Influence of Connecting Two Standalone Mobile Three-Dimensional Scanners on Accuracy Comparing with a Standard Device in Facial Scanning

Ali Modabber[1,a], Florian Peters[1,a], Anna Brokmeier[1], Evgeny Goloborodko[1], Alireza Ghassemi[1], Bernd Lethaus[1], Frank Hölzle[1], Stephan Christian Möhlhenrich[1]

[1]Department of Oral, Maxillofacial and Plastic Facial Surgery, School of Medicine, University Hospital RWTH Aachen, Aachen, Germany.
[a]Both first authors contributed equally.

Corresponding Author:
Ali Modabber
Department of Oral, Maxillofacial and Plastic Facial Surgery, School of Medicine
University Hospital RWTH Aachen
Pauwelsstr. 30, 52074 Aachen
Germany
Phone: +49241/ 80-88231
Fax: +49241/ 80-82430
E-mail: amodabber@ukaachen.de

ABSTRACT

Objectives: In this study is investigated if bundling of two scanners leads to better accuracy in recording faces than a standard face-scanning device.

Material and Methods: In a group of 28 volunteers, two test specimens were attached to their faces: one on their forehead and one turned 90° on their cheek. Each volunteer was scanned by FaceScan3D® and two bundled Artec EVA® scanners. The scans were aligned to a three-dimensional model of the test specimen, and the mean error was recorded. Length, width and angles between the test specimen's planes were compared.

Results: The mean deviation is significantly lower for the cheek test specimen in alignment ($P < 0.001$), length and width ($P < 0.001$) but not for the forehead test specimen in alignment and length and width ($P > 0.05$) using FaceScan3D®. The aberration from the original angle between two sides of the test specimen is significantly lower measured with Artec EVA® for the angle between the front and the bottom plane of both test specimens ($P < 0.01$). Besides the angle between the right plane and the bottom plane as well as the top plane of the test specimen mounted to the cheek, the deviation of the angle between the other side planes to each other is significantly lower ($P > 0.05$) scanned with Artec EVA®.

Conclusions: Compared to FaceScan3D®, two bundled Artec EVA® scanners provide different accuracies depending on the location of the measured parameters. The accuracy measured for both scanners is inside the range found in the literature.

Keywords: dimensional measurement accuracy; three-dimensional imaging; optical devices.

INTRODUCTION

Today, numerous new technological methods are used in medicine [1,2]. A common one is capturing three-dimensional surface data of patients. These data can be used for different purposes such as planning for surgical treatment, visualizing complex procedures for the patient or comparing the patient's outcome after treatment [3-7]. At present there are different techniques for acquiring the three-dimensional data available in the market [8]. Using a computed tomography (CT) or magnetic resonance imaging scanner results in detailed three-dimensional data from the inside and the outside of the patient [9]. Major disadvantages are the limited availability, high costs, and in the case of CT, a lot of ionizing radiation. For receiving three-dimensional data from the outer surface of the patients, coordinate measuring machines have been used. Even this technique comes with the disadvantage of touching the patient. Another alternative is using a laser scanner or a scanner that uses structured light for capturing its data. Currently, numerous devices are available in the market and are used in medicine. To increase their share of the market, manufacturers develop new features that should make their devices more attractive. All of them say that their product leads to the best result.

Recently, three-dimensional data of the human face have been increasingly used. Receiving exact three-dimensional surface data of the human face is not trivial. The face consists of different complicated and fine geometric structures. Even if it is possible to capture the face with some devices, there are few literature reviews to evaluate their accuracy [4,8-14]. For this study, we have chosen two optical three-dimensional scanners using structured light. FaceScan3D® (3D-Shape GmbH, Erlangen, Germany) is already commonly used in literature [7,15-18]. The other device, Artec EVA® (Artec Group, Luxembourg, Luxembourg), has not been used for medical purposes that often. Until now, it has been used in the technical environment [19-22].

In this study, the accuracy achieved by two coupled Artec EVA® scanners against the accuracy achieved by a FaceScan3D® is compared. The aim is to evaluate if investing in two scanners and setting up a bundle for scanning results in significantly more precise scans.

MATERIAL AND METHODS

The study was conducted according to the declaration of Helsinki. After institutional approval of the ethics committee of University Hospital RWTH Aachen, Aachen, Germany (EK 168/16), written informed consent was obtained from a group of 28 volunteers consisting of 16 females and 12 males. None of them underwent facial surgery, were suffering severe facial malformation or were afflicted with a seizure disorder triggered by flashing lights.

Artec EVA®

Artec EVA® is a mobile three-dimensional scanning device. According to the technical data provided by the Artec Group the scanner is small (261.5 mm × 158.2 mm × 63.7 mm) and lightweight (800 g). It was designed for creating three-dimensional models of huge objects that do not fit into common three-dimensional scanners. Another feature of this device is that it can create a bundle with up to four scanners of the same type or even third party scanners. The number of scanners that can be bundled is limited to the amount of processors mounted inside the scanning PC. Every scanner uses its own thread. Pursuant to the manual, scanners used in bundles have to be set up in defined positions to each other. The field of view must overlap each other. For acquiring surface information, structured light is used. On account of this, the scanner consists of a projector, a colour camera and two black and white (b/w) cameras. A striped pattern is projected on the surface of the scanned object and is recorded by the b/w cameras mounted in different but known positions. The texture is recorded by the colour camera in the middle of the scanner. Using this technique, Artec EVA® records up to 16 frames per second. The data is sent to every personal computer (PC) connected to the scanner. The software Artec Studio 9.2 (Artec Group, Luxembourg, Luxembourg) aligns all frames captured to each other regarding three-dimensional surface data and texture information. Next, the frames can be fused to a three-dimensional model and can be provided with a coloured texture. Finally, a three-dimensional model consisting of triangles can be exported as Stereolithography (.stl) or Wavefront Object (.obj). For mapping the texture to the object, a Material Template file (.mtl) is created. Texture data is stored in a Joint Photographic Experts Group Interchange Format (.jpg).

FaceScan3D®

FaceScan3D® is a stationary three-dimensional scanner. It consists of a mirror construction around the patient, and on the opposite side is a case with two b/w cameras, a projector, a standard digital

photo camera and two professional flashes. For controlling and post-processing, a standard PC is used, which is a part of this scanner. The scanner case and the mirror construction are fixed to the bottom so it is not possible to move them around. For acquiring the three-dimensional surface data, the scanner also uses the structured light technique. The projector displays different striped patterns on the volunteer's face. These patterns are recorded by the two b/w cameras mounted in different known positions. Next, a photograph is taken by the photo camera for creating a texture. While taking the photograph, the volunteer is illuminated by the flashes. Because of the mirror construction around the volunteers head, it is possible to get a 180° three-dimensional picture of the volunteer with only capturing the volunteer once. Recording this image takes 800 ms according to the technical data provided by 3D-Shape. After taking the image, the data is post-processed on a common PC. Finally, a Wavefront Object (.obj) together with a coloured texture in a Joint Photographic Experts Group Interchange Format (.jpg) and a Material Template file (.mtl) is exported.
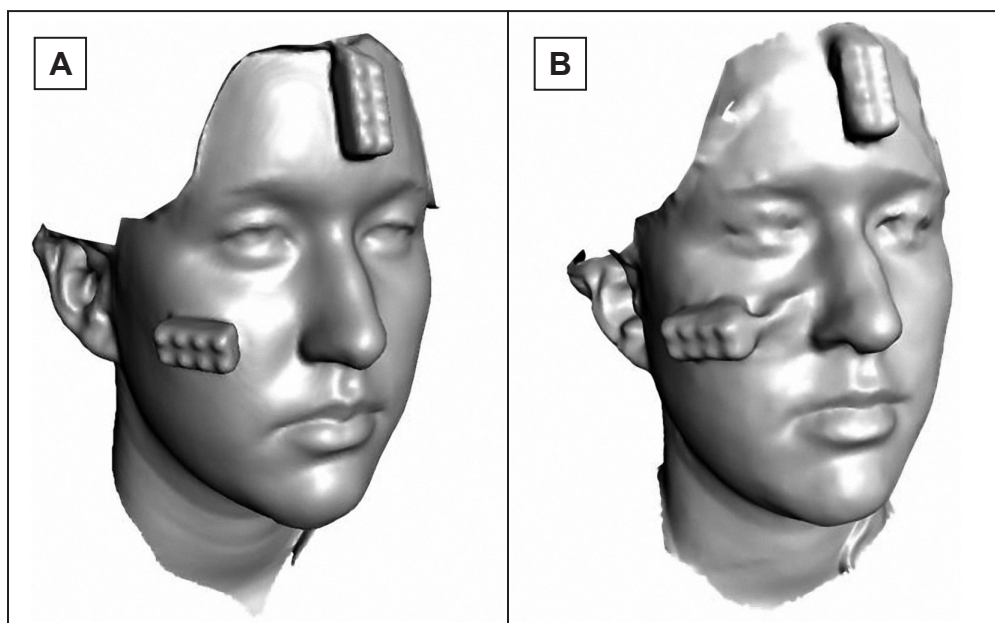
Test specimen

During the scans, two test specimens were mounted to the volunteers' faces. As a specimen, ordinary 4 × 2 Lego (LEGO A/S, Billund, Denmark) bricks were chosen. Every brick has a length of 30.8 mm and a width of 15.8 mm. Every plane is angled 90° to another plane. Before using the brick as a test specimen, they were dulled using Perlablast 50 μm (BEGO, Bremen, Germany) blast-cleaning abrasive.

A pressure of 0.5 bar was used for dulling them. After this, every brick was measured with a digital caliper (Mitutoyo Deutschland GmbH, Neuss, Germany). No differences in its original length and width could be measured. The uncertainty of measuring, according to the technical data provided by Mitutoyo, was ±0.02 mm.

Study protocol

Two test specimens were attached to every volunteer's face. One of the test specimens was mounted to the middle of the volunteers' forehead, and the other one was turned 90° to the right prominence of the cheekbone (Figure 1). All further scanning took place in the same room. The volunteers were asked to sit down inside the mirror construction of FaceScan3D®. Volunteers were aligned to the cross displayed by FaceScan3D®. Before taking the three-dimensional picture, volunteers were asked to relax their mimics and look towards the scanning device responsible for recording the texture of the later three-dimensional model. Adjacent to that, the volunteers sat down on a chair to be scanned by two Artec EVA® scanners. Both Artec EVA® scanners were mounted on a tripod 1.3 m in height and were calibrated using a test volunteer. Before scanning, the volunteer on the chair was aligned at 1.3 m with its nose tip. According to the technical data of Artec EVA®, the distance between the volunteer and both of the scanners was set to 70 cm, which is the middle of the working distance. The volunteers were asked to relax their mimics again, and the scan was started.

Figure 1. Example of volunteer with test specimen mounted to the volunteer's face.
A = scanned with FaceScan3D®; B = scanned with Artec EVA® bundle.

Three-dimensional analysis

For analysing the three-dimensional models taken from the volunteers, the .obj data was imported into Geomagic Control 2014 Software (3D Systems Corporation, Rock Hill, USA) running on a Fujitsu Siemens PC (Fujitsu Siemens Computers, Munich, Germany). For measuring the overall accuracy achieved, a three-dimensional model of a 4 × 2 Lego brick with its original dimensions was imported. Subsequently, the three-dimensional model of the Lego brick automatically was fitted to the recorded data by the best fit function. The average error is reported (Figure 2). Afterwards, the planes of the scanned test specimen were marked by the same experienced user (FP), and an equalisation plane was created by Geomagic Studio. The dimensions in length and width, angles of the side planes to the neighbouring ones and angles between the top plane and the side planes were measured.

Statistical analysis

Three-dimensional model results were reported by an experienced rater (FP), repeating his assessment 4 weeks later to determine the intrarater reliability. GraphPad Software Quick Calcs (GraphPad Software, Inc. La Jolla, USA) was used to estimate Fleiss Kappa statistics for the intrarater reliability calculations.

Statistical analyses of the measured values were performed using the Statistical Package for Social Sciences SPSS v23 (IBM, Chicago, IL, USA) running on a Fujitsu Siemens PC (Fujitsu Siemens Computers, Munich, Germany). The Shapiro-Wilks normality test and the Levene variance homogeneity test were applied to the data. The data was normally distributed, and there was homogeneity of variance among the groups. For statistical analysis, the Student t-test was used. The level of significance was set at $P \leq 0.05$. All data are expressed as mean and standard deviation (M [SD]).
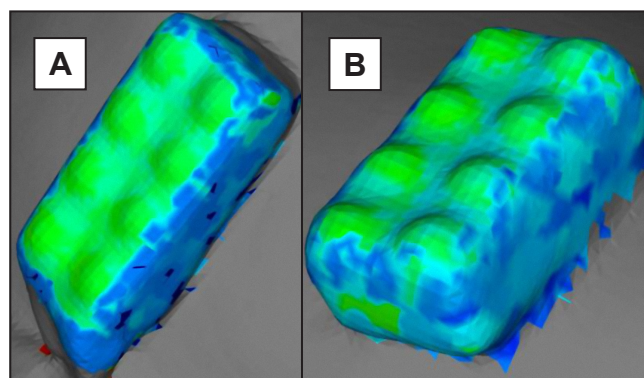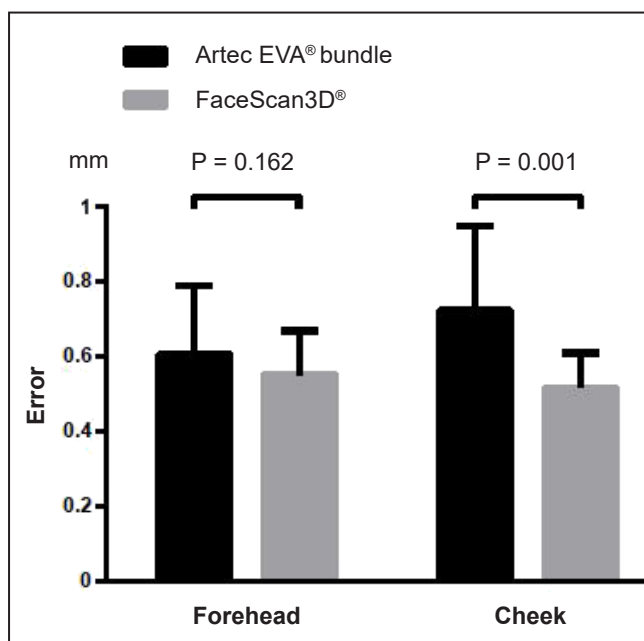
RESULTS
Intra-observer reliability

Intra-observer reliability was substantial ($\kappa = 0.61$ - 0.8).

Alignment

Automatic alignments of the scanned test specimen and the model of the Lego brick resulted in errors of

Figure 2. Sample of automatic alignment of the reference Lego brick scanned with FaceScan3D®.
A = forehead; B = check.

Figure 3. Boxplot showing mean error in best fit alignment of the test specimen (mm) in scans using Artec EVA® and FaceScan3D®, as well as corresponding P-values.

0.605 (0.183) mm for the forehead test specimen and 0.722 (0.225) mm for the cheek test specimen scanned with a bundle of two Artec EVA® scanners. Scanning with FaceScan3D® resulted in mean errors of 0.551 (0.118) mm for the forehead test specimen and 0.517 (0.092) mm for the test specimen mounted to the cheek of the volunteer. The difference between the two scanners for the alignment error is not significant for the test specimen mounted to the forehead ($P = 0.162$). The error for the test specimen mounted to the cheek differs significantly ($P = 0.001$) between the two scanner systems (Figure 3).

Length and width
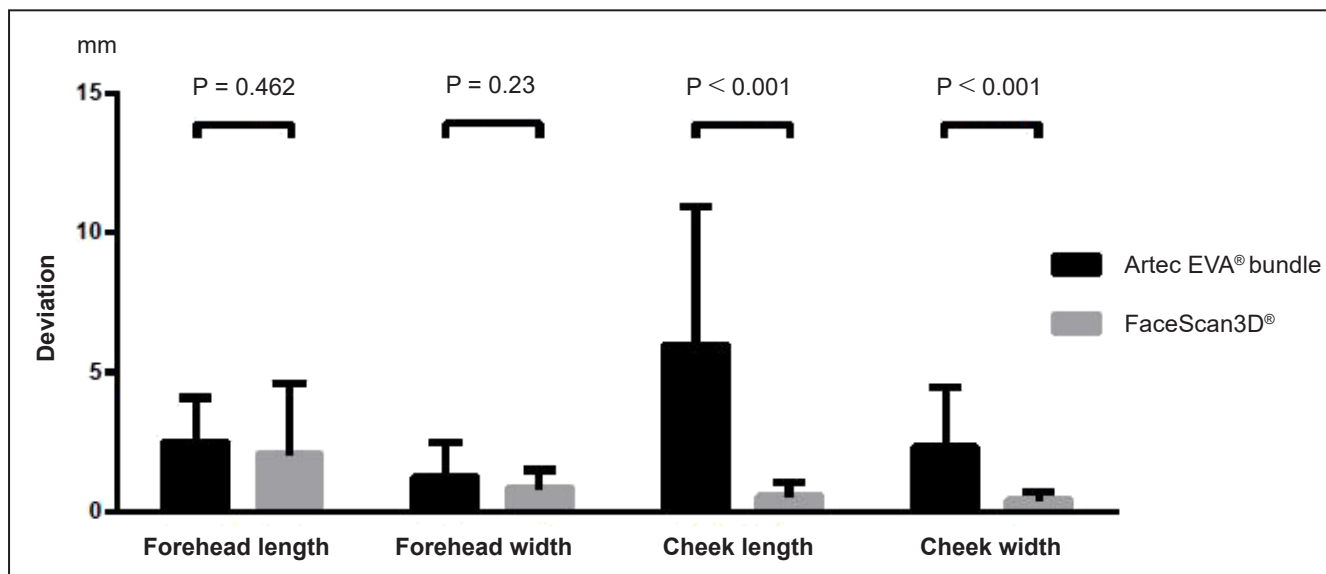
The mean deviations from the original length and

Table 1. Mean deviation (M [SD]) of length and width according to original in mm

	Artec EVA® bundle		FaceScan3D®		P-values	
	Forehead	**Cheek**	**Forehead**	**Cheek**	**Forehead**	**Cheek**
Length	2.48 (1.619)	5.968 (4.965)	2.066 (2.537)	0.543 (0.528)	0.462[b]	< 0.001[a]
Width	1.228 (1.276)	2.311 (2.151)	0.839 (0.672)	0.414 (0.288)	0.23[b]	< 0.001[a]
Total	2.997		0.966			

[a]Statistically significant at the level P < 0.05 (Student *t*-test).
[b]No statistically significant at the level P < 0.05 (Student *t*-test).
SD = standard deviation.

Figure 4. Boxplot showing mean deviation in length and width of test specimen (mm) in scans using Artec EVA® and FaceScan3D®, as well as corresponding P-values.

Table 2. Mean deviation (M [SD]) of angles from sides to front plane according to original in degree

	Artec EVA® bundle		FaceScan3D®		P-values	
Angle front to	**Forehead**	**Cheek**	**Forehead**	**Cheek**	**Forehead**	**Cheek**
Top plane	24.461 (10.583)	14.025 (8.326)	19.878 (11.484)	13.488 (10.598)	0.108[b]	0.417[b]
Bottom plane	7.745 (5.055)	16.443 (7.63)	13.053 (9.223)	27.372 (14.104)	0.006[a]	< 0.001[a]
Left plane	5.041 (7.11)	5.111 (4.717)	3.642 (3.012)	14.726 (10.865)	0.27[b]	< 0.001[a]
Right plane	4.086 (2.653)	17.784 (12.296)	3.93 (4.179)	7.029 (7.17)	0.871[b]	< 0.001[a]

[a]Statistically significant at the level P < 0.05 (Student *t*-test).
[b]No statistically significant at the level P < 0.05 (Student *t*-test).
SD = standard deviation.

width for the test specimen mounted to the volunteers' foreheads and the volunteers' cheeks are shown in Table 1. The difference in length and width do not differ significantly (length: P = 0.462; width: P = 0.23) between the two scanning systems used for the test specimens stuck to the volunteers' foreheads. For the length and width of the test specimens attached to the volunteers' cheeks, FaceScan3D® shows a significantly lower (P < 0.001) error than Artec EVA® (Figure 4).
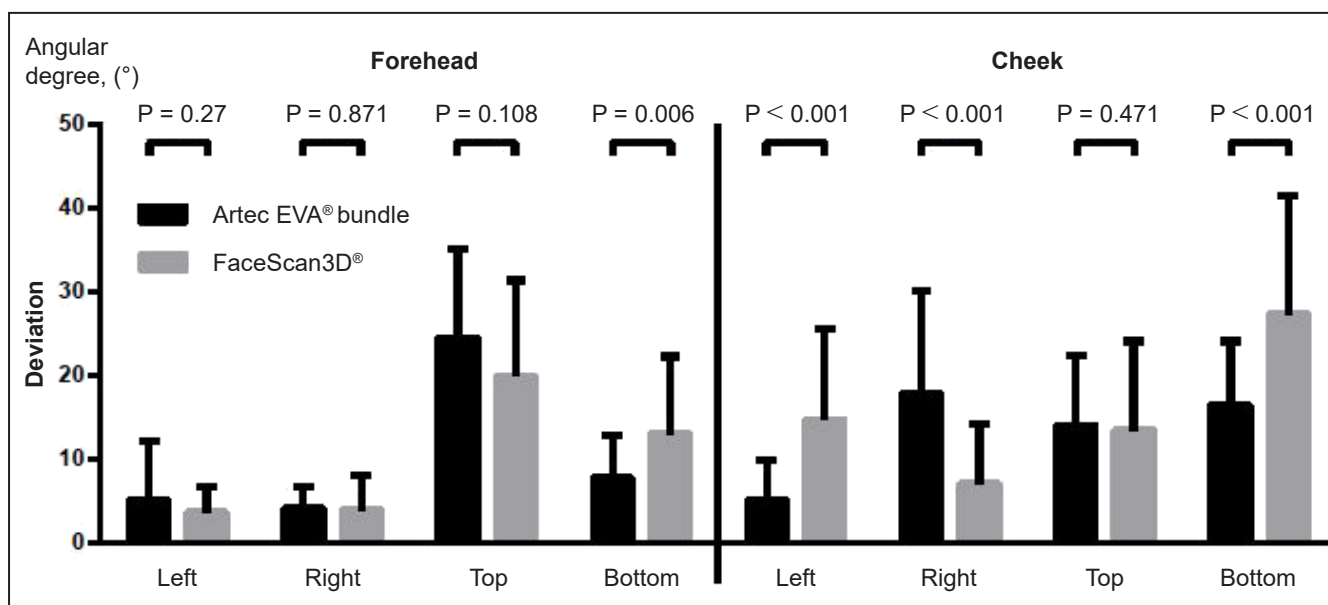
Angles between front plane and side planes

The deviations from the original angle of 90° between the front plane and the side planes for both test specimens measured with Artec EVA® and FaceScan3D® are shown in Table 2. The angle between the front plane and the bottom plane of the Lego brick on the volunteers' foreheads is measured significantly more accurately (P = 0.006) by Artec EVA® than by FaceScan3D®.

The deviation between the other planes and the front plane of the test specimen at the volunteers' foreheads do not differ significantly (P = 0.108, P = 0.27, P = 0.871) between both scanning systems used. The deviations from the original angle measured between the front planes and the bottom planes as well as between the front planes and the left planes for the test specimen at the volunteers' cheeks are significantly lower (P < 0.001) when measured with Artec EVA®. The aberration metered between the original angle of 90° and the one measured on the scan for the angle between the front plane and the right plane is significantly lower (P < 0.001) when measured with FaceScan3D®. The discrepancy between the original angle and the measured one between the front plane and the top plane for the test specimen mounted to the cheek is not significantly different (P = 0.417) between scanning with Artec EVA® or FaceScan3D® (Figure 5).

Angles between side neighbouring side planes

The aberrations between the original angle of 90° between neighbouring side planes and the angles measured at the scans taken with Artec EVA® and FaceScan3D® are shown in Table 3. All angles between the neighbouring side planes of the test specimens mounted to the volunteers' foreheads show a significantly lower (P = 0.008, P = 0.02, P < 0.001, P < 0.001) deviation from the original angles when measured with Artec EVA®. The divergences between the original angle and the angles between the left and the top planes as well as the angles between the left and the bottom planes are significantly lower (P < 0.001) when measured with Artec EVA® for at the test specimens attached to the volunteers' cheeks. The deviations between the original angle and the other angles measured are not significantly different (P = 0.077, P = 0.112) for the test specimens mounted to the volunteers' cheeks when measured with the two three-dimensional scanning systems (Figure 6).

Figure 5. Boxplot showing mean deviation of angles between front plane and side planes of test specimen (angular degree, [°]) in scans using Artec EVA® and FaceScan3D®, as well as corresponding P-values.
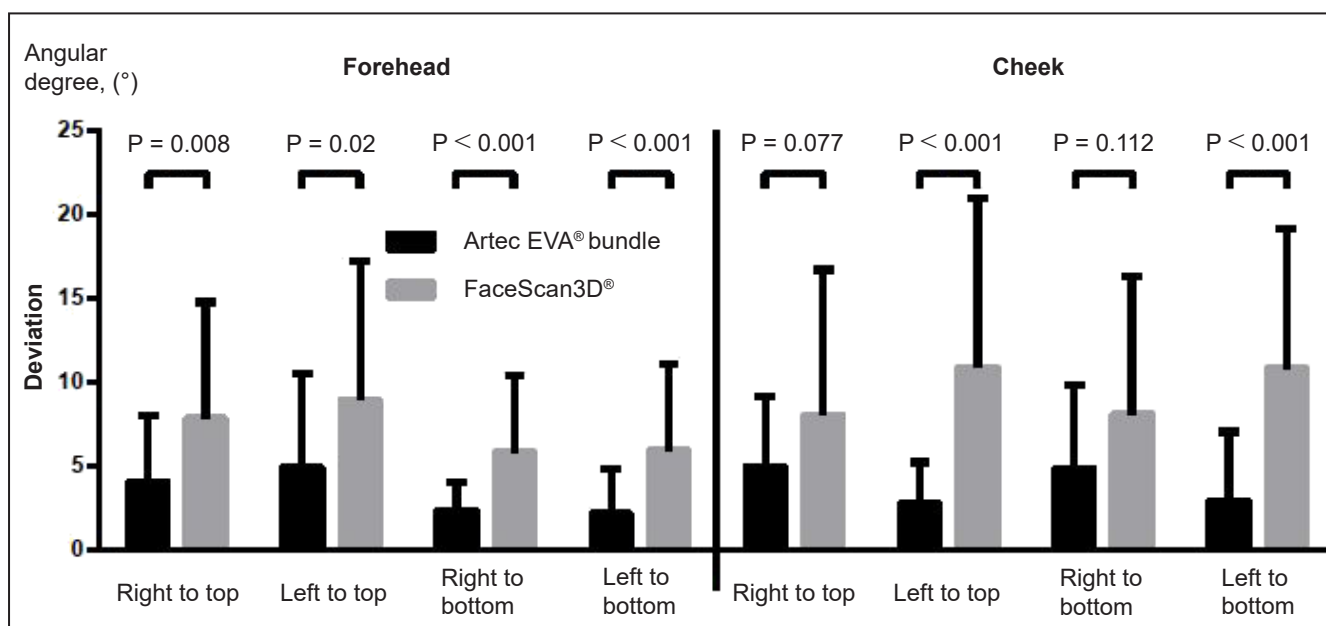
Table 3. Mean deviation (M [SD]) of angles between neighbouring side planes according to original in degree

	Artec EVA® bundle		FaceScan3D®		P-values	
	Forehead	**Cheek**	**Forehead**	**Cheek**	**Forehead**	**Cheek**
Right to top plane	4.059 (3.934)	4.696 (4.206)	7.848 (6.91)	8.04 (8.656)	0.008[a]	0.077[b]
Left to top plane	4.925 (5.592)	2.788 (2.447)	8.954 (8.229)	10.89 (10.1)	0.02[a]	< 0.001[a]
Right to bottom plane	2.349 (1.699)	4.854 (4.998)	5.784 (4.65)	8.101 (8.24)	< 0.001[a]	0.112[b]
Left to bottom plane	2.157 (2.652)	2.9 (4.153)	5.955 (5.128)	10.852 (8.309)	< 0.001[a]	< 0.001[a]

[a]Statistically significant at the level P < 0.05 (Student *t*-test).
[b]No statistically significant at the level P < 0.05 (Student *t*-test).
SD = standard deviation.

Figure 6. Boxplot showing mean deviation of angles between neighbouring side planes of test specimen (angular degree, [°]) in scans using Artec EVA® and FaceScan3D®, as well as corresponding P-values.

DISCUSSION

In our study, a new feature of a three-dimensional scanner is used. To our knowledge, no other scanning system provides the possibility of creating bundles of up to four standalone scanners, limited by the PC used, to increase the field of view and accuracy of capturing data while scanning time is reduced. For creating a bundle of scanners, it is necessary to put them into a position to each other that does not change during the whole recording with this bundle. Therefore, the scanners have to be set up and have to be aligned before using them.

For aligning them, it is necessary that a small piece of the field of view of each scanner overlaps with the field of view of another one. Without that, it is not possible for the Artec Studio software to determine the scanners position in space. Setting up a bundle of two scanners took us nearly 15 min until the scanners where ready to capture the first object. Preparing FaceScan3D® took the examiner at most 3 min. Depending on the setting that the three-dimensional scanner should be used, the length of preparation time of a scanner bundle has to be considered.

For comparing the differences in the two scanning systems, we decided to use test specimens attached to volunteers' faces. These test specimens were mounted to the forehead in the middle of the face and the right cheek. Both test specimens were angled 90° to each other and fixed to the faces so that one of the side planes faced the outer margin of the field of view of the scanning systems. As a test specimen

we chose regular 4 × 2 Lego bricks. These are prismatic and provide sharp edges and 90° angles. Because of this geometric appearance, more than just distances can be measured. Angles also can be measured that give information about the scanned form of the test specimen. Lego bricks deliver prominent geometric parts that are needed by the scanners to align the different frames taken to each other [23]. The Lego bricks have been dulled before capturing them because this results in better images. Without dulling them, the specular flares emitted by them lead to severe errors in capturing data [24]. After dulling them, they could be scanned in good quality.

To measure the accuracy of three-dimensional images, often landmarks set by the examiner are used [8-10,12-14]. An advantage of using test specimens together with Geomagic Studio is the possibility of marking whole planes up by the examiner and letting the software compute an equalisation plane. Even though Khambay et al. [12] and colleagues showed that the error is a mean between 0.06 and 0.07 mm and Ayoub et al. [10] showed a mean error of 0.2 mm, it was our goal to automate the process of measuring as far as possible to reduce the error created by humans. In this analysis, the examiner marks the planes strictly to their edges and lets the software calculate the mean from numerous points. Every distance and angle mentioned in this study is calculated between these equalisation planes.

According to our results for the test specimen's dimensions, the deviation measured by FaceScan3D® is less than that measured with a bundle of two Artec EVA® scanners. Not every discrepancy differs

significantly from each other (Table 1 - 3). It stands out that the mean deviation of the angle between the front plane and the bottom plane on the forehead and the left plane on the cheek is significantly lower when recorded with Artec EVA® (Table 2). This is caused by their orientation towards the field of view of the Artec EVA® scanners and leads to the idea that the field of view of only two coupled Artec EVA® devices is not big enough to scan a human face sufficiently. An interesting fact is the discrepancy of the angle between the two neighbouring side planes. The mean deviation captured with Artec EVA® is always lower than that captured with FaceScan3D® (Table 3). The most common reason is that a few recorded points of a plane are enough information for Artec Studio to determine the orientation of planes inside space and display them in the final three-dimensional model. Despite the bigger field of view, FaceScan3D® and the Slim3D software are not working this well.

Compared with other three-dimensional scanners used in the literature whose accuracy has been measured, like C3D Imaging System with a mean error of 0.83 mm determined by Ayoub et al. [10], GFM TopoCam or Polhemus FastSCAN with a mean error ranging between 0.05 and 1.49 mm determined by Eder et al. [8] as well as the error of the 3dMD system ranging from 0.067 to 0.74 mm as stated by Weinberg et al. [13], and ranging from 0 to 3.2 mm specified by Metzger et al. [14], the exactness of FaceScan3D® for measuring distances with a mean 0.966 mm inaccuracy ranges in the same area. Using the bundle of two Artec EVA® scanners for scanning distances results in a mean inaccuracy of 2.997 mm, which is nearly 3 times as much as the imprecision of FaceScan3D®. This error of the scanner bundle can only be compared with the error created by the 3dMD scanning system according to Metzger et al. [14] Most other reviewed scanning systems result in lower errors. It could be possible that this larger error while using the bundle of two Artec EVA® scanners results

from the technique used for recording the volunteers. Arranging the two scanners to the same height increases the field of view only horizontally and not vertically. Furthermore, the horizontal extension of the field of view is not as effective as using a mirror construction to capture more data like FaceScan3D® does. To increase the field of view vertically and horizontally, more than two scanners have to be bundled. Further research has to be done to evaluate the advantage of more than two bundled Artec EVA® scanners. It should be evaluated if an enlargement of the scanner bundle significantly improves the accuracy enough so that the capital asset for more scanners and the length of time for setting up and calibrating the scanners are worthwhile.

CONCLUSIONS

Compared to FaceScan3D®, a bundle of two Artec EVA® scanners provides different levels of accuracies depending on the location and configuration of measured parameters. The accuracy measured for both scanners is inside the range found in the literature for other facial scanning systems. At present, sometime is necessary to set up the scanner bundle, and the second scanner is a major capital asset. Determining if a single or a bundle of more than two Artec EVA® scanners results in a higher accuracy has to be evaluated in further studies.

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