysis in all four quadrants, particularly in the upper right arch compared to the lower left arch, thereby supporting the integration of digital techniques in forensic applications.

Further studies are necessary to validate the digital technique on a larger sample, including subjects with different dental characteristics, bite dynamics, and varying types of supports and substrates.

INTRODUCTION

Although dental patterns are unique, the use of bitemark analysis in personal identification remains controversial. The longstanding debate between the scientific validity of bitemark evidence and its judicial value in court highlights the role of forensic odontologists in determining the degree of concordance or exclusion between different dental patterns. This determination is based on the objective collection and analysis of marks, along with scientific rigor in drawing conclusions, while leaving the determination of guilt to the judicial system. According to the 2023 review report by the National Institute of Standards and Technology (NIST), forensic bitemark analysis still lacks sufficient scientific support for reliably recognizing complete dental patterns transferred onto human skin or objects, accurately registering identifying characteristics, and using appropriate techniques to compare different dentitions and draw conclusions regarding the exclusion or inclusion of individuals as potential perpetrators of bites.

To minimize errors and subjectivity, odontologists are advised to follow established guidelines, recommendations, and standards for bitemark analysis procedures, as well as to engage in rigorous scientific research assessing the validity and reliability of both metric and non-metric methods .

Bitemark records can be created using two-dimensional methods, which involve photographic analysis performed with specific standards (e.g., ABFO No. 2 reference scale) for both wounds presumed to be bites and dental impressions/casts of potential biters' arches. These are then compared through image superimposition, using techniques such as hand tracing from study casts, hand tracing from wax impressions, xerographic methods, radiopaque impression methods, and 2D computer-based methods. However, these techniques carry a risk of error, as they attempt to represent three-dimensional models in a two-dimensional format, leading to inevitable distortions and alterations in both qualitative and metric aspects.

To address these limitations, physical three-dimensional techniques have been developed, where the model of the suspected biter's dental arch is superimposed onto the model of the bite obtained through impressions (e.g., in alginate or silicone), either directly on the object or on the skin . These methods also have significant limitations, particularly due to the challenges in obtaining clear and accurate wound models using traditional dental impression materials. Furthermore, there is a distinction between bitemarks left on different types of objects, especially food, and those left on skin. The variability in bitemark characteristics on human skin is partly due to the nonspecificity of some marks, which often manifest as superficial bruises with imperfections and abrasions, as well as distortions caused by the biological processes of injury healing, tooth wear, and the skin's malleability and deformation. These factors are influenced by the body part affected, the dynamics of the event, the force applied, and any movement by the victim.

To accurately reproduce and compare three-dimensional models of bitemarks and dental arches, three-dimensional scanning technology is required. Intraoral scanners are now commonly used in clinical dental practice, providing digital impressions that are accurate, stable, and can be analyzed using specialized software that is continually advancing.

This study aims to compare the results obtained from two different bitemark analysis techniques: the direct comparison of digital scans and the physical superimposition of impressions and resin casts produced by 3D printers.

MATERIALS AND METHODS

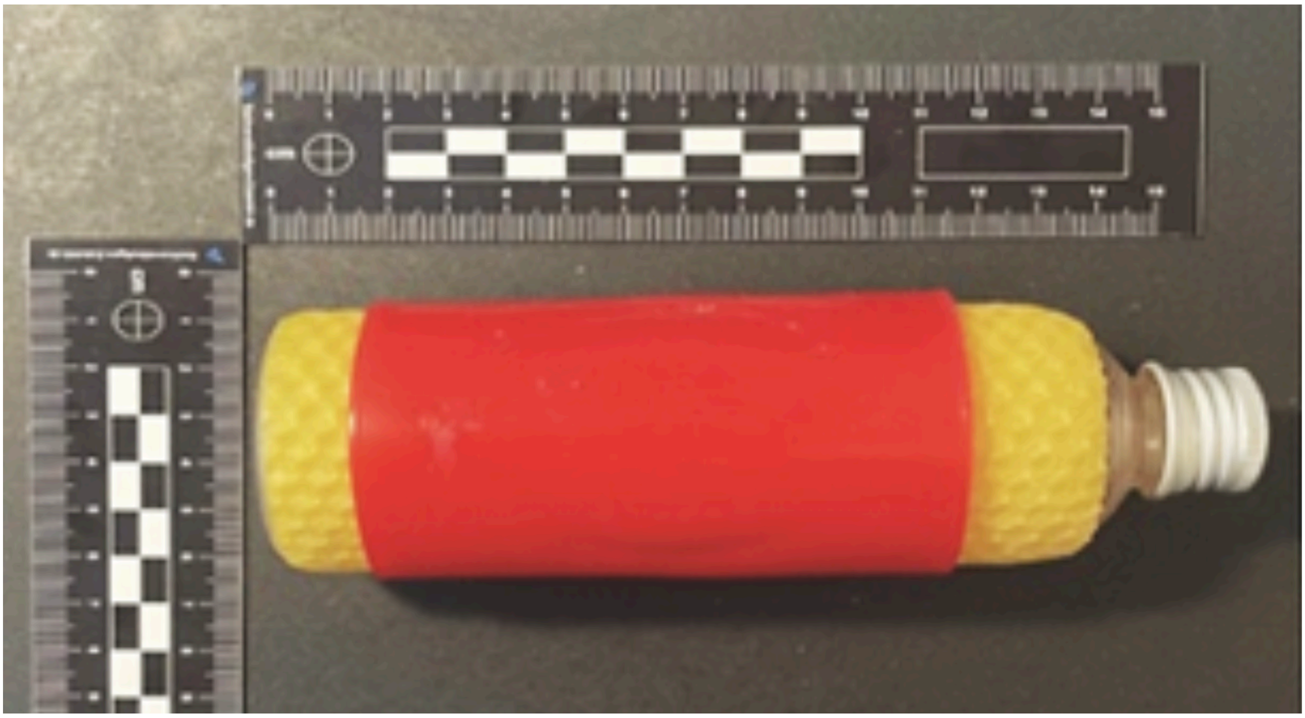
Sample collection - Biters

Volunteer subjects were recruited from among the students and assistants of the Master's Course in Dentistry at the University of Brescia, Italy. The inclusion criteria were male and female subjects without specific dental anomalies, such as dental malposition, restorative or prosthetic treatments, dental agenesis, severe tooth wear, or orthodontic brackets. Subjects who did not meet one or more of the inclusion criteria were excluded from the study.

Sample development – Test bite supports

Special supports were designed to closely replicate the shape, bone rigidity, and deformable surface of a female subject's wrist with a circumference between 14-18 cm. Semi-rigid plastic bottles with a diameter of 4.5 cm and a height of 15 cm were used, coated with beeswax and dental wax. To create the test bite supports, each plastic bottle was made semi-rigid by filling at least two-thirds of its volume with water to simulate bone support. The bottles were then coated with an initial layer of beeswax, which was manually modeled to adapt to the smooth surface of the support, mimicking the deformability of the deeper layers of the skin (dermis and hypodermis). An additional layer of dental wax was applied on the outer surface, simulating the deformability of the epidermis and allowing for the recording of bite marks (Fig. 1).

Figure 1. Support for bite tests: semi-rigid plastic bottle coated with two layers of wax to simulate the superficial deformability of the skin and record bite marks.



Impression materials and intraoral scanner
Bitemark impressions on the test bite supports were made using a light-consistency polyvinylsiloxane (PVS). Scans of the PVS impressions and the direct dental arches of the biters were conducted using the Carestream CS3600 intraoral scanner.

3D printing
Resin casts of the bitemark impressions were produced using the Anycubic Photon M3 benchtop printer, along with the Anycubic Wash & Cure Machine 2.0 benchtop washing and curing system.

Software for images processing and comparison
The CS ScanFlow software, installed on Carestream systems, was used to process the STL files generated by the CS3600 scanner. Meshmixer software was employed to eliminate scanning defects in the native STL files and to create virtual bases for 3D printing. The Anycubic Photon Workshop software, provided with the Anycubic printer, was used to generate the necessary supports for the 3D printer to recreate impressions in resin and to slice the STL files. CloudCompare, an open-source software, was used to process the acquired 3D images into point clouds (reference and alignment clouds: point-to-point analysis) for the purpose of superimposing bitemark impression scans onto the dental arches of the biters.

Study design
- Test bites and arches scans. Each subject bit one of the developed supports, applying a medium force sufficient to leave clear dental marks in the dental wax without deforming the bottle. Scans of the arches were then performed using an intraoral scanner and saved as STL files.
- Impressions of test bites and impressions scans. Test bite impressions were made using a double-layer technique with light-consistency polyvinylsiloxane (PVS) to ensure the durability and stability of the bite impressions. These

impressions were then scanned with the intraoral scanner and saved as STL files.

- Scans superimposition analysis. Using CloudCompare software, each scan was digitally transformed into a cloud of points (reference clouds for arch scans and alignment clouds for bitemark scans) to superimpose corresponding reference areas for each pair of arch-bite scans. Following the method proposed by Fournier et al. [25], at least three landmarks must be selected for alignment calculations in CloudCompare and must be identifiable on each arch and corresponding bite. The more landmarks identified, the lower the likelihood of computational errors.
- 3D printing resin casts. The STL files were processed using Meshmixer software to eliminate scanning defects, prepared for slicing, and then printed with the Anycubic Photon M printer using photopolymerizable resin that is washable in water. The processing time was approximately 90-110 minutes per cast, with the impressions of the arches printed in light blue and the bitemark impressions printed in grey to distinguish between them.
- Resin casts overlap analysis. An operator, who was not involved in the sample collection or execution of the bite tests, performed the physical matching of the resin casts of the maxillary and mandibular arches with the corresponding bitemark impressions. This operator was blind to the prior acquisition of casts and the CloudCompare results. Each matched arch-bite pair was then analyzed by a second operator, who visually identified landmarks with no or minimal overlap, marked them in red, and photographed them to allow for direct comparison with the overlays generated by the software (Fig. 3).

RESULTS

A sample of 12 volunteers, consisting of 6 males and 6 females with a mean age of 26 years, was collected as biters.

The reference areas were based on the positions of 10 landmarks (Fig. 2), chosen for their anatomical consistency and ease of identification in replicable positions on antagonistic teeth, as indicated in Table 1.

Figure 3 presents an example of superimposition analysis performed using both digital and manual techniques.

Figure 2. Panel A: a scan of a maxilla with the landmarks positioned from R0 to R9; Panel B: a mandibular scan with respectively landmarks from R0 to R9.

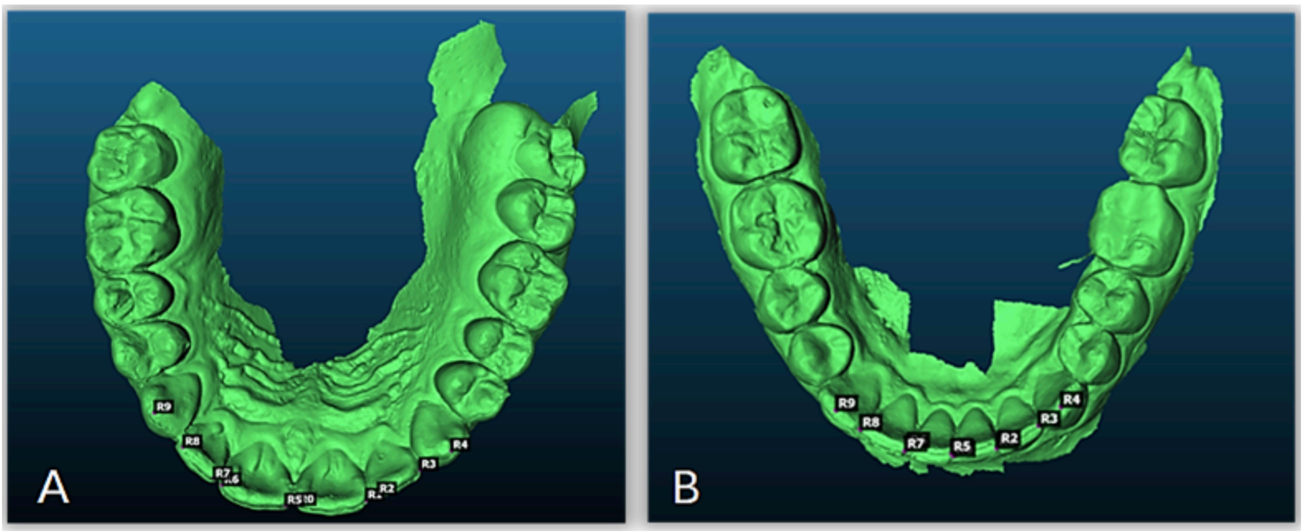


Table 1. Selected reference areas for superimposition based on the position of 10 landmarks from R0 up to R9.

Landmarks	Anatomical areas on antagonists teeth *
R0	Mesial angle of incisal edge of dental elements 1.1 and 3.1
R1	Distal angle of incisal edge of dental elements 1.1 and 3.1

R2	Mesial angle of incisal edge of dental elements 1.2 and 3.2
R3	Distal angle of incisal edge of dental elements 1.2 and 3.2
R4	Cusp tip of dental elements 1.3 and 3.3
R5	Mesial angle of incisal edge of dental elements 2.1 and 4.1
R6	Distal angle of incisal edge of dental elements 2.1 and 4.1
R7	Mesial angle of incisal edge of dental elements 2.2 and 4.2
R8	Distal angle of incisal edge of dental elements 2.2 and 4.2
R9	Cusp tip of dental elements 2.3 and 4.3

* According to the Fédération Dentaire Internationale (FDI) dental numbering system [26]

Figure 3. Example of superimposition analysis. Panel A: maxillary (upper image) and mandibular (lower image) scans overlapped on bite scans carried out with *CloudCompare*; Panel B: overlapping of the maxillary (upper image) and mandibular (lower image) resin casts on bite casts carried out manually. Non-overlapped landmarks are circled in red.

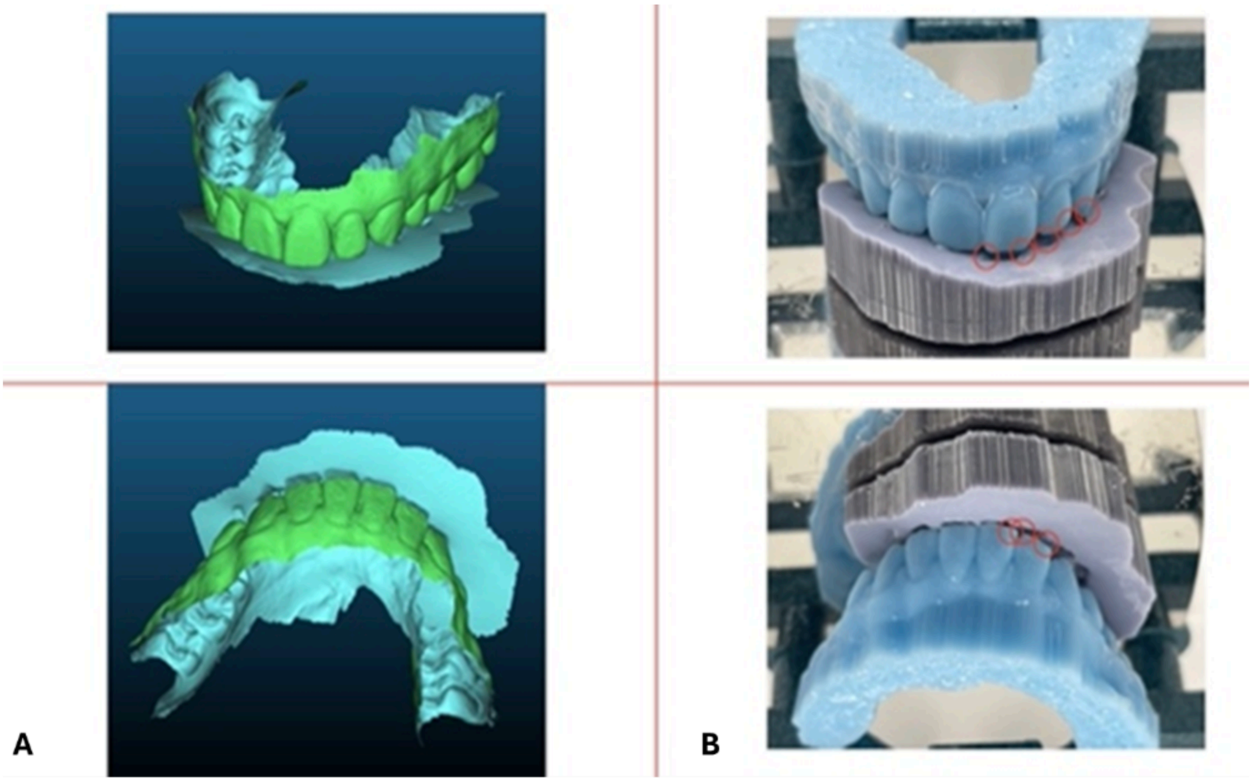


Table 2 shows the superimposition results according to the number of correctly overlapped landmarks for both the digital analysis using CloudCompare software and the visual analysis of the resin casts. The digital superimposition showed an average concordance of 92.5% for the upper arch landmarks and 85% for the lower arch, with an overall average of 88.8% when both arches were considered together. In contrast, the visual analysis of the resin casts showed an average concordance of 77.5% for the upper arch landmarks and 76.7% for the lower arch, with an overall average of 77.1% when both arches were considered together.

Table 3 reports the incidence of errors in landmark overlapping. In the analysis performed with CloudCompare, the maxillary arch demonstrated better superimposition, with 4 landmarks (R0, R1, R2, R5) overlapping in every case, whereas the mandibular arch had at least one instance of non-overlapping landmarks. Conversely, in the analysis of the resin casts, two landmarks (R6, R8) failed to overlap in 4 out of 12 cases for the maxillary arch, and there was at least one instance of non-overlap for each landmark. Additionally, R1 failed to overlap in 5 cases and R3 in 6 cases for the mandibular arch, showing the highest frequency of error.

Table 4 classifies the results by quadrants, showing the percentage of cases with non-concordant overlaps based on the distribution of landmarks between the left and right sides of both the maxillary and mandibular arches, comparing digital and visual analyses. The digital analysis outperformed the visual analysis in all four quadrants, and the upper arch showed better results compared to the lower arch.

Table 2. Number of concordant landmarks between maxillary/mandibular arches and digital scans or resin casts: comparison between digital and visual analysis.

ID case	Maxillary digital analysis	Mandibular digital analysis	Both arches digital analysis	Digital analysis concordance percentage	Maxillary visual analysis	Mandibular visual analysis	Both arches visual analysis	Visual analysis concordance percentage
1	10/10	9/10	19/20	95%	10/10	7/10	17/20	85%
2	9/10	10/10	19/20	95%	4/10	9/10	13/20	65%
3	10/10	3/10	13/20	65%	10/10	4/10	14/20	70%
4	10/10	10/10	20/20	100%	5/10	7/10	12/20	60%
5	9/10	9/10	19/20	95%	7/10	7/10	14/20	70%
6	9/10	9/10	18/20	90%	9/10	8/10	17/20	85%
7	10/10	10/10	20/20	100%	9/10	10/10	19/20	95%
8	10/10	10/10	20/20	100%	10/10	9/10	19/20	95%
9	10/10	9/10	19/20	95%	7/10	9/10	16/20	80%
10	7/10	4/10	11/20	55%	7/10	5/10	12/20	60%
11	9/10	9/10	18/20	90%	8/10	10/10	18/20	90%
12	8/10	10/10	18/20	90%	7/10	7/10	14/20	70%
Total	111/120	102/120	213/240	-	93/120	92/120	185/240	-
Tot %	92,5%	85%	88,8%	-	77,5%	76,7%	77,1%	-

Table 3. Incidence of errors in superimposition, according to the kind of landmarks, the maxillary/mandibular arch, and digital or visual analysis.

Landmarks	Maxillary digital analysis	Mandibular digital analysis	Maxillary visual analysis	Mandibular visual analysis
R0	0/12	2/12	1/12	3/12
R1	0/12	2/12	2/12	5/12
R2	0/12	2/12	1/12	2/12
R3	1/12	1/12	2/12	6/12
R4	2/12	1/12	3/12	1/12
R5	0/12	2/12	3/12	3/12
R6	2/12	2/12	4/12	3/12
R7	1/12	1/12	3/12	3/12
R8	2/12	1/12	4/12	2/12
R9	1/12	2/12	1/12	0/12

Table 4. Percentage of cases with non-concordant overlap according to landmarks distribution between left and right of both maxillary and mandibular arch, comparing digital and visual analyses.

Quadrant	Digital analysis	Visual analysis
I	5%	15%
II	10%	25%
III	13,3%	28,3%
IV	13,3%	18,3%

DISCUSSION

The increasing development of digital tools in clinical practice has also opened new possibilities in the forensic field, particularly in personal identification. [27-29] Numerous studies have demonstrated the usefulness of 2D and 3D radiography, intraoral scanners, and facial scanners for recording the morphological and morphometric characteristics of skeletal and dental structures, which are valuable for identification purposes. [30-37]

Bitemark analysis has long been a primary application in forensic odontology. However, the reliability of techniques for identifying dental patterns remains debated, and the validity of recording and comparing bitemarks is still controversial. [38] Biting is a dynamic phenomenon, and the physical "marks" left by dental elements on the skin are often unevenly distorted due to factors such as the victim's position, skin characteristics, dental arch features, and the strength and movements of both the biter and the victim. [39-40] Therefore, it is crucial to have reliable methods for recording and comparing bitemarks that can accurately reconstruct the three-dimensional structure of both the arches and the bitemarks, preserving critical information for pattern overlap analysis. [41]

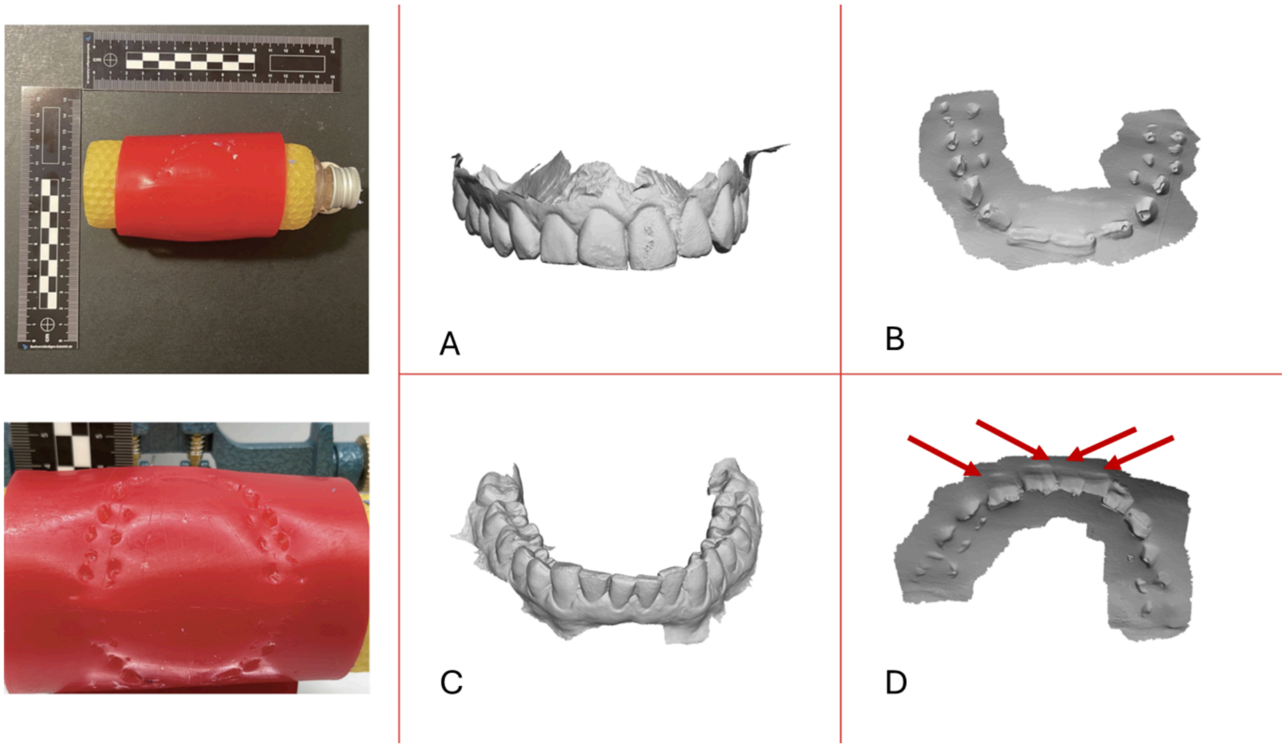
This study investigated and compared the results obtained from two different methods of recording and analyzing bitemarks: one entirely digital, based on intraoral scans of dental arches and bitemarks, and the other based on the physical comparison of resin casts and silicone impressions.

An ad hoc test model (bite tests) was developed to reproduce the three-dimensional patterns of dental arches on an elastic and compressible surface, simulating human skin. This model allowed for the evaluation of a larger scale of tests in vitro, even though it is challenging to obtain real samples of skin or cadaveric limbs for research purposes. It is also important to note that cadaveric skin or limbs do not fully represent the characteristics of living tissue, as they lack the typical signs of lesion vitality. [42-45]

To compare the two methods, we selected and applied the same 10 reference points (landmarks R0 to R9, Table 1) on the canines and central and lateral incisors of both the upper and lower arches. [46] A sample of male and female subjects without specific dental features (such as dental malposition, conservative or prosthetic treatments, dental agenesis, severe tooth wear, orthodontic brackets) was collected to verify the reproducibility of comparisons based on specific natural landmarks (dental morphology, position, and distances). Although the small number of tests does not satisfy a sample size suitable for statistical analysis, it was considered valid for observational purposes to identify discrepancies between the two methods and serve as a foundation for future, larger studies.

When considering all landmarks for both arches (Table 2), the digital analysis conducted using an intraoral scanner and CloudCompare software achieved a concordance between arches and bitemarks of approximately 90%, with better results for the upper arch (92.5%) compared to the lower arch (85%). For the maxillary arches, 6 out of 12 cases showed concordance across all selected landmarks, 4 cases had 9 out of 10 concordant points, and only 2 cases had fewer than 9 concordant points. In the mandibular arches, full concordance of all landmarks occurred in 5 out of 12 cases, while 5 other cases had 9 out of 10 concordant points. This discrepancy could be attributed to the different dynamics between upper and lower arches, even when impressed simultaneously. The teeth's impact during the bite test likely involved progressively increasing pressure and direction adjustment, especially for the mandibular arches (Figure 4), as the nervous system adjusted to the action and the characteristics of the support being bitten (e.g., size, consistency, flavor). The subsequent closure of the bite by the lower arch may have caused slight tooth movements in the wax, leading to inaccuracies in some reference points. [22, 47]

Figure 4. Case 3 (referring to Tab. 2). Panel A-B: maxillary arch and bitemark impressed; Panel C-D: mandibular arch and bitemark impressed with signs of anterior dragging of the incisor teeth (red arrows).



The visual analysis of the resin cast superimpositions showed a concordance of 77.5% for the upper arch reference points and 76.7% for the lower arch, with an overall average of 77.1%. Full concordance of landmarks was observed in 3 out of 12 cases for the maxillary arch and 2 out of 12 cases for the mandibular arch. In both the upper and lower arches, there was only one case with 4 out of 10 visually superimposable points, representing the minimum registered match (Table 2). Notably, case 3 and case 10 demonstrated the worst performance for the lower arch (4 and 5 concordant landmarks, respectively), with better concordance for the maxillary arch, suggesting mandibular distortion due to inferior dragging and a subsequent greater error in recognizing and superimposing the reference landmarks.

Additionally, case 3 and case 10 showed slightly worse performance in the visual analysis (70% and 60% concordance, respectively) compared to the digital analysis (65% and 55%). This suggests that cases with significant distortion, particularly in the mandibular arches, are better recorded by physical casts than by a 3D digital scanner (Table 2). Overall, the digital analysis proved to be more effective in overlapping landmarks, but its success seems to be closely tied to the quality of the scans, particularly in cases of distortion that cannot be modified or corrected using software. [37]

The landmarks most frequently involved in overlapping errors (Table 3) were identified as 3 points for the upper arch (R4, R6, R8 – canines and distal angles of the incisal edge on the left side) and 6 points for the lower arch (R0, R1, R2, R5, R6, R9 – mesial and distal angles of the incisal edge on both the left and right sides, and canines on the left side) in the digital analysis. Conversely, 4 landmarks (R0, R1, R2, R4) of the maxillary arch achieved full concordance in all samples, unlike any case involving the mandibular arch. In the visual analysis of resin casts, landmarks R6 and R8 of the maxillary arch showed the highest frequency of non-overlap, along with landmark R3 for the mandibular arch. No landmarks achieved full concordance for the upper arch, while only R9 (left canine) did so for the mandibular arch (Table 3). These results confirm that the lower arch is the weaker link in both methods, likely due to the smaller size of the teeth and the greater variability in force applied during the biting process, making it more challenging to distinguish very close landmarks, as selected in this study. [13, 24-25, 48]

As shown in Table 4, there is a greater discrepancy in the mandibular arches across all quadrants (II-III on the left and I-IV on the right) in the visual analysis compared to the digital analysis, with the highest number of errors occurring on the left side in both analyses. This could be explained by the fact that the sample predominantly consisted of right-handed individuals (90% versus 10% left-handed), leading to an asymmetric distribution of force between the left and right sides. A study focused on left-handed subjects would be necessary to better support this hypothesis.

The main limitation of this study is the small sample size, which precludes statistical inference from the results obtained. However, since few studies are available on the use of intraoral scanners for bitemark analysis, the preliminary results suggest that digital analysis improves the comparison between dental patterns and bitemarks on an elastic and deformable support compared to the direct superimposition of resin casts and dental impressions. Therefore, this study supports the limited literature that highlights the usefulness and reliability of digital techniques for bitemark analysis, but further research on larger samples, different supports, and various types of scanners is needed.

CONCLUSION

The superior performance of digital approaches in bitemark analysis for both maxillary and mandibular arches suggests that digital techniques should be increasingly adopted in forensic fields. However, the traditional method of directly comparing resin casts with dental impressions still demonstrates excellent reliability, particularly in cases with significant distortion, especially for the lower arch, due to the varying dynamics of the bite and the type of substrate.

Moreover, the digital technique simplifies the recording and comparison of dental patterns, making it more accessible for less experienced operators and reducing visual subjectivity in identifying landmark concordance.

Further studies are needed to validate the digital technique with larger sample sizes, diverse dental characteristics, varying bite dynamics, and different types of supports and substrates.

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