11-1-2009

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Published Version. Journal of Forensic Identification, Vol. 59, No. 6 (2009):609-625. Publisher Link.

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Technical Note

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Abstract: The considerations for admissibility suggested by the Daubert trilogy challenge forensic experts to provide scientific support for opinion testimony. The defense bar has questioned the reliability of bitemark analysis. Under an award from the U. S. Department of Justice, via the Midwest Forensic Resource Center, a two-year feasibility study was undertaken to quantify six dental characteristics. Using two computer programs, the exemplars of 419 volunteers were digitally scanned, characteristics were measured, and frequency was calculated. The study demonstrates that there were outliers or rare dental characteristics in measurements. An analysis of the intra-observer and inter-observer consistency demonstrated a high degree of agreement. Expansion of the sample size through collaboration with other academic researchers will be necessary to be able to quantify the occurrence of these characteristics in the general population. The automated software application, Tom's Toolbox, developed specifically for this research project, could also provide a template for precisely quantifying other pattern evidence.

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Received January 30, 2009; accepted April 7, 2009

Introduction

Very few studies have been published on the quantification of dental characteristics. A literature search reveals several early studies. MacFarlane authored an early study that is frequently cited [1], followed by Rawson et al. [2] Other studies have been recently accomplished on arch width [3], individual discrimination [4], the analysis of skin bitemarks [5], and angles of rotation [6]. The use of a shape analysis computer program to do a quantitative analysis of bitemarks was published [7]. Although it is at times possible to visually demonstrate to the court a corresponding agreement in the relative size, shape, position, spacing, and accidental features of a suspect's dentition when compared with the pattern in a distinctly registered bitemark, the odontologist's opinion testimony lacks scientific support. Currently, forensic odontologists, in the analysis of bitemark evidence, are not able to quantitatively state the frequency with which a given set of dental characteristics occurs in the population. That is, what is the probability that another individual would have the same characteristic pattern? Without the ability to quantify the frequency, there is a lack of scientific basis for an expression of probability in the conclusions of the examiner regarding concordance between patterned injuries and the characteristics of the teeth of a suspect. The expert's opinion is limited to exclusion, indeterminate, consistent with, or a general opinion of probability to a reasonable degree of certainty [8].

The forensic examiners of all pattern evidence are being challenged to provide a scientific basis for testimony supporting an opinion of the agreement between the known and unknown. Questions arise in the analysis of all patterns as to the probability that any two patterns would have the same characteristics. The Daubert considerations suggest that admissibility of scientific testimony should be based on methods that have been or can be tested for validity, have been peer reviewed, have known or potential error rates, have accepted standards with controls, and are works that have been accepted by the scientific community. These considerations were developed to assist the court in determining whether scientific or technical testimony should be admissible under Section 702 of the Federal Rules of Evidence [9], but have been a source of confusion. The Daubert suggestions are frequently misunderstood to be mandates and have been unevenly applied by the courts. Because all, some, or none of the Daubert suggestions could be required by the trial court, the expert could be uncertain as to whether he would be able to testify. Numerous studies exist that compare bitemarks to individuality and attempt to quantify them visually. Very few studies attempt to quantify individual dental characteristics as they appear in a given population by direct measurement. The process started with the works of MacFarlane [1], Rawson [2], Barsley [3], and Bernitz [4-6] and constitutes the beginnings of the answers to the suggestions by the U.S. Supreme Court Daubert trilogy. A study on the frequency distribution of commonly observed characteristics in the human dentition has to begin with an empirical study upon which to build. This study is somewhat analogous to those studies used to quantify certain angular skeletal relationships to a norm established by orthodontic literature. A comparison of the findings from a patient's cephalometric tracing with these normal values provides the orthodontist with a diagnosis of the patient's skeletal pattern [9].

The objectives of this paper are to show that dental characteristics can be quantified and such measurements are reproducible. We feel that we have been able to demonstrate that dental characteristics can be quantified, the measurements are reproducible, and that independent observers using standardized methodology can substantially agree.

Methods

To assure that the management of digital images conformed to the guidelines of the Scientific Working Group on Imaging Technology (SWGIT) [10], the Wisconsin Department of Justice assigned two forensic imaging scientists.

Following the development of the concept and study design, but before beginning the research project, a complete protocol was submitted and approved by the University's Institutional Review Board (IRB). Because the study involved human subjects, it was necessary to assure the IRB that the study followed procedures in accordance with ethical standards for each individual's health, welfare, and privacy. An informed consent form was developed and approved. The researchers were trained and certified for human subject research. All imprints of the teeth and brief dental histories had to be anonymous and recorded only by an alphanumeric sample designation.

Sample size is dependent upon the purpose of the study and there are several ways by which it can be determined [11]. For the purpose of this limited study, a convenience sample was used. It does not necessarily represent all of the males in the age range in the state of Wisconsin. This feasibility study bases "n" on the latest population data for Wisconsin [24]. In 2000, census figures indicated a total population for Wisconsin of 5,363,675. Males represented 49.4% of the total. Included in this study were those males between the ages of 18 and 44 years. There were 1,038,665 individuals in that category. Each characteristic that was quantified in this study was done so separately to limit "n" to a workable size to evaluate any deficiencies in the design of the project. In this instance, "n" was calculated using nQuery Advisor (Statistical Solutions, Saugus, MA), a sample size and power analysis calculator. The "n" was corroborated by applying sample size tables for a reliability or confidence level of ±5% for a population where "n" is larger than 100,000. For this study, "n" was calculated to be a minimum of 400 exemplars for each arch for a precision of ±5%. This number provided for a 95% confidence level. Final calculations were accomplished using SAS Statistical Analysis Software (SAS Institute, NC). The volunteer samples were derived from male Marquette University dental school clinic patients and volunteers from two Wisconsin Air National Guard Wings in Milwaukee and Madison, Wisconsin, representing a population composed of White, Black, Asian, and Hispanic males, age eighteen to forty-four. The sample closely mimicked U.S. Census Bureau ethnic background statistics for Wisconsin (Table 1).

A suitable material for registering the imprints of the teeth was necessary. There are several accurate dental materials available for the registration of the exemplars bearing the American Dental Association (ADA) Seal of Acceptance. The considerations for the selection for this project were accuracy of the material, simplicity of the technique, a product and technique already familiar to the research group, the ability to judge the depth of penetration, a material having superior contrast for scanning, minimal inconvenience and time for the volunteers, minimal preparation time, clean to use, and a manageable cost per unit because of the volume of material necessary to complete the study. The registration material selected was CoprWax Bite Wafers (Heraeus Kulzer, Inc., NY). It is an ADA-accepted dental product for bite registration. The method of obtaining exemplars, scanning techniques, and data management has been previously reported [13].

Six dental characteristics were measured using the measure tool in Adobe Photoshop: (1) arch width, (2) tooth width, (3) labio or linguo-version position in the arch, (4) degree of rotation of individual teeth, (5) spacing between teeth (diastema), and (6) pattern of missing teeth. Each characteristic was evaluated in relation to its frequency in the group being studied. A pairwise Pearson's correlation was selected to determine the interdependence of the position of the teeth.

After the ten points were identified, the computer software (Tom's Toolbox) performed two quality checks. The first check identified whether any one of the ten points was missing. In both the upper and lower jaw samples, the mesial and distal widths of the four incisor teeth were recorded. Tom's Toolbox reports a quality error as a missing point if one point is identified and the other is not identified. The second quality check evaluated the pixel columns for points 1 through 10 to validate proper sequencing.

The distribution of the arch widths and other measurement followed, as would be expected, with 95% falling within a normal curve fitted over a histogram. The data compared favorably with that of an earlier study [3].

Since tooth position does not occur independently, pairwise Pearson product-moment correlations were computed to describe associations between teeth. The estimated correlation and p-value for the null hypothesis of "no association" is reported in Figure 1 and Figure 2. The pattern of correlation is stronger and more consistent in the mandibular arch.

In a similar manner to Bernitz et al. [5], tooth rotations, tooth widths, and arch widths were characterized as common, uncommon, or very uncommon in the 1st, 5th, 95th, and 99th percentiles. Results of values found in arch and tooth widths are reported in Table 2. The distributions of widths for the maxillary and mandibular arches are reported in Figure 3 and Figure 4.

An alpha level of 0.05 was used throughout to denote statistical significance. All statistical analyses were performed using SAS v 9.1.3. Angles of rotation, especially negative rotation (the mesial surface turned inward), were found to be the most significant, as reported in Table 3.

The lateral incisor was found to be the most frequently missing tooth. This is consistent with the lateral incisor being the most frequently congenitally missing tooth. The pattern of missing teeth in the study is shown in Table 4.

Allowance for the difference in hand–eye coordination of each observer in placing the pixels (a tolerance of 1 mm for mandibular measurements, 0.5 mm for incisor width, and 5°) was established for the level of consistency or agreement between observers. The level of agreement between the observers is illustrated in Table 5.

Inter-observer consistency in determining measurements that were considered to be outliers was also calculated. Measurements were considered to be an outlier if they fell below the 5th percentile or above the 95th percentile of the observed sample distribution. The characteristics that were used were arch width; tooth width; and rotation for # 23, # 24, # 25, and # 26 incisors. Table 6 illustrates the consistency between the observers in determining outliers.

To measure intra-observer replication of pixel placement, differences of 1 mm for arch measurements, 0.5 mm for incisor width, and 5° for the angles of rotation were used for establishing the level of consistency or agreement. The intra-observer level of agreement is illustrated in Table 7.

Measurements were also taken to determine the presence and size of diastemas (spaces). Findings are shown in Table 8.

Discussion

There has been considerable discussion concerning the reliability of the analysis of bitemark patterns, particularly in human skin [15, 16]. In fact, there are those who believe that individualization cannot be proven [17]. This study was designed to establish quantitative criteria for a number of dental characteristics frequently used in court. The approach in this study was to establish whether dental characteristics can be quantified. The application of the quantification data and the use of the automated software applications are the subjects of additional research. The statistics generated in this study comprise only a data set for males age 18 through 44 in Wisconsin, limited by convenience of sampling. The statistics developed comprise only a data set, applicable only to the particular convenience sample studied. It should not be assumed to represent a basis for supporting opinion on characteristics analyzed for the general population. This feasibility study demonstrates that the six characteristics selected could be quantified. Most valuable are not only the measurements of the characteristics that fall outside of two standard deviations from the mean and norm, but the overall combination of these individual characteristics found in the questioned pattern. An examination of the data for all 419 exemplars demonstrated that no two were exactly the same. These are the characteristics that could statistically support opinion testimony on the probability of any two patterns being the same.

Considerable literature has been published in connection with the reliability of human bites on skin and the misuse of patterned evidence in the criminal justice system. There have been several unfortunate cases that have resulted in mistaken identification and conviction. It is the opinion of the authors that all pattern evidence, including human bitemarks, can have forensic value in the investigation of crime if significant detail is present. In the opinion of the authors, the principal cause of the misidentifications or diametrically opposing testimony among experts is the attempt to analyze indistinct patterns. In any medical or dental procedure, case selection is paramount. One should not attempt to draw conclusions from indistiguishable bruises. Most human bitemarks, in our estimation, probably meet this “smoke ring” description. There are, however, human bitemarks that do reflect distinctly registered tooth characteristics. Unfortunately, in the experience of the authors, the most clearly registered patterns have been observed in homicides and were probably inflicted in a perimortem period. Because blood pressure is extremely low or nonexistent in the agonal phase of death, the inflammatory response does not occur. These patterns frequently exhibit very little, if any, bruising and are demonstrated principally as pressure marks and indentations, present for a considerable period after the time of death. These patterns should be documented and investigated, because they may contribute significant information to the investigation. It is necessary to also keep in mind that, although considerable discussion involves bitemarks left on human skin, bitemarks can and do occur on inanimate objects. In our experience, they have been processed from a kid glove, a soft burrito, a bar of soap, a wad of chewing gum, an apple, and an automobile windshield visor.

Although this study established evidence that quantification of dental characteristics can be accomplished, we now need to expand the sample size to begin to build a data base reflecting the occurrence of these six characteristics in the general population.

Conclusion

This study has begun to address some of the considerations concerning the quantification of dental characteristics posed by the Daubert trilogy and the questions concerning intra-observer and inter-observer consistency. The study has shown that both inter-observer and intra-observer consistency can be tested and documented. We demonstrated that a high level of inter-observer agreement was achieved between independent examiners. In addition, there was a high level of intra-observer consistency. The study established that selected tooth characteristics are quantifiable. The interdependence of the relation of some of the anterior teeth was further demonstrated using pairwise Pearson correlation. Statistics on the rotation of the incisors, especially the inward rotation of the mesial surface (considered negative rotation), was shown to be especially significant and was similar to the findings of angles of rotation studied by Bernitz [5]. Bernitz's measurements, however, differed because they were from an entirely different population sample composed of both males and females in a broad age range.

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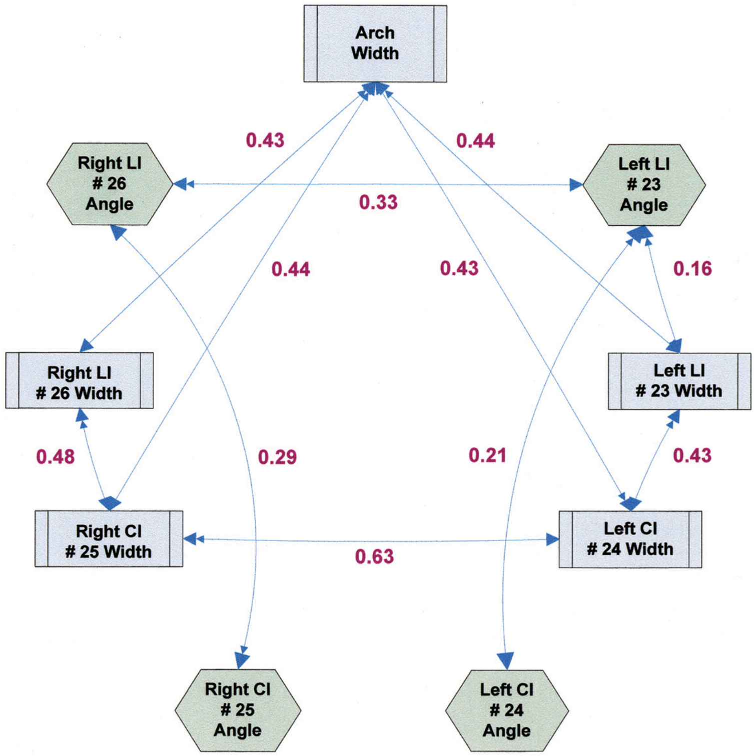

Figure 1

Graphical association model for mandibular dental arch. Numbers denote pairwise Pearson correlation between measurements. LI = lateral incisor; CI = central incisor.

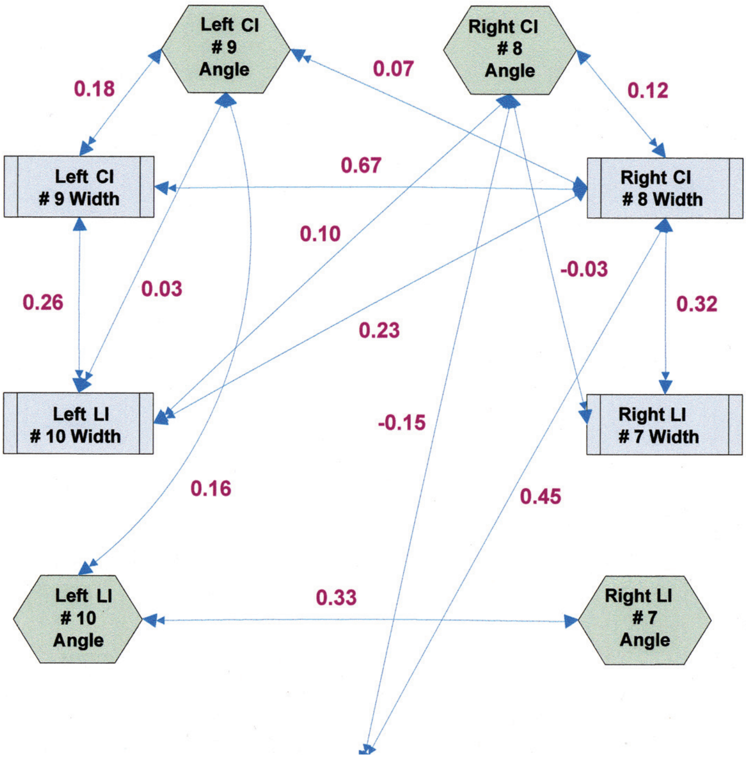

Figure 2

Graphical association model for maxillary dental arch. Numbers denote pairwise Pearson correlation between measurements. LI = lateral incisor; CI = central incisor.

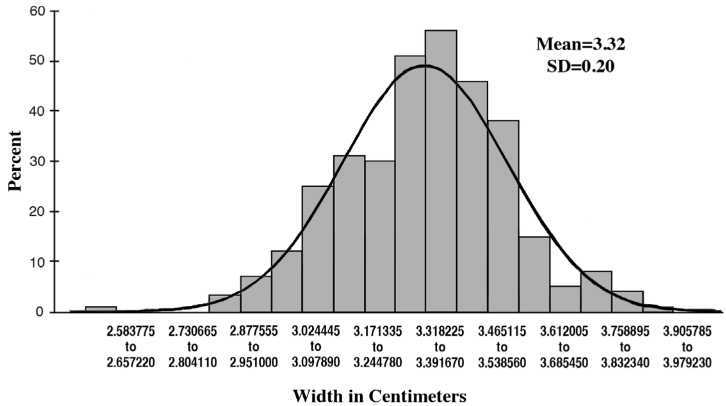

Figure 3

Maxillary arch width. Histogram with fitted normal curve.

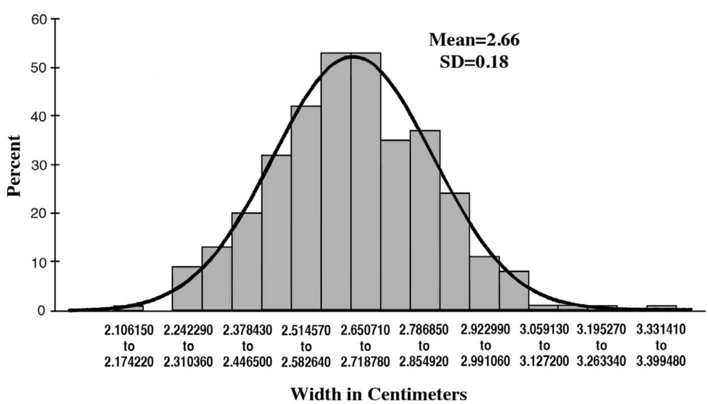

Figure 4

Mandibular arch width. Histogram with fitted normal curve.

ACS Demographic Estimates	Estimate	Percent	U.S.
Total population	5,363,675		
Male	2,649,041	49.4	49.1%
Female	2,714,634	50.6	50.9%
Median age (years)	36	(x)	35.3%
Under 5 years	342,340	6.4	6.8%
18 years and over	3,994,919	74.5	74.3%
65 years and over	702,553	13.1	12.4%
One race	5,296,780	98.8	97.6%
White	4,769,857	88.9	75.1%
Black or African American	304,460	5.7	12.3%
American Indian and Alaska Native	47,228	0.9	0.9%
Asian	88,763	1.7	3.6%
Native Hawaiian and Other Pacific Islander	1,630	0	0.1%
Some other race	84,842	1.6	5.5%
Two or more races	66,895	1.2	2.4%
Hispanic or Latino (of any race)	192,921	3.6	12.50%

Table 1

2000 U.S. Census Bureau statistics for Wisconsin.

	N	Very Uncommon Lower Width Values	Uncommon Lower Width Values	Common Width Values	Uncommon Upper Width Values	Very Uncommon Upper Width Values
Mandibular Arch						
Arch width (cm)	415	≤ 2.26	> 2.26 to ≤ 2.37	> 2.37 to ≤ 2.96	> 2.93 to ≤ 3.11	> 3.11
Right lateral incisor #26 (mm)	416	≤ 4.6	> 4.66 to ≤ 5.02	> 5.02 to ≤ 6.75	> 6.75 to ≤ 7.00	> 7.00
Right central incisor #25 (mm)	419	≤ 4.33	> 4.33 to ≤ 4.58	> 4.58 to ≤ 6.20	> 6.20 to ≤ 6.63	> 6.63
Left central incisor #24 (mm)	419	≤ 4.24	> 4.24 to ≤ 4.63	> 4.63 to ≤ 6.12	> 6.12 to ≤ 6.52	> 6.52
Left lateral incisor #23 (mm)	416	≤ 4.40	> 4.40 to ≤ 5.09	> 5.09 to ≤ 6.82	> 6.82 to ≤ 7.14	> 7.14
Maxillary Arch						
Arch width (cm)	412	≤ 2.86	> 2.86 to ≤ 3.00	> 3.00 to ≤ 3.66	> 3.66 to ≤ 3.77	> 3.77
Right lateral incisor #7 (mm)	416	≤ 3.46	> 3.46 to ≤ 4.59	> 4.59 to ≤ 7.44	> 7.44 to ≤ 7.73	> 7.73
Right central incisor #8 (mm)	419	≤ 6.95	> 6.95 to ≤ 7.41	> 7.41 to ≤ 9.57	> 9.57 to ≤ 10.06	> 10.06
Left central incisor #9 (mm)	418	≤ 6.66	> 6.66 to ≤ 7.38	> 7.38 to ≤ 9.49	> 9.49 to ≤ 9.91	> 9.91
Left lateral incisor #10 (mm)	419	≤ 3.92	> 3.92 to ≤ 4.61	> 4.61 to ≤ 7.24	> 7.24 to ≤ 7.78	> 7.78

Table 2

Results of values found in arch and tooth widths.

	N	Very Uncommon Lower Rotation Values	Uncommon Lower Rotation Values	Common Rotation Values	Uncommon Upper Rotation Values	Very Uncommon Upper Rotation Values
Mandibular Arch						
Right lateral incisor #26 (mm)	416	≤ -10.38	> -10.38 to ≤ 2.82	> 2.82 to ≤ 43.42	> 43.42 to ≤ 50.46	> 50.46
Right central incisor #25 (mm)	419	≤ -19.44	> -19.44 to ≤ -10.82	> -10.82 to ≤ 21.80	> 21.80 to ≤ 29.13	> 29.13
Left central incisor #24 (mm)	419	≤ -25.07	> -25.07 to ≤ -14.74	> -14.74 to ≤ 18.44	> 18.44 to ≤ 29.31	> 29.31
Left lateral incisor #23 (mm)	416	≤ -4.57	> -4.57 to ≤ 4.61	> 4.61 to ≤ 37.94	> 37.94 to ≤ 41.71	> 41.71
Maxillary Arch						
Right lateral incisor #7 (mm)	416	≤ 5.13	> 5.13 to ≤ 19.77	> 19.77 to ≤ 48.95	> 48.95 to ≤ 58.86	> 58.56
Right central incisor #8 (mm)	419	≤ -11.69	> -11.69 to ≤ -2.27	> -2.27 to ≤ 24.02	> 24.02 to ≤ 30.38	> 30.38
Left central incisor #9 (mm)	418	≤ -7.20	> -7.20 to ≤ 0.62	> .62 to ≤ 27.02	> 27.02 to ≤ 33.14	> 33.14
Left lateral incisor #10 (mm)	419	≤ 14.59	> 14.59 to ≤ 22.46	> 22.46 to ≤ 51.71	> 51.71 to ≤ 66.68	> 66.68

Table 3

Angles of rotation.

	Tooth	# Missing	Percent
Mandibular Arch	26	3	0.7%
	25	0	0.0%
	24	0	0.0%
	23	3	0.7%
Maxillary Arch	7	4	1.0%
	8	1	0.2%
	9	2	0.5%
	10	1	0.2%

Table 4

Pattern of missing teeth.

Characteristic	Tolerance	% Within Tolerance
Arch Width	1 mm	83.6%
#23 Width	0.5 mm	93.9%
#23Angle	5°	85.8%
#24 Width	0.5 mm	93.2%
#24 Angle	5°	92.9%
#25 Width	0.5 mm	94.2%
#25 Angle	5°	91.5%
#26 Width	0.5 mm	89.3%
#26 Angle	5°	82.4%

(a)

Characteristic	Tolerance	% Within Tolerance
Arch Width	1 mm	97.8%
#7 Width	0.5 mm	96.1%
#7 Angle	5°	88.8%
#8 Width	0.5 mm	93.2%
#8 Angle	5°	88.4%
#9 Width	0.5 mm	93.9%
#9 Angle	5°	88.6%
#10 Width	0.5 mm	95.6%
#10 Angle	5°	87.3%

(b)

Table 5

Inter-observer agreement (a) mandible; (b) maxilla.

Collector Number of Exemplars Number of Outlying Traits	Radmer 416 n (%)	Johnson 410 n (%)
0	205 (49.3)	204 (49.8)
1	109 (26.2)	102 (24.9)
2	61 (14.7)	61 (14.9)
3	22 (5.3)	23 (5.6)
4	9 (2.2)	13 (3.2)
5	8 (1.9)	7 (1.7)
6	2 (0.5)	0 (0.0)

Table 6

Consistency between the observers in determing outliers.

		% Within Tolerance	
Characteristic	Tolerance	Examiner 1 (N=35)	Examiner 2 (N=49)
Arch Width	1 mm	34/34 (100%)	46/48 (95.8%)
#7 Width	0.5 mm	33/34 (97.1%)	48/48 (100%)
#7 Angle	5°	33/34 (97.1%)	48/48 (100%)
#8 Width	0.5 mm	34/35 (97.1%)	48/49 (97.8%)
#8 Angle	5°	33/35 (94.3%)	49/49 (100%)
#9 Width	0.5 mm	33/34 (97.1%)	48/48 (100%)
#9 Angle	5°	34/34 (100%)	46/48 (95.8%)
#10 Width	0.5 mm	34/35 (97.1%)	49/49 (100%)
#10 Angle	5°	32/35 (91.4%)	48/48 (100%)

Examiner 1: Dr. Johnson
Examiner 2: Dr. Radmer

Table 7

Intra-observer arch measurement agreement (maxilla).

Mandible		Mean	SD	Q5	Median	Q95
Diastema	23-24	0.991	0.65	0.379	0.729	2.258
Diastema	24-25	0.966	0.597	0.379	0.763	2.174
Diastema	25-26	0.998	0.675	0.379	0.758	2.485
Maxilla		**Mean**	**SD**	**Q5**	**Median**	**Q95**
Diastema	7-8	1.3	0.783	0.536	1.105	2.786
Diastema	8-9	0.918	0.495	0.432	0.781	1.949
Diastema	9-10	1.255	0.762	0.494	1.072	2.896

SD = Standard deviation
Q5 = 5th percentile
Q95 = 95th percentile

Table 8

Diastema size and location.