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Original article

Full arch digital scanning systems performances for implant-supported fixed dental prostheses: a comparative study of 8 intraoral scanners

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ABSTRACT

Purpose: Compare the accuracy of intraoral digital impression in full-arch implant-supported fixed dental prosthesis acquired with eight different intraoral scanner (Ios).

Methods: A polymethyl methacrylate acrylic model of an edentulous mandible with six scan-abutment was used as a master model and its dimensions measured with a coordinate measuring machine. Eight different Ios were used to generate digital impression: True Definition, Trios, Cerec Omnicam, 3D progress, CS3500, CS3600, Planmeca Emelard and Dental Wings. Fifteen digital impressions were made. A software called "Scan-abut" was developed to analyse and compare the digital impression with the master model, obtaining the scanning accuracy. The three-dimensional (3D) position and distance analysis were performed.

Results: Mean value of the 3D position analysis showed that the True Definition (31 μm ± 8 μm) and Trios (32 μm ± 5 μm) have the best performance of the group. The Cerec Omnicam (71 μm ± 55 μm), CS3600 (61 μm ± 14 μm) have an average performance. The CS3500 (107 μm ± 28 μm) and Planmeca Emelard (101 μm ± 38 μm) present a middle-low performance, while the 3D progress (344 μm ± 121 μm) and Dental Wings (148 μm ± 64 μm) show the low performance. The 3D distance analysis showed a good linear relationship between the errors and scan-abutment distance only with the True Definition and CS3600.

Conclusions: Not all scanners are suitable for digital impression in full-arch implant-supported fixed dental prosthesis and the weight of the output files is independent from the accuracy of the Ios.

1. Introduction

The passive fit is a primary factor for long term clinical success and survival of an implant-supported fixed dental prosthesis (FDP). The precise transfer of the three-dimensional (3D) intraoral implant relationship to the master cast is a critical step to achieve a passive fit [1,2]. The insufficient accuracy during the impression-making technique and/or manual steps during prosthesis fabrication may lead to misfit of the prosthesis and subsequent to technical, mechanical, and biological complications [1–3]. In literature different authors tried to define the misfit numerically, but there were many opinions. Branemark et al. [4] concluded that the misfit should be not more than 10 μm, instead Jemt [5] declared that a misfit around 150 μm will be acceptable. However, different reviews affirmed that there is still no consensus on the value of misfit [6,7]. Today, conventional impression with different techniques and materials represent a commonly used procedure in general dental practice [8–10], but with the development of the intraoral digital impression many traditional prosthetic procedures have been eliminated [11,12]. The main factor for the use of digital intraoral impression is their equivalent accuracy to traditional impression. Regarding the digital intraoral impression for single dental crown [13–15] and for single-implant crown [16] several authors have showed that no statistical significant difference was found between the marginal fit of dental crowns

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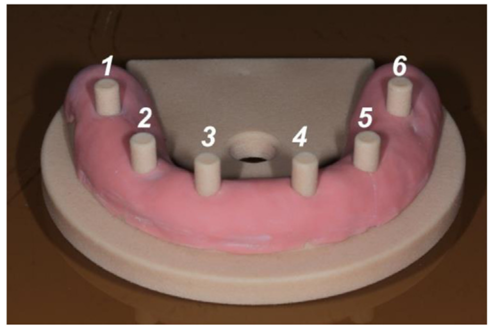

Fig. 1. Master model.

fabricated by digital intraoral impression compared with those fabricated by conventional impression methods. However, in literature, regarding the digital intraoral impression for full-arch there are contradictory results. Some authors concluded that the intraoral digital impression for full-arch showed similar accuracy to of the conventional impression [17–20]. Conversely, other studies showed that the digital impression was less accurate respect the traditional impression [21–25]. Nevertheless, the contradictory results can be explained by the different methods of analysis of the accuracy for intraoral digital impression. The master models used to evaluate intraoral scanners (Ios) were different. Several authors used a complete maxillary dental arch [17,18,21,22,26], others an edentulous mandible with five or six dental implants [20,22,24–28]. Different acquisition systems were used to calibrate the master model, many authors used a laboratory scanner [17,19,20,21,23,28,29], others a microscope, while a few authors used coordinated measuring machines (CMM) [22,24–27,30]. Different softwares for superimposition of the Standard Tessellation Language (STL) datasets and different data analysis as chromatic scales [19], position analysis [17,20,21,23,28,29] and distance analysis [22,24,25,27] were proposed. Therefore, the purpose of the present study was to compare the accuracy of intraoral digital impression in full-arch implant-supported fixed dental prosthesis acquired with eight different Ios with a standardized metrological methodology.

2. Materials and methods

2.1. Master model

A virtual model of a mandibular edentulous with six scan-abutment positioned vertically at different height was designed by means of a computer-aided design (CAD) software (Dassault Systèmes SolidWorks Corpor.,Waltham, MA, USA). The shape of the master model resembled a mandibular implant-supported full arch rehabilitation. Six scan-abutments were positioned symmetrically corresponding to the mandibular first molars, first premolars, and lateral incisors. All the scan-abutment geometries (i.e., regular cylinders) were parallel to each other with a diameter of 4 mm and incorporated into the master model. The regular geometry of scan-abutments was chosen, following metrologists expertise due to: (i) the favourable design to perform the calibration measurements using a coordinate measuring machine, (ii) the unfavourable design to stress stitching algorithm/procedure adopted by scanning systems. Subsequently the master model, with integrated scan-abutments, was manufactured in polymethyl methacrylate acrylic (PMMA) by a computer numerical control (CNC) machine tool to serve as a clinically relevant simulation model (master model). PMMA as the master model material was adopted in order to ensure adequate stiffness, strength, dimensional stability and to eliminate the need for spraying the model. The scan-abutment in position 46 was classified as first. The scan-abutment were located with the following height in the z-axis: (1) scan-abutment in position 46 and 36 at 13 mm; (2) scan-abutment in position 44 and 34 at 12.8 mm; (3) scan-abutment in position 42 and 32 at 14 mm. All the scan-abutment were parallel to each other with a diameter of 4 mm. This kind of scan-abutment was chosen following the metrologies expertise because of the favourable design to make the measurements in the best possible way using coordinated measuring machine. Soft tissue was simulated using silicone (Vestogum, 3M ESPE, St. Paul, MN, USA) in order to enable accurate measurements [Fig.1].

2.2. Calibration plan and procedure

The experimental campaign consisted in three phases: (1) calibration of the master model using the optical gaging products (OGP) SmartScope Flash CNC 300 with the contact system; (2) acquisition of the master model by expert operators with eight Ios; (3) recurrent calibration of the master model using the CMM with the contact system. The flowchart of methodology is represented in Fig. 2. The master model was measured with a coordinate measuring machine (CMM) (SmartScope Flash,CNC 300, OGP, Rochester, NY, USA), an optomechanical system that is

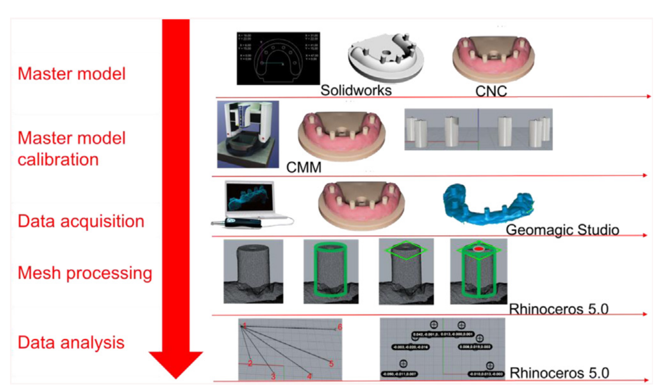

Fig. 2. Flowchart of methodology protocol.

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capable of moving a measuring probe to determine the spatial coordinates of points on a workpiece surface. The measuring system is capable of a 3D maximum error assessed as E3-xyz (L) = 2.8 + 5 L/1000 μm (with L, in millimeters, equal to the measured distance, according to ISO 10360 standard) [2,31,32]. A high-accuracy contact-probe with ruby sphere of 1.5 mm of diameter was used to measure the points of the scan-abutment upper and lateral surfaces to locate them in a x, y and z coordinate reference frame. Recurrent verification of the master model was required between scanning sessions with Ios to check the dimensional stability of the master model. The calibrations of the master model were performed based on the points in Fig. 3a and b: a partial, preliminary, reference frame on the master model was defined, then the scan-abutments were measured. For each scan-abutment a plane [Fig. 3c] and a cylinder [Fig. 3d] were identified, adopting specific sets of points. Finally, the position of each scan-abutment was computed as the intersection between the plane and the axis of the cylinder. The coordinates of the probed points and intersections were transferred into a 3D CAD geometric modelling software program (Rhinoceros 5.0 Beta, Robert McNeel &Associates Europe, Barcelona,Spain) and analyzed with a specific evaluation protocol, developed in IronPython, to estimate the position and orientation of each scan-abutment. This procedure was repeated five times. A mean of the five measurements performed with the CMM was used as reference position of scan-abutments for the evaluation of the accuracy of each digital impression obtained by eight different Ios.

2.3. Digital impression acquisition and processing

The master model was scanned with eight different Ios: True Definition (3M ESPE, St. Paul, MN, USA, software version 5.1.1), Trios 3 (3Shape,Copenhagen, Denmark, software version 16.4), Cerec Omnicam AC (Sirona Dental System GmbH, Bensheim, German, software version 4.3.1), 3D progress (MHT,Verona, Italy, software version Exoscan-mht-2012-12-19), CS3500 (Carestream, Rochester, NY, USA, software version 2016–4,release 2.1.4.10) CS3600 (Carestream, Rochester, NY, USA, software version 1.2.6), Planmeca Emelard (Planmeca OY, Helsinki, Finland, Romexis 2018-1) and Dental Wings (Dental Wings Inc, Montreal, Canada, software version 3.7.0.26). The scanning was performed according to the manufacturer's instructions for each scanner. Fifteen digital impressions were made. Once the digital impression was made and classified, the STL file was sent to Geomagic Studio Software (Geomagic GmbH v4.1.0.0; 3D Systems) to clean the mesh from portions not related to the research and finally imported in the 3D CAD geometric modelling software (Rhinoceros 5.0).

2.4. Accuracy assessment

The STL file imported in the 3D CAD software (Rhinoceros 5.0) was furtherly processed to perform 3D position and distance analysis. A software plug-in called "Scan-abut" was developed in order to automatically segment the mesh of the scan-abutment by curvature analysis [Fig. 4]. The segmented dataset was then filtered (reduced), with 2σ Gaussian criterion, and two independent fitting were computed to calculate the upper plane surface and the later cylindrical surface of the scan-abutment [Fig. 5a,b]. From the intersection of the cylinder axis with the plane, a centre point was assessed, which identifies the scan-abutment position [Fig. 5c].

To evaluate the absolute position error of scan-abutments, the six scan-abutment positions were aligned with the six reference positions measured by CMM, using a least-square best fitting algorithm. The position error is defined as the 3D distance between a scan-abutment position and the corresponding reference position. The 3D position analysis (i.e., 3D position error) between digital impression and reference points of the master model were calculated at each scan-abutment position for all digital impressions.

To investigate the accuracy of scanning systems with respect to arch length, a 3D intra-abutment distance was calculated as the 3D linear distance between paired scan-abutments (i.e., distance from scan-abutment 1 to scan-abutment 6). A total of fifteen 3D distances, considering any combinations of six scan-abutments, were calculated for each digital impression.

The 3D distance error was calculated as the difference between the effective 3D distance between scan-abutments of the digital impression and the reference 3D distance between scan-abutments of the master model, measured with CMM.

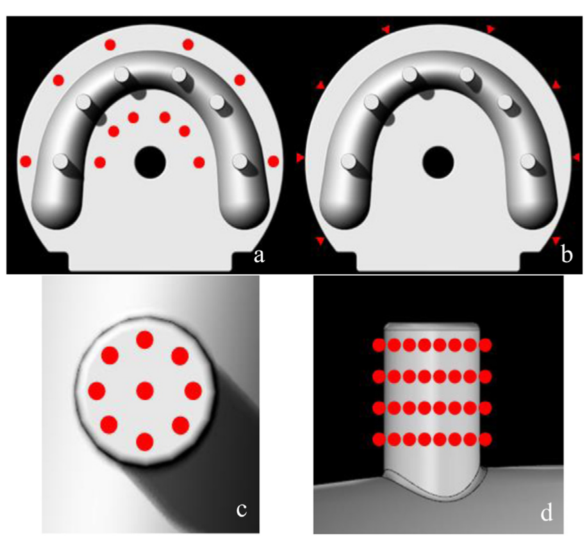

Fig. 3. The measurements of the master cast: (a)Points in the XY plane. (b) Points on the outer circumference. (c) Measurement of 9 points on the upper plane of the scan-abutment. (d) Acquisition of 4 circular sections (260 points) perpendicular to the axis of the scan-abutment.

The accuracy of an impression was referred to both trueness and precision (ISO 5725-1 and -2) with the aim of defines values which describe, in quantitative terms the ability of a measurement system to give a correct result (trueness) or to replicate a given result (precision). Accordingly, the "trueness" described the mean deviation of a group of digital impression, pertaining to a single scanning system, from the reference geometry [33,34], the "precision" described the distribution of the deviations within the impressions pertaining to the same group [33,34]. The mean deviation (error) of the 3D position was considered as the trueness, while the standard deviation of the 3D position errors relevant to the group sample (i.e. fifteen digital impressions) as the precision. The distance error was used to evaluate the relationship between the error and the distance as an indicator of the maximum permissible error (MPE) of the scanning system in accordance to ISO 10360 standards.

2.5. Statistical analysis

The digital impression was considered as the statistical unit. The primary variable was the 3D position error, the distance (μm) from the position point of the single scan-abutment, on the digital impression, to the reference point of the same scan-abutment in the master model. Six numerical values were recorded for each impression which correspond to the deviations of the six scan-abutments; then for each impression were performed the average of the six position errors to obtain a single numerical value. The 3D mean position error was used in comparative statistics. The Wilcoxon matched-pairs signed-rank test (one-tailed) was used to compare Ios. The level of statistical significance was set as $\alpha = 0.05$ and with a statistical power of 80%. Statistical analysis was performed using statistical software SPSS 16.0 (SPSS Inc).

3. Results

The descriptive statistic of the 3D position errors of each Ios is given in Table 1. The mean 3D position errors values were used in comparative statistics between digital impressions. No statistical significant difference emerged between True Definition vs Trios 3 (p-value = 0.47); Cerec Omnicam vs CS3600 (p-value = 0.24) and CS3500 vs Planmeca Emelard (p-value = 0.28). All the remaining groups presented statistical difference ($p\text{-value} < 0.05$). The 3D distance analysis of different Ios were reported in Fig. 6a–h. The 3D distance analysis showed a good linear relationship between the errors and scan-abutment distance only with the True Definition and CS3600. The weight of the output file was independent from the accuracy of the Ios.

4. Discussion

Accuracy is an important factor for the success and survival of an implant-retained prosthesis [1–10]. The 3D position analysis showed that not all Ios are valid for executing digital impression for a full arch. The 3D position analysis showed that the True Definition and Trios 3 have the better performance of the group. The Cerec Omnicam, CS3600 have average performance. The CS3500 and Planmeca Emelard present a middle-low performance while the 3D Progress and Dental Wings low performance. In literature, the clinically desirable value of the position errors, that represented the misfit, in a full arch rehabilitation varies from 10 μm [4] to 150 μm [5], but the authors believe that the clinicians must try to obtain position errors around 30–50 μm to avoid mechanical and biological complications. The 3D distance analysis showed a good linear relationship between the errors and scan-abutment distance

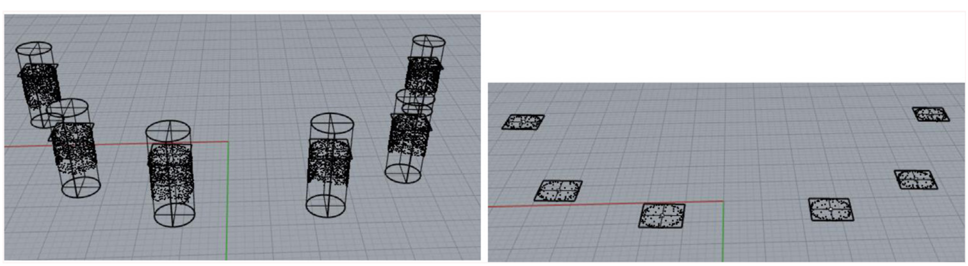

Fig. 4. The software application called "Scan-abut" was realized as a plug-in for Rhinoceros. The software "scan-abut" segments automatically the surfaces of the scan-abutment (cylindrical area and plan area).

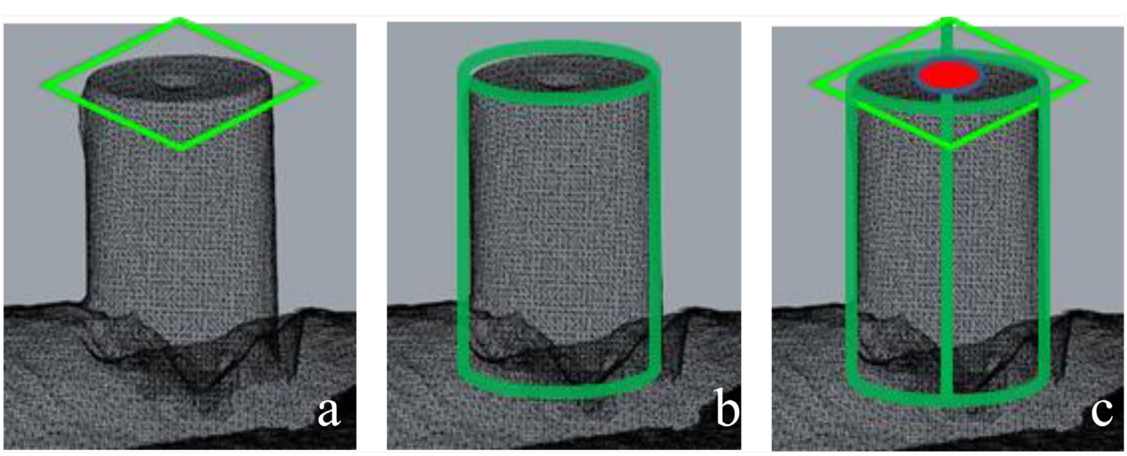

Fig. 5. Construction of the geometric elements during calibration master model: (a) construction of the plan of fitting through 9 points measured above. (b) Construction of the cylinders of fitting on 4 circular sections. (c) Intersection of the axis of this cylinder with the upper floor to define a reference point for each individual scan-abutments.

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Table 1. Mean position errors (μm) of the digital impression respect the master model in three axis and 3D.

Ios	ΔX	ΔY	ΔZ	3D	3D	
	Mean μm (SD)	Mean μm (SD)	Mean μm (SD)	Mean μm (SD)	Min μm	Max μm
True Definition	25.64 (11.69)	13.52 (7.84)	5.17 (1.46)	31 (8)	18	47
Trios 3	19.68 (20.59)	11.21 (5.02)	9.89 (2.25)	32 (5)	23	41
Cerec Omnicam	45.23 (18.10)	19.85 (14.64)	10.60 (6.81)	71 (55)	30	243
CS3500	39.30 (44.54)	14.28 (11.85)	5.13 (5.20)	107 (28)	40	146
3D Progress	75.00 (21.72)	85.22 (51.85)	89.42 (5.54)	344 (121)	117	571
CS3600	37.67 (19.10)	18.16 (10.71)	12.30 (4.39)	61 (14)	35	87
Planmeca Emelard	29.19 (21.36)	18.45 (13.87)	13.72 (12.13)	101 (38)	44	188
Dental Wings	82.76 (27.46)	45.63 (32.43)	62.62 (41.49)	148 (64)	44	285

with the True Definition and CS3600 [Fig. 6a and f]. Errors dispersion might be related to incorrect software stitching process during the acquisition or processing. In literature one article only investigated the relationship between accuracy and resolution of four Ios (Trios, True Definition, Cerec Omnicam and iTero) [35]. The authors concluded that there is no relationship between resolution and accuracy, in terms of trueness and precision. The same results were obtained in this research.

Different articles investigated the accuracy of the digital impression in full arch rehabilitation. The heterogeneous results can be explained by the different methodology of evaluation of the accuracy. Some authors used a master model that represented a complete maxillary dental arch [17,19,21,23,36], others an edentulous mandible with five or six dental implants [22,24,25–30,37–39]. Ender and Mehl [17,21,23] used a maxillary dental arch with 2 complete crown preparations and 1 inlay preparation, Patzelt et al. [19] and Renne et al. [36] a complete dental arch. Also Güth et al. [26] used a mandible complete dental arch, but the authors inserted into their master model a metal bar. Giménez et al. [22,24,25,27], Papaspyridakos et al. [20], Amin et al. [28], Vandeweghe et al. [29], Ciocca et al. [30], Malik et al. [38], Imburgia et al. [37] and Pesce et al. [39] used an edentulous mandible with five or six dental implants with the respective scan-abutment. From the analysis of any critical issues pertaining to master models described in the literature, in our research a mandibular edentulous with six scan-abutments positioned vertically at different height with a diameter of 4 mm was used; contrary to other master models, scan-abutments were incorporated in our master model which therefore consists of a unique part and not of many parts assembled together [22,24,25–30,37–39]. The scan-abutment geometry was chosen following the metrologists expertise with a favourable design to make an accurate calibration while not to favour an Ios over the others. All the geometric features of the scan-abutment allowed to construct geometric elements by fitting (planes and cylinders) and to calculate deviations (position and distance) of actual points relevant to reference points. On the contrary, the estimate of deviations in master models with dental arch and without geometric feature were usually calculated by mesh alignment. To avoid the mesh alignment Güth et al. [26] inserted into the master model a bar in order to have

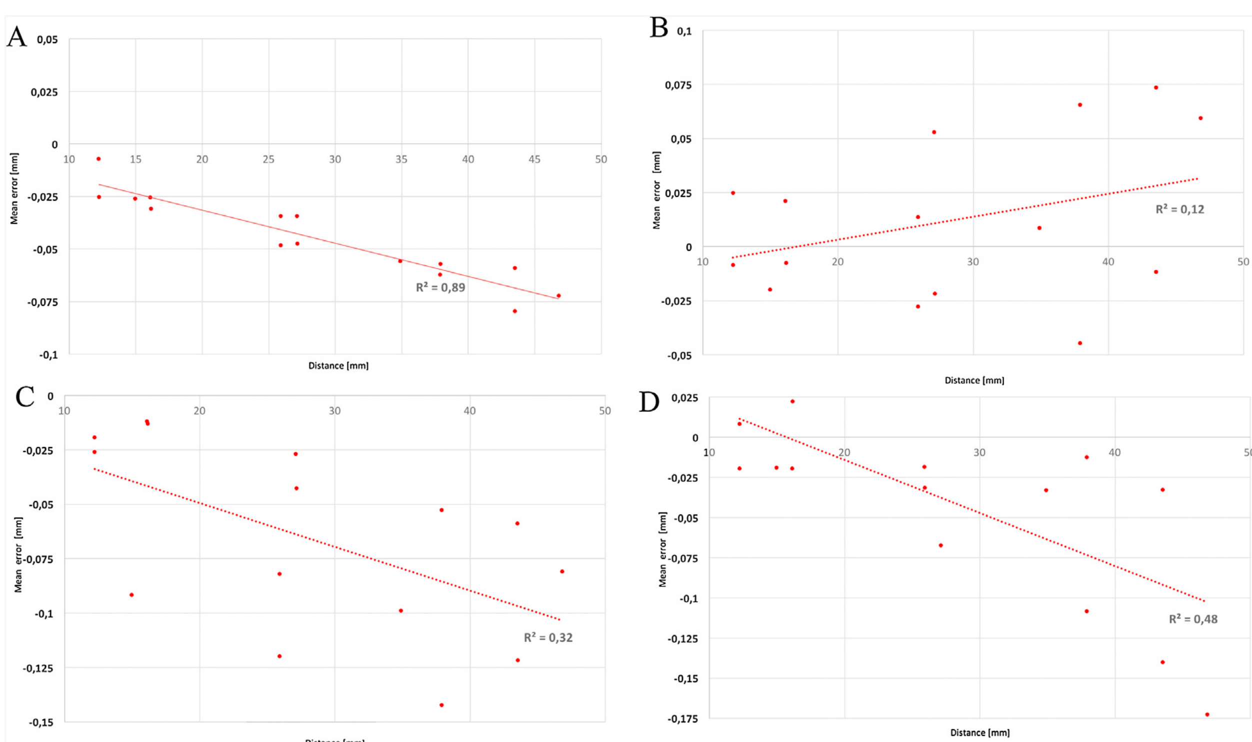

Fig. 6. (a) 3D distance analysis with regression line for True Definition. (b) 3D distance analysis with regression line for Trios 3. (c) 3D distance analysis with regression line for Cerec Omnicam. (d) 3D distance analysis with regression line for CS3500. (e) 3D distance analysis with regression line for CS3600. (f) 3D distance analysis with regression line for 3D Progress. (g) 3D distance analysis with regression line for Planmeca Emerald. (h) 3D distance analysis with regression line for Dental Wings.

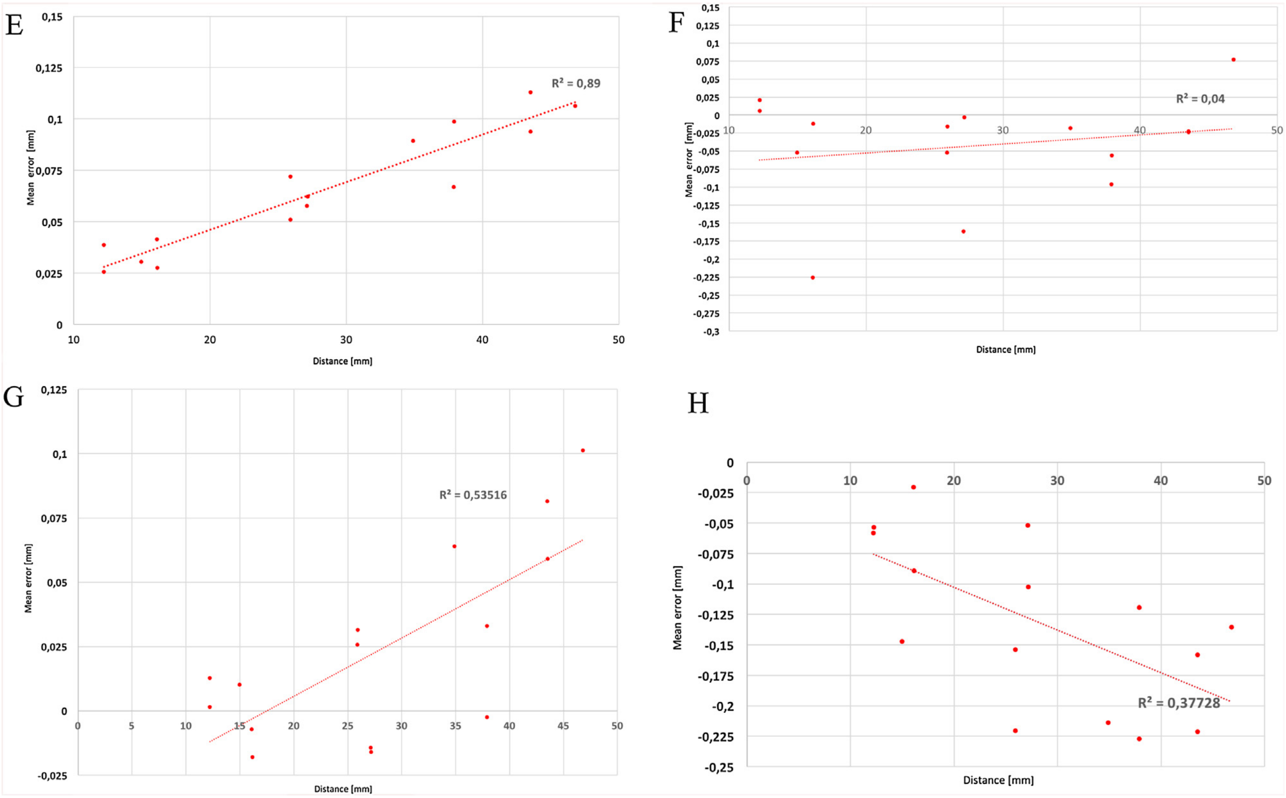

Fig. 6. (Continued)

geometric features of fitting to calculate the deviations by reference points. However, the insertion of a bar as a geometric reference figure is not achievable clinically: we used the geometries of scan-abutments that can be effectively positioned in the oral cavity of our patients. Different acquisition systems were used to calibrate the master model: many authors used a laboratory scanner [17,19,20,21,23,28,29,37–39] and only three authors use a CMM [22,24–27,30]. The acquisition system used in this research is capable of a maximum permissible error that is 10 times lower than the performance of laboratory scanners [2,30–32]. Different mesh processing procedure and different data analysis as position analysis [17,19,21,23,28,29,36–39] and distance analysis [20,22,24,25,27] were proposed. Ender and Mehl [17,21,23] used CAD software with a best fit algorithm to perform mesh-to-mesh alignment. The distance was calculated between the digital impression and the calibrated master model to perform the position analysis. This methodology for verification of accuracy in digital impression of full arch was the first to be published [17], consequently other authors have used this methodology [17–21,23,24,28,29,36–39]. The results may be affected by the reference scanner and/or the choice of the superimposition points. The accuracy estimate given by this methodology is not acceptable from a metrological point of view to assess Ios performance, according to ISO 10360 standards. Instead, the distance analysis was conducted by Giménez et al. [22,24,25,27]. The mesh processing consisted in identifying the central point of the scan-abutment through the original CAD files used to product the scan-abutment. The central point identified on the scan-abutment in position 27 was considered as the reference point for measurements. The distances (27–25, 27–22, 27–12, 27–15 and 27–17) between the scan-abutment's centre points of the digital impression were performed. The same distances were calculated on the master model measured with the CMM. Finally, the analysis of the distances was calculated subtracting the two distance. Güth et al. [26] presented a method without need of a best-fit algorithm allowed to measure linear shifts in all three dimensions. In our calculation method mesh processing as well as reference and actual points identification, position and distance analyses are performed automatically by an ad hoc software plug-in, without the intervention of an operator. Analysing the results of the researches, we noted different conclusions. In literature, the first authors that published an article regarding this topic are Ender and Mehl [17]. Ender and Mehl concluded that the accuracy of the conventional impression was more accurate respect the digital impression [17,21,23]. However, the results were different with the same Ios. In the first research [17], the authors showed that the trueness were 40.3 ± 14.1 μm with Lava Cos (precision 60.1 ± 31.3 μm), 49 ± 14.2 μm with Cerec Bluecam (precision 30.9 ± 7.1 μm) and 55 ± 21.8 μm for conventional impression using polyether (precision 61.3 ± 17.9 μm). In another study [23] the same authors concluded that the trueness of the conventional impression with vinylsiloxane material was 13 ± 2.9 μm (precision 12.3 ± 2.5 μm) and 60 ± 25 μm with polyether material (precision 66 ± 18.5 μm). Instead, the trueness of the digital impression with Cerec Bluecam was 29.4 ± 8.2 μm (precision 19.5 ± 3.9 μm), Cerec Omnicam 37.3 ± 14.3 μm (precision 35.5 ± 11.4 μm), iTero 32.4 ± 7.1 μm (precision 36.4 ± 21.6 μm) and Lava Cos 44.9 ± 22.4 μm (precision 63 ± 32.8 μm). The same authors in another study [21] on the basis of the same methodology concluded that the trueness of conventional impression with vinylsiloxanether material was trueness 20.4 ± 2.2 μm (precision 12.5 ± 2.5 μm), instead the trueness of digital impression with Cerec Bluecam was 58.6 ± 15.8 μm (precision 32.4 ± 9.6 μm). Patzelt et al. [19] showed a mean trueness of 49.0 ± 13.6 μm for iTero, 332.9 ± 64.8 μm for Cerec Bluecam, 38.0 ± 14.3 for Lava C.O.S. μm and 73.7 ± 26.6 μm for Zfx Intrascan. Instead, Giménez et al. [22,24,25,27] evaluated the accuracy of a digital impression system considering clinical parameters as experience of the operator, the angulation, and the depth of the implants, therefore not comparable. The mean trueness of conventional impression using a polyether was 77 μm (SD 36 μm) and for digital impression was 89 μm (SD 48 μm) with True Definition according the research of Güth et al. [26]. Amin et al. [28] showed a mean trueness of 167.93 μm (SD 50.37) for conventional impression using polyether material, instead for digital impression the mean trueness was of 46.41 μm (SD 7.34) for Cerec Omnicam and 19.32 μm (SD 2.77) for True Definition. The results of Vandeweghe et al. [29] showed a mean trueness of 112 μm for Lava C.O.S., 35 μm for True Definition, 28 μm for Trios and 61 μm for Cerec Omnicam. Renne et al. [36] used seven different scanner, but one (3 Shape D800) is an extraoral scanner. However, the authors concluded that the order of trueness for complete arch scanning was as follows: 3Shape D800 (43.6 μm) > iTero (56.2 μm) > 3Shape TRIOS3(69.4 μm) > Carestream 3500 (76 μm) > Planscan Plameca (96.2 μm) > CEREC Omnicam (101.5 μm) > CEREC Bluecam (140.5 μm). Malik et al. [38] showed that the conventional full-arch impression with vinylsiloxane (trueness 21.7 μm) was more accurate respect the digital impression (trueness Trios and Cerec Omnicam respectively 49.9 μm and 36.5 μm). Imburgia et al. [37] concluded that the CS 3600 had the best trueness (60.6 ± 11.7 μm), followed by Cerec Omnicam (66.4 ± 3.9 μm), Trios 3 (67.2 ± 6.9 μm) and True Definition (106.4 ± 23.1 μm). The results of this research are similar to some articles [28–30], but different from others [17,19,21,23,26,36–38]. However, in our research the digital impression of some Ios showed higher accuracy than the conventional impression reported in literature [17,21,23,26,28]. Position and distance errors represented a significant clinical problem called misfit. The need to have a universal evaluation method is of fundamental importance to understand the performance of the different Ios. Overall, the measurement method could be considered more standardized than those described in the literature, because the data processing are performed automatically and thus independently from the operator. The methodology can also be applied in vivo, however, one limitation of this study is the lack of the control group (i.e. conventional impressions). Not all scanners can be used for digital impression in full-arch implant-supported fixed dental prosthesis and the weight of the output files is independent from the accuracy of the intra-oral scanner. More studies in vivo, investigating the accuracy of digital impression with different Ios in full arch are needed to understand the performance of this devices.

5. Conclusion

Not all scanners can be used for digital impressions in full-arch implant-supported fixed dental prosthesis, however new research in vivo investigating this topic are needed.

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