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Reproducibility and accuracy of the virtual occlusal record

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

By

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Table of Contents

List of Tables

List of Figures

Abstract

REPRODUCIBILITY AND ACCURACY OF THE VIRTUAL OCCLUSAL RECORD

By: Anne Miller Harper, D.M.D.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

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Purpose: Digital impressions and bite records are commonly used in orthodontics for diagnosing, treatment planning, and treating patients. They must be reproducible and accurate. The aim of this study was to evaluate the reproducibility and accuracy of the virtual occlusal record in comparison to the gold standard physical bite record.

Methods: Two physical bite records of Regisil 2x™ polyvinyl siloxane (PVS) and two virtual bites using an iTero Element scanner were obtained from 22 participants. Intraoral scans were exported as stereolithography (STL) files, and virtual occlusal records were created. Cone-beam computed tomography (CBCT) images were taken of physical occlusal records and converted to STL files. Paired STL files were superimposed using Geomagic Control X™ (CX) Software to determine reproducibility within and between bite types using a best fit algorithm to measure similarities and differences. Root mean square (RMS) values and percent similarity within 0.25 mm tolerance were compared at a significance level of 0.05.

Results: Average RMS between physical records was 0.34, which was significantly higher than repeat virtual bite comparisons ($p<0.0001$), with an average percent within tolerance of 76.33%, which was significantly lower than repeat virtual bite comparisons ($p<0.0001$). Average RMS between repeated virtual records was 0.12 with an average percent within tolerance of 97.84%. Average RMS between physical and virtual records was 0.61, which was significantly higher than both repeat comparisons for physical and virtual records ($p<0.0001$), with an average percent within tolerance of 50.88%, which was significantly lower than both repeat comparisons for physical and virtual records ($p<0.0001$).

Conclusion: Virtual occlusal records are significantly more reproducible than physical occlusal records. Statistically and clinically significant differences exist between virtual and physical bite records. Some of the differences between physical and virtual bite records could have been due to variations in the physical bite records themselves. Virtual occlusal records may be more accurate than physical PVS bite records, but additional research is needed to confirm this.

Introduction

Digital impressions obtained from intraoral scanners have a wide range of clinical applications and advantages for dental practitioners.[1] Advantages of obtaining digital impressions using intraoral scanners include patient comfort, time efficiency, simplified clinical procedures, digital storage capability, better communication with dental technicians, and better communication with patients.[1] Additionally, if the digital impressions and the digital interocclusal record have been obtained accurately, the need to articulate casts manually is also eliminated.[2] As orthodontic and all dental practices adopt and embrace this technology, evidence is needed regarding the reproducibility and accuracy of scanners and the supporting software applications which analyze the virtual data.

Computer-aided design models are obtained from a data acquisition unit commonly called an intraoral scanner.[3] To obtain these patient models, intraoral scanners take a series of photographs or a video to seamlessly collect information from a patient's teeth to record dental and adjacent oral tissue features.[4] Depending on the system used, visible blue light or red laser may be used as the light source to collect the digital data.[3] Other features that differ from unit to unit include necessity of powder coat spray, operative process, and output file format. This technology has a distinct superiority in work efficiency and conservation of materials and has led to wide use in dentistry.[3]

Studies have been conducted on the accuracy of intraoral scans compared to conventional impression techniques. One systematic review which included 35 relevant articles showed that digital models are as reliable as traditional plaster models, reporting high accuracy, reliability, and reproducibility.[5] In another previous study, seven scanners were examined for trueness and precision on cadaver maxillae to stimulate an intraoral digital workflow. The models obtained were deemed accurate and precise.[6] In a similar study comparing digital scanners and conventional impressions, investigators determined that virtual impressions had comparable accuracy to conventional impression methods.[7]

One diagnostic tool used by practitioners is the virtual occlusal record obtained from an intraoral scan. This record is a digital representation of the relationship between a patient's upper and lower arches when they are biting in maximum intercuspation. Orthodontists strive to create a functional occlusion for each patient;[8] location of contacts, number of contacts, and area of contacts can be used to help describe a patient's ability to function.[9,10] It is important that the digital occlusal scheme provided from the intraoral scan be accurate and consistent because practitioners use occlusal data to aid in diagnosing and treating patients.

One study recently analyzed the reproducibility (but not the accuracy) of the virtual occlusal record obtained using the Carestream CS3600 Intraoral scanner. The findings suggested that the Carestream intraoral scanner software produced adequate precision when identifying the size of contacts and their location, but there was inadequate precision when acquiring the intensities in the bite records.[11] Those intensities described the actual and near contacts the patient had between the upper and lower arch. The authors emphasized that additional research was needed to investigate the accuracy and precision of the virtual occlusal record.[11]

While the accuracy of intraoral scans compared to conventional impressions has been well studied and proven to be acceptable, research specifically regarding the accuracy of the three-dimensional virtual occlusal record is lacking. There are no previous clinical studies demonstrating the accuracy of the virtual occlusal record. Physical bite records have been used in dentistry for decades and are assumed to be accurate. For any occlusal record to be clinically useful, it needs to be both reproducible and accurate. The purpose of this study, therefore, was to evaluate and compare reproducibility between the physical and virtual occlusal bite records and to determine the degree of similarity between the two types of bite records. The null hypothesis was that there would be no difference in reproducibility between physical and virtual bite records and that there would be a high degree of similarity between them.

Methods

Participant Recruitment

Approval to conduct this study was obtained from Virginia Commonwealth University's Institutional Review Board (HM 20018325). Both verbal and written consent were obtained from all participants.

A previous study evaluating precision of the virtual occlusal record found significant results with a sample size of 20 subjects.[11] Therefore, 22 participants were recruited who met the following inclusion criteria: 18 to 26-years of age with a full permanent dentition excluding 3rd molars, and no functional shift. Participants were excluded if they had an anterior crossbite, posterior crossbite, or an anterior open bite.

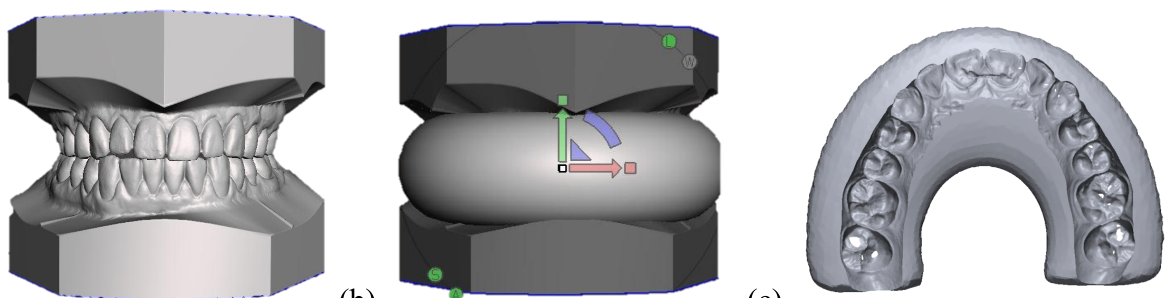
Participant Involvement

Two physical bite records were obtained from each participant using polyvinyl siloxane (PVS) bite registration material (Regisil 2x ™, Dentsply Sirona, York, PA) since this method has widely been considered as the gold standard.[12–14] Each participant practiced biting two times under supervision. This practice ensured that participants occluded reproducibly. Then, the PVS material was expressed onto the lower arch. The participant was instructed to close and hold their bite for two minutes until the material was set, and the bite was recorded. This was done two times for each subject. The virtual occlusal record was obtained using an iTero Element (Align

Technology, Inc.; Morrisville, NC) scanner to scan both arches and record the virtual bite twice for each participant.

Obtaining Virtual Occlusal Records

Intraoral scans were exported as stereolithography (STL) file models of the occluded arches and uploaded in Meshmixer (Autodesk, Inc.; San Rafeal, CA) freeware. As **Figure 1** shows, a flattened disc was superimposed virtually between the two models to serve as the virtual bite record. The virtual models were subtracted from the flattened disc to obtain the virtual occlusal record.



(a) (b) (c)

Figure 1: Virtual occlusal record acquisition

(a) Virtual model from intraoral scanning. (b) Flattened disc superimposed between the two arches. (c) Resultant virtual bite record acquired once both arches were subtracted from the superimposed disc.

Obtaining Physical Occlusal Records

Cone-beam computed tomography (CBCT) images were taken of both physical occlusal records from subjects using an i-CAT FLX (Imaging Sciences International LLC; Hatfield, PA) at a voxel size of 0.125mm. Images were uploaded into 3D Slicer (Slicer Solutions; Singapore,

Singapore) freeware and converted to STL files. **Figure 2** shows a physical bite record after its conversion to an STL file.

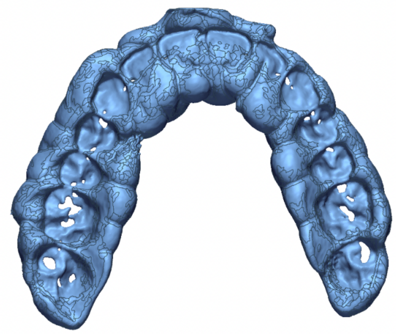


Figure 2: PVS physical occlusal record of a participant after being converted to an STL file and uploaded into Geomagic™ Control X software

Comparison within and between Bite Records

Once both the virtual and physical records were converted to STL files, they were uploaded into Geomagic™ Control X (CX) Software (3D Systems, Inc,; Rock Hill, SC). Two physical bite records from the same participant were superimposed on the occlusal surfaces to determine similarities and differences between the two physical bites using the 3D Compare feature of CX. Only the occlusal surfaces of teeth were carefully selected for comparison to rid the analysis of extraneous data. **Figure 3** shows the outlined occlusal surfaces of a physical bite record, used for both superimposition and comparison; the occlusal surfaces were outlined in light blue. **Figure 4** shows an example of a color mapped surface of a physical bite record after superimposition and 3D comparison. From this superimposition, reproducibility of the physical bite record was determined.

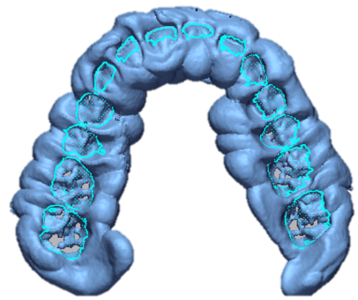
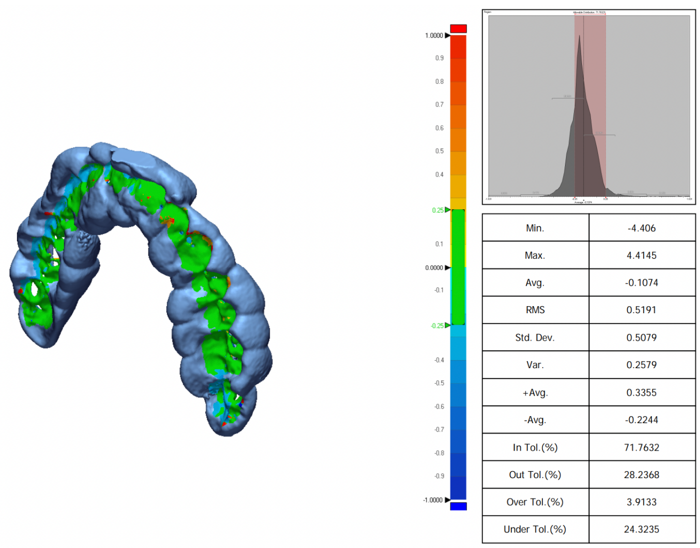


Figure 3: Selection of the occlusal surface of a physical bite record



Min.	-4.406
Max.	4.4145
Avg.	-0.1074
RMS	0.5191
Std. Dev.	0.5079
Var.	0.2579
+Avg.	0.3355
-Avg.	-0.2244
In Tol.(%)	71.7632
Out Tol.(%)	28.2368
Over Tol.(%)	3.9133
Under Tol.(%)	24.3235

Figure 4: Geomagic™ Control X superimposition of a bite record: Example of 3D comparison

The following equations and values were used to quantify CX superimpositions. CX calculated a deviation value for every vertex in the measured data. The total number of points in the 3D compare was *n*. Each measured vertex was defined by a measured position (*Pm*) and was associated with a reference position (*Pr*), which was defined by the projection direction. For this study, the projection direction was selected to be the shortest direction.[15]

$$P_m = \langle x_m, y_m, z_m \rangle \qquad P_r = \langle x_r, y_r, z_r \rangle$$

For each measured point, CX calculated a gap vector (*GV*), which was a vector from *Pr* to the *Pm*.[15]

$$GV = \langle x_m - x_r,\ y_m - y_r,\ z_m - z_r \rangle$$

This gap vector was then converted to a scalar magnitude called the gap distance (*D*). Gap distance was the deviation value at any given point. If the measured point was on the negative side of the reference data, the gap distance was given as a negative value.[15]

$$D = \sqrt{GV_x^{\,2} + GV_y^{\,2} + GV_z^{\,2}}$$

Root Mean Square (RMS) was a measure of the magnitude of all deviation or gap distance values.

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} D_i^{\,2}}$$

Percent within Tolerance (%) was the percentage of points that had a deviation or gap distance within the defined tolerance.

Results from best fit superimpositions were reported using means and standard deviations for RMS and percent within the pre-specified tolerance of +/-0.25 mm. This tolerance was chosen because a change in 0.15-0.25 mm from a tooth to an appliance or fabricated aligner could cause tooth movement.[16]

The two virtual bite records were superimposed from each participant to determine similarities and differences in the virtual bites from the same subject. The same previously described methods for occlusal selection, superimposition, and comparison were used for the virtual bites. From this superimposition, reproducibility of the virtual occlusal record from scan to scan was determined.

Both disinfected physical PVS impressions from each participant were stored in the same bag, and one was drawn at random to be used as the reference for comparison to each of the two virtual bite records. The physical bite record was used as the reference for each superimposition and analysis, as it served as the gold standard. Careful selection of the occlusal surfaces of the reference, the physical bite record, was performed as previously described and depicted in **Figure 3** so that extraneous portions of the PVS were not analyzed against the virtual records.

One rater performed all measurements in CX. Two weeks later, measurements were taken again to assess intra-rater reliability based on the intraclass correlation coefficient.

Statistics

Repeated measures ANOVA was used to test for differences in RMS and percent within tolerance based on the comparisons. Repeated measures were adjusted for repeated impressions (virtual and physical) on subjects. Post hoc pairwise comparisons were adjusted using Tukey's adjustment. Significance level was set at 0.05. All analyses were performed in SAS EG v.8.2 (SAS Institute, Cary, NC).

Results

One rater performed all measurements in CX. Intra-rater reliability was tested based on the intraclass correlation coefficient (ICC) by taking measurements performed in CX again at a 2-week interval. The results showed that the measurements were nearly the same. ICC was equal to 0.98 for RMS and 0.99 for percent within tolerance.

Between repeated physical bite records obtained from the same subject, the average RMS was 0.34 (SD=0.11) and 76.33% was within tolerance (SD=18.30). The average RMS was 0.12 (SD=0.07) and 97.84% within tolerance (SD=1.76) comparing the repeated virtual scans. The average RMS was significantly lower for comparisons of two virtual bite records than comparisons of replicate physical bite records by an average of 0.22 (95% CI: 0.09, 0.35; adjusted $p=0.0005$). The average percent within tolerance was significantly higher for comparisons of two virtual bite records than comparisons of replicate physical bite records by an average of 21.51% (95% CI: 11.33, 31.69; adjusted $p<0.0001$).

There were statistically significant differences in both RMS ($p<0.0001$) and percent within tolerance ($p<0.0001$) between the repeat physical and repeat virtual bite records. These results are presented in **Table 1**.

Combination	RMS (Mean, SE)	% within Tol (Mean, SE)
Physical:Physical	0.34, 0.04	76.33, 3.02
Virtual:Virtual	0.12, 0.04	97.84, 3.02

*Estimated from repeated measures ANOVA

Table 1: Estimated RMS and Percent within Tolerance for Virtual and Physical Bite Records (Mean, SE)

One physical bite record from each participant was compared to each of the two virtual bite records. The difference in RMS was not significantly different based on the virtual scan (p=0.9782), nor was the percent within tolerance significantly different (p=0.2904) when comparing the physical bite record to the two virtual occlusal records. The difference in RMS was estimated to be 0.002 (95% CI: -0.15, 0.15) based on the two different virtual bite records, (A vs B) and the difference in percent in tolerance was estimated to be 4.90 (95% CI: -4.33, 14.12). These results are displayed in **Table 2**.

Comparisons	RMS (Mean, SE)	% within Tol (Mean, SE)
Physical: Virtual A	0.62, 0.05	53.33, 3.23
Physical: Virtual B	0.61, 0.05	48.43, 3.23
Difference	<0.01, 0.07	4.90, 4.57

*Estimated from repeated measures ANOVA

Table 2: Estimated RMS and Percent within Tolerance for Comparison of Physical Bite Record to Virtual Scans (Mean, SE)

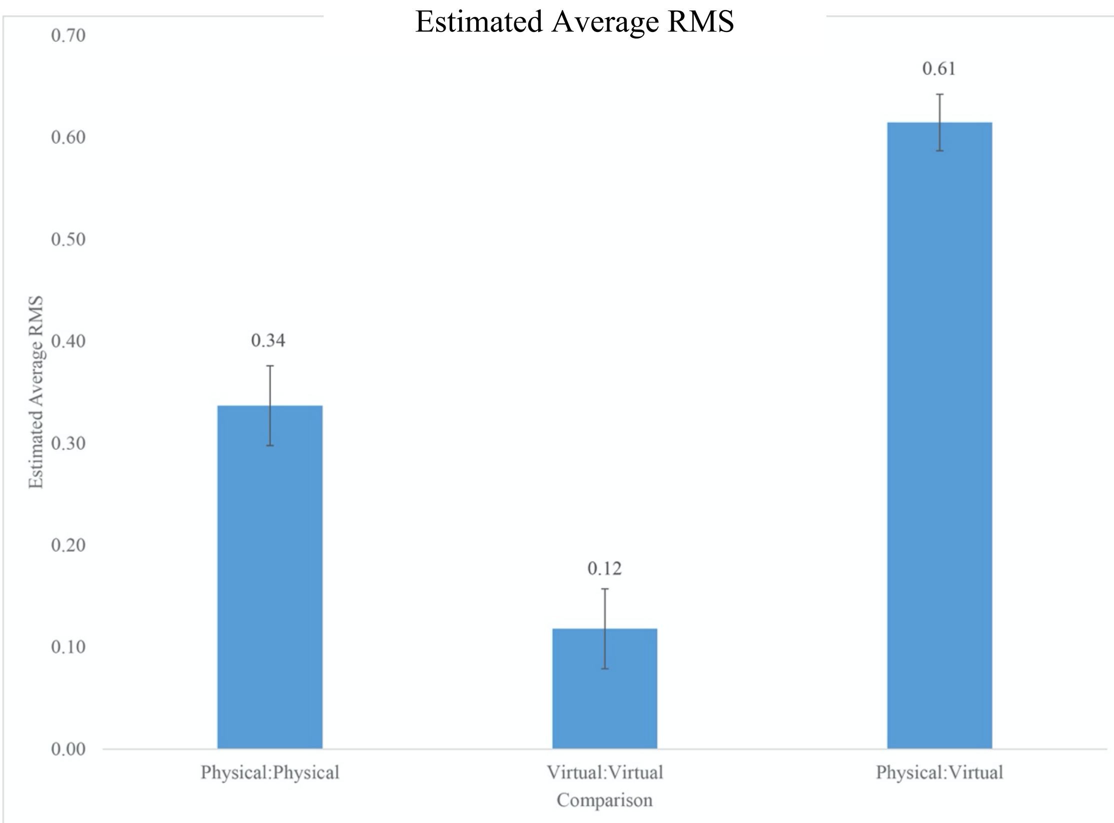
The average RMS value for comparisons between the physical impression and the two virtual bite records was 0.61 (SD=0.24) with an average percent within tolerance of 50.88% (SD=15.19). These results are displayed in **Table 3**. Repeated physical bite records had significantly lower RMS than physical to virtual comparisons by an average of 0.28 (95% CI: 0.16, 0.39; adjusted p<0.0001). Replicate physical bite records had significantly higher percent within tolerance than physical to virtual comparisons by an average of 25.45% (95% CI: 16.64, 34.27; adjusted p<0.0001). Repeated virtual bite records had significantly lower RMS than physical to virtual comparisons by an average of 0.50 (95% CI: 0.38, 0.61; adjusted p<0.0001). Replicate virtual bite records had significantly higher percent within tolerance than comparisons of physical to virtual by an average of 46.96% (95% CI: 38.15, 55.78; adjusted p<0.0001).

Combination	**RMS** (Mean, SE)	**% within Tol** (Mean, SE)
Physical:Virtual	0.61, 0.03	50.88, 2.13

*Estimated from repeated measures ANOVA

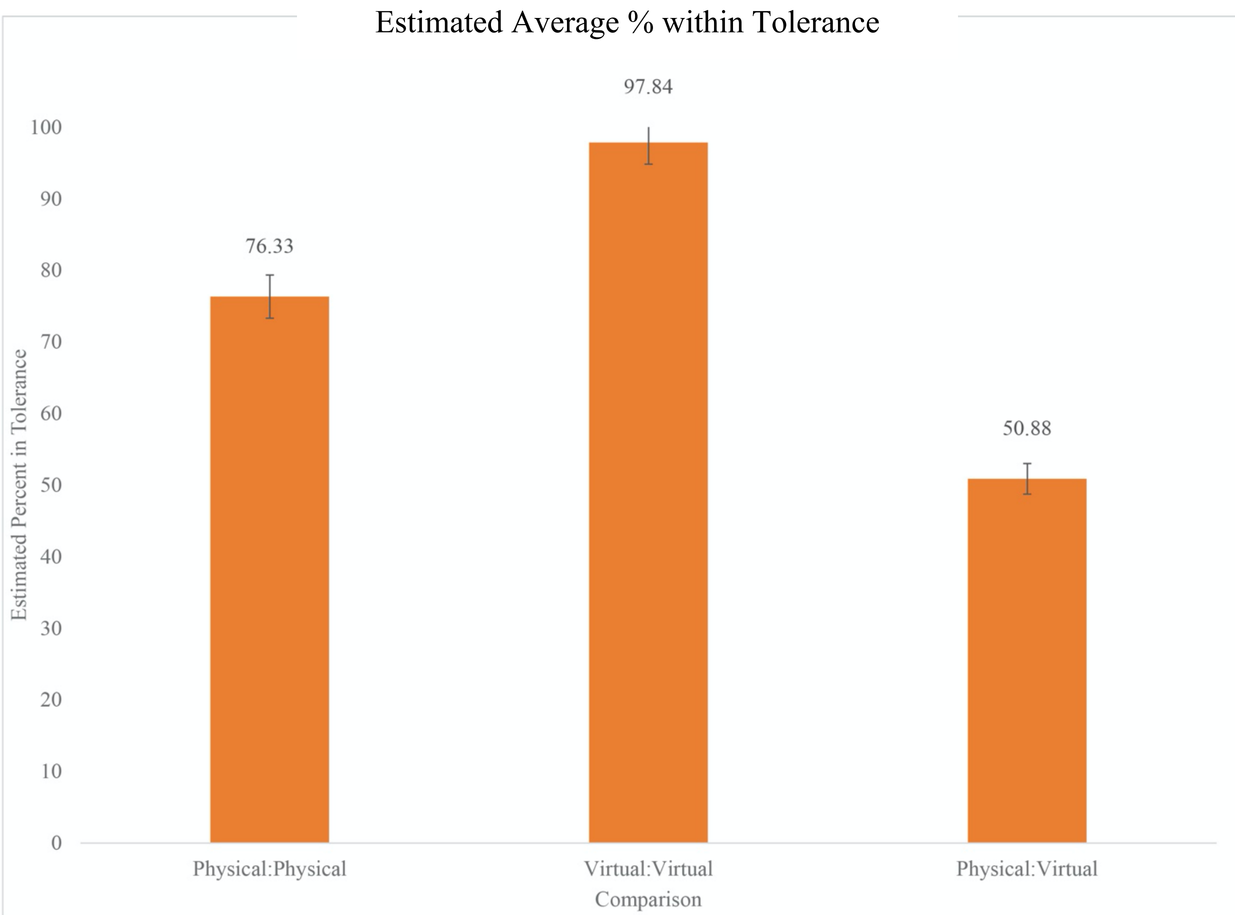
Table 3: Average Estimated RMS and Percent within Tolerance for Comparison of Virtual and Physical Bite Records (Mean, SE)

Figure 5 shows the average RMS across comparisons of physical to physical bite records, virtual to virtual bite records, and physical to virtual bite records. **Figure 6** shows the percent within tolerance across comparisons of physical to physical bite records, virtual to virtual bite records, and physical to virtual bite records.



Average and standard error bars from repeated measures ANOVA models

Figure 5: Estimated Average RMS by Comparison



*Tolerance preset at +/-0.25 mm; Average and standard error bars from repeated measures ANOVA models

Figure 6: Estimated Average Percent within Tolerance* by Comparison

Discussion

Occlusal records should be both reproducible and accurate to be clinically useful. They have traditionally been obtained with conventional materials such as dental wax, metal oxide pastes, acrylic resins, and elastomeric materials like polyether and addition silicones.[17] Polyvinyl siloxane (PVS) occlusal records were chosen for this study because they are currently considered the occlusal record gold standard.[12–14] Virtual occlusal records made using an iTero scanner were compared with the physical PVS records for 22 participants. Repeated physical and virtual bite records were compared to determine the reproducibility for both types of occlusal records. The physical and virtual bite records were then compared to determine the accuracy of the virtual occlusal record.

The virtual occlusal records were significantly more reproducible than the physical occlusal records. For repeated virtual records, the RMS was 0.12 and percent within tolerance was 97.84%, indicating that almost 98% of the data points compared were within the specified tolerance of 0.25mm. The physical bite records, however, were less reproducible with an RMS was 0.34 and percent within tolerance was 76.33%.

Previous studies also demonstrated that virtual occlusal records were highly reproducible. One study reported that the location of contacts between two virtual scans demonstrated what the authors classified as “moderate” agreement (Kappa = 0.67).[11] Another study found that virtual interocclusal records were reproducible, consistently identifying the same sites of close proximity (portions of the physical bite registrations <100 micrometers thick) and sites of clearance (portions of the physical bite registrations >100 micrometers thick).[18]

In the current study, participants' virtual models were interdigitated by recording the buccal bite record. The buccal surfaces of participants' teeth were scanned after they were fully occluded. The scanner software used the scanned buccal segments to orient the teeth into occlusion. However, there are several ways to virtually fit the teeth into occlusion, and there is controversy about which is the best. One study compared using buccal bite scans to interdigitate virtual models to using digital images of physical interocclusal records between the upper and lower casts. The virtual methods were compared to transillumination of PVS bite records and also shim stock for determining actual interocclusal contacts. They found that the accuracy of the interocclusal contacts were clinically acceptable when using the buccal bite scan.[19] Another study showed that the buccal bite scan method was less consistent than using segmented tooth registrations, occlusal contact area registrations, or using a combination of both of those, beginning with the segmented tooth registration and then using the occlusal contact registration afterward. [20]

Using a scanner to capture the virtual bite allowed for some penetration of contact points between teeth to move past or overlap each other. This phenomenon is called an interocclusal perforation. In a natural dentition or for conventional models, this phenomenon cannot occur because two contacting, solid teeth cannot penetrate or overlap each other as can happen virtually.[21] Virtual perforations that do occur are corrected mathematically by the scanner software during construction of the bite, which may affect and change the occlusal areas.[22]

Physical PVS occlusal record material has many positive physical properties for recording an occlusal bite. It has limited resistance before it sets, and dimensional stability and resistance to compression after setting; it accurately records the incisal and occlusal surfaces of the teeth, is easy to handle, and is biocompatible.[23] While PVS has many desirable qualities, one study confirmed that vertical discrepancies existed for many types of physical interocclusal records, including PVS. In that study, a PVS record was taken between two models, removed, and repositioned back on the same models. Vertical discrepancies between the two timepoints using the same interocclusal record were as great as 0.17 mm. While PVS had the least amount of vertical discrepancy among the physical bite registration materials tested, all physical materials showed clinical imprecision in the vertical dimension.[24]

In the current study, repeated physical bite records were more similar to each other than they were to the corresponding virtual bite records. Comparing physical to virtual bite records, the RMS was 0.61 and percent within tolerance was 50.88%, indicating that only 50% of the data points compared were within the specified tolerance of 0.25mm. This suggested that the virtual record was different from the physical record but did not indicate whether it was more or less accurate.

One degree of variability that may have caused differences between the physical and virtual records could have been introduced with the CBCT capture of the physical bite. CBCT images can vary based on the settings selected at acquisition. Voxel size, time of exposure and field of view can greatly affect the produced image.[25] Voxel size was shown to have the most effect on resolution, followed by time of exposure; the smaller the voxel size and longer the exposure time, the better the image spatial resolution.[25] Even so, a 0.2 mm voxel scan was shown to have an average spatial resolution of about 0.4 mm. A smaller voxel size would be more appropriate for studying small structures[26] but, even using a voxel size of 0.125 mm, as in the current study, may have resulted in a spatial resolution that did not detect very thin portions of

PVS material between two contacting or nearly contacting teeth. Physical bite records in the current study were somewhat ill-defined after conversion to an STL file. However, the virtual bite records were very detailed with no obvious physical defects, distortions, or data loss due to file conversion. This difference may have affected the comparison.

Subjects were instructed to bite in the same manner each time a record was taken whether physical or virtual. Participants' force magnitude for each bite, however, could have changed unintentionally depending on the presence or absence of an interposed material (PVS) during registration of the physical and virtual occlusal records, respectively. Since each subjects' bone and periodontal ligament were not completely rigid, there was likely some tooth movement during closure to obtain a buccal bite record and a physical bite record through compression of the periodontal ligament and bending of the alveolar bone.[27] This may have influenced and changed occlusal contacts.

One way to interpret the data could be to conclude that the virtual bite records were more accurate than the physical bite records. A previous study compared conventional and virtual occlusal records by scanning mounted models in occlusion and comparing those to photographs of the occlusal surfaces of the same mounted casts with contacts marked with articulating paper.[28] Virtual occlusal contacts were compared point by point to the mounted models marked with articulating paper. It was found that the accuracy of the virtual occlusal record was greater than that of the traditional method using articulating paper for marking occlusal contacts.[28]

Limitations of this study included the potential error introduced with the CBCT imaging of physical bite records to convert physical data into STL files. Having only one rater to obtain the 3D comparison data through CX could have also introduced bias, so having an independent, blinded technician perform the comparisons would have improved the study design.

Future studies could investigate whether scanning physical bite records with the same scanner used for the virtual records would acquire more data from the physical bite records than converting them using CBCT imaging. This scanning would produce an STL file, allowing both physical and virtual bites to be compared. However, this could also introduce scanning error into both the physical and virtual records. Continuation of this study using fixed reference points or determined reference planes on participants' teeth could allow for repeatable, reliable measures to confirm and support these findings.

Conclusion

- Virtual occlusal records are significantly more reproducible than physical occlusal records.
- Statistically and clinically significant differences exist between virtual and physical bite records.
- Some of the differences between physical and virtual bite records could have been due to variations in the physical bite records themselves.
- Virtual occlusal records may be more accurate than physical PVS bite records, but additional research is needed to confirm this.

References

1. Mangano F, Gandolfi A, Luongo G, Logozzo S. Intraoral scanners in dentistry: A review of the current literature. *BMC Oral Health* 2017;17(1):1–11.

2. Christensen GJ. Impressions are changing. *J. Am. Dent. Assoc.* 2009;140:1301–4.

3. Ting-Shu S, Jian S. Intraoral Digital Impression Technique: A Review. *J. Prosthodont.* 2015;24:313–21.

4. Anon. *iTero Element 5D User Manual.*; 2020. Available at: www.aligntech.com.

5. Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL. Diagnostic accuracy and measurement sensitivity of digital models for orthodontic purposes: A systematic review. *Am. J. Orthod. Dentofac. Orthop.* 2016;149(2):161–70.

6. Mennito DMD AS, Evans DMD ZP, Nash JB, et al. Evaluation of the trueness and precision of complete arch digital impressions on a human maxilla using seven different intraoral digital impression systems and a laboratory scanner. *J. Esthet. Restor. Dent.* 2019;31:369–77.

7. Ender A, Zimmermann M, Attin T, Mehl A. In vivo precision of conventional and digital methods for obtaining quadrant dental impressions. *Clin. Oral Investig.* 2016;20:1495–504.

8. Angle EH. *Treatment of Malocclusion of the Teeth. Angle's System.* Philadelphia; 1907.

9. Julien KC, Buschang PH, Throckmorton GS, Dechow PC. Normal masticatory performance in young adults and children. *Arch. Oral Biol.* 1996;41(1):69–75.

10. Owens S, Buschang PH, Throckmorton GS, Palmer L, English J. Masticatory performance and areas of occlusal contact and near contact in subjects with normal occlusion and malocclusion. *Am. J. Orthod. Dentofac. Orthop.* 2002;121(6):602–9.

11. Botsford KP, Frazier MC, Ghoneima AAM, Utreja A, Bhamidipalli SS, Stewart KT. Precision of the virtual occlusal record. *Angle Orthod.* 2019;89(5):751–7.

12. Durbin DS, Sadowsky C. Changes in tooth contacts following orthodontic treatment. *Am. J. Orthod. Dentofac. Orthop.* 1986;90(5):375–82.

13. Wieckiewicz M, Grychowska N, Zietek M, Wieckiewicz W. Evaluation of the Elastic Properties of Thirteen Silicone Interocclusal Recording Materials. *Biomed Res. Int.* 2016:1–8.

14. Baba, Kazuyoshi; Tsukiyama, Yoshihiro; Clark G. Reliability, validity, and utility of various occlusal measurement methods and techniques. *J. Prosthet. Dent.* 2000;83(January):83–9.

15. Anon. 3D Compare Statistics Control X. Available at:

https://support.3dsystems.com/s/article/3D-Compare-Statistics-Control-X?language=en_US.

16. Boyd RL, Waskalic V. Three-dimensional diagnosis and orthodontic treatment of complex malocclusions with the invisalign appliance. *Semin. Orthod.* 2001;7(4):274–93.

17. Megremis S, Tiba A, Vogt K. An Evaluation of Eight Elastomeric Occlusal Registration Materials. *J. Am. Dent. Assoc.* 2012;143(12):1358–60.

18. Abdulateef S, Edher F, Hannam AG, Tobias DL, Wyatt CCL. Clinical accuracy and reproducibility of virtual interocclusal records. *J. Prosthet. Dent.* 2020;124(6):667–73.

19. DeLong R, Knorr S, Anderson GC, Hodges J, Pintado MR. Accuracy of contacts calculated from 3D images of occlusal surfaces. *J. Dent.* 2007;35(6):528–34.

20. Li L, Chen H, Wang Y, Sun Y. Construction of virtual intercuspal occlusion: Considering tooth displacement. *J. Oral Rehabil.* 2021;(November 2020):1–10.

21. Edher F, Hannam A, Tobias D, Wyatt C. The accuracy of virtual interocclusal registration during intraoral scanning. *J. Prosthet. Dent.* 2018;120(6):904–12.

22. Ayuso-Montero R, Mariano-Hernandez Y, Khoury-Ribas L, Rovira-Lastra B, Willaert E, Martinez-Gomis J. Reliability and Validity of T-scan and 3D Intraoral Scanning for Measuring the Occlusal Contact Area. *J. Prosthodont.* 2020;29(1):19–25.

23. Malone W, Koth D. *Tylman's Theory and Practice of Fixed Prosthodontics*. 8th ed. St. Louis, MO: EuroAmerica; 1989.

24. Vergos VK, Tripodakis APD. Evaluation of vertical accuracy of interocclusal records. *Int. J. Prosthodont.* 2003;16(4):365–8.

25. Ballrick JW, Palomo JM, Ruch E, Amberman BD, Hans MG. Image distortion and spatial resolution of a commercially available cone-beam computed tomography machine. *Am. J. Orthod. Dentofac. Orthop.* 2008;134(4):573–82.

26. Molen AD. Considerations in the use of cone-beam computed tomography for buccal bone measurements. *Am. J. Orthod. Dentofac. Orthop.* 2010;137(4, Supplement 1):S130–5.

27. Davidovitch Z. Tooth movement. *Crit. Rev. Oral Biol. Med.* 1991;2(4):411–50.

28. Solaberrieta E, Otegi JR, Goicoechea N, Brizuela A, Pradies G. Comparison of a conventional and virtual occlusal record. *J. Prosthet. Dent.* 2015;114(1):92–7.