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SUPPLEMENT ARTICLE

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Three-dimensional evaluation of the holographic projection in digital dental model superimposition using HoloLens device

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Structured Abstract

Objective: To assess validity and reliability of palatal superimposition of holograms of 3D digital dental models using a customized software, (Ortho Mechanics Sequential Analyzer OMSA), installed on Microsoft HoloLens device as compared to the OMSA application running on a regular computer screen.

Methods: The sample consisted of pre- and post-treatment digital maxillary dental models of 20 orthodontic cases (12.3 ± 1.9 years) treated by rapid maxillary expansion (two turns per day). For each case, the pre- and post-treatment digital models were superimposed using hand gestures for marking the dental models holograms in mixed reality using the Microsoft HoloLens. The same models were then superimposed using the conventional landmark-based method with OMSA software running on a regular computer screen. The same set of dental arch parameters was measured on the superimposed 3D data by the two software versions for comparison. Agreement in the superimposition outcomes among the two superimposition methods was assessed using Dahlberg error (DE), concordance correlation coefficients (CCCs) using two-way ANOVA mixed model for absolute agreement and Bland-Altman analysis.

Results: Repeatability was acceptable for all variables based on the high values of CCCs over 0.99 with a lower 95% confidence limit over 0.95 for any variable. The DE ranged from 0.14 mm to 0.36 mm. The absolute error did not exceed 0.5 mm for any variable.

Conclusion: Using the depth vision capabilities of the Microsoft HoloLens, 3D digital dental models can be reliably superimposed allowing virtual assessment of orthodontic treatment outcomes.

KEYWORDS
digital dental models, HoloLens, superimposition

1 | INTRODUCTION

The increased utility of three-dimensional (3D) digital conversion has been strengthened by the advent of cone beam computerized tomography (CBCT) and the refinement of 3D facial imaging as well as the advent of digital study model scanning.[1] The replacement of plaster orthodontic models with virtual information has potential benefits including instant accessibility of 3D information without need for the retrieval of plaster models from a storage area, the ability to perform accurate and simple diagnostic set-ups of various extraction patterns, and the virtual images may be transferred anywhere in the world for instant referral or consultation.[2]

Augmented reality (AR) is a recent cutting-edge technology used for both educational and interventional purposes. AR supplements the real world with virtual objects that are generated digitally so that they appear to coexist in real space and enhance the user's perception and interaction with the real object.[3,4] Virtual objects are generated from specific graphical markers, which are transformed into moving 3D images through an optical reader attached to a digital program. The virtual objects display information that is not often directly detected by people with their own senses. The information reported by virtual objects helps the user perform real-world tasks such as implants positioning, orthognathic surgical planning and superimpositions.[5,6]

AR technology was first introduced in 2003, mainly associated with educational experiences in medicine. It is still in a rapidly progressing stage of development with many challenges. Despite its infancy, attempts to apply AR in surgery have been successful and promising. Neurosurgery, otolaryngology and maxillofacial surgery are the main disciplines that have used this technology to navigate their specific surgical fields.[7,8] It was used in operative dentistry with the aid of AR graphic markers that magnify and better visualize details of the images on the digital screens.[9] The technology has also been used for medical interventions trials such as in treatment of orbital hypertelorism, retinal and spine surgeries.[10–13] AR was also used in oral and maxillofacial surgeries.[4,5,14] Variable dental specialties utilize the AR tools to facilitate its operative procedures, for example in endodontics[15] and in orthodontics.[16] A growing amount of orthodontics research is based on 3D meshes or 3D volumes.[17,18] The majority of this research use some type of computer applications to display, manipulate and analyze the 3D objects which usually depends on selecting landmarks or arbitrary points on the 3D object. However, it should be noted that this type of 3D interaction is not the most appropriate, as the operators are only interacting with a 2D projected image of the actual 3D object.[19] For the human visual system, this displayed image is not different perceptually from any other 2D image.

In order for the brain to build a real 3D solid object perception, it must rely on stereovision (Stereopsis or binocular vision), that is on using both right and left eyes to send the same image with two slightly different angles. In order to reproduce the depth perception experience, a computer program must generate two images, each as viewed from a camera aiming at slightly different angle than the other to the same point.[20] These two images are projected on each eye's retina through some type of device, in our case; the Microsoft HoloLens, to reproduce a genuine experience of 3D depth vision, allowing a correct perception of the displayed object.

Superimposition of a patient's 2D cephalograms is traditionally indicated whenever evaluation of orthodontic treatment and/or growth is needed. More recently, superimposing the 3D digital models or CBCT images makes it possible to assess these changes in a 3D manner.[21] A recently developed software (Ortho Mechanics Sequential Analyzer OMSA) was introduced to enable visualization and superimposition of digital dental models.[22] The input of this program is the STL files derived from either laser-scanned plaster casts or dental impressions. This software application is based on an innovative algorithm that reduces the amount of work needed to superimpose the 3D scanned dental models to a minimum.[23] The aim of this study was to assess the validity and reliability of 3D palatal superimposition of holograms of digital dental models using OMSA software running on the HoloLens device, compared to the conventional OMSA application running on a regular computer screen. Conventional OMSA application's validity and reliability have been proven in earlier research studies.[22,23]

2 | MATERIALS AND METHODS

The study convenience sample consisted of pre- and post-treatment digital maxillary dental models of 20 orthodontic patients treated with rapid maxillary expansion (two turns per day) using Hyrax palatal expanders as part of their comprehensive orthodontic treatment. The study was approved by the Indiana University Purdue University Indianapolis Institutional Review Board Committee. The same sample was previously utilized to confirm the reliability of linear and angular dental measurements with the OMSA software.[22,23] Patients' age ranged from 8 to 15 years (12.3 ± 1.9 years). Cases were treated by the palatal expanders over a period of 3 months. Models with any dental abnormalities, distortions or those treated by surgically assisted palatal expansion were excluded. These were excluded because the distal end of the incisive papilla and midpalatal raphe were used as reference landmarks for superimposing the laser-scanned pre- and post-treatment digital maxillary models. Dental models were scanned using Ortho Insight 3D laser scanner (version 5.1, Motionview, Hixson, TN) with scanning resolution set at 20 μm. The scan data were then exported from the laser scanner in STL format file extension, and the files were imported into the OMSA. Pre- and post-treatment digital models were superimposed with the OMSA software using the landmark-based method.[22,23] The medial rugae area was considered a stable reference area for maxillary dental models' superimposition.[24,25] In order to superimpose the pre- and post-treatment 3D digital maxillary models using OMSA on the conventional comuter screen, three points were registered on each of the pre- and post-treatment digital maxillary models: the first point was located at the distal end of the incisive papilla, the other two points were located arbitrary distal to the first point along the midpalatal raphe (Figure 1A). The exact algorithm by which the superimposition was performed by these three registration points along the midpalatal raphe was described in an earlier study.[23] The Microsoft HoloLens (Microsoft, Redmond, Washington) was used to upload the STL files of the pre- and post-treatment 3D digital maxillary models.

The HoloLens can track the user hands and fingers gestures and translate them to meaningful input intentions. Selection of landmarks on the digital dental models was done through free head movement and clicking using finger gestures (Figure 1C). The previous steps were operated in augmented reality after installing OMSA

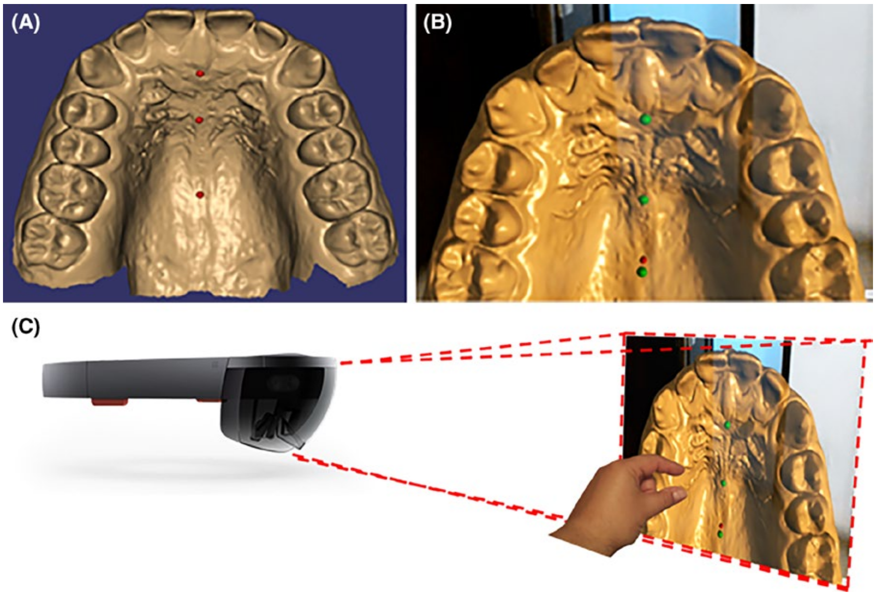

FIGURE 1 The three landmarks used for superimposition using OMSA on computer screen (A) and on HoloLens (B). Using stereovision to locate landmarks by HoloLens hand gestures (C)

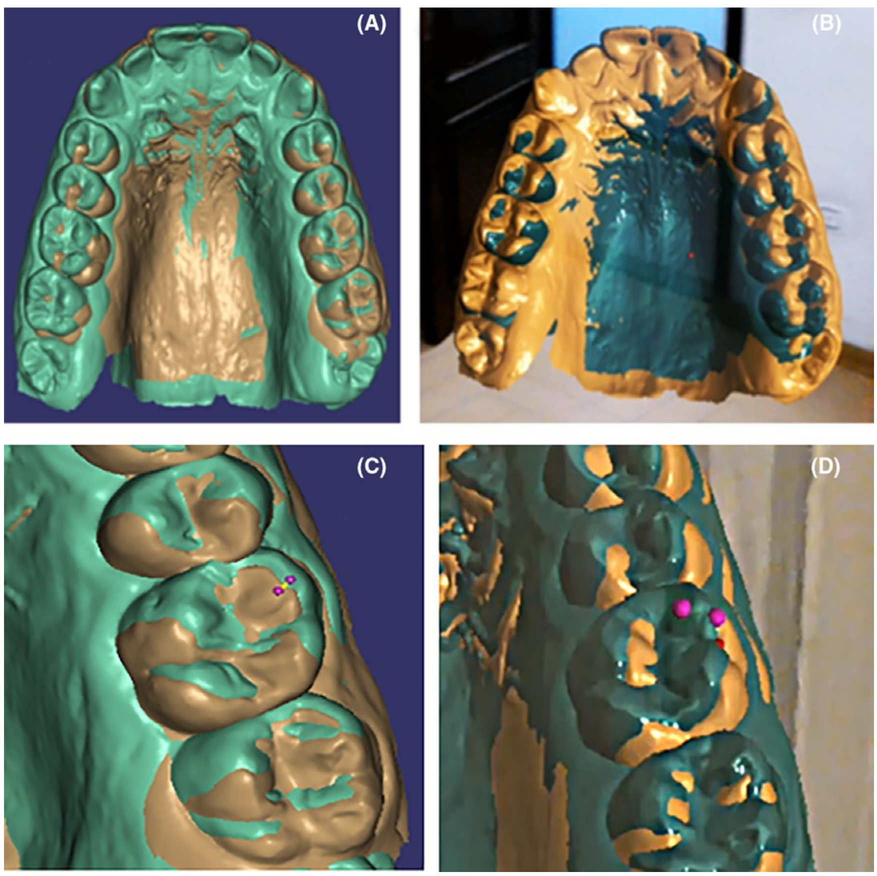

FIGURE 2 Superimposed pre- and post-treatment digital maxillary models as seen on: (A) computer screen and (B) Microsoft HoloLens. Measurement of the distance between the maxillary left first molar MB cusp tips of the Superimposed pre- and post-treatment digital models using OMSA software: (C) on Computer screen and (D) on the HoloLens

on the HoloLens; the three registration points were marked on the holograms of the pre- and post-treatment digital models using the hand gestures (Figure 1B). The superimposed models allowed a real 3D assessment of the achieved orthodontic tooth movement in a 3D interactive hologram. Screen shots were taken for the superimposed models from the OMSA running on regular computer screen (Figure 2A) and a video capture recorded while operating the OMSA software on the HoloLens (Figure 2B).

TABLE 1 Parameters measured on the superimposed pre- and post-treatment models using the two softwares (Computer-based OMSA, HoloLens-based OMSA)

R6 MB	Distance between the maxillary right first molar mesiobuccal cusp tips of the superimposed pre- and post-treatment digital models. Same parameter was measure on the left side (L6 MB).
R6 DB	Distance between the maxillary right first molar distobuccal cusp tips of the superimposed pre- and post-treatment digital models. Same parameter was measured on the left side (L6 DB).
R3	Distance between the maxillary right canine cusp tips of the superimposed pre- and post-treatment digital models. Same parameter was measured on the left side (L3).
R1	Distance between the midpoint of the incisal edges of the maxillary right central incisors of the superimposed pre- and post-treatment digital models. Same parameter was measured on the left side (L1).

DB, distobuccal; L, left; MB, mesiobuccal; R,: right.

The same set of parameters (Table 1) were measured twice on the superimposed 3D data, first by using OMSA software on the computer screen (Figure 2C) and then by using the HoloLens technology (Figure 2D). Additionally, intercanine and intermolar widths were considered on the pre- and post-treatment Digital models and compared statistically to test the reliability of the scan data when viewed by the OMSA on the two interfaces; the computer and the HoloLens. Measurements on the HoloLens were repeated twice under the same conditions with a time interval of one week to assess interrater reliability. All measurements were made by the same examiner (S.T.). All data were collected, tabulated and subjected to statistical analysis.

For assessment of the agreement between the computer-based OMSA and the HoloLens-based OMSA measurements, Dahlberg error and Relative Dahlberg error (RDE) were used to quantify measurement error. Concordance correlation coefficients (CCC) including the 95% confidence limits of the coefficient was calculated based on Lins algorithm. To measure and quantify the size of the differences, Bland-Altman 95% confidence limits of agreements (LOA) were applied.

For reliability analysis, Dahlberg error and Relative Dahlberg error (RDE) were used together with concordance correlation coefficients (CCC) including the 95% confidence limits of the coefficient. Independent samples *t* test was used for comparing the mean Dahlberg error of both methods. Significance level was set at $P < 0.05$ and two tailed *t* test was applied. Reliability was determined as the extent to which the measurements on the digital models and the 3D images were repeatable under the same conditions. Validity was considered as the extent to which the measurements on the digital models by the two interfaces (computer screen and HoloLens) yielded equal results.

3 | RESULTS

The Dahelberg error (DE) ranged from as low as 0.14 mm to 0.35 mm (Table 2, Figure 3). The absolute error did not exceed 0.5 mm for any variable. The relative Dahelberg error (RDE) ranged from as low as 0.46% to 15.33% with only two variables exceeding 10% namely R1 and L1 due to the small value of their mean that makes RDE high although their absolute DE are small 0.19 mm and 0.23 mm, respectively. The mean difference between HoloLens-based OMSA and computer-based OMSA ranged from −0.18 mm up to 0.17 mm indicating small bias or shift from zero. For 9 variables, the mean differences were negative meaning that HoloLens-based OMSA tended to give larger values, while the other three variables (L3 cusp tip, inter 3-3 post-treatment and inter 6-6 post-treatment) the mean differences were positive. Standard deviation SD of the difference ranged from 0.2 mm to 0.48 mm again less than 0.5 mm for any variables.

Concordance correlation coefficients ranged from 0.968 to 0.998 with its lower 95% confidence limit ranging from 0.932 to 0.996 indicating strong agreement. The four variables inter 3-3 pretreatment, inter 3-3 post-treatment, inter 6-6 pretreatment and inter 6-6 post-treatment had in general the lowest RDE less than 1% and the highest CCC all values above 0.98. Thus, these variables showed almost identical results or excellent agreement.

4 | DISCUSSION

We are currently in a rare moment of paradigm shift in technology and augmented reality (AR) is an example. AR allows the user to interact with a real-life virtual object and gain a special experience without being totally engaged in virtual life. Advantages of AR include a less costly and more easy fabrication process when compared to virtual reality and the quick and easy dissemination of medical information among unlimited number of users. However, AR also has its own shortcomings like limited storage capacity, which renders the production of complex models difficult. Another drawback is the need of using several software during the fabrication process.[26] The HoloLens is a recent application of AR with promising utility in the medical field. HoloLens has three forms of interaction: gaze, gesture and voice. In this research study, the gaze and gesture capabilities of the HoloLens were utilized.

The HoloLens uses a position tracking technology to locate and track the user in his 3D environment and an orientation tracking technology to recognize what the user is looking at.[27,28] It collects information about the surrounding environment and objects using

TABLE 2 Error assessment between measurements performed using computer-based OMSA versus HoloLens-based OMSA

Measurements	Mean	SD	Dahlberg error (DE)	Relative Dahlberg Error RDE	Mean±SD of Difference (HoloLens based-computer based)	CCC	95% confidence limits	
							Lower	Upper
R6 MB cusp tip								
Computer-based OMSA	4.12	1.34	0.22	5.4%	0.165 ± 0.27	0.972	0.941	0.987
HoloLens-based OMSA	4.29	1.36						
R6 DB cusp tip								
Computer-based OMSA	4.00	1.40	0.17	4.2%	0.11 ± 0.22	0.985	0.968	0.993
HoloLens-based OMSA	4.11	1.40						
L6 MB cusp tip								
Computer-based OMSA	4.14	1.76	0.23	5.5%	0.09 ± 0.32	0.982	0.962	0.991
HoloLens-based OMSA	4.24	1.68						
L6 DB cusp tip								
Computer-based OMSA	4.09	1.56	0.18	4.4%	0.07 ± 0.25	0.985	0.971	0.992
HoloLens-based OMSA	4.16	1.42						
R3 cusp tip								
Computer-based OMSA	2.61	1.77	0.20	7.7%	0.04 ± 0.29	0.987	0.974	0.994
HoloLens-based OMSA	2.65	1.88						
L3 Cusp tip								
Computer-based OMSA	2.41	1.64	0.19	8.1%	0.01 ± .28	0.985	0.968	0.993
HoloLens-based OMSA	2.40	1.60						
R 1								
Computer-based OMSA	1.29	1.14	0.19	14.9%	0.105 ± .26	0.970	0.936	0.986
HoloLens-based OMSA	1.39	1.12						
L1								
Computer-based OMSA	1.50	1.32	0.23	15.3%	0.05 ± 0.33	0.968	0.932	0.985
HoloLens-based OMSA	1.55	1.29						
Inter 3-3 pretreatment								
Computer-based OMSA	31.17	3.25	0.14	0.5%	0.59 ± .20	0.998	0.996	0.999
HoloLens-based OMSA	31.22	3.21						
Inter 3-3 post- treatment								
Computer-based OMSA	33.51	3.29	0.18	0.5%	0.01 ± 0.26	0.997	0.993	0.999
HoloLens-based OMSA	33.50	3.27						
Inter 6-6 pretreatment								
Computer-based OMSA	45.60	3.66	0.21	0.5%	0.02 ± 0.30	0.996	0.993	0.998
HoloLens-based OMSA	45.62	3.56						
Inter 6-6 post- treatment								
Computer-based OMSA	52.15	4.21	0.35	0.7%	0.01 ± .28	0.993	0.984	0.997
HoloLens-based OMSA	51.97	4.28						

multiple sensors of different types as inertial measurement unit, environment understanding cameras, depth camera, ambient light sensor, microphones, high definition colour camera and others. For holographic output, the HoloLens use see-through holographic optics to beam the 3D scene directly to the user's eyes. Various processors are built in the HoloLens; in addition to the CPU (Central Processing Unit) and GPU (Graphics Processing Unit), Microsoft introduced the HPU (Holographic Processing Unit). The HPU is designed to collect all information from the multiple cameras and sensors in real time.

The aim of this study was to run a digital dental model software on the Microsoft HoloLens to assess reliability and the potential of better visualization and interactive assessment of orthodontic treatment outcomes. A recently developed software program, the Ortho

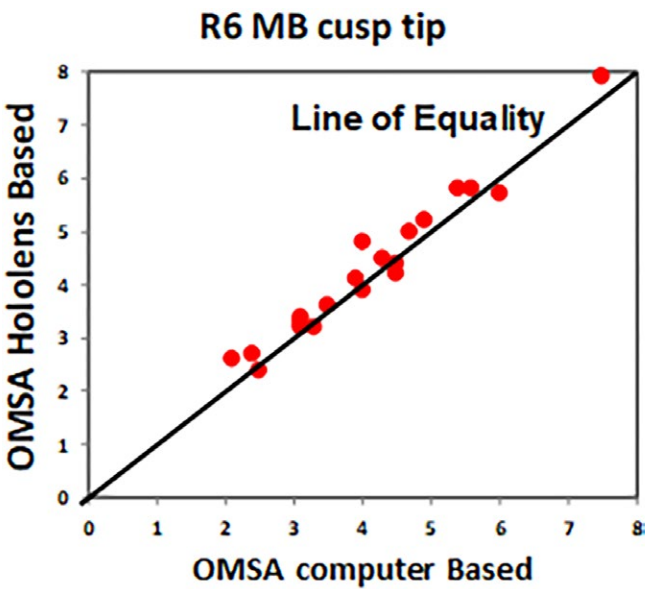

FIGURE 3 Scatter plots of Bland-Altman limits of agreement for one of the measured parameters by both techniques

Mechanics Sequential Analyzer™ (OMSA) (US patent 61/771,328), was introduced to enable visualization and superimposition of dental models. The input for this program is the STL files derived from either scanned plaster models or dental impressions. This software application is based on an innovative algorithm that reduces the amount of work needed to superimpose the 3D scanned dental models to a minimum (three mouse clicks only). The OMSA successfully worked in augmented reality using the HoloLens. The three registration points were marked on the holograms of the pre- and post-treatment digital models using the hand gestures. In this research, we substituted the standard 2D monitor and mouse clicks by the HoloLens, which acts as a 3D input device and as a stereovision output (display) device at the same time.

Using the depth vision capabilities of the HoloLens, the user can now inspect any 3D object with a genuine stereovision experience, and select the required landmarks, as user would do in real life directly interacting with the physical plaster model. Selection is done through free head movement, and clicking using finger gestures.

To test the reliability and validity of the superimposition achieved by the OMSA algorithm on the HoloLens device, it was compared to the superimposition results achieved for the same sample on a regular 2D computer screen. Results showed a strong agreement between the two techniques. The mean difference between HoloLens-based OMSA and computer-based OMSA ranged from -0.18 mm to 0.17 mm indicating small bias or shift from zero. This indicated that the use of the HoloLens to superimpose maxillary digital dental models yielded reliable information when compared with the more conventional method. In addition to validity and reliability of the measures performed on the superimposed digital maxillary models' holograms, the holograms enabled the user to perform a real 3D assessment of the achieved orthodontic tooth movement in 3D interactive scenes. Extensive future studies on larger sample sizes and inter-examiner variability testing are necessary to validate the potential uses in orthodontics as well as general dentistry applications.

5 | CONCLUSION

Using the depth vision capabilities of the Microsoft HoloLens, 3D digital dental models can be reliably superimposed allowing virtual assessment of orthodontic treatment outcomes.

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