Trueness of Maxillomandibular Relationship in 3D-printed and Conventional Casts

Liudas Auškalnis [a,*], Mykolas Akulauskas [b], Cecilie Osnes [c], Marta Revilla-León [d], Aistė Kernen Gintautė [e] (shared last authorship), Vygandas Rutkūnas [f]

[a] PhD student, Department of Prosthodontics, Institute of Odontology, Faculty of Medicine, Vilnius University, Vilnius, Lithuania

[b] PhD student, Biomedical Engineering Institute, Kaunas University of Technology, Kaunas, Lithuania

[c] Research Assistant, School of Dentistry, University of Leeds, Leeds, UK

[d] DDS, MSD, PhD, Affiliate Assistant Professor, Graduate Prosthodontics, Department of Restorative Dentistry, School of Dentistry, University of Washington, Seattle, Wash and Faculty and Director, Research and Digital Dentistry, Kois Center, Seattle, Wash; Adjunct Professor, Department of Prosthodontics, School of Dental Medicine, Tufts University, Boston, Mass

[e] Dr. med. dent., University Hospital Freiburg, Center for Dental Medicine, Department of Prosthetic Dentistry

[f] Professor, PhD, Department of Prosthodontics, Institute of Odontology, Faculty of Medicine, Vilnius University, Vilnius, Lithuania

[*] Corresponding author

E-mail addresses: liudas.auskalnis@gmail.com (L. Auškalnis), akulauskas.m@gmail.com (M. Akulauskas), C.A.Osnes@leeds.ac.uk (C. Osnes), marta.revilla.leon@gmail.com (M. Revilla-Leon), aiste.gintaute@unibas.ch (A. Gintautė), vygandasr@gmail.com (V. Rutkūnas)

Funding:

Lithuanian Business Support Agency grant Nr. J05-LVPA-K-01-0055 and DIGITORUM research group and laboratory support for material preparation and data acquisition.

#

Trueness of Maxillomandibular Relationship in 3D-printed and Conventional Casts

ABSTRACT

Objectives. To compare the trueness of maxillomandibular relationship between articulated 3D-printed and conventional diagnostic casts in maximum intercuspation (MIP).

Methods. Reference casts were articulated in MIP, and scanned using a Coordinate Measurement Machine (CMM, n=1). Digital scans were made from the reference casts by using an intraoral scanner (IOS, n=10) (Trios 4; 3Shape A/S). IOS scans were processed to create 3D-printed casts by using MAX UV385 (Asiga) and NextDent 5100 (3DSystems) 3D-printers. The conventional workflow implemented vinylpolysiloxane (VPS) impressions and Type IV stone. Stone and 3D-printed casts were articulated and digitized with a laboratory scanner (E4; 3Shape A/S). The 3D-printed casts were scanned on two occasions: with and without positioning pins. Inter-arch distances and 3D-contact area were measured and compared. Statistical tests used were Shapiro-Wilk, Levene's, Welch's t-test, and 2-way ANOVA (α=.05).

Results. IOS group showed similar or better maxillomandibular relationship trueness than stone casts and 3D-printed casts ($p<0.05$). 3D-contact area analysis showed similar deviations between 3D-printed and stone casts ($p>0.05$). The choice of 3D-printer and presence of positioning pins on the casts significantly influenced maxillomandibular relationship trueness ($p<0.05$).

Conclusions. Articulated 3D-printed and stone casts exhibited similar maxillomandibular relationship trueness.

Clinical Significance. Although 3D-printing methods can introduce a considerable amount of deviations, the maxillomandibular relationship trueness of articulated 3D-printed and stone casts in MIP can be considered similar.

KEYWORDS: Intraoral scanner; 3D-printing; Trueness; Dental Occlusion

1. Introduction

The inaccurate replication of the maxillomandibular relationship in dental casts can lead to a range of clinical challenges. These include imbalances in force distribution during mastication, which may stress periodontal tissues [1,2], increase wear on dental surfaces, lead to restoration chipping or failure, and result in patient discomfort and dissatisfaction [3–5]. Moreover, correcting such inaccuracies intraorally in multiple restorations is time-consuming and negatively impacts both clinical efficiency and patient experience [6].

Dental stone casts derived from conventional impressions are still considered a gold standard and are widely used in dentistry [7]. However, stone casts bear several limitations, such as time-consuming manufacturing, potential distortions, and propensity to break [8–10]. In contrast, digital technologies offer an alternative to conventional procedures. It provides immediate visualization, rapid iteration potential, improved patient comfort, and simplified data storage and sharing [11–14]. Yet, despite the advantages, the evaluation and representation of a digital maxillomandibular relationship in maximum intercuspation position (MIP) is still missing [15–17]. Moreover, a recent systematic review reported that the accuracy of MIP acquired by IOS can be highly influenced by the IOS technology, scan extension, edentulous areas, number, location, and extension of occlusal records, occlusal force, tooth mobility, and alignment methods [18].

The advent of digital technologies may allow a transition into a fully digital workflow, eliminating the need for physical casts [19–21]. However, as of the present, a hybrid workflow is still necessary in many clinical cases, combining digital technologies with the manual skills of dental technicians and additively manufactured (AM, or 3D-printed) casts [6,10,22,23]. Notwithstanding the diversity of AM technologies in cast fabrication, Stereolithography (SLA), Direct Light Processing (DLP) and Liquid Crystal Display (LCD) methods have gained prominence [10,24,25]. The accuracy of individual casts created using these photopolymerization-based techniques is well-researched [10,22,24], nevertheless, there is a lack of comprehensive investigation into the accuracy of the maxillomandibular relationship [26]. This highlights the importance of investigating and comparing the accuracy of 3D-printed and conventional stone casts. Therefore, the study aims to evaluate the trueness of the maxillomandibular relationship of digitally and conventionally manufactured dental casts. The null hypothesis of this study was that the accuracy of the maxillomandibular relationship (3D-contact area and inter-arch distances) does not differ between 3D-printed and stone casts.

2. Materials and methods

2.1. Study design

Two types of measurements were conducted: 3D-contact area and inter-arch distances. The study scheme is provided in **Figure 1**.

2.2. Reference casts

Partially edentulous maxillary and fully dentate mandibular casts were additively manufactured (MAX UV385; Asiga, Sydney, Australia) and used as the reference casts. Five precision spheres (Micro Surface Engineering, Inc., Los Angeles, California), with a diameter of 5 mm, were attached with an auto-polymerizing acrylic resin (Pattern Resin; GC America Inc., Alsip, IL, USA) at the base of each cast (**Fig. 2**). The sphere centre was later used to calculate distances between the maxillary and mandibular arches. Both reference casts were mounted in an articulator (PROTARevo 7; KaVo Dental GmbH, Biberach, Germany). After four weeks, the position of the maxillary cast was recorded using a facebow (ARCUSevo; KaVo). The same facebow record and the same articulator were used to fix all study casts. Thus, the identical cast position and standardized measurements were ensured.

2.3. Reference data set

The reference casts were subsequently scanned using a coordinate measurement machine (CMM) equipped with an LC15Dx laser scanning head (ALTERA 10.7.6; Nikon, Shinagawa, Tokyo, Japan). Initially, maxillary and mandibular casts were digitized separately. Then, both casts were fixed in the articulator, stabilized with a twisted rubber band (3Shape A/S, Copenhagen, Denmark), and a buccal scan was performed (**Fig. 3**). The scan data was exported into a Standard Tessellation Language (STL) format and the reference dataset was generated (CMM, n=1).

2.4. Test data set

Digital impressions with an intraoral scanner were conducted within 48 hours following the CMM scanning procedure. Initially, the precision spheres of the reference casts were uniformly coated with a white occlusion spray (O-Spray; S&S Scheftner GmbH, Mainz, Germany). Ten digital scans were performed according to the manufacturer's instructions by one experienced clinician using a Trios 4 IOS, version 20.1.3 (3Shape A/S) (IOS, n=10). There was no direct lighting from the dental chair lamp or sun, no rescanning was needed, and the maxillary arch was scanned including the palate. The scanner was calibrated every five scans and the "Adjust for contacts" feature was enabled.

The IOS data was imported into the CAD (Computer-Aided Design) software (Dental Designer 2021 and Model Builder 2021; 3Shape A/S), and virtual casts were generated from each scan (n=10). For the mandible, a horseshoe-shaped cast base was selected; all maxillary arches included the palate and were constructed to be hollow, with a minimum wall thickness of 2.5 mm. A digital articulator (Simple Full Arch v2.3; 3Shape A/S), also known as positioning pins, was added in the molar region. It supported the casts in the registered maxillomandibular relationship and reduced the possible intra-arch deviations after 3D-printing procedure [20]. Finally, the casts were manufactured using two different systems: MAX UV385 3D-printer with DentaMODEL resin (Asiga, firmware 2019-09-17) and NextDent 5100 3D-printer with Model 2.0 resin (3D Systems, Rock Hill, South Carolina, United States, firmware v1.1.1). Each cast was placed horizontally at the center of the build platform and manufactured in a separate print job with a 50 μm layer thickness. Both 3D-printers were calibrated every fifth print and the post-processing of the casts was carried out strictly following the manufacturers' instructions, namely the support structures were removed before post-processing.

After resting for 1 day at room temperature in a light-proof compartment, all casts were mounted in the same articulator and scanned twice using a calibrated laboratory scanner (E4; 3Shape A/S): first with the digital articulator pins in place and then after pins removal (**Fig 4**).

Each scan represented a different type of articulation method. Further, the "Adjust for contacts" feature in the CAD software (Dental Designer 2021; 3Shape A/S) was disabled, and the files were subsequently exported into a STL format.

2.5. Control data set

Conventional vinylpolysiloxane (VPS) impressions (Imprint 4; 3M ESPE, Saint Paul, Minnesota, United States) of the reference casts (n=10) were taken at room temperature using a double mix custom tray impression technique immediately after the digital scanning procedure was finished. Impression setting time was set twice as long in order to compensate for temperature differences and avoid unnecessary deformations.

The impressions were poured with Type IV dental stone (GC Fujirock EP; GC EUROPE N.V., Leuven, Belgium) following a vacuum mixing process according to the manufacturers' guidelines. Once the stone casts were fully set, they were articulated and digitized with a calibrated laboratory scanner (E4; 3Shape A/S) in the aforementioned manner.

2.6. Measurements

All pairs of virtual casts were evaluated by measuring the inter-arch distances between the spheres (1-5) and the 3D-contact area in MIP. Scans conducted with IOS were compared to the digital dataset of the stone and 3D-printed casts. Additional comparison was performed between the stone and 3D-printed casts as well as in between the 3D-printed cast groups with and without pins (**Fig. 1**).

2.6.1 Inter-arch distances

Initially, all STL data sets were imported into metrology software (Geomagic Control X; 3D Systems), in which the centre point of each precision sphere was automatically detected. Thus, five vertical distances between the centre points of the spheres in upper and lower dental arches were found and measured (**Fig. 5**).

2.6.2 3D-contact area in virtual casts

A digital assessment of contact points was undertaken for each pair of scanned casts (maxillary and mandibular) (**Fig. 6**). Occlusal contact was defined as an occlusal separation of 0.012 mm or less, including all negative distances, such as mesh interpenetration or occlusal collusion. To avoid false negative values, all meshes containing holes were filled before analysis. Most of the IOS-generated meshes had been hole-filled during the scanning procedure. Each 3D-scan was first uniformly subsampled to create point clouds with a sample (vertex point) every 0.025 mm. This was necessary to avoid uneven sampling across variable-sized triangles in the meshes during analysis. These new vertices were all valid positions on the face of a mesh. For each scan pair, the number of points in the upper arch that were within 0.012 mm of the closest point in the lower arch and negative penetrating points were recorded. All negative (penetrating) values farther away than -0.5 mm were excluded from the analysis. This method provided a measure of the total surface area of the contact points. In all cases, custom software provided by author C.O. was used.

2.7. Data analysis

For statistical analysis, a statistical program (SPSS 27.0; IBM SPSS software; IBM Corporation) was used. Comparisons were performed by analysing the difference between groups for each type of measurement: inter-arch distances and 3D-contact areas. The normality of the data was evaluated using the Shapiro-Wilk test, and the homogeneity of variance across groups was assessed using Leven's test. Additionally, for each group comparison, Welch's t-test was utilized. A 2-way ANOVA was chosen to examine the potential interaction between the 3D-printer, the articulation method, and their influence on the respective measurements. If statistically significant differences were observed in the ANOVA results, post hoc comparisons were conducted using the Tukey-HSD test. The significance level was set at α=.05 for all statistical tests.

3. Results

The results of inter-arch measurements and statistical tests are presented in **Tables 1-3** and **Fig. 7**; the 3D-contact area calculations - in **Tables 4-6** and **Fig. 8**. The deviation difference between the groups is marked with Δ and is considered statistically significant with p-value <0.05.

3.1. IOS versus stone cast

The inter-arch distances found in digital impressions (IOS) and compared with distances of stone casts showed no significant differences (**Table 2**, $p>0.05$, Δ=-1.94 µm). However, the trueness of the 3D-contact area in IOS group was significantly higher than in stone casts (**Table 5**, $p<0.05$, Δ=7.47 mm^2)

3.2. IOS versus 3D-printed casts

3D-printed casts with positioning pins (Asiga_Pins, NextDent_Pins) exhibited lower mean inter-arch trueness compared to the IOS group (**Table 2**, $p<0.05$, $\Delta \leq -425.05$ μm). However, a similar trueness was observed in the 3D-contact area between Asiga_Pins, NextDent_Pins, and IOS groups (**Table 5**, $p>0.05$, $\Delta \leq -5.02$ mm^2).

After the removal of the positioning pins, the trueness of inter-arch distances in 3D-printed casts increased significantly when compared to IOS (**Table 2**, $p<0.05$, $\Delta \leq -253.08$ μm). On the contrary, 3D-contact area analysis showed a significant decrease in the trueness of 3D-printed casts' maxillomandibular relationship (**Table 5**, $p<0.05$, $\Delta \leq -11.97$ mm2).

3.3. 3D-printed casts versus stone casts

Asiga and NextDent casts (no matter with or without positioning pins) exhibited significantly lower trueness of inter-arch distances compared to the Stone group (**Table 2**, $p<0.05$, $\Delta \leq -426.99$ μm). However, the 3D-contact area did not reveal significant differences between the 3D-printed and stone casts (**Table 5**, $p>0.05$, $\Delta \leq -4.51$ mm^2). Except for one instance, when Asiga_Pins group demonstrated higher 3D-contact area trueness than stone casts (**Table 5**, $p<0.05$, $\Delta = 7.61$ mm^2).

3.4. Effect of factors: (A) 3D-printer (Asiga or NextDent) and (B) type of articulation (with or without positioning pins)

A two-way ANOVA statistical test demonstrated that both factors, namely 3D-printer and type of articulation (with or without positioning pins), had a significant influence on the mean inter-arch distance trueness of 3D-printed casts. NextDent 5100 (3DSystems) performed significantly better than MAX UV385 (Asiga) (**Tables 1, 3**, $p<0.001$). 3D-printed casts without positioning pins had significantly higher inter-arch distance trueness than the casts with pins (Pins) (**Tables 1, 3**, $p<0.001$). However, the combined effect of both factors did not have a significant effect (**Table 3**, $p=0.11$).

The two-way ANOVA statistical test conducted with the 3D-contact area measurements showed also significant influence. MAX UV385 (Asiga) exhibited higher 3D-contact area trueness compared to NextDent 5100 (3DSystems) (**Tables 4, 6**, $p=0.01$). Significantly higher 3D-contact area trueness was achieved when 3D-printed casts had positioning pins (Pins), rather than after removal of the pins (**Tables 4, 6**, $p=0.05$). The combined effect of both factors did not have a significant effect (**Table 6**, $p=0.55$).

4. Discussion

The purpose of this study was to analyse and compare the trueness of maxillomandibular relationship of digital scans, 3D-printed and physical stone casts. Additionally, the effect of AM device and type of articulation was evaluated. Two different analyses were completed: inter-arch distance and 3D-contact area measurements. The null hypothesis that the trueness of the maxillomandibular relationship of 3D-printed casts would not differ from the stone casts was partly approved.

The study findings indicate that digital scans generated with IOS have comparable or even superior trueness of maxillomandibular relationship than conventionally articulated dental stone casts. It corresponds with a study published by Ries et al. [27], in which maxillomandibular relationship records obtained through a completely digital workflow using IOS (TRIOS 3; 3Shape A/S) were more accurate than those obtained by digitizing conventional interocclusal records and gypsum casts. Furthermore, an in vivo study conducted by Iwauchi et al. [28] demonstrated that IOS devices (3M True Definition; 3M ESPE and TRIOS 3; 3Shape A/S) provided better precision of maxillomandibular relationship measurements than conventional methods. It should be also noted that the accuracy of maxillomandibular relationships in intraoral scans can be affected by various clinical and technical factors. According to a recent systematic review by Revilla-León et al. [29], factors such as the chosen IOS system, the extent of the arch scan (half arch versus complete arch), the location and span of edentulous regions, the type of virtual occlusal record, the occlusal force during the bite scan, tooth mobility, and virtual alignment methods can all influence the accuracy of the maxillomandibular relationship in virtual casts. Specifically, in the presence of edentulous regions, studies have found that the accuracy of maxillomandibular relationships reduces as the number of opposing teeth pairs decreases [15,30]. In the present study, the IOS has demonstrated high occlusal contact area trueness when compared to stone casts, despite a tendency of possible intra-arch deviations. Osnes et al. [31] reported maxillary arch inter-molar deviations of 183 ± 61 μm when scanned with the IOS Cerec Omnicam (Dentsply Sirona, Charlotte, North Carolina, United States). Similarly, a study by Auskalnis et al. [22] noted that mandibular arch inter-molar deviations (Trios 4, 3Shape A/S) can reach a level of 416.4 ± 124.2 μm. However, the buccal scan itself appears to be precise, namely <50 μm [28,31].

Building on the aforementioned study results, our investigation continued to examine the trueness of the maxillomandibular relationship in digital scans compared to 3D-printed models. It showed that 3D-printed models generally have lower level of trueness. Nonetheless, some observations indicated no significant deviations ($p<0.05$) of the 3D-contact area between the IOS and 3D-printing groups before the removal of articulation pins (Asiga_Pins, NextDent_Pins). The accuracy of the maxillomandibular relationship observed in 3D-printed casts can be affected by the shrinkage effect, which was already well-documented in several studies [32–34]. The shrinkage and warpage of the printed objects can be caused if the resin layers are not fully polymerized and additional processing is needed [35]. To the best of the authors' knowledge, there are no recent studies which compared the trueness of the maxillomandibular relationship between digital scans and 3D-printed casts in MIP.

Furthermore, the primary goal of this study was to compare the digital and conventional workflows for dental casts manufacturing with a particular focus on the trueness of maxillomandibular relationship. The 3D-contact area analysis revealed no significant differences between 3D-printed and stone casts. However, the measurement of inter-arch distances demonstrated significantly greater trueness in stone casts compared to their 3D-printed counterparts. It is important to note that the precision of these inter-arch measurements depends heavily on the accurate replication of spherical markers and is influenced by occlusal spray, as well as the accuracy of scanning and 3D-printing device. Future research could benefit from employing a 'markerless' key point transplantation technique, as proposed by Osnes et al. [31], which eliminates the need for additional physical reference objects and simulates a clinical scanning environment more closely. Considering the possibility that 3D-contact area analysis may provide a more reliable assessment of trueness, this study partially supports the null hypothesis that 3D-printed models and stone casts demonstrate comparable trueness of maxillomandibular relationship. To the best of the authors' knowledge, there are no studies that have directly compared the trueness of maxillomandibular relationship in 3D-printed versus stone casts.

Various studies assessing the accuracy of 3D-printed casts are not consistent due to diverse IOS and 3D-printing processes [36] as well as measuring methods of maxillomandibular relationship [47]. In our study the casts were positioned centrally on the build platform in order to avoid major deviations, which can occur at the platform's corners due to the angular incidence of the projector's light beam [37]. The printing layer thickness was chosen to be 50 µm because of the adequate accuracy-to-efficiency ratio of the 3D-cast fabrication process [37–41]. To ensure structural integrity, all 3D-printed casts had a minimum wall thickness of 2 mm and were manufactured hollow as recommended in other studies [37,42–44]. It was also decided to include the palate in the maxillary casts fabrication and transversally connect the molar region of the mandibular casts, based on studies which showed that such design enhances the stability of the printed casts [43,45]. Furthermore, it is imperative to consider that each individual print job may yield distinct outcomes. Therefore, the casts in this study were fabricated in separate print jobs to reflect the 3D-printer's consistency [36]. Strict adherence to the manufacturer's post-processing instructions, encompassing washing, drying, and curing, were ensured in order to increase the repeatability of the recent study [46].

Researchers reported different physical cast evaluation methods based on digital calliper [16] and occlusal datasets (e.g. T-Scan III; Tekscan, Boston, MA, USA) [48,49], as well as transillumination of interocclusal VPS records [50–52]. Analysis of virtual casts though enables automated measurements and significantly minimizes the chance of human assessment errors. Several studies by Revilla-León et al. [17,53,54] employed a technique involving 36 linear inter-landmark measurements for each cast pair. In total, authors selected 12 markers (points on the tooth surface) on the maxillary and mandibular reference casts and transferred these points to the corresponding test specimens. A similar approach was utilized in the investigations by Gintaute et al. [15] and Osnes et al. [55], where the authors employed small sections (with a 10 mm radius) of a reference cast around the markers for their transposition onto the test casts. Inter-landmark measurements were then conducted among these points on a given pair of articulated casts.

Gintaute et al. [15] also made contact point surface area calculations using custom-made software, and visual inspection of occluding units in virtual casts. Therefore, two different measurements methods were included in the present study, namely inter-arch measurements and 3D-contact area analysis, to reduce the risk of measurement sensitivity.

While offering valuable insights, this study encounters also some limitations that need to be addressed. This includes an in vitro study design, the use of a laboratory scanner, and a limited number of digital devices tested. The presence of saliva, mobile areas of soft tissues, difficulties in accessing all scanning areas, and other in vivo factors may affect the accuracy of IOS [56–58]. Additionally, a laboratory scanner can introduce further deviations, affecting the reliability of measurements. Nevertheless, the laboratory scanner used in our research had a specified accuracy of 4 µm [59]. Finally, the application of different IOSs and AM devices can also lead to different trueness results. Further research is needed to investigate various combinations of different IOSs and 3D-printers to analyse their influence on the accuracy of the maxillomandibular relationship.

5. Conclusions

To conclude, this study aimed to investigate the trueness of the maxillomandibular relationship of dental casts obtained by digital and conventional techniques. The results suggest that 3D-printed casts had lower maxillomandibular relationship trueness than digital scans; the type of 3D-printed cast articulation (with and without pins) and the 3D-printer itself had a significant impact on the maxillomandibular relationship trueness; and finally, the trueness of maxillomandibular relationship can be considered similar between the 3D-printed and conventional stone casts.

6. References

[1] S. Ishigaki, T. Kurozumi, E. Morishige, H. Yatani, Occlusal interference during mastication can cause pathological tooth mobility, J. Periodontal Res. 41 (2006) 189–192. https://doi.org/10.1111/j.1600-0765.2005.00856.x.

[2] G.T. Clark, Y. Tsukiyama, K. Baba, T. Watanabe, Sixty-eight years of experimental occlusal interference studies: what have we learned?, J. Prosthet. Dent. 82 (1999) 704–713. https://doi.org/10.1016/s0022-3913(99)70012-0.

[3] R.J. Wilding, The association between chewing efficiency and occlusal contact area in man, Arch. Oral Biol. 38 (1993) 589–596. https://doi.org/10.1016/0003-9969(93)90124-5.

[4] V. Koenig, A.J. Vanheusden, S.O. Le Goff, A.K. Mainjot, Clinical risk factors related to failures with zirconia-based restorations: an up to 9-year retrospective study, J. Dent. 41 (2013) 1164–1174. https://doi.org/10.1016/j.jdent.2013.10.009.

[5] J.F. Esquivel-Upshaw, J.J. Mecholsky, A.E. Clark, R. Jenkins, S.M. Hsu, D. Neal, F. Ren, Factors influencing the survival of implant-supported ceramic-ceramic prostheses: A randomized, controlled clinical trial, J. Dent. 103S (2020) 100017. https://doi.org/10.1016/j.jjodo.2020.100017.

[6] T. Graf, J.-F. Güth, C. Diegritz, A. Liebermann, J. Schweiger, O. Schubert, Efficiency of occlusal and interproximal adjustments in CAD-CAM manufactured single implant crowns - cast-free vs 3D printed cast-based, J. Adv. Prosthodont. 13 (2021) 351–360. https://doi.org/10.4047/jap.2021.13.6.351.

[7] A. Ender, A. Mehl, Accuracy of complete-arch dental impressions: A new method of measuring trueness and precision, J. Prosthet. Dent. 109 (2013) 121–128. https://doi.org/10.1016/S0022-3913(13)60028-1.

[8] G. Rossini, S. Parrini, T. Castroflorio, A. Deregibus, C.L. Debernardi, Diagnostic accuracy and measurement sensitivity of digital models for orthodontic purposes: A systematic review, Am. J. Orthod. Dentofac. Orthop. Off. Publ. Am. Assoc. Orthod. Its Const. Soc. Am. Board Orthod. 149 (2016) 161–170. https://doi.org/10.1016/j.ajodo.2015.06.029.

[9] H. Parize, J. Dias Corpa Tardelli, L. Bohner, N. Sesma, V.A. Muglia, A. Cândido Dos Reis, Digital versus conventional workflow for the fabrication of physical casts for fixed prosthodontics: A systematic review of accuracy, J. Prosthet. Dent. (2021). https://doi.org/10.1016/j.prosdent.2020.12.008.

[10] Y. Etemad-Shahidi, O.B. Qallandar, J. Evenden, F. Alifui-Segbaya, K.E. Ahmed, Accuracy of 3-Dimensionally Printed Full-Arch Dental Models: A Systematic Review, J. Clin. Med. 9 (2020). https://doi.org/10.3390/jcm9103357.

[11] F. Mangano, A. Gandolfi, G. Luongo, S. Logozzo, Intraoral scanners in dentistry: a review of the current literature, BMC Oral Health 17 (2017) 149. https://doi.org/10.1186/s12903-017-0442-x.

[12] H. Kihara, W. Hatakeyama, F. Komine, K. Takafuji, T. Takahashi, J. Yokota, K. Oriso, H. Kondo, Accuracy and practicality of intraoral scanner in dentistry: A literature review, J. Prosthodont. Res. 64 (2020) 109–113. https://doi.org/10.1016/j.jpor.2019.07.010.

[13] T. Joda, U. Brägger, Patient-centered outcomes comparing digital and conventional implant impression procedures: a randomized crossover trial, Clin. Oral Implants Res. 27 (2016) e185–e189. https://doi.org/10.1111/clr.12600.

[14] M.F. Sfondrini, P. Gandini, M. Malfatto, F. Di Corato, F. Trovati, A. Scribante, Computerized Casts for Orthodontic Purpose Using Powder-Free Intraoral Scanners:

Accuracy, Execution Time, and Patient Feedback, BioMed Res. Int. 2018 (2018) 4103232. https://doi.org/10.1155/2018/4103232.
[15] A. Gintaute, A.J. Keeling, C.A. Osnes, N.U. Zitzmann, M. Ferrari, T. Joda, Precision of maxillo-mandibular registration with intraoral scanners in vitro, J. Prosthodont. Res. 64 (2020) 114–119. https://doi.org/10.1016/j.jpor.2019.05.006.
[16] W.-J. Choi, S.-J. Lee, C.-H. Moon, Evaluation of accuracy of 3-dimensional printed dental models in reproducing intermaxillary relational measurements: Based on inter-operator differences, Korean J. Orthod. 52 (2022) 20–28. https://doi.org/10.4041/kjod.2022.52.1.20.
[17] M. Revilla-León, R. Agustín-Panadero, J.M. Zeitler, A.B. Barmak, B. Yilmaz, J.C. Kois, J.A. Pérez-Barquero, Differences in maxillomandibular relationship recorded at centric relation when using a conventional method, four intraoral scanners, and a jaw tracking system: A clinical study, J. Prosthet. Dent. (2023) S0022-3913(22)00795–8. https://doi.org/10.1016/j.prosdent.2022.12.007.
[18] M. Revilla-León, M. Gómez-Polo, A.B. Barmak, J.C. Kois, B. Yilmaz, J. Alonso Pérez-Barquero, Influence of occlusal collision corrections completed by two intraoral scanners or a dental design program on the accuracy of the maxillomandibular relationship, J. Prosthet. Dent. (2023) S0022-3913(23)00345–1. https://doi.org/10.1016/j.prosdent.2023.05.015.
[19] G. Michelinakis, D. Apostolakis, P. Kamposiora, G. Papavasiliou, M. Özcan, The direct digital workflow in fixed implant prosthodontics: a narrative review, BMC Oral Health 21 (2021) 37. https://doi.org/10.1186/s12903-021-01398-2.
[20] T. Joda, F. Zarone, M. Ferrari, The complete digital workflow in fixed prosthodontics: a systematic review, BMC Oral Health 17 (2017) 124. https://doi.org/10.1186/s12903-017-0415-0.
[21] P. Papaspyridakos, A. De Souza, A. Bathija, K. Kang, K. Chochlidakis, Complete Digital Workflow for Mandibular Full-Arch Implant Rehabilitation in 3 Appointments, J. Prosthodont. Off. J. Am. Coll. Prosthodont. 30 (2021) 548–552. https://doi.org/10.1111/jopr.13356.
[22] L. Auškalnis, M. Akulauskas, D. Jegelevičius, T. Simonaitis, V. Rutkūnas, Error propagation from intraoral scanning to additive manufacturing of complete-arch dentate models: An in vitro study, J. Dent. 121 (2022) 104136. https://doi.org/10.1016/j.jdent.2022.104136.
[23] F.G. Mangano, O. Admakin, M. Bonacina, F. Biaggini, D. Farronato, H. Lerner, Accuracy of 6 Desktop 3D Printers in Dentistry: A Comparative In Vitro Study, Eur. J. Prosthodont. Restor. Dent. 28 (2020) 75–85. https://doi.org/10.1922/EJPRD_2050Mangano11.
[24] I.A. Tsolakis, S. Gizani, N. Panayi, G. Antonopoulos, A.I. Tsolakis, Three-Dimensional Printing Technology in Orthodontics for Dental Models: A Systematic Review, Child. Basel Switz. 9 (2022) 1106. https://doi.org/10.3390/children9081106.
[25] A. Alammar, J.C. Kois, M. Revilla-León, W. Att, Additive Manufacturing Technologies: Current Status and Future Perspectives, J. Prosthodont. Off. J. Am. Coll. Prosthodont. 31 (2022) 4–12. https://doi.org/10.1111/jopr.13477.
[26] J.D. Lee, G.O. Gallucci, S.J. Lee, An In-Vitro Evaluation of Articulation Accuracy for Digitally Milled Models vs. Conventional Gypsum Casts, Dent. J. 10 (2022) 11. https://doi.org/10.3390/dj10010011.
[27] J.M. Ries, C. Grünler, M. Wichmann, R.-E. Matta, Three-dimensional analysis of the accuracy of conventional and completely digital interocclusal registration methods, J. Prosthet. Dent. (2021) S0022-3913(21)00140–2. https://doi.org/10.1016/j.prosdent.2021.03.005.

[28] Y. Iwauchi, S. Tanaka, E. Kamimura-Sugimura, K. Baba, Clinical evaluation of the precision of interocclusal registration by using digital and conventional techniques, J. Prosthet. Dent. (2021) S0022-3913(21)00066–4. https://doi.org/10.1016/j.prosdent.2021.01.021.
[29] M. Revilla-León, A.B. Barmak, H. Tohme, B. Yilmaz, J.C. Kois, M. Gómez-Polo, Factors that influence the accuracy of maxillomandibular relationship at maximum intercuspation acquired by using intraoral scanners: A systematic review, J. Dent. 138 (2023) 104718. https://doi.org/10.1016/j.jdent.2023.104718.
[30] S. Ren, D. Morton, W.-S. Lin, Accuracy of virtual interocclusal records for partially edentulous patients, J. Prosthet. Dent. 123 (2020) 860–865. https://doi.org/10.1016/j.prosdent.2019.08.013.
[31] C. Osnes, J. Wu, M. Ferrari, T. Joda, A. Keeling, Sources of error in maximum intercuspation from complete dentate full-arch intraoral scans in vitro, Int. J. Comput. Dent. 24 (2021) 283–291.
[32] E. Faruk, A. Simel, Accuracy evaluation of complete-arch models manufactured by three different 3D printing technologies: a three-dimensional analysis, J. Prosthodont. Res. (2020). https://doi.org/10.2186/jpr.JPOR_2019_579.
[33] J.-Y. Sim, Y. Jang, W.-C. Kim, H.-Y. Kim, D.-H. Lee, J.-H. Kim, Comparing the accuracy (trueness and precision) of models of fixed dental prostheses fabricated by digital and conventional workflows, J. Prosthodont. Res. 63 (2019) 25–30. https://doi.org/10.1016/j.jpor.2018.02.002.
[34] J. Abduo, Accuracy of casts produced from conventional and digital workflows: A qualitative and quantitative analyses, J. Adv. Prosthodont. 11 (2019) 138–146. https://doi.org/10.4047/jap.2019.11.2.138.
[35] N. Nestler, C. Wesemann, B.C. Spies, F. Beuer, A. Bumann, Dimensional accuracy of extrusion- and photopolymerization-based 3D printers: In vitro study comparing printed casts, J. Prosthet. Dent. 125 (2021) 103–110. https://doi.org/10.1016/j.prosdent.2019.11.011.
[36] M. Braian, R. Jimbo, A. Wennerberg, Production tolerance of additive manufactured polymeric objects for clinical applications, Dent. Mater. Off. Publ. Acad. Dent. Mater. 32 (2016) 853–861. https://doi.org/10.1016/j.dental.2016.03.020.
[37] S.L. Sherman, O. Kadioglu, G.F. Currier, J.P. Kierl, J. Li, Accuracy of digital light processing printing of 3-dimensional dental models, Am. J. Orthod. Dentofac. Orthop. Off. Publ. Am. Assoc. Orthod. Its Const. Soc. Am. Board Orthod. 157 (2020) 422–428. https://doi.org/10.1016/j.ajodo.2019.10.012.
[38] W.A. Loflin, J.D. English, C. Borders, L.M. Harris, A. Moon, J.N. Holland, F.K. Kasper, Effect of print layer height on the assessment of 3D-printed models, Am. J. Orthod. Dentofac. Orthop. Off. Publ. Am. Assoc. Orthod. Its Const. Soc. Am. Board Orthod. 156 (2019) 283–289. https://doi.org/10.1016/j.ajodo.2019.02.013.
[39] Z.-C. Zhang, P.-L. Li, F.-T. Chu, G. Shen, Influence of the three-dimensional printing technique and printing layer thickness on model accuracy, J. Orofac. Orthop. Fortschritte Kieferorthopadie OrganOfficial J. Dtsch. Ges. Kieferorthopadie 80 (2019) 194–204. https://doi.org/10.1007/s00056-019-00180-y.
[40] J. Ko, R.D. Bloomstein, D. Briss, J.N. Holland, H.M. Morsy, F.K. Kasper, W. Huang, Effect of build angle and layer height on the accuracy of 3-dimensional printed dental models, Am. J. Orthod. Dentofac. Orthop. Off. Publ. Am. Assoc. Orthod. Its Const. Soc. Am. Board Orthod. 160 (2021) 451-458.e2. https://doi.org/10.1016/j.ajodo.2020.11.039.

[41] J.-W. Choi, J.-J. Ahn, K. Son, J.-B. Huh, Three-Dimensional Evaluation on Accuracy of Conventional and Milled Gypsum Models and 3D Printed Photopolymer Models, Mater. Basel Switz. 12 (2019). https://doi.org/10.3390/ma12213499.
[42] M. Revilla-León, W. Piedra-Cascón, R. Aragoneses, M. Sadeghpour, B.A. Barmak, A. Zandinejad, A.J. Raigrodski, Influence of base design on the manufacturing accuracy of vat-polymerized diagnostic casts: An in vitro study, J. Prosthet. Dent. (2021) S0022-3913(21)00254–7. https://doi.org/10.1016/j.prosdent.2021.03.035.
[43] S.-H. Shin, J.-H. Lim, Y.-J. Kang, J.-H. Kim, J.-S. Shim, J.-E. Kim, Evaluation of the 3D Printing Accuracy of a Dental Model According to Its Internal Structure and Cross-Arch Plate Design: An In Vitro Study, Mater. Basel Switz. 13 (2020). https://doi.org/10.3390/ma13235433.
[44] K.B. Kenning, D.C. Risinger, J.D. English, B.E. Cozad, L.M. Harris, J.C. Ontiveros, F.K. Kasper, Evaluation of the dimensional accuracy of thermoformed appliances taken from 3D printed models with varied shell thicknesses: An in vitro study, Int. Orthod. 19 (2021) 137–146. https://doi.org/10.1016/j.ortho.2021.01.005.
[45] L.T. Camardella, O. de Vasconcellos Vilella, H. Breuning, Accuracy of printed dental models made with 2 prototype technologies and different designs of model bases, Am. J. Orthod. Dentofacial Orthop. 151 (2017) 1178–1187. https://doi.org/10.1016/j.ajodo.2017.03.012.
[46] D. Mostafavi, M.M. Methani, W. Piedra-Cascón, A. Zandinejad, W. Att, M. Revilla-León, Influence of the polymerization post-processing procedures on the accuracy of additively manufactured dental model material, Int. J. Prosthodont. (2021). https://doi.org/10.11607/ijp.7349.
[47] H. Lee, J. Cha, Y.-S. Chun, M. Kim, Comparison of the occlusal contact area of virtual models and actual models: a comparative in vitro study on Class I and Class II malocclusion models, BMC Oral Health 18 (2018) 109. https://doi.org/10.1186/s12903-018-0566-7.
[48] C. Fraile, A. Ferreiroa, M. Romeo, R. Alonso, G. Pradíes, Clinical study comparing the accuracy of interocclusal records, digitally obtained by three different devices, Clin. Oral Investig. 26 (2022) 1957–1962. https://doi.org/10.1007/s00784-021-04174-2.
[49] R. Ayuso-Montero, Y. Mariano-Hernandez, L. Khoury-Ribas, B. Rovira-Lastra, E. Willaert, J. Martinez-Gomis, Reliability and Validity of T-scan and 3D Intraoral Scanning for Measuring the Occlusal Contact Area, J. Prosthodont. n/a (n.d.). https://doi.org/10.1111/jopr.13096.
[50] F. Edher, A.G. Hannam, D.L. Tobias, C.C.L. Wyatt, The accuracy of virtual interocclusal registration during intraoral scanning, J. Prosthet. Dent. 120 (2018) 904–912. https://doi.org/10.1016/j.prosdent.2018.01.024.
[51] S. Abdulateef, F. Edher, A.G. Hannam, D.L. Tobias, C.C.L. Wyatt, Clinical accuracy and reproducibility of virtual interocclusal records, J. Prosthet. Dent. 124 (2020) 667–673. https://doi.org/10.1016/j.prosdent.2019.11.014.
[52] J.T. Krahenbuhl, S.-H. Cho, J. Irelan, N.K. Bansal, Accuracy and precision of occlusal contacts of stereolithographic casts mounted by digital interocclusal registrations, J. Prosthet. Dent. 116 (2016) 231–236. https://doi.org/10.1016/j.prosdent.2016.01.029.
[53] M. Revilla-León, L. Fernández-Estevan, A.B. Barmak, J.C. Kois, J.A. Pérez-Barquero, Accuracy of the maxillomandibular relationship at centric relation position recorded by using 3 different intraoral scanners with or without an optical jaw tracking system: An in vivo pilot study, J. Dent. 132 (2023) 104478. https://doi.org/10.1016/j.jdent.2023.104478.

[54] M. Revilla-León, J. Alonso Pérez-Barquero, Á. Zubizarreta-Macho, A.B. Barmak, W. Att, J.C. Kois, Influence of the Number of Teeth and Location of the Virtual Occlusal Record on the Accuracy of the Maxillo-Mandibular Relationship Obtained by Using An Intraoral Scanner, J. Prosthodont. Off. J. Am. Coll. Prosthodont. (2022). https://doi.org/10.1111/jopr.13526.
[55] C. Osnes, J. Patel, A. Wagstaff, M. Ferrari, A. Keeling, Optimal Use of Physical Centric Relation Records for Digital Workflows, Eur. J. Prosthodont. Restor. Dent. 29 (2021) 223–229. https://doi.org/10.1922/EJPRD_2263Osnes07.
[56] V. Rutkūnas, A. Gečiauskaitė, D. Jegelevičius, M. Vaitiekūnas, Accuracy of digital implant impressions with intraoral scanners. A systematic review, Eur. J. Oral Implantol. 10 Suppl 1 (2017) 101–120.
[57] F.G. Mangano, O. Admakin, M. Bonacina, H. Lerner, V. Rutkunas, C. Mangano, Trueness of 12 intraoral scanners in the full-arch implant impression: a comparative in vitro study, BMC Oral Health 20 (2020) 263. https://doi.org/10.1186/s12903-020-01254-9.
[58] V. Rutkunas, A. Gedrimiene, M. Akulauskas, V. Fehmer, I. Sailer, D. Jegelevicius, In vitro and in vivo accuracy of full-arch digital implant impressions, Clin. Oral Implants Res. (2021). https://doi.org/10.1111/clr.13844.
[59] A New E4 lab scanner is released - 3Shape Press, 3Shape (n.d.). https://www.3shape.com/en/press/2019/double-up-your-labs-scanning-speed-and-accuracy (accessed September 19, 2023).