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Error propagation from intraoral scanning to additive manufacturing of complete-arch dentate models: An *in vitro* study

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ABSTRACT

Objectives: To evaluate deviation propagation from data acquisition with an intraoral scanner to additive manufacturing of complete-arch dentate models.

Methods: A reference (Ref) mandibular dentate model having 5 precision spheres was scanned with a coordinate measurement machine equipped with a laser scanning head (ALTERA; Nikon) producing a Ni reference data set ($n = 1$). Digital impressions were taken of the Ref model with intraoral scanner (IOS) (Trios4; 3Shape) with Insane (T4_Imo) and Classic (T4_Cmo) scanning modes (each $n = 10$). T4_Imo scans were used as a second reference data set and to produce test models with two additive manufacturing (AM) devices (each $n = 10$): MAX UV385 (Asiga) and NextDent 5100 (3DSystems). As for the control group, dual viscosity vinyl polysiloxane impressions were taken of the Ref model and poured with Type IV dental stone ($n = 10$). All AM and stone models were scanned with a laboratory scanner (E4; 3Shape). Trueness and precision of linear (intermolar and intercanine width, arch length) and surface deviations were measured between reference (Ni, T4_Imo), test (T4_Cmo, AM), and control (stone) groups using best-fit alignments (Geomagic Control X; 3D Systems). The normality of data and differences between the groups were analyzed using Shapiro-Wilk, Levene's, Mann-Whitney U, Welch's *t*-test statistical analysis ($p<0.05$).

Results: The accuracy of the IOS impression was not significantly affected by the scanning mode ($p>0.05$). Stone models showed significantly better trueness than IOS impressions ($p<0.05$). AM models had higher trueness than IOS Imo digital impressions ($p<0.05$). The precision of AM models was comparable (linear, $p>0.05$) or lower (surface, $p<0.05$) than of IOS Imo digital impressions. Trueness was insignificantly different among the stone and AM models ($p>0.05$). Higher trueness was achieved by Max UV385 than with Nextdent 5100 ($p<0.05$). The majority of linear and all surface deviations of IOS impressions and AM models were below 200 µm.

Conclusions: Within the limitations of this *in vitro* study, digital IOS impressions and AM models using the aforementioned equipment have acceptable accuracy for orthodontic and prosthodontic applications when complete-arch dentate records are used.

Clinical Significance: IOS and AM devices can have a significant influence on error propagation when applying digital workflow with complete-arch dentate models

1. Introduction

Accurate complete-arch dental models are required in prosthodontic and orthodontic procedures. They are used for initial case analysis, treatment planning, fabrication of dental restorations and appliances [1–3]. A limit of clinically acceptable deviations for complete-arch fully dentate models depends on the clinical purpose and different values were suggested in the literature - up to 200 µm for prosthodontic and up to 500 µm for orthodontic applications [2].

Selection of impression material and tray, disinfection,

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transportation, patient discomfort are some of the negative aspects associated with conventional impressions [4]. Furthermore, the production of dental stone models is labor-intensive [1]. They are prone to breakage, deformation, and storage occupies a significant amount of space [2,3,5]. Computer-aided design computer-aided manufacturing (CAD/CAM) technologies enabled the use of digital impressions and physical dental models which can be produced using subtractive and additive manufacturing devices.

The virtual dental model can be obtained by scanning a stone model with a laboratory scanner or by scanning the patient's dental arches directly with an intraoral scanner (IOS). IOS has many advantages over conventional impressions: less patient discomfort [6,7], ability to re-scan selected parts of the dental arch [8], time-efficiency [6,7], do not require stone model [8], better communication with dental technicians and patients [9].

To produce a physical dental model from the digital data, two manufacturing processes can be utilized: subtractive or additive. In contrast to subtractive, additive manufacturing (AM), also known as rapid prototyping, rapid manufacturing, 3D printing, generates less waste material, can produce more complex geometries, and is not limited to the diameter and wear of the burs [10,11]. Digital light processing (DLP) is one of the commonly used technologies in dentistry to manufacture resin models [1,2,12]. Liquid photopolymer in DLP device is cured by a projector light layer by layer until final object geometries are reached.

The accuracy of the final physical AM dental model is influenced by the accuracy of IOS impression and AM. Various factors may influence the accuracy of IOS scan: hardware [13,14], software [13,14], the experience of the operator [14,15], multiple clinical factors [14]. It was also shown, that scanning strategy and protocol might have a significant impact on accuracy [14,16,17]. Depending on the IOS manufacturer, a user can often choose between different scanning parameters, such as scanning depth [18], speed mode [19], resolution [19]. Then, accuracy is further affected by the factors related to additive manufacturing: hardware [20–23], model filling pattern [24–26], shell thickness [25–27], base design [25,26,28], support structures [29], build angle [29–31], placement on the build platform [24], layer-thickness [24], post-processing of the parts [32,33], photopolymer shrinkage [10,34], and other. Several studies show that AM models are unstable and accuracy decreases over time [10,34]. Since CAD/CAM technologies are rapidly progressing, there is a continuous need to evaluate the accuracy of available devices.

Best-fit alignment and 3D deviation analysis techniques as well as various linear measurements to evaluate the accuracy of virtual dental models are frequently used in the studies [23,28,35,36]. The linear measurements might be susceptible to the precision of landmark identification [3]. According to ISO 5725 standard, accuracy consists of two terms: trueness and precision [37]. Trueness is defined by "*the closeness of agreement between the average value obtained from a large series of test results and an accepted reference value*". While precision is explained by "*the closeness of agreement between independent test results obtained under stipulated conditions*". However, there are no reliable techniques to obtain true reference values of complete dental arch *in-vivo* [9,38,39]. Therefore, *in vitro* studies, true reference data is obtained by scanning a model with an industrial-grade scanner.

This *in vitro* study aimed to assess the error propagation when digital impressions of the complete dentate arch are taken and AM models are manufactured. A further aim was to compare the accuracy of digital and conventional methods of model production. The null hypothesis of this study was that IOS impressions and AM models were not significantly different from the reference and conventional stone models.

2. Materials and methods

2.1. Study design

An *in vitro* study design was chosen to evaluate the accuracy of the digitally and conventionally produced complete-arch dentate models. The study scheme is provided in Fig. 1.

2.2. Reference data set

To create a reference (Ref) model, a mandibular dentate practice model (ANA-4; Frasaco GmbH, Tettnang, Germany) was scanned and digitally modified by adding 5 sphere holders at the buccal aspect of the model base. The obtained file was used to additively manufacture a physical Ref model using MAX UV385 (Asiga, Sydney, Australia) AM device with DentaMODEL (Asiga) resin. Precision spheres (Micro Surface Engineering, Inc., Los Angeles, California) of 5 mm (± 1 μm) in diameter were attached to each of the sphere holders with self-curing acrylic resin (Pattern resin; GC America Inc., Alsip, IL, USA) (Fig. 2). After 4 weeks, the Ref model was firstly scanned with a coordinate measurement machine (CMM) equipped with an LC15Dx laser scanning head (ALTERA 10.7.6; Nikon, Shinagawa, Tokyo, Japan) (Fig. 3). Data were exported in standard tessellation language (STL) file format producing Ni data set ($n = 1$).

2.3. Digital workflow

Within 48 h after the CMM scanning, digital impressions were taken. Firstly, precision spheres of the Ref model were uniformly coated once with white occlusion spray (O-Spray; S&S Scheftner GmbH, Mainz, Germany). Digital impressions were taken with a Trios4 (3Shape, Copenhagen, Denmark, software 20.1.3) intraoral scanner (IOS). Insane (Imo) (T4_Imo) and Classic (Cmo) (T4_Cmo) scanning modes (each $n = 10$) were utilized. IOS scanning of the Ref model followed the manufacturer's instructions. IOS was calibrated before every 5 scans.

IOS Imo scanning data was imported to dental software (Dental Designer 2021 and Model Builder 2021; 3Shape) and complete-arch printable models were generated from each scan ($n = 10$). A horseshoe-shaped model base with a transverse supporting bar design was chosen. As for the filling pattern, models were made hollow with a minimum wall thickness of 2.5 mm. Physical models were then produced with MAX UV385 (Asiga, firmware 2020–11–13) and NextDent 5100 (3D Systems, Rock Hill, South Carolina, United States, firmware v1.1.2) AM devices (Fig. 4). DentaMODEL (Asiga) and Model 2.0 (3D Systems) resins were used respectively. Each model was positioned horizontally at the center of the build platform and manufactured in a separate print job with a 50 μm layer thickness. Both AM devices were calibrated before every 5 printings. AM and post-processing of the resin models strictly followed manufacturers' instructions. Support structures were removed before post-processing. After resting for 1 or 2 days at room temperature in a light-proof compartment, resin models were scanned with the calibrated laboratory scanner (E4; 3Shape) producing two STL data sets: AsMax ($n = 10$) and Nd ($n = 10$).

2.4. Conventional workflow

Immediately after the IOS, 10 conventional impressions were taken of the Ref model at room temperature with a 1-step custom tray technique (Fig. 5). Vinyl polysiloxane (VPS) impression materials of light and putty viscosity (Imprint 4; 3 M ESPE, St.Paul, Minnesota, USA) were used. The impressions were poured with Type IV dental stone (GC Fujirock EP; GC EUROPE N.V., Leuven, Belgium) after mixing under the vacuum (Fig. 6). Both impression-taking and pouring followed the manufacturers' guidelines. After complete-arch stone models were fully set, they were scanned with the calibrated laboratory E4 (3Shape) scanner ($n = 10$, An).

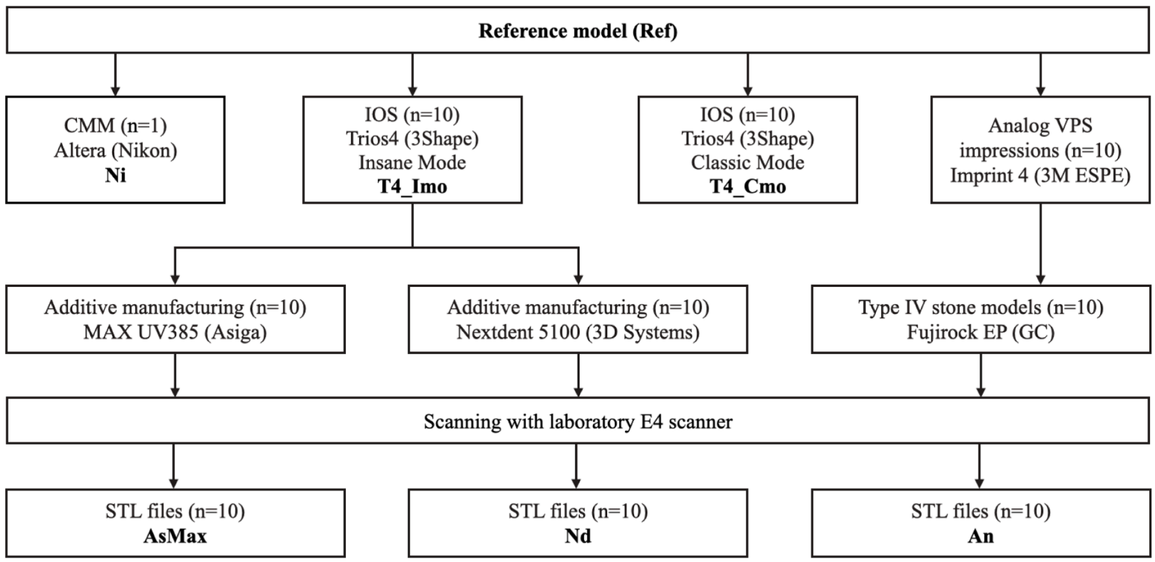

Fig. 1. Study scheme.

Fig. 2. Reference model.

2.5. Measurements

All scanning data sets were imported into metrology software (Geomagic Control X; 3D Systems) for trueness and precision evaluation. Linear distances between spheres' centers and 3D surface deviations were measured. Signed and unsigned values of deviations were recorded. Test models were stated to be undersized compared to the reference data set when average values were negative, and oversized when positive.

Surfaces in the digital models that resemble spheres were manually selected and the center points were automatically detected by the software. Six distances between spheres' center points were measured in each model (Fig. 7). Three linear measurements were calculated and compared statistically: intermolar width (IM, distance 1), intercanine width (IC, distance 6), and arch length (AL, distances 2 + 3 + 4 + 5).

As for the 3D surface deviation measurements, spheres and unnecessary areas located under the gingival margin were trimmed away (Fig. 8). Trimmed models were then superimposed using the best-fit alignment algorithm. RMS (root mean square) and Average values of surface deviations were recorded.

Five comparison categories were established (Table 1). To compare the trueness of two different AM devices, the T4_Imo data set was used as a reference. The other four comparisons used Ni data as a reference. For precision evaluation, pairwise comparisons were done using 10 models in each acquired data set. Precision evaluation for linear measurements was conducted using pairwise comparison within a data set in each of six distances thus the total number of comparisons from the same data set was $N = 6*(10–1)*10/2 = 270$. For 3D surface precision evaluation, models from the same data set were superimposed with one another in a non-repeating fashion. A total number of comparisons per group $n= (10–1)*10/2 = 45$.

2.6. Data analysis

Statistical analysis was performed with Python 3.8 programming language (Python software foundation, https://www.python.org) using SciPy library (version 1.5.2). For statistical analysis of linear and surface deviation, data were compared in five different categories consisting of two groups (Table 1). Trueness and precision data were compared between the groups. Mean and standard deviation (SD) values were presented for linear measurements and surface deviation data, additionally unsigned values for linear measurements were shown. For statistical comparison tests unsigned linear and surface deviation values were used. All groups were subjected to the Shapiro-Wilk normality test (α=0.05). To verify homogeneity of variance between groups Levene's test was used (α=0.05). For linear and surface deviation precision group comparison non-parametric Mann-Whitney U test was used (α=0.05). For trueness group comparison Welch's *t*-test was used (α=0.05).

3. Results

3.1. Linear deviation results

The signed and unsigned results of linear deviation trueness and precision measurements are shown in Tables 2–4 and Figs. 9–11. Shapiro-Wilk statistical test showed mostly normal distribution of unsigned trueness results and mostly not normal distribution of unsigned precision results. Statistical tests' p-values and differences (Δ, µm) between the groups of unsigned linear deviations are presented in Table 5.

The accuracy (precision and trueness) of the IOS (Trios4; 3Shape) impression dimensions were not significantly affected by the scanning

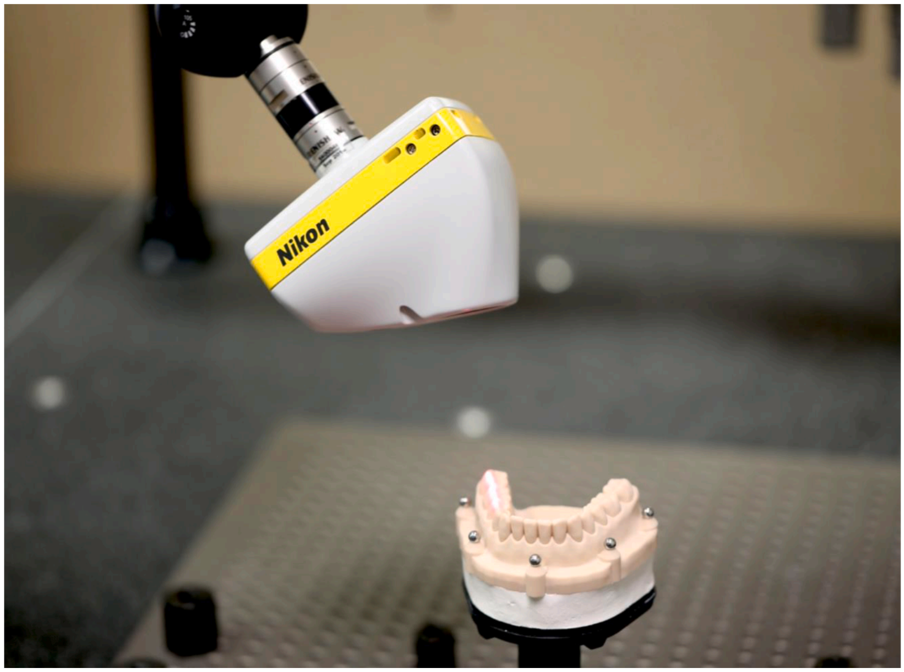

Fig. 3. Scanning with Nikon Altera.

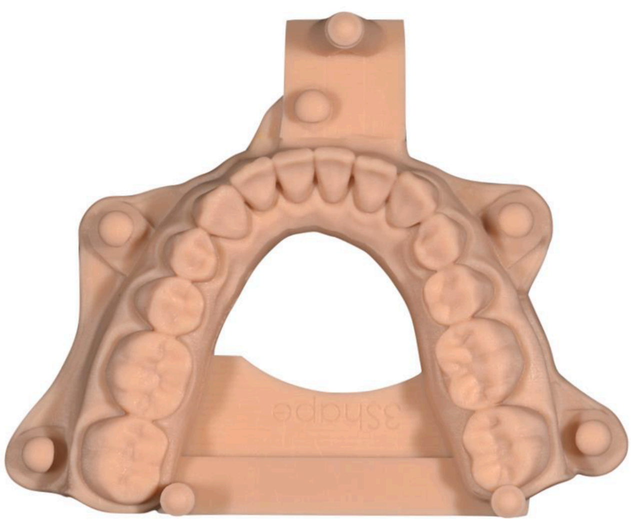

Fig. 4. AM model.

mode (p>0.05, Δ≤87 μm). When comparing stone models and IOS digital impressions, the accuracy of IC and IM was significantly higher in stone models (p = 0.00, Δ_{IM}≥104 μm). However, AL trueness was comparable between the IOS impressions and stone models (p>0.05, Δ≤21 μm). Some linear measurements had significantly higher trueness in AM models than in IOS Imo digital impressions when compared to reference data: IC and AL in the Asiga Max group (p ≤ 0.05, Δ≥63 μm) and IM in NextDent 5100 group (p = 0.01, Δ=154 μm). Precision was mostly insignificantly different between the AM models and IOS impressions (p>0.05, Δ≤26 μm). When comparing the accuracy of final physical models produced in an analog and digital ways, stone models had significantly better IM trueness (p = 0.00, Δ≥176 μm) and overall precision (p = 0.00, Δ≥33 μm) when compared to AM models. However, trueness deviations of IC and AL were insignificant between AM and stone models (p>0.05, Δ≤41 μm). When compared to IOS Imo digital impressions, there were insignificant IM and AL precision differences between the two evaluated AM devices (p>0.05, Δ≤7 μm). However,

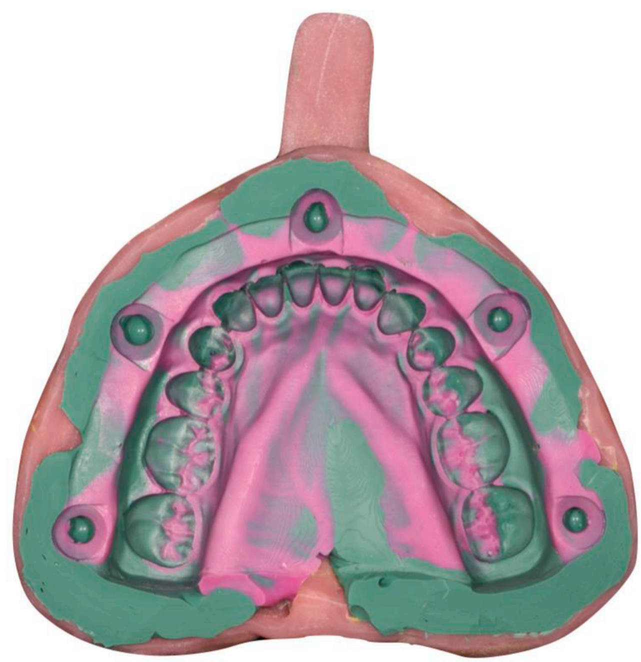

Fig. 5. VPS impression.

the trueness of Asiga Max UV385 was superior to that of NextDent 5100 (p = 0.00, Δ≥43 μm).

Deviations introduced by IOS have resulted in oversized digital impressions (Table 3). When compared to IOS digital impressions, AM has presented negative deviations and under-sizing of the models. When analyzing the whole digital workflow of producing physical dental models, it is evident that IM is still oversized, but the IC became undersized. AL depends on the AM device used: Asiga Max produced longer and NextDent 5100 shorter span arches. Stone models were also oversized when compared to the Ref model.

Fig. 6. Dental stone model.

3.2. Surface deviation results

The RMS and Average values of surface deviation trueness and precision measurements are shown in Tables 6, 7, and Figs. 12–14. Shapiro-Wilk statistical test showed mostly normal distribution of trueness RMS

Table 1
Comparison groups for accuracy evaluation. Each comparison made between Group 1 and Group 2.

Comparison Category	Group 1	Group 2
Scanning mode *	T4_Imo	T4_Cmo
IOS VS Analog *	T4_Imo T4_Cmo	An
IOS Imo VS AM *	T4_Imo	AsMax Nd
Analog VS AM *	An	AsMax Nd
AM **	AsMax	Nd

* Reference Ni.
** Reference T4_Imo.

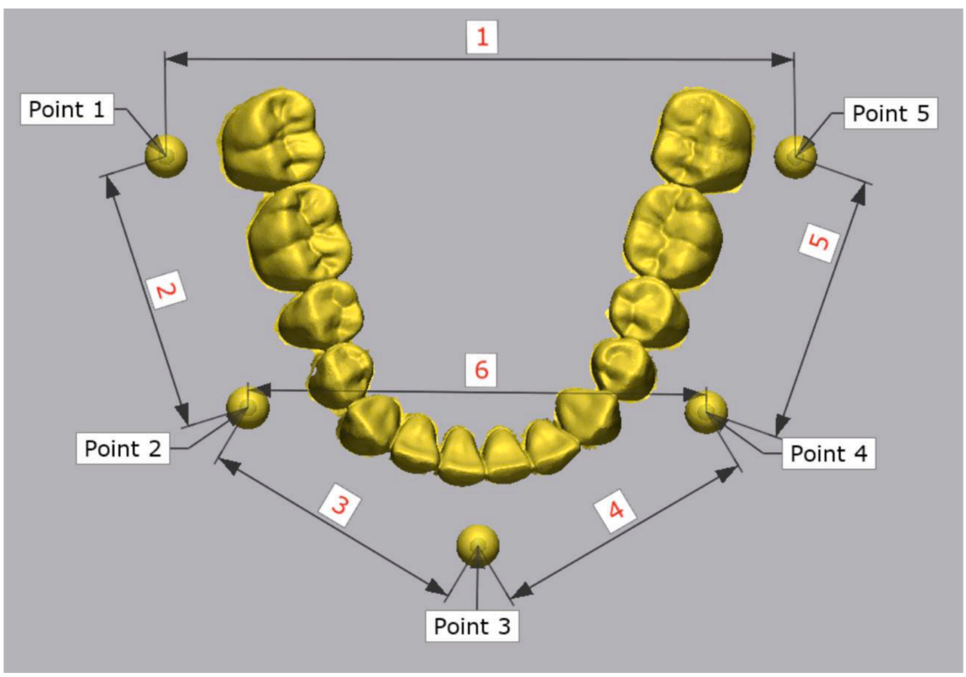

Fig. 7. Linear deviations and numeration (IM = 1, IC = 6, AL = 2 + 3 + 4 + 5).

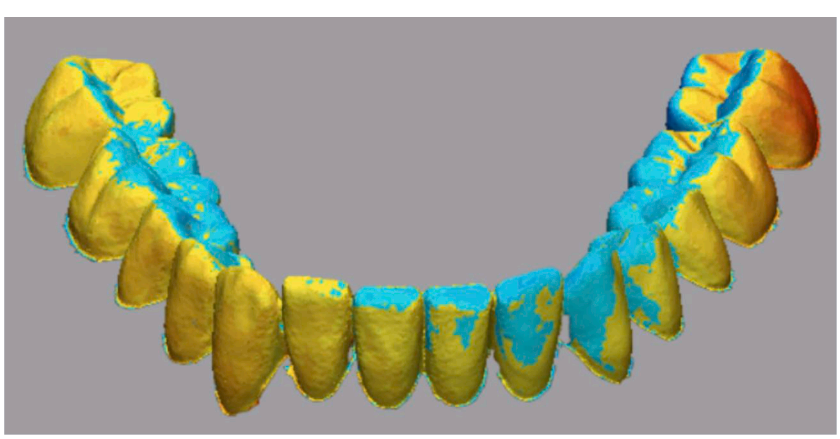

Fig. 8. 3D surface deviations.

Table 2
Trueness unsigned values (mean and SD) of the linear deviations.

Reference	Group	Distance (μm)		
		IM	IC	AL
Ni	T4_Cmo	329.3 (109.3)	116.2 (34.6)	161.0 (54.7)
	T4_Imo	416.4 (124.2)	123.6 (49.9)	199.7 (85.7)
T4_Imo	AsMax	48.1 (31.9)	159.4 (25.0)	85.6 (74.6)
	Nd	154.7 (71.6)	203.1 (40.0)	352.0 (79.7)
Ni	AsMax	368.3 (125.2)	51.3 (31.3)	136.9 (73.1)
	Nd	261.8 (132.6)	87.4 (59.2)	152.3 (102.4)
	An	85.7 (19.9)	58.1 (16.3)	177.9 (43.0)

Table 3
Trueness signed values (mean and SD) of the linear deviations.

Reference	Group	Distance (μm)		
		IM	IC	AL
	T4_Cmo	329.3 (109.3)	116.7 (32.8)	158.1 (52.7)
Ni	T4_Imo	416.4 (124.2)	123.6 (49.9)	199.7 (85.7)
T4_Imo	AsMax	−48.1 (31.9)	−159.4 (25.0)	−80.4 (80.7)
	Nd	−154.7 (71.6)	−203.1 (40.0)	−352.0 (79.7)
Ni	AsMax	368.3 (125.2)	−35.8 (49.6)	119.3 (101.5)
	Nd	261.8 (132.6)	−79.5 (70.3)	−152.3 (102.4)
	An	85.7 (19.9)	58.1 (16.3)	177.9 (43.0)

Table 4
Precision unsigned values (mean and SD) of the linear deviations.

Group	Distance (μm)		
	IM	IC	AL
T4_Cmo	128.8 (85.5)	41.5 (25.7)	61.1 (47.4)
T4_Imo	125.3 (95.6)	49.3 (31.7)	99.3 (70.7)
AsMax	135.7 (98.0)	52.8 (39.0)	126.3 (83.0)
Nd	142.6 (92.1)	70.3 (47.4)	118.4 (84.9)
An	21.1 (18.7)	19.3 (12.5)	51.1 (32.9)

results and mostly not normal distribution of precision RMS results. Statistical tests' p-values and differences (Δ, μm) between the groups of surface deviations are presented in Table 8.

No significant accuracy differences were seen between digital impressions produced with different Trios4 (3Shape) scanning modes (p>0.05, Δ≤10 μm). The trueness of stone models was significantly higher when compared to the IOS Imo digital impressions (p = 0.04, Δ=13 μm). However, the precision of stone models was significantly lower than IOS impressions (p = 0.00, Δ≥38 μm). When compared to the Ni data set, significantly better trueness was observed in AM models produced with NextDent 5100 than in IOS Imo digital impressions (p = 0.03, Δ=14 μm). Trueness was comparable between IOS Imo and Asiga Max groups (p = 0.33, Δ=7 μm). The precision of AM was significantly lower in both Asiga Max and NextDent 5100 groups than in the IOS Imo group (p = 0.00, Δ≥14 μm). The differences in surface trueness measurements were insignificant between stone and AM models (p>0.05, Δ≤6 μm). However, the precision of stone models was significantly lower than that of AM models (p = 0.00, Δ≥18 μm). Surface trueness is significantly affected by the model of AM devices. When compared to IOS Imo digital impressions, NextDent 5100 showed lower trueness than Asiga Max (p = 0.02, Δ=13 μm). However, precision was not significantly different among the groups of different AM devices (p = 0.15, Δ=7 μm).

Surface deviations introduced by the IOS have resulted in oversized digital impressions. AM has presented negative deviations and undersizing of the models. When evaluating the whole digital workflow of producing physical dental models by Surface Deviation analysis, it is evident that AM physical models were oversized when compared to the Ref model. AM did not fully compensate for the deviations introduced by the IOS. Similarly, oversized models were observed in the analog workflow as well.

4. Discussion

The current study aimed to analyze the accuracy of IOS impressions and AM complete-arch dentate mandibular models in comparison to the

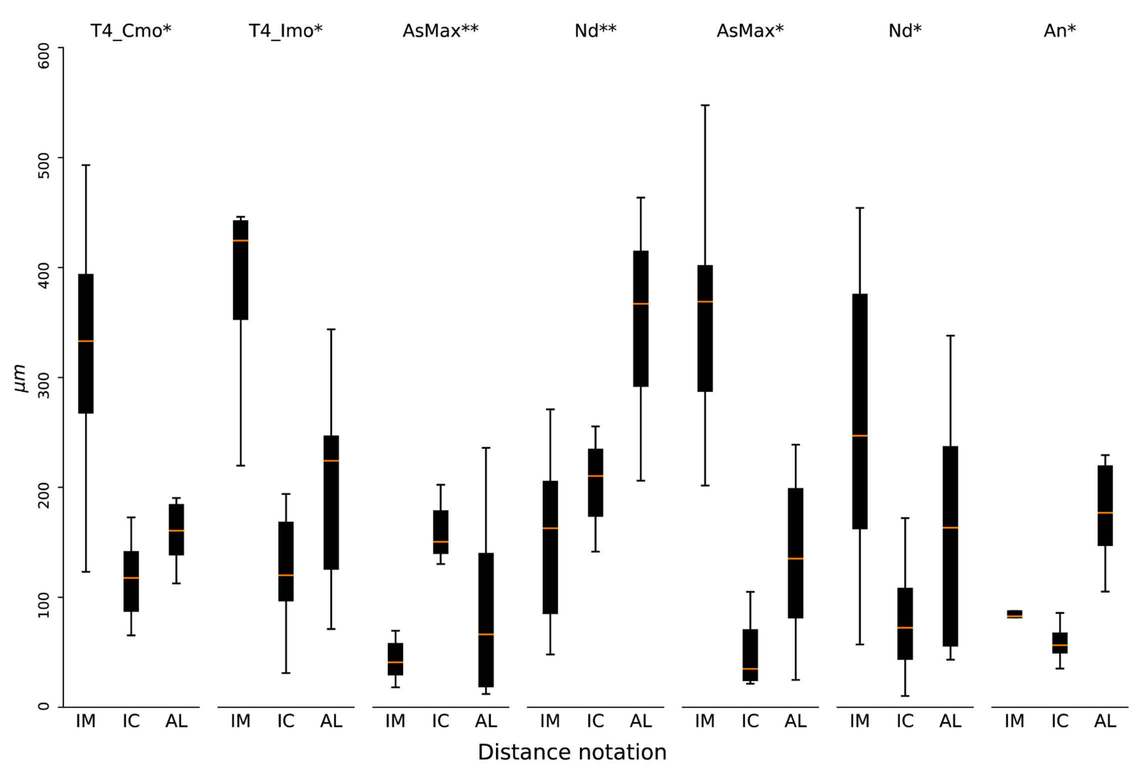

Fig. 9. Unsigned trueness values of intermolar (IM), intercanine (IC), and arch length (AL) linear deviation (without outliers).* - reference Ni, ** - reference T4_Imo.

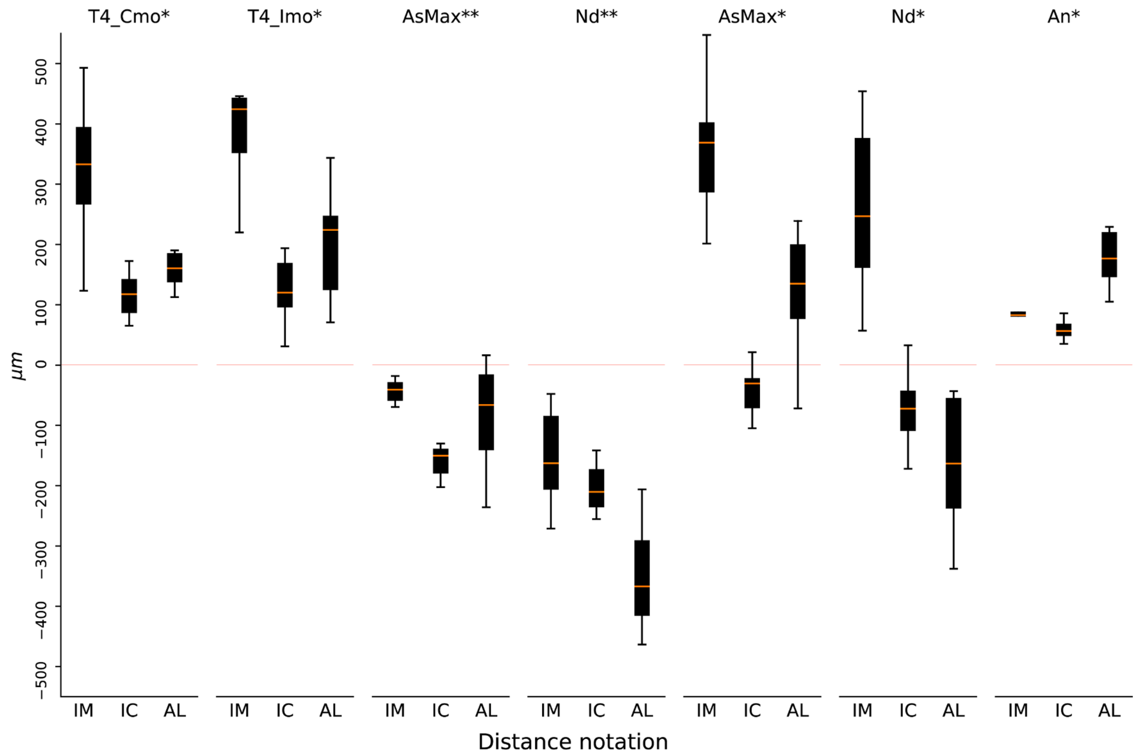

Fig. 10. Signed trueness values of intermolar (IM), intercanine (IC), and arch length (AL) linear deviation (without outliers). * - reference Ni, ** - reference T4_Imo.

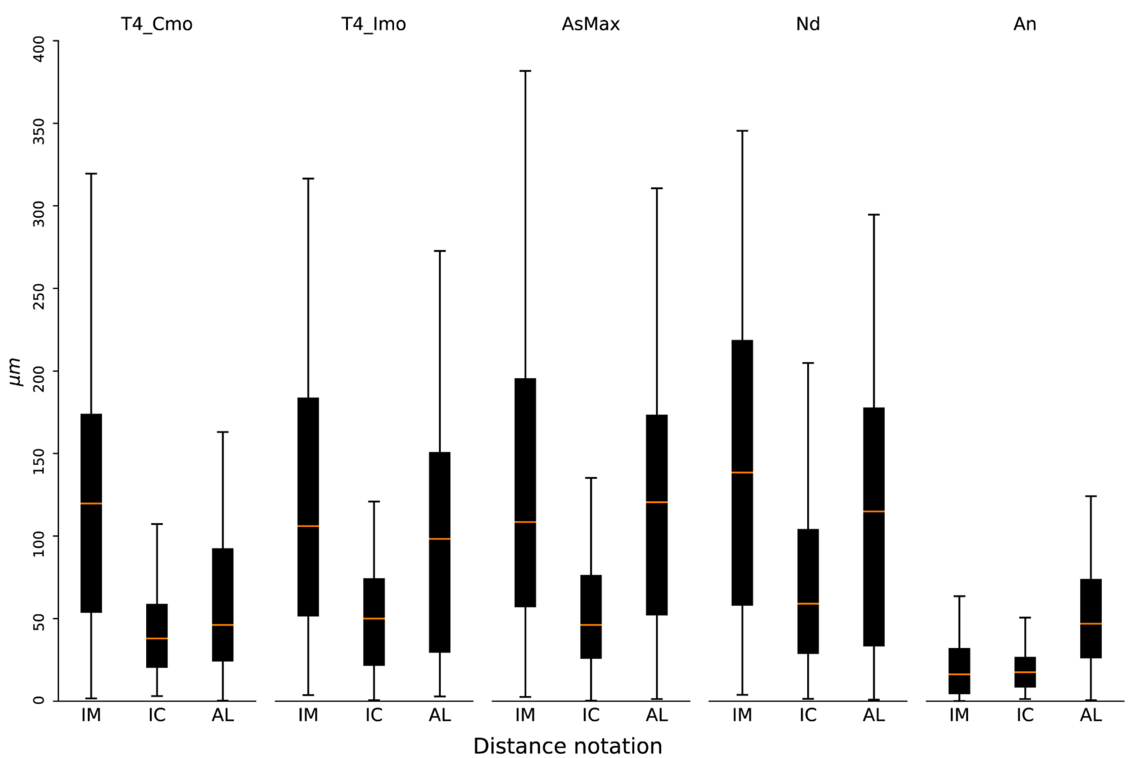

Fig. 11. Unsigned precision values of intermolar (IM), intercanine (IC), and arch length (AL) linear deviation (without outliers).

stone models. In the current study, stone models showed significantly better trueness than IOS impressions in most measurements and similar trueness to AM models (except for intermolar distance). Precision results are conflicting. Therefore, the null hypothesis that the trueness and precision of IOS impressions and AM models were not significantly different from conventional stone models was partially rejected.

Firstly, the accuracy of complete-arch IOS impression with Trios 4 (3Shape) was not significantly affected by the scanning mode (p>0.05). Complete arch digital impression with Insane scanning mode of Trios4 (3Shape) is more time-efficient and of comparable accuracy than the

Table 5
Unsigned linear deviation statistical tests' *p*-values and differences (Δ, μm) between the groups using mean (positive value showing higher deviations of Group 1).

Reference	Group 1	Group 2	Trueness						Precision					
			IM		IC		AL		IM		IC		AL	
			p	Δ	p	Δ	p	Δ	p	Δ	p	Δ	p	Δ
Ni	T4_Cmo	T4_Imo	0.09	−87	0.37	−7	0.13	−38	0.37	3	0.16	−7	0.00*	−38
Ni	T4_Cmo	An	0.00*	243	0.00*	58	0.14	−16	0.00*	107	0.00*	22	0.28	9
	T4_Imo		0.00*	330	0.00*	65	0.25	21	0.00*	104	0.00*	30	0.00*	48
Ni	T4_Imo	AsMax	0.16	48	0.00*	72	0.05*	63	0.31	−10	0.47	−3	0.08	−26
		Nd	0.01*	154	0.06	36	0.11	47	0.15	−17	0.02*	−21	0.17	−19
Ni	An	AsMax	0.00*	−282	0.19	7	0.09	41	0.00*	−114	0.00*	−33	0.00*	−75
		Nd	0.00*	−176	0.17	−29	0.38	25	0.00*	−121	0.00*	−51	0.00*	−67
T4_Imo	AsMax	Nd	0.00*	−106	0.00*	−43	0.00*	−266	0.33	−6	0.04*	−17	0.33	7

* $p \leq 0.05$.

Table 6
Trueness RMS and Average values (mean and SD) of the surface deviations.

Reference	Group	RMS	Average
	T4_Cmo	88.1 (9.5)	19.1 (1.0)
Ni	T4_Imo	98.5 (15.7)	21.9 (2.6)
	AsMax	41.7(5.7)	−0.8 (2.1)
T4_Imo	Nd	49.0 (6.2)	−2.1 (3.1)
	AsMax	91.8 (14.1)	21.6 (3.1)
Ni	Nd	84 (9.8)	20.5 (2.4)
	An	85.4 (8.8)	32.9 (3.3)

Table 7
Precision values (mean and SD) of the surface deviations.

Group	RMS	Average
T4_Cmo	46.4 (8.0)	0.1 (2.7)
T4_Imo	53.8 (19.3)	−1.1 (6.2)
AsMax	74.4 (28.3)	−0.3 (6.7)
Nd	67.7 (21.1)	−2.5 (5.7)
An	92.2 (17.3)	−4.0 (8.4)

Classic mode. To the best of the authors' knowledge, no studies have evaluated this factor so far.

Stone models showed significantly better IC and IM accuracy than IOS impressions of either scanning mode ($p = 0.00$), but AL trueness was comparable ($p>0.05$). Moreover, stone models presented higher surface trueness when compared to T4_Imo ($p = 0.04$, Δ=13 μm). Precision comparison between stone and IOS models showed conflicting results. The highest deviations in IOS digital impressions were seen in the IM distance which ranged from 100 μm to 500 μm. It could be explained that each scanning frame is stitched together and errors accumulate at the most distant part of the arch [40]. Therefore, the use of IOS for long-span prosthodontic work might be challenging, but the accuracy is sufficient for orthodontic applications [3,8,9]. However, different results could be expected when using other commercially available hardware [8,41]. In a recent study by Nulty [42], different surface accuracy results were observed between nine IOS, but the mean trueness deviations were below 60 μm.

The trueness of AM models was comparable to or higher than IOS Imo digital impressions when the Ref model was taken as a reference. AM with Max UV385 (Asiga) significantly improved the trueness of IC (Δ=72 μm) and AL (Δ=63 μm). On the other hand, Nextdent 5100 produced models with higher IM (Δ=154 μm) and surface (Δ=14 μm) trueness. The precision of AM models was comparable (linear, $p>0.05$) or lower (surface, $p = 0.00$) than of IOS Imo impressions. If IOS

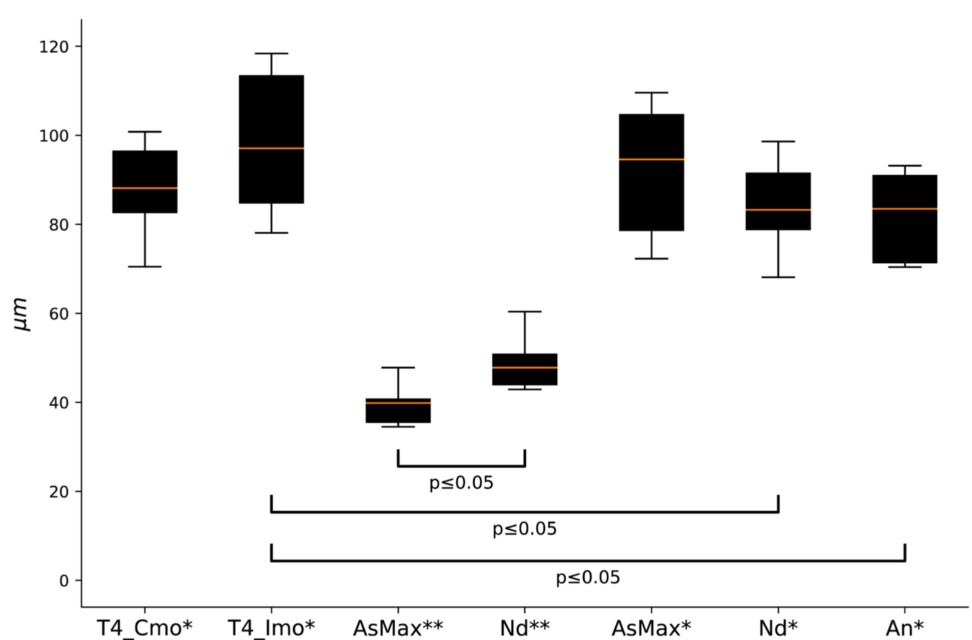

Fig. 12. Trueness RMS values of surface deviation (without outliers). Lines connecting data imply a significant difference ($p<0.05$) between them. * - reference Ni, ** - reference T4_Imo.

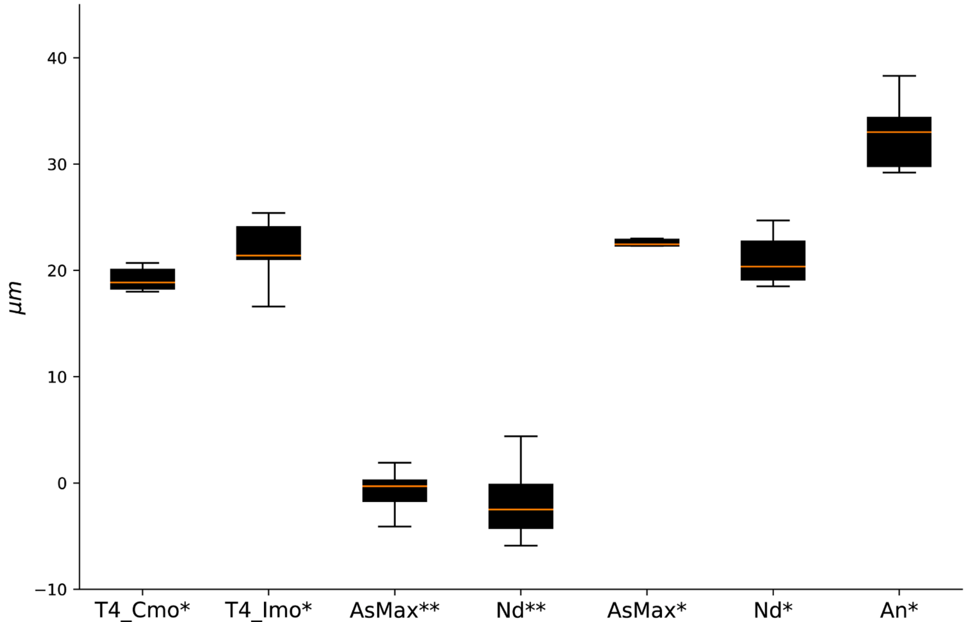

Fig. 13. Trueness Average values of surface deviation (without outliers). * - reference Ni, ** - reference T4_Imo.

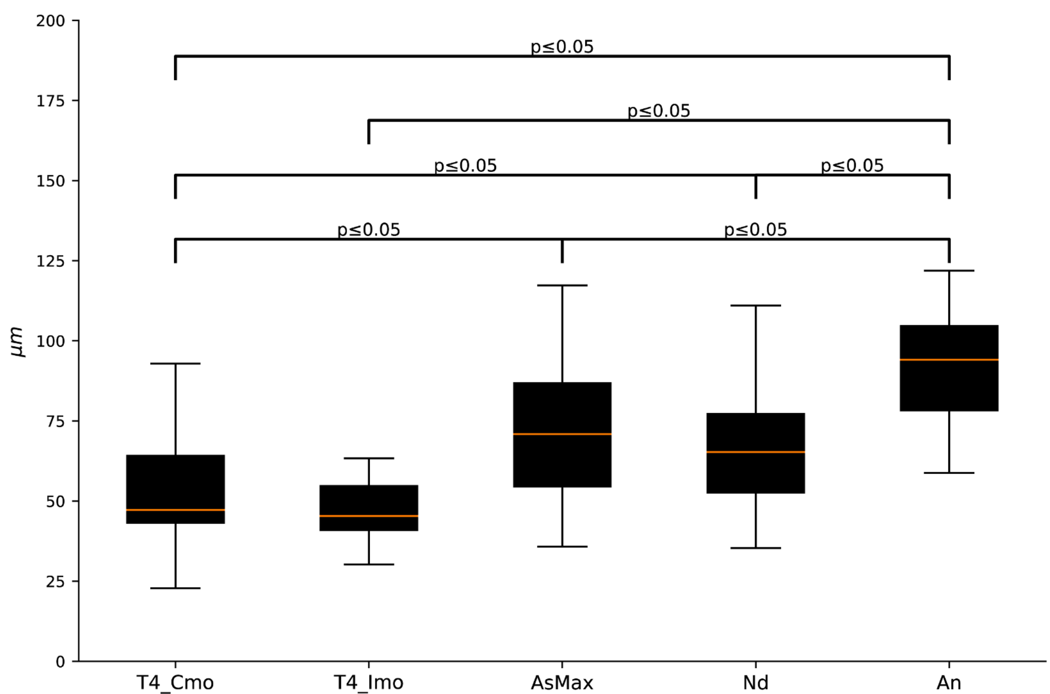

Fig. 14. Precision RMS values of surface deviation (without outliers). Lines connecting data imply a significant difference ($p<0.05$) between them.

(reference Ni) and AM (reference T4_Imo) steps are compared separately, considerably higher deviations in linear and surface trueness were presented by IOS rather than AM. On the contrary, AM introduced higher precision deviations than IOS in the digital workflow. Considering the signed values, IOS produced oversized digital impressions while AM shrank the dimensions resulting in partial compensation of the deviations introduced by the IOS. Similarly, in the study by Ellakany et al. [43] AM also reduced the errors which were introduced with IOS. The contraction effect of the AM models produced with vat polymerization techniques was reported by other authors as well [5,20,22,44,45]. The incomplete polymerization of the layers by the AM device and the need for post-processing of the resin models could be the primary reason for shrinkage and warpage effect [22]. The most accurate distance reproduced by AM (reference T4_Imo) was intermolar width. Theoretically, if AM models were designed without the transverse supporting bar, the polymer shrinkage at the posterior regions of the model could have further improved the trueness.

Accuracy comparison of the whole analog and digital workflow showed similar trueness of the dental models. IC, AL, and surface trueness were insignificantly different among the stone and AM models ($p>0.05$). However, IM trueness was significantly higher in stone models ($p = 0.00$, $\Delta \geq 176$ µm). As for the precision, the two evaluation methods in the present study showed conflicting results. Since precision spheres on the Ref model were affected by occlusion spray, IOS frame stitching,

Table 8
Trueness and precision RMS surface deviation statistical tests' p-values and differences (Δ, μm) between the groups using mean (positive value showing higher deviations of Group 1).

Reference	Group 1	Group 2	Trueness		Precision	
			p	Δ	p	Δ
Ni	T4_Cmo	T4_Imo	0.09	−10	0.07	−7
Ni	T4_Cmo	An	0.52	3	0.00*	−46
	T4_Imo		0.04*	13	0.00*	−38
Ni	T4_Imo	AsMax	0.33	7	0.00*	−21
		Nd	0.03*	14	0.00*	−14
Ni	An	AsMax	0.24	−6	0.00*	18
		Nd	0.74	1	0.00*	25
T4_Imo	AsMax	Nd	0.02*	−13	0.15	7

* $p \leq 0.05$.

and AM deviations, surface precision evaluation could be considered more reliable, which shows inferior precision of stone models rather than AM ones ($p = 0.00$, $\Delta \geq 18$ μm). Findings of the trueness in the current study do not coincide with a systematic review of Etemad-Shahidi et al. [2] in which the majority of selected studies reported lower mean trueness error of the stone models rather than AM counterparts. However, comparable accuracy of the AM and conventional stone models was found in other studies as well [5,43]. Similarly as with IOS, the accuracy of the models is highly influenced by the AM system used [2,10,46]. Using other combinations of IOS and AM might determine different model accuracy results. In the study by Aly and Mohsen [36], Trios (3Shape) scanner and a ProJet 6000 (3D Systems) AM device produced dentate models with smaller IM (mean=19 μm, SD=10 μm) and IC (mean=21 μm, SD=7 μm) trueness error. When considering Average surface deviations, all model groups (IOS, AM, and stone) were oversized when compared to the Ni data set. Oversized final physical models were seen in most of the cases in a systematic review by Etemad-Shahidi et al. [2].

Finally, when the accuracy of models produced with two different AM devices was compared (reference T4_Imo), the higher surface and linear measurement trueness was achieved by Asiga Max UV385 rather than Nextdent 5100 ($p<0.05$, $\Delta \geq 13$ μm). Deviations introduced to IC and AL trueness by NextDent 5100 device are clinically significant for prosthodontic applications (>200 μm). On the other hand, precision between the groups was comparable ($p>0.05$). According to Camardella et al. [28], IM distance deviations are reduced when a transverse supporting bar is incorporated into the horseshoe-shaped model base design. Other studies that evaluated deviations introduced by AM devices with DLP technology confirm a clinically acceptable accuracy [24].

In the present study, the majority of linear and all surface deviations of both digital IOS impressions and physical AM models were less than 200 μm. The highest deviations were observed in the IM distance and arch length measurements of the digitally produced models, but they did not exceed the 500 μm error limit.

Among many possibilities to measure the accuracy of a dental model, linear and surface deviation measurements using computer software were employed in the present study. However, these methods are susceptible to additional accumulation of errors arising from landmark identification and model digitization [3,22]. To address this, precision spheres were fixed to the model base which allowed automatic center detection by the metrology software.

Some disadvantages in the measurement methods were inevitable. The surface accuracy of the precision spheres could have been altered by the occlusion spray and AM. Moreover, since the spheres were separate from the teeth, the position of the spheres could have been influenced by the frame stitching process of the IOS. However, the spheres and the nearest dental structures fitted into the same single IOS scanning frame and the gingiva in-between did not move.

Other limitations of this study include an *in vitro* study design, the use of a separate laboratory scanner, and a limited number of digital devices tested. Such *in vivo* factors as saliva, moving soft tissues, and limited area for scanner movement may further affect the accuracy of IOS [13,14]. Only one IOS and 2 AM devices were tested in the current study. However, there are a plethora of different combinations using other commercially available equipment.

5. Conclusions

Although it was an *in vitro* study and a limited number of hardware and software were tested, some conclusions can be drawn. The accuracy of IOS impression with Trios 4 (3Shape) was not significantly affected by the scanning mode. Stone models showed significantly better trueness than IOS impressions, but precision results are conflicting. AM compensates dental model deviations introduced by IOS and increases the trueness. The precision of AM models is comparable to or lower than of IOS impressions. The trueness of digital and analog workflow of producing complete-arch dentate models is insignificantly different, but precision results are conflicting. The significantly higher trueness was achieved by Asiga Max UV385 than with Nextdent 5100. Precision was comparable between the two devices. Complete-arch dental models produced in a digital way using the aforementioned equipment have clinically acceptable accuracy for orthodontic and prosthodontic applications when complete-arch dentate records are required. Further *in vitro* and *in vivo* studies evaluating new AM equipment, with more precise landmark identification methods and more accurate scanners to digitize the test models are needed.

CRediT authorship contribution statement

Liudas Auškalnis: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Visualization, Project administration. **Mykolas Akulauskas:** Data curation, Formal analysis, Visualization. **Darius Jegelevičius:** Methodology, Formal analysis, Supervision. **Tomas Simonaitis:** Data curation, Investigation. **Vygandas Rutkūnas:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – review & editing, Visualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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