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ORIGINAL ARTICLE / ОРИГИНАЛНИ РАД

A novel method of photogrammetry measurements of study models in orthodontics

Marijana Arapović-Savić[1], Mihajlo Savić[2], Mirjana Umićević-Davidović[1], Adriana Arbutina[1], Nenad Nedeljković[3], Branislav Glišić[3]

[1]University of Banja, Luka Faculty of Medicine, Department of Orthodontics, Banja Luka, Republic of Srpska, Bosnia and Herzegovina;
[2]University of Banja Luka, Faculty of Electrical Engineering, Banja Luka, Republic of Srpska, Bosnia and Herzegovina;
[3]University of Belgrade, Faculty of Dental Medicine, Department of Orthodontics, Belgrade, Serbia

SUMMARY

Introduction/Objective Rapid developments in information technologies lead to the wider use of digital representations of dental study models in orthodontics. Most popular way of digitizing the models is to use a 3D scanner and then perform measurements on 3D models, which requires additional and expensive hardware and software resources. In this paper we present an alternative approach based on the use of photogrammetry in the newly developed OrthoPhoto4D software that calculates and corrects perspective distortion errors.

Methods We measured individual tooth width for 24 teeth, 12 two-teeth segments as well as inter-molar and inter-canine distances on 50 models. Measurements are performed in OrthoPhoto4D software that uses four photographs of each model for measurements, uses QR codes for automation, calculates the camera position and corrects perspective distortion-caused errors in measurements. Obtained measurements are compared to ones obtained from models generated by structured light 3D scanner.

Results Statistical analysis strongly indicates that there is no significant difference between the two methods. The recorded differences also have no clinical impact as they have mean values of 0.2 mm for individual tooth widths, approximately 0.2 mm for two teeth segments, and under 0.3 mm for both inter-canine and inter-molar distances. All recorded differences fall within the expected measurement error.

Conclusion We concluded that the described photogrammetry measurements performed in OrthoPhoto4D can be used in diagnosis and therapy planning.

Keywords: orthodontics; 3D scanning; photogrammetry; diagnosis; therapy

INTRODUCTION

Analysis of study models is one of the cornerstones of diagnostic protocol in orthodontics. By study models examination, we can obtain detailed data critical for correct diagnosis and therapy planning. Plaster study models are often regarded as a "golden standard" and posses many qualities, but there are significant downsides to their use, mostly related to storage and durability requirements [1]. Due to rapid developments in information technologies and digital imaging, the use of digital representations of study models has seen a wide adoption in orthodontic clinical practice. Digital models are simple to store, do not suffer from physical handling, and can be easily copied, transported and shared. They also enable more efficient patients tracking throughout therapy. Usability of 3D scanned models in clinical practice has been widely examined [2] and various studies have come to a conclusion that 3D models can be used in place of plaster study models [3, 4, 5]. Main issues related to more widespread use of digital 3D models revolve around the need to use specialized hardware and software. In order to obtain a 3D model, one needs to perform a process of 3D scanning which includes the use of relatively expensive 3D scanners, with high resolution and accuracy, as the scanned models are used in diagnosis and therapy. Software component usually includes specialized software that needs to be installed on the orthodontist's computer and can have a steep learning curve [6]. This presents another barrier for entry of many orthodontists.

Aside from 3D scanning, there were various attempts to use digital photographs to perform measurements – a process referred to as photogrammetry. These attempts ranged from very simple use of rulers present in photograph to provide a scale to specialized hardware and commercial software [7, 8, 9].

All aforementioned studies compared measurements made manually by using calipers with measurements made in photogrammetry software, while we were unable to find an earlier study that compared measurements between the ones made on 3D scanned models and same models measured by the photogrammetry software.

The basis of our approach is to perform measurements on four photographs of the model from top, left, right and front sides,

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Correspondence to:
Marijana ARAPOVIĆ-SAVIĆ
Save Mrkalja 14
78000 Banja Luka
Republic of Srpska
Bosnia and Herzegovina
marijana.arapovic-savic@med.unibl.org

positioned in a custom-made apparatus while compensating for measurement errors caused by perspective distortion. Measurements will be statistically analyzed.

The aim of this study is to present a novel approach to measurements of orthodontic study models based on a set of four photographs of the model and to compare them with measurements made on 3D scanned models.

METHODS

For the needs of this research we have chosen 50 plaster study models of the maxilla and mandible to perform measurements on. Every model was scanned and photographed and subsequently measured in custom developed measuring software – OP4D for 3D scanned models and OrthoPhoto4D for photogrammetry. The accuracy of OP4D was previously tested against widely used 3D modeling software Meshlab [6]. Every models' measurements were taken of each mesiodistal width of the tooth 1 to 6 in every quadrant, as well as mesiodistal width of two teeth segments 6–5, 4–3 and 2–1, also in all four quadrants. Measurements of intercanine and inter-molar distances were also taken. Measurements by both methods were performed at the same time by the same orthodontist on two computers stationed next to each other in order to eliminate possible external factors from interfering with measurement process.

3D scanned models

3D scanning process is performed by using Steinbichler Comet L3D 5M [10] industrial scanner which has been previously calibrated to use 25 mm projector and camera lenses. This combination allows for scanning of objects with sizes up to 260 mm × 216 mm × 140 mm in single pass with point resolution of 0.1 mm. Scanned objects are positioned on an automated turntable which allows 360^0 scanning with arbitrary number of scans. For models that were difficult to scan, final scan was produced by merging of several partial scans. All scanned meshes were processed in the provided Steinbichler COMETPlus 9.63 software. Upon processing, meshes were exported to Stanford PLY format and loaded into custom built web-based software OP4D for measurements [11].

OP4D software is a web-based application that provides users with possibility to perform measurements of 3D models from their browsers. It supports 3D mesh models in Stanford PLY and Nexus NXS formats and uses HOP3D library to perform rendering and measurement calculations. Models can be stored on the server hosting the application or on a third-party server in which case the OP4D software has no direct access to the models themselves [11, 12]. This mode of operation is suitable when working on sensitive models that cannot be stored on publicly accessible servers. Administrative users can describe measurement types by defining the names, labels and types of each required measurement for a given type. Each model can have an arbitrary number of measurements of any type, so the system can also be used to perform studies based

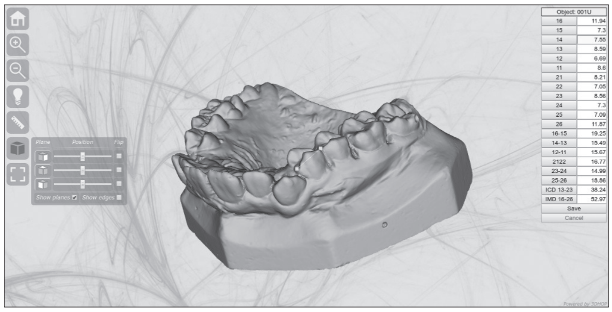

Figure 1. OP4D Web Application – Measurement User Interface

around repeatability of measurements or calculating values based on different measurements inputs.

Measurement user interface of the software is presented in Figure 1. The user selects the desired measurement from the list on the right side of the screen. Distance value field is highlighted during the measurement in order to minimize the possibility of error in selecting the right measurement. User can freely adjust the rotation, translation and scale of the measured model on screen while performing measurements. Once the starting point of the line is visible, user clicks it, adjusts the object until the end point is visible, and clicks it. Once both points are selected, the green line is drawn in 3D space with green square markers denoting the end of the line. User can now proceed to the next measurement. This process is repeated until all measurements for a given model are made and saved or the user cancels the session without saving the results.

For this research, once the measurements of all models have been made, they were exported in JSON format for further use and analysis [13].

Orthophoto 4D photogrammetry software

Just like in any use of photography in medicine, operator has to take care of several important aspects. Camera and lens have to be suitable for this use and we opted for a 28 MP camera with 200 mm zoom lens used at aperture f/22. Light sources are positioned in such a way to provide for soft and fairly uniform illumination of the subject, while providing enough shading to discern the model features.

Perspective distortion is caused by forming of the image on a 2D image plane (camera sensor) of a 3D real world object. This effect causes the object to appear smaller as it moves away from the camera and larger as it comes closer. Since we are photographing a real-world object that is not perfectly flat and has points closer and farther away from the image plane, they appear distorted with the "front" part of the object appearing larger than the "back" part of the object. For example, if we place a plaster study model on paper with millimeter ruler and photograph it from three different distances, we will come to conclusion that the intercanine distance is different in each of the photos. This is illustrated in Figure 2. In this example we have photographed the same model from three different distances while keeping the same portion of the frame occupied by the object by using a zoom lens. Base plane with millimeter ruler was kept the same size in all photographs. Top photograph was taken

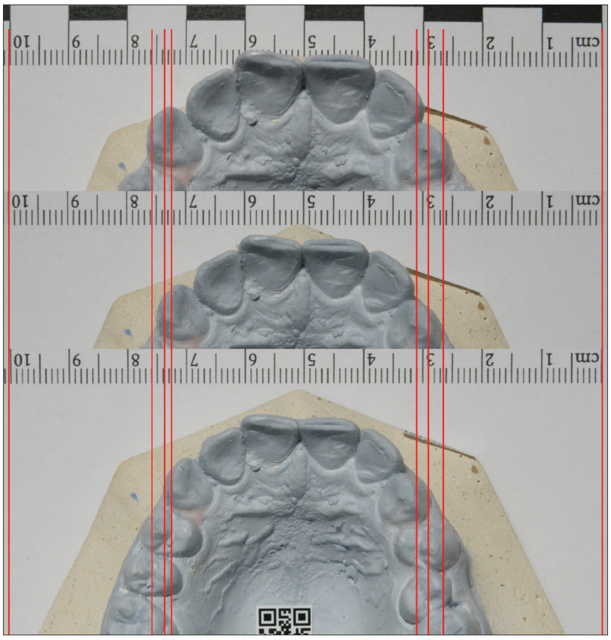

Figure 2. Perspective distortion example

from the smallest distance (16 mm focal length) and inter-canine distance can be measured to be approximately 4.95 cm. Middle photograph was taken with 25 mm focal length and inter-canine distance appears to be 4.45 cm. Bottom photograph was taken with 50 mm focal length (maximum camera distance) and measured value appears to be 4.15 cm. The same effect can be observed with measured widths of 11–12 segment that ranges from 2.4 cm to 2 cm.

Another problem with measuring of 3D objects from 2D representations lies in the fact that it is impossible to measure lengths that are perpendicular to image. For example, from the photographs in Figure 2 we cannot measure the distance between the gingiva and the top of the teeth or any other similar distance.

In order to produce acceptably accurate measurements, we have created a measurement apparatus consisting of a stand and a model mount and perform measurements based on a set of four photographs for each model. The stand is fixed to steady the surface and should not move relatively to the camera during the photographing. It consists of a base plate (which is connected to the surface via two screws), a back plate and a front plate. The base plate contains a series of ridges and guides that enable flexible positioning of back and front plates, as well as a stable positioning for the model mount. Both back and front plates also contain center guide lines that enable proper positioning of the camera. Models are fixed to the model mount via a single screw with soft rubber padding in order to avoid model damage. Model mount has a QR code and letter designation on each of the four sides intended for photographing: T – top, F – front, R – right and L – left. It is also worth noting that each model also contains a QR marker that contains a model identification and provides for simpler and automated processing and classification procedure in processing work flow. All of the above-mentioned elements are illustrated in Figure 3.

Once the model or multiple models have been photographed, as shown in Figure 4, the photographs are

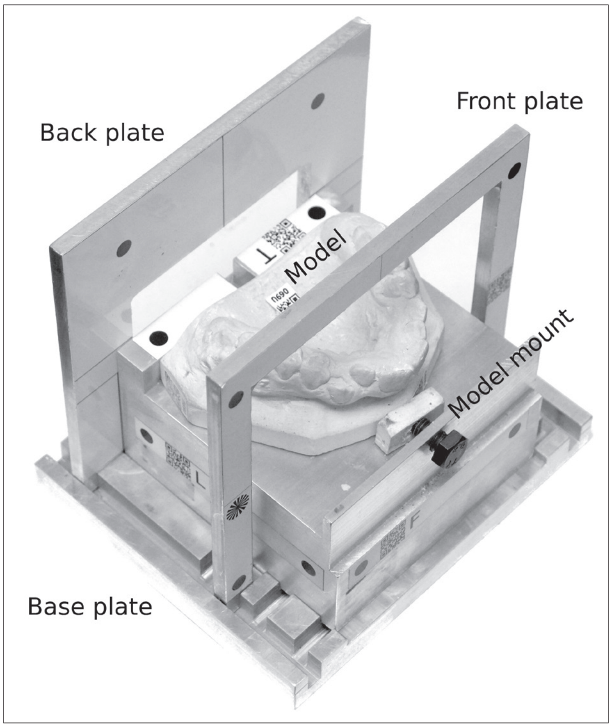

Figure 3. Measurement apparatus

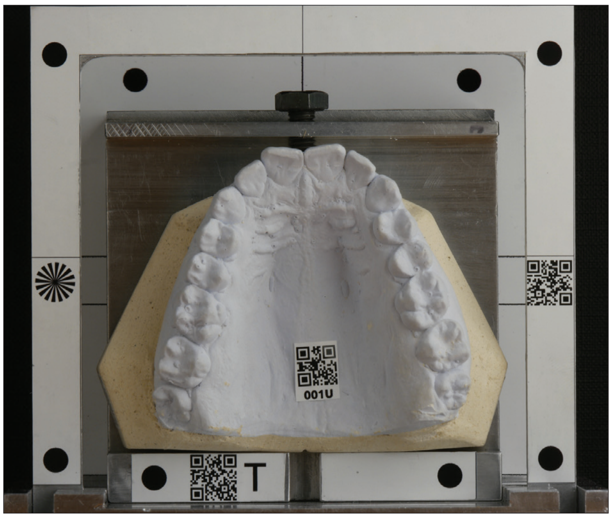

Figure 4. Unprocessed image of model

processed and camera parameters are calculated by a custom developed software. Processing photographs includes several steps:

1. Converting the color image to gray-scale.
2. Identifying the QR markers and interpreting their contents by using ZBar library [14].
3. Finding the measurement markers by utilizing OpenCV library [15].
4. Calculating the camera distance and perspective parameters from detected locations of markers on back and front plates.
5. Cropping the image to working area defined by centers of the front plate markers and saving under a defined name to corresponding case directory. All calculated parameters are kept as a JSON encoded

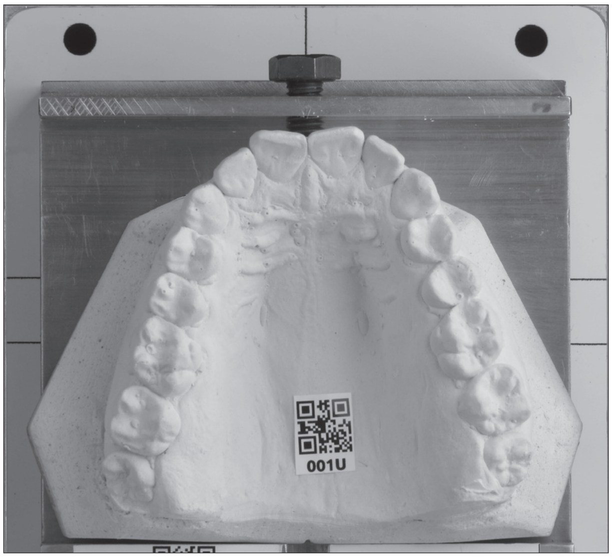

Figure 5. Processed image of model

document inside of the file in an EXIF field. This ensures simpler and more efficient potential transfer and sharing of documents.

One example of fully processed image is shown in Figure 5.

Measuring process in OrthoPhoto4D software

Main screen of OrthoPhoto4D is divided into six main components placed in a grid with three columns and two rows. Top row contains the images representing front and side views, while the top view is in the middle section of the bottom row. Bottom left section contains a measurement point chooser enabling the operator to choose to measure individual mesiodistal tooth width, two-teeth segment widths, as well as inter-canine and inter-molar distances. Since only the maxilla or mandible can be displayed one at the time, the model images will be updated with correct ones when the user chooses the desired measurement. This section also houses a drop-down box enabling for the selected model to be measured as well as buttons for saving or re-loading of the measurement data. Bottom right section contains calculated measurement values.

For every length to be measured user has to choose the measurement and one of the two ends, for example 16 and M. User can move and zoom in/out the images which will all move and zoom in accord until the desired point is visible in at least two images. For example, user can select the point in ”top” image and then select the same point in “right” image. This is necessary as the program needs a 3D position of the point and selecting it in only one image will not produce enough data. It is worth noting that the first point selected is used as a basis for calculations so the user has to only select the proper missing axis position on the second image (in our case just the vertical position). When the process is finished for both ends of the line, the software calculates the distance in 3D space and fills the corresponding field in the measurement values section. All finished measurements have green background color while currently selected point is red or orange depending on the operation.

Statistical analysis

In order to perform the statistical analysis, we have compared measurements performed in OP4D web-based application on 3D scanned models and measurements performed on photographs in OrtoPhoto4D application. This analysis included calculating measurement differences for every measured value, as well as calculating mean and standard deviation of each difference. We have also calculated the Pearson product-moment correlation coefficient

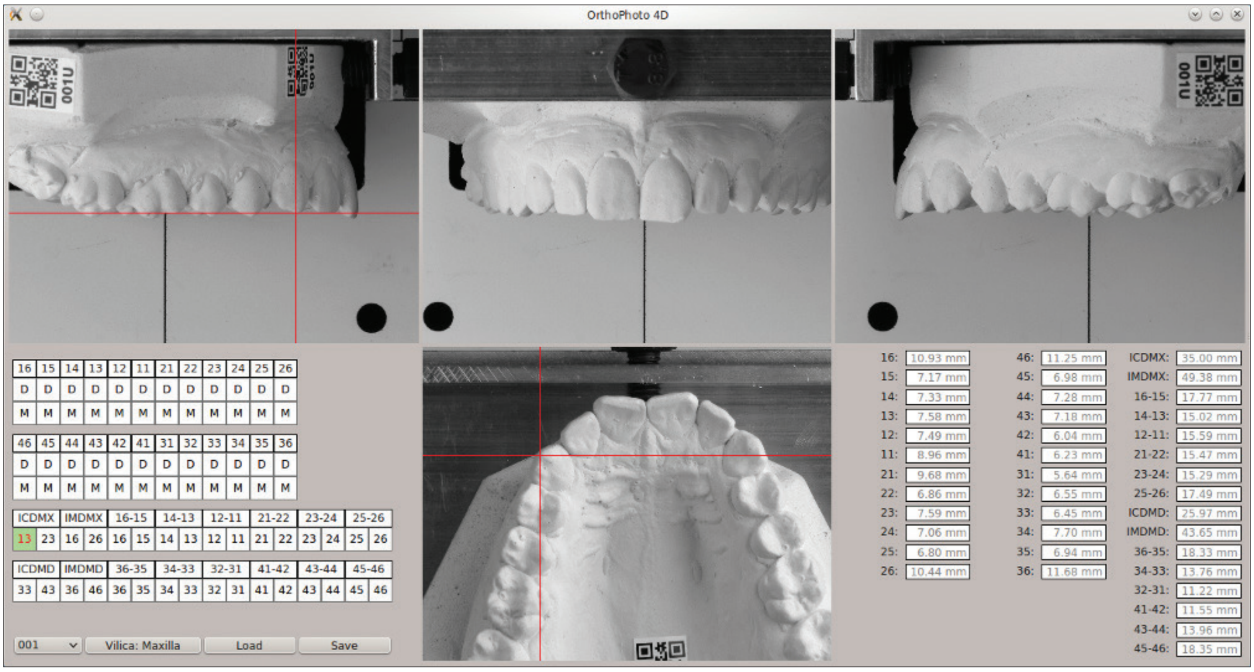

Figure 6. OrthoPhoto4D User Interface

Table 1. Analysis of tooth width (TW) measurements including mean error (E_{mean}), standard deviation (E_{sd}), maximum error (E_{max}) and correlation coefficient

Value	TW 16	TW 15	TW 14	TW 13	TW 12	TW 11	Worst	Mean
E_{mean}	0.1786	0.1742	0.1764	0.1718	0.2034	0.2056	**0.2056**	**0.1850**
E_{sd}	0.0846	0.0536	0.0782	0.0712	0.0738	0.0812	**0.0846**	**0.0738**
E_{max}	0.3500	0.2900	0.3200	0.3300	0.3900	0.3800	**0.3900**	**0.3433**
Correlation	0.9959	0.9934	0.9852	0.9926	0.9927	0.9919	**0.9852**	**0.9919**
Value	TW 21	TW 22	TW 23	TW 24	TW 25	TW 26	**Worst**	**Mean**
E_{mean}	0.1778	0.1548	0.1998	0.1006	0.1314	0.2110	**0.2110**	**0.1626**
E_{sd}	0.0633	0.0457	0.0930	0.1050	0.0816	0.0830	**0.1050**	**0.0786**
E_{max}	0.3000	0.2700	0.4300	0.3700	0.3400	0.4000	**0.4300**	**0.3517**
Correlation	0.9959	0.9963	0.9938	0.9737	0.9859	0.9956	**0.9737**	**0.9902**
Value	TW 36	TW 35	TW 34	TW 33	TW 32	TW 31	**Worst**	**Mean**
E_{mean}	0.1954	0.1960	0.1848	0.2090	0.1284	0.0984	**0.2090**	**0.1687**
E_{sd}	0.0954	0.0689	0.0782	0.0867	0.0749	0.0606	**0.0954**	**0.0775**
E_{max}	0.4600	0.3400	0.3500	0.4300	0.3600	0.2900	**0.4600**	**0.3717**
Correlation	0.9918	0.9902	0.9871	0.9930	0.9900	0.9915	**0.9871**	**0.9906**
Value	TW 41	TW 42	TW 43	TW 44	TW 45	TW 46	**Worst**	**Mean**
E_{mean}	0.0978	0.1478	0.1222	0.1256	0.2566	0.2204	**0.2566**	**0.1617**
E_{sd}	0.0734	0.0800	0.0896	0.0995	0.0682	0.0597	**0.0995**	**0.0784**
E_{max}	0.2300	0.3100	0.3500	0.3700	0.4100	0.3200	**0.4100**	**0.3317**
Correlation	0.9998	0.9902	0.9997	0.9743	0.9938	0.9962	**0.9743**	**0.9923**

Table 2. Analysis of two teeth segment measurements including mean error (E_{mean}), standard deviation (E_{sd}), maximum error (E_{max}) and correlation coefficient

Value	Tooth segments						Worst	Mean
	16 15	14 13	12 11	21 22	23 24	25 26		
E_{mean}	0.2234	0.2688	0.1748	0.1542	0.2324	0.2108	**0.2688**	**0.2107**
E_{sd}	0.0622	0.0781	0.0487	0.0601	0.0563	0.0914	**0.0914**	**0.0661**
E_{max}	0.3700	0.4800	0.2800	0.2800	0.3600	0.4000	**0.4800**	**0.3617**
Correlation	0.9987	0.9974	0.9990	0.9991	0.9986	0.9976	**0.9974**	**0.9984**
Value	36 35	34 33	32 31	41 42	43 44	45 46	**Worst**	**Mean**
E_{mean}	0.1544	0.2174	0.1782	0.1772	0.2390	0.2116	**0.2390**	**0.1963**
E_{sd}	0.0615	0.0455	0.0775	0.0586	0.0578	0.0801	**0.0801**	**0.0635**
E_{max}	0.3000	0.2900	0.3600	0.3200	0.3900	0.3600	**0.3900**	**0.3367**
Correlation	0.9990	0.9989	0.9964	0.9990	0.9985	0.9981	**0.9964**	**0.9983**

(correlation in further text). Results of this analysis are presented in tables and accompanying text.

RESULTS

First, we performed statistical analysis on measurements of mesiodistal widths of individual teeth, measuring first six teeth in every quadrant. This data is presented in Table 1. As can be seen from the data, mean value of error is less than 0.2 mm with the worst case being 0.2566 mm. Standard deviation of error is under 0.1 mm with the worst case being 0.0995 mm. Correlation is close to 1 in all cases with the worst case being 0.9737.

In second step, we performed analysis on measurements of the mesiodistal width of two teeth segments. This is presented in Table 2. Even though these measurements are roughly twice the values of individual teeth, errors are still approximately 0.2 mm with the worst case being 0.2688 mm. Standard deviations of errors are under 0.1 mm with the worst case being 0.0914 mm. Correlation is close to 1 for every observed measurement with the worst case still being over 0.99 with value of 0.9964.

Finally, we measured inter-canine and inter-molar distances in both maxilla and mandible. As these distances are significantly larger than individual teeth or two-teeth segments, this measurement can provide additional insight into quality of measurements. Results of the analysis are presented in Table 3. All four measured values have errors of under 0.3 mm with mean value being 0.2741 mm and worst case being 0.2904 mm. Standard deviations are also under 0.1 mm, correlation is very close to 1 with the lowest correlation of 0.9990.

DISCUSSION

Described approach takes into consideration perspective distortion effects created by finite distance between the model and the camera, and enables measurements in 3D

Table 3. Analysis of inter-canine and inter-molar distances measurements including mean error (E_{mean}), standard deviation (E_{sd}), maximum error (E_{max}) and correlation coefficient

Value	Inter-canine distance		Inter-molar distance		Worst	Mean
	Maxilla	Mandible	Maxilla	Mandible		
E_{mean}	0.2804	0.2904	0.2556	0.2700	**0.2904**	**0.2741**
E_{sd}	0.0915	0.0936	0.0764	0.0857	**0.0936**	**0.0868**
E_{max}	0.5200	0.5400	0.4700	0.4500	**0.5400**	**0.4950**
Correlation	0.9993	0.9990	0.9999	0.9996	**0.9990**	**0.9994**

space by using a set of four photographs instead of just one. We have also developed two software packages: OP4D web-based application for measurements of 3D scanned objects and OrthoPhoto4D for photogrammetry measurements. To the best of our knowledge and accessible literature, this is the first paper directly comparing this kind of photogrammetry measurements to the measurements performed on 3D scanned models as other papers compare photogrammetry to manual measurements on study models or performed comparisons between measurements made on 3D objects reconstructed by using different methods.

Normando et al. [7] have performed similar measurements on 16 patients, comparing manual measurement on study models and photogrammetry method, but using a single photograph only and without taking into account the perspective distortion. They did position the measurement pattern as close to measurement plane as possible for each photograph. They have recorded average difference of between 0.02 mm and 0.33 mm for individual tooth width, while our differences are under 0.2 mm. They found an average 0.23 mm difference for upper inter-molar and 0.19 mm for inter-canine distance, 0.50 mm for lower inter-molar and 0.16 mm for lower inter-canine distance, with our method producing measurement differences of under 0.3 mm in all cases. The authors also performed interclass correlation analysis with reliability ranging 0.66–0.99, which compares to our study which produced the correlation coefficients above 0.99. Authors conclude that these results are acceptable as the recorded measurement differences are comparable to measurement differences of repeated measurements of the same model and are not significant in clinical practice as they are close to resolution of the unaided human eye [7]. As our recorded differences are comparable or smaller, the same conclusion can be made for our approach as well.

Al-Khatib et al. [8] utilized stereophotogrammetric system to conduct measurements on study models and compared it to manual measurements. The system consisted of two calibrated cameras and a calibration board, after which the study model was photographed. Thanks to the use of two cameras, they were able to perform measurements in 3D space. Average recorded errors for individual teeth width were under 0.21 mm, while average errors for inter-canine and inter-molar distances were under 0.1 mm. Authors conclude that due to measurement difference of under 0.5 mm in most cases there is no importance of statistically significant difference found as errors fall within expected range of measurement error in clinical practice. Our approach does not require calibrated stereo cameras or use of external software while providing for similar measurement differences which fall well within suggested 0.5 mm acceptable margin of error.

Malik et al. [9] performed measurements on 30 study models comparing manual measurements to photogrammetry measurements. Photographs were taken from the distance of 30 cm from the lens to object, and a millimeter ruler was used as a reference. They also came to a conclusion that photography-based measurements can be used in clinical practice and that recorded differences in measurements are acceptable. By using computer vision and QR codes we are able to automate several steps of the process and, in doing so, increase the measurement process efficacy.

Fu et al. [16] compared measurements obtained on a 3D scanned model to measurements on 3D model reconstructed from a series of 72 photographs and used Meshlab software for measurements. Authors conclude that measurement errors of up to 0.4 mm are not clinically significant even when statistically significant difference was observed. In our method, we based measurements on the set of four photograph eliminating the need for a large number of photographs and compute resource intensive process of structure-from-motion 3D reconstruction thus enabling for faster processing and measuring of the models while producing comparable results.

Makki et al. [17] analyzed irregularity index calculated from direct, 3D model measurements in 3Shape program and ones obtained on single photograph in ImageJ software. They conclude that none of the observed differences between methods were clinically significant as average differences were under 0.5 mm. Numerous other studies, including ones lead by Leifert et al. [18], Okunami et al. [19] and Asquith et al. [20] all came to conclusion that although there may be statistically significant differences between measurement methods, errors up to 0.5 mm for individual tooth and 5% for longer lengths are clinically acceptable. None of the measurement differences produced in our study are outside of proposed 0.5 mm or 5% acceptable margin. It is also worth noting that by using QR codes and markers suitable for computer vision processing, we can eliminate several possible issues related to human error, from misidentification of the model to having to manually define a scale on the photograph which is present in all studies that rely on millimeter ruler or similar tool for providing scale. Additionally, this paper compares measurements produced by two systems based on digital representations – 2D photogrammetry and 3D scanning, while other studies compare photogrammetric measurements to measurements made manually on plaster study model or use reconstructed 3D model of the object based on a large series of 2D photographs.

Presented data strongly suggests that OrthoPhoto4D software is of comparable quality to measuring of 3D scanned models in diagnostic and clinical uses in orthodontics. No significant differences in measured values have been found, values produced by two methods strongly correlate and measured differences are on the order of 0.2 mm and as such are irrelevant in practice.

In the future research, we are planning on conducting a reproducibility study for both 3D based and OrthoPhoto4D based measurements.

CONCLUSION

Produced results strongly suggest that photogrammetry measurements corrected for perspective distortion measurement error in OrthoPhoto4D software can be used in both diagnosis and therapy in clinical practice.

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Нови метод фотограметријских мерења студијских модела у ортодонцији

Маријана Араповић-Савић[1], Михајло Савић[2], Мирјана Умићевић-Давидовић[1], Адриана Арбутина[1], Ненад Недељковић[3], Бранислав Глишић[3]

[1]Универзитет у Бањој Луци, Медицински факултет, Одсек за стоматологију, Бања Лука, Република Српска, Босна и Херцеговина;
[2]Универзитет у Бањој Луци, Електротехнички факултет, Бања Лука, Република Српска, Босна и Херцеговина;
[3]Универзитет у Београду, Стоматолошки факултет, Београд, Србија

САЖЕТАК

Увод/Циљ Брзи развој информационих технологија довео је до широке употребе дигиталних студијских модела у ортодонцији. Најпопуларнији начин дигитализације модела је коришћење 3*D* скенера, а затим и мерења на 3*D* моделима, што захтева додатне и скупе хардверске и софтверске ресурсе. У овом раду представљамо алтернативни приступ заснован на коришћењу фотограметрије у новоразвијеном софтверу *OrthoPhoto4D*, који израчунава и исправља грешке настале као последица перспективне дисторзије.

Метод На 50 студијских модела мерена је мезиодистална ширина за 24 зуба, ширина 12 сегмената двоструких зуба, као и интерканина и интермоларна ширина. Мерења су вршена у програму *OrthoPhoto4D*, који користи четири фотографије сваког мереног модела, *QR* кодове за аутоматизацију, рачуна удаљеност камере и коригује грешке мерења изазване перспективом. Мерења су поређена са резултатима добијеним на моделима генерисаним 3*D* скенером.

Резултати Анализа резултата снажно указује на то да не постоји статистички значајна разлика између два метода. Забележене разлике такође немају клинички значај, јер су средње вредности до 0,2 *mm* за појединачне ширине зуба, до приближно 0,2 *mm* за сегменте од два зуба и испод 0,3 *mm* за интерканину и интермоларну ширину. Све забележене разлике су унутар очекиване грешке мерења.

Закључак Описани метод фотограметријских мерења у програму *OrthoPhoto4D* се може користити у дијагнози и планирању ортодонтске терапије.

Кључне речи: ортодонција; 3*D* скенирање; фотограметрија; дијагноза; терапија