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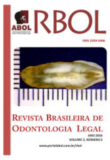

Forensic Odontology

VALIDATION OF 3D METRIC AND SUPERIMPOSITION TOOLS IN THREE SOFTWARE PACKAGES FOR THE MORPHOLOGICAL COMPARISON OF LASER SCANNED ANTERIOR DENTITION MODELS

Validação de ferramentas tridimensionais de três softwares para mensuração e sobreposição tridimensional de modelos odontológicos visando à comparação morfológica

Ademir FRANCO[1,2], Guy WILLEMS[1], Paulo Henrique Couto SOUZA[2], Sérgio Aparecido IGNÁCIO[3], Patrick THEVISSEN[1].

1. Department of Oral Health Sciences – Forensic Dentistry, KU Leuven & Dentistry, University Hospitals Leuven, Leuven, Belgium.
2. Stomatology, School of Health and Biosciences, Pontifícia Universidade Católica do Paraná, Curitiba, Brazil.
3. Biostatistics, School of Health and Biosciences, Pontifícia Universidade Católica do Paraná, Curitiba, Brazil.

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Autor para correspondência

Ademir Franco
Department of Oral Health Sciences - Forensic Dentistry
KU Leuven and Dentistry, University Hospitals Leuven
Kapucijnenvoer 7, block B, 3000 Leuven, Belgium
E-mail: franco.gat@gmail.com

ABSTRACT

Introduction: Few studies succeeded on demonstrating that dentitions are unique. Methodological limitations may have influenced these outcomes. Objective: The present study aims to validate software packages for comparing human dentitions. Material and methods: A pool of 40 dental casts were laser scanned (XCAD 3D®, XCADCAM Technology®, São Paulo, Brazil) and implemented in Geomagic Studio® (GS) (3D Systems®, Rock Hill, USA), Cloud Compare® (CC) (Telecom Paris Tech® and EDF®, Paris, France), and Maestro 3D Ortho Studio® (MS) (AGE Solutions®, Pontedera, Italy) software packages to evaluate metric and superimposition tools. Results: Software performances did not significantly differ ($p>0.05$) considering cropping, landmarking and superimposition functions. GS was more precise for detecting identical models ($p<0.05$). Inter and intra examiner reproducibility reached optimal outcomes. Calibration was assured for software measuring tools and scanning process. Conclusion: Both GS and CC may be used for comparing 3D anterior dentitions. However, more practical and less operator-depending procedures are available in GS.

KEYWORDS

Forensic Sciences; Forensic Dentistry; Dentition; Morphology; 3D Imaging; Software.

INTRODUCTION

Uniqueness of the human dentition (UHD) is essential in forensic dentistry to guarantee that two persons will not present the same dental characteristics. In dental identifications, the UHD assures that the deceased body belongs exclusively to the identified victim. In bitemark analysis, the UHD guarantees that the bite mark could only be inflicted by one biter. Although essential, the UHD is still assumed and rises increasing uncertainty over the last years[1,2] on the reliability of the related forensic evidences.

The dental identification is, together with fingerprint and DNA analysis[3,4], one of the three scientifically pathways, accepted for human identification[5]. The dental identification procedure is performed initially comparing ante-mortem (AM) and post-mortem (PM) data[3,4,6] in order to match dental evidences. The identification outcomes depend on the quality and quantity of these evidences. The quality of evidences is represented by the specific traits within the human teeth present after dental treatment and the morphology of the teeth. The quantity of evidences is related to the number of teeth available for analysis. Bitemark analysis should enable to link a bite patterned impression with the dentition of a suspect biter[7]. Proving the UHD in a bitemark context becomes more difficult. The quantity of dental evidences is considerably reduced, because the analysis is mainly restricted to the six anterior teeth of each dental arch[6-8]. Additionally, only the tooth parts intruding the bitten surface are significant for analysis. The quality of the evidences is restricted to the morphology of these tooth parts (mainly the incisal edges of the anterior teeth). The decrease in the quantity and quality of evidences makes the proof of UHD more difficult in the context of bitemarks.

A practical way to prove the UHD is the pair-wise comparison of dental casts[9-12]. If a match is found between casts of different subjects, uniqueness may not be claimed[11]. Efforts were made to enhance these comparisons. In particular, two[9,11] and three-dimensional (3D)[12,13] analyses of the human dentition were aspired; specific software for were developed[14] and tested[15] statistics were enhanced[16] and specific populations were sampled for investigation[17]. However, methodological limitations remained. Further studies in the field need to implement tools enabling to perform in 3D the pair-wise morphological comparison of dental casts and allowing to distinguish the quality and quantity of the investigated dentitions.

The present research aims to validate the metric and superimposition tools of three software packages enabling optimal pair-wise comparison of 3D dental casts to support further researches on the uniqueness of the human dentition.

MATERIAL AND METHODS

The present problem-based retrospective experimental research was approved by the Committee of Ethics in Research of the Pontifícia Universidade Católica do Paraná, Brazil, under the protocol number: 19575613.2.0000.0020.

A sample of 20 individuals (10 females, 10 males) with an intact permanent anterior dentition completely erupted and without any dental treatment was collected.

Their maxillary and mandibular dentitions were impressed using manually-mixed alginate (Jeltrate Dustless®, Dentsply®, York, PA, USA) with metallic dental trays (Tecnodent®, São Paulo, SP, Brazil) and casted in dental models with plaster type IV (Durone®, Dentsply®, York, PA, USA). The obtained impressions were casted in rubber mould base formers and each model was manually trimmed in maximum intercuspation[18], according to a standard procedure described by Dofka[19]. All the technical steps were performed by a single examiner following the manufacturers' instructions. Next, the dental models were scanned using the XCAD 3D® (XCADCAM Technology®, São Paulo, SP, Brazil) automated motion device with angular laser scanning, at a precision of <20 microns and a volume capture of 80mm (x-axis) x 50mm (y-axis) x 80mm (z-axis). The 3D dental model images (3D-DMI) were stored as .STL and .OrthoStudio files and imported for analysis in 3 different software packages designed for 3D geometric analysis namely: Geomagic Studio® (GS) (3D Systems®, Rock Hill, SC, USA); Cloud Compare® (CC) (Telecom Paris Tech® and EDF®, Paris, France); and Maestro 3D Ortho Studio® (MS) (AGE Solutions®, Pontedera, PI, Italy). The pool of 40 imported 3D-DMI images was used to investigate in 10 tests (Figure 1) the performances of metric (2 dimensional, 2D) and superimposition (3dimensional, 3D) tools of each software. The metric tools were available in the 3 software, while superimposition was only possible in GS and CC. The 2D and 3D test results were compared between the corresponding software.

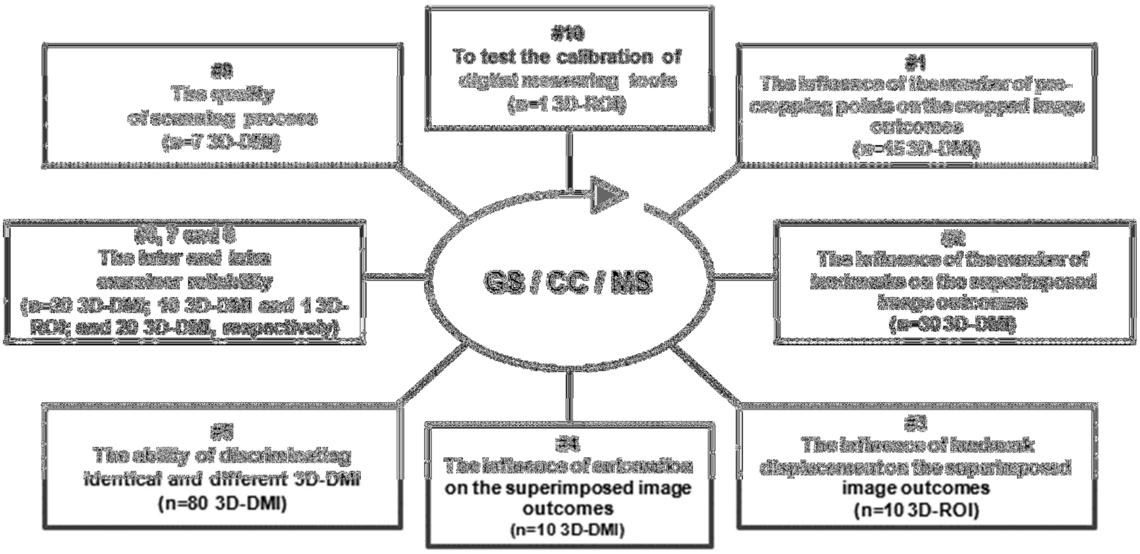

Figure 1 – Overview of the performed quantitative research tests. Legend: Geomagic Studio® (GS), Cloud Compare® (CC) and Maestro Ortho Studio® (MS) software packaged were used to perform 10 different qualitative research tests, and compared based on the obtained test results. In each test (#) a specific number (n) of three-dimensional dental model images (3D-DMI) or rectangular object images (3D-ROI) were evaluated.

For reference purposes, a copy of a rectangular object was made impressing, casting and digitalizing it according to the protocols previously mentioned. For uniform analyses, standard positioning of the imported 3D-DMI and the 3D rectangular object image (3D-ROI) was established in the studied software. The 3D-DMI were positioned in occlusal view with the posterior base border parallel to the horizontal plane. The 3D-ROI was positioned with one of the corners in the center of the screen, enabling the visualization of the vertices in the x-, y- and z- axes. For certain tests, the .STL and .OrthoStudio files of the 3D-DMI and the 3D-ROI were copied using the “copy” and “paste” command tools of the Microsoft Windows® (Microsoft Corp.®, Redmond, WA, USA) operating system.

The 3D analyses required two operator-dependent steps for the pair wise superimposition of 3D-DMI parts of interest: cropping and landmarking. In particular, a manual reference demarcation of the 3D-DMI was necessary in the former placing pre-cropping points and in the latter positioning landmarks. Prior to automated, semi-automated, and manual superimpositions, the manual pre-cropping point positioning was performed along the cemento-enamel junction of the anterior teeth. It enabled the software to sort out the anterior tooth crowns. A first test was developed and applied to verify the influence of the number of pre-cropping points placed, on the cropped image outcomes. Three sets of 5 copied mandibular 3D-DMI (n=15) were studied. The first set was cropped after positioning 28 pre-cropping points (15 points on the lingual surface + 13 points on the vestibular surface); the second set after positioning 58 pre-cropping points (25 points on the lingual surface + 23 points on the vestibular surface); and the third set after positioning 94 pre-cropping points (49 points on the lingual surface + 45 points on the vestibular surface) (Figure 2). The cropped 3D-DMI and their respective copies were imported in GS and CC and superimposed automatically. Existing morphological differences in the pair wise 3D-DMI comparisons were quantified in each software.

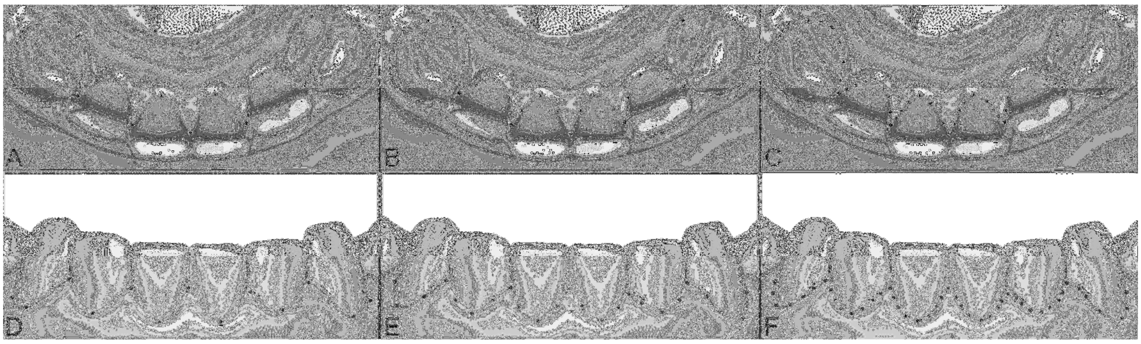

Figure 2 – Pre-cropping point distributions used to test the influence of the number of pre-cropping points on the cropped image outcomes (test #1). The lingual (panels A, B and C) and vestibular (panels D, E and F) pre-cropping point arrangements, using 28, 58, and 94 pre-cropping points, respectively, are illustrated. In Geomagic Studio® software package the cropping is performed according to curved lines automatically positioned between the pre-cropping points and matched with the gingival contours.

The landmarking procedure was essential prior to the semi-automated and the manual superimpositions. A second test was developed and applied to verify the influence of the number of landmarks used, on the superimposition outcomes. Five different maxillary 3D-DMI were each copied 3 times, and grouped (group A, n=15). Next, 5 new maxillary 3D-DMI were each copied 3 times and grouped (group B, n=15). The 3D-DMI of each image set from group A and B was pair wise superimposed placing 4, 10 and 18 landmarks respectively (Figure 3). In GS and CC the morphological differences between the pair wise compared 3D-DMI were quantified.

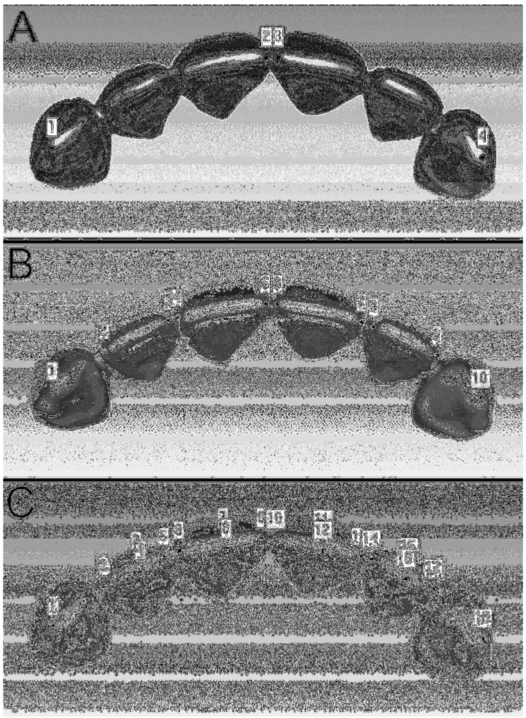

Figure 3 – Landmark distributions used to test the influence of the number of landmarks on the superimposed image outcomes (test #2). The cropped anterior dentitions of the 3D dental model images were landmarked with sets of 4 (A), 10 (B) and 18 (C) landmarks, respectively. The first set included the cusp tips of the canines and the most mesial point of the incisal edges of the central incisors (A). The second set included the landmarks of the first set and added the most mesial and distal point of each incisal incisor edge (B). The third set included the landmarks of the previous two sets and added the most vestibular and palatal points in the center of all incisal edges (C).

A third test was developed and applied to verify the influence of the landmark position on the superimposition outcomes. This test was performed differently in GS and CC. The 3D-ROI was copied four times (n=5) and imported in GS. Next, the original and the four copied 3D-ROI were positioned on a background scaled grid. The original 3D-ROI was landmarked in a fixed region, while the copies were landmarked with increasing landmark displacements (0.5mm, 1mm; 2mm; and 5mm, respectively). Due to the lack of a background grid in CC, the original 3D-ROI was landmarked in a fixed region and the four copies (n=5) were landmarked using the linear measuring tool with displacements from the fixed region of 0.5mm; 1mm; 2mm; and 5mm, respectively. The morphological differences between the original and copied 3D-ROI were quantified in each software.

A fourth test was established to verify superimposition differences between automated (no landmark), semi-automated and manual superimpositions. GS and CC allow manual and semi-automated superimpositions. The automated superimposition is only available in GS (the same tool is under research in CC). Between 2 sets of 5 different mandibular 3D-DMI pair wise manual; semi-automated and automated superimpositions were performed. The morphological differences between the pair wise compared 3D-DMI were quantified in each software.

A fifth test was developed and applied to verify the ability of the software to discriminate identical (3D-DMI and their copies) and different 3D-DMI. Forty 3D-DMI (20 maxillary and 20 mandibular) were selected together with 20 (10 maxillary and 10 mandibular) other 3D-DMI and their respective copies. All 3D-DMI (n=80) were cropped, landmarked and pair wise superimposed. The cropping procedure was performed placing 58 pre-cropping points along the cemento-enamel junction of the anterior teeth, always including the highest point at the interdental papillae and the lowest point of the cemento-enamel junction contour. The landmarking procedure was performed placing 10 landmarks on the anterior teeth, in which 8 were distributed in the most distal and most mesial point of the incisal edge of central and lateral incisors and 2 on the cusp tip of canines. The morphological differences between the pair wise compared 3D-DMI were quantified. The mean morphological difference found between identical 3D-DMI was used as threshold to verify if mismatches were occurring among the different 3D-DMI. Specifically, if the pair wise comparison between different 3D-DMI had mean morphological difference below the threshold it was considered a mismatch.

The sixth, seventh and eighth tests were performed to asses inter/intra examiner reliability. In the sixth test 10 3D-DMI (5 maxillary and 5 mandibular) were copied (n=20) and used to test the reproducibility of the cropping procedure. The 3D-DMI and the respective copies were imported in GS and CC and cropped in each software by a first examiner, placing 58 pre-cropping points along the cemento-enamel junction. For the assessment of inter examiner reproducibility, a second examiner performed independently the same procedure. For the assessment of intra examiner reproducibility, the first examiner repeated the same procedure within 14 days. In each software the morphological differences between the pair wise compared 3D-DMI were quantified per examiner.

In the seventh test 10 maxillary 3D-DMI were used to 2D test the reproducibility of the landmarking. Ten landmarks were placed by two examiners in each 3D-DMI, using separately GS, CC and MS. On forehand, a third examiner placed a single reference landmark on the most frontal vertex of each 3D-DMI. Screenshots were taken from the landmarked files and implemented in Adobe Photoshop® CS5 (Adobe Systems®, San Jose, California, USA) as image layers. The image layers of the first examiner were kept with 100% opacity levels, while the opacity levels of the image layers of the second examiner were reduced to 50%. The image layers of the first and second examiners were superimposed in 2D, using as references the landmark placed by the third examiner and the posterior base border of the cast in the 3D-DMI parallel to the horizontal plane. A similar procedure was performed using the 3D-ROI. The first and second examiner placed independently 4 landmarks on each visible vertex, except for the central vertex which was landmarked by a third examiner and used as a reference point (Figures 4 and 5). The screenshots of each examiner were 2D superimposed in Adobe Photoshop® as image layers with different opacity and aligned using the reference landmark placed by the third examiner. The difference between the corresponding landmarks of the first and the second examiner were measured using Photoshop's ruler tool. For the inter examiner reproducibility, the distances measured after the landmarking of the second examiner were compared with the distances of the first examiner, obtained from the 3D-DMI and the

3D-ROI in each software. For the intra examiner reproducibility, the first examiner repeated the procedures on the 3D-DMI and the 3D-ROI in each software within 14 days and the distances between both examinations were compared per software.

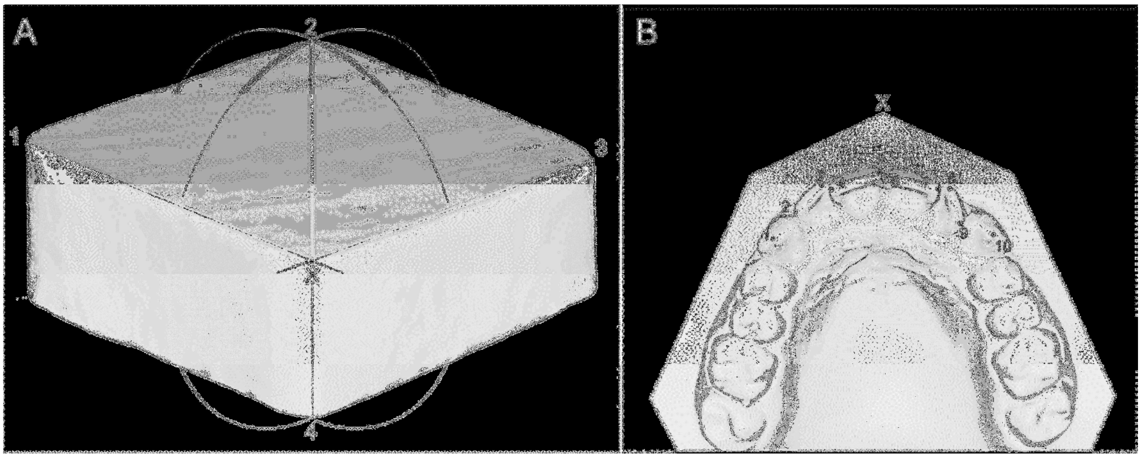

Figure 4 – Standard positions for landmarking the 3D-ROI and the 3D-DMI. The 3D rectangular model image (3D-ROI) (A) and the 3D dental model image (3D-DMI) (B) were landmarked with the reference point (x) for metric analysis and with additional points (from 1 to 10) both for metric and superimposition analysis. For orientation the 3D-DMI were positioned in occlusal view with the posterior base border parallel to the horizontal plane, while the 3D-ROI was positioned centralizing one of its corners on the screen, allowing the visualization of vertices in x-, y- and z- axes.

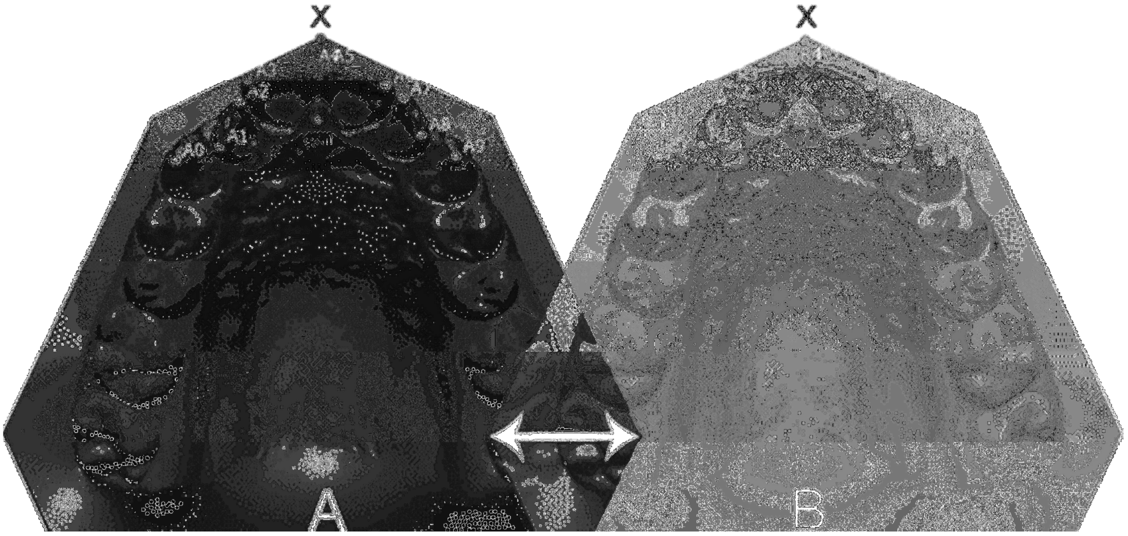

Figure 5 – Superimposition of image layers used to test the examiner reliability for the landmarking procedure with Adobe PhotoShop® (test #7). Layers of the first (A) and second (B) examiners, with opacity levels of 100% and 50%, respectively, will be superimposed with the posterior base of the models and the fixed reference landmark (x) as references. The superimposition procedure is performed dragging one layer over the other using Adobe Photoshop's "move" tool, assuring superimposition within overlap of the reference points.

In the eighth test 10 3D-DMI (5 mandibular and 5 maxillary) were copied (n=20) and used to 3D test the reproducibility of the landmarking. The 3D-DMI were imported in GS and CC and landmarked by a first examiner following the set up described in test seven. For the assessment of inter examiner reproducibility, a second examiner performed the same procedure in each software. For the assessment of intra examiner reproducibility, the first examiner repeated the same procedure in each software within 14 days. In both software the original and the corresponding copied 3D-DMI were pair wise superimposed using the landmarks as reference. Appearing morphological differences were quantified per examiner and compared.

Test nine verified the quality of the scanning process. A blind analysis was developed and applied scanning a mandibular 3D-DMI two times with the same scanning device. In the analysis, one of the obtained digital files was copied. The three files (2 scans and 1 copy) were pooled with 4 randomly chosen mandibular 3D-DMI. The 7 3D-DMI were pair wise compared (21 combinations) in each software and the morphological differences were quantified.

The tenth test was developed and applied to assess the calibration of software measurement tools. The rectangular object was measured in situ, with a digital caliper and an ABFO scale #2 and digitally, with the measuring tools of each of the software. Differences between in situ and digital measurements were quantified.

The quantification of morphological differences was automatically performed in GS and CC for all the tests, except tests #7 and #10. The morphological differences were assessed comparing pair wise the spatial position of homologous points in the examined 3D-DMI and reported as a mean morphological difference (bias) with a respective standard deviation (precision), both expressed in millimeters (mm). The quantification of measurement differences was established subtracting the absolute linear measurement values (in mm) from the 3D-DMI or 3D-ROI pairs respectively compared.

The calculated morphological differences in tests 1, 2, and 4 were assessed for normality using Shapiro-Wilk statistical test. Their mean values were compared between pre-cropping point groups (28 *vs.* 58; 28 *vs.* 94; 58 *vs.* 94); landmark groups (4 *vs.* 10; 4 *vs.* 18; 10 *vs.* 18); and superimposition groups (automated *vs.* semi-automated; automated *vs.* manual; semi-automated *vs.* manual) using Student's t-test for paired samples and Wilcoxon signed rank test assuming normal and not normal distribution. In test 5 the mean values of morphological differences between identical and non identical groups was compared using Student's t-test for independent samples. In tests 6, 7 and 8 the examiner reliability was statistically measured with: Dahlberg's error, which correlates the total variance with error variance and indicates the level of reproducibility; Pearson's correlation coefficient and reliability coefficient, indicating the correlations between the examiner outcomes; and Student's t-test for paired samples to evaluate the systematic error. The outcomes of tests 3, 9 and 10 were assessed with descriptive statistics.

The mean values of the morphological differences in tests 1, 2, 4, 5, 6, 7 and 8 were compared between software using Student's t-test for independent samples and nonparametric Mann-Whitney U test assuming normal and not normal distribution. For all the tests statistical significance was set at $p<0.05$. Student's t-test outcomes indicated larger morphological difference with positive or negative increase in t values. The statistical analyses were performed with SPSS® 23.0 (IBM® Corp., Armonk, New York, USA) software.

After the quantitative approach, the software were qualitatively analyzed based on the integrated tools, their costs and their compatibility with the imported file format and the operational systems.

RESULTS

Normal distribution was observed for all the calculated morphological differences, except for the 18 landmark placement (test 2).

No statistically significant differences were observed comparing the calculated morphological differences within software using a different number of pre-cropping points (test 1), landmarks (test 2), or level of automation (test 4) (Table 1).

Table 1 – Within test results of test #1, #2, #3, #4 and #5 compared with Student's t-test for paired samples and Wilcoxon signed rank test, within each software.

#	Variables	Software	MMD	*SD*	*t* (*p*)
1	**Number of pre-cropping points**				
	28 points / 58 points	GS	21.03 / 19.41	2.77 / 6.29	0.97 (0.38)
	28 points / 94 points	GS	21.03 / 17.81	2.77 / 3.52	2.11 (0.10)
	58 points / 94 points	GS	19.41 / 17.81	6.29 / 3.52	0.86 (0.43)
	28 points / 58 points	CC	16.63 / 15.35	3.76 / 6.55	0.41 (0.49)
	28 points / 94 points	CC	16.63 / 16.48	3.76 / 1.67	0.15 (0.88)
	58 points / 94 points	CC	15.35 / 16.48	6.55 / 1.67	0.40 (0.70)
2	**Number of landmarks**				
	4 landmarks / 10 landmarks	GS	0.11 / 0.16	0.08 / 0.19	-0.61 (0.57)
	4 landmarks / 18 landmarks	GS	0.11 / 0.11	0.08 / 0.20	0.02 (0.98)*
	10 landmarks / 18 landmarks	GS	0.16 / 0.11	0.19 / 0.20	0.99 (0.37)*
	4 landmarks / 10 landmarks	CC	1.32 / 0.23	1.22 / 0.19	1.74 (0.15)
	4 landmarks / 18 landmarks	CC	1.32 / 0.72	1.22 / 1.18	-0.67 (0.50)*
	10 landmarks / 18 landmarks	CC	0.23 / 0.72	0.19 / 1.18	-0.40 (0.68)*
3	**Landmark displacement**				
	0.05 mm	GS	0.00	0.04	d/s
	1.00 mm	GS	0.00	0.04	d/s
	2.00 mm	GS	0.00	0.50	d/s
	5.00 mm	GS	0.33	3.03	d/s
	0.05 mm	CC	0.00	0.10	d/s
	1.00 mm	CC	0.02	0.22	d/s
	2.00 mm	CC	0.03	0.37	d/s
	5.00 mm	CC	0.57	1.00	d/s
4	**Level of automation**				
	Automated / semi-automated	GS	0.09 / 0.12	0.05 / 0.09	-1.35 (0.24)
	Automated / manual	GS	0.09 / 0.13	0.05 / 0.09	-2.01 (0.11)
	Semi-automated / manual	GS	0.12 / 0.13	0.09 / 0.09	-1.11 (0.32)
	Semi-automated / manual	CC	0.13 / 0.21	0.10 / 0.10	1.33 (0.25)
5	**Discrimination of 3D-DMI**				
	Different mandibular 3D-DMI	GS	-0.06	1.27	n/a
	Different maxillary 3D-DMI	GS	0.14	1.38	n/a
	Identical mandibular 3D-DMI	GS	0.00	0.01	t/s
	Identical maxillary 3D-DMI	GS	0.00	0.01	t/s
	Different mandibular 3D-DMI	CC	0.17	1.14	n/a
	Different maxillary 3D-DMI	CC	0.27	1.13	n/a
	Identical mandibular 3D-DMI	CC	0.00	0.03	t/s
	Identical maxillary 3D-DMI	CC	0.00	0.04	t/s

#: test number; MMD: mean morphological difference; t: Student's "*t*" value; *p*: significance rate set at 95%; GS: Geomagic Studio®; CC: Cloud Compare®; *: must be interpreted as Wilcoxon's Z value; 3D-DMI: Three-dimensional dental model image; d/s descriptive statistics; t/s threshold setting; n/a: not applicable; SD: standard deviation; MMD and SD expressed in millimeters.

Testing the displacement of landmarks (test 3) a wider range in the calculated morphological difference between the 3D-ROI and its copies was observed with an increase in level of landmark displacement (Table 1).

Comparing the mean morphological differences between identical and different 3D-DMI (test 5) revealed no mismatch results below the obtained threshold values, both for the mandible and maxilla within each software (test 5) (Table 1).

The inter and intra reliability tests for the cropping (test 6), 2D landmarking (test 7), the 3D landmarking (test 8) indicated optimal reliability between examiners within each software (Table 2). The Outcomes of the examiner reliability test for cropping (test 6) resulted in total variance and error variance equal to zero for all performed statistical tests.

Table 2 – Examiner reliability test results for landmarking with Adobe PhotoShop® (test #7) and software tools (test #8) within each software.

#	Test	Software	Dahlberg's error (%)	Reliability coefficient (%)	Pearson's coefficient (%)
7	Inter	GS	0.46	99.54	99.63
		CC	4.06	95.94	96.56
		MS	3.14	96.86	97.07
	Intra	GS	0.97	99.03	99.22
		CC	1.57	98.43	98.73
		MS	1.87	98.13	98.38
8	Inter	GS	n/a	n/a	n/a
		CC	3.82	96.18	97.97
	Intra	GS	n/a	n/a	n/a
		CC	8.27	91.73	95.27

GS: Geomagic Studio®; CC: Cloud Compare®; MS: Maestro Ortho Studio®; Student's t-test for paired samples did not reveal statistically significant differences or systematic error between examiners (p>0.05).

Testing the quality of the scanning process (test 9) indicated no morphological differences in 3D-DMI between the original and rescanned; between the original and copied; and between the copied and rescanned groups.

In the test calibrating the measuring tools (test 10) no differences were observed between the calculated morphological differences in 3D-DMI comparing the in situ and digital measurements.

No difference in performance was observed between software using different number of pre-cropping points (test 1), landmarks (test 2), or level of automation (test 4) (Table 3).

A statistically significant higher mean morphological difference was observed in CC (0.001mm) compared to GS (0.000mm) considering the performance to discriminate identical 3D-DMI (test #5). However, both software performed a perfect discrimination of identical/different 3D-DMI (Table 3).

Inter and intra reliability tests for the cropping (test 6), 2D landmarking (test 7), the 3D landmarking (test 8) were not statistically different between software (Table 3).

Table 3 – Within test results of test #1, #2, #4, #5, #6, #7 and #8 compared with Student's t-test for paired samples and Wilcoxon signed rank test, between software.

#	**Variable**	**Software**	**MMD**	**SD**	***t* (*p*)**
1	**Number of pre-cropping points**				
	28	GS CC	21.03 16.63	2.77 3.76	2.10 (0.06)
	58	GS CC	19.41 15.35	6.29 6.55	1.00 (0.34)
	94	GS CC	17.81 16.48	3.52 1.67	0.76 (0.47)
2	**Number of landmarks**				
	4	GS CC	0.11 1.32	0.08 1.22	-2.09 (0.09)
	10	GS CC	0.16 0.23	0.19 0.19	-0.55 (0.59)
	18	GS CC	0.11 0.72	0.20 1.18	-0.73 (0.46)[a]
4	**Level of automation**				
	Automated	GS CC	0.09 n/a	0.05 n/a	n/a
	semi-automated	GS CC	0.12 0.10	0.09 0.10	-0.23 (0.81)
	Manual	GS CC	0.13 0.21	0.09 0.10	-1.29 (0.23)
5	**Discrimination of 3D-DMI**				
	Identical 3D-DMI	GS CC	0.0000 0.0010	0.00 0.00	-3.42 (0.00)
	Different 3D-DMI	GS CC	0.04 0.22	0.53 0.33	-1.29 (0.20)
6	**Examiner reliability - Cropping**				
	Inter examiner	GS CC	0.00 0.00	0.00 0.00	n/a n/a
	Intra-examiner	GS CC	0.00 0.00	0.00 0.00	n/a n/a
8	**Examiner reliability – Landmarking (Software tools)**				
	Inter examiner	GS CC	0.00 -0.02	0.00 0.13	-0.04 (0.96)
	Intra-examiner	GS CC	0.00 -0.02	0.00 0.06	1.18 (0.25)
7	**Examiner reliability – Landmarking (PhotoShop®)**				
			MLM		
	Inter examiner	GS CC	17.99 16.71	8.01 7.17	0.53 (0.59)
		GS MS	17.99 20.45	8.01 8.97	0.91 (0.36)
		CC MS	16.71 20.45	7.17 8.97	-1.45 (0.15)
	Intra-examiner	GS CC	18.00 16.46	7.95 7.06	0.64 (0.52)
		GS MS	18.00 20.36	7.95 9.02	0.87 (0.38)
		CC MS	16.46 20.36	7.06 9.02	-1.52 (0.13)

#: test number; MMD: mean morphological difference; SD: standard deviation; MLM: mean linear measurement; *p*: significance rate set at 95%; *t*: Student's "*t*" value; GS: Geomagic Studio®; CC: Cloud Compare®; MS: Maestro Ortho Studio®; [a]: Mann-Whitney's Z value; n/a: not applicable MMD, SD and MLM expressed in millimeters.

The qualitative evaluation revealed GS as practically the best performing and most extensive software, because CC was less precise for the discrimination of identical 3D-DMI and did not allow automated superimpositions, while MS was limited by the lack of superimposition and cropping tools (Table 4).

Table 4 – Available tools and properties in the three examined software packages.

Tool / Property	Advantages and disadvantages	GS	CC	MS
Cropping	3D visualization while cropping	+	-	-
	Cropping with curved lines	+	-	-
Landmarking	3D visualization while landmarking	+	+	-
	Immediate Cartesian coordinate	-	+	-
Superimposition	Automated	+	-	-
Acquisition	Freeware / open source	-	+	-
Compatible operating system	Windows®	+	+	+
	MacOS®	-	+	-
File format	Import .stl files	+	+	-
	Import specific file	+	+	-

+: present; -: absent; GS: Geomagic Studio®; CC: Cloud Compare®; MS: Maestro Ortho Studio®.

DISCUSSION

The term uniqueness is often wrongly used in a forensic odontological context. Commonly, during human identifications, uniqueness is used to confirm that AM/PM dental data positively match. However, a positive match only indicates that AM/PM evidences are highly similar or identical. Uniqueness covers more than a positive match between AM/PM evidences[20]. It also guarantees that no other person in the world exists with AM evidence having the same dental characteristics as the presented PM evidence[20]. The social and legal consequence of the lack of proven uniqueness is that a ground is provided for non acceptance of the established identification by the relatives of the victim, based on the theoretical possibility that the body could belong to somebody else. Yet bitemark analyses rely on uniqueness interpreted in a different context. Specifically, it assumes that the anterior dentition of two different persons will not create equal or identical impression patterns on the human skin. In this context, the lack of proven uniqueness favors the perpetrator, who could claim that the bite impression belongs to another person with the same dentition. Several techniques for the analysis of bitemarks were used to prove the relation between the injury and the offender. These techniques varied from overlaying hand drawn transparent on photographs, to 3D digital superimpositions[21]. The validation of these techniques indicated that the best outcomes for bitemark analysis probably result from the 3D comparison of the dental morphology[21,22]. In this context, the present research was developed to test the ability of available software packages to compare the morphology of 3D laser scanned dentition. The present study did not aim to prove the UHD, but yet tested and validated software packages for further studies in the field.

Different studies investigated the UHD[8]. Most of them were designed in the context of bitemark analysis, examining the six anterior teeth[8]. The methods used in these studies varied, depending on the comparison technique used, the software applied, the tooth models considered, and the morphometric analysis technique utilized[8]. All the methods commonly consider morphological tooth information, such as the size and shape; and the relation of the tooth in the dental arch, such as its angulation and position[8]. The outcomes of these studies were not uniformly proving the UHD[9,17]. Because of the limitations in these studies, such as the lack of 3D image registration and the use of operator-depending procedures, the present study aimed to select and validate existing object comparison software applicable for unbiased 3D comparison of the morphology of the human dentition.

Similar to previous studies[9–11,16,17] it was chosen to restrict the area of interest to the six anterior teeth. Therefore cropping the imported 3D-DMI was necessary to select and study the anterior teeth in the collected 3D-DMI. Considering that cropping was an operator-depending procedure, the present study evaluated the degree of potentially included bias. The first test indicated that no difference was observed placing 28, 58 or 94 pre-cropping points along the cemento enamel junction. It indicated that cropping was a stable procedure, not generating discrepant outcomes. Moreover, no statistically significant difference was observed comparing the performances of the two software. These findings were confirmed in the sixth test, which revealed optimal intra and inter examiner cropping reproducibility.

A second manual procedure consisted of landmarking[8]. This procedure was necessary to align two objects prior to comparison. However, two landmarks can hardly be placed in the exact the same anatomic position over the time. In previous research, the landmarking was mainly considered in occlusal view, varying the landmark arrangement and number – e.g. 14[10,11], 24[9] or 30[13] landmarks. The second test of the present study demonstrated that the number of landmarks was not statistically significantly influencing the 3D-DMI comparison outcomes. However, a higher number of landmarks maybe translated in more positional information, and consequently more operator interventions. Moreover, the third test demonstrated that a systematic error of 0.5mm to 5mm gradually occurs from landmark misplacement, highlighting that even small landmark displacements may interfere with the outcomes. In order to increase the landmarking reliability, exhaustive operator training and calibration is required. Tests seven and eight indicated high examiner reproducibility, proving optimal landmarking reproducibility in the present study. To eliminate the need for manual interventions in further studies, automated landmarking and/or image superimposition procedures are necessary. In the present study only GS offered this modality. Until the present, no studies aiming to prove the UHD applied automated image superimpositions.

The fourth test compared the automated superimposition with the semi-automated and the manual superimpositions, revealing no statistically significant difference within (Table 1) and between (Table 3) software. For further studies the automated system is the most adequate, because once it rules out the need for landmarking and reduces the number of operator-depending procedures.

The fifth test simulated investigation procedures enabling to prove the UHD. Based on that, a threshold value was obtained in GS and CC from the comparison of identical 3D-DMI, separately for the mandible and maxilla. The threshold mean and standard deviation were slightly higher in CC than in GS, for the mandible as well as the maxilla (Table 1). Consequently CC had more bias and less precision compared to GS. This inconsistency between software was statistically significant (Table 3). Therefore GS is recommended in the search for identical 3D-DMI.

The ninth test was necessary to verify the quality of the scanning process using the XCAD 3D® (XCADCAM Technology®, São Paulo, SP, Brazil) scanning device. The precision of this device for image acquisition is nearly 20 microns. Other authors reported 3D scanning image quality from 10[16] to 100[12] microns, whereas flat bed (2D) scanners reached 85 microns[16]. The scanning device used in the present study revealed satisfactory outcomes, without increasing the mean error in hundredths of millimeters (<0.00mm). In the same context, the tenth test assessed the calibration of the measuring tools of each software and revealed optimal performances for GS, CC and MS. No difference was detected comparing in situ and digital measurements.

Applicability and operating modes of the evaluated software were compared and GS was found to perform superiorly. MS was designed for orthodontic purposes and consequently presented less application tools compared to the GS and CC software, developed for engineering and graphic design. For this reason, most of tests performed in the present study were not possible within MS, which missed the essential 3D tools that allows the cropping and the superimposition commands. GS was most advantageous, mainly due to the automated superimposition and to the cropping toolbox, which allowed for simultaneous manipulation and delimitation of curves. CC is certainly useful for the morphological analysis of the human teeth but compared to GS it requires more time and manual work to prepare the images for comparison. CC is freeware and is also compatible with Mac OS® (Apple Inc., Cupertino, California, USA) operating system (Table 4).

CONCLUSION

Considering its superior toolbox for cropping procedures; its options for automated superimposition; and its most precise discrimination of identical 3D-DMI, GS figured as the most appropriate software for further investigations on the UHD. Its application is recommended in the context of forensic bitemark and identification research.

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CONFLICT OF INTERESTS

The authors declare no conflict of interests.

RESUMO

Introdução: Poucos estudos obtiveram êxito em demonstrar a unicidade da dentição humana. Falhas metodológicas podem ter influenciado os resultados destes estudos. Objetivo: O presente estudo objetivou validar ferramentas contidas em pacotes de software existentes para comparar dentições humanas. Material e método: Uma amostra de 40 modelos odontológicos digitalizados (XCAD 3D®, XCADCAM Technology®, São Paulo, Brazil) foi selecionada e analisada utilizando os seguintes softwares: Geomagic Studio® (GS) (3D Systems®, Rock Hill, USA), Cloud Compare® (CC) (Telecom Paris Tech® and EDF®, Paris, France), and Maestro 3D Ortho Studio® (MS) (AGE Solutions®, Pontedera, Italy). Resultados: Os softwares não apresentaram performances com diferença estatisticamente significante ($p>0.05$) considerando os procedimentos de recorte, colocação de pontos de referência (landmarks) e sobreposição de modelos. O software GS apresentou maior precisão para detectar modelos idênticos ($p<0.05$). Testes intra e interexaminador resultaram em ótima concordância. Os softwares apresentaram ótima calibração de ferramentas métricas. Conclusão: Ambos os softwares GS e CC podem ser utilizados para comparar modelos odontológicos digitalizados. Contudo, performances mais práticas e independentes do operador podem ser alcançadas por meio do software GS.

PALAVRAS-CHAVE

Ciências Forenses; Odontologia Legal; Dentes; Morfologia; Imaginologia.

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