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Accuracy Analysis of Extraoral 3D Scanning in Dental Prosthetic

Analiza točnosti ekstraoralnoga 3D skeniranja u dentalnoj protetici

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Abstract

Objective: The study has evaluated the accuracy (trueness and precision) of seven extraoral scanners when scanning two different types of jaws: simplified jaw with sharp edges and abutments and realistic jaw with natural teeth. The accuracies of extraoral scanners were compared, and their compliance with the required clinical accuracy levels was discussed. **Material and methods:** Ten scans were made with each scanner for both models. The comparison of the selected dental scanners relied on reference scans made for both models. Trueness, precision, and the distribution and value of laboratory scan points' deviations were assessed for each scanner across the models. **Results:** The trueness for the model of the simplified jaw with abutments ranged from 16.15 to 49.78 µm. The measured precision values for the same model ranged from 4.33 to 29.49 µm. For the model of the realistic jaw with natural teeth, the trueness results ranged from 11.32 to 24.55 µm, while the obtained precision values were between 2.29 and 18.06 µm. **Conclusion:** The revealed dissimilarities in the accuracies of scanners and their ranking when scanning different models lead to the conclusion that model selection is critical for the research design. All the scanners met the clinical accuracy requirements and are suitable for use in laboratories for scanning jaws with abutments and jaws with natural teeth. However, the accuracy values reported by the manufacturers of scanners are better than those obtained in this study. Furthermore, the results suggested that blue light scanners outperform white light and laser scanners.

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Introduction

The introduction of digital technologies has greatly impacted the dental industry in recent decades (1–4). CAD/CAM systems have been introduced in a variety of dental offices, laboratories, and production centers due to the emergence of new materials suitable for industrial production (1, 2, 5, 6). These systems enabled a reduction of the production time, an increase in productivity (6), and an improvement in dimensional reliability. Therefore, the introduction of the CAD/CAM systems has enabled the time- and cost-effective production of individual prosthetic replacements (3).

CAD/CAM systems consist of three basic components: 3D scanner, computer software, and production technology (3). The 3D scanner converts the geometry of a prepared tooth or an entire jaw into a digital shape, based on which a prosthetic replacement is designed. Next, the software derives a CAD model of a prosthetic replacement according to the geometry of the obtained digital shape. Finally, the de-

Uvod

Uvođenje digitalnih tehnologija znatno je utjecalo na stomatološku industriju tijekom posljednjih desetljeća (1 – 4). Zbog pojave novih materijala pogodnih za industrijsku proizvodnju, CAD/CAM sustavi uvedeni su u različite stomatološke ordinacije, laboratorije i proizvodne centre (1, 2, 5, 6). Ti su sustavi smanjili vrijeme potrebno za proizvodnju, povećali produktivnost (6) i poboljšali dimenzijsku pouzdanost. Posljedično uvođenje CAD/CAM sustava omogućilo je brzu i isplativu izradu pojedinačnih protetičkih nadomjestaka (3).

CAD/CAM sustavi sastoje se od triju osnovnih komponenti: 3D skenera, računalnog alata i proizvodne tehnologije (3). 3D skenerom prebacuje se geometrija pripremljenoga zuba ili cijele čeljusti u digitalni oblik na osnovi kojega se dizajnira protetički nadomjestak. Poslije toga se računalnim alatom oblikuje njegov CAD model prema geometriji prije dobivenoga digitalnog oblika. Konačno, prema pripremljesigned CAD model is used to prepare the code for production (CAM process).

3D scanners for dental use are classified as intraoral and extraoral. Scanning represents the first step in designing and producing individual prosthetic replacements (7). Thus, scanner accuracy is a vital prerequisite for the final product quality. If the model's surface is scanned with insufficient accuracy, the obtained product will have wrong measurements and shape, thus causing cement loosening (8, 9) and potentially leading to periodontal diseases (10, 11), secondary caries (12), or microleakage (13).

Numerous studies evaluated the accuracy of 3D scanners for dental use (14–27). In these studies, the accuracy of scanners is commonly assessed with regards to trueness and precision. Trueness is defined as the deviation of the object's scanned dimensions from its actual dimensions, whereas precision is regarded as either the deviation of dimensions between multiple scans of a particular object (21) or as the deviation of dimensions within an individual scan (22). High trueness signals that the scanner produces the scans very close to the actual dimensions of the scanned object. High precision indicates that the scanner gives reproducible scan results.

Previous studies utilized various validation methods and metrics for trueness and precision, hampering comparisons across different studies. Furthermore, the existing studies assessed the accuracy of scanners using models of different shapes and materials. For example, scanners achieved better accuracy when scanning a single tooth or prepared tooth models than when the entire jaw model was scanned (17).

Extraoral scanners generally have better accuracy than intraoral scanners, which varies less along the dental arch (28). In addition, the accuracy of intraoral scanners is inadequate for scanning edentulous arches with implants (29). These distinctions stem from differences in scanning technologies. Intraoral scanners capture images or videos while moving along the arc of the dental arch (30), as opposed to extraoral scanners, which capture the entire dental arch positioned at different angles. Individual images are then combined to obtain a virtual 3D model (31). The software recognizes common points in the images, that is, two coordinates of each point (x and y) are estimated in the figure. In contrast, the z-coordinate is determined independently by calculating the object's distance from the cameras. The z-coordinate estimation results in errors that further propagate through the process.

Sharp edges are another factor that may have a detrimental effect on the scanning quality. Previous studies highlighted the differences in the accuracy of scanners when scanning smooth surfaces in comparison to scanning sharp edges or undermined areas (14). The main reason for such discrepancies is that 3D scanners sample 3D shapes' surfaces uniformly, without aligning the samples with the sharp edges and corners of the original shape. The interpolating triangle meshes thus chamfer the sharp features, resulting in significant errors (32).

The main objective of this study is to evaluate the trueness and precision of seven extraoral scanners when scanning two different types of jaws: simplified jaw with abutments and sharp edges and genuine jaw with natural teeth. The accura-

nom CAD modelu, priprema se kod za proizvodnju (CAM proces).

3D skeneri za stomatološku upotrebu dijele se na intraoralne i ekstraoralne. Skeniranje je prvi korak u oblikovanju i izradi individualnih protetičkih nadomjestaka (7). Zato je točnost tih uređaja ključan preduvjet za kvalitetu konačnog proizvoda. Ako je točnost skeniranja nedovoljna, dobiveni proizvod imat će pogrešne mjere i oblik, prouzročit će opuštanje cementa (8, 9) i potencijalno će se pojaviti parodontološke bolesti (10, 11), sekundarni karijes (12) ili mikropropuštanja (13).

U mnogobrojnim istraživanjima autori su ocjenjivali točnost 3D skenera u stomatološkoj primjeni (14 – 27). Pritom se točnost tipično temeljila na vjerodostojnosti i preciznosti. Vjerodostojnost je definirana kao odstupanje skeniranih dimenzija od stvarnih dimenzija objekta, a preciznost je mjerena koristeći se odstupanjem dimenzija između više skenova nekog objekta (21), ili odstupanjem dimenzija unutar pojedinog skena (22). Visoka vjerodostojnost upućuje na to da je dobiveni sken vrlo blizak stvarnim dimenzijama snimljenoga objekta. Visoka preciznost pokazuje visoku ponovljivost rezultata skeniranja određenim skenerom.

U dosadašnjim studijama autori su upotrebljavali različite metode i mjere za vjerodostojnost i preciznost, što otežava usporedbu između različitih istraživanja. Nadalje, koristeći se modelima različitih oblika i materijala, ocjenjivala se točnost skenera. Primjerice, skenerima se postizala bolja točnost pri skeniranju pojedinačnih zuba ili pripremljenih modela zuba, nego pri skeniranju cijeloga modela čeljusti (17).

Točnost ekstraoralnih skenera tipično je bolja od one intraoralnih skenera, posebice duž dentalnoga luka (28). Nadalje, točnost intraoralnih skenera nedovoljna je za skeniranje bezubih lukova s implantatima (29). Te razlike nastaju zbog korištenih tehnologija skeniranja. Intraoralnim skenerima snimaju se slike i videa tijekom pomicanja duž dentalnoga luka (30), a ekstraoralnima se obuhvaća cijeli luk pod različitim kutovima. Pojedinačne snimke se zatim kombiniraju da bi se dobio virtualni 3D model (31). Pritom softver, raspoznajući na slici po dvije koordinate svake točke (x i y), prepoznaje zajedničke točke na snimkama. Preostala (z) koordinata postavlja se neovisno računanjem udaljenosti objekta od kamera. Procjena z-koordinate rezultira pogreškom koja se dalje propagira tijekom procesa.

Oštri rubovi još su jedan čimbenik koji može negativno utjecati na kvalitetu skeniranja. U dosadašnjim studijama istaknute su razlike u točnostima skenera pri snimanju glatkih površina prema skeniranju oštrih rubova i nepravilnih područja (14). Glavni razlog za te razlike jest u činjenici da 3D skeneri jednolično uzorkuju površine 3D oblika, bez usklađivanja uzoraka s oštrim rubovima i kutovima izvornog oblika. Interpolirajuće mreže trokuta zato zaobljuju oštre karakteristike, što rezultira značajnim pogreškama (32).

Cilj ovog istraživanja bio je ocijeniti vjerodostojnost i preciznost sedam ekstraoralnih skenera pri snimanju dvaju tipova čeljusti – pojednostavljene s implantološkim nadogradnjama i oštrim rubovima te realistične s prirodnim zubima. Uspoređena je točnost ekstraoralnih skenera, a raspravljena cies of extraoral scanners were compared, and their compliance with the required clinical accuracy levels was discussed.

Material and methods

Experimental procedure

The existing studies typically analyze scans of only one model (33). Nevertheless, their results indicate the influence of geometry complexity on 3D scanning accuracy. In this study, two models were utilized to enable comparison between scanners regarding model types. The first model, A model, was an arch-shaped model mimicking the mandibular arch with abutments designed using the CAD software solution SolidWorks. The model comprised six identical abutments (9 mm in height, 8 mm in diameter at the bottom, and with a 6° inclination), arranged on a flat surface in the positions of the right second molar, right second premolar, right lateral incisor, left lateral incisor, left second premolar, and left second molar (Fig. 1). B model was created in Exocad by scanning a maxillary arch with healthy natural teeth from the right second molar to the left second molar (Fig. 1). Both designs were milled on Dental Plus RS5 milling machine from a polyetheretherketone (PEEK) disk. This material was selected due to good mechanical and chemical resistance and optical properties that enable a good scan of the surface.

Seven extraoral scanners listed in Table 1 were evaluated in this study. Ten scans were made with each scanner for both models. The scan data were exported in standard tessellation language (STL).

The comparison of the selected dental scanners relies on reference scans made for both master models using the industrial 3D scanner Atos Core 135. Before scanning, the reference scanner was calibrated according to VDI/VDIE 2634 Part 3 (16) with a calibration panel (GOM Type CPI40-170-40288). The calibration identified 0.001 mm probing error (sigma), -0.005 mm probing error (size), 0.005 mm sphere spacing error, and 0.006 mm length measurement error.

3D analysis

Each scanner's trueness was assessed using deviation values yielded by comparing the reference model scans with the corresponding ten laboratory scans. Scans were compared using 3D analysis based on the ICP algorithm using Geomagic Control X – software for 3D quality control and dimen-

je i njihova usklađenost s potrebnim kliničkim razinama točnosti.

Materijali i metode

Eksperimentalni postupak

U dosadašnjim studijama uglavnom se analiziraju samo skenovi jednog modela (33), no rezultati upućuju na utjecaj kompleksnosti geometrije na točnost 3D skeniranja. Zato su u ovoj studiji korištena dva modela kako bi se omogućila usporedba skenera s obzirom na vrstu modela. Prvi je model Model A i on u obliku luka oponaša donju čeljust s implantološkim nadogradnjama te je oblikovan u CAD alatu SolidWorks. Sastoji se od šest identičnih nadogradnji (visine 9 mm, promjera na dnu 8 mm i nagiba 6°) postavljenih na ravnoj površini na pozicijama desnoga drugog kutnjaka, desnoga drugog pretkutnjaka, desnoga lateralnog sjekutića, lijevoga lateralnog sjekutića, lijevoga drugog pretkutnjaka i lijevoga drugog kutnjaka (slika 1.). Model B pripremljen je u alatu Exocad skenirajući maksilarni luk sa zdravim prirodnim zubima od desnoga drugog kutnjaka do lijevoga drugog kutnjaka (slika 1.). Oba modela izglodana su na CNC stroju Dental Plus RS5 iz polieter-eter-ketonskoga (PEEK) diska. Taj je materijal odabran zbog dobre mehaničke i kemijske otpornosti te optičkih svojstava koja omogućuju dobar sken površine.

U ovom istraživanju razmatrano je sedam ekstraoralnih skenera popisanih u tablici 1. Svakim uređajem napravljeno je po deset skenova pojedinog modela, a podatci su zapisani u STL formatu.

Za usporedbu odabranih stomatoloških skenera korišteni su referentni skenovi modela dobiveni industrijskim 3D skenerom Atos Core 135. Prije skeniranja, referentni skener kalibriran je prema standardu VDI/VDIE 2634 Part 3 (16) uz kalibracijsku pločicu GOM Type CPI40-170-40288. Kalibracijom su utvrđene sljedeće pogreške: 0,001 mm probing error (sigma), -0,005 mm probing error (size), 0,005 mm sphere spacing error i 0,006 mm length measurement error.

3D analiza

Točnost pojedinog skenera ocijenjena je na osnovi vrijednosti odstupanja njegovih deset laboratorijskih skenova od referentnog skena. Skenovi su analizirani 3D analizom temeljenom na ICP algoritmu koristeći se Geomagic Control X – softverom za 3D kontrolu kvalitete i inspekciju dimenzi-

Table 1 Characteristics of scanners used in this study
Tablica 1. Karakteristike skenera korištenih u ovom istraživanju

	Scanner • Skener						
	UP360	UP300	DWS3	D810	D2000	Freedom HD	Identica
Manufacturer • Proizvođač	Up3D	Up3D	Dental Wings	3Shape	3Shape	DOF	Medit
Light • Tehnologija	Blue light	Blue light	Laser	Red laser	Blue LED Multi-line	White light LED	Blue LED
Cameras • Kamere	2 x 1,3 MP	2 x 2 MP	2	2 x 5 MP	4 x 5 MP	2 x 2 MP	1
Accuracy (according to manufacturer) • Točnost (prema proizvođaču)	< 6 µm	< 10 µm	< 20 µm	< 15 µm	< 8 µm	< 10 µm	< 10 µm

sional inspection (16, 17, 22). First, each laboratory scan was aligned with the reference scan using the best fit alignment with a 100% sampling ratio, 100 iteration count, and maximal average deviation of 0.001 mm. Then, the 3D deviation (*x*, *y*, and *z*) from the reference scan point was calculated for every laboratory scan point. Finally, since the root mean square (RMS) captures the magnitude of deviations from the reference scan, it was calculated for each analysis (N=140) and used to determine the scanners' trueness (15–17).

Precision was assessed by superimposing each (except the first) scan of a particular scanner over the scanner's first scan. Standard deviation across all points was calculated for each superimposed pair (N=126).

Finally, the software provided color-coded deviation maps, thus showing the distribution and value of laboratory scan points' deviations from the reference scans.

Statistical analysis

The statistical analysis was performed in R, and a significance level was set to 0.05. The Shapiro-Wilk test was utilized to assess the distributions' normality, whereas the Levine's test was used for testing the homogeneity of variance. If the tests indicated no violation of the assumptions, ANOVA was used for the general significance of the differences, followed by the Tukey test to review significant differences between scanner pairs. However, in the case of heteroscedastic data, Welch ANOVA was utilized, and the post hoc Games-Howell test was performed. When the normality assumption was violated, the Kruskal-Wallis test was used, followed by the Mann-Whitney-Wilcoxon test with Holm correction for multiple comparisons.

Results

The experiments assessed the scanners' accuracy by measuring their trueness and precision.

Trueness

Trueness is defined as the deviations of the scanned models' points from the reference model. It is measured using RMS values (15–17). For each scanner and both models, ten scans were analyzed.

A model

The scanners' RMS values when scanning A Model are presented in Table 2.

Identica has the lowest mean RMS (16.15 μm), and its RMS values span the smallest range between 10 scans (from 15.56 to 17.44 μm). D2000 achieved the second-best result (18.58 μm), but with a broader range (from 13.76 to 21.92 μm), thus indicating that D2000 is a less consistent scanner. DWS3 demonstrated the highest mean RMS (49.78 μm), and its RMS values vary the most (from 38.34 to 56.37 μm).

The UP360 data violate the normality assumption (p = 0.0217), and the deviation from the homoscedasticity assumption was detected (p = 0.0006). The Welch-ANOVA test showed statistically significant differences between the tested scanners (p = $2.2 \cdot 10^{-16}$). Significant differences were

ja (16, 17, 22). Svaki laboratorijski sken najprije je poravnan s referentnim s pomoću best fit poravnanja koristeći se svim mjerenim točkama (100 %), stotinom iteracija te maksimalnim prosječnim odstupanjem od 0,001 mm. Zatim je za svaku točku laboratorijskog skena izračunato 3D odstupanje (*x*, *y* i *z*) od odgovarajuće referentne točke. Konačno, budući da korijen srednje kvadratne pogreške (RMS) odražava magnitudu odstupanja skena od referentnoga, ta je metrika korištena pri ocjeni vjerodostojnosti (15 – 17) svakog skena (N = 140).

Preciznost je ocijenjena koristeći se superimpozicijom svih (osim prvoga) skenova nekog skenera preko njegova prvog skena. Standardna devijacija svih točaka izračunata je za svaki takav par skenova (N = 126).

Konačno, softverom su generirane obojene mape odstupanja koje pokazuju distribuciju i vrijednost odstupanja točaka laboratorijskog skena od referentnoga.

Statistička analiza

Podatci su statistički obrađeni i analizirani u programu R, a kao odabrana razina statističke značajnosti korištena je vrijednost 0,05. Pretpostavke normalnosti distribucija provjerene su Shapiro-Wilkovim testom, a Levenov test upotrijebljen je da bi se provjerila pretpostavka o homogenosti varijanci. U slučaju da testovi nisu upozorili na odstupanje od pretpostavki, generalna značajnost razlika utvrđena je ANOVA testom, a Tukeyjev test korišten je da bi se ispitale razlike među pojedinim parovima skenera. U slučaju heteroskedastičnosti korišten je Welchov ANOVA test uz Games-Howellov test kao *post-hoc* test. Kada pretpostavka normalnosti nije bila zadovoljena, korišten je Kruskal-Wallisov test te zatim Mann-Whitney-Wilcoxonov test uz Holmovu korekciju za višestruke usporedbe.

Rezultati

Točnost skenera procijenjena je na temelju metrike vjerodostojnosti i preciznosti.

Vjerodostojnost

Vjerodostojnost je definirana kao odstupanje točaka skeniranog modela od referentnoga, a kao metrika koristi se korijen srednje kvadratne pogreške – RMS (15 – 17). Za pojedini skener i model prikupljeno je i analizirano po 10 skenova.

Model A

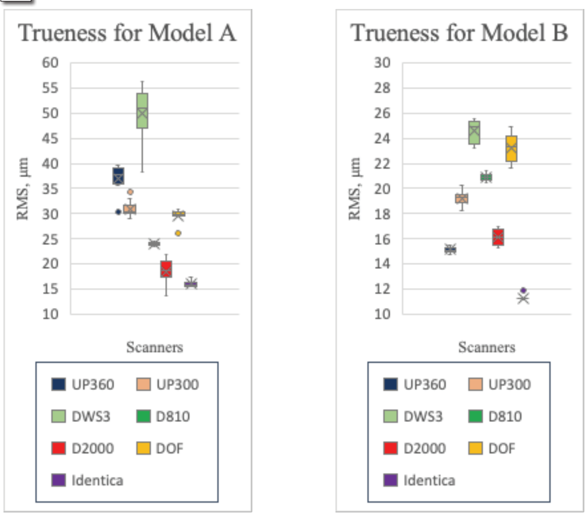
Postignute RMS vrijednosti pri skeniranju Modela A odabranim skenerima opisane su u tablici 2.

Skenerom Identica postignut je najniži prosječni RMS (16,15 μm) te njegove RMS vrijednosti na 10 skenova imaju najmanji raspon (od 15,56 do 17,44 μm). D2000 ostvaren je drugi najbolji rezultat (18,58 μm), no s većim rasponom (od 13,76 do 21,92 μm), što sugerira nižu konzistentnost među skenovima. Najviša prosječna RMS vrijednost dobivena je uređajem DWS3 (49,78 μm), pri čemu njegove RMS vrijednosti i najviše variraju (od 38,34 do 56,37 μm).

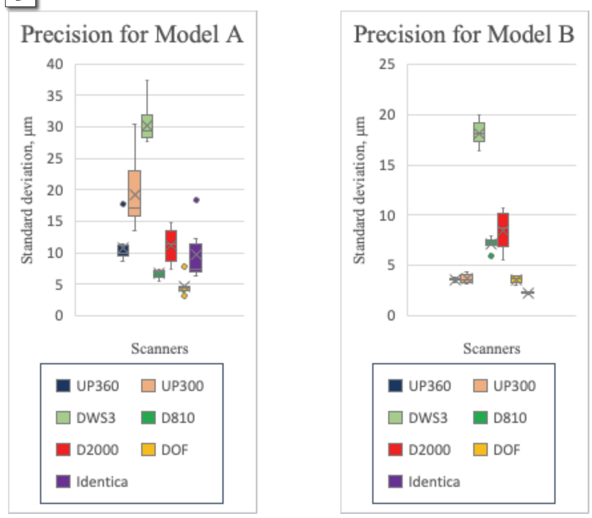
Podatci skenera UP360 značajno odstupaju od normalne distribucije (p = 0,0217). Nadalje, uočeno je odstupanje od pretpostavke o jednakosti varijanci (p = 0,0006). Welch-ANOVA test upozorio je na statistički značajne razlike među

1

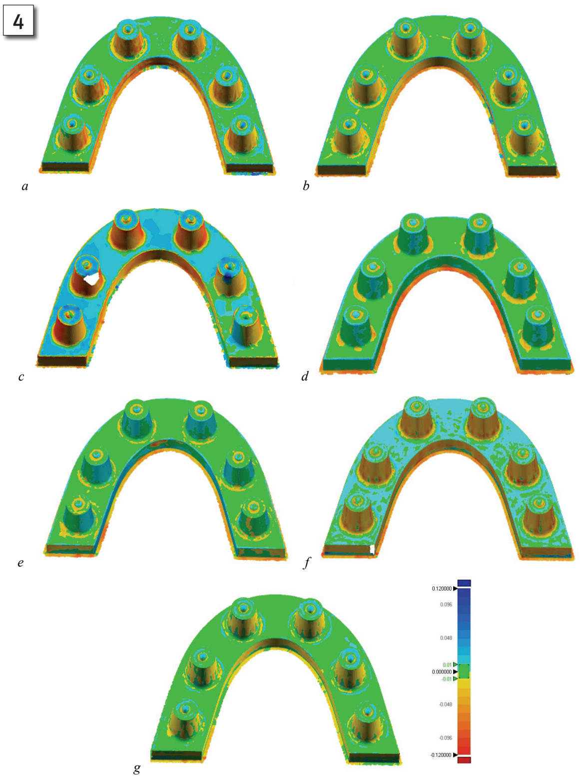
2



3



4



5

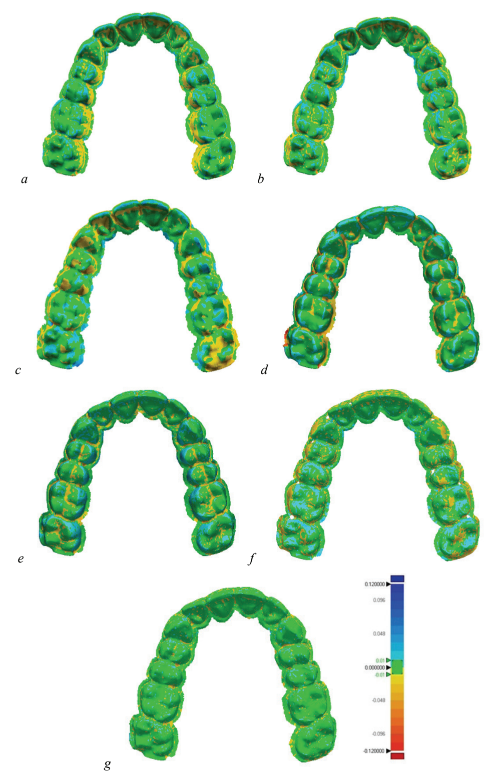


Figure 1 Models A (left) and B (right) utilized in this study
Slika 1. Modeli A (lijevo) i B (desno) korišteni u ovom istraživanju
Figure 2 The scanners' trueness comparison - Box-plot diagrams of RMS (µm) values for both models
Slika 2. Usporedba vjerodostojnosti skenera – kutijasti dijagrami RMS vrijednosti (µm) za oba modela
Figure 3 The scanner's precision comparison - Box-plot diagram of standard deviations (µm) for both models
Slika 3. Usporedba preciznosti skenera – kutijasti dijagrami standardnih devijacija odstupanja (µm) za oba modela
Figure 4 Color-coded maps for A Model: a) UP360; b) UP300 c) DWS3 d) D810 e) D2000 f) DOF g) Identica
Slika 4. Prikaz distribucije odstupanja na Modelu A: a) UP360; b) UP300 c) DWS3 d) D810 e) D2000 f) DOF g) Identica
Figure 5 Color-coded maps for Model B: a) UP360; b) UP300 c) DWS3 d) D810 e) D2000 f) DOF g) Identica
Slika 5. Prikaz distribucije odstupanja na Modelu B: a) UP360; b) UP300 c) DWS3 d) D810 e) D2000 f) DOF g) Identica

found between all scanner pairs except between DOF and UP300, and Identica and D2000 (Table 3).

B model

The scanner's RMS values when scanning Model B are presented in Table *4*.

The Identica scans again had the lowest mean RMS (11.32 µm) and the smallest RMS range (11.2 – 11.87 µm). UP360 achieved a better result when scanning Model B than Model A and is ranked second with the mean RMS of 15.15 µm and a lower range (14.81 – 15.53 µm). D2000 also showed a low mean RMS value (16.12 µm), and its RMS varied less on Model B than on Model A (15.3 – 16.97 µm). DWS3 is again ranked last, as it has the highest mean RMS (24.55 µm). DOF's mean RMS equals 23.19 µm.

In this case, Identica's data violate the normality assumption ($p = 1.67 \cdot 10^{-5}$), and a violation of variances' homogeneity assumption was detected ($p = 6.61 \cdot 10^{-8}$). Statistically significant differences between the tested scanners were found for all scanner pairs, except between DOF and DWS3 (Table 5).

For both models, the results are presented graphically in Fig. 2.

Precision

Following the works by Su and Sun (18) and Kim et al. (21), this study conceptualized a scanner's precision as the deviation between its scans. More precisely, for each scanner, its first scan was compared to every other scan via superimposition and the assessment of deviations. Overall, 18 scan comparisons were made for each scanner (nine for each model).

razmatranim skenerima ($p = 2{,}2 \cdot 10^{-16}$). Statistički značajne razlike pronađene su između svih parova skenera, osim između DOF-a i UP300 te Identice i D2000 (tablica 3.).

Model B

RMS vrijednosti postignute pri skeniranju Modela B opisane su u tablici 4.

Skenovi skenera Identica i na ovom modelu imaju najnižu prosječnu RMS vrijednost (11,32 µm) i najuži raspon RMS vrijednosti (11,2 – 11,87 µm). Uporabom UP360 postignut je bolji rezultat pri skeniranju Modela B u usporedbi s Modelom A, te je rangiran kao drugi s prosječnom RMS vrijednošću jednakom 15,15 µm i manjim rasponom (14,81 – 15,53 µm). Slično tomu, D2000 ima nisku prosječnu RMS vrijednost (16,12 µm), a raspon RMS-a manje varira na Modelu B nego na Modelu A (15,3 – 16,97 µm). DWS3 je i u ovom slučaju na posljednjem mjestu s najvećom prosječnom RMS vrijednošću (24,55 µm), a prosječna RMS vrijednost za skener DOF jednaka je 23,19 µm.

U ovom slučaju podatci za skener Identica značajno odstupaju od normalne distribucije ($p = 1{,}67 \cdot 10^{-5}$). Uočeno je također odstupanje od pretpostavke o homogenosti varijanci ($p = 6{,}61 \cdot 10^{-8}$). Statistički značajne razlike između ispitivanih skenera pronađene su za sve parove, osim za par DOF i DWS3 (tablica 5.).

Rezultati za oba modela prikazani su grafički na slici 2.

Preciznost

Slijedeći pristup Sua i Suna (18) te Kima i suradnika (21), u ovom je istraživanju preciznost skenera definirana kao odstupanje među njegovim skenovima. Preciznije, za pojedini skener je prvi sken modela uspoređen s preostalim skenovima putem superimpozicije na kojoj je zatim izračunata standardna devijacija odstupanja. Ukupno je učinjeno 18 usporedbi skenova za svaki skener (po devet za pojedini model).

Table 2 RMS values (µm) for scanners when scanning A model
Tablica 2. Postignute RMS (µm) vrijednosti pri skeniranju modela A

	RMS				
	Mean • Aritmetička sredina	**SD**	**Median • Medijan**	**Min • Minimum**	**Max • Maksimum**
Model A					
UP360	37.07	2.73	37.85	30.28	39.73
UP300	30.94	1.61	30.45	28.92	34.38
DWS3	49.78	5.25	51.03	38.34	56.37
D810	24.09	0.31	24.06	23.62	24.63
D2000	18.58	2.34	18.67	13.76	21.92
DOF	29.63	1.28	29.78	26.22	30.98
Identica	16.15	0.6	15.94	15.56	17.44

Table 3 Statistical significance (p-values) of differences in the scanners' RMS values on A model
Tablica 3. Statistička značajnost (p-vrijednost) razlika među postignutim RMS vrijednostima na modelu A

	UP360	**UP300**	**DWS3**	**D810**	**D2000**	**DOF**
UP300	$3.5 \cdot 10^{-4}$					
DWS3	$1.64 \cdot 10^{-4}$	$6.35 \cdot 10^{-6}$				
D810	$1.26 \cdot 10^{-6}$	$2.36 \cdot 10^{-6}$	$1.16 \cdot 10^{-6}$			
D2000	$8.91 \cdot 10^{-11}$	$5.07 \cdot 10^{-9}$	$8.44 \cdot 10^{-9}$	$4.51 \cdot 10^{-4}$		
DOF	$5.09 \cdot 10^{-5}$	0.442	$4.68 \cdot 10^{-6}$	$1.58 \cdot 10^{-6}$	$5.22 \cdot 10^{-8}$	
Identica	$4.93 \cdot 10^{-9}$	$5.02 \cdot 10^{-11}$	$8.35 \cdot 10^{-8}$	$2.46 \cdot 10^{-12}$	0.094	$6.9 \cdot 10^{-12}$

Table 4 RMS values (μm) for scanners when scanning B model
Tablica 4. Postignute RMS (μm) vrijednosti pri skeniranju modela B

	RMS				
	Mean • Aritmetička sredina	SD	Median • Medijan	Min • Minimum	Max • Maksimum
Model B					
UP360	15.15	0.21	15.09	14.81	15.53
UP300	19.24	0.53	19.27	18.23	20.21
DWS3	24.55	0.88	24.91	23.23	25.55
D810	20.9	0.29	20.93	20.44	21.44
D2000	16.12	0.61	16.12	15.3	16.97
DOF	23.19	1.19	23.33	21.66	24.87
Identica	11.32	0.19	11.27	11.2	11.87

Table 5 Statistical significance (p-values) of differences in the scanners' RMS values on B model
Tablica 5. Statistička značajnost (p-vrijednost) razlika među postignutim RMS vrijednostima na modelu B

	UP360	UP300	DWS3	D810	D2000	DOF
UP300	$8.17 \cdot 10^{-10}$					
DWS3	$2.6 \cdot 10^{-10}$	$1.26 \cdot 10^{-9}$				
D810	$1.65 \cdot 10^{-13}$	$9.85 \cdot 10^{-6}$	$1.33 \cdot 10^{-6}$			
D2000	0.0080	$1.02 \cdot 10^{-8}$	$7.73 \cdot 10^{-13}$	$2.36 \cdot 10^{-10}$		
DOF	$3.14 \cdot 10^{-8}$	$6.21 \cdot 10^{-6}$	0.1130	0.0020	$3.38 \cdot 10^{-9}$	
Identica	$4.42 \cdot 10^{-14}$	0	$5.72 \cdot 10^{-11}$	0	$1.39 \cdot 10^{-9}$	$3.38 \cdot 10^{-9}$

A model

The scanners' standard deviations when scanning A model are presented in Table 6.

On average, DOF showed the best precision performance, with the mean standard deviation between its scans equaling 4.33 μm, followed by D810, whose mean standard deviation between scans was 6.56 μm. Further, D810 scans showed the smallest variation in standard deviation results (5.37 – 7.21 μm). In contrast, DWS3 had the weakest average performance (mean standard deviation = 29.49 μm), whereas UP300's results spanned across the broadest range (from 13.35 μm to 30.35 μm).

The data collected using Identica, UP360, UP300, and DWS3 scanners violate the normality assumption (p = 0.017, p = 0.0048, p = 0.0462, and p = 0.0055, respectively). No significant violation of the homoscedasticity assumption was found (p = 0.0844). No statistically significant difference was found among Identica, UP360, and D2000 scanner pairs (p = 1). Similarly, Identica and D810 did not differ significantly (p = 0.37565). Nevertheless, all other pairs differed significantly (Table 7).

B model

Similar to A model, the scanners' standard deviations when scanning B model are presented in Table 8.

In the case of B model, Identica outperforms other scanners, as the superimpositions of its scans yielded the lowest mean standard deviation (2.29 μm), as well the smallest range of standard deviation values (2.17 – 2.36 μm) followed by UP300 , with the mean standard deviation equal to 3.57 μm and the standard deviations ranging from 3.08 to 4.17 μm. The worst results were obtained using DWS3, whose superimpositions again had the highest mean standard deviation (18.06 μm).

Model A

Vrijednosti standardnih devijacija odstupanja pojedinog skenera pri skeniranju Modela A opisane su u tablici 6.

U prosjeku se DOF ističe najboljom preciznošću, s prosječnom standardnom devijacijom odstupanja među skenovima od 4,33 μm. Slijedi D810 čija je prosječna standardna devijacija odstupanja između skenova 6,56 μm. Štoviše, standardne devijacije odstupanja među skenovima uređaja D810 najmanje variraju (između 5,37 i 7,21 μm). S druge strane, DWS3 ima najnižu prosječnu preciznost (prosječna vrijednost standardne devijacije = 29,49 μm), a rezultati UP300 variraju u najvećem rasponu (od 13,35 μm do 30,35 μm).

Podatci prikupljeni skenerima Identica, UP360, UP300 i DWS3 značajno odstupaju od normalne distribucije (p = 0,017, p = 0,0048, p = 0,0462, odnosno p = 0,0055). Nije uočeno statistički značajno kršenje pretpostavke o homoskedastičnosti (p = 0,0844). Nisu pronađene statistički značajne razlike između parova skenera Identica, UP360 i D2000 (p = 1). Slično tomu, skeneri Identica i D810 nisu se značajno razlikovali (p = 0,37565). No među svim preostalim parovima pronađene su statistički značajne razlike (tablica 7).

Model B

Kao i u slučaju Modela A, standardne devijacije odstupanja među skenovima pojedinog skenera pri skeniranju Modela B prikazane su u tablici 8.

U slučaju Modela B, skener Identica nadmašuje ostale jer superimpozicije njegovih skenova imaju najnižu prosječnu standardnu devijaciju odstupanja (2,29 μm) i najmanji raspon standardnih devijacija odstupanja (2,17 – 2,36 μm). UP300 je drugi, uz prosječnu standardnu devijaciju odstupanja jednaku 3,57 μm te raspon standardnih devijacija odstupanja od 3,08 do 4,17 μm. Najlošiji rezultat postignut je skenerom DWS3 čije su superimpozicije i u ovom slučaju imale

Table 6 Standard deviations of scanners (μm) when scanning A model
Tablica 6. Standardne devijacije (μm) među skenovima pojedinog skenera pri skeniranju modela A

	Standard deviation • Standardna devijacija				
	Mean • Aritmetička sredina	**SD**	**Median • Medijan**	**Min • Minimum**	**Max • Maksimum**
Model A					
UP360	10.38	2.04	9.75	8.54	15.39
UP300	19.20	5.66	16.98	13.35	30.35
DWS3	29.49	2.33	28.59	27.15	33.55
D810	6.56	0.61	6.77	5.37	7.21
D2000	9.61	2.25	9.56	6.37	13.21
DOF	4.33	0.81	4.23	3.05	6.15
Identica	9.44	3.99	7.07	6.20	18.42

Table 7 Statistical significance (p-values) of differences between scanners regarding their precision on A model
Tablica 7. Statistička značajnost (p-vrijednost) razlika među skenerima s obzirom na postignutu preciznost na modelu A

	UP360	UP300	DWS3	D810	D2000	DOF
UP300	0.00148					
DWS3	0.00086	0.01111				
D810	0.00086	0.00086	0.00086			
D2000	1	0.00086	0.00086	0.01111		
DOF	0.00086	0.00086	0.00086	0.00148	0.00086	
Identica	1.00000	0.00864	0.00086	0.37565	1	0.00086

No violation of the normality assumption was detected for any of the scanners. However, a violation of the homoscedasticity assumption was found ($p = 1.783 \cdot 10^{-11}$). Thus, the Welch ANOVA test was employed, thus revealing statistically significant differences between the tested scanners ($p = 2.2 \cdot 10^{-16}$). More precisely, significant differences were found for all scanner pairs, except the differences between UP360-UP300, UP360-DOF, DOF-UP360, and D2000-D810 (Table 9).

Figure 3 depicts the precision results for both models.

najvišu prosječnu standardnu devijaciju odstupanja (18,06 μm).

Nijedan skener ne odstupa od pretpostavke o normalnoj distribuciji. No primijećeno je odstupanje od pretpostavke o homoskedastičnosti ($p = 1{,}783 \cdot 10^{-11}$). Zato je primijenjen Welchov ANOVA test koji je upozorio na statistički značajne razlike među testiranim skenerima (p = 2,2·10-16). Preciznije, uočene su značajne razlike između svih parova skenera, osim između UP360 i UP300, UP360 i DOF, DOF i UP360, te D2000 i D810 (tablica 9.).

Na slici 3. su vrijednosti preciznosti skenera za oba modela.

Deviation distribution analysis

Color-coded maps are utilized to depict the distribution of scan data deviations from the reference data. The analysis enables identifying critical areas, i.e., the areas where the scans have the highest deviation from the reference. For each scanner, a laboratory scan whose RMS value was the closest to the corresponding scanners' mean RMS was selected as a representative scan and utilized in the deviation analysis of color-coded difference images (Table 10).

A model

Figure 4 shows the color-coded maps for all scanners when scanning A model. The deviations are colored as follows. Areas with nominal deviations, ranging from -10 to 10 μm, are marked in green following Emir and Ayyildiz (16). Yellow and orange tones show areas with positive deviations, ranging from 10 to 120 μm, modeled based on Medina-Sotomayor et al. (22) and in accordance with clinical accuracy limits (8). Areas with deviations higher than 120 μm are colored red. In contrast, blue tones highlight areas of negative deviations, ranging from -10 to -100 μm. Areas with devia-

Analiza distribucije odstupanja

Obojenim mapama prikazuju se odstupanja skenova od referentnih modela. Analiza omogućuje identifikaciju kritičnih područja, tj. područja na kojima skenovi najviše odstupaju od referentnih. Za svaki skener odabran je onaj laboratorijski sken čija je vrijednost RMS-a bila najbliža srednjoj vrijednosti RMS-a svih skenova toga skenera te je on korišten u analizi razlika i odstupanja na obojenim mapama (tablica 10.).

Model A

Na slici 4. obojene su mape skenera pri skeniranju Modela A. Odstupanja su prikazana bojama na sljedeći način: područja nominalnih odstupanja, u rasponu od -10 do 10 μm, označena su zelenom bojom prema Emiru i Ayyildizu (16); žute i narančaste nijanse pokazuju područja pozitivnih odstupanja u rasponu od 10 do 120 μm prema radu Medina-Sotomayora i suradnika (22) te u skladu s granicama klinički prihvatljive točnosti (8); područja s odstupanjima većima od 120 μm obojena su crveno. S druge strane, plave nijanse ističu područja negativnih odstupanja u rasponu od -10 do -100

Table 8 Standard deviations (μm) for scanners when scanning B model
Tablica 8. Standardne devijacije (μm) među skenovima pojedinog skenera pri skeniranju modela B

	Standard deviation • Standardna devijacija				
	Mean • Aritmetička sredina	SD	Median • Medijan	Min • Minimum	Max • Maksimum
Model B					
UP360	3.61	0.12	3.59	3.37	3.82
UP300	3.57	0.40	3.46	3.08	4.17
DWS3	18.06	1.07	17.96	16.38	19.84
D810	7.18	0.53	7.25	6.00	7.91
D2000	7.37	1.46	7.70	4.99	9.20
DOF	3.63	0.38	3.69	3.00	4.02
Identica	2.29	0.05	2.29	2.17	2.36

Table 9 Statistical significance (p-values) of differences between scanners regarding their precision on B model
Tablica 9. Statistička značajnost (p-vrijednost) razlika među skenerima s obzirom na postignutu preciznost na modelu B

	UP360	UP300	DWS3	D810	D2000	DOF
UP300	1					
DWS3	$3.43 \cdot 10^{-9}$	$3.22 \cdot 10^{-11}$				
D810	$3.22 \cdot 10^{-11}$	$1.2 \cdot 10^{-9}$	$2.76 \cdot 10^{-8}$			
D2000	$6.59 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$	$4.59 \cdot 10^{-10}$	1		
DOF	1	1	$1.38 \cdot 10^{-10}$	$1.9 \cdot 10^{-9}$	$5.08 \cdot 10^{-4}$	
Identica	$2.94 \cdot 10^{-11}$	$1.3 \cdot 10^{-4}$	$1.86 \cdot 10^{-9}$	$2.76 \cdot 10^{-8}$	$7.64 \cdot 10^{-5}$	$4.83 \cdot 10^{-5}$

Table 10 Selected scans for the deviation analysis
Tablica 10. Redni broj skenova korištenih pri analizi odstupanja

	Model A		Model B	
Scanner • Skener	Scan No. • Broj skena	RMS value (μm) • RMS (μm)	Scan No. • Broj skena	RMS value (μm) • RMS (μm)
UP360	7	36.7	5	15.12
UP300	10	30.94	5	19.25
DWS3	8	50.53	7	24.95
D810	10	24.1	2	20.91
D2000	5	18.43	5	15.98
DOF	6	29.63	6	22.62
Identica	7	16.3	1	11.32

tion values higher than -120 μm are colored dark blue.

Figure 4 shows that lateral areas of the abutments and the side of the arch along the model have predominantly positive deviations (a, b, c, f, and g) or slightly negative deviations (d and e). The surface where abutments are located has minimal deviations – nominal (a, b, d, e, and g) or slightly negative (c and f).

B model

Figure 5 presents the color-coded maps of all scanners when scanning B model. Again, the deviations are colored following the same rules as described in the previous section.

The color-coded maps look more uniform in this case than in the case of A model. Nevertheless, one can note a superior performance of Identica since map *g* has few small areas out of the nominal range. Other maps show negative deviations on incisal edges and occlusal surfaces (a, b, c, d, and e), whereas positive deviations are seen on palatal surfaces (a, b, c, d) and fissures (d, e, f).

μm. Područja s vrijednostima odstupanja manjima od -120 μm obojena su tamnoplavo.

Slika 4. pokazuje da bočna površina implantoloških nadogradnji te bokovi uzduž lukova modela uglavnom imaju pozitivna (a, b, c, f i g) ili blago negativna (d i e) odstupanja. Površina na kojoj se nalaze nadogradnje ima najmanja odstupanja – nominalna (a, b, d, e i g) ili blago negativna (c i f).

Model B

Na slici 5. su obojene mape svih skenera pri skeniranju Modela B. Korištene nijanse i ovdje slijede ista pravila kao u gornjem odlomku.

Obojene mape u ovom slučaju izgledaju ujednačenije, nego kad je riječ o Modelu A. Ipak, može se uočiti superiornost skenera Identica jer mapa *g* sadržava samo nekoliko malih područja izvan nominalnog raspona. Ostale mape sadržavaju negativna odstupanja na incizalnim rubovima te okluzivnim plohama (a, b, c, d i e), a pozitivna odstupanja uočavaju se na palatinalnim plohama (a, b, c, d) i fisurama (d, e, f).

Discussion

The existing studies define and measure trueness and precision differently. Researchers expressed a scanner's trueness using the mean RMS values (15–17, 27) or the mean MAD values (14, 21–23, 25). The precision of a particular scanner is commonly measured as the mean variability within its scans (i.e., variability in one scan's deviations from the reference) by, for example, averaging the standard deviations of each scan's data (14–16, 18, 22, 25). Others conceptualized precision as the variability among scans of a particular scanner. In such a case, precision was assessed by superimposing the scans, calculating the absolute deviations, and finally averaging them to obtain a precision value (18, 21, 24, 26). Compared to intraoral studies, the accuracy of extraoral scanners was found to be higher and it varied less along the dental arch (17, 18, 21, 22).

In contrast to most existing studies, this study utilized two models to evaluate the scanners' trueness and precision. When scanning A model, Identica showed the highest trueness (i.e., the lowest RMS). However, its performance did not differ significantly from D2000, whose RMS value was only slightly higher. Based on trueness performance, the two scanners were followed by D810, then DOF and UP300 (which are statistically indistinguishable), UP360, and, finally, DWS3. Identica also achieved the best trueness result when scanning B Model, but other scanners were ranked differently: UP360, D2000, UP300, D810, DOF, and DWS3.

When measuring precision on A model, the best scanner was DOF, followed by D810. Identica, UP360, and D2000 shared third place, UP300 was penultimate, and DWS3 was again ranked last. "However, Identica was the most precise scanner when scanning Model B. UP300, UP360, and DOF followed, then D810 and D2000, and lastly, DWS3. Therefore, except for the precision score on A model, Identica achieved the best results. In contrast, DWS3 was consistently ranked last. The variations in scanners' ranks when scanning different models highlight the impact of model selection on research findings.

The trueness results for A model can be contrasted to the results obtained by Emir and Ayyildiz (16) since the study investigated extraoral scanners' performance using a similar model of a simplified edentulous jaw with abutments. The trueness values (as proxied by RMS) ranged from 17.4 to 33.3 µm. The study presented herein obtained slightly different values (16.15 – 49.78 µm). Furthermore, in the study by Emir and Ayyildiz (16), scanner D2000 achieved the highest trueness result (17.4 µm). However, when testing this scanner within the study at hand, it scored slightly worse mean trueness (18.58 µm) and was ranked second.

For B model, the trueness results range from 11.32 to 24.55 µm, and the obtained precision values are between 2.29 and 18.06 µm. When scanning a similar model, Park et al. (17) found that trueness of extraoral scanners ranges from 19.6 to 67.3 µm. In addition, the extraoral scanner achieved the 8.67 – 24.33 µm precision on a model similar to B Model, as reported by Su and Sun (18). Another related study found that extraoral scanners achieved trueness from 7.7 to 28.6 µm

Rasprava

U dosadašnjim studijama različito se definiraju i mjere vjerodostojnost i preciznost. Istraživači su tako izražavali vjerodostojnost skenera koristeći se prosječnom RMS vrijednošću (15 – 17,27) ili prosječnom MAD vrijednošću (14, 21 – 23, 25). Preciznost skenera često je mjerena kao prosječna varijabilnost unutar skena (tj. varijabilnost odstupanja točaka pojedinog skena od referentnog skena), pa se kao preciznost uređaja uzimala, primjerice, prosječna standardna devijacija takvih odstupanja (14 – 16, 18, 22, 25). Drugi su definirali preciznost kao varijabilnost između skenova pojedinog skenera. Tada je preciznost mjerena koristeći se superimpozicijom skenova te računajući prosjek apsolutnih odstupanja (18, 21, 24, 26). U usporedbi s intraoralnim skenerima, točnost ekstraoralnih veća je i manje varira duž dentalnoga luka (17, 18, 21, 22).

Za razliku od većine dosadašnjih studija, u ovom radu korištena su dva modela kako bi se ocijenila vjerodostojnost i preciznost skenera. Pri skeniranju Modela A, skener Identica pokazao je najvišu vjerodostojnost (tj. najniži RMS). No izvedba toga skenera ne razlikuje se značajno od D2000, čija je vrijednost RMS-a neznatno viša. S obzirom na vjerodostojnost, slijede D810, zatim DOF i UP300 (koji su statistički neodvojivi), UP360 i naposljetku DWS3. Skenerom Identica također je postignut najbolji rezultat kad je riječ o vjerodostojnosti pri skeniranju Modela B, ali drugi skeneri rangirani su drukčije: UP360, D2000, UP300, D810, DOF te DWS3.

S obzirom na preciznost na Modelu A, najbolji skener je DOF, a zatim D810. Identica, UP360 i D2000 dijele treće mjesto, UP300 je pretposljednji, a DWS3 ponovno je posljednji. No pri skeniranju Modela B, Identica je najpreciznija. Slijede UP300, UP360 i DOF, zatim D810 i D2000 te na kraju DWS3. Zato, osim kad je riječ o preciznosti na Modelu A, skenerom Identica postignuti su najbolji rezultati. Nasuprot tomu, DWS3 je kontinuirano posljednji. Varijacije u rangovima skenera pri skeniranju različitih modela ističu utjecaj odabira modela znanstvene spoznaje.

Budući da su se u svojoj studiji o performansama ekstraoralnih skenera koristili modelom pojednostavljene bezube čeljusti s nadogradnjama, rezultate točnosti koje su dobili Emir i Ayyildiz (16) možemo usporediti s rezultatima za Model A. Vrijednosti točnosti (izražene kao RMS) kretale su se u rasponu od 17,4 do 33,3 µm, u ovom istraživanju dobivene su nešto drukčije vrijednosti (16,15 – 49,78 µm). Nadalje, u istraživanju Emira i Ayyildiza (16), skenerom D2000 postignuta je najveća točnost (17,4 µm). Međutim, u našoj studiji tim je skenerom postignuta niža prosječna točnost (18,58 µm) te je rangiran kao drugi.

Na Modelu B rezultati točnosti kreću se u rasponu od 11,32 do 24,55 µm, a dobivene vrijednosti preciznosti su između 2,29 i 18,06 µm. Skenirajući sličan model, Park i suradnici (17) utvrdili su da točnost ekstraoralnih skenera varira između 19,6 i 67,3 µm. Nadalje, ekstraoralnim skenerom korištenim u studiji Sua i Suna (18) postignuta je preciznost u rasponu od 8,67 do 24,33 µm na modelu sličnom Modelu B. U sličnoj studiji autori su ustanovili da se ekstraoralnim skenerima postiže točnost u rasponu od 7,7 do 28,6 µm i preand precision from 4 to 19.5 μm when scanning a single abutment (15). Furthermore, de Villaumbrosia et al. (14) reported that results of scanning the prepared tooth ranged from 29 to 46 μm regarding MAD (i.e., trueness), and from 37.6 to 50.6 μm for standard deviation (i.e., precision).

Table 1 reveals that the accuracy values reported by the scanner manufacturers are not compatible with the presented results. The reason might lie in different scanning conditions and the utilized accuracy parameters. Hence, the detected discrepancies highlight the necessity of reporting detailed information regarding the scanned model, as well as the way scans are performed and evaluated.

However, there is no established limit to the value of clinical accuracy of dental scanners, as current literature reported the required accuracy being below 50-75 μm (15), 80 μm (34), 100 μm (35), 120 μm (8), or 150 μm (36). Most studies follow McLean and Fraunhofer (37), who argue that the fit on the margin between the batter and the replacement must be less than 120 μm. It should also be noted that the CAD/CAM process error should be calculated with respect to clinical accuracy limit value, rendering the scanner deviation error smaller.

For both models and at the level of the entire jaw, all tested scanners achieved values of trueness and precision that meet the minimum specified limit (50 – 75 μm). Nevertheless, it is insufficient to reflect on clinical accuracy using only the accuracy values aggregated for whole arches (i.e., jaws). The accuracy on the sides of the abutments and teeth shown in the color-coded maps should be compared. The color-coded maps show a substantial difference in deviations on the surface when scanning A model. Deviations are especially large at the abutment areas where several scanners have reached results close to maximum allowable positive deviation. Since these areas are vital for the final function of the prosthetic replacement, the deviations should remain limited. Large deviations at the abutment areas might occur due to simplified design with completely flat, smooth jaw surfaces and equal, steep, and smooth abutment surfaces. These high and steep abutments can create shadows that prevent properly capturing the shaded areas unless the scanner tilts the model plate sufficiently. Such significant deviations can occur due to the inadequate rotation angle of the scanner model plate (for structured light scanners) or the scanner camera (for laser scanners). As in previous studies, scanners had problems when scanning sharp edges or undermined areas (14). Such results are obtained because 3D scanners sample surfaces of 3D shapes uniformly and do not attempt to align the samples with the sharp edges and corners of the original shape. This problem can be solved by adding algorithms for sharp features recovering in triangulations (29).

With regards to scanning technology, blue light scanners (Identica, D2000, UP360, and UP300) achieved generally better results than white light scanners (DOF) and laser scanners (D810, DWS3). These findings correspond to the ones reported by Emir and Ayyildiz (16), showing that the structured blue light scanners produce fewer errors, and their outputs have greater repeatability.

To further explore the relationship between the differenc-

ciznost od 4 do 19,5 μm pri skeniranju pojedinačne implantološke nadogradnje (15). Konačno, u istraživanju skeniranja pripremljenog zuba koje su proveli de Villaumbrosia i suradnici (14), MAD vrijednosti (vjerodostojnost) bile su u rasponu od 29 do 46 μm, a standardna devijacija (preciznost) od 37,6 do 50,6 μm.

Tablica 1. otkriva da vrijednosti točnosti koje su naveli proizvođači skenera nisu usklađene s predstavljenim rezultatima. Različiti uvjeti skeniranja i korišteni parametri točnosti mogući su uzrok tih razlika. Posljedično, ističe se važnost detaljnog navođenja informacija vezanih za skenirani model te način obavljanja i evaluacije skeniranja.

No trenutačno ne postoji općeprihvaćeni prag vrijednosti kliničke točnosti dentalnih skenera. Naime, u dosadašnjim izvještajima o potrebnoj točnosti sugerira se da bi ta vrijednost trebala biti manja od 50 do 75 μm (15), 80 μm (34), 100 μm (35), 120 μm (8), ili 150 μm (36). Većina istraživanja slijedi rad McLeana i Fraunhofera (37) koji tvrde da dosjed na margini između bataljka i nadomjeska mora biti manji 120 μm. Također treba napomenuti da se pogreška u CAD/CAM procesu treba izračunati s obzirom na granicu kliničke točnosti pa iznos pogreške skenera mora biti manji.

Na oba modela i na razini cijele čeljusti, svim testiranim skenerima postignute su vrijednosti vjerodostojnosti i preciznosti koje zadovoljavaju minimalno propisano ograničenje (50 – 75 μm). Ipak, nedostatno je razmatrati kliničku točnost ako se koriste samo agregirane vrijednosti točnosti za cijele lukove (tj. čeljusti). Potrebno ju je usporediti na bočnim površinama nadogradnji i zuba prikazom na obojenim mapama. Obojene mape pokazuju značajnu razliku u odstupanjima na površini pri skeniranju Modela A. Odstupanja su posebno velika na područjima implantoloških nadogradnji gdje su se nekim skenerima postigli rezultati blizu najvišega dopuštenoga pozitivnog odstupanja. Budući da su ta područja ključna za konačnu funkcionalnost protetičkoga nadomjeska, odstupanja bi trebala ostati ograničena. Mogući uzrok za velika odstupanja na područjima nadogradnji jest u pojednostavljenom dizajnu s potpuno ravnim i glatkim površinama čeljusti i jednako strmim i glatkim površinama nadomjestaka. Takvi visoki i strmi nadomjestci mogu stvarati sjene koje sprječavaju pravilno skeniranje područja u sjeni ako skener nedovoljno nagne pločicu modela. Značajna odstupanja mogu se pojaviti zbog nedovoljnog kutnog pomaka pločice s modelom (kod skenera sa strukturiranim svjetlom) ili kamere skenera (kod laserskih skenera). Problemi pri skeniranju oštrih rubova ili nepravilnih područja istaknuti su i u dosadašnjim studijama (14). Problem se pojavljuje zbog uniformnog uzorkovanja površina 3D oblika, bez pokušaja usklađivanja uzoraka s oštrim rubovima i kutovima izvornog oblika. To se može umanjiti dodavanjem algoritama za rekonstrukciju oštrih značajki pri triangulaciji (29).

S obzirom na tehnologiju skeniranja, skenerima s plavim svjetlom (Identica, D2000, UP360 i UP300) generalno su postignuti bolji rezultati nego skenerima s bijelim svjetlom (DOF) i laserskim skenerima (D810, DWS3). Slično su ustanovili i Emir i Ayyildiz (16), pokazujući da skeneri sa strukturiranim plavim svjetlom imaju manju pogrešku i veću ponovljivosti skenova.

es in extraoral scanners' accuracy and the utilized scanning technologies, the presented study should be expanded to include a larger number of scanners of different generations. Furthermore, the research can be improved by utilizing additional models, such as models of whole arches with prepared teeth, models with scanning bodies, or models of an individual prepared tooth. Finally, another step in gaining a detailed insight into the accuracy of all types of dental scanners in different situations in dentistry would be to contrast the results obtained by extraoral scanners to those obtained by intraoral scanners.

Conclusion

The presented *in-vitro* study demonstrated that the scanning accuracy depends on the type of the scanned model. The revealed dissimilarities in the scanners' accuracy and their ranking when scanning different models lead to conclusions that model selection is critical for the research design, as it can significantly impact the obtained findings. Therefore, there is a need for creating a scanning methodology which will ensure the appropriate evaluation of scanners accuracy and enable comparison across the results of different studies.

Of the tested scanners, Identica showed the best accuracy when scanning jaws with abutments and jaws with natural teeth. On the other hand, DWS3 obtained the lowest accuracy results. Furthermore, the accuracy values reported by the scanner' manufacturers are better than those obtained in this study. Nevertheless, all scanners satisfied the clinical accuracy requirements and are suitable for use in laboratories for scanning jaws with abutments and jaws with natural teeth. With regards to scanning technology, the obtained results demonstrated that blue light scanners (Identica, D2000, UP360, and UP300) generally outperform white light scanners (DOF) and laser scanners (D810, DWS3).

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Conflicts of Interest

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Daljnja istraživanja odnosa između razlika u preciznosti ekstraoralnih skenera te korištenih tehnologija skeniranja trebala bi proširiti ovu studiju uključivanjem većeg broja skenera različitih generacija. Nadalje, istraživanje se može poboljšati korištenjem dodatnih modela, poput modela cijelih lukova s pripremljenim zubima (bataljcima), modela s tijelima za skeniranje ili modela pojedinačnih bataljaka. Konačno, dodatni korak prema dobivanju detaljnog uvida u preciznost svih vrsta dentalnih skenera u različitim stomatološkim situacijama bio bi ostvaren usporedbom dobivenih rezultata ekstraoralnih skenera s rezultatima intraoralnih skenera.

Zaključak

Ova studija *in-vitro* pokazala je da točnost skeniranja ovisi o tipu skeniranog modela. Otkrivene razlike u točnosti te poretku skenera pri skeniranju različitih modela pokazuju da odabir modela može znatno utjecati na rezultate i spoznaje, te se ističe važnost odabira modela pri dizajnu istraživanja. Zato je potrebno kreirati metodologiju skeniranja koja će osigurati odgovarajuću procjenu točnosti skenera i omogućiti usporedbu rezultata iz različitih studija.

Skenerom Identica postignuta je najveća točnost u usporedbi s ostalim testiranim skenerima, kako pri skeniranju čeljusti s implantološkim nadogradnjama, tako i pri skeniranju čeljusti s prirodnim zubima. S druge strane, uređajem DWS3 ostvareni su najniži rezultati kad je riječ o točnosti. Nadalje, vrijednosti točnosti prema specifikaciji proizvođača skenera trebale su biti više od onih dobivenih u ovom istraživanju. Unatoč tomu, svi su skeneri zadovoljili zahtjeve kliničke točnosti te su prikladni za upotrebu u laboratorijima za skeniranje čeljusti s implantološkim nadogradnjama i čeljusti s prirodnim zubima. Što se tiče tehnologije skeniranja, dobiveni rezultati pokazuju da se skenerima s plavim svjetlom (Identica, D2000, UP360 i UP300) općenito postižu bolji rezultati u usporedbi s onima koji se koriste bijelim svjetlom (DOF) ili laserskom tehnologijom (D810, DWS3).

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Autori nisu bili u sukobu interesa.

Etičko odobrenje

Svi postupci provedeni u istraživanju koji su uključivali ljudske sudionike bili su u skladu s etičkim standardima institucionalnog i/ili nacionalnog istraživačkog odbora te s Helsinškom deklaracijom iz 1964. i njezinim kasnijim amandmanima ili usporedivim etičkim standardima.

Informirani pristanak

Informirani pristanak dobiven je od svih sudionika uključenih u studiju.

Consent for publication

Consent for publication was obtained for every individual person's data included in the study.

Data Availability

All data are available upon request.

Author contributions: **M.T** and **S.Š.** - data collection; **M.T., S.Š.,** and **M.M.P.** - data analysis; **M.T.** - visualizations. All authors have been involved in data interpretation, drafting the manuscript and revising it critically. All authors have read and agreed to the published version of the manuscript. **F.L.** - contributed to the conceptualization, methodology and design of the study and participated in the interpretation of data, drafting the manuscript and its critical revision. All authors have made substantial contributions to the study conceptualization, methodology, and design.

Suglasnost za objavu

Sve osobe uključene u ovo istraživanje suglasne su s objavom članka.

Dostupnost podataka

Svi podatci dostupni su na upit.

Doprinos autora: **M. T. i S. Š.** – prikupljanje podataka, konceptualizacija, metodologija, dizajn, pisanje teksta, kritička revizija; **M. T., S. Š., i M. M. P.** – analiza podataka, konceptualizacija, metodologija, dizajn, pisanje teksta, kritička revizija; **M. T.** – vizualizacije, konceptualizacija, metodologija, dizajn, pisanje teksta, kritička revizija. **F.L.** – doprinjela konceptualizaciji, metodologiji i dizajnu studije te je sudjelovala u interpretaciji podataka, izradi rukopisa i njegovoj kritičkoj reviziji. Svi autori pročitali su i složili se s objavljenom verzijom rukopisa.

Sažetak

Cilj: U ovom istraživanju procijenjena je točnost (vjerodostojnost i preciznost) sedam ekstraoralnih skenera pri snimanju dvaju različitih tipova čeljusti – pojednostavljene čeljusti s oštrim rubovima i implantološkim nadogradnjama te realistične čeljusti s prirodnim zubima. Uspoređene su točnosti ekstraoralnih skenera, a raspravljena je i njihova usklađenost s propisanim kliničkim razinama točnosti. **Materijali i metode:** Modeli su pojedinim skenerom snimljeni po deset puta, a usporedba odabranih skenera temeljena je na referentnim skenovima napravljenima za oba modela. Vjerodostojnost, preciznost te raspodjela i vrijednost odstupanja točaka laboratorijskih skenova procijenjeni su za svaki skener na oba modela. **Rezultati:** Vrijednosti vjerodostojnosti za model pojednostavljene čeljusti s implantološkim nadogradnjama kretala se od 16,15 do 49,78 µm, a izmjerene vrijednosti preciznosti za isti model bile su od 4,33 do 29,49 µm. Na modelu realistične čeljusti s prirodnim zubima rezultati vjerodostojnosti varirali su od 11,32 do 24,55 µm, a dobivene vrijednosti preciznosti bile u rasponu od 2,29 do 18,06 µm. **Zaključak:** Otkrivene razlike u točnosti skenera i njihovu poretku pri skeniranju različitih modela dovode do zaključka da je odabir modela ključan za dizajn istraživanja. Svi skeneri zadovoljavaju kliničke zahtjeve za točnost i prikladni su za upotrebu u laboratorijima za skeniranje čeljusti s implantološkim nadogradnjama i čeljusti s prirodnim zubima. Međutim, vrijednosti točnosti koje je naveo proizvođač bolje su od onih dobivenih u ovom istraživanju. Nadalje, rezultati sugeriraju da skeneri s plavim svjetlom nadmašuju one s bijelim svjetlom i laserske skenere.

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