

1-1-2014

Replication of Known Dental Characteristics in Porcine Skin: Emerging Technologies for the Imaging Specialist

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The author(s) shown below used Federal funds provided by the U.S. Department of Justice and prepared the following final report:

Document Title: Replication of Known Dental Characteristics in Porcine Skin: Emerging Technologies for the Imaging Specialist

Author(s): L. Thomas Johnson, Thomas W. Radmer, Dean Jeutter, Gary L. Stafford, Joseph Thulin, Thomas Wirtz, George Corliss, Kwang Woo Ahn, Alexis Visotky, Ronald L. Groffy

Document No.: 244568

Date Received: January 2014

Award Number: 2010-DN-BX-K176

This report has not been published by the U.S. Department of Justice. To provide better customer service, NCJRS has made this Federally-funded grant report available electronically.

Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

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REPLICATION OF KNOWN DENTAL CHARACTERISTICS IN PORCINE SKIN; EMERGING TECHNOLOGIES FOR THE IMAGING SPECIALIST

FINAL TECHNICAL REPORT

Award NIJ 2010-DN-BX-K176

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This document is a research report submitted to the U.S. Department of Justice. This report has not been published by the Department. Opinions or points of view expressed are those of the author(s) and do not necessarily reflect the official position or policies of the U.S. Department of Justice.

1 **Replication of Known Dental Characteristics in Porcine Skin:**
2 **Emerging Technologies for the Imaging Specialist**

3 **NIJ 2010-DN-BX-K176**

4 **Award period October 1, 2010 – September 30, 2013**

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7
8 **Abstract**

9 This research project was proposed to study whether it is possible to replicate the patterns
10 of human teeth (bite marks) in porcine skin, be able to scientifically analyze any of these
11 patterns and correlate the pattern with a degree of probability to members of our established
12 population data set.

13 The null hypothesis states: It is not possible to replicate bite mark patterns in porcine
14 skin, nor can these bite mark patterns be scientifically correlated to a known population
15 data set with any degree of probability.

16 Bite marks were produced on twenty-five pigs with a bite pattern replication device using 50
17 sets of models of blinded dentitions. The models were selected randomly from a previously
18 quantified data set of 469. Prototyped dental models were mounted on a semi-automated
19 mechanical device which records the model number, physical location on the pig where the
20 force applied and the duration it was applied. Four patterns were created on each side of
21 twenty-five anesthetized pigs in predetermined areas. These sites were tested previously in a
22 pilot study; notably the hind quarter, abdomen, thorax and fore limb. Digital photographs of the
23 patterned injuries (bite marks) were exposed following the guidelines of the Scientific Working
24 Group on Imaging Technology (SWGIT) and the American Board of Forensic Odontology

25 (ABFO). Two hundred images of each dental arch were selected from the eight hundred
26 photographs taken during the laboratory sessions and analyzed biometrically using a previously
27 validated software program. Images were categorized as complete, partially complete or
28 unusable, based on the presence, partial presence or absence of the six anterior teeth in each
29 arch. Intersecting angles, the widths of the lateral and central incisors and the arch width
30 measured on the scaled images of the unknown models. The images were analyzed
31 independently by two investigators. Their measurements were then statistically compared to
32 an established population data set of 469 males, ages 18 to 44 years. Statistical analysis was
33 achieved using two models; Pearson's correlations and distance metric analysis. Pearson's
34 correlation results based on width only, angle only and widths plus angles were reported by
35 each investigator. Angles measured along with widths and compared to the known data set
36 ranked each set of models from 1 to 469 with a ranking of one showing the lowest p values.
37 Investigator #1 ranked 5 out of 143 images as number 1, 10 out of 143 in the top 1%, 34 out of
38 143 in the top 5% and 59 out of 143 in the top 10 %. Investigator #2 ranked 2 out of 156 as
39 number 1, 13 out of 156 in the top 1%, 36 out of 156 in the top 5% and 54 out of 156 in the top
40 10%. The second statistical model using distance metric analysis had a sample count of 102
41 images with 3 out of 102 within 1% of the population, 16 out of 102 within 5% of the population
42 and 23 out of 102 within 10% of the population when evaluating the results of the upper jaw only
43 from investigator #1. The concept of using an incisal line is based on geometric principles of line
44 segments and the angles they form when extended. The use of this concept will aid the crime
45 laboratory imaging specialist and forensic odontologist in their analysis of bite marks (patterned
46 injuries).

47 MeSH terms; forensic odontology, bite mark, dental characteristics, bite force, incisal line,
48 quantification of dental characteristics, statistical analysis, load cell, FlexiForce sensor.

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243 These included selecting a suitable material to strong enough to duplicate natural tooth
244 strengths, developing a mechanism to and accurately transfer a pattern of dental
245 characteristics to porcine skin and developing a standardized method of mounting the
246 dental models on a device which would produce a patterned injury (bite mark). It was
247 also necessary to determine the force necessary to create a legible pattern in skin and
248 calibrate each of the fifty replication device to deliver a standardized bite force for a
249 specific time period. To be able to establish the probability that an image of a bite mark
250 (patterned injury) on the pig could be correlated to a member (target) of the population
251 data set with a level of probability, ranking the patterned injuries to the population data
252 set was accomplished using both Pearson's correlations and a distance metric analysis
253 model

254 **Research Design**

255 The selection of a material with natural tooth strengths included a trial using
256 Castone™ dental models, cold cured methyl methacrylate dental resin and prototyping
257 models using sintered steriolithography (SLS). The sintered form of prototyping by the
258 3M™ Corporation produced a model of the strength required for this research.

259 The use of a modified Irwin C-clamp to transfer patterns of dental characteristics to
260 skin was previously reported. [17]. The incorporation of a load cell to calibrate each
261 FlexiForce® transducer in each of the 50 pattern replication devices required to record
262 the force applied had not previously been used. Initial trials of a prototype pattern
263 replication device resulted in torqueing of upper models when force was applied. The
264 use of ten parallel pins placed in the base of the upper dental models prevented this

265 and ensured that all forces were directed to the incisal edges of the six anterior teeth
266 and directly against the FlexiForce[®] transducer.

267 Force transducers, load cells and piezoelectric concepts were incorporated in the
268 replicator device. Accurate measurement of the forces involved experimentation with
269 materials that had limited hysteresis or fade during force loading. Ultimately a machined
270 aluminum button attached to the piezoelectric sensor (FFT) provided for the most
271 sustainable of compressive forces when applied for any interval of time.

272 The literature provides for a wide range of pounds force calibration in the incisor
273 region from 20 to 122 PSI. These forces are influenced by numerous factors including
274 pain, gender, age, musculature and the individuals existing occlusion. This study's
275 determination of bite force necessary to create a patterned injury was based on a
276 sampling of individuals between the ages of 22 and 32 showing a range of 25 to 131.1
277 pounds force consistent with previous reports.

278 Calibration of each of the force sensors in the 50 replication devices by bench testing
279 was accomplished prior to each animal laboratory session. A means of recording and
280 sustaining the bite force for a 15 second time interval was required. This was
281 accomplished with a complete Phidgets data acquisition system which consisted of a
282 voltage divider, a precision voltage reference source, an Analog to Digital Converter
283 board (ADC), USB interface and a laptop computer. Using a modification of a similar
284 apparatus used in an earlier study the models were mounted on a modified Irwin[™]
285 welder's vise grip. By incorporating a force sensor, (FlexiForce[®] 100 lb. sensor), the
286 Phidgets[®] device was bridged to a notebook computer running Lab View[®] software

287 creating an auto-recording pattern replication device. This device allowed the replication
288 of patterned injuries to be repeatable, consistent and measurable. The calibration
289 procedure involved connecting the embedded FlexiForce[®] Transducer (FFT) to the
290 Phidgets[®] data acquisition system and verifying its operation on the connected laptop
291 computer running the custom software application, Lab View[®]. The load cell was placed
292 in the replication apparatus, arranged mechanically in series with the embedded FFT
293 sensor such that both transducers experienced the same biting force. Force was
294 applied at 25, 50 and 100 pounds-force increments then removed at 50, 25 and 0
295 pounds force increments. Corresponding data from the FFT and the load cell were
296 taken at each force increment and stored in a time and date stamped computer file for
297 each of the 50 models and 50 corresponding pig locations.

298 **Animal Laboratory Sessions**

299 Animal research sessions were conducted in accordance with the standards of the
300 *Guide for the Care and Use of Laboratory Animals* (8th edition, National Academies of
301 Sciences, 2011) and were approved by the Medical College of Wisconsin, Institutional
302 Animal Care and Use Committee (IACUC).

303 Mixed-breed young pigs, weighing 30-40 kg were obtained from a commercial
304 breeder and acclimated in the large animal laboratory research facility for a period of at
305 least 2 days before the laboratory procedures were performed. Anesthesia was induced
306 with a combination of tiletamine/zolazepam (Telezol[®], 4.4 mg/kg) and xylazine (2.2 mg.
307 /kg) administered intramuscularly. Following induction, an endotracheal tube was placed
308 and hair from the anatomical sites of interest removed using a commercial hair clipper,

309 razor, and/or depilatory cream. To conserve body temperature, animals were placed on
310 heated pads on the surgical tables and covered with towels and a PolarShield®
311 Emergency Survival blanket (RothCo3015 Veterans Memorial Highway, Ronkonkoma,
312 New York 11779-0512). The pigs' body temperatures were maintained between 36.2
313 and 39.3 degrees C and monitored by participating veterinary technicians. Using a
314 rectal thermometer, the mean procedural temperature recorded was 38.1C (36.2C –
315 39.3C). The mean low 36.2C (33.9C – 37.0C) and the mean loss was 1.8C (0.2C –
316 4.3C). Following animal preparation, a surgical plane of anesthesia was maintained
317 using isoflurane administered through the endotracheal tube using a precision vaporizer
318 and compressed oxygen. Basal anesthesia was augmented as needed in some animals
319 with pentobarbital administered intravenously to effect stage III general anesthesia.

320 The four designated sites to receive the patterned injury were the lateral aspects of
321 the upper hind limb/thigh, abdomen/flank, thorax, and shoulder/upper forelimb of the
322 animals. These were designated as site A, B, C and D referenced on the ABFO #2
323 scale label in the photographic image.

324 **Photography**

325 The injuries were digitally photographed at 1:1 scale (life size) by an forensic
326 photographer 15 minutes after their creation, using a Cannon™ EOS 5d Mark II, ~ 21mp
327 with a Cannon Macro EF 100mm 1:2.8 USM lens, set to autofocus. Lighting was
328 provided with a Canon 580 EX II flash set to Manual 1:2 power. The flash unit was
329 used off camera held oblique to the bite pattern. Camera settings were at the manual
330 exposure of 1/200th @ f16-32, 100 I.S.O. with the white balance set on Flash. Large

331 JPEG format imaging process consisted of converting RAW images in Adobe
332 Photoshop CS5 (cropped to 4x4 inches) and then calibrated to 1:1 at 300 ppi and saved
333 in TIFF format. The calibration of the patterned injury proceeded by determining the
334 total number of pixels within a known distance. The forensic photographer used the
335 least distorted portion of the scale for the calibrations. A flat field lens was employed to
336 help reduce optical distortion. At the lab, the images were calibrated to 1:1 and the
337 analysis measurements were made using the technique previously reported for Tom's
338 Toolbox[®]. Sorting and selection of the best image for each of the eight sites on the
339 twenty-five pigs was accomplished. Since a scaled image of each dental arch was
340 required to be analyzed separately by the semi-automated software, Tom's Toolbox[®], a
341 total of four hundred scaled digital images were calibrated at 300 dpi, duplicated and
342 saved as working images in TIFF format. Those patterns which registered all six of the
343 anterior teeth were considered complete, while those which registered only some of the
344 anterior teeth were classified as partially usable. A third category, unusable, was
345 assigned to those patterns which lacked sufficient detail. Duplicate working files were
346 created for each of the investigators to independently measure the characteristics
347 available. The duplicate working files were uploaded into the semi-automated computer
348 application, Tom's Toolbox[®], where they were measured by Investigators 1 and 2. The
349 data was saved in an electronic data log.

350 Findings

351 The inter-observer agreement between Investigator 1 and Investigator 2 in the
352 measurement of the 50 Coprwx[™] exemplar patterns using SAS software was 0.984,
353 showing an extremely high consistency when measuring widths of tooth patterns in an

354 American Dental Association (ADA) accepted dental bite registration material.
355 Determination of the inter-observer agreement in measuring tooth widths of patterns
356 registered in porcine skin was calculated with SAS software resulting in a correlation of
357 0.716.

358 Measuring the intersecting angles as a means of determining an additional dental
359 characteristic has not previously been utilized in pattern research. The intersecting
360 angles formed between incisor teeth identified as A and B, A and C, A and D, B and C,
361 B and C and D were identified and compared to the corresponding angles from original
362 data of the known population data set patterns. The correlations between bitemarks in
363 porcine skin compared to the known measurements of the 469 dental models were
364 ranked from 1 to 469. Each unknown model could only be ranked once as either 1 or
365 some other number between 1 and 469. For Investigator 1, 84.6% of the
366 measurement's showed that their true models were ranked in top 10%. For Investigator
367 2, 85% of the measurements showed that their true models were ranked in top 10%.

368 Pearson's correlation identified 2 and 5 ranking as number 1 by researcher 1 and 2
369 respectively when ranking from 1 to 469. In considering additional characteristics,
370 correlations between a bite mark and its true dental model were highly ranked. For
371 example, 10 out of the 143 (Investigator 1) and 13 out of the 156 (Investigator 2) were
372 within in top 1%. Additional results can be interpreted similarly. All show a better
373 performance than random with p-values < 0.0001. (Random in a statistical description
374 indicates that selecting models until a match is made is not possible). Outliers were
375 calculated using an N =469 to represent the population data. A calculated mean and

376 standard deviation was recorded as $\pm 2 \times \text{SD}$. Width and angle calculations revealed
377 more outliers than considering width alone or angles alone.

378 To verify the initial statistical model of analysis, a second statistical model using
379 distance metric analysis was employed. The Distance Metric family of models computes
380 a distance in an n -dimensional factor space from a Sample (unknown pig pattern) to
381 each member of the known population data set of 469. The score for a particular
382 member of the Distance Metric family of models is the percentage of the Population that
383 is closer to the specific sample (pig pattern) than the correct matching Target member
384 of the population data set from which the sample image was made. In three (3) (2.9 %) of
385 the 102 Sample images scored, only 1% of the Population was closer to the Sample
386 than the Target; 16 (15.7%) of the Samples found their Target within 5% of the
387 Population; and 23 (22.5 %) of the Samples found their Target within 10% of the
388 Population. For this data set, the Distance Metric Model performs a little better on the
389 upper jaw Samples than on the lower jaw Samples, and there was no appreciable
390 difference in performance using the Sample and Population measurements of each
391 researcher. In summary, in more than 20% of the Samples in this study, the Distance
392 Metric Model finds the Target within the closest 5% of the Population. In more than 6%
393 of the Samples, it finds the Target within the closest 1% of the Population. This
394 demonstrates that it is possible to determine scientifically that a given Sample must
395 belong to a very small (e.g., 5% or even 1%) proportion of the Population.

396 **Conclusions**

397 The production of a legible pattern replicating the teeth in skin depends upon
398 multiple factors in addition to the substrate and the mechanism. Firm substrates such as

399 cheese, soap, plastic and leather, to cite several media, register dimensions best. The
400 mechanism of creating the bitemarks in skin can be divided into two categories;
401 dynamic and static. Dynamic distortion occurs when there is movement by either or both
402 victim and assailant. Static distortion is less common and in the opinion of the authors
403 occurs more often in the pattern of the lower teeth because it is not fixed in position as
404 is the maxilla. A variable even in a static bite is the degree of elasticity in the skin and
405 the inability to capture the exact dimensions of the teeth. The evidentiary value of the
406 injury pattern is related to the amount of distortion in the bite mark (injury pattern).
407 However, even a distorted bite mark may still contain measureable characteristics that
408 provide evidentiary value. When agreement exists in the analysis of a pattern between
409 all examiners, there still is a need for a scientific basis and level of confidence for their
410 opinion.

411 Prior to this report, to accomplish the frequency distribution of the dental
412 characteristics, making an individual's dentition distinctive, a series of studies were
413 instituted to establish a methodology for quantification dental characteristics in both two
414 and three dimensions. This was initially utilized to build a data set of seven dental
415 characteristics. Additional research confirmed the reliability of measurements, testing
416 both intra-operator and inter-operator agreement in analysis. The initial quantification of
417 width, damage, angles of rotation, missing teeth, diastema characteristics (spaces) and
418 arch width were subsequently augmented by a study of the displacement of the
419 anterior teeth, labially or lingually, from the individual's physiologic dental arch form.
420 Later a three-dimensional study of the position of the incisal edge of the anterior teeth
421 on the horizontal (Z) plane was conducted. This study adds a practical application to

422 this data set. It incorporates a geometric approach to determining the angles of rotation
423 of the four maxillary and mandibular incisors. This concept utilizes the measurement of
424 the angles at the intersection of the extended incisal lines, projected through the mesial
425 and distal markers of each of the incisors. This method of measuring rotation of the
426 intersecting angles of the incisal lines is beneficial for several reasons. It eliminates
427 subjective establishment of an X (horizontal) axis. It is also more universal. One or
428 more teeth may be missing or indistinct. If two or more anterior teeth can be identified
429 (e.g. tooth 7 and 9), computation of the angle of the intersecting incisal lines can still be
430 determined. This method of establishing tooth rotation also provides an expanded
431 scope of search analysis, since it includes two additional characteristic items. In the
432 earlier studies when an x axis could be established from the presence of posterior teeth,
433 it was possible to determine four angles of rotation using a standardized and adjustable
434 x/y axis template. With the alternate method of the intersecting angles formed by the
435 incisal lines, it is possible to measure six angles of rotation.

436 Although the actual width of the pattern of the incisor in skin may be less than that of
437 the known source, the angle of rotation remains a constant. Most significant in
438 predicting probability of a correlation to a target in the population data set will be the
439 presence of outlying angles of rotation. This procedure adds four additional
440 characteristics to statistically calculate the probability of correlation between the
441 unknown and a known source.

442 The interpretation of the combination of quantified dental characteristics making up
443 the initial two-dimensional data set, also utilized the data obtained in the three-
444 dimensional study, since the anterior teeth are not always all at the same level of

445 eruption on the horizontal plane (Z plane). In knowing this, questions regarding whether
446 certain teeth are present or missing in a patterned injury cited by past investigators
447 could be addressed. This groundwork research is only the beginning. By establishing a
448 scientific template continued research should continue to develop this relatively new
449 scientific approach to pattern analysis.

450 Whether dental characteristics are reliably replicated in a bite mark in human skin is
451 the current challenge. The scientific validation of the correlation of bite marks, or tooth
452 patterns to their origin, in the opinion of the authors, predictably will be established by
453 statistical probability. That is, how many outlying characteristics demonstrated in a
454 pattern(s) would reliably predict the probability of another individual in the population
455 having the same combination of dental characteristics? For those images of the
456 bitemarks that include all six anterior teeth, or several teeth that enable the investigators
457 to insert all ten, or at least some of the markers from Tom's Toolbox[®], measurements of
458 distances and angles could be determined, saved, calculated, stored in an internal data
459 set ranked in percentiles. This application establishes outliers for those specific
460 characteristics for a data set that includes males between the ages of 18 and 44 years
461 in the State of Wisconsin. This is not to imply that only males bite. Women children, and
462 animals also bite others and even inanimate objects. In the personal experience of the
463 authors, perpetrators of human bites in violent crime are predominately males 18-44
464 years of age. This and limiting the number of samples required was the rationale for our
465 original study to that group. The study is meant to augment the established guidelines of
466 the American Board of Forensic Odontology. It should not be used in testimony or legal
467 proceedings.

468

Introduction

469 The National Academy of Science (NAS) report *Strengthening Forensic Science in*
470 *the United States: A Path Forward* (2009) challenged the forensic science community to
471 develop comprehensive reforms in using scientific methodology, guidelines and
472 standards for the analysis and reporting of an examiner's conclusions. [1] This research
473 is the culmination of ten years of applied science, studying bite mark analysis. It
474 demonstrates that human bite patterns can be replicated in porcine skin under some
475 conditions. The study also illustrates that analysis and recovery of meaningful data in
476 these patterns can be accomplished using a software application that recognizes the
477 systematic placement of markers and calculates angles and distances (Biometrics).
478 This pattern analysis software was developed by the investigative team in earlier
479 research. This basic drag and drop marker program was developed as a tool for the
480 forensic image specialists and forensic odontologists' use in the evaluation of patterned
481 injuries. It also would initially assist crime laboratories and investigating agencies in
482 determining whether there is the need for the expert services of a forensic odontologist
483 to interpret the patterns.

484

485 Statement of Problem

486 The scientific basis for bite mark analysis has been questioned. The National
487 Institute of Justice awarded a three-year research grant to determine whether the
488 patterns of human teeth can be replicated in skin and correlated to the source with a
489 degree of probability. Additionally a proposal was made to develop a template for
490 forensic odontologists and forensic imaging specialist in ascertaining the forensic value

491 of the pattern. This template is not rigid in the software and materials that future
492 researcher use. It is only a general plan (template) for future researchers to follow to
493 expand the testing of a scientific method in the replication and analysis of bite marks in
494 human skin. Prior research provided the accuracy and validation of a software
495 application (Tom's Toolbox[®]) which demonstrated it was reliable, repeatable and
496 consistent with acceptable scientific methods. A blind study was designed and used to
497 determine the statistical probability of a best fit. Two hundred patterned injuries were
498 produced in porcine skin, documented by scaled digital images and analyzed. Two
499 statistical models were used to establish the probability of a correlation of a replicated
500 pattern with the known model in the population dataset. Confidence intervals and levels
501 are reported. Factorial conclusions are presented based on the demographics of a
502 male population between the ages of 18 and 44 years in the State of Wisconsin.

503 **Literature Review**

504 In prior research, the investigative team developed a means of measuring and
505 quantifying seven specific characteristics of the human dentition. [2] This established a
506 population dataset of 469 samples from males 18 – 44 years old that closely mirrors the
507 distribution of the ethnic population in the State of Wisconsin. [3] The methodology
508 employed was validated by testing repeatedly for reliability and accuracy. [4] Inter-
509 operator and intra-operator agreement was studied and found to be extremely high. The
510 result of repeated testing demonstrated that the methodology and protocol have a
511 confidence level of 95% and a confidence interval of ± 1.55 .

512 The methods of bite mark analysis, used over time, have ranged from:

- 513 ▪ Simple observation;
- 514 ▪ The direct comparison of a known dental model to the injury pattern;
- 515 ▪ Hand-traced outlines on clear acetate of a model of known dentition;
- 516 ▪ Radiographs of Barium filled wax imprints of the known model as an overlay;
- 517 ▪ Photographic transparent prints of images of the teeth utilized as an overlay;
- 518 ▪ The use of optically scanned images of the dentition to produce overlays in
- 519 Adobe Photoshop®
- 520 ▪ Computer assisted analysis.

521 All of these techniques have their limitations, which include the viscoelasticity of skin,
522 distortion from movement, photographic distortion and many other problems that are
523 frequently cited and are well known to forensic examiners. Although these problems can
524 occur, bite mark patterns may still provide details which have value. It is also important
525 to point out, though most bite marks involve those observed in human skin; human
526 tooth patterns have been recovered from inanimate objects and analyzed by the
527 authors, e.g. kid gloves, automobile visors and steering wheels, a soft burrito, a bar
528 soap, a wad of chewing gum and an apple.

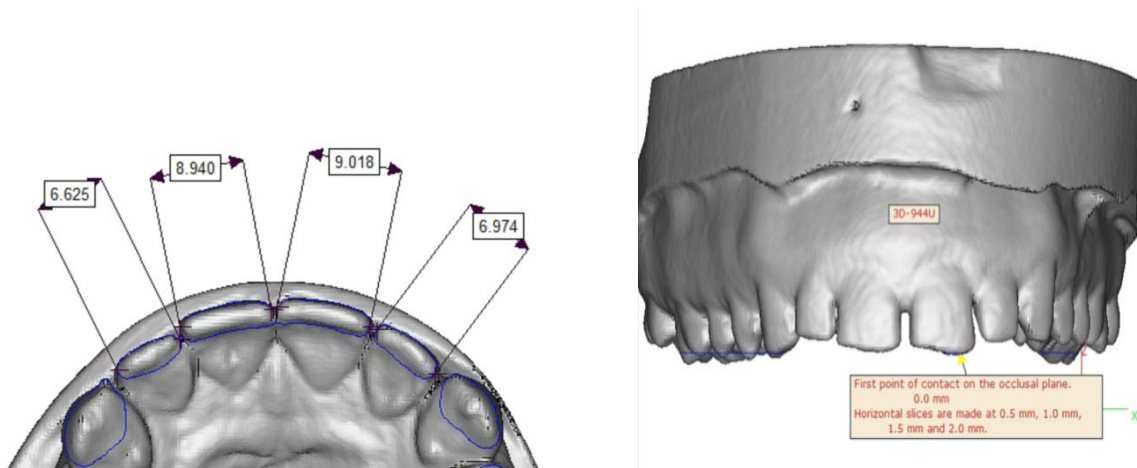
529 An additional study of a seventh dental characteristic, quantifying the displacement
530 of anterior teeth from the physical or native curve of each dental arch, was subsequently
531 conducted and published. [5]

532 To establish the amount of displacement of the teeth, a baseline was necessary.
533 Testing was conducted to determine whether an ellipse, a Bezier curve, or polynomial
534 curve would provide the best fit. A third degree polynomial curve was determined to be
535 the most appropriate. An algorithm was written for the ten markers to be placed in a 1:1
536 scaled image of the anterior teeth. The markers were placed at the center of the contra-
537 lateral canine teeth to serve as the anchors and a marker was placed at the center point
538 of each of the four incisors. This generated a third degree (best fit) polynomial curve.
539 Based on this technique of establishing a baseline which follows the physiologic curve
540 of the specific jaw and from which measurements could be made, the investigators were
541 able to quantify displacement in labio-version or linguo-version, a seventh individual
542 dental characteristic. It was also possible in this study to again establish inter-observer
543 and intra-observer error rates. .

544 Adding to the data of the pattern reflecting width of the incisors which may not all be
545 on the same horizontal (Z) plane, a three dimensional study was undertaken. Advances
546 in Cone Beam Computer Technology (CBCT) have established that linear
547 measurements in 3-D imaging programs are statistically no different than using a direct
548 digital caliper measurement method considered by orthodontists to be the most accurate
549 for these measurements. [6] [7] [8] [9] This three-dimensional, expanded data set on the
550 width of the eight incisors in 0.5 mm incremental “slices” on the Z plane has been
551 reported and published. [10]. Three-dimensional, digital Imaging communication in
552 Medicine (DICOM) images were obtained from the scanning the dental stone models,
553 utilizing Cone Beam Computer technology. These DICOM format files were then
554 converted to an STL format. The width of the incisors in the three-dimensional images

555 of the dentitions were measured on the "z" plane using Materialise® MiniMagics®
556 software. (Figure 1)

557



558

559

560 **Figure 1.** Illustrates the width of the maxillary incisor teeth measured at 1.0 mm
561 above the first point of initial contact on the horizontal (Z) plane using the MiniMagics®
562 software.

563

564 An additional paper providing data on the correlation of arch width with ethnicity was
565 published.[3] McFarland, Rawson, Barsley and Bernitz have all contributed to the
566 quantification of individual characteristics of the human dentition and identified problems
567 that existed regarding a statistical evaluation of individuality. [11] [12][13] [14] None of
568 these papers included a data set of significant statistical size, compared to that
569 developed by the current research team, nor did they include the analysis in the third
570 dimension on the (Z plane).

571 **Statement of Null Hypothesis**

572 It is not possible to replicate bite mark patterns in porcine skin, nor can these bite
573 mark patterns be scientifically correlated to a known population data set with any
574 degree of probability.

575

576 **Methodology**

577 To obtain pattern characteristic correlations using a two-dimensional comparison of
578 the unknown injury patterns (bite marks) to the known population data set, this study
579 proposes to:

- 580 • Demonstrate whether it is possible to replicate, in vivo, known dental pattern
581 characteristics (bite marks) in porcine skin.
- 582 ▪ In a blind study, use 50 models randomly chosen from 500 previously measured
583 Castone[®] models to be prototyped in a hard polymer by sintered
584 stereolithography (SLS),
- 585 ▪ Document, analyze the patterns recorded and develop analytic models which
586 could establish the statistical probability of a correlation of any of the pattern
587 registrations in the pig skin (pattern replication), would have to the authors'
588 population data set of known characteristics.
- 589 ▪ Determine the circumstances; area of the skin, the number of pounds force (lb^f)
590 and duration of the applied force which produced identifiable and measureable
591 patterns.
- 592 ▪ In the absence of the other landmarks to establish an X axis, develop
593 modifications of Tom's Toolbox[®], enabling the measurement of the angles of

594 rotation of individual incisor teeth using the intersection of an extended incisal
595 line, based on Euclidean geometry. Determine the range of pounds force (lb^f)
596 produced by males, age 18 – 44 when creating a bite mark.

- 597 ▪ Based upon all of the preceding, establish a basic template and technology for
598 the forensic imaging specialist and forensic odontologist to use in analyzing and
599 evaluating patterned evidence.
- 600 ▪ Provide a scientific template for future research with an enlarged population
601 database and more sophisticated imaging software.

602

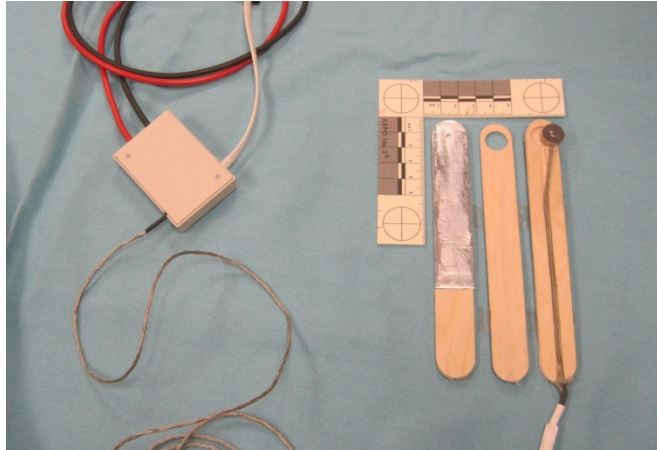
603 **Establishing bite forces**

604 Bite force measurements in the central incisor area were established using a mini
605 load cell from Omega Engineering, Inc. (One Omega Drive, P.O. Box 4047, Stamford,
606 Connecticut 06907-0047), serial no. 291633 and recorded using a precision Bridge
607 Excitation voltage, $V_B = 5.000$ VDC. Subjects were instructed to bite as hard as they
608 could over a 10 second period. The initial output offset voltage, V_{OS} , mV and the
609 resultant maximum load cell output reading V_{out} , were mV recorded. All output voltages
610 were corrected by subtracting V_{OS} and subsequently converted to actual biting forces in
611 pounds force (lb^f). These conversions were accomplished using manufacturer
612 calibration data (5-Point NIST Traceable Calibration) that accompanied the load cell.
613 The results were plotted graphically using lb^f for the y axis and individual results on the
614 x axis. Those results that fell outside two standard deviations were discarded. The
615 resulting N of 31 was totaled and the average recorded.

616 In replication of patterns utilizing the pounds force (lb^f) cited in the literature by
617 Anusavice, the authors determined that the 20 to 30 lb^f cited in the text was insufficient
618 to produce the degree of tissue injury commonly observed in bite marks. [15] In order to
619 ascertain whether this observation was valid, an additional study was developed.

620 Caucasian male dental students who volunteered to participate were examined. The
621 initial IRB protocol limited participation to 50 individuals. Nineteen individuals were
622 dropped, making the final total thirty-one. Three were eliminated because they
623 exceeded the 22 to 32 age range of dental student volunteers cited in the IRB protocol.
624 Sixteen were excluded because the initial design of the load cell force transducer
625 produced evidence of hysteresis or fade. A modification in the design of the bite force
626 transducer included an intervening strip of stainless steel and a vinyl index to guide the
627 lower incisor directly over the location of the load cell. The average bite force for males
628 between the ages of 22 and 32 years with N=31 was 62.5 lb^f or 278.01N. This is
629 significantly higher than the average bite force reported by Anusavice [15]. The actual
630 minimal to maximum forces generated was 19.2 lb^f to 132.1 lb^f or 111.21 N to 587.61N.

631 The force was calculated using an Omega[™] model LCKD-100 load cell force
632 transducer sandwiched between two parallel wooden tongue depressors with a metal
633 plate directly over the sensor to avoid compression [Figure 2], that could result in
634 hysteresis in evaluating applied force. Sample results are shown in [Table 1] which
635 indicated an average of 62.5 pounds force, with a maximum of 132.1 pounds force and
636 a minimum of 19.2 pounds force for a group of volunteers on a given recording date.



637

638 **Figure 2.** An exploded view of the prototype bite force transducer using the Omega™
639 model LCKD-100 mini load cell, to determine the range of pounds force (lb^f) generated
640 by twenty males ages 22 to 32. The insertion of a sheet of stainless steel controlled
641 hysteresis.

642

Bite Measurements Dates 14 December 20 2012, 4 Jan 2013, 11 Jan 2013
 Load cell Serial No. -291633 By: D Jetter and T. Radmer
 Bridge Excitation V= 5.000
 SoD Room 1060
 Note: Stainless steel inner layer and incisal alignment guide added to transducer

Subject Code Number	Subject age	Initial offset V_{out} , mV	Load cell V_{out} , mV	Actual Bite Force #F	Notes
617	29	0.146	9.475	132.1	
34	26	0.142	2.76	37.1	
519	26	0.142	1.78	23.2	
409	24	0.137	3.57	48.6	
225	26	0.154	5.76	79.4	
599	27	0.137	3.47	47.2	
41	25	0.137	3.7	50.5	one incisal restoration
218	26	0.134	5.66	78.2	
415	24	0.134	3.98	54.5	
259	27	0.141	3.164	42.8	
398	24	0.138	4.378	60	
945	39	0.142	1.863		dropped
797	25	0.147	5.46	75.2	
322	34	0.144	3.66		dropped
380	25	0.146	1.5	19.2	
540	31	0.134	5.66	78.2	
67	25	0.136	4.1	56.1	
199	25	0.117	8.097	112.7	
52	23	0.028	6.355	89.6	
376	26	0.032	6.849	96.5	
326	25	0.059	3.78	52.7	
35	27	0.046	6.13	86.2	
496	23	0.047	6.399	89.9	
662	27	0.04	3.95	55.4	
591	25	0.045	3.78	52.9	
749	25	0.039	2.146	29.8	
804	25	0.057	2.56	35.4	
303	26	0.048	4.96	69.6	
576	25	0.62	1.826	25	
530	33	0.45	5.08		dropped
51	27	0.044	5.721	80.4	
643	22	0.067	4.84	67.6	
850	22	0.064	3.769	52.5	
568	26	0.09	3.98	55.1	
88	24	0.042	3.96	55.5	
318	26	0.036	5.22	73.4	
			Sum	2062.5	
			average 31 subjects	62.5	

643

644 **Table 1.** Illustrates the range of bite force (lb^f) that can be generated by thirty-one
 645 males age 22–32 in the region of the maxillary incisors. The average (mean) was 62.5
 646 lbs/Force.

647

648 **Procedure for measuring bite mark patterns.**

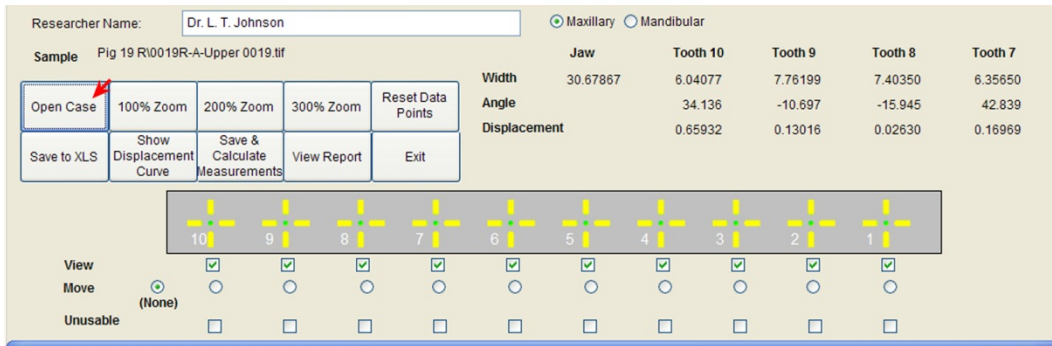
649 Using in-vivo porcine skin to research patterned injuries in human skin has had
 650 widespread acceptance in the medical and dental literature.

651 A literature review of the use of a porcine model in bite mark research and analysis
652 provides only two examples when using the terms bite mark and porcine skin as search
653 criteria [16], [17]. Past and current literature compares the porcine skin model closely
654 with human skin [18].

655 In previous studies, a template for the measurement of individual characteristics of
656 the human dentition in two-dimensions was established by the authors [4]. This included
657 the development of an original software application, copyrighted as Tom's Toolbox[®].
658 [Figure 3] This software is a semi-automated software application using a palette of ten
659 markers which when inserted by the analyst in a scaled digital image, calculates
660 distances and angles based upon the Pythagorean Theorem. It is licensed to
661 governmental and non-profit organizations by Marquette University The markers are
662 inserted in specific locations on a scaled digital image of the bite mark at the starting
663 and ending point of the areas to be measured. The software recognizes the location of
664 each of the markers by column and row. It first performs a quality control procedure to
665 assure that all of the markers have been inserted and are in the correct order. It then
666 calculates distances and angles of rotation.

667

668

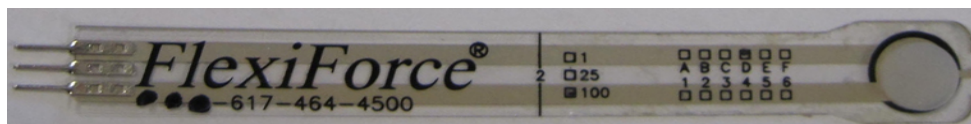


669

670 **Figure 3.** The tools panel used in pattern analysis. The arrow indicates the tool used
 671 to open a case for analysis in Tom's Toolbox^{©i}

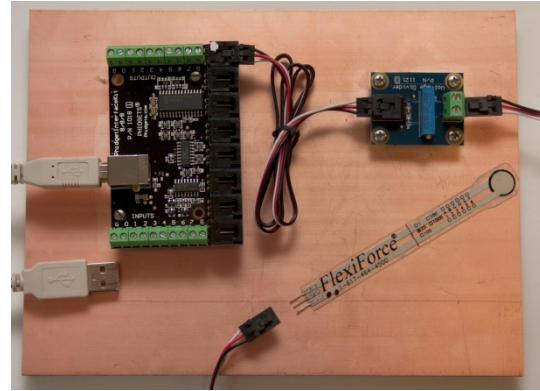
672 **Calibration of the FlexiForce[®] Sensors**

673 A method of providing standardized forces, duplicating the human bite
 674 forces was addressed using FlexiForce[®], sensors (0-100 lbs.), mounted in a
 675 custom designed recording pattern replication device. The FlexiForce[®] sensor is
 676 a versatile, durable piezo-resistive, force sensor that can be constructed in a
 677 variety of shapes and sizes. The device senses resistance inversely proportional
 678 to an applied force. It has a patented ultra-thin (0.008 inches) flexible printed
 679 circuit that senses contact force. It acts as a force sensing resistor in an electrical
 680 circuit. When the sensor is not loaded, resistance is very high and when the force
 681 is applied the resistance decreases proportionately. The FlexiForce[®] sensors
 682 were coupled with an application that measures force-to-voltage in a circuit.
 683 [Figures 4, 5, 6 and 7].



684

685 **Figure 4.** Illustrates a 0-100 lb. FlexiForce[®] sensor
 686 with the supplied silastic pressure button, which resulted
 687 in fade, (hysteresis) when recording applied force.



688

689 **Figure 5.** Omega LCKD 100 mini load cell.

Figure 6. The Phidgets data system

690

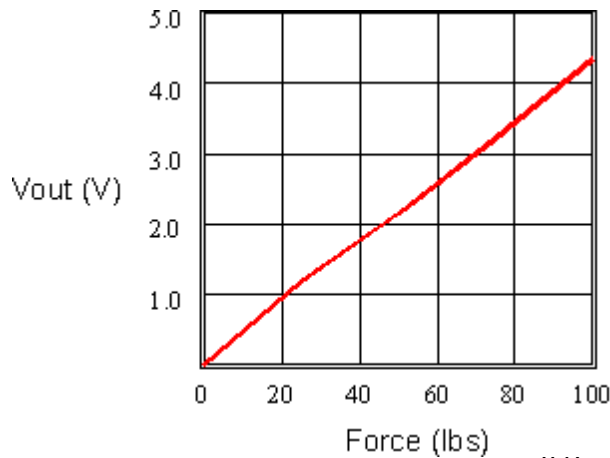


Figure 7. Illustrates the FlexiForce[®] Sensor response graph

www.trossenrobotic.com [20]

698 FlexiForce[®] Transducers (FFT) [20] were incorporated into the apparatus to measure
 699 the applied force, as described elsewhere.[21] These thin transducers are in the Force
 700 Sensing Resistor (FSR) family that changes resistance from open circuit at 0 lb^f, applied
 701 forces to a resistance that progressively decreases as additional force is applied. The
 702 resistance output is linear ($\pm 3\%$) with applied input force. The FFTs were calibrated *in*
 703 *situ* after mounting in the bite replication model. Calibration of each FFT in the pattern
 704 replication device was accomplished by inserting a commercial subminiature industrial
 705 compression Omega load cell model LCKD-100 with a capacity of 0 to 444.82 N
 706 (Omega Engineering Inc., Stamford, Connecticut, U.S.A., 06907-0047) in series with the

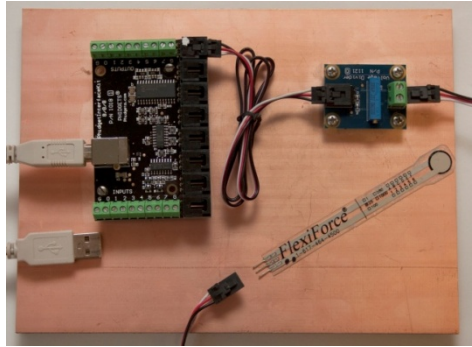
707 FFT while forces were applied. This is the same Omega load cell which was used
708 directly in the tongue depressor bite force transducer, measuring the dental students'
709 bite force. Each bite replication model's calibrations data was recorded in spreadsheets.

710 The FFT selected for bite force measurement, (0-100 lb. FlexiForce[®] resistive
711 sensor) is manufactured by Tekscan, Inc. (model A201 E) 134 Tekscan Inc. 307 West
712 First Street, South Boston, Ma., U.S.A. 02127-1309). It is basically a flexible plastic film
713 printed circuit approximately 0.22mm thick by 102mm. long by 14 mm. wide. The
714 sensitive force registration area is 0.375 inch (9.53mm) diameter.

715 The FFT was incorporated into a voltage divider circuit to obtain a voltage change
716 that is proportional to the change in applied force. This voltage divider is part of a
717 commercial data acquisition system, a 1120 FlexiForce Adaptor that was purchased
718 from Phidgets, Inc. (Phidgets[®] Inc. Unit 1, 6115- 4th Street S.E., Calgary, Alberta,
719 Canada T2H 2H9) leading into a Phidgets Interface Kit 8/8/8 P/N 1018. [figure8]

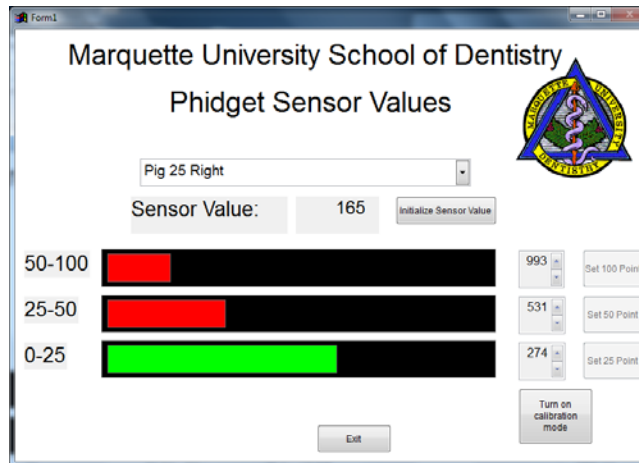
720 The complete Phidgets data acquisition system consisted of a voltage divider, a
721 precision voltage reference source, an Analog to Digital Converter board (ADC), USB
722 interface and a laptop computer [figure 9]

723



724

725 **Figure 8.** The Phidgets / FlexiForce[®] transducer (FFT) system block bridged to a
 726 display and storage application custom designed for the PC laptop by the team's IT
 727 manager.



728

729 **Figure 9.** A screen capture of the computer display of the application which provides
 730 a visual and an audible indication of the applied lb^{force} and the duration it was applied.
 731 The application also creates a complete log of the session.

732

733 **Model duplication and mounting**

734 The dental stone models proved to be brittle and porous and were unsuitable for this
 735 study. They would not withstand the forces applied [figure 10].



736

737 **Fig. 10.** Illustrates one of the original dental stone models used to create the
738 population data set in prior research.

739 Fifty sets of upper and lower dental stone models were randomly selected from the
740 population data set which was established and reported in previous studies. [2][3][5][10]
741 The statisticians for the project created a blind list of models for the investigators
742 numbering the fifty pairs of models in random order, using the identifier of Fig 1R and
743 Fig 1 L to identify the first two sets of models that were selected from the data set of N=
744 469. Subsequent models were similarly identified in alpha numeric fashion by pig
745 numbers 1-25. The fifty hard polymer models were produced by stereolithography,
746 using a 3M™ ESPE Lava COS scanner and Lava Software 3.0. (3M ESPE Divisions,
747 3M Center, St. Paul, MN 55144-1000, U.S.A.).

748 The method determined to be the most expeditious for the duplication of the models
749 was to prototype them in a durable resin capable of withstanding the forces to be
750 applied. The dental stone models were scanned in STL format files utilizing the 3M™
751 Lava COS® scanner, a chair-side optical scanner originally designed to capture a three-
752 dimensional image and directly generate a prototype model of the dentist's prepared
753 tooth for laboratory procedures. It replaced the necessity for an indirect dental
754 impression. (3M™ Corporation, St. Paul, MN). (Figure 11A and 11B)



755

756 3M™ ESPE Lava COS® scanner [11A]

Screen capture of a scanned model [11B]

757 **Figure 11 A and Figure 11 B.** Illustrates the 3M™ ESPE COS chair side optical
758 scanner and a screen capture of a three-dimensional image of the dental stone models
759 in STL format.

760

761 After the models were prototyped by the 3M™ Corporation using sintered
762 stereolithography (SLS) the prototyped models were returned in a hard 3M™ proprietary
763 polymer with sheer strengths equal to or exceeding bite forces of the natural dentition of
764 20-25 pounds force. [15] (Figure 12)



765

766 **Figure 12.** Illustrates the 50 blind prototyped models returned by the 3M™ Corporation.

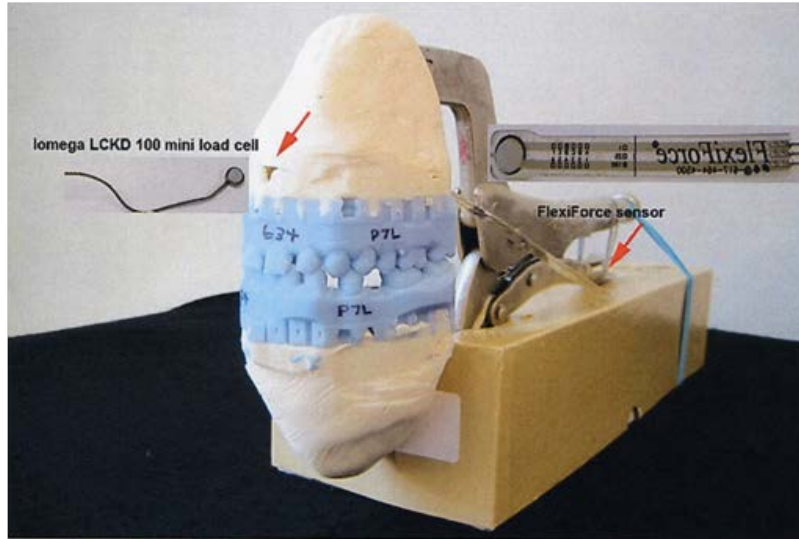
767 A protocol standardizing the replication of dental characteristics in porcine skin was
768 developed using a modification of an apparatus reported in an earlier study. [19][21]
769 The models were mounted on a modified Irwin™ welder vise grip, using dental
770 laboratory acrylic. (Figure 13) (Figure 14) A means of recording the applied pounds
771 force (lb^f) and the duration of the applied force in a log was developed. By incorporating
772 a force sensor, (FlexiForce® 100 lb. sensor), a Phidgets device to bridge the sensor to a
773 notebook computer running Lab View software, an auto-recording, pattern replication
774 device was designed. The models were articulated utilizing a custom jig to standardize
775 the mounting of the models on the 50 replication devices which were required.

776 The models were mounted, using a custom mounting jig developed to align the
777 dental models in a normal occlusal relationship.



778
779 **Figure 13.** Illustrates the mounting jig on the left. The upper mounting base in
780 the center showing the dowels permitting the vertical travel, yet maintaining the
781 inter-arch relationship of the models. On the right, a FlexiForce® sensor is
782 shown inserted directly over the anterior teeth.

783



784

785 **Figure 14.** Illustrate a completely assembled pattern replication device with a channel
 786 above the maxillary incisors for the introduction of the Omega load cell for the
 787 calibration of the FlexiForce sensors in each of the 50 pattern replication devices.

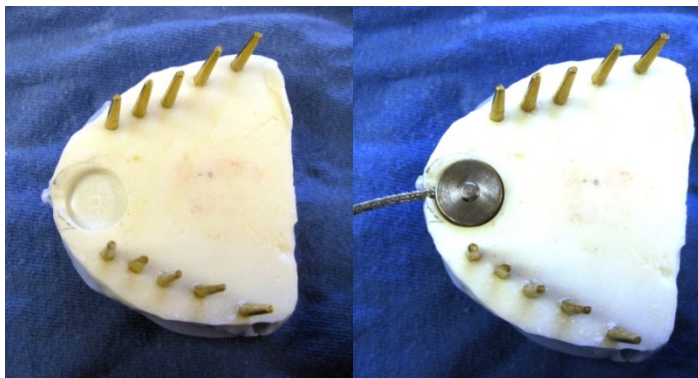
788

789 The mounting was designed so the upper dental model does not adhere to the upper
 790 acrylic base. Its position is maintained, but allowed to travel vertically, using ten parallel
 791 brass dowels, keyed to the upper model's anatomic relation to the lower model. The
 792 dowels were placed in the maxillary molar, premolar and canine locations before the
 793 upper model is mounted to the C-clamp with the laboratory acrylic. Tin foil substitute
 794 was used to permit the model to be separated later for the insertion of the omega load
 795 cell for calibration of a FlexiForce[®] pressure sensor. This step was necessary to prepare
 796 the replication apparatus for the calibration of each FlexiForce[®] sensor.

797 **Biomedical Engineering Laboratory Procedures**

798 Once dismounted from the C-clamp device, a flat bottomed, one half inch recess
 799 was created in the base of the maxillary model with a Forstner 1/2 " drill bit to accept a

800 mini load cell used to calibrate the FlexiForce[®] sensor in each of the 50 pattern
801 replication devices. (Figure 15)



802

803 **Figure 15.** Illustrates the recess created for
804 insertion of the Omega model LCKD-100 mini load cell.

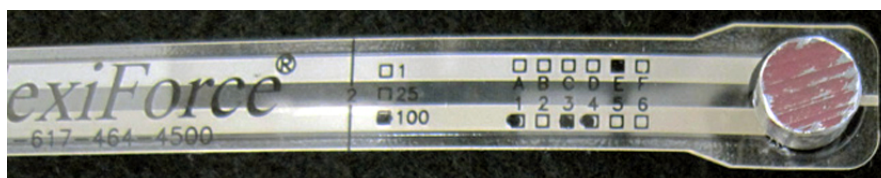
805 To mate the Omega mini load cell and the pressure sensing area of the FlexiForce[®]
806 sensor and minimize hysteresis, a button was machined from a 3/8th aluminum rod,
807 the exact diameter of the pressure sensing area of the 8 inch FlexiForce[®] 0-100 lbs.
808 resistive force sensor (Trossen Robotics, 2749 Curtiss Street, Downers Grove, IL
809 60515). This ensured that the force transmitted through the incisal edges of the
810 maxillary incisors were compressing the entire area of the force sensor and that the
811 force was directed perpendicular to this contact point. (Figure 16)

812 The calibration procedure was carried out by connecting the installed FlexiForce[®]
813 Transducer (FFT) to the Phidgets data acquisition system and verifying its operation on
814 the connected laptop computer, running the software application. (Lab View). Next, the
815 load cell was placed in the replication apparatus, arranged mechanically in series with
816 the embedded FFT sensor so that both transducers experienced the same biting force.
817 Force was applied at 0, 25, 50 and 100 pounds-force increments then removed at 50,

818 25 and 0 pounds force increments. Corresponding data from the FFT and the load cell
819 were taken at each force increment and stored in a time and date stamped computer file
820 for each of the 50 models and 50 corresponding pig locations.

821 Initial experience with the calibration of the FFT revealed that a means of applying
822 force explicitly to its 0.375 inch diameter force sensing area with an incompressible
823 interface is essential. The rigidity of the button material and its diameter are critical to
824 avoid fade or hysteresis in the recording of sustained forces. The solid aluminum discs,
825 machined from aluminum rod, provided the least fade in the pressure force
826 measurements when the anterior dentition was loaded for 15 seconds and provided the
827 desired FFT adaptation to the pattern replication device. The button thickness was
828 selected to properly couple the force generated by the anterior teeth sensing area on
829 the FFT to the button sensor of the mini load cell. The resultant remaining hysteresis in
830 our measurements was that contributed by the FFT at <4.5% of full scale.

831



832

833 **Figure 16.** Illustrates the 0-100 lb. FlexiForce[®] sensor
834 with the custom machined aluminum pressure button.

835 Procedures were developed early on to enable initial testing, evaluation and
836 calibration of the FlexiForce[®] sensors. This allowed for an informed design of the
837 interface buttons, the signal conditioning circuits for the load cell and the Phidgets
838 system for FFT data acquisition. Bench testing was done by placing the load cell

839 mechanically in series with the FFT in a small hobby vise with careful alignment of the
840 FFT, button and load cell. (Figure 17)

841 Bench testing was done by placing the load cell mechanically in series with the FFT in a
842 small hobby vise with careful alignment of the FFT, button and load cell. (Figure 17)



843

844 **Figure 17.** FFT transducer calibration was accomplished in series with
845 the Omega load cell in a small bench vise.

846

847 This simple means of applying a variable force to the FFT and the load cell allowed
848 for an informed incorporation of the FFT sensors into the bite models as well as for
849 system development.

850 The Omega model LCKD-100 load cell force transducer was specifically selected for
851 this force measurement and calibration efforts because of its small size. The 0.5 inch
852 diameter by 0.25 inch thick load cell came with a five point NIST documented calibration
853 with a $\pm 0.25\%$ accuracy, sensitivity of 2mV/V (i.e.: ratio metric), full scale output of 100
854 pounds-force (444.82 N), linearity of $\pm 0.25\%$ of full scale output, $\pm 0.25\%$ hysteresis with
855 respect to full scale output, and a repeatability of $\pm 0.10\%$ repeatability with respect to

856 the 100 pound-force scale capability. The transducer is temperature compensated. This
857 precision load cell provides a force proportional voltage output signal to a custom
858 designed amplifier signal conditioner. These specifications ensured that the load cell
859 could be used as a precision calibration reference for the FFT sensors.

860 The load cell's internal strain gauge sensors are connected in a full 350 Ohm bridge.
861 The bridge was excited with a stable, precision 5 VDC and the differential bridge output
862 signal was connected to the input of a custom designed signal conditioner. The signal
863 conditioner was configured with two stages of gain, regulated power supply voltage and
864 a novel automatic zero calibration. The two operational amplifier (OP AMP) gain stages
865 provided a total gain of $A_v=200V/V$. The two gain stages included an instrumentation
866 Amplifier (IA) cascade with a non-inverting gain amplifier for signal conditioning. The IA
867 has a voltage gain of $A_v=100$. A negative feedback circuit (A to D and D to A
868 converters) was added to the circuit to automatically cancel input offset voltage from the
869 load cell bridge prior to recording data.

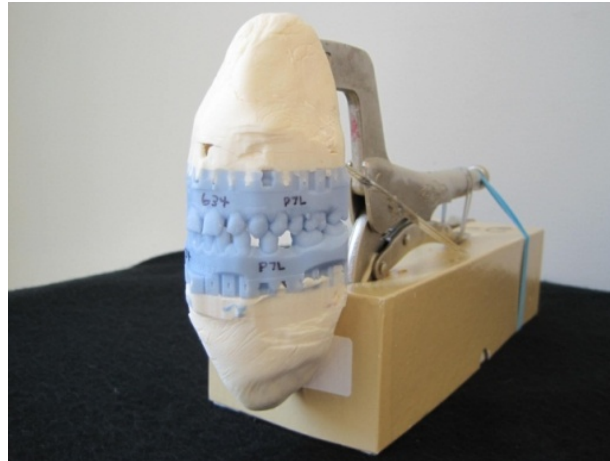
870 The output from the load cell conditioning circuit is given by:

- 871 • $V_{out} = \text{Load cell sensitivity [mV/pound -force]} \times \text{signal conditioner voltage gain [V/V]}$
- 872 • The load cell sensitivity is provided by the manufacturer: e.g. $S = 7.1 \text{ mV at } 100$
873 $\text{pounds-force (or } 71\mu\text{V per pound-force)}$.
- 874 • For example, if the applied force is 50 pounds-force, the load cell output is 3.55
875 mV . So the system output is: $V_{out} = 3.55\text{mV} \times 200 \text{ V/V} = 710\text{mV}$.

876 Calibration was performed on each instrumented bite model prior to its

877 use. (Figure 18A, 18B)

878



879

880

Figure 18A. Depicts an articulated replication device.



881

882

Figure 18B. Upper model travels vertically on ten brass dowels.

883 **Animal Laboratory Procedures**

884 Animal research sessions were conducted in accordance with the standards of the

885 *Guide for the Care and Use of Laboratory Animals* (8th edition, National Academies of

886 Sciences, 2011) and approved by the Medical College of Wisconsin, Institutional Animal
887 Care and Use Committee (IACUC). (Figure 19)



888

889 **Figure 19.** Illustrates the Biomedical Resource Center's large operating suite
890 at the Medical College of Wisconsin where the animal research was conducted.

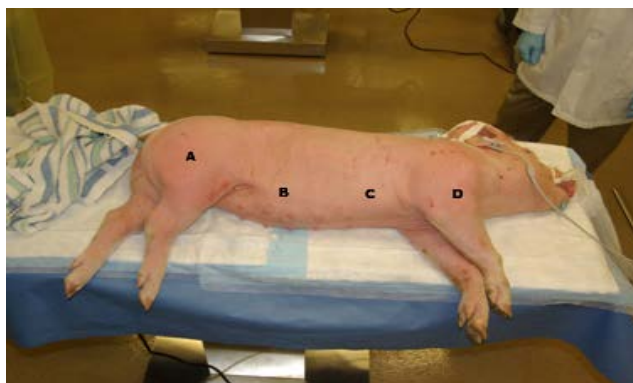
891

892 Mixed-breed young pigs, weighing 30-40 kg were obtained from a commercial
893 breeder and acclimated in the large animal laboratory research facility for a period of at
894 least 2 days before the laboratory procedures were performed. Anesthesia was induced
895 with a combination of tiletamine/zolazepam (Telezol[®], 4.4 mg/kg) and xylazine (2.2 mg.
896 /kg) administered intramuscularly. Following induction, an endotracheal tube was placed
897 and hair from the anatomical sites of interest was removed using a commercial hair
898 clipper, razor, and/or depilatory cream. To conserve body temperature, animals were
899 placed on heated pads on the surgical tables and covered with towels and a
900 PolarShield[®] Emergency Survival blanket (RothCo 3015 Veterans Memorial Highway,
901 Ronkonkoma, and New York 11779-0512). The pigs' body temperatures were

902 maintained between 36.2 and 39.3 degrees C. Using a rectal thermometer, two
903 veterinary technicians monitored the pigs' body temperature and respiration.

904 The mean procedural temperature was 38.1C (36.2C – 39.3C). The mean low 36.2C
905 (33.9C – 37.0C) and the mean loss was 1.8C (0.2C – 4.3C). Following animal
906 preparation, a surgical plane of anesthesia was maintained using isoflurane
907 administered through the endotracheal tube using a precision vaporizer and
908 compressed oxygen. Basal anesthesia was augmented as needed in some animals with
909 pentobarbital administered intravenously.

910 The four designated sites to receive the patterned injury were the lateral aspects of
911 the upper hind limb/thigh, abdomen/flank, thorax, and shoulder/upper forelimb of the
912 animals. (Figure 20)



913

914 **Figure 20.** Depicts the four standard sites selected on each side
915 of the animal for the replication of bite marks (patterned injuries).

916

917 Because the surface and sub-surface features of porcine skin, *Sus scrofa*, vary with
918 the anatomic location, much the way they do in human skin, multiple sites were chosen
919 to receive the replicated bite. In their confocal laser scanning microscopy of porcine skin

920 in wound healing, Vardaxis et al, have demonstrated that the success of such studies is
921 dependent on control and standardization of the injury infliction protocol. [22] The size of
922 the pigs used (20-40 kg) and the skin structure made the production of patterns possible
923 at similar anatomical locations bilaterally, with observations and photography made 15
924 minutes post-infliction to introduce as little variation between areas on the same animal.
925 There were a total of eight (8) replicated bites on each animal. The pounds force (lb^f)
926 necessary to produce the patterns were standardized from 50 to 99 lbs. and were
927 continuously monitored using the described FlexiForce[®] sensor connected to a force-to-
928 voltage circuit and data acquisition system.

929 Each application was held for a minimum of 5 seconds to a maximum of 15
930 seconds, or the estimated time that a human with normal musculature and tempo-
931 mandibular joint function can maintain a sustained force without muscle fatigue. [23]
932 [24]

933 **Forensic Digital Photography**

934 The patterned injuries were created with the custom designed, semi-automated,
935 recording pattern replication apparatus. The injuries were digitally photographed at 1:1
936 scale (life size) by a highly experienced forensic photographer, beginning 15 minutes
937 after their creation, using a Canon[™] EOS 5d Mark II, ~ 21mp with a Canon Macro EF
938 100mm 1:2.8 USM lens, set to autofocus. Lighting was provided with a Canon 580 EX II
939 flash set to Manual 1:2 power. The flash unit was used off camera held oblique to the
940 bite pattern. Camera settings were at the manual exposure of 1/200th @ f16-32, 100
941 I.S.O. with the white balance set on Flash. Large JPEG format imaging process

942 consisted of converting RAW images in Adobe Photoshop CS5 (cropped to 4x4 inches)
943 and then calibrated to 1:1 at 300 ppi and saved in TIFF format. Calibration and
944 correcting for perspective distortion can be two different issues. Even though they are
945 related, they are separate entities. An orthogonal object may not be 1:1 (or calibrated).

946 The calibration of the patterned injury proceeded by determining the total number of
947 pixels within a known distance. Once determined, that known pixel count can be
948 provided into the image size box with the known distance set and the calibrated
949 resolution, for that distance, will be revealed. That resolution is used to determine the
950 exact size of the image by placing it into the image size box with all three known (length,
951 width and resolution) "locked". When perspective distortion is introduced (and most all
952 systems/lenses have some - optical and linear) the calibration may (most will dependent
953 upon amount) become skewed. The forensic photographer used the least distorted
954 portion of the scale for our calibrations. As an alternative, there is a correction for this
955 distortion in Photoshop (especially if it is slight). The other option was to be certain that
956 our scale is perfectly flat upon the pig and the camera plane is parallel and
957 perpendicular. The forensic photographer employed a flat field lens to help reduce
958 optical distortion. At the laboratory, the images were then calibrated to 1:1 and the
959 analysis measurements made using the technique previously reported for Tom's
960 Toolbox[®]. [28]

961 **Image Selection**

962 A total of 800 digital images were exposed, four for each of the 200 sites, exposing
963 digital images from all four compass points following the guidelines of the Scientific

964 Working Group on Imaging Technology (SWGIT) [25] and the guidelines for bite mark
965 evidence of the American Board of Forensic Odontology (ABFO) [26].

966 Sorting and selection of the best quality image for each of the eight sites on the
967 twenty-five pigs was accomplished. Since in Tom's Toolbox[®] a scaled image of each
968 dental arch must analyzed separately by the semi-automated software, a total of four
969 hundred scaled digital images were calibrated at 300 dpi, duplicated and saved as
970 working images in TIFF format. Those patterns which registered all six of the anterior
971 teeth were considered complete, while those which registered only some of the anterior
972 teeth were classified as partially usable. A third category, unusable, was assigned to
973 those patterns which lacked sufficient detail.

974

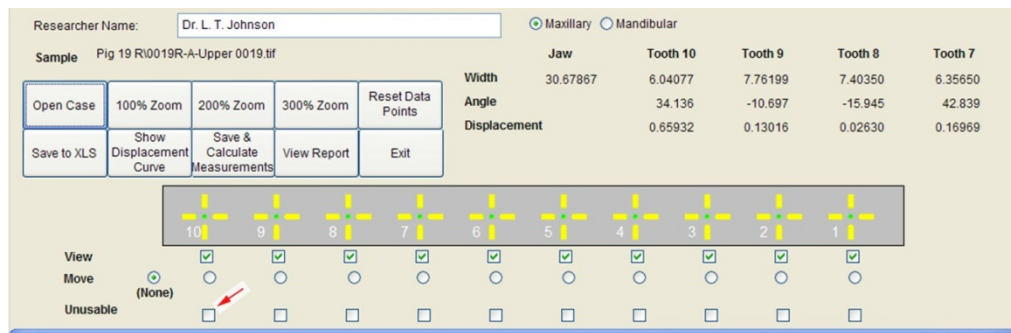
975 **Image analysis and measurement**

976 Duplicate working files of the 200 images were created for each of the investigators
977 to independently measure the characteristics available. The duplicate working files were
978 uploaded into the semi-automated computer application, Tom's Toolbox[®], where they
979 were independently measured and the data saved in an internal log.

980 The semi-automated software application, Tom's Toolbox[®], utilizes ten markers
981 which are inserted in a specific order into the image at the starting and ending points of
982 the pattern to be measured. The application recognizes the location of each marker by
983 column and row, to calculate distances and angles of rotation.

984 The usable and partially usable images were measured for arch widths, tooth widths,
985 angles of rotation, and spacing. The application provides the operator a check box

986 option for indicating whether any or all of the markers for measuring dental
987 characteristics cannot be placed. (Figure 21) Tom's Toolbox© saves the measurements
988 in a data set in an internal log. From the data saved in the internal log a software
989 application can then generate a report on the frequency distribution of the pattern in the
990 population dataset.



991

992 **Figure 21.** The arrow indicates the location of the control button used to
993 indicate that a specific site in the bite mark pattern image where a Toolbox
994 marker could not be inserted at that site.

995

996 The measurements from each examiner's image files were saved in a log within
997 Tom's Toolbox© and then transferred to an Excel spreadsheet for statistical analysis.
998 The spreadsheet is programmed to check for data entry errors.

999 Quality control was accomplished by identifying and correcting any errors or
1000 omissions in measurement or missing image files and a revised spreadsheet was
1001 created.

1002 Once the investigators were satisfied that all of the data in the spreadsheet was
1003 correct, it was transmitted to the collaborating statisticians for statistical analysis.
1004 Statistical programs were created by the consulting statisticians from the Medical

1005 College of Wisconsin and Marquette’s University’s College of Engineering, Department
 1006 of Electrical and Computer Science. These resources were utilized to develop models
 1007 enabling the determination of the probability that measurements of the individual
 1008 characteristics in the injury patterns could be correlated with a degree of probability to
 1009 the known model in our population data set, testing the stated hypothesis of pattern
 1010 replication.

1011 **Image selection**

1012 In the process of evaluating and sorting the suitability of the best 200 image, the
 1013 inter-observer agreement on suitability was highest for those considered to be complete
 1014 (these images exhibited recognizable sites for the insertion of all ten of the markers in
 1015 Tom’s Toolbox[®]). Both examiners agreed there were 87 of the 200 upper arch patterns
 1016 determined to be complete. Agreement differed somewhat in that examiner 1
 1017 determined 116 lower arch patterns were considered complete, while examiner 2
 1018 determined 110 were complete. (Table 2)

1019

	Investigator 1 Lower	Investigator 2 Lower	Investigator 1 Upper	Investigator 2 Upper
Number of Images Considered Partially usable	17 (8.5%)	39 (19.5%)	17 (8.5%)	34 (17%)
Number of Images Considered Completely Unusable	67 (33.5%)	51 (25.5%)	96 (48%)	79 (39.5%)
Number of Images Considered Complete	116 (58%)	110 (55%)	87 (43.5%)	87 (43.5%)
Total	200	200	200	200

1020

1021 **Table 2.** Illustrates the extent of the intra-observer agreement in the
 1022 selection of images for analysis.

1023 An observation related to the finding of image patterns that was considered
1024 completely unusable, is whether the production of the pattern was static or dynamic.
1025 There is little or no movement in a static bite and consequently there is a more distinct
1026 pattern registered.

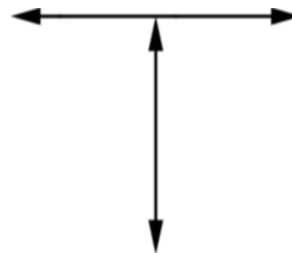
1027 **Determination of Angles of Rotation**

1028 In the earlier studies of complete patterns of the entire dental arch, angles of rotation
1029 were computed for each of the four anterior incisors. Computation was based on an x-
1030 axis established by the principal investigator. To establish an x-axis, an adjustable
1031 template consisting of both an X and a Y member was developed, which would
1032 superimpose a reference line (x axis) between the distal most points of the contra-
1033 lateral first molar teeth. The automatically adjusted Y axis bisects the X axis and
1034 establishes the midline of the arch. Adjustment to the specific landmarks on the image
1035 was accomplished in Adobe Photoshop, using the Edit > Transform > Scale, or >Rotate.
1036 (Figure 22A and Figure 22B)

1037



1038



1039 **Figure 22A.** The X Y axis inserted
1040 in a scaled image for measurement.

Figure 22B. The adjustable X Y template
used to establish the X axis.

1041 In the current pattern replication research project, only the registrations of the six
1042 maxillary and mandibular anterior teeth were imprinted. It then became necessary to

1043 establish an alternate method of determining angles of tooth rotation, independent of
1044 the posterior dentition. This approach measured tooth rotation in relation to the
1045 intersecting angles of an extended line projected on the incisal edge of each of the four
1046 incisors. This was accomplished through a modification of the use Tom's Toolbox[®] and
1047 the absence of X and Y coordinates for the pixel marker placed for each tooth. The
1048 incisal line is defined as a straight line along the incisal edge of the incisor teeth,
1049 connecting the directly opposite mesial point to the distal most point on the tooth's
1050 incisal edge. The extension of this line intersects with an adjacent incisal line of the
1051 other teeth forming a measurable intersecting angle. The computed angle of
1052 intersecting lines based on all combinations of the four anterior teeth was recorded.
1053 Assuming the four anterior teeth are A, B, C, and D, the computed angles of intersection
1054 would be: AB, AC, AD, BC, BD, and CD.

1055 **Recording force and duration**

1056 Using the SAS System and incorporating the Means Procedure, the electronic
1057 Phidgets logbook for the bite pattern replication study recorded 4684 points of data
1058 during the 25 sessions.

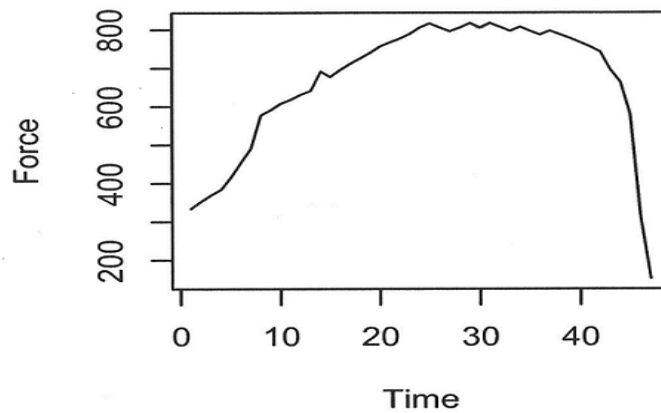
1059 The mean recording for all points in which pressure was applied was 545.6, with a
1060 standard deviation of 278.7 within the range of pressures recorded for each event
1061 between 0 and 997.0 on the FlexiForce[™] sensing device. Each of the FlexiForce[™]
1062 sensors were bench calibrated for pounds force (lb^f) with an Omega[™] model LCKD-100
1063 mini load cell. Force versus Time was plotted for each pig location. As an example,
1064 Pig25_L_A (left side, pig 25, position A) is represented in figure23 and the resultant bite

1065 pattern can be seen in figure 24. Each of the 200 patterns was similarly correlated to the
 1066 maximum force of the device over a period of 15 seconds.

1067 **start_side_site=Pig_25_L_A**

Analysis Variable : value				
N	Mean	Std Dev	Minimum	Maximum
47	665.5531	168.9966	152.0000	817.0000
	915	309	000	000

Pig25_L_A



1068

1069 **Figure 23.** Analysis variable for pig number 25 left side, site A (hind limb)
 1070 representing the mean force of 665.553191 Phidgets sensor reading with minimum and
 1071 maximum loads over 15 seconds of maximum load force.

1072



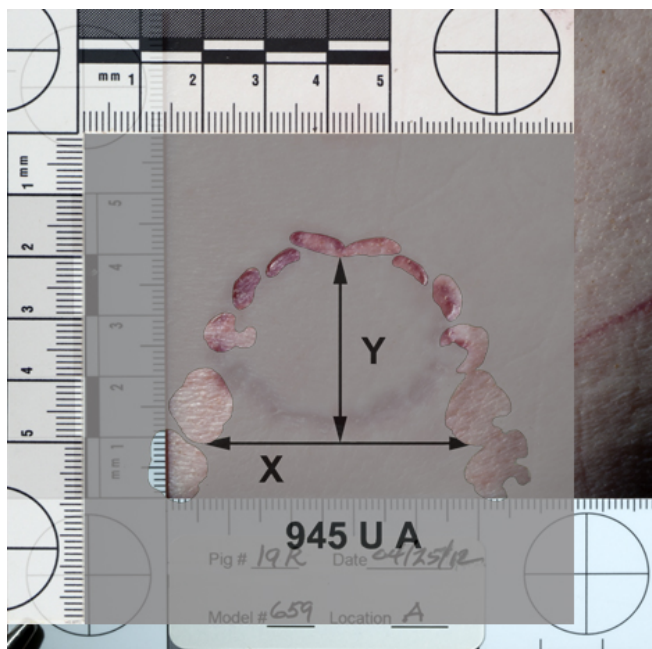
1073

1074 **Figure 24.** bite mark replication pattern for pig number 25L A (left side, position A)
1075 representing the mean force of 665.553191 Phidgets sensor reading
1076 with minimum and maximum loads over 15 seconds maximum load force.

1077

1078 **Image analysis**

1079 Analysis using Tom's Toolbox[®] began once the images had been reviewed and
1080 selected. Of particular importance were the images and resultant forces producing them
1081 that led to a high level of inter- observer agreement. For example the patterns on Pig
1082 19R appeared highly consistent with model 945, when a transparent overlay
1083 comparison was conducted. (Figure 25)

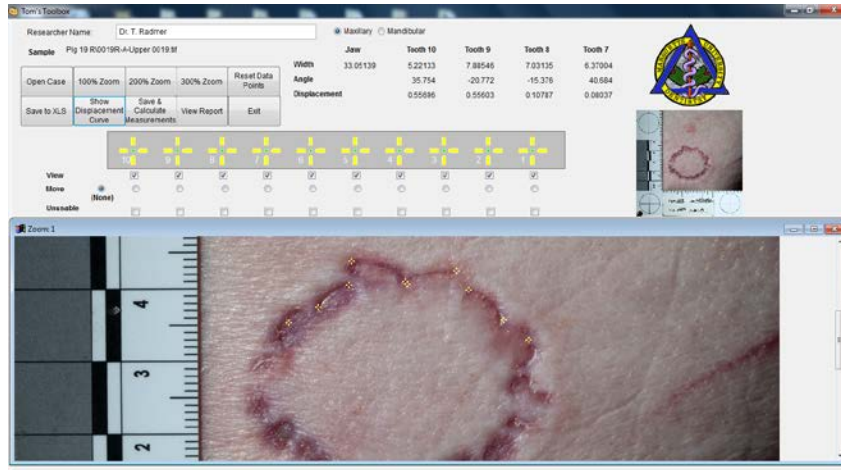


1084

1085 **Figure 25.** Illustrates the consistency of the pattern in dental characteristics in bite
1086 pattern 19R A and the population Target member 945 U A, using a computer generated
1087 semi-transparent overlay.

1088

1089 Consistency in all characteristics does not quantify the frequency with which the
1090 pattern occurs in the population. The strength of the correlation of model number 945 with
1091 pattern 19R, site A, required constructing statistical models. The resultant pixel
1092 placement and forces used to create the bite mark are illustrated in Figure 26A, 26B and
1093 26C.



1094

1095 **Figure 26A.** Illustrates the placement of the measurement markers in Tom's Toolbox[®]
 1096 for the maxillary incisors in the replicated bite mark for pig 19R, site A.

1097

1098

1099

1100

1101

1102

1103

1104

1105

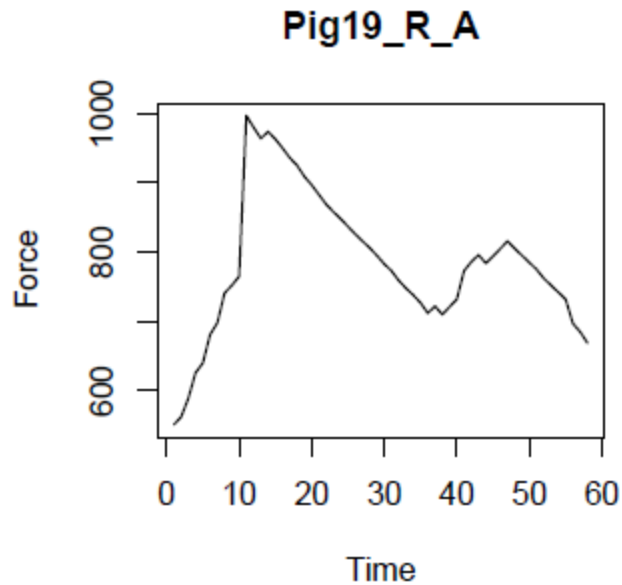
1106

Analysis Variable : value				
N	Mean	Std Dev	Minimum	Maximum
58	784.7586	101.9286	551.000000	997.000000
	207	490		

1107

1108
1109

Figure 26B. Depicts the force applied to produce the replicated pattern of the bite mark on Fig 19 R, site A



1110

1111
1112

Figure 26C. Illustrates the FlexiForce scale recording of the force at 10 seconds to 25 seconds over the 60 second duration of the contact with porcine skin, Fig 19R, site A.

1113

1114

1115

1116

1117

1118

1119 **Results**

1120
1121 **Statement of Results Using Pearson Correlations**

1122 Statisticians evaluated width measurements for outliers utilizing two different
1123 analytic models. The results are found in table 3 for widths for standard deviation,
1124 median, minimum, and maximum width measurements in porcine skin for each tooth in
1125 each jaw.

1126

	Mean ± StDev	Median	Minimum	Maximum
Upper				
Tooth 7	5.07 ± 1.05	5.15	2.12	7.88
Tooth 8	6.47 ± 1.16	6.66	2.29	8.39
Tooth 9	6.50 ± 1.18	6.70	2.86	8.87
Tooth 10	4.83 ± 1.07	5.00	1.22	7.80
Lower				
Tooth 23	4.97 ± 0.76	4.98	2.01	6.99
Tooth 24	4.74 ± 0.74	4.81	1.86	6.80
Tooth 25	4.64 ± 0.81	4.68	1.53	6.58
Tooth 26	4.91 ± 0.69	4.94	2.92	7.30

1127
1128 **Table 3.** The measured widths for each tooth in porcine skin expressed in millimeters

1129 These widths were compared to the known widths established by the two
1130 investigators using Coprwax™ exemplars, a standard dental material for bite

1131 registration. An illustration of the results when searching for outliers in individual tooth
1132 widths is found in Table 4.

	Investigator 1	Investigator 2
Width and angle	23.42%	26.83%
Width	35.3%	50.1%
Angle	15.33%	10.21%

1133
1134 **Table 4.** The percentage of outliers in tooth widths plus angles, widths and angles only
1135 by investigators 1 and 2.

1136 The viscoelasticity of the skin and the rebound that occurs restricted meaningful
1137 comparison when width was considered as a single characteristic. Analysis found that
1138 there were many bite mark patterns in porcine skin which exhibited several outlying
1139 measurements for each tooth.

1140 The inter-observer agreement using SAS software between Investigator 1 and
1141 Investigator 2 in the measurement of the 50 CoprWax™ dental patterns was 0.984,
1142 showing an extremely high consistency when measuring widths of tooth patterns in
1143 CoprWax™, an American Dental Association (ADA) accepted bite registration material.
1144 Determination of the inter-observer agreement in measuring tooth widths of patterns
1145 registered in porcine skin was calculated with SAS software resulting in a correlation of
1146 0.716.

1147 Measuring the intersecting angles as a means of determining an additional dental
1148 characteristic has not previously been utilized in pattern research. The intersecting
1149 angles between teeth identified A and B, A and C, A and D, B and C, B and D and C
1150 and D were identified and compared to the corresponding angles recorded in the
1151 dataset. (Figure 27) The correlations between bitemarks in porcine skin compared to

1152 the known measurements of the 469 dental models were ranked from 1 to 469. For
1153 Investigator 1, 84.6% of the measurements showed that their true models were ranked
1154 in top 10%. For Investigator 2, 85% of the measurements showed that their true models
1155 were ranked in top 10%.



1156

1157 **Figure 27.** Illustrates the intersection of the extended incisal lines used to calculate the
1158 angle of rotation of the incisors. Outliers in these angles are used to quantify their
1159 occurrence in the sample population.

1160 Based on the angle correlation, the list can be further narrowed for a comparison of
1161 porcine skin patterns and the set of models used to create true model candidates that
1162 had a confidence interval of 0.984.

1163 The Pearson correlation was used to select a dental model based on the bite mark
1164 patterns. Two hundred bite marks were examined against 469 dental models. For each
1165 bite mark, 469 correlations with the dental models were calculated. Then, the 469
1166 correlations were ranked from 1 to 469. The dental model having rank #1 correlation

1167 was the predicted model. Table 5 illustrates the results based on the all measurements,
1168 i.e., the width and the angles. 143 (Investigator 1) and 156 (Investigator 2) bite marks
1169 out of the 200 had at least one non-missing data entry. The data of the remaining 57
1170 (Investigator 1) and 44 (Investigator 2) bite marks were completely missing (i.e., non-
1171 measurable). As can be seen in Table 5, five (5) out of the one hundred forty-three
1172 (143) (Investigator 1) and two (2) out of the one hundred fifty-six (156) (Investigator 2)
1173 selected correct dental models from the population data set. The models ranked
1174 number one in the data set were from separate members of the population. The P-
1175 values of less than 0.05 shows that this selection is better than random. For example,
1176 identifying 2 correct models out of the 156 (Investigator's Rank #1) shows a better
1177 performance than selecting a correct model completely at random (p-value = 0.0431),
1178 and 5 correct models out of the 143 case (p-value < 0.0001). Although correlation
1179 identified only 5 and 2 correct models, respectively, a lot of the correlations between a
1180 bite mark and its true dental model were still highly ranked. For example, 10 out of the
1181 143 for Investigator 1 and 13 out of the 156 for Investigator 2 were within in top 1%. The
1182 rest of the results can be interpreted similarly. They all show a better performance than
1183 random (p-values < 0.0001).

1184

1185

1186

1187

	Investigator 1		Investigator 2	
	Proportion	P-value	Proportion	P-value
Rank #1	5/143	< 0.0001	2/156	0.0431
Top 1%	10/143	< 0.0001	13/156	< 0.0001
Top 5%	34/143	< 0.0001	36/156	< 0.0001
Top 10%	59/143	< 0.0001	54/156	< 0.0001
Top 20%	78/143	< 0.0001	76/156	< 0.0001
Top 30%	93/143	< 0.0001	105/156	< 0.0001

1188

1189 **Table 5.** The results of an analysis based on the measurement of both width and
1190 angles.

1191 Table 6 shows the results based on width measurements only. 141 (Investigator 1)
1192 and 153 (Investigator 2) bite marks out of the 200 had at least one non-missing data
1193 entry. The data of the remaining 59 (Investigator 1) and 47 (Investigator 2) bite marks
1194 were completely missing. The correlations from Investigator 2 identified 3 correct
1195 models out of the 153, which is better than random (p-value = 0.0043). The correlations
1196 from Investigator 1 did not identify any correct models. Although Investigator 1
1197 measurements did not show better performance than random selection, investigator 2's
1198 measurements showed a better performance than random (all p-values are less than
1199 0.05).

1200

1201

	Investigator 1		Investigator 2	
	Proportion	P-value	Proportion	P-value
Rank #1	0/141	1	3/153	0.0043
Top 1%	0/141	0.4106	8/153	0.0002
Top 5%	7/141	1	15/153	0.0136
Top 10%	14/141	1	26/153	0.0067
Top 20%	32/141	0.4014	45/153	0.0060
Top 30%	41/141	0.8546	64/153	0.0019

1202

1203 **Table 6.** This table illustrates the investigators' difficulty in measuring incisor width only.
 1204 This is due to the viscoelasticity of the skin, resulting in inaccurate measurements in
 1205 distance.

1206

1207 Table 7 shows the results based on angular measurements only. 136 (Investigator 1)
 1208 and 131 (Investigator 2) bite marks out of the 200 had at least one non-missing data
 1209 entry. The data of the remaining 64 (Investigator 1) and 69 (Investigator 2) bite marks
 1210 was not useable. . The correlations from Investigator 1 identified 3 correct models out of
 1211 the 136, which is better than random (p-value = 0.0031). Although the correlations from
 1212 Investigator 2 did not identify any correct models, some correlations between width
 1213 measurements of a bite mark and its true dental model's width was still ranked high,
 1214 which is better than random (p-value < 0.0001 for top 5% to top 30%).

1215

1216

	Investigator 1		Investigator 2	
	Proportion	P-value	Proportion	P-value
Rank #1	3/136	0.0031	0/131	1
Top 1%	10/136	< 0.0001	10/131	< 0.0001
Top 5%	30/136	< 0.0001	32/131	< 0.0001
Top 10%	46/136	< 0.0001	43/131	< 0.0001
Top 20%	75/136	< 0.0001	67/131	< 0.0001
Top 30%	87/136	< 0.0001	85/131	< 0.0001

1217

1218 **Table 7.** Illustrates the Investigators accuracy and consistency in an analysis based on
 1219 angular measurements only.
 1220

1221 Outliers were calculated using an N =469 to represent the population dataset. For
 1222 each column (for example, the width of Tooth 24 or the angle of AB for upper tooth), a
 1223 calculated mean and standard deviation was recorded as $\pm 2 \times \text{SD}$.

1224 Since the location of the observations is unknown, an iterative algorithm was used to
 1225 find the best dental model to match the bite marks. To do this, all possible combinations
 1226 between observations and dental models were examined. The best matched bite mark
 1227 and dental model was determined by choosing the dental model and teeth marks that
 1228 produced the minimum sum of absolute values of the differences between observations
 1229 and measurements of the dental models. For example, when there were four
 1230 observations of widths, a comparison was made using these four observed widths and
 1231 all possible four measurements from all known dental models. Starting with the first
 1232 tooth of each model, the absolute difference of teeth marks and models was compared.

1233 This was then repeated around the entirety of the model until every combination of
1234 matching had been compared. The corresponding, dental model was chosen by
1235 producing the absolute minimum difference between observations and measurements
1236 from the dental models. For analysis, the outcome was whether the chosen dental
1237 model was correct, which created binary outcomes. Finally, generalized estimating
1238 equations (GEE) were employed to perform multivariate analysis of the predictability of
1239 the model selection.

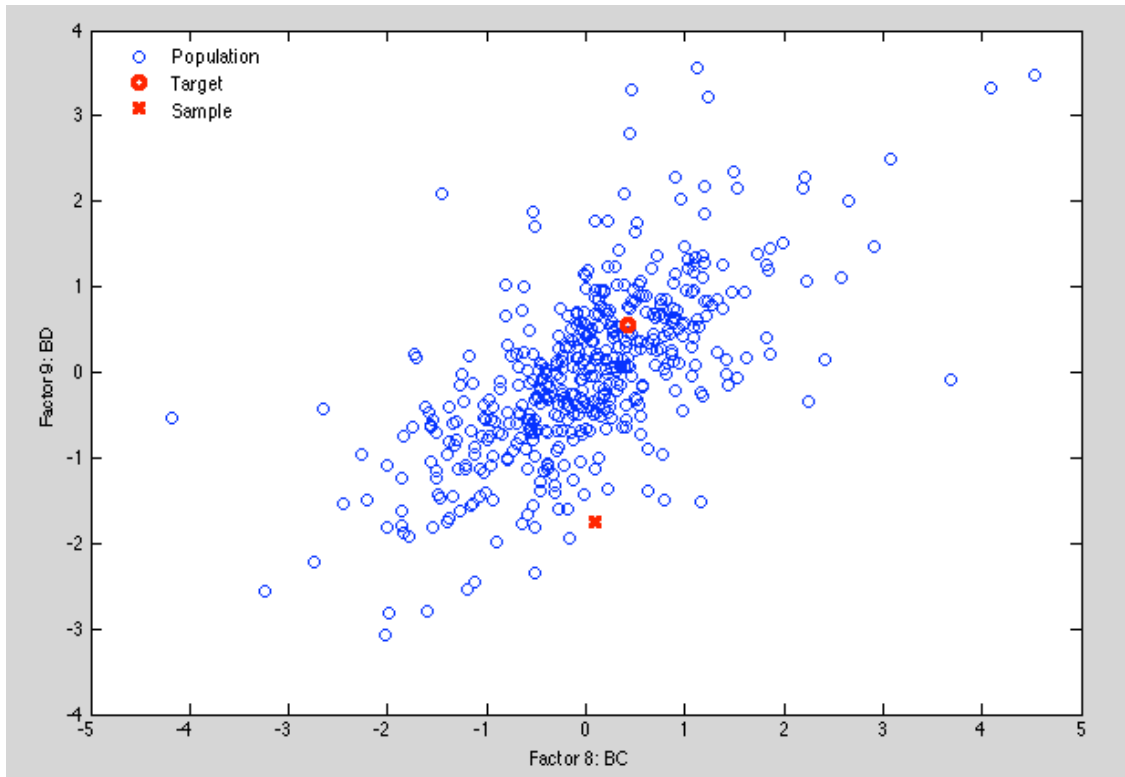
1240 In addition to the above multivariate analysis, further investigation of outliers such as
1241 missing teeth and significantly large/small measurements remain to be calculated
1242 beyond the scope of this investigation. In cases where there were outliers in
1243 observations, only dental models which had outliers were considered in order to perform
1244 the multivariate analysis as mentioned above.

1245 **Statement of Results Using a Distance Metric Model**

1246 A second scientific model was also selected to compare the population to the
1247 unknown injury patterns based on distance metric analysis. The Distance Metric Model
1248 addresses the question; What proportion of the population (CoprWax[®] exemplars) is
1249 similar to a specific sample image of an injury pattern on one of the pigs? The Distance
1250 Metric family of models computes a distance in an n -dimensional factor space from a
1251 sample (pig injury image) to each member of the population (CoprWax[®] images). The
1252 score for a particular member of the Distance Metric family of models is the percentage
1253 of the population that is closer to the specific sample, than the correct matching target

1254 member of the population from which the sample image was made as suggested by
1255 Figure 28.

1256



1257

1258 **Figure 28.** A visualization of the Distance in factor space
1259 from the Sample to the matching Target of the Population.

1260

1261 In Figure 28, “X” denotes a Sample image, and the heavy “O” denotes the
1262 matching target member of the population, represented in two of the angle
1263 measurement factors for upper jaw measurements by Investigator 1. In this view, it
1264 appears that most of the populati theon is closer to the sample than the target member
1265 of the population, but less than 5% of the population is closer to the sample than the
1266 target.

1267 For analysis, data from 469 pairs of lower and upper jaws was provided and scored
1268 by two researchers independently. The factors scored were:

1269 • Lower jaw: Tooth 23 width, Tooth 24 width, Tooth 25 width, Tooth 26 width,
1270 and angles AB, AC, AD, BC, BD, and CD.

1271

1272 • Upper jaw: Tooth 10 width, Tooth 9 width, Tooth 8 width, Tooth 7 width, and
1273 angles AB, AC, AD, BC, BD, and CD.

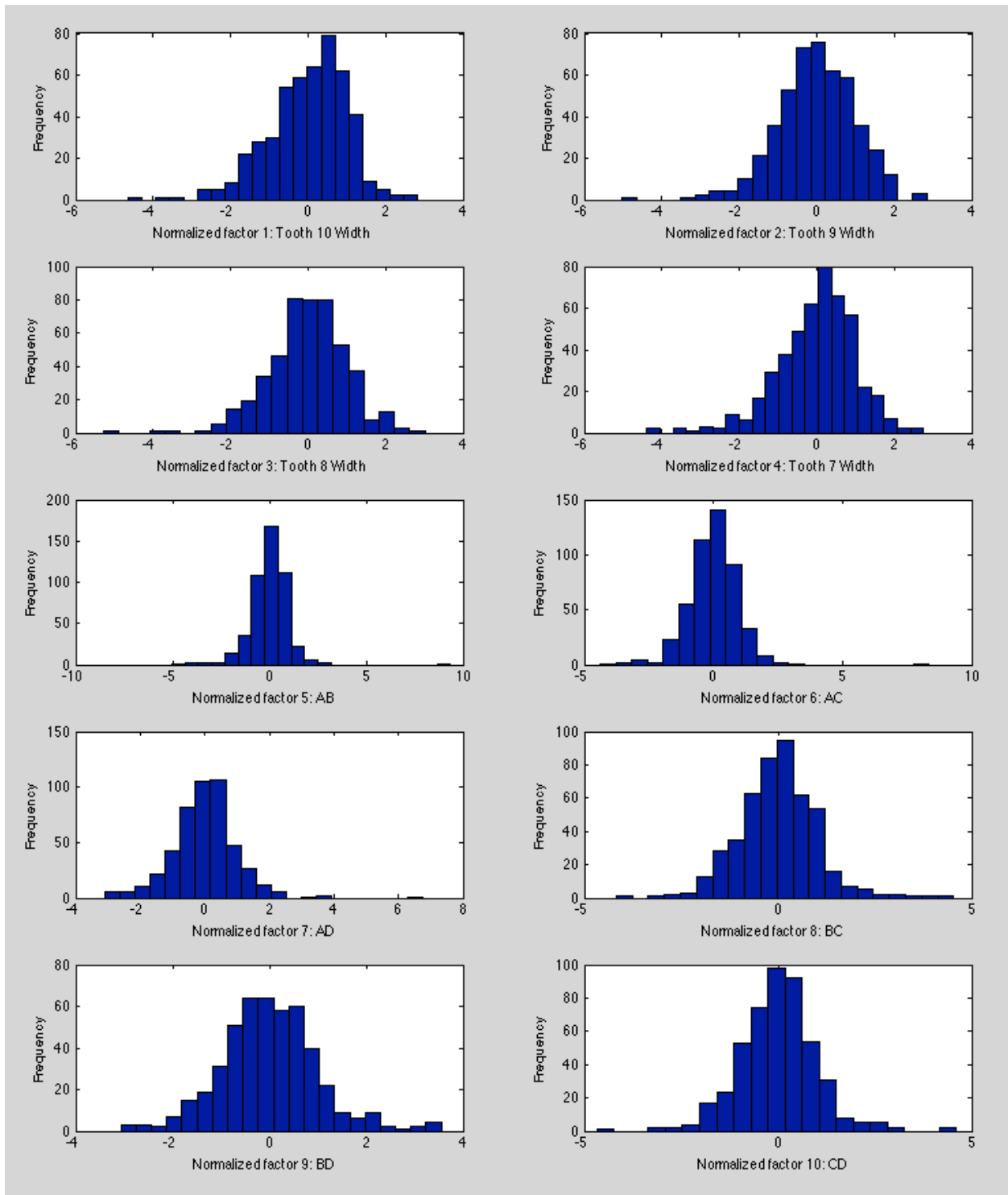
1274

1275 The lower jaw images had 7 missing teeth noted by the two independent
1276 researchers. The upper jaw images had 9 - 11 missing teeth. So that distances could
1277 be computed using multiple factors, each width and angle measurement was replaced
1278 by its corresponding z-score by subtracting factor means and dividing by factor standard
1279 deviations, ignoring missing teeth, and considering scores from each researcher
1280 separately

1281 For analysis, 50 members of the population were selected as blind samples. Four
1282 separate simulated bite marks were made from each sample, giving 400 images each
1283 from lower and upper jaws. The two investigators independently scored the same 10
1284 factors for each of the 400 images. Some of the population selected for the samples
1285 had missing teeth, but of the 800 teeth measured from each jaw by each researcher,
1286 between 276 and 420 (investigator 1 and investigator 2) missing teeth could not be
1287 distinguished in the images with sufficient clarity to assign factor measurements. Not all
1288 impressions were clear enough for analysis.

1289 So that distances could be computed using multiple factors, each factor was
1290 normalized by subtracting population factor means and dividing by population factor
1291 standard deviations, considering scores from each researcher separately.

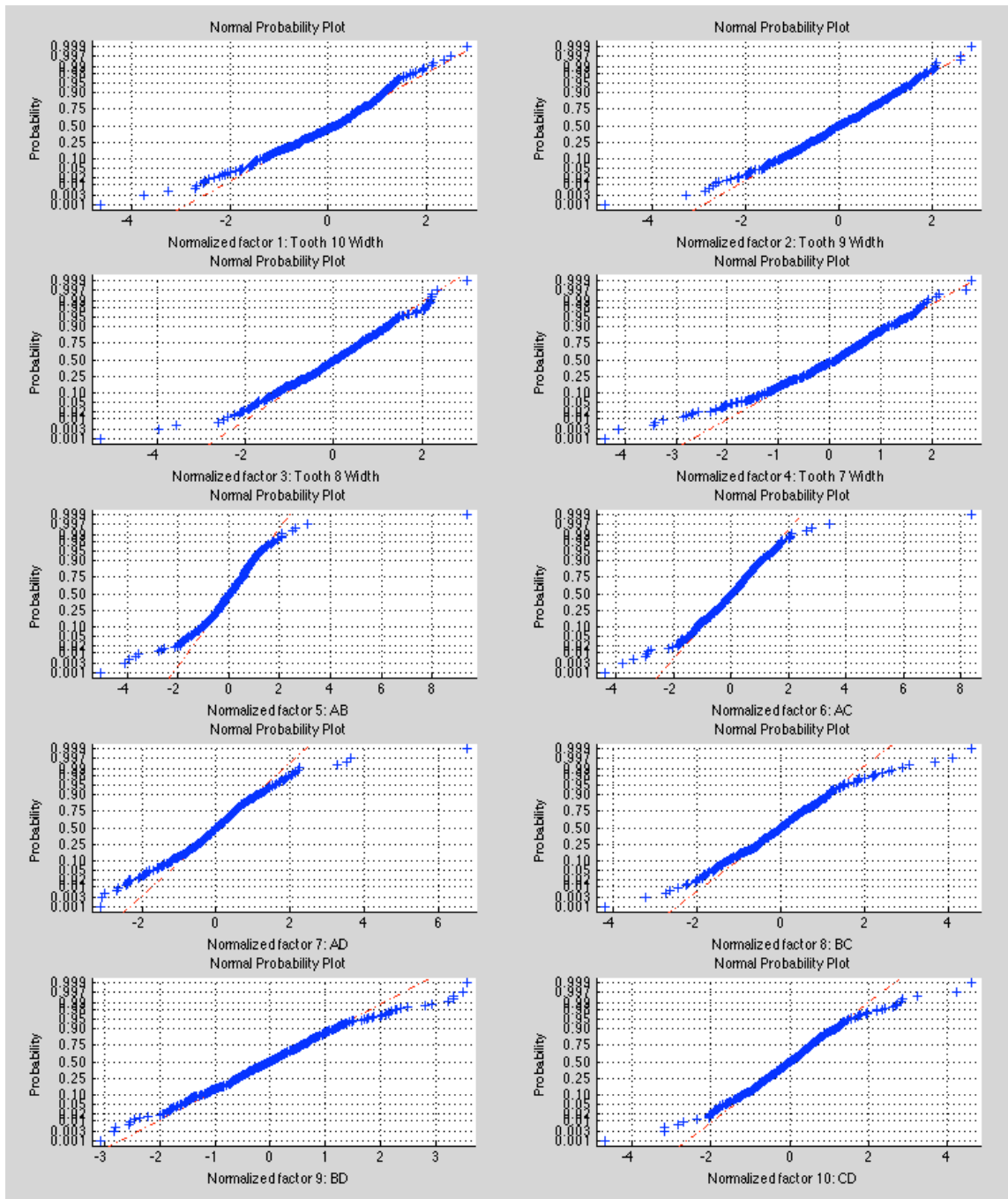
1292 Before applying the Distance Metric Model, the data was visualized by looking at
1293 histograms for each factor (e.g., Figure 29), Normal Probability Plots (e.g., Figure 30),
1294 and scatter diagrams of each pair of factors (e.g., Figure 31). Figures 31, 32, and 33
1295 show the plots for the upper jaw measurements from researcher 1; corresponding plots
1296 for lower jaws and for researcher 2 are very similar.



1297

1298 **Figure 29.** Histograms of ten normalized factors from upper jaw measurements by
 1299 researcher 1. Distributions appear roughly bell shaped, but there are outliers.

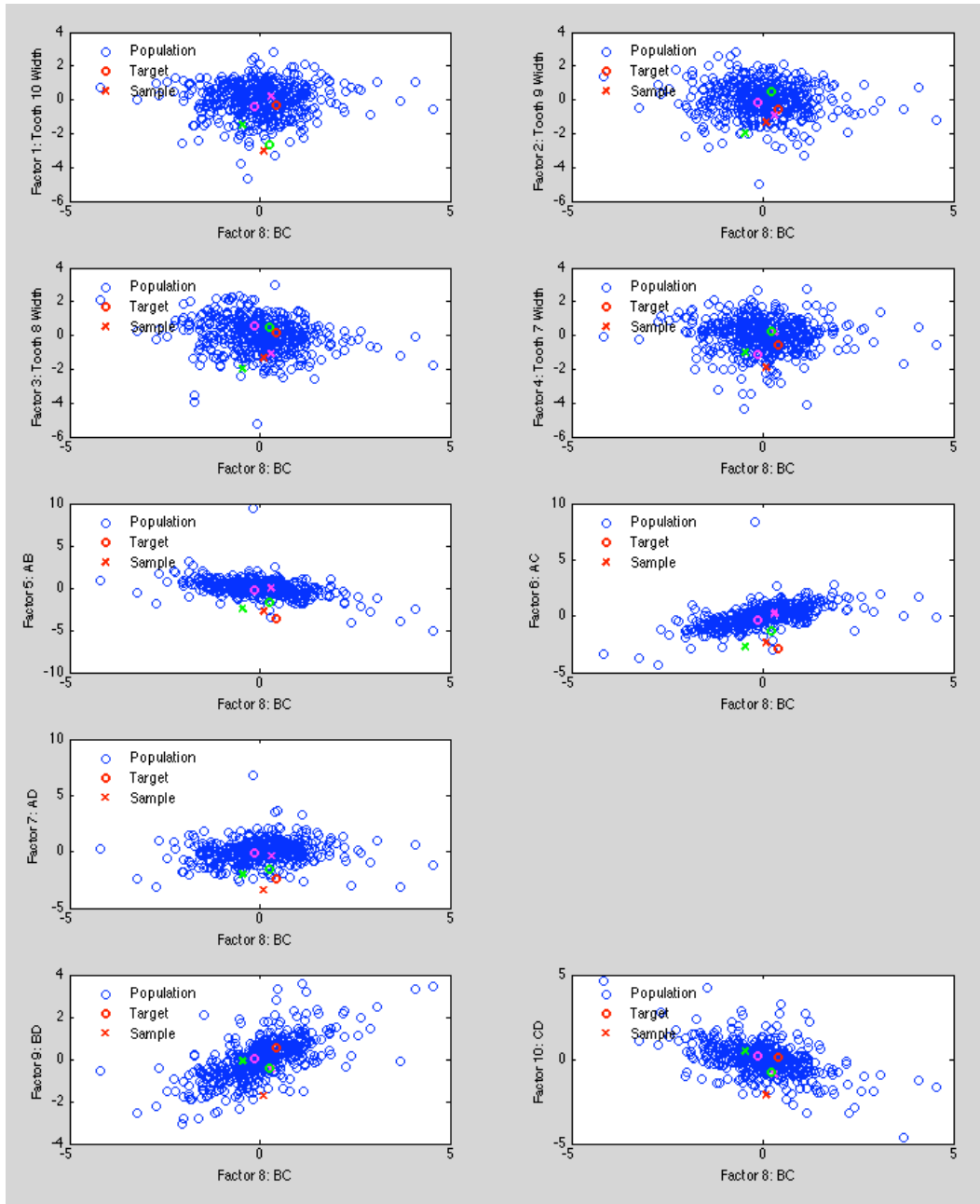
1300



1301

1302 **Figure 30.** Normal Probability Plots of ten normalized factors from upper jaw
 1303 measurements by researcher 1. If the observed distribution is normal, it follows the
 1304 dashed red diagonal lines. Distributions of these factors tend to have thick tails, and
 1305 some are skewed.

1306



1307

1308 **Figure 31.** Scatter diagrams – Other factors vs. factor 8 (angle BC) for Population.
 1309 Colored “X” are three Samples, with corresponding Target members of the Population
 1310 marked “O”

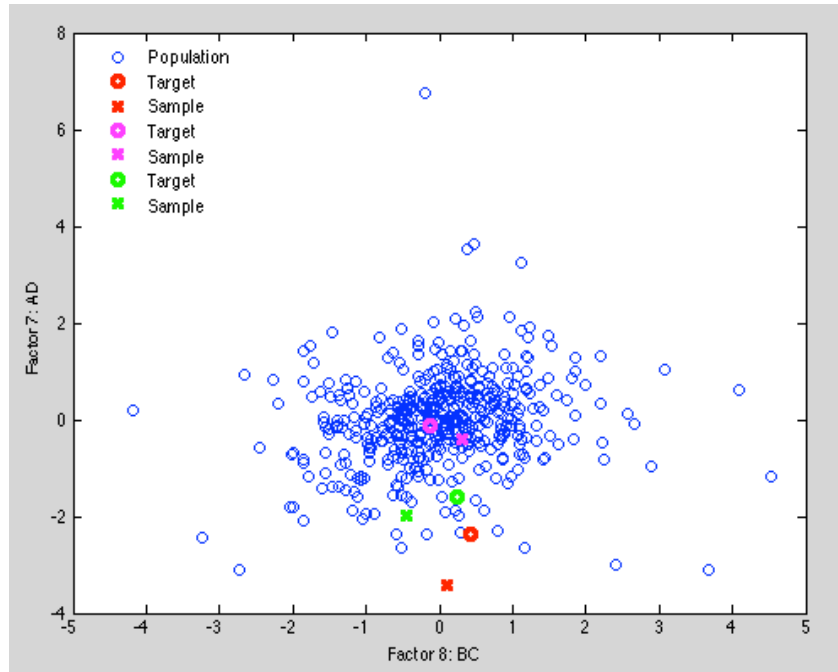
1311

1312 For each Sample, the Distance Metric Model computes the distance (in n -
 1313 dimensional z-score-normalized factor space) to each member of the population and

1314 then sorts the results in order of increasing distance. For each sample, the number of
1315 population members that lie closer to the sample than its corresponding target member
1316 of the population (the dental model that was used to create the sample image) was
1317 counted.

1318 Figures 32 and 33 help visualize how the Distance Metric Model computes the
1319 distance between Samples and members of the Population. Figures 30 and 31 are
1320 enlargements of subfigures from Figure 29, showing scatter diagrams of factors 7
1321 (angle AD) and 9 (angle BD), respectively, vs. factor 8 (angle BC). There are several
1322 outlier measurements, which provide good characterizations, but the choice was to
1323 focus here on more difficult Samples, marked with red, magenta, and green “X”
1324 (Samples) and “O” (Targets). The Distance Metric Model counts the number of
1325 Population members (blue “O”) that are closer to the Sample (“X”) than its
1326 corresponding Target (“O”). For these three pairs, the percentages are 4.8 %, 1.7 %,
1327 and 23% for red, green, and magenta pairs, respectively.

1328



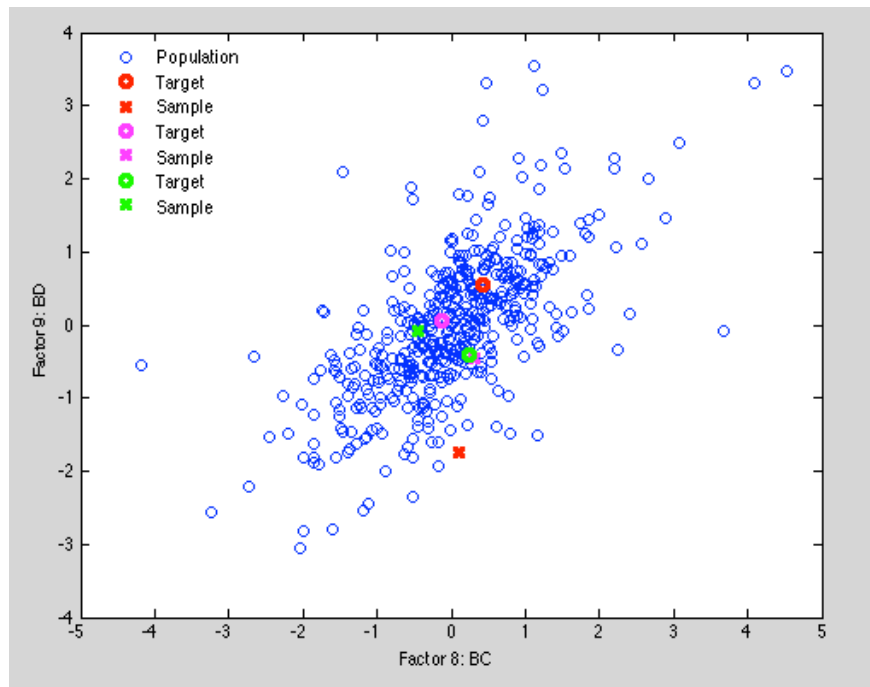
1329

Figure 32. Factor 7 (angle AD) vs. factor 8 (angle BC) showing three Sample – Target pairs.

1330

1331

1332



1333

Figure 33. Factor 9 (angle BD) vs. factor 8 (angle BC) showing three Sample – Target pairs.

1334

1335

1336 These figures illustrate the effect of measuring the distance in a high-dimensional
1337 factor space, rather than in the two-dimensional spaces. One pair of dimensions alone
1338 is insufficient, but by considering all factors, one may resolve pairs that appear widely
1339 separated in a single feature pair.

1340 By having the 10 factors provided in the data set for the upper jaw Samples
1341 measured by researcher 1, we get the results shown in Table 8. Results for lower jaws
1342 and for measurements by researcher 2 are similar.

Average target percent: 39.1
Sample count: 102
Within 1% of population: 3, 2.9 % of samples
Within 5% of population: 16, 15.7 % of samples
Within 10% of population: 23, 22.5 % of samples

1343
1344 **Table 8.** The Percent of the Population closer to selected Sample than the
1345 corresponding Target for the upper jaw. Samples were measured by Researcher 1.

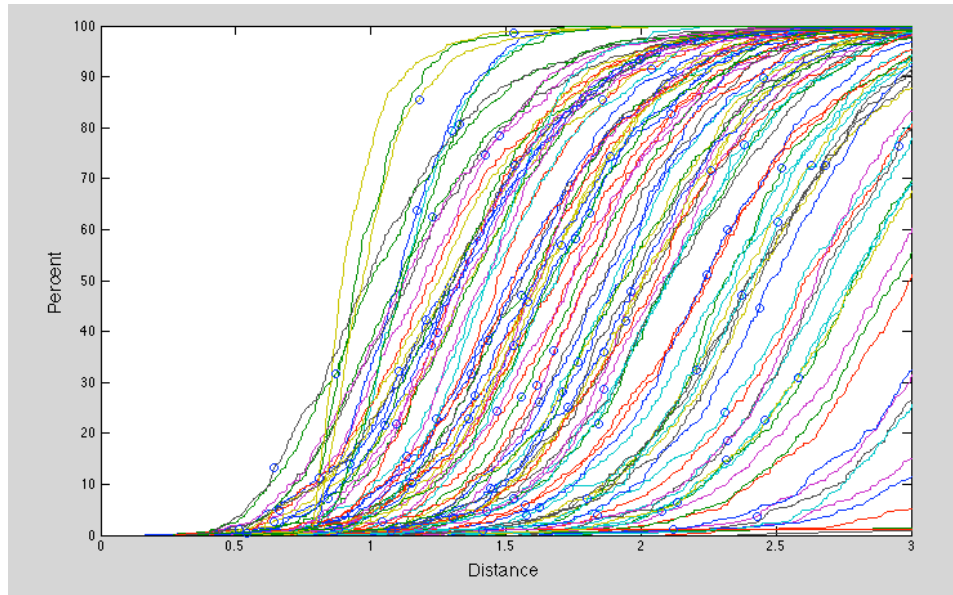
1346
1347 Table 9 shows that for 3 (2.9 %) of the 102 sample images scored, only 1% of the
1348 population was closer to the sample than the target; 16 (15.7%) of the samples found
1349 their target within 5% of the population; and 23 (22.5 %) of the samples found their
1350 target within 10% of the population.

1351 Figures 34 and 35 provide different views of the performance of the Distance Metric
1352 Model. Figure 34 shows a distance Cumulative Density Function for each sample. That
1353 is, each sample has a curve showing how fast the percent of the population increases
1354 with distance measured from that sample. Curves toward the left of Figure 35
1355 correspond to Samples for which there are nearby members of the population, while
1356 curves toward the left correspond to samples for which there are very few nearby
1357 members of the population. Curves that rise sharply are including regions in which the
1358 population is dense, so a slight increase in distance includes many additional members
1359 of the population. On the other hand, curves that rise slowly are including regions in
1360 which the population is sparse, so even a relatively large increase in distance includes
1361 few additional members of the population.

1362 In Figure 34, the blue circles represent the Target for each sample; a blue circle near
1363 the horizontal axis represents a target close to its sample, while a blue circle in the
1364 upper half of the figure represents a target far from its sample.

1365 Figure 35 is a Cumulative Density Function, a graphical representation of the
1366 information in Table 8. It plots the percent of the Population closer to each Sample than
1367 its corresponding Target. There are 23 Samples whose Target is within 10% of the
1368 Population and 49 Samples whose Target is within 40% of the Population. Of course,
1369 the worst case Sample finds its Target within 100% of the Population. If the Distance
1370 Metric Model is performing well, the graph remains low through many Samples, jumping
1371 up to 100% only for the few Samples it finds far from their respective Targets.

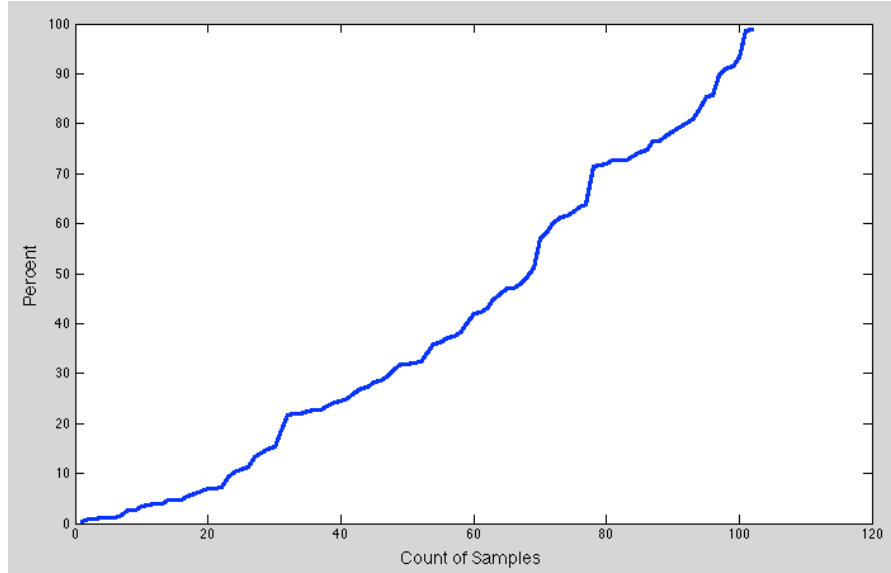
1372



1373

Figure 34. Proportion of Population vs. distance for each upper jaw Sample scored by researcher 1.

1374
1375
1376
1377



1378

Figure 35. Cumulative Density Function, a graphical representation of the information in Table 8, the percent of the Population closer to each Sample than its corresponding Target.

1382

1383 In principle, the distance can be computed using any subset of the 10 factors
1384 provided in the data set. For example, if we ignore the tooth width measurements and
1385 use only the factors representing measurements of angles, we get the results shown in
1386 Table 9.

Average target percent: 26.2
Sample count: 95
Within 1% of population: 8, 8.4 % of samples
Within 5% of population: 24, 25.3 % of samples
Within 10% of population: 35, 36.8 % of samples

1387

1388 **Table 9.** The Percent of Population closer to selected Sample than the
1389 corresponding Target for upper jaw Samples measured by researcher 1,
1390 using use only the factors representing measurements of angles.

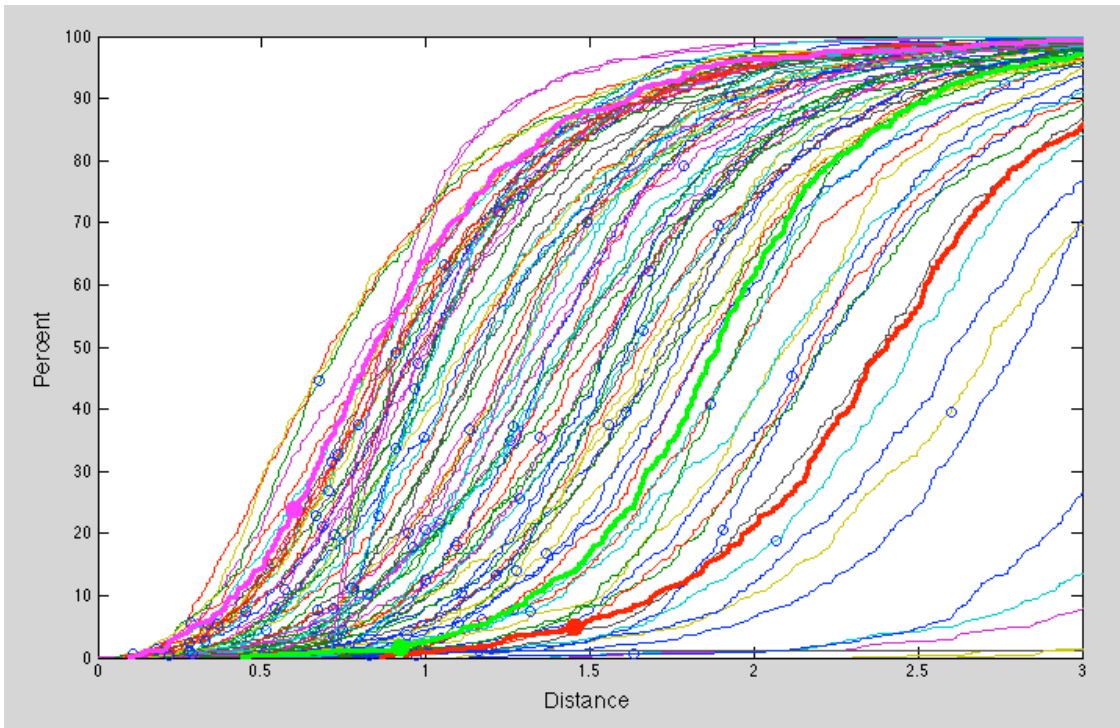
1391

1392 Compared with Table 8, Table 9 shows that omitting tooth width factors improved the
1393 overall performance from an average target percent of 39% to 26%, and 8%, 25%, and
1394 37% (vs. 3 %, 16 %, and 22 %) of the Samples found their corresponding Target within
1395 1%, 5%, and 10% of the Population, respectively. The Sample count decreases
1396 because the number of Samples with a relatively high proportion of missing information
1397 increases.

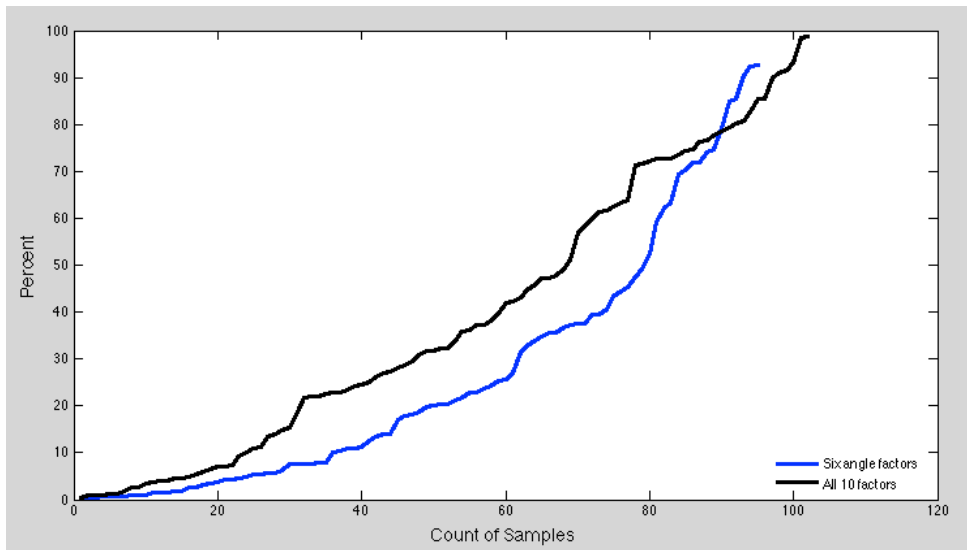
1398 Figure 36 corresponds to Figure 34, except that the Distance Metric Model is using
1399 use only the factors representing measurements of angles. The red, magenta, and
1400 green curves are the density functions for the samples. If the magenta curve is toward
1401 the left of the figure, it indicates that the sample is in a region where the population is
1402 dense, yielding 23% of the population closer than the corresponding target, while the
1403 red curve is toward the right of the figure, indicating that the sample is in a relatively
1404 sparse region of the population, yielding only 4.8 % of the population closer than the
1405 corresponding target.

1406 Figure 37 shows the Cumulative Density Function corresponding to Figure 36,
1407 except that the Distance Metric Model is using use only the factors representing
1408 measurements of angles. The blue curve for the smaller six-factor model remains low
1409 for more samples, indicating its improved performance.

1410



1411
 1412 **Figure 36.** Proportion of Population vs. distance for each upper jaw Sample scored by
 1413 researcher 1, using use only the factors representing measurements of angles.
 1414



1415
 1416
 1417 **Figure 37.** Cumulative Density Function, showings the percent of
 1418 the Population closer to each Sample than its corresponding Target.
 1419

1420 This presents only the results from upper jaw Samples and Populations measured
1421 by Researcher 1 to help explain the Distance Metric Model. Table 9 shows the percent
1422 of population closer to selected sample than the corresponding target, using only the
1423 factors representing measurements of angles, for both lower and upper jaws and for the
1424 measurements from both researcher 1 and researcher 2. For this data set, the Distance
1425 Metric Model performs a little better on the upper jaw samples than on the lower jaw
1426 samples, and there was no appreciable difference in performance using the sample and
1427 population measurements of each researcher.

1428 In comparing the results in Table 9 with those in Table 10, the Distance Metric Model
1429 seemed to perform better ignoring the tooth width factors and using only the angle
1430 factors. Table 11 summarizes the performance of the Distance Metric Model using
1431 several different factor subsets:

- 1432 • All ten factors, four tooth width factors and six angle factors,
- 1433 • Six angle factors,
- 1434 • Five angle factors, omitting the first of the six (angle AB),
- 1435 • Five angle factors, omitting the second of the six (angle AC),
- 1436 • Five angle factors, omitting the third of the six (angle AD),
- 1437 • Five angle factors, omitting the fourth of the six (angle BC),
- 1438 • Five angle factors, omitting the fifth of the six (angle BD), and
- 1439 • Five angle factors, omitting the sixth of the six (angle CD).

1440

Lower - Investigator 1		
Count samples:	125	
Samples within	1 % of the population	6 4.8 % of the samples
Samples within	5% of the population	25 20.0 % of the samples
Samples within	10 % of the population	36 28.8 % of the samples
Lower - Investigator 2		
Count samples	132	
Samples within	1 % of the population	5 3.8 % of the samples
Samples within	5% of the population	23 17.4 % of the samples
Samples within	10 % of the population	33 25.0 % of the samples
Upper - Investigator 1		
Count samples	95	
Samples within	1 % of the population	8 8.4 % of the samples
Samples within	5% of the population	24 25.3 % of the samples
Samples within	10 % of the population	35 36.8 % of the samples
Upper - Investigator 2		
Count samples	98	
Samples within	1 % of the population	9 9.2 % of the samples
Samples within	5% of the population	26 26.5 % of the samples
Samples within	10 % of the population	32 32.7% of the samples

1441

1442 **Table10.** Illustration of the percentage of Population closer to selected Sample, than
 1443 the corresponding Target, use only the factors representing measurements of angles.

1444

1445 Each row in Table 11 summarizes performance as shown in the “In total:” portion of
 1446 Table 3 for each subset of factors, across both lower and upper jaws and across both
 1447 researchers For this data set, the Distance Metric Model using only the six angle factors
 1448 performed better than when also using the four tooth width factors. No further
 1449 improvement was observed by omitting any one of the six angle factors.

1450

1451

Factors	Population count within 1% (%)	Population count within 5% (%)	Population count within 10% (%)	Samples
All 10	14 (2.9)	69 (14.1)	117 (23.9)	489
Six angles	28 (6.2)	98 (21.8)	136 (30.2)	450
Omit 1st of 6	32 (7.5)	93 (21.7)	142 (33.1)	429
Omit 2nd of 6	29 (6.8)	97 (22.7)	138 (32.3)	427
Omit 3rd of 6	28 (6.4)	92 (20.9)	140 (31.8)	440
Omit 4th of 6	26 (6.2)	85 (20.4)	130 (31.2)	417
Omit 5th of 6	26 (6.0)	95 (22.1)	130 (30.2)	430
Omit 6th of 6	25 (5.8)	78 (18.2)	126 (29.4)	428

1452

1453 **Table 11.** Total performance using different factor subsets in the Distance Metric
1454 Model.

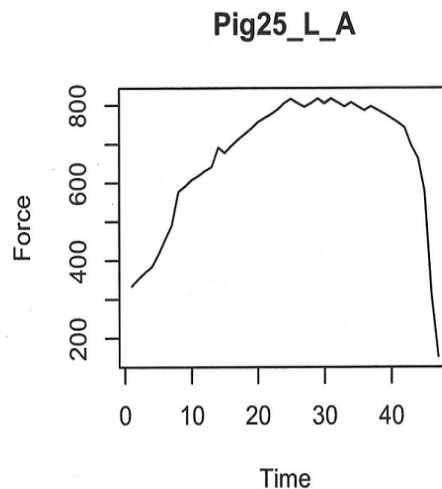
1455 In summary, in more than 20% of the Samples in this study, the Distance Metric
1456 Model finds the Target within the closest 5% of the Population. In more than 6% of the
1457 Samples, it finds the Target within the closest 1% of the Population. This demonstrates
1458 that it is often possible to determine scientifically that a given Sample must belong to a
1459 very small (e.g., 5% or even 1%) proportion of the Population.

1460 **Results of forces applied**

1461 Using the SAS[®] System and incorporating the Means Procedure, the Phidgets log
1462 record for bite infliction recorded 4684 points of data during the course of the production
1463 and documentation of 200 patterns on twenty-five pigs. The mean recording for all
1464 points in which pressure was applied with the replication device was 545.62 with a
1465 standard deviation of 278.78 within the range of pressures recorded for each event
1466 between 0 and 997.00 on the FlexiForce[®] to the computer with a Phidgets device. Each
1467 of the Flexi Force[®] sensors was bridged to the computer with a Phidgets device. Each of

1468 the sensors had been bench calibrated with an Omega model LCKD-100 load cell.
1469 Force versus Time was plotted for each pig location. As an example, Pig 25 L A (left
1470 side, position A) is represented in figure 38 and the resultant bite pattern can be seen in
1471 figure 39. Each of the 200 patterns was similarly correlated to the maximum force of the
1472 device over a period of 15 seconds.

1473 Image measurement using Tom's Toolbox[®] began, once the 200 highest quality
1474 images were selected and their resolution established at 300 dpi and their file format as
1475 TIFF verified. Of particular importance were the images and resultant forces producing
1476 them that lead to a high degree of inter-operator agreement. Pig 19R using blind model
1477 659 was directly correlated to the stereolithography model from the original series
1478 represented by model number 945. The resultant pixel placement and forces used to
1479 create the bite mark are illustrated in Figure 40.



1480

1481 **Figure 38.** Analysis variable for pig number 25 left side site A, or hind limb,
1482 representing the mean force of 665.553191 Phidgets sensor reading with
1483 minimum and maximum loads over 20 second maximum load force.



1484

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1486

Figure 39. Illustrates a replicated bite mark with a mean force of 665.553191 Phidgets sensor reading. start_side_site=Pig19_R_A.

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Conclusions

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Discussion of Findings

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Many factors exist which can alter the value and weight that should be given to the Interpretation of a patterned injury. These include, but are not limited to, the applied force, the area of the body where the bite occurred (e.g., the skin on the human back is much thicker, as opposed to that of the female breast) Rawson [27], the underlying structures beneath the skin, whether the bite occurs ante mortem, peri mortem, or post mortem and the techniques used in the preservation and analysis. Any of these may affect the ability of the examiner to be able to correlate the patterned injury with any degree of scientific probability to a known individual.[28] [29] [30] [31] In one study, 50 volunteers were selected to inflict bite marks on each other, the patterns were analyzed by two photographic techniques that included painting and a 2D Polyline technique,

1501 measuring the arch width from cusp tip to cusp tip and the angle of rotation from this
1502 base-line along the mesial distal widths of the incisal edges of the four anterior
1503 teeth.[32] Measurements were made using the tools found in Adobe Photoshop, which
1504 required hand-eye coordination. Additionally, measurements in Adobe Photoshop are
1505 limited by the software to the nearest tenth of a decimal point. The authors' previous
1506 studies provided a methodology to standardize measurements and accuracies in both
1507 the two-dimensional and three- dimensional planes. [2] [10] Inter-operator and intra-
1508 operator error rates have been reported. Forces and stresses necessary to inflict a bite
1509 mark patterned injury have been limited to either individual pig models [16] or the use of
1510 limited number of human cadavers. [19] For a number of reasons, statistical
1511 comparisons of results from these previous studies were not possible. There was no
1512 method of comparing results to a known data set, reflecting a specific population group.
1513 In a study by Bush , a single model was physically changed by grinding away the incisal
1514 edges of existing teeth to show substantive changes in reported angles of rotation
1515 regardless of how these nine changes would have occurred, or if they were present in a
1516 given population.[30] These changes would not have involved physiologic changes
1517 such as mesial drift of the teeth that occurs with the forces of mastication nor the
1518 loading and tilting of dentitions that naturally occur when inflicting a patterned injury in
1519 vital skin. A cadaver model has its own sets of limitations such as the inelasticity of the
1520 skin, the lack of an inflammatory response that enhances patterns in vivo and the ability
1521 of tissue to maintain the patterns, when the event is coordinated with a peri-mortem
1522 period. Porcine skin has been shown to offer the best experimental model for research
1523 as a substitute for vital human skin. [18] Other investigators have noted that the dermal-

1524 epidermal ratio in the porcine model is comparable to those of human skin [33], and that
1525 the kinetics of epidermal proliferation, cell layering and the elastin deposits are
1526 remarkably similar to humans. A search of current literature did not find a study that
1527 correlates quantified human dental characteristics in a known data set to an individual
1528 bite mark pattern.

1529 The 2009 National Academy of Science report, *Strengthening Forensic Science in*
1530 *the United States: A Path Forward*, has energized the field of Forensic Odontology to
1531 search for more scientific methods eliminating subjectivity, bias, and the
1532 misinterpretation of results. [1] In fact, since 1984 and long prior to the NAS 2009
1533 recommendations, the American Board of Forensic Odontology (ABFO), has been
1534 developing guidelines. The National Academy of Science Report states that more
1535 scientific methods should be initiated in all of the comparative sciences. [1] To
1536 accomplish this objective, a series of studies was instituted to establish a methodology
1537 for constructing a dataset of dental characteristics, quantify dental characteristics in
1538 both two dimensional and three dimensional views and establishing reliability of
1539 measurements in both intra and inter operator error analysis. The initial quantifications
1540 of widths, damages, angles of rotation, missing teeth, diastema and arch width analysis,
1541 were subsequently augmented by displacement and three dimensional analyses. [2] [3]
1542 [5] [10] This study adds practical application of these data sets to replication of
1543 patterned injury in porcine skin and the interpretation of the combination of quantified
1544 characteristics of the dental arches making up the initial data set. Additionally
1545 information regarding intersecting angles formed by extending incisal lines to adjacent
1546 and cross arch teeth accounted for the ability to accurately access rotations when the

1547 native curve could not be generated. In doing so, the criticisms of past investigators
1548 regarding bias, distortion, replication and interpretations were addressed. Ball
1549 introduced the basis for errors in utilizing an acetate overlay technique in bite mark
1550 pattern analysis in which a sheet of acetate paper is used to trace the biting edges of
1551 and then comparing those visually to a patterned injury.[34] Errors in digital
1552 photography, the lack of standardized methodology, subjectivity in generating overlays,
1553 problems with accuracy and problems with reproducibility along with photographic
1554 distortions, and the reliability of computer generated overlays were among the most
1555 significant criticisms. Ball concludes that a standard was not established by this method
1556 alone. [34]

1557 The initial portion of this study focused on creating a bite pattern in porcine skin that
1558 could be quantified. In order to accomplish this goal, a method of delivering a force that
1559 could provide a distinct pattern in skin was developed. There have been numerous
1560 studies that have reported bite forces in the anterior tooth region that range from 20-22
1561 PSI to 122 PSI. [15] [35] [36] [37]. The forces are influenced by numerous factors. Koc
1562 et al described these influential factors as pain, gender, age morphology and the
1563 individuals existing occlusion pattern. [38] Our determination of bite force needed to
1564 create a patterned injury was based on our findings of a range between 25 and 131.1
1565 PSI was consistent with these reports. Calibrating each device and measuring forces
1566 inflicted during the biting process added consistency and repeatability to the process of
1567 creating a bite that would closely replicate an actual event. As Koc, et.al. concluded:
1568 "...recording devices and techniques are important factors in bite force measurement
1569 Therefore, one should be careful when comparing the bite force values reported in the

1570 research.” [38] The use of a Flexiforce[®] transducer (FlexiForce[®], Tekscan Inc., South
1571 Boston, USA) has been previously reported. [21] Because the scale established thru the
1572 Phidgets device did not report in pounds per square inch, the FlexiForce[®] sensor
1573 imbedded in each set of the 50 pattern replication devices required calibration prior to
1574 each pig session. This insured that forces applied were within the physiologic range and
1575 consistently applied.

1576 Porcine skin has been established as an in vivo model for human skin. [17] A
1577 number of citations in the literature point to distortions common to patterned injury
1578 evaluation in skin. [39] [40] Sheasby and MacDonald reported on a classification
1579 system. [39] They concluded that distortion can occur at various stages during the biting
1580 process. If it occurs at “the time of biting” they defined this as “primary distortion.” [39] If
1581 distortion occurs subsequent to the biting, this was defined as “secondary distortion.”
1582 Sheasby and MacDonald further point out that primary distortion can occur either as a
1583 dynamic or as a tissue component. Distortion is produced by the dynamics of biting and
1584 depends on the degree of movement during the process. If movement is absent or
1585 slight a static bite mark may result. With extreme movement the bite mark appears
1586 distorted and linear striations (scrape marks) may be present. Additionally they point out
1587 that the quantity of tissue is taken into the mouth may produce “tenting” of the tissue
1588 which results in dimensional changes in the skin. They also classify three categories of
1589 secondary distortion. These would be distortions that are time related, posture distortion
1590 and photographic distortion. .An exact match in arch size is fortuitous and
1591 unpredictable. Exact superimposition is only possible in bite marks exhibiting minimal
1592 distortion and size matching techniques are only applicable to bite marks exhibiting

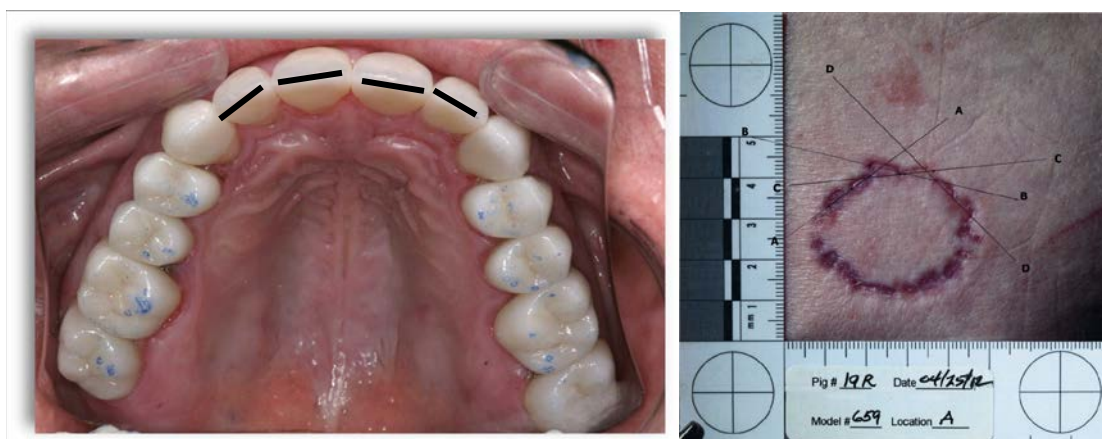
1593 minimal distortion. The incidences of discrete morphological points of comparison or
1594 distinctive features in a bite mark are the most significant criteria in bite mark analysis
1595 since they are relatively immune to distortion. As the degree of distortion increases, bite
1596 mark analysis relies progressively more on distinctive features [39]. This project aimed
1597 at producing as little distortion as possible. Pigs 1, 2 and 3 demonstrated the distortion
1598 and lack of pattern production in a dynamic bite (see Figure 41) further evidence that,
1599 underlying tissue morphology can also impact bite mark interpretation. [27]



1600
1601 **Figure 40.** An illustration of the lack of a distinct pattern in a dynamic bite.

1602 Kieser et al, characterized the uniqueness of the human anterior dentition. [41] The
1603 authors found uniqueness of the anterior dentition in both arches based on geometric
1604 morphometric analysis of individuals that were selected because they had similar
1605 orthodontic treatment, making their dentitions similar at the onset of the investigation.
1606 The geometric morphometric analysis focused on capturing subtle differences about

1607 morphology and spatial locations of the anterior teeth in both arches The study
1608 supported the findings of Rawson's initial study which concluded that certain
1609 characteristics occur that are inter related. These include, shape, number, mesio-palatal
1610 rotations and restorations. [42] These results were substantiated by our initial
1611 investigations. [2][3][5][10]. Not used in prior investigations was the concept of
1612 measuring angles formed by the intersecting extension of a line drawn on the incisal
1613 edge of each of the 4 anterior teeth in each arch. These were computed by placing
1614 markers directly opposite of each other on the mesial and distal outline of the teeth in a
1615 recognizable patterned injury. The principle of intersecting angles being that parallel
1616 lines do not cross and line segments continue past the incisal widths to intersect in a
1617 two dimensional photograph regardless of curvatures in the skin. Thus the concept of
1618 intersecting line angles is based on this incisal line, which the authors define as a
1619 straight line across the incisal edge of the teeth connecting the mesial to the distal most
1620 point on the tooth's biting (incisal) edge. This line intersects with adjacent incisal lines
1621 of the other anterior teeth at a measurable angle and is graphically represented in
1622 figures 41.



1623

1624 **Figure 41.** Extension of the incisal lines of the anterior teeth
1625 eventually intersect with an adjacent incisal line, forming a measureable angle.
1626 The angles of intersection for the maxilla are illustrated in this image. Intersecting
1627 incisal lines forming angles AB, AC, AD, BC, BD and CD in the four maxillary
1628 incisors. Tooth 10=A, Tooth 9=B, Tooth 8=C Tooth 7=D.C (Actual photo on right is a
1629 scaled view of figure 28 for comparison)

1630

1631 Reliability enters into any discussion of the comparative sciences. A number of
1632 authored opinions are critical of such issues as the direct comparison methods [43], the
1633 lack of reporting of error rates [44], the claims of uniqueness [45] and the reliability of
1634 testing. [46]. In addition, photographic techniques have been questioned. The American
1635 Board of Forensic Odontology has established among their guidelines one that address
1636 distortions in photography. [48] These and SWIGIT guidelines were rigorously followed
1637 in the documenting of the photographic images used in this study. Within this study
1638 were the inter operator error rates established for the known group of data. As reported
1639 by using two methods of statistical analysis inter-operator agreement was 0.984 in the
1640 known population, using Pearson correlation and within 1% of each other when
1641 calculating the population closest to the target using distance metric analysis. Because
1642 the individual characteristics of the human dentition do not transfer equally, the authors
1643 recommend using all the characteristics previously cited in the literature in analyzing a
1644 patterned injury. The substrate in which the pattern occurs will dictate the weight given
1645 to each characteristic. In this study, widths were not transferred from the natural
1646 dentition to the porcine skin as readily as the characteristics of intersecting angles. For
1647 porcine skin, the characteristics of intersecting angulation, displacement, individual
1648 missing teeth, rotations, spacing or diastemas and angulation of teeth to the x/y axis if
1649 posterior teeth are in the pattern, visually appear to transfer well and need further

1650 analysis . Tom's Toolbox has proven to be a valuable asset in quantifying individual
1651 patterns. The authors suggest that for the imaging specialist it can serve as asset in
1652 initial evaluation of bite patterned injuries.

1653 **Implications for policy and practice.**

1654 Interest in the forensic value of patterns caused by human teeth (bite marks or tooth
1655 marks) has a long history. Anecdotal history records Agrippa recognizing the
1656 decapitated head of a rival from a peculiar tooth. Early in legal history, tooth patterns
1657 were used to authenticate a document by having the responsible official bite into the
1658 sealing wax when it was applied to the document. The literature later records the use of
1659 dental charts and radiographs in human identification. The value of patterns produced
1660 by teeth (bite marks) have long been considered by many scientists world-wide, as
1661 possible identifiers of the individual. It is assumed by most dentists, that the
1662 characteristics of the human dentition are unique to each individual. Evidence in the
1663 research literature supports this concept. [42],[43],[44],[45],[46] Disagreements exist
1664 between scientists occur over whether these unique patterns of the human dentition, if
1665 true, can be replicated in human skin. Although human tooth patterns can and have
1666 occurred in inanimate objects, those that that are present in human skin, because of its
1667 viscoelasticity, present the most difficulties in interpretation. Several variables can and
1668 do occur. Distortions, either dynamic or photographic are the most common problems.
1669 The ABFO Standard Reference Scale #2 with its three circles, was developed by
1670 George Hyzer and Thomas Krauss and provided a means of detecting and correcting
1671 moderate photographic distortion. It is broadly accepted in evidence photography [47]

1672 The production of a legible pattern replicating the pattern of teeth in skin depends
1673 upon multiple factors in addition to the substrate and the mechanism. Firm substrates
1674 such as cheese, soap, plastic and leather, to cite several media, register dimensions
1675 best. The mechanism can be divided into two categories; dynamic and static. Dynamic
1676 distortion occurs when there is movement by either or both victim and assailant. Static
1677 distortion occurs less commonly and in the opinion of the authors occurs more often in
1678 the pattern of the lower teeth since the mandible is not fixed in position, as is the
1679 maxilla. Another variable, even in a static bite is the degree of elasticity in the skin and
1680 the inability to capture the exact dimensions of the teeth. The evidentiary value of the
1681 injury pattern can be influenced by the amount of distortion in the injury pattern. Even
1682 when agreement exists in the analysis of a pattern between all examiners, there is still a
1683 need for a scientific level of confidence for the opinion. This research is only a template
1684 for continued research. It is not the Rosetta stone. Continued research to develop this
1685 relatively new applied science of pattern analysis should not be stifled. The National
1686 Academy of Science Forensic Report in 2009, *Strengthening Forensic Science in the*
1687 *United States: A Path Forward*, recommended that scientific methods be initiated in all
1688 of the comparative sciences. [1]

1689 Whether dental characteristics are reliably replicated in a bite mark in human skin
1690 and whether the replicated pattern can be correlated with a degree of probability to the
1691 source is the current challenge. Several recently published studies have demonstrated
1692 that at least seven characteristics of the human dentition can be quantified. [2] [5] [10]
1693 A data set quantifying eight dental characteristics, in both two and three-dimensions,
1694 has now been developed from research and published by the authors.

1695 The scientific validation of the correlation of bite marks, or tooth patterns to their
1696 origin, in the opinion of the authors, predictably will be established by statistical /
1697 mathematical probability. That is, which combination of outlying characteristics
1698 demonstrated in a pattern(s) would reliably predict the probability of another individual in
1699 the population having the same combination of dental characteristics? For those
1700 images of the patterned images that include all six anterior teeth, or even several teeth
1701 that enable the investigators to insert markers, measurements were saved in Tom's
1702 Toolbox[®], calculated, saved in an internal data set and an internal report function ranks
1703 the combination of characteristics in percentiles. The application also established
1704 outliers for those specific characteristics.

1705 Prior to this report, to accomplish the frequency distribution of the dental
1706 characteristics, which make each individual's dentition individual, a series of studies
1707 were instituted to establish a methodology for quantification in both two and three-
1708 dimensions. This methodology was utilized to build a dataset of seven dental
1709 characteristics. Additional research established the reliability of the measurements,
1710 testing both intra-operator and inter-operator agreement in analysis. The initial
1711 quantification of width, damage, angles of rotation, missing teeth, diastema
1712 characteristics (spaces) and arch length were subsequently augmented by a study of
1713 displacement of the anterior teeth, either labially or lingually, from the normal
1714 physiologic dental arch form. A three- dimensional study of the width and incisal position
1715 of the anterior teeth on the horizontal (Z) plane supplemented the data. This study adds
1716 a practical application of the data set. An additional geometric approach to determining
1717 the angles of rotation of the four maxillary and mandibular incisors was developed. This

1718 concept utilizes the measurement of the angles at the intersection of the incisal lines,
1719 projected through the mesial and distal markers of each of the incisors. This geometric
1720 method of determining rotation through the measurement of the intersecting angles of
1721 the incisal lines is beneficial for several reasons. First, it eliminates subjective
1722 establishment of a base X axis. It is also more universal. One or more teeth may be
1723 missing or indistinct. If two or more anterior teeth can be identified (e.g. tooth 7 and 9),
1724 computation of the angle of intersecting lines can still be determined. This method of
1725 establishing tooth rotation also provides an expanded scope of search analysis, since it
1726 includes two additional characteristic items. In the earlier studies when an x axis could
1727 be established, we were able to determine four angles of rotation. With the alternate
1728 method of utilizing the intersecting angles formed by the incisal lines, enable the
1729 measurement of six angles of rotation.

1730 Although the width of the teeth in injury pattern in skin may be less exact than that of
1731 the known source, the intersecting angle formed by the extension of the incisal lines
1732 remains a constant. Most significant in establishing the degree of probability of a
1733 correlation will be the presence of multiple outliers in these angles. This procedure adds
1734 four additional characteristics to enable statistically the probability of a correlation
1735 between the unknown and a known source.

1736 The interpretation of the combination of quantified dental characteristics making up
1737 the initial two-dimension data set, also utilized the data obtained in the three-
1738 dimensional study, since the anterior teeth are not always all at the same level of
1739 eruption (Z plane). In doing so, the questions regarding whether certain teeth were
1740 present or missing in a patterned injury cited by past investigators were addressed.

1741 In more than 20% of the Samples in this study, the Distance Metric Model found the
1742 Target within the closest 5% of the sample population. In more than 6% of the Samples,
1743 it found the Target within the closest 1% of the Population.

1744 **Implications for further research**

1745 This study demonstrates that it is sometimes possible to replicate patterns of human
1746 teeth in porcine skin and determine scientifically, that a given injury pattern (bite mark)
1747 belongs to a very small proportion of our population data set, e.g. 5%, or even 1%.
1748 Predictably, building on this template, with a sufficiently large database of samples
1749 reflecting the diverse world population, a sophisticated imaging software application
1750 requiring operators inserting parameters for measurement and additional methods of
1751 applying forces for research need further investigation. This is applied science for injury
1752 pattern analysis and is only foundational research. It should not be cited in testimony
1753 and judicial procedures. It is intended to supplement and not contradict current
1754 guidelines of the American Board of Forensic Odontology (ABFO) concerning bite mark
1755 analysis and comparisons. A much larger population data base must still be developed.
1756 This research serves as a template, refining the ability to scientifically calculate that an
1757 unknown bite mark replicated in skin can correlated with probability to a member of the
1758 population data base. This template does not limit future researchers to use specific
1759 imaging software or pattern replication apparatus. All of the research materials and
1760 records will be maintained by Marquette University for a period of three years for
1761 repeatability of the study. The authors encourage questions and challenges.

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1764

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1882

1883 **Dissemination of Research Findings**

- 1884 1. A one hour summary of the research was presented to the Marquette University
1885 School of Dentistry faculty and students, July 16, 2013, Milwaukee Wisconsin.
- 1886 2. A one hour summary of the research was presented to the graduate students
1887 and faculty in the Department of Biomedical Engineering, Marquette University,
1888 College of Engineering on November 12, 2012.

- 1889 3. A one hour PowerPoint summary of the research findings was presented at the
1890 97th Annual Educational Conference of the International Association for
1891 Identification, on August 5, 2013 at Providence, Rhode Island.
- 1892 4. A lecture capture video of the research has been recorded for dissemination via
1893 a link posted on several forensic organizations' web pages is being prepared for
1894 distribution. The Midwest Forensic Resource Center and other forensic
1895 organizations have been approached requesting that they post a link to the video
1896 on their web sites.
- 1897 5. Overtures have been made to the National Association of Medical Examiners
1898 (NAME) and regional / state divisions of the International Association for
1899 Identification as possible educational presentations.
1900