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A quantitative method for comparing human dentition with tooth marks using three-dimensional technology and geometric morphometric analysis

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Abstract

Objective. To develop a quantitative method to compare 3D overlays from dental casts with experimental bitemarks by using geometric morphometric analysis. ***Materials and methods.*** Thirteen upper and lower dental casts and corresponding simulated bitemarks were 3D-scanned to generate comparison overlays with DentalPrint software©. This study considered the inter-canine distance and four incisal angles. A matrix was created to compare all possible combinations of matches and non-matches between models and bites, i.e. 169 combinations (13 models × 13 bites), of which 13 were true matches. For each combination, the percentage difference was calculated between the variables in the model and the same variables in the bitemark. Logistic regression was used to obtain a predictive model (algorithm) for a match, calculating the discriminative values (area under the ROC curve, sensitivity and specificity) for each measure and for the logistic model. ***Results.*** Statistically significant discriminative power was found for all single (angle or distance) and combined (logistic model) variables, with lower 95% CI limits > 0.50 for areas under the ROC curves and sensitivity/specificity values > 50% in both maxilla and mandible. ***Conclusions.*** This quantitative method has sufficient discriminative power to be utilized in forensic cases.

Key Words: *Forensic dentistry, bitemarks, three-dimensional, geometric morphometric, logistic regression*

Introduction

Bitemark evidence has long been routinely admitted in many legal systems. However, there is a growing awareness among the legal profession of the lack of vigorous scientific evaluation methods to substantiate the opinions of forensic experts. The need for a quantitative approach has been highlighted in several well-publicized cases of false convictions due to erroneous forensic odontological evidence on human-to-human bitemarks [1]. In particular, DNA analyses have demonstrated the innocence of persons whose conviction had been largely or partially based on misinterpreted dermal bitemark analyses [2,3].

The discipline of bite-mark analysis was heavily criticized in the 2009 report of the National Academy of Sciences (NAS) [4]. It complained about the utilization of bite-marks as evidence in criminal trials with no meaningful scientific validation, determination of error rates or reliability testing to establish the limits of the discipline and it bemoaned the lack of fundamental scientific research in this respect [4,5]. The International Organization for Forensic Odonto-Stomatology (IOFOS) has also recommended that expert's conclusions were based on scientific probabilistic studies [6]. Research efforts to develop the science of bite-mark analysis have intensified over recent years [7] and the resulting changes have generally been adopted by practitioners [1]. Notably, it is increasingly recognized that approaches based on 3D technology are the most appropriate, given the three-dimensional nature of the injury [8–12]. 3D methodology has been found to improve the accuracy of human bitemark analysis and reduce subjective bias; however, it cannot solve all of the problems involved, such as those related to skin distortion, and there remains a need for further scientific research on this technique. It is clear from the appellate rulings on false convictions related to bitemark analysis that odontologists have differing views as to

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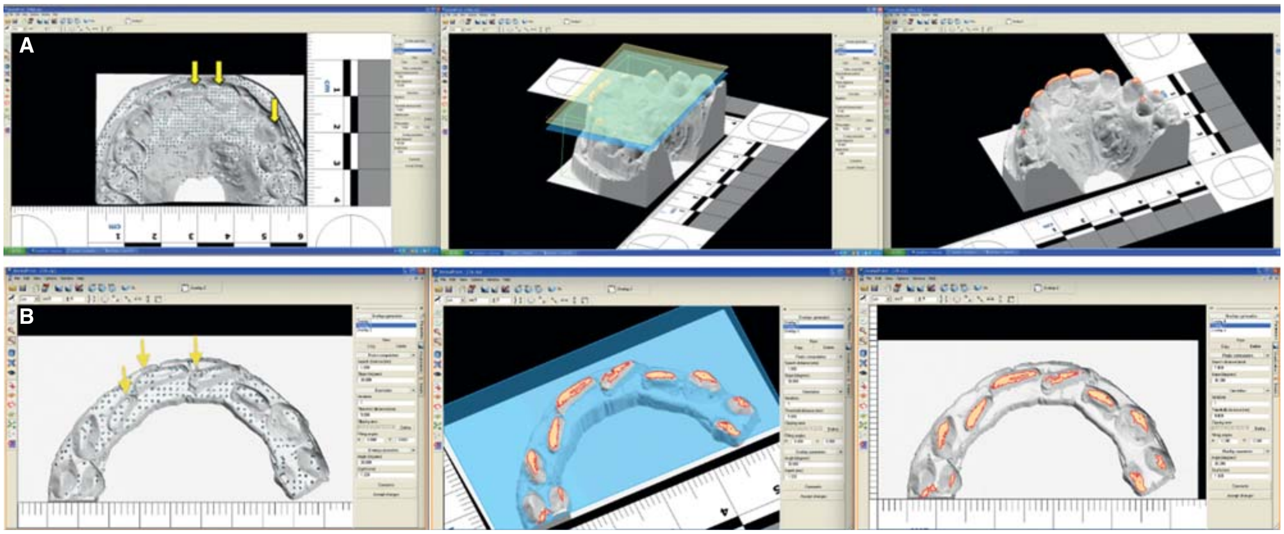

Figure 1. Example of 3D comparison overlay generation using DentalPrint© software: (A) from a 3-D image of upper dental cast and (B) from a 3-D image of bite impression. Highest points (blue dots) were detected from defined small areas of the 3D images. The three highest points (arrows) were used to define the contact plane that extends deep into the teeth to create the biting edge areas.

the certainty of conclusions based on bitemark evidence [13]. In order to resolve this issue, there is a need for methods that provide quantitative comparative data between 3D images of dental casts and bite injuries.

Geometric morphometric (GM) analysis, which is used to describe and compare biological shapes, has been applied to bitemarks [14,15]. Shapes are quantitatively analysed by capturing the geometry of morphological structures of interest. Advances in 3D bitemark digital imaging have facilitated the plotting of GM 'landmark positions' for 3D visualization, allowing the precise calculation of inter-canine widths, mesial-distal lengths, rotations and variations in tooth height, among other variables.

The purpose of this study was to develop a quantitative method for comparing dental casts with experimental bitemarks using 3D overlays and GM analysis.

Materials and methods

Study models and simulated bitemarks

Thirteen dental casts (upper and lower) were obtained from patients (seven females and six males) of the School of Dentistry at the University of Granada, Spain: three children (aged 6–9 years) and 10 adults (17–63 years).

Simulated bitemarks were creating by applying vaseline to each dental cast with a brush before placing it on a tray filled with red dental wax (ColtèneWhaledent, New York, NY) and using light hand pressure to create indentations 1–2 mm in depth. Impressions of the indentations were taken with a polyvinyl siloxane-based addition-curing material (Futar D Fast, Kettenbach, Eschemburg, Germany) that sets rapidly (45 s) and remains stable and hard (shore-D 43) [16,17].

3D-comparison overlay generation

Dental casts and simulated bitemark impressions were scanned with a 3D contact-type scan (Roland, Picza 3D, Pix-3, Roland DG Corp, Japan). The 3D images obtained were processed with DentalPrint software© [9] to generate comparison overlays. Comparison overlays of 3D images of dental casts and bite impressions were produced in three steps, as previously described [9], selecting six upper and six lower anterior tooth positions for analysis. A contact plane was created from the three highest points on the 3D images of the dental casts and bite impressions. Finally, biting edges were obtained by using DentalPrint©, which allows the contact plane to extend deep into the teeth. This is a reliable and accurate method for generating comparison overlays [11] and the procedures are depicted in Figure 1. Further information can be obtained at http://www.ugr.es/local/stella/dentalprint, from which a demo version of the software can be downloaded free of charge.

Comparison method

The comparison overlays generated from the 3D images of the dental casts and the bitemark impressions were analysed with Dig v. 2.10 morphometric software (Stony Brook, 2006) [18]. Comparison overlay images included an ABFO n°2 scale as internal reference. The shapes of all specimens were quantified by using the landmark method [19–23]. Landmarks were positioned at the mesial and distal endpoints of the incisal edges of the four incisor overlays

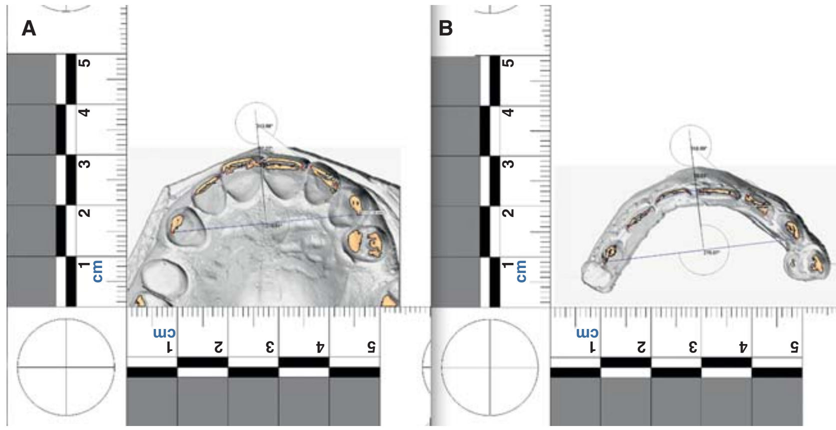

Figure 2. Example of the morphometric analysis (tps Dig v.2.10 software) to measure the rotation of the four incisors and the inter-canine distance of the biting edges previously obtained using DentalPrint© software: (A) from 3-D image of upper dental cast; and (B) from 3-D image of bite impression.

and at the distal point of each canine overlay. This resulted in a set of 10 landmarks recorded as cartesian co-ordinate pairs. The inter-canine distance (ICD) was determined by measuring the distance between the landmarks on each canine.

The ICD line was also used to create a perpendicular middle line (ML) between the central incisors. The incisal angle was determined by crossing the ML with the lines that resulted from joining the landmarks on every incisor, yielding a measurable angle that represents the rotation of each tooth (Figure 2). Hence, five measurement variables, i.e. four incisal angles and the ICD, were considered in the comparison. Most of the procedure was developed by 3D technology, given that the dental casts were 3D-scanned and the biting edges, in which angles and distances were measured, were 3D-generated.

Statistical analysis

SPSS-Windows 15.0 (SPSS Inc., Chicago, IL) was used for the statistical analysis. All tests were independently performed for the maxilla and mandible. Following the procedure published by Blackwell et al. [10], a matrix was created to compare all possible combinations of matches and non-matches of models and bites using the measurement variables (incisal angles and ICD). For each combination, the percentage difference between the variables in the model and the same variables in the bite were calculated as $[(x1 - x2)/x2] \times 100$, where $x1$ is the highest measurement for the variable in each match (in either bitemark or cast) and $x2$ is the lowest. The percentage differences describe the proximity between model and bite in a quantitative manner. The matrix consisted of 169 combinations (13 models × 13 bites), 13 of which were true matches.

Logistic regression was used to obtain a predictive model (algorithm) for a match, forcing the $\log_{10}$ of all measures as predictors. Cross-validation was performed, removing each bite in turn from the data set, fitting a logistic regression model to the remaining data and then using this model to make predictions for the 13 combinations in the omitted data; this process was repeated for each model. Hence, the data used to make predictions were separate from the data used to estimate the performance of the algorithm in all cases, thereby yielding unbiased estimates of discriminative values. These values (area under the receiver operating characteristic [ROC] curve, sensitivity and specificity) were calculated for each measure and for the logistic model. Bootstrapping (1000 iterations) was performed to estimate standard errors and 95%-confidence intervals, defined as mean ± 1.96 × standard error. The reason for using bootstrapping for standard errors calculation, instead of more simple statistical techniques, is due to a lack of appropriate statistical formulae; the created database contains replication of data, i.e. observations are not statistically independent.

Results

Table I lists the measurements of the incisal angles and ICDs in the dental casts and bitemark impressions. Mean percentage matching values (between bitemark and cast) for each of these measurements are reported in Table II. Statistically significant discriminative power was found for each single measurement (angle or ICD) or for the combined measurement (logistic model) in either the maxilla or mandible, given that the lower 95%CI limit of the area under the ROC curve was > 0.50 or the sensitivity/specificity value was > 50% (Table II).

Discussion

The individuality of anterior teeth has been supported by geometric morphometric analyses in 2D [23] and 3D dental cast images, obtaining better results with

Table I. Data for each subject[a] (n = 13) by arch.

	Experimental bitemark							Dental cast		
Subject n°	Angle (°)	Angle (°)	Angle (°)	Angle (°)	ICD[b] (mm)	Angle (°)	Angle (°)	Angle (°)	Angle (°)	ICD[b] (mm)
Max. (tooth)	(11)	(12)	(21)	(22)		(11)	(12)	(21)	(22)	
1	78.2	58.0	103.1	41.1	38.5	79.5	57.3	78.5	46.3	37.4
2	95.4	54.3	84.2	65.2	31.6	96.7	53.5	86.6	66.6	31.0
3	69.3	64.7	67.7	44.4	34.0	65.3	67.1	68.0	53.6	33.6
4	79.2	73.6	87.7	—	39.3	79.0	63.4	84.5	52.6	39.0
5	87.4	37.8	83.5	88.0	38.0	86.3	29.9	89.6	93.8	38.4
6	72.9	35.3	108.7	51.9	34.9	76.6	35.9	99.9	55.9	35.1
7	46.7	—	34.2	—	26.3	46.3	—	33.9	—	26.4
8	72.4	38.4	48.9	36.4	29.3	75.9	39.0	50.7	37.4	29.0
9	83.1	43.3	94.9	53.6	36.5	79.4	40.5	93.4	51.0	37.7
10	99.9	56.1	82.0	66.6	31.4	75.3	49.0	93.4	61.9	34.1
11	73.3	51.4	82.3	37.4	29.9	74.5	50.5	83.9	40.8	30.3
12	92.0	53.9	92.5	76.2	35.8	90.8	53.3	93.7	74.6	36.1
13	65.1	31.1	—	37.8	30.8	64.3	34.6	—	36.0	30.9
Mean	78.1	49.8	80.8	54.4	33.6	76.1	47.8	79.7	55.9	33.8
SD	14.1	12.8	21.4	17.4	4.0	12.7	11.8	19.6	16.6	4.0
Mand. (tooth)	(31)	(32)	(41)	(42)		(31)	(32)	(41)	(42)	
1	98.2	109.7	77.9	106.7	27.0	98.3	103.4	77.9	103.7	27.5
2	84.6	108.6	99.0	92.7	30.9	90.1	112.4	83.6	75.3	24.0
3	100.6	124.4	105.6	122.7	26.5	98.3	123.5	104.7	128.2	26.5
4	86.6	118.1	125.2	126.7	28.8	84.3	119.8	86.2	122.7	28.7
5	94.9	117.2	105.6	154.0	29.9	83.1	109.4	101.1	119.0	23.6
6	119.2	139.7	101.8	137.3	25.8	120.2	136.9	100.3	137.4	26.5
7	—	—	—	87.4	22.9	91.8	—	103.3	84.1	23.3
8	119.5	119.5	60.9	142.3	26.0	107.5	—	70.9	69.9	20.1
9	105.5	114.6	76.4	113.1	29.4	98.8	110.4	80.8	112.2	29.1
10	78.1	118.6	97.6	—	26.5	76.7	115.4	95.1	115.6	26.4
11	—	114.3	76.2	126.3	23.5	—	113.6	68.7	122.9	23.0
12	100.1	97.1	102.4	94.2	30.3	101.9	94.6	96.3	87.7	30.7
13	100.8	—	81.7	92.8	24.3	100.8	—	83.3	97.7	24.4
Mean	98.9	116.5	92.5	116.3	27.1	96.0	113.9	88.6	105.9	25.7
SD	13.0	10.5	17.9	22.0	2.6	11.8	11.4	12.3	21.4	2.9

[a]7 females and 6 males aged between 6–70 years. Mean ± standard deviation (SD) = 31.1 ± 21.7.
[b]Inter-canine distance.

the latter [24]. However, bitemark analysis needs the scientific support of parameters that allow discrimination between dental cast, specifically anterior teeth and dental marks transferred to a bitten substrate. In this study, we considered parameters that identify the arrangement of teeth in the arch and their relative alignment in dental casts and bite injuries, using these quantitative data to calculate probabilistic conclusions on identification.

The discrepancy between the measurement variables (incisal angles and ICD) was much smaller when they matched than when they didn't match. In matchings, the most accurate variable was the maxillary ICD (1.8 ± 2.2%), followed by the angle of 32 (3.1 ± 2.2%). It should be borne in mind that more data were available for the ICDs than for incisal angles, because incisors were more frequently missing than canines in the study sample. The least favourable result was for the angle of the teeth 42, in which the discrepancy in matching reached 15.6 ± 29.2%, indicating that results from this tooth alone are not sufficient for identification purposes.

The discrepancy between matching and non-matching incisal angle values was smaller in the mandible than in the maxilla, indicating a lesser individuality of incisor rotation in the former. With respect to the ICDs, the difference between matching and non-matching was 15-fold in the maxilla and 2-fold in the mandible. In contrast, other authors have noted a greater discrepancy in mandibular vs maxillary dentitions, which they attributed to a higher incidence of crowding in the lower arch [25], although their findings cannot be extrapolated to bite injuries.

The critical question for bitemark analysis methods is whether they offer sufficient accuracy for identification purposes. The area under the ROC curve was > 0.8 for all variables and was slightly higher for the maxilla. A diagnostic test is considered 'highly accurate' when this area is 0.9, 'useful for some purposes' when it is 0.7–0.9 and 'poor' when

Table II. Percentage discrepancy (percentage)[a] in matches[b] between bitemarks and dental casts by arch with discriminative values.

		Matching		Non-matching	Discriminative values						
					Area under the ROC curve			Sensitivity		Specificity	
Measurement	n^b	% discrepancy (M ± SD)	n	% discrepancy (M ± SD)	M ± SE	95% CI	Youden point[d]	M ± SE	95% CI	M ± SE	95% CI
Maxillary											
Angle 11	13	4.8 ± 8.6	156	25.1 ± 24.2	0.9 ± 0.1	0.8–1.0	≤ 6.1	92 ± 7	78–100	82 ± 3	76–88
Angle 12	12	7.4 ± 8.1	132	38.8 ± 30.2	0.9 ± 0.1	0.8–1.0	≤ 16.0	92 ± 8	76–100	71 ± 4	63–78
Angle 21	12	6.5 ± 8.8	132	46.6 ± 54.8	0.8 ± 0.1	0.7–0.9	≤ 8.8	83 ± 11	62–100	76 ± 4	68–83
Angle 22	11	7.4 ± 5.4	121	45.7 ± 36.2	0.9 ± 0.1	0.8–0.9	≤ 12.7	91 ± 8	75–100	84 ± 3	77–90
Inter-canine distance	13	1.8 ± 2.2	156	15.8 ± 11.5	0.9 ± 0.1	0.9–1.0	≤ 3.1	92 ± 8	78–100	88 ± 3	83–93
Unbiased Logistic[c]	13	0.72 ± 0.35	156	0.02 ± 0.11	0.9 ± 0.1	0.8–1.0	> 0.11	92 ± 7	78–100	96 ± 2	93–99
Mandible											
Angle 31	11	4.4 ± 4.7	121	16.5 ± 12.8	0.8 ± 0.1	0.7–0.9	≤ 6.8	82 ± 11	60–100	73 ± 4	65–80
Angle 32	10	3.1 ± 2.2	100	11.8 ± 9.6	0.8 ± 0.1	0.7–0.9	≤ 3.8	80 ± 13	55–100	80 ± 4	72–88
Angle 41	12	9.5 ± 12.8	144	23.4 ± 18.3	0.8 ± 0.1	0.6–0.9	≤ 18.5	92 ± 8	76–100	57 ± 4	49–65
Angle 42	12	15.6 ± 29.2	144	29.6 ± 23.6	0.8 ± 0.1	0.6–1.0	≤ 7.4	75 ± 13	50–100	86 ± 3	80–92
Inter-canine distance	13	7.4 ± 11.9	156	14.3 ± 10.9	0.8 ± 0.1	0.6–0.9	≤ 2.7	77 ± 12	53–100	87 ± 3	81–92
Unbiased Logistic	13	0.51 ± 0.37	156	0.04 ± 0.10	0.9 ± 0.1	0.7–1.0	> 0.25	77 ± 12	54–100	97 ± 1	95–100

[a]Calculated as $[(x1 - x2)/x2] \times 100$, where $x1$ is the largest measurement in the bitemark-cast pair and $x2$ is the smallest.
[b]There are 13 subjects; therefore, the maximum number of combinations is 169 (13 × 13), i.e. 13 positive and 153 negative matches. Lower 'n' values are due to cases missing a mark.
[c]Logistic model (see Methods).
[d]Percentage discrepancy cut-off point that maximizes the sum of sensitivity and specificity.
SD, standard deviation; SE, standard error calculated with bootstrapping (see Methods).

0.5–0.7 [26]. All measurements and predictive models, with the exception of the angles of the teeth 41 and 42 and the mandibular ICD, can be considered useful to detect the dentition that produced the bitemark, with a lower 95% CI limit of > 0.7. Applying the same strict statistical interpretation, the maxillary ICD proved highly accurate for the identification procedure, showing an area under the ROC curve of 0.9 ± 0.1 with a lower 95% CI limit of 0.9.

Sensitivity values were > 90% for the angles of the teeth 11, 12, 22 and 41, the maxillary ICD and the maxillary predictive model; i.e. the likelihood of detecting dentitions that produce the tooth mark was very high. Less favourable sensitivity values were obtained for the angle of the teeth 42, the mandibular ICD and the mandibular predictive model. The highest specificity values (> 95%) were obtained for the predictive models, indicating that it may be possible to rule out dentitions that did not produce the bitemark with a high degree of certainty. The best discriminative value was achieved with the maxillary predictive model, which obtained the highest sensitivity (92 ± 7%) and specificity (96 ± 2%) values and an area under the ROC curve of 0.9 ± 0.1 (95% CI = 0.8–1.0), which was second only to the area for the maxillary ICD. The use of the Youden Index (i.e. that maximizing the sum sensitivity + specificity) makes false positive and false negative equally important in the Court decision. This is a standard analysis that could be better focused for each law environment, changing the better cut-off point (for example, maximizing false positives).

Only one previous study used 3D technology for the quantitative comparison of human dentitions with simulated bitemarks, reporting sensitivity and specificity values of 78% and 85%, respectively [10]. Another recent study of experimental bitemarks was designed to quantify the probability of a given match but used 2D images of a 3D model and the authors acknowledged that a more realistic set of bitemarks was required [27]. Both studies called for further investigation in this line.

The present method proved valid and accurate for bite-mark analysis, but account should be taken of some limitations. Most importantly, it requires the presence of indentations in the injury, which have a very high forensic significance, but these are frequently absent by the time that the analysis is conducted [28]. Furthermore, the results were obtained by using artificial bite-marks and dental wax cannot faithfully reproduce the viscoelastic properties of human skin, the anatomical location of the bite injury or the movement of the skin during the bite. Nevertheless, all 'gold standards' for evaluating bitemark diagnostic tests have limitations and even real forensic cases cannot be considered 100% reliable [29]. It should also be borne in mind that we can only report a tendency for the logistic model to be superior to the individual measurements and for the maxilla to offer better results than the mandible, due to overlap of the 95% CI of the areas under the ROC curves and overlap of the specificity and sensitivity values for these variables. Studies with larger sample sizes are required to verify these differences.

Conclusion

This quantitative method of comparing dental casts and experimental bitemarks by means of 3D and morphometric technologies demonstrated adequate discriminative power to be used in forensic cases. Further research is required to establish a solid foundation for decision-making. In all judicial cases, experts must explain the technology and its limitations and report statistical analysis results to allow probabilistic conclusions to be drawn.

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