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RESEARCH

Accuracy of intraoral scans of the edentulous maxilla – an in vitro study

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Abstract

Objective Investigation of the accuracy of various digitalization methods and the accuracy of digitalization of different regions of the edentulous maxilla.

Material and method A PEEK edentulous maxilla with four spherical reference geometries served as the testing model. A reference dataset (REF) was generated using a highly accurate 3D measuring instrument. The testing model was digitized as follows ($n=25$/group). Direct digitalization (DD) with intraoral scanners (IOS): 1) Cerec AC Primescan (PRI), 2) Trios 4 Move (TR4), 3) Trios 3 Wireless (TR3), 4) Indirect digitalization of PVS impression with laboratory scanner 3Shape D810 (D8I). Three-dimensional deviations between REF and TEST were evaluated (GOM Inspect) in different areas of the model: 1) Complete Surface, 2) Alveolar Ridge, 3) Vestibular Ridge, 4) Palate, 5) Posterior Seal, 6) Border. Significant differences were analyzed with the Games-Howell test for trueness ($p<0.05$) and multiple comparisons Levene's test for precision (for IOS: $p<0.008$, for area: $p<0.003$).

Results Group D8I revealed the best trueness for Complete Surface (7.95 µm), Palate (9.11 µm), and Border (20.22 µm). Alveolar Ridge showed for PRI (16.45 µm) and TR4 (8.96 µm) the highest trueness. Groups TR4 and PRI resulted in significantly higher precision for Alveolar Ridge. Groups TR4 and D8I demonstrated the highest precision for Palate. Complete Surface and Alveolar Ridge showed for all digitalization methods significantly higher precision.

Conclusions Indirect digitalization of impressions remains the most accurate approach for capturing edentulous jaws, whereas IOS deliver datasets with clinically acceptable accuracy. Peripheral regions characterized by limited accessibility and smooth surface morphology tend to demonstrate increased deviations in the resulting digital datasets.

Clinical relevance. Indirect digitalization of the impression still appears to be the most appropriate technique to access the clinical workflow for full dentures due to the superior digitalization trueness and inclusion of functional movements. Direct and indirect digitalization show nearly equal values for precision.

Keywords Accuracy · Coordinate-based data analysis · Digital dentistry · Intraoral scanner · Precision · Trueness · Digital full-arch impression · Edentulous

Introduction

Over the past decades technological innovations in dental workflows and materials have profoundly transformed diverse aspects of the profession. Apart from the field of fixed prosthodontics, CAD/CAM processes have numerous applications in one of the oldest therapeutic practices in dentistry, namely the complete denture [1, 2]. Computer assisted design with the use of dedicated software, digital articulators, expansive teeth libraries, and seamless combination of face scans, patient's photographs and digital models offer improved efficiency, reduced time, and cost [3, 4]. Simultaneously, novel polymer materials used to mill the basis or teeth of the denture provide higher stability, better biocompatibility, less microorganism adhesion and result in better base adaptation, lower incidence of pressure points and correction appointments [3–5].

Intraoral scanners (IOS) have been well established for the digitalization of fully dentate jaws and have been proven to be as accurate as conventional impressions for the entire arch in certain clinical scenarios [6, 7]. Still CAD/CAM workflows for

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complete dentures rely mainly on conventional impressions or casts for the acquisition of the edentulous anatomy [2]. When applying IOS for completely edentulous situations the main limitations described are the scarcity of anatomical landmarks, the functional borders, and the posterior palatal seal [2, 8]. In fully dentate arches the tooth morphology is utilized by the superimposition algorithm to correctly align the captured images. For edentulous areas this process cannot be carried out as efficiently due to the lack of dental geometries. This in turn can result in larger inaccuracies and deformities in the digital model [9–11]. Furthermore, IOS achieve a purely mucostatic record of the intraoral anatomy, whereas indirect digitalization includes information about functional muscle extension, vibrating line spread and depth or displacement of mucosal areas of varying compressibility [12–14]. These features have long been regarded as key components for the realization of adequate retention and stability in complete prostheses [15, 16]. Recently many researchers have theorized that for CAD/CAM milled dentures, despite IOS data lacking peripheral seal information, the accuracy of digitalization may be sufficient to achieve high conformity between the denture base and the underlying mucosa, ensuring adequate retention according to the mucostatic principle [13, 17–20].

However, the current body of evidence on the accuracy of direct digitalization of edentulous jaws remains limited, both in terms of volume and content of available research [8, 21]. The determination of the accuracy of digital datasets for edentulous jaws presents some methodological complexities and requires a three-dimensional comparison of the digital datasets with the anatomy of the denture-bearing area. Previous investigations have mostly focused on comparisons of IOS and digitized conventional impressions, without the use of highly accurate reference datasets [12, 13, 22–25]. Furthermore, researchers almost exclusively employ global best fit algorithms for the orientation of data, which has been proven to obscure true inaccuracies and result in potentially lower deviations, especially regarding larger datasets [26]. Moreover, comparisons of the accuracy between various areas of the edentulous digital models are usually relayed with color coded maps of selected representative datasets, without quantitative analysis on the entirety of generated data or statistical evaluation of the results [12, 23, 27–29]. These differences in the methodological design complicate the comparison of the study results with each other.

The aim of the present in vitro study is to assess the accuracy (trueness and precision) of direct and indirect digitalization on an edentulous maxillary model as well as the accuracy of digitalization for different parts of the edentulous maxilla. The first null hypothesis is that there are no significant differences in the accuracy of different digitalization methods. The second null hypothesis states that there are no significant differences in the accuracy of varying areas of the digital edentulous maxillary models achieved with each method.

Fig. 1 Testing model milled from PEEK

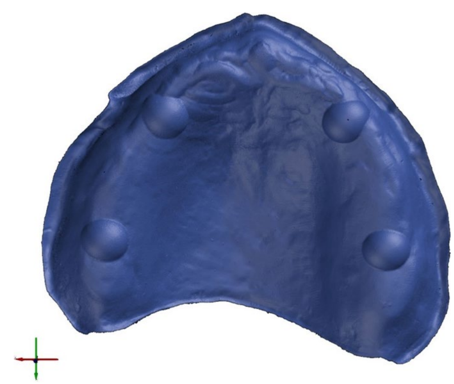


Fig. 2 Reference dataset

Materials and methods

Testing model

An edentulous maxillary model with four identical hemispheres in the location of the canines and second molars on the residual ridge was milled from PEEK (Polyether ether ketone) (PEEK Biosolution, LOT no 32116; Merz Dental GmbH, Lütjenberg, Germany) and used as the testing model (Fig. 1). To produce a highly accurate reference dataset (REF, Fig. 2), the testing model was optically measured using the Infinite Focus G5 scanner (Alicona Imaging GmbH, Graz, Austria; objective 5x, resolution: finest topographic lateral = 3.51 µm, vertical = 410 nm).

Direct digitalization

Direct digitalization of the PEEK testing model was completed with the following IOS (n = 25/group):

- Cerec Primescan AC (group PRI; Software version 5.0.2, Dentsply Sirona, Bensheim, Germany).
- Trios 4 Move (group TR4; Software Version 1.19.2.4, 3 Shape, Copenhagen, Denmark).

- Trios 3 Wireless (group TR3; Software version 1.4.7.4, 3 Shape, Copenhagen, Denmark).

Cerec Primescan AC and Trios 3 were calibrated at the beginning of every scanning session, whereas for Trios 4 no calibration was required as per manufacturer's recommendation. All scans were conducted by one single experienced user, with a five-minute intermission between each scan.

The following strategy was applied: first the vestibular side of the residual ridge was scanned commencing with the tuberosity of the first quadrant and concluding in the tuberosity of the second quadrant, followed by the palatal surface of the ridge in the reverse direction. Lastly the palate was recorded in a zig zag path. Test datasets were post-processed and exported as STL.

Indirect digitalization

Twenty-five conventional impressions were conducted with scannable polyvinyl siloxane (PVS) impression material. The impressions were carried though in a one-step/double mix impression technique. Light body material (Flexitime Fast&Scan light flow, LOT no K010022; Kulzer GmbH, Hanau, Germany) was directly injected on the testing model, while medium body material (Flexitime Monophase Pro Scan, LOT no R010022; Kulzer GmbH, Hanau, Germany) was applied in the custom tray (Fig. 3). The tray was then positioned and held without pressure on the model for four minutes. After removal the impressions were disinfected (ORBI-Sept Abformdesinfektion, LOT no A0984; Orbis Dental, Münster, Germany) for two minutes, cleaned under running water and air-dried.

Following a twenty-four-hour storing period, the PVS impressions were digitized with the D810 laboratory scanner (group D8I; Software Version Dental System 2014–1 $\times$64—build 1.4.7.4–16.08.2018 Dental System, 3 Shape; $n = 25$/group).

Analysis of datasets

All generated datasets as well as the reference dataset were imported into the metrological software GOM Inspect (GOM Inspect 2020, GOM GmbH, Braunschweig, Germany; software version: 133088). Artifacts were removed and margins were trimmed up to the edge of the border. For each group the test and REF datasets were aligned using a local best fit on the hemispheres located in both canine positions and the second molar of the first quadrant (Fig. 4).

After alignment, the following areas were manually selected on the REF: *Complete Surface, Alveolar Ridge, Vestibular Ridge, Palate, Posterior Seal, Border* (Fig. 5). For each dataset the distances of individual points between REF and test dataset in every selected area were calculated (Fig. 6). All measured values were exported into Microsoft Excel and the median of the absolute values was determined. Accuracy of digitalization was assessed as the trueness and precision of the data as defined by the ISO 5725–1 [30]. Trueness was calculated from the difference between measured and reference data. For the examination of precision, the spread of the values represented by the standard deviation was examined.

Fig. 3 PVS impression

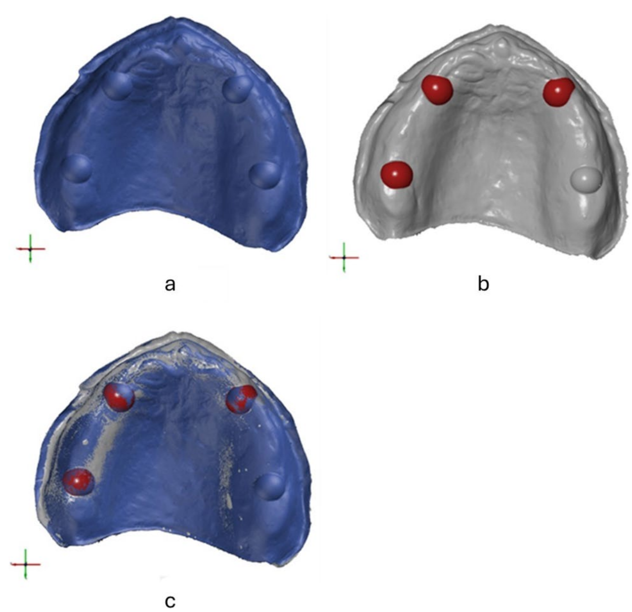


Fig. 4 Alignment of test datasets with REF. **a**. REF. **b**. Best fit alignment on selected areas. **c**. Aligned test and REF datasets

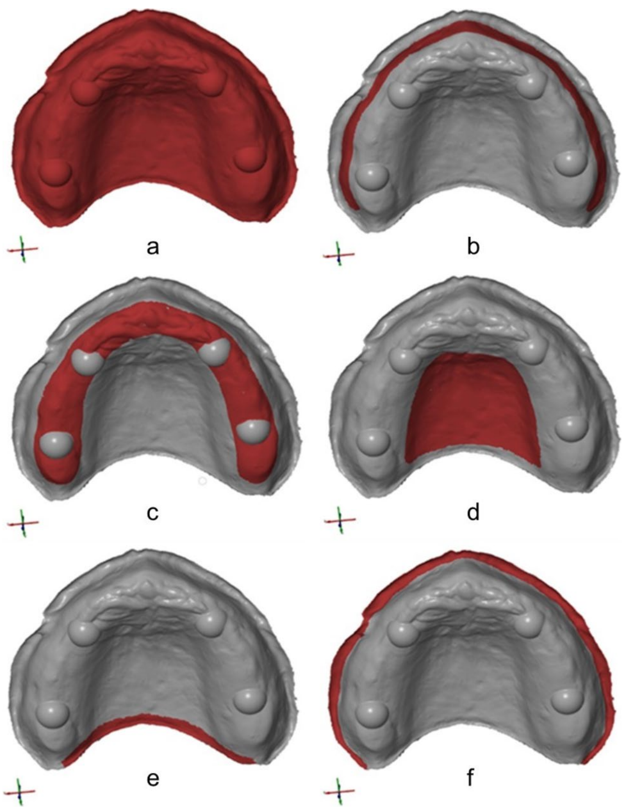


Fig. 5 Investigated areas: **a**. Complete Surface. **b**. Vestibular Ridge. **c**. Alveolar Ridge. **d**. Palate. **e**. Posterior Seal. **f**. Border

Statistical analysis

For statistical analysis the Statistical Package for the Social Sciences, Version 25 (SPSS Inc., Chicago, USA) was used. Descriptive statistics (mean, standard deviation, 95% confidence intervals) were given for each parameter and group. An analysis of variance (ANOVA) test was applied to assess the null hypothesis. Normality of data distribution was tested using Kolmogorov–Smirnov and Shapiro–Wilk test. Significant differences in trueness were examined by a post-hoc Games-Howell test with significance level of $p = 0.05$. Regarding precision significant differences in variance were analyzed by multiple comparison Levene's Test, where the significance level was set at $p = 0.008$ for the digitalization method and $p = 0.003$ for the area.

Results

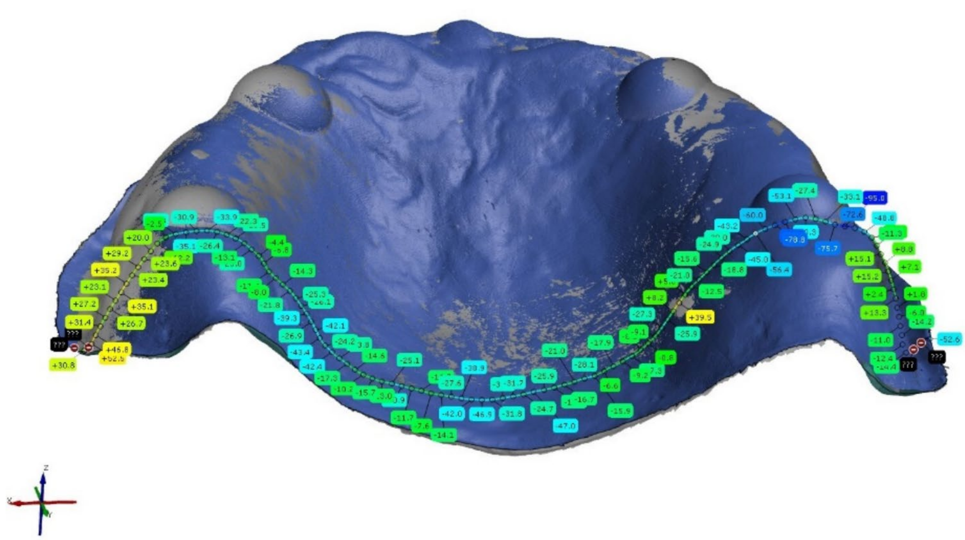
Table 1 reports the descriptive statistics (mean, standard deviation (SD), median (Med), minimum (Min), maximum (Max), and 95% confidence interval (CI)) for each parameter (Tables 2 and 3). Table 2 and Table 4 depict the p values of the Games-Howell post-hoc test for trueness. Table 3 and Table 5 depict the p values of Levene's test for precision. Figure 7 shows the boxplots.

Accuracy of digitalization method:

For *Complete Surface, Palate* and *Border* D8I exhibited the significant highest trueness while TR3 resulted in significantly lowest trueness. For *Alveolar Ridge* D8I and TR4 exhibited the highest trueness. For *Vestibular Ridge* D8I and PRI demonstrated significantly the highest trueness. For *Posterior Seal* D8I, PRI, and TR4 demonstrated significantly higher trueness than group TR3.

For *Alveolar Ridge* TR4 showed significantly higher precision than D8I and TR3. For *Palate* TR4 and D8I revealed significantly higher precision than PRI and TR3. For

Fig. 6 Cross section of measured distances between points on REF and test datasets in the metrological software



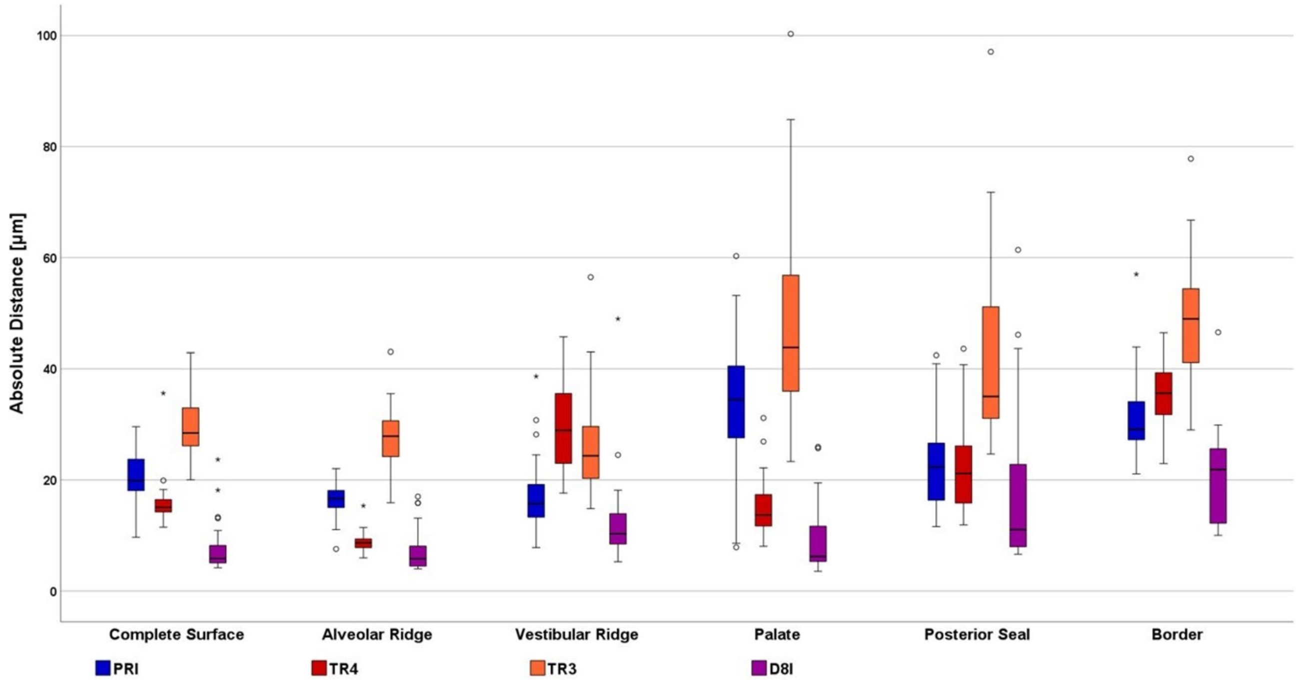


Fig. 7 Boxplots for digitalization methods (Cerec AC Primescan (PRI), Trios 4 Move (TR4), Trios 3 Wireless (TR3), Indirect digitalization of PVS impression with laboratory scanner 3Shape D810 (D8I)) and digitalization areas (Complete Surface, Alveolar Ridge, Vestibular Ridge, Palate, Posterior Seal, Border)

Posterior Seal PRI demonstrated significantly the highest precision. For *Complete Surface*, *Vestibular Ridge* and *Border* no significant differences have been found for precision between the digitalization methods.

Accuracy of digitalization area:

For PRI and TR4 the significantly highest trueness was exhibited at *Alveolar Ridge*. For TR3 *Complete Surface*, *Alveolar Ridge* and *Vestibular Ridge* showed significantly higher trueness than *Palate, Posterior Seal* and *Border*. For D8I the significantly highest trueness was observed at *Complete Surface and Alveolar Ridge* while *Border* showed the significantly lowest trueness.

For PRI, TR4, TR3 and D8I the significantly highest precision was found in *Complete Surface* and *Alveolar Ridge.*

Discussion

In the present in vitro study, the accuracy of different digitalization processes as well as the accuracy of digitalization for distinctive areas of the edentulous maxilla were investigated. The first null hypothesis that stated no differences between the digitalization methods could be detected must be rejected. The superior accuracy demonstrated by indirect digitalization of impressions compared to direct digitalization has been confirmed by several authors for dentate as well as for edentulous anatomies [23, 31–33]. Laboratory scanners are less error-prone than IOS since they operate in controlled environments with standardized procedures. The larger optical sensors can capture broader segments with more features, requiring fewer images and reducing stitching inaccuracies [34, 35]. In accordance with current results, recent in vivo investigations presented lower trueness for the direct digitalization with Trios 3 compared to digitalization of PVS impressions [12, 36]. By contrast, Zarone et al. reported a higher trueness and precision for Trios 3 than for conventional impressions, using polysulfide material [24]. Several authors have disclosed similar performance for Trios 3 for impressions and casts in vivo, however these comparisons have not been based on a reference dataset [13, 25].

Disparities in IOS performance have been attributed to multiple factors including optical scanning technology, specific hardware components of each system such as head size, lens, area of the scanning window as well as the software [29, 37, 38]. A larger scanning window facilitates the capture of fewer images that contain more morphological information and can be more efficiently stitched together resulting in improved accuracy [37]. Consequently, the superior performance of TR4 compared to PRI may be attributed to the larger scanning window of the device (19.20 × 16.30 mm compared to 18.0 × 16.10 mm). In a

Table 1 Descriptive statistics: Mean, standard deviation (SD), median (Med), minimum (Min), maximum (Max), and 95% confidence interval (CI)

Digitalization Method	Area	Absolute Distance (µm)					
		Mean	SD	Med	Min	Max	95% CI
PRI	*Complete Surface*	$20.44^{C, b, 1, \alpha}$	4.80	19.90	9.66	29.59	18.46
	Alveolar Ridge	$16.42^{B, a, 1, 2, \alpha}$	3.25	16.64	7.56	22.03	15.08
	Vestibular Ridge	$17.02^{A, a, b, 1, \alpha, \beta}$	7.45	15.74	7.82	38.65	13.94
	Palate	$32.73^{C, c, 2, \beta}$	13.85	34.47	7.86	60.28	27.02
	Posterior Seal	$22.58^{A, b, 1, \beta}$	7.85	22.36	11.59	42.44	19.34
	Border	$31.27^{B, c, 1, \alpha, \beta}$	7.51	29.13	21.07	56.99	28.17
TR4	*Complete Surface*	$16.04^{B, b, 1, \alpha, \beta}$	4.45	15.07	11.49	35.61	14.20
	Alveolar Ridge	$8.96^{A, a, 1, \alpha}$	1.80	8.66	5.96	15.34	8.22
	Vestibular Ridge	$29.13^{B, c, 1, \gamma}$	7.43	28.92	17.63	45.72	26.06
	Palate	$15.40^{B, b, 1, \beta, \gamma}$	5.53	13.70	8.03	31.16	13.11
	Posterior Seal	$23.49^{A, c, 1, 2, \gamma}$	9.61	21.17	11.90	43.58	19.53
	Border	$35.50^{B, d, 1, \beta, \gamma}$	6.20	35.61	22.94	46.47	32.94
TR3	*Complete Surface*	$29.94^{D, a, 1, \alpha}$	5.82	28.47	20.03	42.90	27.54
	Alveolar Ridge	$27.67^{C, a, 2, \alpha}$	15.88	27.87	15.88	43.05	25.30
	Vestibular Ridge	$27.02^{B, a, 1, \alpha, \beta}$	9.60	24.35	14.83	56.47	23.06
	Palate	$48.32^{D, b, 2, \beta}$	19.40	43.81	23.31	100.3	40.31
	Posterior Seal	$42.36^{B, b, 2, \beta}$	16.97	35.03	24.67	97.07	35.35
	Border	$48.97^{C, b, 1, \alpha, \beta}$	11.39	48.95	29.01	77.80	44.26
D8I	*Complete Surface*	$7.95^{A, a, 1, \alpha}$	4.75	5.84	4.18	23.67	5.99
	Alveolar Ridge	$7.61^{A, a, 2, \alpha}$	4.08	5.80	3.98	17.01	5.93
	Vestibular Ridge	$12.68^{A, a, b, 1, \alpha, \beta, \gamma}$	8.79	10.32	5.26	48.96	9.05
	Palate	$9.11^{A, a, b, 1, \alpha, \beta}$	6.23	6.20	3.53	25.95	6.54
	Posterior Seal	$18.88^{A, b, c, 2, \gamma}$	15.20	11.04	6.62	61.39	12.60
	Border	$20.22^{A, c, 1, \beta, \gamma}$	8.70	21.87	10.02	46.54	16.63

Superscript upper-case letters indicate significant differences in trueness between different digitalization methods

Superscript lower-case letters indicate significant differences in trueness between areas

Superscript numbers indicate significant differences in precision between different digitalization methods

Superscript Greek lowercase letters indicate significant differences in precision between different areas

Table 2 *P*-values for trueness of digitalization method

	Complete Surface					*Palate*			
	PRI	TR4	TR3	D8I		PRI	TR4	TR3	D8I
PRI		0.008	< 0.001	< 0.001	PRI		< 0.001	0.011	< 0.001
TR4	0.008		< 0.001	< 0.001	TR4	< 0.001		< 0.001	0.002
TR3	< 0.001	< 0.001		< 0.001	TR3	0.011	< 0.001		< 0.001
D8I	< 0.001	< 0.001	< 0.001		D8I	< 0.001	0.002	< 0.001	
	Alveolar Ridge					*Posterior Seal*			
	PRI	TR4	TR3	D8I		PRI	TR4	TR3	D8I
PRI		< 0.001	< 0.001	< 0.001	PRI		0.983	< 0.001	0.702
TR4	< 0.001		< 0.001	0.440	TR4	0.983		< 0.001	0.578
TR3	< 0.001	< 0.001		< 0.001	TR3	< 0.001	< 0.001		< 0.001
D8I	< 0.001	0.440	< 0.001		D8I	0.702	0.578	< 0.001	
	Vestibular Ridge					*Border*			
	PRI	TR4	TR3	D8I		PRI	TR4	TR3	D8I
PRI		< 0.001	< 0.001	0.249	PRI		0.147	< 0.001	< 0.001
TR4	< 0.001		0.821	< 0.001	TR4	0.147		< 0.001	< 0.001
TR3	< 0.001	0.821		< 0.001	TR3	< 0.001	< 0.001		< 0.001
D8I	0.249	< 0.001	< 0.001		D8I	< 0.001	< 0.001	< 0.001	

Table 3 *P*-values for the precision of digitalization method

	Complete Surface					*Palate*			
	PRI	TR4	TR3	D8I		PRI	TR4	TR3	D8I
PRI		0.143	0.303	0.644	PRI		0.001	0.237	0.003
TR4	0.143		0.025	0.319	TR4	0.001		< 0.001	0.606
TR3	0.303	0.025		0.163	TR3	0.237	< 0.001		< 0.001
D8I	0.644	0.319	0.163		D8I	0.003	0.606	< 0.001	
	Alveolar Ridge					*Posterior Seal*			
	PRI	TR4	TR3	D8I		PRI	TR4	TR3	D8I
PRI		0.023	0.021	0.261	PRI		0.229	0.004	0.007
TR4	0.023		< 0.001	0.001	TR4	0.229		0.033	0.060
TR3	0.021	< 0.001		0.089	TR3	0.004	0.033		0.692
D8I	0.261	0.001	0.089		D8I	0.007	0.060	0.692	
	Vestibular Ridge					*Border*			
	PRI	TR4	TR3	D8I		PRI	TR4	TR3	D8I
PRI		0.507	0.294	0.896	PRI		0.823	0.032	0.179
TR4	0.507		0.558	0.508	TR4	0.823		0.010	0.069
TR3	0.294	0.558		0.312	TR3	0.032	0.010		0.267
D8I	0.896	0.508	0.312		D8I	0.179	0.069	0.267	

similar setup Osman et al. determined the size of scanning window to affect the precision of the generated dataset [29]. Apart from hardware differences, the older algorithm utilized for image superimposition and processing may account for the poorer accuracy observed for TR3. This is in accordance with the conclusions of Schmalz et al. who found higher deviations for the digitalization with Trios 3 compared to Trios 4 [39]. Conversely, a previous investigation conducted on an edentulous cadaver maxilla found no differences in trueness and precision between Cerec Primescan, Trios 4 and Trios 3 when the same software version has been installed [40].

The second null hypothesis predicting no significant differences between the different areas of the maxillary model must be also rejected. IOS demonstrated higher trueness in *Alveolar Ridge*, which may be attributed to the scan strategy initiating at the maxillary ridge. Similarly, Zarone et al. concluded for edentulous anatomy that an early recording of areas which negatively influence the stitching process can reduce the scanning accuracy [41]. Furthermore, the distinctive morphological features of the edentulous ridge facilitated a more precise image alignment by the algorithm compared to other anatomical regions [42]. By contrast, Gutmacher et al. attributed the superior trueness of IOS digitalization for the palate in comparison to the ridge to the lower resilience of the tissue, presence of rugae, and smaller area but found no significant differences in precision [40]. The improved accuracy of PRI at the *Vestibular Ridge* can be attributed to the "Smart Sensor" technology. This component employs a rapidly moving lens to acquire a large number of images, varying focus in a small amount of time, increasing the scanning depth range enabling efficient correction of the abrupt depth variations in this area [43].

Irrespective of digitalization method *Border* demonstrated the poorest trueness, possibly due to the steep and narrow geometry of the area, which limits access for optical systems and can result in distortion or voids in the generated dataset. In addition, the *Border* is a smooth and rounded surface and lacks distinctive characteristics that may be used by the superimposition algorithm. In congruence with current results, Al Hamad et al. reported higher deviations for the peripheral areas scanned with Trios 4 [44].

In the current study a "localized best fit" alignment was applied on the surface of defined spherical geometries, while all other areas were excluded for the alignment. This method was chosen to ensure that possible disadvantages of the methodology – such as the distribution of local discrepancies over the entire dataset and the underestimation of true inaccuracies – would be minimized [26, 45]. Furthermore, the absolute value of surface point distances between datasets was used to avoid neutralization of error through averaging of positive and negative values [45, 46]. With the current set up it is possible to quantitatively evaluate and compare trueness and precision for different areas of the edentulous maxilla, which was previously mainly assessed by use of color-coded superimposition graphs [12, 23, 28, 29, 42].

The current results must be assessed considering the study design limitations. Firstly, a maxillary PEEK model was used with different reflective properties than oral mucosa. This may potentially bias the results in favor of optical systems [47]. Additionally, the examination was conducted in vitro.

Table 4 *P*-values for trueness of digitalized area

	PRI					
	Complete Surface	*Alveolar Ridge*	*Vestibular Ridge*	*Palate*	*Posterior Seal*	*Border*
Complete Surface		0.014	0.397	0.003	0.852	< 0.001
Alveolar Ridge	0.014		0.999	< 0.001	0.012	< 0.001
Vestibular Ridge	0.397	0.999		< 0.001	0.124	< 0.001
Palate	0.003	< 0.001	< 0.001		0.032	0.997
Posterior Seal	0.852	0.012	0.124	0.032		0.003
Border	< 0.001	< 0.001	< 0.001	0.997	0.003	
	TR4					
	Complete Surface	*Alveolar Ridge*	*Vestibular Ridge*	*Palate*	*Posterior Seal*	*Border*
Complete Surface		< 0.001	< 0.001	0.977	0.015	< 0.001
Alveolar Ridge	< 0.001		< 0.001	< 0.001	< 0.001	< 0.001
Vestibular Ridge	< 0.001	< 0.001		< 0.001	0.207	0.022
Palate	0.997	< 0.001	< 0.001		0.021	< 0.001
Posterior Seal	0.015	< 0.001	0.207	< 0.001		< 0.001
Border	< 0.001	< 0.001	0.022	0.009	< 0.001	
	TR3					
	Complete Surface	*Alveolar Ridge*	*Vestibular Ridge*	*Palate*	*Posterior Seal*	*Border*
Complete Surface		0.735	0.782	0.001	0.019	< 0.001
Alveolar Ridge	0.735		1.000	< 0.001	0.004	< 0.001
Vestibular Ridge	0.782	1.000		< 0.001	0.004	< 0.001
Palate	0.001	< 0.001	< 0.001		0.855	1.000
Posterior Seal	0.019	0.004	0.004	0.855		0.592
Border	< 0.001	< 0.001	< 0.001	1.000	0.592	
	D8I					
	Complete Surface	*Palate*	*Vestibular Ridge*	*Palate*	*Posterior Seal*	*Border*
Complete Surface		1.000	0.194	0.975	0.021	< 0.001
Alveolar Ridge	1.000		0.121	0.913	0.015	< 0.001
Vestibular Ridge	0.194	0.121		0.567	0.499	0.041
Alveolar Ridge	0.975	0.913	0.567		0.057	< 0.001
Posterior Seal	0.021	0.015	0.499	0.057		0.999
Border	< 0.001	< 0.001	0.041	< 0.001	0.999	

However, in clinical settings, factors like saliva, soft tissue mobility, patient movement, as well as spatial limitations can negatively impact the digitalization accuracy for IOS [48]. Additionally, this study focused exclusively on the accuracy of digitizing the edentulous maxilla. The larger area of attached tissues in the palate provides more information for image superimposition, enhancing the scanning accuracy [31]. Further research in a similar set up should be directed also on the digitalization of edentulous mandibles. Furthermore, the present study investigated only the procedure of data acquisition and not the complete manufacturing procedure.

The accuracy threshold necessary for the fabrication of complete dentures is accepted to be within the range of 300—500 µm and pertains to the compressibility of intraoral mucosa [12, 22, 27, 49]. Deviations between the intaglio surface of final prosthesis and the edentulous anatomy within the range of mucosal thickness can be absorbed by the underlying tissues. Larger discrepancies may result in sore spots, insufficient fit, and instability [14, 21]. Presently all investigated methods exhibited accuracy well below the aforementioned value, in accordance with the findings of contemporary research [12, 13, 21, 22, 27, 41]. Regardless of the method, digitalization of the edentulous maxilla produced higher deviations in the peripheral areas of the anatomy, namely *Border* and *Palatal Seal*. Consequently, for CAD/CAM dentures incongruencies between base and the supporting tissue are expected to be more pronounced in the periphery, where corrections or even a reline may be more frequently necessary. Furthermore, for CAD/CAM workflows that require the superimposition of additional data (e.g. CBCT scans, digital set ups, bite rims) with datasets acquired through direct digitalization, a matching over the edentulous ridge may be more reliable than including areas of the palate [50–52]. Bearing in mind the possible

Table 5 *P*-values for precision of digitalized area

PRI						
	Complete Surface	*Alveolar Ridge*	*Vestibular Ridge*	*Palate*	*Posterior Seal*	*Border*
Complete Surface		0.065	0.147	< 0.001	0.070	0.347
Alveolar Ridge	0.065		0.007	< 0.001	0.002	0.021
Vestibular Ridge	0.147	0.007		0.013	0.745	0.841
Palate	< 0.001	< 0.001	0.013		0.024	0.010
Posterior Seal	0.070	0.002	0.745	0.024		0.610
Border	0.347	0.021	0.841	0.010	0.610	
	TR4					
	Complete Surface	*Alveolar Ridge*	*Vestibular Ridge*	*Palate*	*Posterior Seal*	*Border*
Complete Surface		0.165	< 0.001	0.104	< 0.001	0.021
Alveolar Ridge	0.165		< 0.001	< 0.001	< 0.001	< 0.001
Vestibular Ridge	< 0.001	< 0.001		0.014	0.128	0.185
Palate	0.104	*< 0.001*	0.014		0.008	0.456
Posterior Seal	*< 0.001*	*< 0.001*	0.128	0.008		0.036
Border	0.021	*< 0.001*	0.185	0.456	0.036	
	TR3					
	Complete Surface	Alveolar Ridge	Vestibular Ridge	Palate	Posterior Seal	Border
Complete Surface		0.774	0.089	*< 0.001*	*< 0.001*	0.006
Alveolar Ridge	0.774		0.063	< 0.001	*< 0.001*	0.004
Vestibular Ridge	0.089	0.063		0.005	0.022	0.324
Palate	*< 0.001*	*< 0.001*	0.005		0.528	0.033
Posterior Seal	*< 0.001*	*< 0.001*	0.022	0.528		0.120
Border	0.006	0.004	0.324	0.033	0.120	
	D8I					
	Complete Surface	Alveolar Ridge	Vestibular Ridge	Palate	Posterior Seal	Border
Complete Surface		0.809	0.231	0.220	*< 0.001*	*0.002*
Alveolar Ridge	0.809		0.169	0.123	< 0.001	*< 0.001*
Vestibular Ridge	0.231	0.169		0.721	0.006	0.270
Palate	0.220	0.123	0.721		*< 0.001*	0.054
Posterior Seal	*< 0.001*	*< 0.001*	0.006	< 0.001		0.027
Border	*0.002*	< 0.001	0.270	0.054	0.027	

advantages and limitations discussed, direct digitalization remains practical in procuring data for preliminary impressions, digital set up or simulation of prosthetic treatment, and implant planning [52–54]. In addition, digitalization by IOS can be a reliable method for the fabrication of immediate dentures, since peripheral and palatal seal are going to be relined after a period of tissue remodeling [55, 56]. IOS are also indicated when conventional impressions are hindered by factors like a strong gag reflex or limited mouth opening [57, 58]. At the same time, in cases of excessive soft tissue mobility and flabby ridges, the intraoral digitalization without exerting any pressure can be considered as advantageous [13, 59]. Still, indirect digitalization of the impression seems to be the most reliable method for the acquisition of the edentulous anatomy, since it demonstrated the best results and includes information about the peripheral seal.

Conclusions

Considering the limitations of the current study, the following conclusions can be summarized for the digitalization of edentulous jaws:

- The digitalization of edentulous anatomy depends on the morphology of the scanned area. Areas with limited accessibility and unclear surface structure with sparse features generally show higher deviations in the virtual model dataset.
- The indirect digitalization of the impression seems to be still the most accurate and reliable method.
- Digitalization by IOS can be a reliable method for the fabrication of interims and immediate dentures.

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Declarations

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