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Technical Note

The Quantification of Tooth Displacement

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Abstract: By using reference points from a single pixel marker placed at the center point of the cuspid teeth and the center point on each of the incisor teeth, a polynomial curve was generated as a native curve for each dental arch studied. The polynomial curve generated from actual tooth position in each arch provides the forensic odontologist with another reference point that is quantifiable. The study represents that individual characteristics, such as tooth displacement, can be quantified in a simple, reliable, and repeatable format.

Introduction

Much has been written on bite mark analysis and science as it relates to the legal system [1]. Studies have shown that it is possible to quantify dental characteristics [2, 3]. In 1984, Rawson et al. completed a study of all the possible positions each anterior tooth could occupy [4]. McFarland et al. characterized problems with identification analysis [5]. Reviews of the legal issues have drawn attention to the fact that a scientific basis for analysis is needed [6].

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This study adds an additional characteristic to those studies that previously concentrated on tooth widths of the six anterior maxillary and mandibular teeth, their angulations in relation to an x and y axis, the presence or absence of teeth, spacing between teeth, and arch widths as measured from the center points of the two cuspid teeth in each arch. Arch widths were investigated in a sample population of males between the ages of 18 and 44 to correlate ethnicity with the findings.

Using reference points from a single pixel marker placed at the center point of the cuspid teeth and the center point on each of the incisor teeth, a polynomial curve was generated as a native curve for each dental arch studied. Results demonstrated outliers in tooth displacement either to the buccal or lingual in the dental arch. Frequencies in the population studied were calculated statistically to demonstrate extreme displacements. As with the characterization of arch width, tooth sizes, spacing, missing teeth, and rotations from the x and y axis, anterior and posterior displacements can be quantified.

Theoretical Basis

Frequencies of patterns in the human dentition can be quantified. It should be possible for the forensic odontologist to state with a reasonable degree of certainty the frequency that a given pattern exists. This should lead to the exclusion or inclusion of a suspect of a crime when adequate bite mark evidence exists. With each increase in patterns studied, further probability of inclusion or exclusion could approach the reliability of mtDNA as a data base is acquired. One such pattern is the anterior or posterior displacement of a tooth with regards to a native curve generated for each individual. In geometry, the locus point moving according to a specified condition describes a curve. A circle, for example, would be the loci of all points equidistant from a given point. Dentistry has used the curve analysis in the fields of orthodontics and prosthetics in the past. One such descriptive curve is the curve of Spee[1]. This curve is defined as the curvature of the mandibular occlusal plane beginning at the tip of the lower cuspid and following the buccal cusps of the posterior teeth, continuing to the terminal molar. The functional significance of the curvature has not been completely

1 Ferdinand Graf von Spee, German embryologist (1855-1937), was first to describe anatomic relations of human teeth in the sagittal plane.

understood [7]. The curve of Spee has been linked to incisor overbite, lower arch circumference, lower incisor proclination, and craniofacial morphology [8]. It is a standardized curve often used in prosthetics to describe an ideal anterior, posterior, mesial, and distal relationship of the dental arch and is not individualized. In the dentate individual, the standard curve may not fit the morphology to the mandibular or maxillary alveolar process, which ultimately limits tooth position in each arch. The polynomial curve generated from actual tooth position in each arch provides the forensic odontologist with a reference point that is quantifiable and unique for each arch studied. This allows the odontologist as well as orthodontists to characterize displacement from a reference point that is not arbitrary. The orthodontic literature is replete with articles ascribing form, symmetry, and assymetry of the dental arch in different groups [9, 10, 11].

Materials and Methods

Imprints were created in dental exemplars [12]. Five hundred exemplars were gathered from males between the ages of 18 and 44 from patients seeking care at Marquette University's School of Dentistry, two military reserve units, and participants in the Wisconsin Dental Association's May 2006 conference. Seventy-nine exemplars were discarded because they were distorted. Error rates for obtaining the exemplars were calculated by repeating the imprints from a single individual ten times and comparing the generation of a polynomial curve by the two investigators during repeated impression gathering.

As previously reported [13], a system dubbed "Tom's Toolbox" used a single pixel marker placed in each arch at ten different locations representing the center point of each cuspid impression measured mesially or distally and buccal lingually as well as the mesial and distal edge of the four incisor teeth in each of the maxillary and mandibular arches. The center point of each of the four incisor teeth was calculated using this automated program. From the six center points of teeth, a native or polynomial curve was established for each of the maxillary and mandibular arches studied in the population base (Figure 1). The individual displacements from the native curve were calculated by the automated program and were corroborated using the measuring tool in Adobe Photoshop CS2 in ten percent of the working files for each arch. Measurements were taken from the outside edge of the cross hair marker to the inside edge of the generated polynomial curve in each case for each of the fourteen points. The images that were used were generated in a previously reported methodology study that ensured that SWGIT guidelines for images were followed. The scanning equipment was calibrated frequently to ensure that measurement error was not an issue with regards to the value of *theta* [12]. Each of the corroborated measurements was saved in a screen capture file as a read only document (Figure 2). The inter- and intra-operator consistency rates were calculated by repeating ten per cent of the measurements and comparing results to the initial placements of the pixel markers. The automated program used fourteen points to calculate the distance and direction of displacement from the native curves generated for each arch in the data sets. Mean and average displacements were calculated for each of these points. The displacements were further subdivided into labial (anterior) or lingual (posterior) versions for each point. All data was analyzed using the statistical package program SPSS version 10 (SPSS Inc., Chicago, IL). Descriptive statistics, including mean and standard deviation values, were calculated for each of the groups. Analysis of variance was used to determine whether significant differences were present in the measurements used in the study between observers. Statistical analysis was used to determine correlation coefficients between the amount of displacement from the polynomial curve and other variables in the study, such as inter- and intra-operator error rates, using both the automated and Adobe Photoshop CS2 measuring tools. *P* values of 0.05 or less were considered statistically significant.

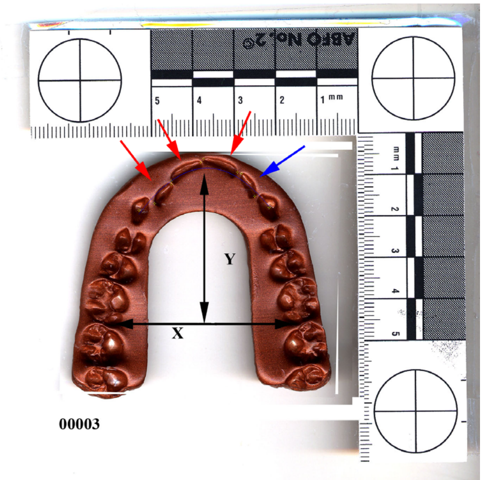


Figure 1

A polynomial curve is generated for the maxillary arch. Note the displacement of teeth eight, nine, and ten (red arrows) versus rotation of tooth seven (blue arrow).

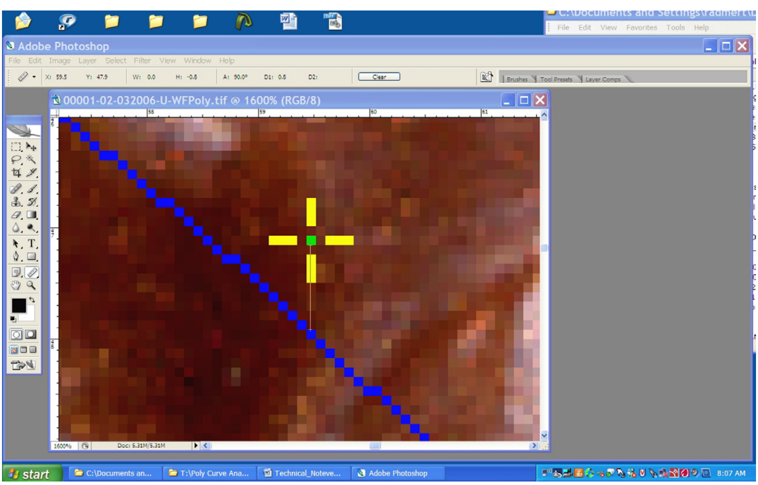


Figure 2

Screen capture of manual measurement of displacement at the pixel level, 1600 %, using the measure tool in Adobe Photoshop CS2.

Results and Discussion

The use of a polynomial curve generated by the actual location of the six anterior teeth in an arch provides the forensic odontologist with a native curve that eliminates the hand-eye co-ordination when using a curve generated as a parabola, a Bezier, an elipse, or a cantenary curve [9]. The disadvantage of these curves is the assessment of the operator in placing a standardized curve into an arch when ideally it does not fit. Further, the elliptical curve uses the cuspid foci as the loci of the generated curve, making their displacement not inclusive in the analysis. The Bezier curve must be magnified in its placement by some factor because it is generated to the lingual surface of the dentition in each arch. Several choices are available for each of the Bezier curve analysis so that the placement becomes a choice of the individual investigator.

Lu demonstrated a close fit to the human dental arch when using a fourth-order polynomial curve when describing arch symmetry [14]. The polynomial curve generated for each of the subject's arches was analyzed using pairwise comparisons. The repetition of obtaining a new exemplar from a single patient ten times and repeating the process of pixel placement and polynomial curve generation for each operator provided an error rate (Tables 1 and 2) with a standard deviation, mean, and median calculation for this portion of the procedure.

An example of recorded mean and average displacements of the fourteen points investigated for each maxillary and mandibular arch is shown in Table 1 and 2 for investigator #1. Standard deviations for each point were reported as minimum and median values for each quartile. The tables represent those for the first quartile of the data. Outliers were those that exceeded two standard deviations from the average displacement for each point measured. In this instance, the center point of a tooth could lie on the polynomial curve, for example, but the degree of tooth rotation could be so severe that both the mesial and distal aspect would represent an outlier of extreme rotation. A similar situation could exist when the center point of the tooth does not lie on the curve and rotation occurs at either the mesial or distal aspect of the tooth.

Figure 3 characterizes the frequency each point occurred with no displacement or displacement in either the labial (anterior) or lingual (posterior) position with regards to the maxillary and mandibular arch. A displacement of a tooth has not occurred if the midpoint of the tooth width falls on the polynomial curve [15]. As described above, this represents rotation only.

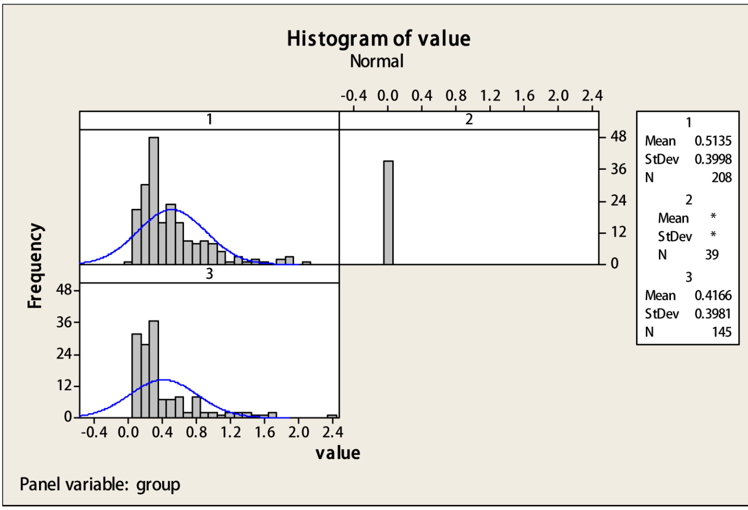
Table 3 represents data collected from repeating the exemplar process in the same individual ten times by each examiner to determine whether the process represents a difficulty in obtaining the exemplars in the first instance. Histograms representing the differences in standard deviations and means are presented with this process. Interoperative values varied between 0.0017 mm (one pixel equals 0.847 mm) and 0.317 mm, or only a fraction of a pixel when calibrating placements by each examiner.

When looking at the characteristic of displacement alone, the current sample size does not represent any generalities that can be ascribed to the population as a whole. Coupled with the six previously studied characteristics and their frequency of occurrence, the displacement characteristic adds an additional descriptor that, when present, further defines frequencies that any three of the characteristics, or for that matter all seven, will occur in a single individual. For example, a tooth can be displaced but maintain rotational angles that fall within a typical parabolic curve histogram for rotation that predicts this population will have rotations of a certain degree from the y axis plus or minus two standard deviations (Figure 3).

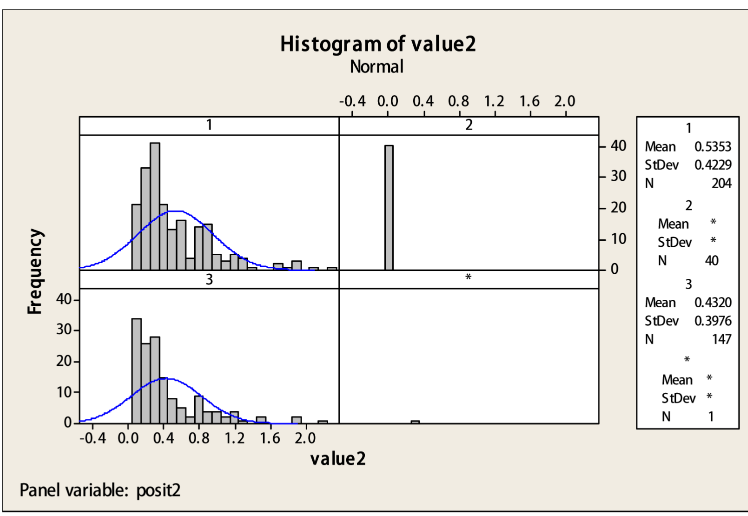
With any study, there are certain limitations and additional questions that become apparent. Most obvious are, What happens in a third dimension with displacement in the z axis? Can these results be applied to the general population? Can this be applied to an actual forensic bitemark case? The short answers are, that is what is needed next, no correlation to the general population is inferred, and no correlation to an actual bitemark case is suggested. The benefit here is the development of a means of quantifying dental characteristics that is simple, inexpensive, and reliable. Inter- and intra-operator error rates have been previously reported for the characteristics of individual tooth width, arch width, and rotation; frequency of missing teeth; size and location of diastemas; or spacing and presence of tooth damage. The inter- and intra-operator error rates for displacement are found in Table 3. Correlation coefficients calculated for these error rates have a confidence level of 95%, both inter- and intra-operator. Only the degree of rotation becomes an enigma for the pilot study. As previously reported, that is a consequence of placing the pixel indicators at a high level of magnification [15]. The 1200 DPI magnification in this study was not an influence on error rate. There may be some benefit in reporting the shortest distance to the polynomial curve rather than the distance to the x axis. As the automated program becomes more frequent and familiar to investigators, that data will be reported. The shortest distance to the polynomial curve using Photoshop CS2 is a measurement that is not readily repeatable with that program. Vertical right angle distances to the polynomial curve are easily obtainable by the investigator by holding down the shift key during the measurement. Thus, more accuracy is incorporated into the measurement.

Figures 4, 5, and 6 are graphic representations of the results from the two investigators when measuring displacement in the maxilla or mandible. Displacements were characterized as being either to the labial (position 2) or to the lingual (position 3) in the maxilla as shown in Figure 4. Displacement in the mandible was shown to be to the lingual (position 2) as represented by Figure 5 or to the labial (position 3) as represented by Figure 6. Of specific note was the comparison of histograms by the individual investigators. Both investigators demonstrated mean and standard deviations that were very close. Data for the figures are combined to demonstrate this finding. Confidence intervals are included in the figures for comparison.

Finally, as part of the overall quantification exercise, Tom's Toolbox is being made available to those governmental and nonprofit agencies who are regularly engaged in the evaluation of patterned evidence.



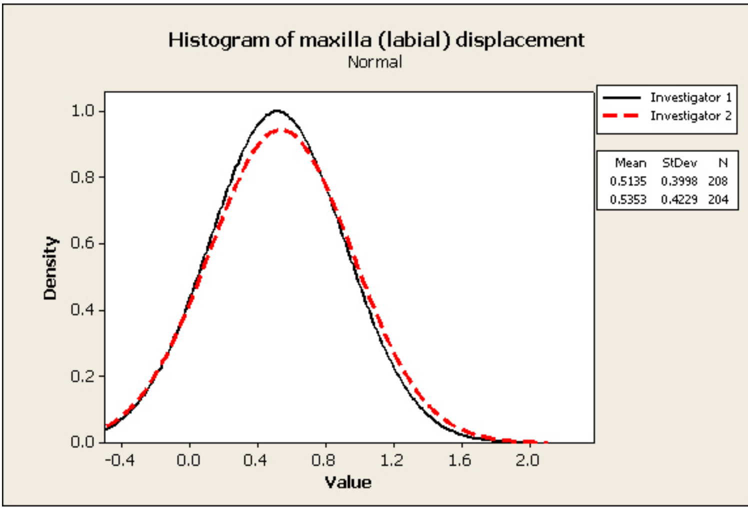
(a)



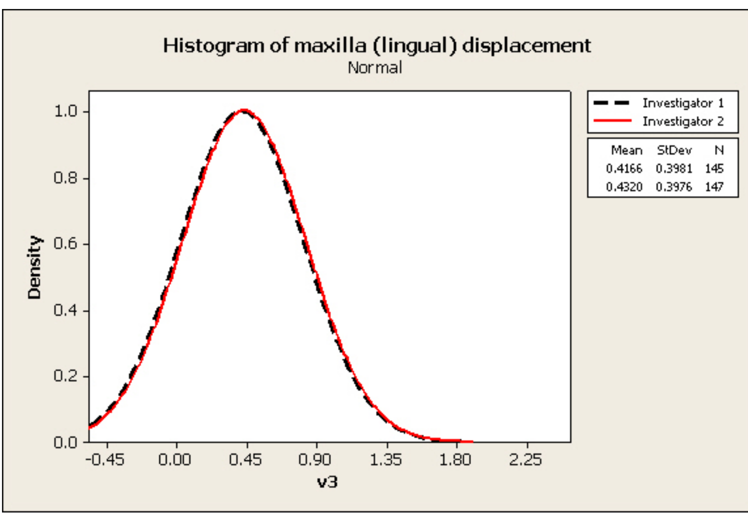
(b)

Figure 3

Frequency in histogram format for automated values of displacement in the mandible and maxilla. (a) Investigator # 1 mandible. (b) Investigator # 2 mandible.



(a)



(b)

Figure 4

Comparison values of maxillary displacements between individual investigators in the labial (a) and lingual (b) direction.

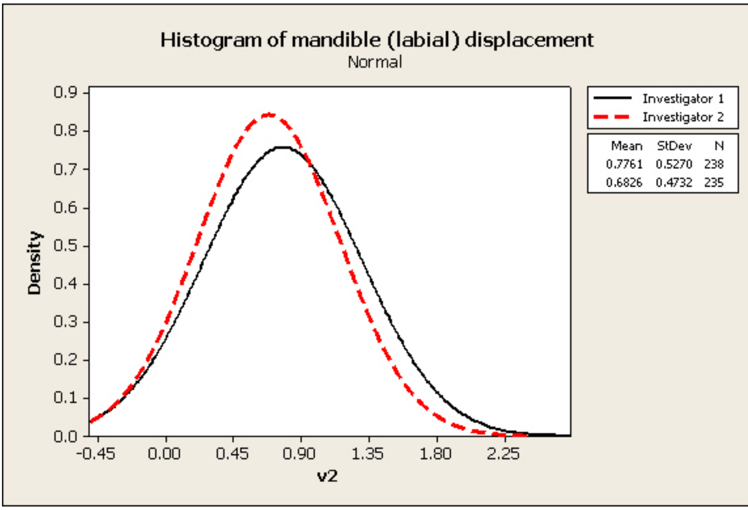


Figure 5

Comparison of values of mandibular labial displacements between individual investigators.

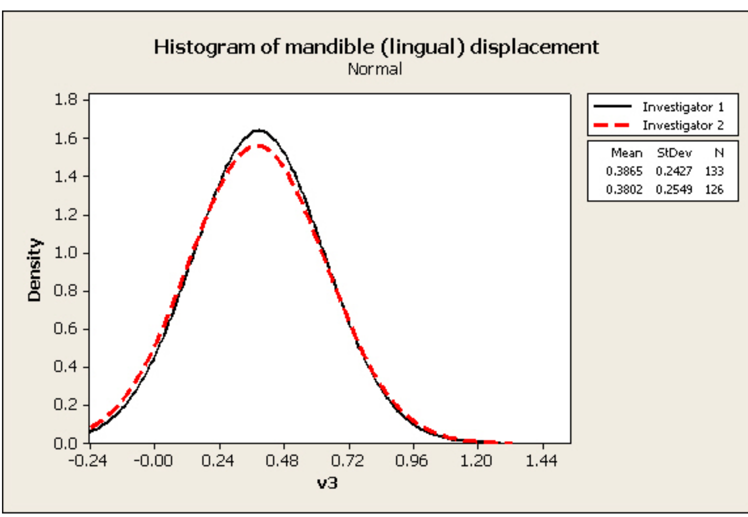


Figure 6

Comparison of values of mandibular lingual displacements between individual investigators.

Conclusion

Because the sample size was limited, additional exemplars need to be gathered from the population as a whole. The data could be extrapolated to the United States population. The study represents only that individual characteristics, such as tooth displacement, can be quantified in a simple, reliable, and repeatable format.

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Variable	Teeth	N	Mean	SE Mean	St Dev	Minimum	Q1	Median
Value	6	5	0.1600	0.0400	0.0894	0.1000	0.1000	0.1000
	11	4	0.1750	0.0479	0.0957	0.1000	0.1000	0.1500
	7(1)	25	0.7400	0.0827	0.4133	0.1000	0.3500	0.8000
	7(2)	25	0.7080	0.0746	0.3730	0.2000	0.4000	0.6000
	7(3)	26	1.227	0.126	0.641	0.300	0.700	1.100
	8(1)	13	0.4154	0.0724	0.2609	0.1000	0.2000	0.4000
	8(2)	1	0.50000	*	*	0.50000	*	0.50000
	8(3)	23	0.6826	0.0912	0.4376	0.1000	0.2000	0.6000
	9(1)	24	0.883	0.141	0.689	0.100	0.400	0.800
	9(2)	3	0.767	0.120	0.208	0.600	0.600	0.700
	9(3)	13	0.415	0.101	0.363	0.100	0.150	0.300
	10(1)	27	1.026	0.106	0.550	0.200	0.700	1.000
	10(2)	25	0.7200	0.0624	0.3122	0.2000	0.4500	0.7000
	10(3)	24	0.788	0.102	0.501	0.100	0.325	0.650

Table 1

The occurrence (N) of displacement values for each of the maxillary teeth where tooth 6 and tooth 11 are the cuspids and 7, 8, 9, and 10 are the right lateral, right central, left central, and left lateral incisors. The last digits following the tooth numbers indicate (1) labial displacement, (2) no displacement, and (3) lingual displacement for the first quartile (Q1).

Variable	Teeth	N	Mean	SE Mean	St Dev	Minimum	Q1	Median
Value	22	10	0.2200	0.0200	0.0632	0.1000	0.2000	0.2000
	27	11	0.2545	0.0835	0.2770	0.0000	0.1000	0.1000
	23(1)	22	0.786	0.116	0.542	0.100	0.475	0.650
	23(2)	15	0.3600	0.0660	0.2558	0.1000	0.2000	0.3000
	23(3)	16	0.4313	0.0681	0.2726	0.1000	0.3000	0.3000
	24(1)	21	0.5381	0.0829	0.3801	0.3000	0.3000	0.4000
	24(2)	8	0.588	0.169	0.479	0.100	0.200	0.500
	24(3)	11	0.845	0.158	0.524	0.200	0.300	0.800
	25(1)	14	0.486	0.107	0.400	0.100	0.275	0.300
	25(2)	11	0.3909	0.0476	0.1578	0.2000	0.3000	0.3000
	25(3)	20	0.5450	0.0776	0.3471	0.1000	0.2250	0.5000
	26(1)	19	0.4895	0.0648	0.2826	0.1000	0.2000	0.5000
	26(2)	12	0.2667	0.0482	0.1670	0.1000	0.1000	0.2500
	26(3)	18	0.689	0.115	0.486	0.200	0.300	0.550

Table 2

The occurrence(N) of displacement values for each of the mandibular teeth where tooth 22 and tooth 27 are the left and right cuspids, respectively, 23 is the left lateral, 24 the left central, 25 the right central, and 26 the right lateral incisor. The last digits following the tooth numbers represents (1) labial, (2) no displacement, and (3) lingual displacements for the first quartile (Q1).

Width measured Tooth #	Investigator 1 Mean	Investigator 1 SD	Investigator 2 Mean	Investigator 2 SD	Variance Mean in mm	SD variance in mm
26 width (mm)	5.645	0.1544	5.393	0.2840	0.253	0.1296
25 width (mm)	4.287	0.1831	4.041	0.1959	0.246	0.0128
24 width (mm)	4.546	0.1051	4.370	0.1155	0.176	0.0104
23 width (mm)	5.556	0.2680	5.239	0.3228	0.317	0.0548
Arch Width (cm) Mandible	**2.550**	**0.03067**	**2.567**	**0.03202**	**0.0017**	**0.00135**
10 width (mm)	5.277	0.1577	5.172	0.1498	0.105	0.0079
9 width (mm)	7.426	0.1404	7.418	0.1323	0.008	0.0081
8 width (mm)	8.080	0.1322	7.956	0.2341	0.124	0.1019
7 width (mm)	5.880	0.1867	5.798	0.1983	0.091	0.028
Arch Width (cm) Maxilla	**3.204**	**0.03478**	**3.244**	**0.05249**	**0.040**	**0.0177**

Table 3

Differences in standard deviations and means for repeated exemplars single individual N=10.