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ORIGINAL ARTICLE

Accuracy and reproducibility of measurements on plaster models and digital models created using an intraoral scanner

Genauigkeit und Reproduzierarkeit von Messungen an Gipsmodellen und digitalen Modellen

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Abstract

Aim The purpose of the present study was to evaluate the accuracy and reproducibility of measurements made on digital models created using an intraoral color scanner compared to measurements on dental plaster models.

Methods This study included impressions of 28 volunteers. Alginate impressions were used to make plaster models, and each volunteers' dentition was scanned with a TRIOS Color intraoral scanner. Two examiners performed measurements on the plaster models using a digital caliper and measured the digital models using Ortho Analyzer software. The examiners measured 52 distances, including tooth diameter and height, overjet, overbite, intercanine and intermolar distances, and the sagittal relationship. The paired t test was used to assess intra-examiner performance and measurement accuracy of the two examiners for both plaster and digital models. The level of clinically relevant differences between the measurements according to the threshold used was evaluated and a formula was applied to calculate the chance of finding clinically relevant errors on measurements on plaster and digital models.

Results For several parameters, statistically significant differences were found between the measurements on the two different models. However, most of these discrepancies were not considered clinically significant. The measurement of the crown height of upper central incisors had the highest measurement error for both examiners. Based on the interexaminer performance, reproducibility of the measurements was poor for some of the parameters.

Conclusions Overall, our findings showed that most of the measurements on digital models created using the TRIOS Color scanner and measured with Ortho Analyzer software had a clinically acceptable accuracy compared to the same measurements made with a caliper on plaster models, but the measuring method can affect the reproducibility of the measurements.

Keywords Digital model · Plaster model · Dental measurement · Intraoral scanning

Zusammenfassung

Zielsetzung Genauigkeit und Reproduzierbarkeit von Messungen auf digitalen Modellen, die nach intraoralen Farbscans hergestellt wurden, sollten verglichen werden mit der Genauigkeit und der Reproduzierbarkeit von auf Gipsmodellen vorgenommenen Messungen.

Methoden An der vorliegenden Studie nahmen 28 freiwillige Probanden teil. Zur Anfertigung von Gipsmodellen dienten Alginatabdrücke. Die Bezahnung jedes Probanden wurde mit dem TRIOS Color Intraoralscanner gescannt. Alle Modelle wurden von 2 Untersuchern vermessen: die Gipsmodelle mit einer digitalen Schieblehre, die digitalen Modelle mit der Software Ortho Analyzer. Vermessen wurden 52 Strecken, darunter

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Zahndurchmesser und –höhe, Overjet, Overbite, intercanine Distanz, der Intermolarenabstand sowie die sagittale Beziehung. Um die Intra-Untersucher-Performance und die Messgenauigkeit für die Untersucher und die beiden Modelle zu bestimmen, diente der gepaarte t-Test. Das Ausmaß klinisch relevanter Unterschiede zwischen den Messungen, je nach Schwellenwert, wurde evaluiert. Klinisch relevanter Messfehler an beiden Modellarten wurden berechnet.

Ergebnisse Für etliche Parameter zeigten sich statistisch signifikante Differenzen zwischen den Messungen auf den 2 unterschiedlichen Modelltypen, von denen die meisten allerdings als klinisch nicht signifikante Diskrepanzen angesehen wurden. Der größte Messfehler beider Untersucher zeigte sich bei der Messung der Kronenhöhe der oberen zentralen Inzisiven. Auf Grundlage der Inter-Untersucher-Performance erwies sich Reproduzierbarkeit der Messungen für einige Parameter als unzureichend.

Schlussfolgerungen Die Daten zeigen, dass die Genauigkeit der meisten Messungen mit der Software Ortho Analyzer auf digitalen Modellen, die unter Verwendung des Systems TRIOS Color Scanner erstellt wurden, im Vergleich mit der Genauigkeit der Schieblehremessungen an Gipsmodellen klinisch akzeptabel ist. Allerdings kann die verwendete Messmethode die Reproduzierbarkeit der Messungen beeinflussen.

Schlüsselwörter Digitales Modell · Gipsmodell · Vermessung · Intraorale Scans

Introduction

Digital models in orthodontics are often obtained via an indirect method that requires the transport of plaster models or impressions of the dentition to a specialized company for laser or CT scanning [1, 3, 5, 8, 13–16, 19–22, 24–26]. During transportation, it is possible that plaster models can fracture [2] and the dental dimensions of the impressions can change [20, 22]. Thus, there is interest in direct methods to copy the dentition. Directly measuring of the dentition with calipers is possible, but this method is difficult and time consuming [20] and does not result in a physical dental model which is available for later use. Cone beam computer tomography (CBCT) radiographs can also be used for dental analysis [5, 11, 14], but this method involves exposing the patient to radiation [5]. An alternative that does not involve radiation exposure is the intraoral scanning, which also has the advantage of improved detailing of the dental anatomy compared to CBCT images of the dentition [2].

Intraoral scanners have been recently introduced as a replacement for the dental impression-taking procedure. An intraoral scanner is easy to use and generates stereolithographic (STL) files that can be used to make digital models. Registration of an occlusion with an intraoral scanner does not require a separate material for bite registration [24, 25]. Most patients have reported that the intraoral scanning procedure is more comfortable than conventional impression taking, although some studies have reported the opposite conclusion [10]. Currently, the mean time needed for intraoral scanning is shorter than that required for taking traditional PVS impressions (one impression with heavy material and a second impression with soft impression material), but the intraoral scanning time is longer than required for the alginate impression procedure [10]. It is expected that improvements of the scanners, the scanning software, and the use of faster computers enable reduction of the scanning time. Although several intraoral scanners have been commercialized for use in orthodontics, only the scanners Lava COS (3 M ESPE, St Paul, MN, USA) and iTero (Align Technologies, San Jose, CA, USA) were tested under clinical conditions [9].

The intraoral scanning procedure could be more accurate than traditional impression taking, as intraoral scanning is not prone to some of the errors that can occur in the traditional impression-taking procedure, such as air bubbles, rupture of impression material, inaccurate impression tray dimensions, too much or too little impression material, inappropriate adhesion of the impression to the impression tray, and impression material distortion due to the disinfection procedure [23]. Intraoral scanning could also be particularly advantageous for patients with anxiety during impression taking (especially for the upper impression), and for cleft palate patients who could carry an increased risk of aspiration of impression material and for whom standard impression trays are not suitable [4]. Intraoral scanning could also be an advantage for patients currently undergoing orthodontic treatment with fixed appliances, for whom a traditional impression will be severely distorted because of the presence of orthodontic appliances.

The cost of purchasing an intraoral scanner could be a profitable investment for an orthodontic office, as the intraoral scanning procedure will decrease the need to retake inaccurate dental impressions, as well as the need for impression disinfection and transportation. In addition, the use of digital models will eliminate the need for dedicated space to store dental plaster models in an orthodontic office. Another advantage is that the digital models are immediately available and can be used to discuss treatment with the patient during the record taking visit. Software for intraoral scanners can be used for digital model analysis, and segmentation software can be used for dental crown segmentation to make a digital dental setup for digital planning of orthodontic treatment. Furthermore, a digital model can be electronically sent to an orthodontic laboratory anywhere in the world to order custom removable or fixed orthodontic appliances. If needed, a physical dental model can be printed using a 3D printer in the orthodontic lab or in the orthodontic office [12].

Several studies have evaluated the accuracy and reliability of making digital models using different acquisition methods, including laser scanning of plaster models [1, 3, 14–16, 19–21], laser scanning of impressions [3, 8, 13, 26], CT scanning of impressions [5, 10, 22, 24, 25], and intraoral scanning [2, 4, 7, 10, 17, 23, 25]. These studies used different scanners and different software programs, which limits the comparability of the results. Most of these studies found statistically different measurements of digital models as compared to the same measurements made on plaster models, but few of these measurement differences were clinically relevant [22, 24].

The present study aimed to evaluate the accuracy and reproducibility of digital models constructed from the files of intraoral scans of volunteers with the TRIOS Color scanner (3Shape®, Copenhagen, Denmark), which has not been previously studied in a clinical setting [9]. Measurements on plaster models of these volunteers were compared to measurements on the digital models with the Ortho Analyzer® software (3Shape®, Copenhagen, Denmark).

Materials and methods

Using plaster models of 10 individuals, a power study was performed applying the formula described by Pandis [18], assuming 90% power and an α of 0.05. This power study showed that a series of dental models and intraoral scans from at least 29 individuals were needed to reveal a 1-mm difference in measurements with a 1.16 mm standard deviation.

Volunteers were recruited at the Department of Orthodontics of Federal Fluminense University. A total of 30 volunteers included in this study had fully erupted permanent dentition (including all upper and lower first permanent molars). Exclusion criteria were: dental anomalies in size and shape, severe gingival recessions, dental crown abrasions, attritions and erosions, or fixed orthodontic retention. At the time of impression taking, the volunteers were all between 21 and 39 years of age, with an average age of 27 years. All volunteers were informed about the study procedures and signed an informed consent form prior to participation. The local ethical committee approved this study (number 221.664) on February 1, 2013.

Participants underwent a clinical examination, after which alginate impressions of the upper and lower arch were made with Hydrogum® (Zhermack, Badia Polesine, Rovigo, Italy), following the manufacturer's guidelines. Bite registration in maximum intercuspation was obtained with a number 7 dental wax (Clássico®, São Paulo, Brazil) and was used to trim the plaster models. The teeth and alveolar ridges in the alginate impressions were filled with type IV plaster (Vigodent®, Rio de Janeiro, Brazil) within 1 h after the impression taking, and the base of the models was made from white plaster (Mossoró, Rio de Janeiro, Brazil) (Fig. 1).

The volunteers also underwent intraoral scanning of their dentition with the TRIOS Color scanner. Before the start of this study, one examiner was trained in the optimal use of the intraoral scanner. During intraoral scanning, a frame on the computer monitor appears in green (indicating best capture), yellow (regular catch) or red (no image capture). Once the dentist had learned to use the intraoral scanner properly and effectively, the scanning of the dentition of the selected volunteers started.

Following the manufacturer's instructions for the machine, the upper arch was scanned first, followed by the lower arch. After scanning both arches, the volunteer was instructed to occlude in maximum intercuspation to enable scanning of the occlusion on both the right and left sides of the arches. The scanner software then positioned the arches in occlusion. Upon completion of the scanning procedure, the STL files were transferred to Ortho Analyzer software to create digital models (Fig. 2). Analyzing the digital model quality revealed that two pair of the digital models included in the collection of the material for this study were inadequate. These two volunteers were asked to return for rescanning but could not comply. Thus, the final study sample included digital models of 28 volunteers.

Fifty-two defined distances (Table 1) were measured on the dental models by two trained and calibrated examiners. Measurements on plaster models were made using a digital caliper with an accuracy of hundredths of millimeters (Starrett, Itu, São Paulo, Brazil) (Fig. 3). Measurements on digital models were performed using the Ortho Analyzer® software (Fig. 4). To investigate the error involved with

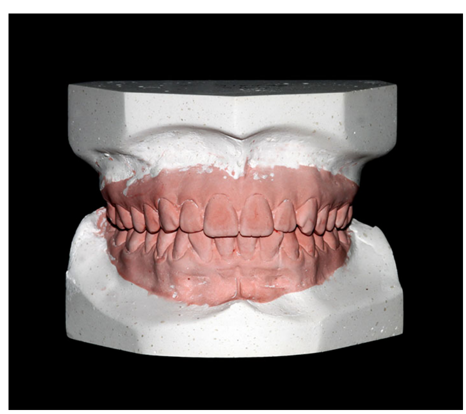

Fig. 1 Example of a plaster model
Abb. 1 Beispiel eines Gipsmodells

Fig. 2 Digital model from the intraoral scanner (TRIOS Color)
Abb. 2 Digitales Modell nach Verwendung eines Intraoralscans (TRIOS Color)

each method, the measurements of 10 cases of the sample (randomly selected) were repeated after 15 days by the examiners.

Statistical analysis

Statistical analyses were performed using the SPSS program, version 20.0 (IBM, Chicago, IL, USA). The measurements on plaster models were defined as a gold standard and the outcome of these measurements was compared to the measurements on the digital models from the TRIOS intraoral scanner with the paired *t*-test. For each outcome, a threshold, as described in the literature, was defined to discriminate between a relatively small difference in measurements and a difference that could influence treatment decisions or the accuracy of appliances made on these models (a clinically relevant difference). According to the literature, differences larger than 0.3 mm for the overjet, overbite, and tooth size (tooth diameter and tooth height) and larger than 0.4 mm for transverse and sagittal parameters were considered clinically relevant [6, 15, 17]. For clinically relevant differences in the sum of 6 anterior teeth in the upper or lower dental arch, a threshold of 0.75 mm was used. For the sum of 12 teeth in the upper or lower arch, a difference of 1.5 mm was used as a threshold [21, 25]. For each outcome and for both observers separately, the chance that a measurement error was larger than this threshold was calculated. The mean difference between measurements on the digital and plaster models was calculated (mean dif) and the duplicate measurement error (DME) for digital and plaster models according to each intra-examiner measurements was also registered. The measurement error is the sum

Tab. 1 Parameter definitions
Tab. 1 Definitionen der Parameter

Parameter	Abbreviation	Definition
Mesiodistal diameter	MDD	Upper and lower mesiodistal diameter of each tooth from 1st molar to 1st molar (largest mesiodistal diameter of the mesial contact point to the distal contact point, parallel to the occlusal plane)
Sum of upper 6 teeth	Sum upper 6	Diameter sum of 6 anterior upper teeth
Sum of upper 12 teeth	Sum upper 12	Diameter sum of 12 anterior upper teeth
Sum of lower 6 teeth	Sum lower 6	Diameter sum of 6 anterior lower teeth
Sum of lower 12 teeth	Sum lower 12	Diameter sum of 12 anterior lower teeth
Crown height	CH	Upper and lower crown height of upper and lower 1st molars, 1st premolars, canines and central incisors (from incisal edge or cusp tip to the lower gingival margin from the vestibular axis of each clinical crown—Andrews)
Upper intercanine distance	Upper ICD	Distance between the cusp tip of the upper left canine to cusp tip of the upper right canine
Upper intermolar distance	Upper IMD	Distance between the tip of the mesiobuccal cusp of the upper left 1st molar to the tip of the mesiobuccal cusp of the upper right 1st molar
Lower intercanine distance	Lower ICD	Distance between the cusp tip of the lower left mandibular canine to cusp tip of the lower right canine
Lower intermolar distance	Lower IMD	Distance between the tip of the mesiobuccal cusp of the lower left 1st molar to the tip of the mesiobuccal cusp of the lower right 1st molar
Overjet	Overjet	Distance from the middle of the incisal edge closest to the buccal surface of the upper right maxillary central incisor to the buccal surface of the lower incisor antagonist, parallel to the occlusal plane
Overbite	Overbite	Vertical distance between the marking where the incisal edge of the upper right central incisor overlaps the buccal surface of the lower incisor antagonist until its respective incisal edge
Interarch right sagittal relationship	Right Sag Rel	Distance from the cusp tip of the upper right canine to the marking where the mesiobuccal cusp of the upper right 1st molar occludes to the lower arch
Interarch left sagittal relationship	Left Sag Rel	Distance from the cusp tip of the upper left canine to the marking where the mesiobuccal cusp of the upper left 1st molar occludes to the lower arch

Fig. 3 Measuring the lower intermolar distance on a plaster model with a digital caliper
Abb. 3 Vermessung der intermolaren Distanz im Unterkiefer auf einem Gipsmodell mit einer digitalen Schieblehre

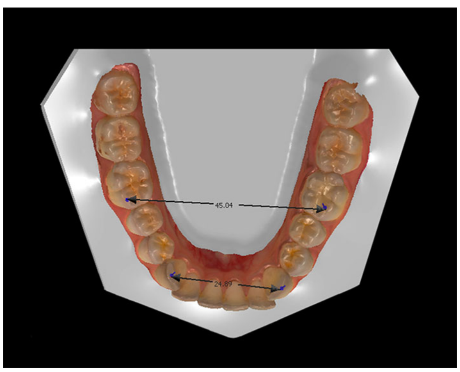

Fig. 4 Measuring the lower intermolar and intercanine distances on a digital model with Ortho Analyzer software
Abb. 4 Vermessung der intermolaren und intercaninen Distanz im Unterkiefer auf einem digitalen Modell mit der Software Ortho Analyzer

of the mean difference and a random error, which is a normally distributed variable with a mean value of 0 and a standard deviation of DME. Then, a statistical formula was used to calculate the chance to find clinically relevant differences, above the thresholds described, named as ClinRel value (clinically relevant value):

$$\text{ClinRel value} = P(\text{mean dif} + \text{random error}) > \text{threshold} + P(\text{mean dif} + \text{random error}) < -\text{threshold}$$
$$= P\left(Z > \left(\frac{threshold - mean\ dif}{DME}\right)\right) + P\left(Z < \left(\frac{-threshold - mean\ dif}{DME}\right)\right)$$

with Z a normally distributed random variable, with mean of 0 and standard deviation (SD) of 1.

For plaster models this formula was used as well. Obviously, the mean difference was 0, as plaster was defined as the gold standard. But repeated measurements revealed a certain random error. So, for the measurement on plaster the formula above was applied but the "mean dif" was left out, because it is 0. This formula calculated the chance that, due to random error alone, a measurement on plaster shows a significant error. A larger ClinRel value means an increased chance of clinically relevant errors. Arbitrarily, it was considered as a reference that ClinRel values larger than 0.3 represent more than 30% of chances to occur measurements differences with a potential clinical impact.

Results

Tables 2 and 3, respectively, describe the results of the measurements of examiners 1 and 2. *P* values of selected parameters regarding the intra-examiner accuracy of the measurements on plaster and digital models and the differences between the measurements made on plaster and digital models are described. Several parameters presented statistically significant differences; however, in the two last columns of Tables 2 and 3, the ClinRel values represent the chances to measure clinically relevant differences on the plaster and digital models.

According to the results of examiner 1, the ClinRel value for measurements on plaster models presented a higher chance of a clinically relevant measurement error in the crown height of upper first molars, lower intercanine distance, overbite, and left sagittal relationship. For measurements on the digital models, the parameters with *ClinRel* values over 0.3 (clinically relevant differences) were as follows: the sum of 6 and 12 lower teeth; crown height of upper first molars, upper central incisors, lower first molars and lower first premolars; upper and lower intercanine distances; lower intermolar distance and left sagittal relationship (Table 2).

The outcome of the measurements of examiner 2 are presented in Table 3. These measurements showed a high chance on a clinically relevant measurement error for measurements on plaster of the upper and lower intermolar distance and for the left sagittal relationship. Regarding the TRIOS measurements, the following parameters had a high chance to find a clinically relevant measurement error: sum of 6 upper teeth, crown height of upper first premolars and upper central incisors, and upper and lower intermolar

Tab. 2 Measurements of examiner 1
Tab. 2 Messwerte, Untersucher 1

Parameter	Mean dif Plaster and Trios (mm)	DME Plaster (mm)	DME Trios (mm)	Intraexaminer performance Plaster *P* value	Intraexaminer performance Trios *P* value	Dif. Plaster and Trios *P* value	Critical value (mm)	**ClinRel value Plaster**	**ClinRel value Trios**
Sum 6 Upper teeth	−0.306	0.159	0.468	0.221	**0.008**	**0.014**	0.75	0.000	0.184
Sum 12 Upper teeth	−0.301	0.327	0.723	0.160	**0.001**	0.181	1.5	0.000	0.055
Sum 6 Lower teeth	−0.743	0.287	0.275	0.102	**0.005**	**0.000**	0.75	0.009	0.490
Sum 12 Lower Teeth	−1.421	0.383	0.575	0.768	**0.000**	**0.000**	1.5	0.000	0.445
CH 16 and 26	−0.230	0.348	0.315	0.521	0.295	**0.001**	0.3	0.389	0.458
CH 14 and 24	−0.109	0.153	0.211	0.290	0.108	**0.008**	0.3	0.051	0.211
CH 13 and 23	−0.195	0.098	0.097	0.582	0.633	**0.000**	0.3	0.002	0.141
CH 11 and 21	−0.337	0.151	0.113	0.781	0.621	**0.000**	0.3	0.047	0.629
CH 36 and 46	−0.157	0.195	0.290	0.173	0.539	**0.008**	0.3	0.124	0.369
CH 34 and 44	−0.002	0.084	0.298	0.063	0.086	0.952	0.3	0.000	0.314
CH 33 and 43	0.024	0.102	0.217	0.070	0.086	0.572	0.3	0.003	0.169
CH 31 and 41	−0.010	0.094	0.124	**0.002**	**0.017**	0.790	0.3	0.001	0.015
Upper ICD	0.401	0.258	0.5877	**0.013**	0.451	**0.008**	0.4	0.122	0.587
Lower ICD	−0.306	0.409	0.519	0.958	0.430	**0.027**	0.4	0.328	0.515
Upper IMD	0.038	0.281	0.214	0.392	0.593	0.606	0.4	0.155	0.065
Lower IMD	−0.423	0.261	0.983	0.375	0.280	**0.002**	0.4	0.125	0.710
Overjet	0.107	0.182	0.043	0.473	0.960	0.159	0.3	0.099	0.000
Overbite	0.181	0.343	0.006	0.500	0.081	0.088	0.3	0.382	0.000
Right Sag Rel	0.133	0.339	0.246	0.165	0.421	0.251	0.4	0.239	0.155
Left Sag Rel	−0.046	0.488	0.396	0.083	0.831	0.732	0.4	0.412	0.316

Bold values indicate $P < 0.05$

mean dif mean difference between measurements on the digital and plaster models was calculated, *DME* duplicate measurement error, other abbreviations provided in Table 1

Tab. 3 Measurements of examiner 2
Tab. 3 Messwerte, Untersucher 2

Parameter	Mean dif. plaster and trios (mm)	DME plaster (mm)	DME trios (mm)	Intraexaminer performance plaster *P* value	Intraexaminer performance trios *P* value	Dif. plaster and Trios *P* value	Critical value (mm)	ClinRel value plaster	ClinRel value trios
Sum 6 upper teeth	0.722	0.321	0.356	0.751	**0.000**	**0.000**	0.75	0.019	0.469
Sum 12 upper teeth	0.635	0.721	0.550	0.562	**0.000**	**0.002**	1.5	0.037	0.058
Sum 6 lower teeth	−0.446	0.244	0.375	0.241	**0.012**	**0.000**	0.75	0.002	0.210
Sum 12 lower Teeth	−0.970	0.538	0.514	0.404	**0.000**	**0.000**	1.5	0.005	0.151
CH 16 and 26	−0.103	0.170	0.209	0.805	0.539	0.124	0.3	0.078	0.201
CH 14 and 24	−0.262	0.176	0.133	0.119	**0.000**	**0.000**	0.3	0.088	0.388
CH 13 and 23	−0.223	0.123	0.131	0.058	0.075	**0.000**	0.3	0.015	0.281
CH 11 and 21	−0.367	0.207	0.069	0.281	**0.021**	**0.000**	0.3	0.1490	0.834
CH 36 and 46	−0.225	0.191	0.135	0.087	0.132	**0.000**	0.3	0.116	0.289
CH 34 and 44	−0.118	0.285	0.101	0.104	0.583	**0.009**	0.3	0.292	0.037
CH 33 and 43	−0.057	0.150	0.092	**0.040**	0.906	0.194	0.3	0.046	0.004
CH 31 and 41	−0.079	0.085	0.082	0.784	0.241	**0.045**	0.3	0.000	0.003
Upper ICD	0.261	0.266	0.203	0.388	0.062	0.066	0.4	0.133	0.247
Lower ICD	−0.085	0.309	0.209	0.922	0.161	0.451	0.4	0.196	0.076
Upper IMD	0.013	0.394	0.403	0.545	0.560	0.869	0.4	0.310	0.321
Lower IMD	0.035	0.432	0.476	0.896	0.301	0.743	0.4	0.354	0.402
Overjet	−0.007	0.129	0.191	0.196	0.190	0.865	0.3	0.020	0.116
Overbite	0.127	0.144	0.024	0.104	**0.026**	0.202	0.3	0.038	0.000
Right Sag Rel	−0.075	0.136	0.308	0.425	0.112	0.546	0.4	0.003	0.207
Left Sag Rel	−0.019	0.467	0.248	0.157	0.060	0.890	0.4	0.392	0.108

Bold values indicate $P < 0.05$

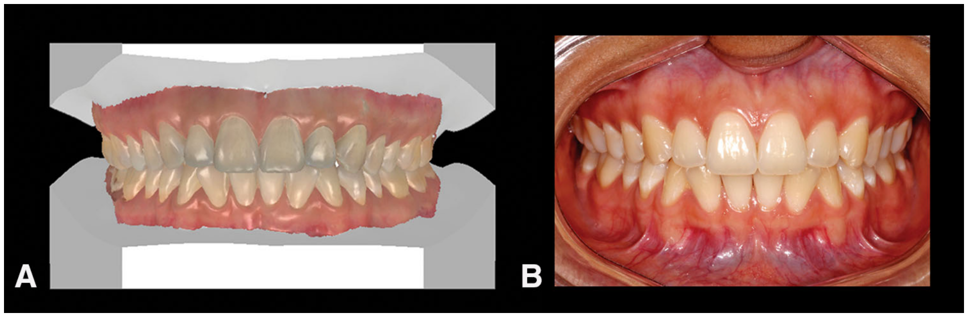

Fig. 5 **a** Digital model from the intraoral scanner (TRIOS Color); **b** Intraoral photograph of the same patient
Abb. 5 **a** Mittels intraoraler Scans erstelltes digitales Modell (TRIOS Color). **b** Intraorales Foto, gleicher Patient

distance. The crown height of upper central incisors presented the largest ClinRel values for both examiners. The DME of digital models showed larger variability when compared to the DME of the plaster models for examiner 1. This difference in DME between the measurements was not found for examiner 2.

Discussion

The use of direct methods to obtain digital dental models is already widely practiced in orthodontics. For the orthodontist, intraoral scanning represents a tool for rapid acquisition of a digital model, and an alternative to the indirect impression method. The TRIOS Color intraoral scanner used in this study, captures the dentition and the oral cavity without the need to apply powder to the patient's teeth and mucosa, and the accuracy of the digital models made with this scanner had not been previously studied [9]. The color display of the dentition and mucosa permits accurate location of the gingival margin, allowing the acquisition of high-definition photos for documentation or communication purposes. According to the manufacturer, the images produced by this scanner could replace traditional intraoral imaging with photographs (Fig. 5). Furthermore, if an error occurs during scanning, the specific region can easily be rescanned without making a new impression, which can save time.

Studies have shown that measurements made on plaster models may not represent the actual dentition measurements due to possible dimensional changes in impression material and the fabrication process of the plaster model [20, 22]. However, plaster models have been used for measurements and appliance fabrication for many years and have been used in the research literature as a standard. Thus, for this reason plaster models were also selected as the gold standard in this study. In the literature it has been suggested that intraoral scanning could result in digital models that represents the intraoral situation more accurately because the direct method could result in fewer sources of error [10]. It would have been better to compare measurements on a 100% reliable reference model with clearly defined measurement markers as a standard and a copy of this reference model (a plaster model and a scanned model).

The selected reference points for defining various measurements may vary between examiners, even when the points are precisely described. In the literature it has been reported that inadequate reference point location directly affects measurement reproducibility [1, 16, 20, 26], and therefore measurements on plaster models and digital models are automatically associated with some degree of interpretation inaccuracy. Measurement on digital dental models with dedicated software could reduce the problem of point identification as it is easier on digital models due to the possibility to enlarge and "clip" the digital model [4].

The procedure to scan the dentition, the alveolar bone, and the palate is not difficult. However, inexperienced practitioners will find completion of the first intraoral scans to be more time consuming [10, 25]. Therefore, a practitioner's level of familiarity with the scanning system will substantially influence the time needed to complete the scans [10]. Examiners also need training to use specific software to measure the dentition. In the present study, both examiners were trained and calibrated for both measurement methods, but according to the DME values, poor reproducibility was found by both examiners especially in transversal and sagittal parameters and in the sum of tooth diameters. In the literature, it was reported that a high reliability for measurements on digital models can be achieved [2, 17, 25], the cause of the low reproducibility found in this study should be evaluated in a future study.

The paired *t*-test showed that several parameters presented clinically relevant differences, especially in transversal and sagittal parameters and in the sum of teeth diameters. In contrast to the results of some other studies [4, 17, 25], the distances measured on digital models were slightly larger compared to the measurements on plaster models. In the sum of upper 6 and 12 teeth, examiner 1 found larger measurement values for digital models, than examiner 2. For the sum of the dimensions of the lower 6 and 12 teeth, both examiners found higher values for the measurements on the digital models. These differences in measurements can be caused by the measuring method (caliper vs. digital measurement) but also by the difference in selection of the measurement point's position. To reduce the measurement error, two examiners performed the measurements in this study twice. For the difference in dental diameters, none of the measurements presented a ClinRel value over 0.3 for examiner 2 for plaster and digital models, but for examiner 1 the ClinRel value for the differences in measurements was over 0.3 for lower first molars and lower canine diameters. Clinically relevant errors were reported for measurements on digital models in the sum of 6 and 12 lower teeth by examiner 1 and in the sum of 6 upper teeth by examiner 2.

In relation to the crown height, the upper central incisors and first molars presented the largest clinical errors, possibly because of the structural differences between the plaster and digital models. The digital measuring tool used (direct measurement) available in Ortho Analyzer software could affect the measurement accuracy especially on teeth with a more buccal inclination as upper central incisor. In this case, other measuring tool as the "digital caliper measurement" could be more accurate to measure the crown height of these teeth. In contrast, most of the crown height of lower teeth presented low ClinRel values. In general, digital models had higher values in crown height compared to the plaster models.

For measurements of the transversal distances the upper and lower intercanine distances showed larger ClinRel values for examiner 1, but not for examiner 2. The upper intermolar distance presented larger values only for examiner 2 and the lower intermolar distance presented larger chances of clinically relevant errors for both examiners. These results were influenced by the high value of DME registered on the digital and plaster models. This can be explained by possible misinterpretations during the selection of reference points (center of the cusp), mainly on teeth with attrition on the reference cusp.

Regarding the interarch relationship parameters (overjet, overbite, and sagittal relationship), no clinically relevant differences were found on digital models, with exception of the left sagittal relationship by examiner 1. Measurement of the overbite showed lower ClinRel values for digital models for both examiners, but examiner 1 presented a large ClinRel value on plaster models. These results suggest that the possibility of clipping the digital models can result in a more accurate measuring method compared to the measuring of the overbite with a caliper on the plaster model.

In the literature, it has been reported that the occlusion of the digital models made by scanning a plaster model or dental impression and the use of a wax bite registration of the interarch relation can be inaccurate [25]. When intraoral scanners are used, a direct method is used to register the relationship between the upper and lower dentition. In this study a similar occlusion of the digital models from the intraoral scanner compared to plaster models was found, so both methods can be considered reliable.

Several studies evaluated the accuracy of digital models made with intraoral scanners, compared to the accuracy of the dentition on scanned plaster models or scanned dry skulls [2, 4, 7, 10, 23]. In other studies, the dentition of volunteers was scanned [7, 10, 17, 25]. One study compared the accuracy of digital models from scanning plaster models with those from intraoral scanning of the dentition of patients. In this study, it was reported that the scanned plaster models had a higher accuracy [7]. In their publication, the authors mention that the inaccuracy of the intraoral scanning of a patient in this study could have been caused by several factors, including movement of the patient during scanning, limited intraoral space, the presence of moisture and saliva, and an inadequate intraoral scanning technique [7].

In our study, several difficulties with the intraoral scanning procedure were registered. The instructions for the scanner used in this present study state that intraoral scanning data will be more accurate when the field to be scanned remains dry during the scanning procedure. But maintaining a dry field during scanning of posterior teeth, especially third molars in patients with limited mouth opening was sometimes difficult. It was sometimes also difficult to scan the bottom of the oral vestibule. This problem was related to the dimensions of the scanning tip, the interference between the tip and the patient's coronoid process, and moisture control. According to a study of Grunheid et al. [10], most patients mentioned that the scanning of the buccal surfaces of the maxillary second and third molars was uncomfortable. As scanning technology continues to evolve, the scanning process can be faster and the design of a thinner scanning tip may improve comfort and this will increase patient acceptance of the scanning procedure. As the accuracy of TRIOS Color intraoral scanner compared to plaster models was clinically acceptable for most of the measurements, this scanner can be used as an alternative for the traditional impression technique. However to improve the reproducibility of the measuring method, the parameters should be better standardized on both plaster and digital models [9].

Conclusion

The results show that some measurements on digital models presented a high chance to find a clinically relevant measurement error compared to measurements on plaster models. The measurement of the crown height of upper central incisors on digital models showed the largest clinically relevant error for both examiners. The differences between the measurements can be caused by actual differences of the models or can be caused by the measurement method. The reproducibility of the measurements was different between the examiners for some parameters. Despite the presence of some clinically relevant chances of error, it can be assumed that digital models from TRIOS Color intraoral scanner can be used to replace the plaster models for clinical use in orthodontics.

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Compliance with ethical guidelines

Conflict of interest L.T. Camardella, H. Breuning, and O. de Vasconcellos Vilella declare that they have no competing interests.
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 was obtained from all individual participants included in the study.

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