Tufts UNIVERSITY | School of Dental Medicine

Accuracy of Two Intra-Oral Scanners in Recording the Static Inter-Occlusal Relationship

A Thesis

Presented to the Faculty of Tufts University School of Dental Medicine

in Partial Fulfillment of the Requirement of the Degree of

Master of Science in Dental Research

by

Abdullah Bokhary

March 2021

THESIS COMMITTEE

Thesis Advisor

Aikaterini Kostagianni DDS, DMD, MS
Assistant Professor
Department of Prosthodontics
Tufts University School of Dental Medicine
Boston MA

Committee Members

Aikaterini Papathanasiou DMD, DDS
Associate Professor
Director, Advanced Education in Esthetic and Operative Dentistry Program
Department Prosthodontics
Tufts University School of Dental Medicine
Boston MA

Matthew Finkelman, PhD
Associate Professor
Department of Public Health and Community Service
Tufts University School of Dental Medicine
Boston MA

Yo-Wei Chen, DDS, MSc
Assistant Professor
Department Prosthodontics
Tufts University School of Dental Medicine
Boston MA

Ala Ali BDS, DMD, MSc, DSc
Assistant Professor
Department of Prosthodontics and Operative Dentistry
Tufts University School of Dental Medicine
Boston MA

ABSTRACT

Statement of problem: Intraoral scanners have played an important role in the development of dental digital technologies. Accurate registration of the inter-occlusal relationship is essential both during the diagnostic and definitive phases; however, there is a lack of scientific data on the accuracy of digital static inter-occlusal registration. The purpose of this study was to evaluate the accuracy of the inter-occlusal registration of two intraoral scanners (Trios3, 3Shape and CEREC Omnicam, Dentsply Sirona) based on a mandibular posterior tooth supported three-unit fixed dental prosthesis.

Material and methods: A typodont with a missing mandibular left first molar (#19) was prepared for a three-unit tooth supported fixed dental prosthesis (#18-#20). Polyether impression material (Impregum Penta Soft Medium, 3M ESPE, St. Paul, MN) was used to make impressions of the maxillary and mandibular arches. These impressions were poured with type IV stone and mounted on an Artex articulator. The master models were digitalized using a desktop scanner (Activity 880). The master models were scanned 25 times with two intra-oral scanners (Group A: Trios3 and Group B: CEREC Omnicam). Geomagic Control X software was used to analyze the discrepancy on the vertical, horizonal and anterior-posterior dimensions. The independent-samples t-test was used to test the differences between the groups. Separate statistical analyses were performed on each of the planes. The significance level was set at 5% ($p < 0.05$).

Results: The independent-samples t-test revealed a statistically significant difference between scanners on the 3 dimensions (vertical $p<0.001$, horizontal $p=0.001$, anterior-posterior $p<0.001$). The mean linear discrepancy of the 3Shape Trios scanner was 272.3 μm (SD = 76.0) on the vertical plane, 323.3 μm (SD = 30.7) on the horizontal plane and 388.7 μm (SD = 51.8) on the anterior-posterior plane. The mean discrepancies of the CEREC Omnicam scanner were 365.3 μm (SD = 34.1), 353.9 μm (SD = 28.6) and 611.8 μm (SD = 47.9) respectively. The direction of the discrepancy was similar for both scanners. The relationship between maxillary and mandibular arches moved coronally, buccally and distally in both scanners.

Conclusion: The discrepancies on the Trios 3 scanner were significantly lower compared to the CEREC Omnicam scanner in terms of recording the static inter-occlusal relationship. The pattern of the discrepancy was similar for both scanners.

DEDICATION

This thesis is dedicated to my parents, who love me unconditionally and support me in my life and education. Also, I would like to dedicate this project to my wife (Reem Zuhairy) and sons (Ibrahim and Elyas) for their patience. Their love and support made this project possible.

ACKNOWLEDGMENT

First and foremost, I would like to acknowledge the principal investigator in this study Dr. Aikaterini Kostagianni for her kind support and supervision in carrying out this project. I would like to thank her for the direction and input during the different stages of my master's project. I would like to thank Dr. Yo-Wei Chen for his guidance during the three-dimensional analysis in the study. The training on geomagic software was very helpful to facilitate the analysis on this study. Finally, I wish to extend my appreciation to my thesis committee members, Drs. Aikaterini Papathanasiou, Matthew Finkelman, Yo-Wei Chen and Ala Ali for their insightful input with the educational aspect of this research project. I am forever grateful for having had the chance to learn from their wealth of knowledge.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Accuracy of Two Intra-Oral Scanners

in Recording the Static Inter-Occlusal Relationship

Introduction

The rapid development of digital dental technology has dramatically changed the field of dentistry. The advantages of these systems include minimized chairside time, reduced production cost, improved efficiency, and greater patient comfort by minimizing the number of steps required. These systems also eliminate the variables associated with multiple laboratory stages and offer standardization in the process of prostheses fabrication.(1) However, these systems are not free of limitations as they are also associated with a high initial purchasing cost, limited accuracy in recording full arch cases,(2) and limited ability to record the margins accurately when they are obstructed by saliva, blood, or soft tissue.(1, 3, 4)

Digital dentistry was first introduced by Duret and colleagues in 1971 as computer-aided design/computer-aided manufacturing (CAD/CAM) and has since been integrated into many aspects of patient care.(5) With early studies being more experimental rather than clinical ones, Heitlinger and Rodder began to share this approach in 1980,(6) followed by a dentist from Switzerland, Dr. Mörmann, and an electrical engineer from Italy, Marco Brandestini, who announced the first digital intraoral scanner for restorative dentistry that developed the concept introduced by Sirona Dental Systems LLC (CEREC®, Charlotte, NC) in 1987. This system was the first chairside CAD/CAM dental restoration system for commercial use.(7)

This CAD/CAM system consists of three elements. First, data acquisition tools include intraoral scanners, laboratory scanners, face scanners, and cone beam computed tomography (CBCT). These devices transform geometry into models (digital data) that can be processed by a computer. Second, the CAD planning and processing software processes the data, merges different digital data, and assists in designing either an implant or tooth supported restorations.

Finally, computer-aided manufacturing (CAM) transforms the digital product into the desired physical product either by subtractive or additive fabrication methods. Depending on the location of these components, the production concepts can be chairside, laboratory, or centralized.[8]

Since then, research and development sectors in several companies have advanced their technologies and developed faster and more user-friendly CAD/CAM system components. These technologies record and reproduce three-dimensional (3D) virtual models of tooth preparation, while dental prostheses can be manufactured by using the virtual models in the form of Standard Tessellation Language (STL), which is used for breaking the geometry of a surface into a series of small triangles or polygons (tessellation).[9] Currently, CAD/CAM is also utilized for purposes other than fabricating definitive restorations. The digital data with the integration of CAD systems can facilitate the design of digital diagnostic wax-up, mill implant-supported provisional restorations, fabricate abutments for implant-supported protheses, and print surgical guides for precise crown lengthening or implant placement.[10]

Accuracy

Accuracy is one of the most important parameters that a scanner needs to cite to be clinically acceptable. According to metrics and engineering, accuracy is defined as the “closeness of agreement between a measured quantity value and a true quantity value of a measurand.”[11, 12] In other words, it is the combination of trueness and precision. Trueness is defined as the ability of a measurement to match the actual value of the quantity being measured. The impression method is considered to have high trueness when it delivers a result that is close or equal to the actual dimensions. On the other hand, precision is defined as the ability of a measurement to be consistently repeated.[11] In other words, the impression method with high precision has the ability to consistently deliver the same dimensions for the same patient. In order to capture high-quality virtual impressions, an intra-oral scanner (IOS) should have high trueness and precision. [13-15]

Scanners

Scanners have played an important role in the development of dental digital technology and have emerged as an alternative to the conventional impression technique. Basically, there are two types of laboratory scanners: intra-oral and extra-oral scanners.

1. Intra-Oral Scanners (IOS)

The IOS are optical scanners that project either a visible light or an amplified light beam (laser) onto the object being scanned. The object can be captured either as individual images of the dentition or a video sequence by a digital sensor.[3, 16] The captured data are processed by the scanning software that generates point clouds that are then triangulated, creating a 3D virtual model.[4] These models can be exported as STL files.

Today, there are more than 22 different IOS systems available in the market, all of which exhibit a relatively similar workflow. However, these systems differ in the techniques of capturing and processing the data. These systems are categorized in two groups: laser beam-based IOS systems and light beam-based IOS systems. Each group has unique technologies used in data acquisition. Laser beam-based IOS systems use either a still image capturing technique (e.g., iTero) or a continuous image capturing technique (e.g., Plan-Scan). These techniques enable the IOS to capture a series of images at various angles and positions. These images are assembled and then rendered three-dimensionally. The three methods implemented in the laser beam-based IOS systems are parallel confocal imaging, laser triangulation imaging, and structured light imaging combined with a laser triangulation technique.(17)

The first method used in this group is the parallel confocal imaging technique from the field of microscopy. When using this technique, parallel laser beams are projected through the scanner's head to the object being scanned. These laser beams hit the object at a specific focal length, bounce off, return through a small pinhole, strike the laser sensor, and are converted to an image. This technique is performed by the iTero scanner (Cadent, Carlstadt, NJ, USA). Parallel red-laser light beams are projected by the scanner at 300 different focal depths spaced approximately 50 μm apart. Within one-third of a second, a field of 14 mm × 18 mm is sampled and the data are digitized afterwards.(18) This spacing allows for an approximate scan depth of between 13 mm and 15 mm. In total, the system captures approximately 3.5 million data points for each arch being scanned.(19) The successor of this system was introduced at the International Dental Show (IDS) 2015 and is called the iTero Element (Align Technology, San Jose, CA, USA). The new version of iTero exhibits enhanced acquisition capabilities by capturing 6,000 frames per second compared to the 800 frames per second captured by its predecessor.(16) A similar technique is the confocal microscope recognition with the Moiré effect, which is used by some IOS systems (e.g., Zfx/Organical Scan Oral/Cyrtina/3D Progress).

The second method is the laser triangulation imaging technique in which the scanner utilizes a red laser beam and micromirrors that rapidly oscillate to capture a series of still images from multiple angles around the object in order to generate the model.[18, 20, 21] This technology is similar to the triangulation technique implemented in laser beam-based IOS systems. However, the triangulation technology of light beam-based IOS systems requires only a single orientation of the camera to capture all the details from a single image.[22, 23] Representative IOS systems that utilize this technique are the E4D system (D4D Technologies LLC, Dallas, TX, USA) and PlanScan (Planmeca, Helsinki, Finland). However, PlanScan utilizes a blue laser beam rather than the red laser beam implemented by E4D.

Finally, structured light imaging, combined with laser triangulation techniques, is another IOS technology that uses a combination of the aforementioned imaging techniques that facilitate continuous image capture to create an accurate 3D representation of the model. This technology is currently implemented in the CS 3500 (Carestream Dental, Atlanta, GA, USA), which utilizes a green laser and four light-emitting diodes (LEDs; UV, blue, green, and red). The green laser is used for the acquisition of the data. On the other hand, the four LEDs are used for the illumination of the object. A complementary metal oxide semiconductor (CMOS) sensor receives the acquired data. According to the manufacturer, the scanner has a field of view of approximately 16 mm × 12 mm and a working depth of -2 mm to 13 mm.[24] The scanner is completely powder-free and enables full-arch scanning.

IOS that use light beam-based systems employ visible light beams for image capture. In this group, the image capture method can vary between still image, video capture, and the ultrafast optical sectioning technique. The majority of IOS systems belonging to this group require the application of titanium dioxide as an antiglare agent.

The still image capture technique utilizes a technology known as active triangulation. The given point in the 3D space is located by the intersection of three linear light beams.[25] This concept has been used in a variety of industrial measuring devices. However, surfaces that disperse light irregularly do not reflect it evenly. In addition, surfaces that are irregular, such as tooth surfaces, adversely affect the accuracy of the scanners that are based on triangulation.[26] In order to avoid this issue, titanium dioxide, an opaque powder coating, is required to provide uniform light dispersion and to enhance the accuracy of the scan.[27] The active triangulation techniques are implemented in the CEREC AC Bluecam system (Sirona Dental Systems, Bensheim, Germany). The CEREC Bluecam utilizes a blue-light technology to scan the dentition.

Prior versions of CEREC utilized infrared light technology at a longer wavelength (820 nm) than the blue light (470 nm) associated with the CEREC Bluecam. This development provides an increased depth of field and is claimed to improve scanning accuracy by around 60%.[23, 27] As for further evolution of the CEREC Bluecam, Dentsply Sirona launched the CEREC Omnicam. The new camera captures images combining continuous and static stripe projection techniques. The main feature of this IOS system is that the teeth, in most cases, do not necessarily require prescan powdering. Furthermore, during the scan procedure, the image data are reproduced with natural colors and in real time on the screen while a full-color 3D model is generated.[28] A study by Jeong et al.[29] evaluated and compared the trueness and precision between CEREC Bluecam and CEREC Omnicam. In their study, they found that the CEREC Omnicam IOS were more accurate than CEREC Bluecam scanners and had the advantage of covering long-span areas.

Video sequence capturing technology, or active wavefront sampling (AWS), is the only technique that captures 3D data in a video sequence[30] and models it in real time.[18] AWS refers to getting 3D information from a single lens imaging system by measuring depth based on the defocusing of the primary optical system. The technique is implemented in the Lava Chairside Oral Scanner (Lava C.O.S, 3M ESPE, Seefeld, Germany) and its successor, the True Definition Scanner (3M ESPE, Seefeld, Germany).[31] Lava COS incorporates 192 blue LEDs for illumination, three sensors, and 22 lenses that capture the object simultaneously from different perspectives.[18, 21] The system captures 20 3D data sets per second while each data set contains 10,000 data points of information, resulting in roughly 24 million data points (or 2,400 data sets) captured per arch.[21] The successor system, True Definition Scanner, implements the same technology as Lava COS, but with fewer LEDs and lenses. The scanning wand of the True Definition Scanner consists of six LEDs for illumination, three optical lenses, and one CMOS sensor for image capturing and data acquisition.

Another technology used in the light beam-based systems is the ultrafast optical sectioning technology, which is similar to the video capture technique and facilitates continuous image captures. This technique uses up to 1,000 3D images to create true geometries based on real data rather than artificially forming interpolated surfaces. The technology is being implemented in the Trios3 IOS system (3Shape, Copenhagen, Denmark). According to the manufacturer, the scanner captures over 3,000 two-dimensional (2D) images per second. This is more than 100 times faster than a conventional video camera. Trios3 does not require the application of an antiglare agent, unlike with other light beam-based systems. The evolution of the existing system resulted in the third generation of Trios, known as the Trios3. The new

IOS system integrates an intra-oral camera for taking high-definition pictures and facilitating practitioner-patient communication.(17)

These different technologies contribute to the accuracy of the intra-oral impression as well as the speed of the scan. Also, certain technologies may work better in some clinical scenarios or oral environments than in others. Renne et al.(32) compared in-vitro the accuracy of six intra-oral scanners and one laboratory scanner in full-arch and sextant scenarios. They concluded that scanners differed regarding their speed, trueness, and precision in both scenarios. The Planscan and the CEREC Omnicam scanners provided the best combination of speed, trueness, and precision in sextant scans, while the Trios3 provided the best combination of speed, trueness, and precision in complete-arch scans.

IOS systems were developed to overcome the problems and disadvantages of the traditional impression fabrication process, including the elimination of trays and impression materials. Voids, tears, and pulls routinely experienced with conventional materials are no longer issues with digital scans and procedures that can be repeated easily, if necessary. In addition, real-time visualization of intra-oral structures may improve the communication with the patient as well as with the laboratory, and the process is more comfortable and time-efficient for both the providers and the patients.(15, 16, 33-35) Although studies have demonstrated that the accuracy of digital impressions is clinically comparable with conventional impressions, errors can still be encountered with the digital workflow.(5, 22-25) Inaccuracies can arise during the scanning procedure, the designing software, and the fabrication method, all of which contribute to the digital workflow's accuracy.

The performance of IOS in fixed prosthodontics is well documented in the literature. Studies have shown the comparable marginal accuracy of fixed dental prosthesis (FDP) fabricated from a digital workflow to those made with conventional impressions. A recent literature review and meta-analysis compared the accuracy of digital impressions versus conventional impressions for single crowns and a short span fixed dental prosthesis (FDP).[36] The authors concluded that the digital impressions provided marginal and internal fits for fixed restorations similar to the conventional method. Another study by Mejīa et al.[37] evaluated the influence of abutment tooth geometry total occlusal convergence (TOC) angles on the accuracy of conventional and digital workflow. They found that conventional dental impressions and those digitized with a laboratory scanner were not reliable in reproducing abutment tooth preparations when the TOC angle was close to zero degrees. In contrast, digital impressions made with IOS precisely record the abutment tooth preparations regardless of their geometry. On the other hand, Ender et al.[38] compared the accuracy of digital and conventional methods of obtaining complete-arch dental impressions. They concluded that the digital workflow had a higher deviation compared to the conventional technique. Meanwhile, digital impressions achieved higher precision than impressions made with irreversible hydrocolloid. Another in-vitro study by Ender et al.[39] evaluated different conventional and digital methods used to obtain full-arch dental impressions. In their study, they found that IOS are capable of recording a full-arch impression. However, conventional impressions were more accurate as digital intraoral impression systems show higher local deviations of the dental arch. Similar findings were demonstrated in an in-vivo study by Atieh et al.[40] where conventional impressions demonstrated higher accuracy than IOS. To summarize, the accuracy of IOS used for single to short-span prosthesis were proven to be accurate. However, long-span and full-arch impressions made with conventional impression material are still considered more accurate.

In implant dentistry, studies on the accuracy of IOS are increasing and the results appear to be promising. An in-vitro study conducted by Lee et al.[41] assessed the accuracy of digital implant impressions versus conventional impressions for a single tooth replacement. They found the accuracy of casts milled from the digital implant impressions to be similar to those of the stone casts made from conventional impressions in most anatomical areas. However, there was a significant vertical discrepancy in the implant position in both groups. The vertical displacement was found in the apical direction in the conventional group and in the coronal direction in the digital group, which resulted in restorations with potentially hyper- and infra-occlusion, respectively. Joda et al.[42, 43] evaluated the fit and time-efficacy of single implant crowns fabricated through digital workflow compared to the conventional approach. They concluded that although crowns can be completed within two clinical appointments for both approaches, the digital workflow was more efficient with respect to the total chair time. In addition, the digital approach produced implant crowns with predictable clinical fit with no or minor occlusal adjustments. The scientific evidence so far on intra-oral scanning is neither exhaustive nor updated in regards to full-arch scans.[33] It should also be pointed out that accuracy and reliability were comprehensively evaluated in only one study by Naidu et al.[44] that aimed at measuring tooth widths and deriving a Bolton ratio that concluded that IOS can be used to measure tooth widths and calculate Bolton ratios with clinically acceptable accuracy and excellent reliability and reproducibility.

2. Laboratory Scanners

The laboratory scanners, or extra-oral scanners, are classified as optic or mechanical scanners. Optical scanners project light (white light, blue light, or laser beams) in order to scan, while mechanical scanners utilize a ruby ball that touches the surface mechanically line by line to capture 3D geometry.(8) Optical laboratory scanners are considered faster compared to the mechanical scanners. However, the mechanical laboratory scanners are not affected by the surface optical properties of the scanned objects.(45)

Several studies have compared the accuracy of the IOS and the laboratory scanners. Bohner et al.(46) evaluated and compared the trueness in teeth prepared for scanning using two intra-oral scanners (3Shape Trios3 and CEREC Blue Cam) and two extra-oral lab scanners (D250 and CEREC InEosX5). They concluded that intra-oral and laboratory scanners showed similar trueness in scanning prepared teeth with a higher frequency of discrepancies in the cervical region and on the occlusal surface. Shimizu et al.(47) compared the accuracy of crowns fabricated digitally using two different intra-oral scanners: 3Shape Trios3 (Copenhagen, Denmark) and a CEREC Omnicam (Sirona Dental GmbH, Salzburg, Austria), as well as an extra-oral laboratory scanner. They concluded that the discrepancy in the impression by the laboratory scanner was lower compared to the impressions by the intra-oral scanners. However, the accuracy of both systems was within the clinically acceptable range. In addition, marginal and internal fit of the digital crowns fabricated using the intra-oral scanner were inferior to those fabricated using the laboratory scanner.

Flügge et al.[48] compared the precision of IOS (iTero) under clinical conditions with that of a laboratory scanner (D250). It was reported that, in complete-arch scans, laboratory scanning had higher precision than intra-oral scanning. The authors related the discrepancy in precision of intra-oral scanning to the need for additional scans from different angles, as image acquisition is incrementally defined. However, the extra-oral scan showed higher deficiency in scanning interdental spaces. In addition, Luthard et al. [39] reported that extra-oral scanning of prepared teeth had greater accuracy. The authors reported a mean deviation of 17 ±1 μm for intra-oral and 9 ±1 μm for extra-oral machines.

Kang et al.[49] evaluated the accuracy of five intra-oral scanners (CS3500, CS3600, Trios2, Trios3, and i500) and two laboratory scanners (3shape E1 and DOF) for complete arch scans. The difference in accuracy according to tooth geographic location (anterior and posterior regions) was evaluated, and it was concluded that both types of scanners showed lower accuracy in the posterior region compared to the anterior region. Additionally, it was reported that laboratory scanners had lower means of discrepancies in terms of accuracy. Similar results were found by Guth et al. [50] Another study by Wesemann et al.[51] evaluated the accuracy and time efficiency of an indirect and direct digitalization workflow. They compared impressions with intra-oral scanners, desktop scanners and cone beam computed tomography (CBCT) and found that conventional impressions, model casting, and optional digitization with desktop scanners remains the recommended workflow for full-arch scans. In addition, it was concluded that full-arch scans using intra-oral scanners are a useful alternative for full-arch scans for orthodontic purposes only. It was also recommended that the scanning scope should be less than one quadrant and three additional teeth when scanning for prosthodontic use.

In conclusion, the evidence about the accuracy of intra-oral scanners in terms of recording a full-arch impression is still not exclusive. Laboratory scanners are superior to the intra-oral scanners in this condition.

Static Inter-Occlusal Relationship

Accurate registration of the inter-occlusal relationship is essential in many dental specialties, including prosthodontics, orthodontics, and oral and maxillofacial surgery. Precision in articulated casts can minimize discrepancies during treatment and save valuable chair time. Recording the static inter-occlusal relationship is crucial through the conventional workflow as well as the digital workflow.

For an ideal inter-occlusal registration with the conventional workflow, there are many factors that need to be considered in relation to the material's properties such as material type, consistency, working and setting times, and dimensional stability.[52, 53] It is also recommended to register three widely spaced contacts (tripod) to obtain an accurate vertical and horizontal relationship.[54] Studies have shown that hand articulation of models without using inter-occlusal registration material has the least variability, if the occlusion is stable and adequate abutments are present for a tripod effect.[55, 56] Walls et al.[56] compared the accuracy of hand articulation of casts using visual and tactile sensation to polyether bite registration material. Hand articulation was more accurate in transferring the inter-occlusal relationship than the use of polyether registration material, unless there were difficulties in establishing the inter-occlusal relationship by visual and tactile methods. Other studies have shown that bite registration repeatability is questionable and is exaggerated by teeth loss.[55, 57, 58]

Materials that have been routinely used to record inter-occlusal relationships are plaster, wax, acrylic resin, zinc oxide-eugenol paste, eugenol free zinc oxide paste, and elastomers (polyether and polyvinylsiloxane).(59-62) Studies have been testing the properties of these materials to assess the most accurate inter-occlusal recording material. Chandu et al.(60) conducted a study to compare the compression resistance of multiple inter-occlusal recording materials (polyvinylsiloxane, polyether, Aluwax, modeling wax, and zinc oxide eugenol). Polyvinylsiloxane (PVS) displayed the highest resistance to compression loads followed by polyether, Aluwax, modeling wax, and zinc oxide eugenol. Chun et al.(63) investigated the polymerization shrinkage of various materials and found that PVS showed the greatest dimensional stability compared to dimethacrylate and polyether. Another study by Park et al.(61) evaluated the accuracy of Aluwax, pattern resin, and Blu-Mousse and concluded that that Blu-Mousse (polyvinylsiloxane) had greater accuracy in terms of recoding the inter-occlusal relationship. Sweeney et al.(58) investigated the effect of five different inter-occlusal recording materials (Regisil Rigid PVS, Futar Scan PVS, Byte Right, Aluwax, and Beauty Pink hydrocarbon wax) on the accuracy of the articulation of digital models. PVS showed higher accuracy in terms of the articulation of virtual models.

During the process of any prosthesis fabrication, an IOS has to precisely register not only the abutments but also the static relationship between the maxillary and mandibular teeth via a buccal bite scan. This allows the operator to design the prosthesis in occlusion with the opposing arch. However, there is now only scant evidence of the accuracy of the inter-occlusal scan function in the IOS systems. Previous testing on the accuracy of intra-oral scanners was on the dimensional accuracy on a single arch. [2, 38, 48, 64-68] Sectional digital impressions for the region of interest, in combination with buccal inter-arch scans, was the focus of early studies with full dentate situations.[69] Other subsequent studies tested the accuracy of the inter-occlusal registration in various scenarios. Wong et al.[70] compared the accuracy of the inter-occlusal relationship of three intraoral scanners (3M True Definition, Trios Color, and CEREC Omnicam) using Straumann tissue-level implants to replace opposing tooth preparation. The study concluded that Trios Color performed better in terms of inter-arch and global inter-occlusal distortions, while the 3M True Definition had the highest discrepancy. Also, negative inter-occlusal distortions were noticed in both the True Definition and CEREC Omnicam scanners that may result in intra-occlusion in the final restoration.

Edher et al.[71] assessed whether the alignment of virtual casts is affected by the location of recording the inter-occlusal relationship for a single unit restoration, and whether the alignment is affected by sectional and complete-arch scans recorded by only one intra-oral scanner (CEREC Omnicam). They concluded that there was a difference in the occlusal contacts obtained from inter-occlusal scans made in different segments, and this was mostly obvious in the complete-arch scans. The discrepancy presented as a tilting effect toward the site of the inter-occlusal scan. The authors suggested that multiple virtual inter-occlusal records may reduce the "tilting effect" produced by taking a single virtual inter-occlusal record. However, a single virtual inter-occlusal record should be made as close as possible to the area of interest if the software does not allow multiple bite scans. In addition, higher trueness was found in occlusal contacts obtained from the scans for virtual quadrants than those obtained from scans for complete virtual arches. Therefore, the authors recommended quadrant scans in single-unit cases to reproduce occlusal representation with higher accuracy.

In another study, Arslan et al.(72) evaluated the accuracy of the CEREC Omnicam system in reproducing the inter-occlusal relationship of the casts, which included posterior teeth preparation for a fixed partial denture for partial- or complete-arch impressions. The authors found that the partial digital impression showed significantly lower trueness in regard to the percentages of presence of indicated contacts compared to the contacts on the gypsum casts. On the other hand, full-arch impressions showed more trueness in terms of reproducing the inter-occlusal relationship. Therefore, it was encouraged to take a full-arch digital impression and design the restoration on full-arch virtual models in cases where no posterior antagonist contact remains after tooth preparation for a fixed dental prosthesis.

Gintaute et al.(73) tested the precision of three IOS and concluded that the maxillo-mandibular relationship had different surface areas of occlusal contact. Future studies were suggested to investigate the trueness of the inter-occlusal relationship produced by IOS. However, based on the findings observed in the study, Trios3 produced an occlusion that was closest to the true value (higher trueness). In addition, Gintaute et al. found that inter-occlusal relationships were more precise in the anterior region compared to the posterior region. However, more studies have to be conducted before a firm recommendation can be made.

To this author's best knowledge, there is a lack of studies comparing the accuracy of digital static inter-occlusal registration for fixed dental prosthesis in the posterior region. Therefore, the aim of this study was to evaluate and compare the accuracy of two IOS commonly used in dentistry: Trios3 (3Shape, Copenhagen, Denmark) and CEREC Omnicam (Dentsply Sirona, Charlotte, North Carolina) in terms of registering the inter-occlusal relationship.

Purpose

The purpose of this study was to evaluate the accuracy of the inter-occlusal registration of two intra-oral scanners: Trios 3 (3Shape, Copenhagen, Denmark) and CEREC Omnicam (Dentsply Sirona, Charlotte, North Carolina) based on a mandibular posterior tooth supported three-unit fixed dental prosthesis.

Clinical Significance

By knowing the accuracy of different intra-oral scanners in registering the inter-occlusal relationship, a provider is more likely to choose the best scanner to obtain a precise and correct inter-occlusal record. This will reduce the clinical time by eliminating the need for extensive adjustments and/or repeating clinical or laboratory steps.

Hypothesis

The null hypothesis was that there is no difference between the accuracy of the IOS scanners in recording the static inter-occlusal relationship.

Material and Methods

1. Master cast fabrication

A typodont (Figure 1; Model PRO2002, Nissin Dental, Tokyo, Japan) with a missing mandibular left first molar (#19) was used to prepare a three-unit tooth supported fixed dental prosthesis (FDP). The abutments were the second premolar (#20) and the second molar (#18), while the rest of the teeth up to 2nd molars on the contralateral side were intact (Figure 2). The maxillary typodont had intact teeth up to the 2nd molars (#2-#15).

A high-speed, air-driven handpiece with a water coolant and a coarse tapered diamond (Burs Diamond Ecoline E856C.314.016, Ecoline, SKSDental, Algemesi, Valencia, Spain) with a round end bur was used to cut 1.5mm deep grooves in the buccal, lingual, and occlusal surfaces (Figure 3). These depth cuts were assessed using a periodontal probe (Figure 4) and marked with a graphite pencil (Figure 5). The axial and occlusal surfaces were reduced following the cuts until the graphite pencil marks disappeared. Cusp tips and line angles were rounded. Consequently, the buccal cusps were reduced up to 2.0 mm and lingual cusp to 1.5 mm. A chamfer finish line was prepared at 0.5 mm supragingival and with a 1.0 mm width (Figure 6).

The static inter-occlusal relationship was recorded using a polyvinylsiloxane-based bite registration material (Blu-Mousse, Parkell Inc., Brentwood, NY). The material was delivered using an auto-mixing tip to the occlusal surfaces of the mandibular arch of the typodont. Then, the typodont was closed and secured with a rubber band until the material was completely set based on the manufacturer’s recommendations (Figure 7). Afterwards, the typodont was opened and the bite material was removed. Blade No. 15 was used to cut off the excess materials (Figure 8).

A regular set with a medium body viscosity polyether impression material (Impregum Penta Soft Medium, 3M ESPE, St. Paul, MN) was used to make impressions for the maxillary and mandibular jaws. On the mandibular arch, the impression material was delivered with a syringe to the margins, axial walls, and occlusal surfaces of the prepared teeth. Then a stock tray was loaded with the impression material and placed on the arch. The tray was maintained in place until the impression material was set completely based on the manufacturer's recommendations (Figure 9). On the maxillary arch, a stock tray was utilized only to capture the impression (Figure 10).

The captured impressions were poured with type IV stone (Resin Rock, Whipmix Corp., Louisville, KY). Powder and liquid ratios followed the manufacturer's instructions. A vacuum mixer was used to mix the stone and water for one minute. Then the mixture was poured into the impression with vibration. The casts were left for 60 minutes to complete the setting reaction of the stone. Then, the models were removed from the impression. The casts were cleaned and trimmed and kept at room temperature for 24 hours until they dried (Figures 11 and 12).

The master stone models were mounted using the mounting stone (Mounting Stone, Whipmix Corp, Louisville, KY) and prefabricated bases on an Artex articulator. The bite registration was used to mount the maxillary and mandibular casts in their static inter-occlusal relationship (Figure 13). The mounted casts were kept at room temperature for one hour until they dried.

On the prepared teeth, a US No. 1/4 round carbide bur was used to make indentations on the buccal, lingual, mesial, distal, and occlusal surfaces. The cutting head was sinked completely on the surface to fabricate the indentations with a depth of 0.5 mm. The indentations were allocated on the center of the surfaces. Two additional indentations were made on the buccal and lingual cusp tips of each preparation. These indentations were used as references during the measurements.

2. Digitalizing the master models

A high-resolution extra-oral reference scanner (Figure 14; Activity 880 scanner; Smart Optics, Bochum, Germany) was calibrated according to the manufacturer's instructions before the digital scanning. This reference scanner was used to digitize the master models. Based on ISO/TC 106/SC/WG11,[(74)] the models were scanned five times and then exported as STL files. The scan of the models started by scanning the maxillary arch. Followed by the mandibular arch. Finally, the models were attached a scan fixator to scan the maxillary and mandibular arches in the mounted occlusion. Followed, the inter-occlusal relationship was scanned. After the scans were completed, the discrepancy between the five scans was tested. The scan with the least discrepancy was used as a reference digital model in the study.

3. Scanning protocol

The master models were scanned with two intra-oral scanners—Group A: Trios 3 (Figure 15; 3Shape, Copenhagen, Denmark) and Group B: CEREC Omnicam (Figure 16; Dentsply Sirona, Charlotte, North Carolina). Each machine was calibrated before the scanning based on the manufacturer's instructions. The operator was calibrated by scanning the master models 10 times per machine before starting the scans for the study. The scanning technique Followed the manufacturer's recommendations for each machine (Figures 17-20). The inter-occlusal relationship was registered only on the left side, starting from the abutments and moving forward until the maxillary and mandibular canines were scanned. After the scanning was completed, the digital models were exported as STL files. The same protocol was followed for each sample on the study (n=25/group).

4. STL dataset superimposition procedure

First, the maxillary and mandibular scans were imported to the Exocad software (Exocad, DentalCAD 2.3 Matera, Woburn, Massachusetts, USA) in the same inter-occlusal relationship of the scanned sample. The scans were cleaned and then exported both together as one STL file (Figure 21). Followed, an inspection software (Geomagic Control X 2020, 3D Systems) was used to superimpose the STL files of each set of casts from the test groups to the STL files of the reference models (digital master models). The maxillary arch was isolated and used solely in the superimposition. After the superimposition each sample, the mandibular STL files were measured for the discrepancy. On each tooth preparation, horizontal, vertical and anterior-posterior virtual planes were created through the indentations (Figures 22-24). The vertical virtual planes were created through the indentations on the buccal and lingual cusps

(Figure 22), the horizontal planes were created through the buccal and lingual indentations (Figure 23) and the anterior-posterior planes were created through the mesial and distal planes (Figure 24). The two-dimensional (2D) linear displacements of the reference and test groups on the horizontal and vertical axes and anterior-posterior were calculated. (Figures 25 and 26). The calculation of the discrepancies was presented as linear distance and was measured in microns (μm). The indentations on the buccal, lingual, mesial, distal, and occlusal surfaces were used as references for the calculation.

Pilot Study

Few studies have compared the accuracy of the bite registration within the same groups; thus, a pilot study was necessary to estimate a sufficient sample size. Accordingly, a pilot study was conducted for the two identified groups. For the purpose of the pilot study, five scans were performed for two groups for a total of 10 scans. All scans were treated with the same protocol as that of the main study.

Sample Size Calculation

The software package nQuery Advisor (Version 7.0) was used to perform a power calculation to determine the sample size of the main study. The calculation used the means and standard deviations of the discrepancies on the vertical axis obtained in the pilot study. Based on the effect size found in the pilot study, a sample size of $n = 25$ per group was found to be adequate to obtain power greater than 99% in detecting a difference in the accuracy between groups, using a significance level of $\alpha = 5\%$. The study's workflow is presented in Figure 27.

Statistical Analysis

Descriptive statistics (means, standard deviations, minima, and maxima) were calculated for the continuous variables for the two study groups. The normality of the data was assessed graphically and with the Shapiro-Wilk test and was found not to be statistically significant for both scanners in all planes ($p > 0.05$). The test indicated that the data did not exhibit significant non-normality. Accordingly, the independent-samples t-test was used to compare the groups in terms of their magnitudes of discrepancies. Separate statistical analyses were performed for each of the planes. The significance level was set at 5% ($p < 0.05$). The software SPSS IBM version 27 was used for all statistical analyses. The difference in the direction of discrepancy between the groups was not tested due to similar behavior of all samples in the study.

Results

Descriptive statistics are presented in Table 1. The mean linear discrepancy of the Trios 3 scanner was 272.3 μm (SD = 76.0) on the vertical plane, 323.3 μm (SD = 30.7) on the horizontal plane and 388.7 μm (SD = 51.8) on the anterior-posterior plane. The discrepancies of the CEREC Omnicam scanner were 365.3 μm (SD = 34.1), 353.9 μm (SD = 28.6) and 611.8 μm (SD = 47.9), respectively. Figure 28 (side-by-side boxplot) is presenting the discrepancies of both scanners in the tested planes. The independent-samples t-test revealed a statistically significant difference for all planes ($p < 0.001$ for both vertical and anterior-posterior planes, and $p = 0.001$ for the horizontal plane). The direction of the discrepancy was similar for both scanners in all samples of the study. The mandibular arch moving coronally, buccally, and distally for both scanners.

Discussion

The objective of this in-vitro study was to compare the accuracy of two intra-oral scanners in terms of recording the static inter-occlusal relationship for a posterior tooth supported 3-unit fixed dental prosthesis. To the authors' knowledge, this is the first study to assess the 3D accuracy of the Trios3 and CEREC Omnicam scanners for this clinical scenario. The null hypothesis was rejected, as the Trios3 scanner demonstrated significantly better 3D accuracy of recording the inter-occlusal relationship compared to the CEREC Omnicam.

The findings from this study showed that the lowest mean 2D linear discrepancy was 272.3 μm, on the vertical dimension analysis of the Trios3 scanner, followed by 323.3 μm on the horizontal analysis of Trios3 scanner. Further, both the Trios3 and CEREC Omnicam scanners had their highest mean 2D linear discrepancy on the anterior-posterior dimension analysis, 388.7 μm and 611.8 μm, respectively. These findings are also consistent with those of Gintaute et al.[73] in terms of the magnitude of the discrepancy. In their study, they tested the precision of three intraoral scanners (CEREC Omnicam, Trios3, and Planmeca) in recording the inter-occlusal relationship in different clinical scenarios. The presence of total surface area of tooth contacts and separation distance between four pairs of key points located around the arch were the two methods to define the inter-cuspal position. It was concluded that the maxillo-mandibular relationship registered by the three intraoral scanners produced significantly different surface areas of occlusal contact. Also, the magnitude of the discrepancy between the intraoral scanners was significant in the posterior region. Similar to our study results, the Trios3 scanner produced occlusion that was closest to the true value (higher trueness).

In our study, although the Trios3 scanner was more accurate in recording the inter-occlusal relationship, the direction of the discrepancies found was similar for both scanners. The mandibular arches in both the Trios3 and the CEREC Omnicam scanners moved occlusally, buccally, and distally.

In an attempt to understand the values of the discrepancy, a possible explanation might be that the distal tooth abutment of the three-unit fixed dental prosthesis was the last remaining tooth on the mandibular arch. In addition, after teeth preparation, that side of the arch was missing occlusal contacts on the last three teeth. The intraoral scanner's accuracy could be affected by this scenario. Ren et al.[75] investigated whether the span and location of edentulous areas may affect the accuracy of virtual inter-occlusal records. In their study, five clinical situations were tested, including unilateral edentulous span missing three teeth on the lower arch. For that scenario, the mean discrepancy in recording the virtual inter-occlusal records was 0.87 mm on the vertical plane. It was concluded that unilateral extended edentulous spans with three or more missing posterior teeth affected the accuracy of virtual records. The vertical discrepancy observed in the current study was lower than what reported in Ren's study. However, Ren and colleagues used a different intraoral scanner from the one used in our study, which could explain why there were different values.

A factor that allows the clinical cut off (acceptable range) to be high is the periodontal ligament (PDL). Hurng et al.[76] conducted a study that measured the difference between the normal and compressed PDL space. The study reported that the deviation from normal PDL space (150-380 μm) to compressed regions (5-50 μm) at the original ligament-bone and ligament-cementum attachment were affected by the occlusal forces and functional demands. In addition, the severity of the symptoms that caused by the inaccurate occlusion as well as the adaptation of the masticatory system and can play an important role. A study by Rise et al.[77] tested the effect of the occlusal interference by adding 0.5 mm thickness of amalgam on the occlusal surfaces of 11 males. They found that disturbance of the occlusion by a small interference led to a significant alteration of the masticatory system by changing the timing and the level of muscular activity during mastication over the first week. Furthermore, there was also a change towards a unilateral chewing pattern, which, if persisting over the years, has been shown to evoke sequalae in the masticatory system. The importance of occlusal stability is further emphasized by the fact that four subjects reported significant pain in jaw muscles and/or temporomandibular joints caused by these small interferences.

The technology that the intraoral scanner uses to capture the impressions may contributes to the accuracy of the digital impressions. Both scanners in our study are based on a light-beam system that employs visible light beams to capture the image. However, the image capture technique is different between the two scanners. CEREC Omnicam uses a video capture technique with a continuous flew of images. This technology is known as active triangulation, in which the intersection of three linear light beams is used to locate a given point in the 3D space. On the other hand, Trios3 uses the ultrafast optical sectioning technique. This technique is similar to video capture techniques that use up to 1,000 3D images to create true geometries based on real data. According to the manufacturer, the scanner captures over 3,000 2D images per second, which is 100 times faster than the conventional video camera.[78] Previous studies have stated that video-based scanners may have better accuracy because they stream the images continuously with large areas for overlapping the images.[78, 79] In conclusion, the scanning technology of the Trios3 scanners may have contributed toward superior accuracy.

Another factor that influences the accuracy of the virtual articulation of the models is scanning the full arch. In an in vivo study by Ender et al,[80] was comparing digital with conventional quadrant impressions. The authors in the study compared the precision of different IOS system during a quadrant impression. In their study, they found that digital impression systems were capable of measuring quadrant impression with clinically satisfying precision. Also, the Trios3 IOS achieved higher precision than CEREC Omnicam, among the IOS tested. This conclusion was parallel with the finding obtained in the study. Another study by Arslan et al.(72) evaluated the accuracy of the CEREC Omnicam system in reproducing the inter-occlusal relationship of the casts, which included posterior teeth preparation for a fixed partial denture and tested partial- and complete-arch digital impressions. The authors found that the partial-digital impressions showed significantly lower trueness regarding the percentages of presence of indicated contacts compared to the contacts on the gypsum casts. In addition, full-arch impressions showed more trueness in terms of reproducing the inter-occlusal relationship. Therefore, the study encouraged taking a full-arch digital impression and designing the restoration on full-arch virtual models in cases where no posterior antagonist contact remained after tooth preparation for a fixed dental prosthesis. Consequently, the full arch scan protocol was used in the current study to achieve higher trueness.

On the other hand, a study by Medina-Sotomayor (65) reported that the trueness of the dental arch scan was affected by the length of the span scan. Complete dental arch scans' accuracy was the lowest compared to sectional scans. Another in-vitro study by Ender(81) reported that both trueness and precision of intraoral scanners were different in full-arch scans compared to partial scans. In their study, the authors reported that both trueness and precision were higher in favor of Trios 3 compared to CEREC Omnicam scanner. This finding is similar to the findings from the current study. A conclusion was stated by Ender et al.(38) when they compared full-arch scans with different conventional impressions. In their study, they found that the inaccuracy of the inter-occlusal records can be exaggerated by having less accurate full-arch scans. Since the orientation of the virtual casts is 3D, the exaggeration can be thought of as a tilting of the virtual casts, in one or more planes, toward the region where the virtual inter-occlusal scan was taken as explained in Edher et al.(71) Thus, the author recommended quadrant scans whenever possible to reproduce occlusal representation with higher accuracy. Also, it was suggested that dual virtual inter-occlusal records may reduce the "tilting effect" by averaging the relationship between the arches to have uniform occlusal contact. However, some of the intra-oral scanners do not support the dual bite scan. In that case, a single virtual inter-occlusal record should be made as close as possible to the area of interest. In our study, although the 3Shape company recommends 2 scans for the inter-occlusal records, a single bite scan protocol was implemented for standardization.

Another factor that could contribute to the accuracy of recording the inter-occlusal relationship is the size of the camera head. A study by Hayama et al. (82) compared trueness and precision of digital impressions obtained by 2 different sizes of the camera head. The authors in the study found that impressions made with larger camera head had better trueness. In the current study, CEREC Omnicam and Trios3 had different sizes of the camera head. The size of the camera head on CEREC Omnicam is 16 mm X 16 mm while Trios 3 is 17 mm X 20 mm. This difference in the size may contributed to the Trios 3 to have less discrepancy in terms of scanning the static inter-occlusal relationship. Finally, the built-in algorithm for the bite scan alignment as well as the software version can affect the inter-occlusal relationship.

A study by Ender et al. [81] compared the trueness and precision for different IOS. In their groups, the authors compared the trueness and precision between CEREC Omnicam version 4.6.1 and CEREC Omnicam version 5.0.0. The latest version of the software had better trueness compared to the older version.

Abdulateef, S. et. al.[83] in an in-vivo study, evaluated the accuracy and reproducibility of the inter-occlusal records of an intra-oral scanning system (CEREC Omnicam) compared with conventional polyvinyl siloxane (PVS) inter-occlusal records. Sixty (60) virtual records were compared with the same number of conventional bite records in sectional scans for sites of close proximity and occlusal clearance. The sensitivity and specificity of the virtual records were tested (87% and 95% respectively). It was concluded that the CEREC Omnicam can register the inter-occlusal record within the acceptable clinical range with fair reproducibility.

In terms of the vertical discrepancy, both the Trios3 and CEREC Omnicam scanners moved occlusally. The clinical effect of this discrepancy clinically will result in less restorative space during the registration. Specifically, Trios3 had a mean vertical discrepancy less than CEREC Omnicam. This will introduce a hyper-occluding (high occlusion) final restoration that can be corrected by the provider before the restoration is placed. On the contrary, Gintaute et al.[73] found that CEREC Omnicam scans produced a posterior open bite in all tested scenarios in their study compared to Trios3 and Planmeca. However, the methodology in

Gintaute et. al. was different from that of our study. They tested the distance between four points allocated in the maxillary and mandibular jaws.

Regarding the horizontal discrepancy, both the Trios3 and the CEREC Omnicam scanners moved buccally. The Trios3 had a mean horizontal discrepancy less than CEREC Omnicam. Clinically, the movement of the mandibular jaw to the buccal direction will lead to the fabrication of the prosthesis with minimal horizontal overlap. This configuration is one of the main causes of cheek and tongue biting.[84] In addition, the cusp-fossa relationship will change and the condition of tooth contacts that diverts the mandible from a normal path of closure to centric relation will be created, known as deflective occlusal contacts.[85] To the author’s knowledge, no studies have tested the discrepancy of the static inter-occlusal relationship on the horizontal plane.

Regarding the anterior-posterior discrepancy, both the Trios3 and the CEREC Omnicam scanners moved distally. In this plane, the CEREC Omnicam had the highest mean of discrepancy among all other tested groups while Trios 3 had a mean anterior-posterior discrepancy less than CEREC Omnicam. In the clinical environment, the movement of the mandibular jaw distally will lead to a restoration fabricated with thicker marginal ridge. This will introduce occlusal interference that will require more chair time for adjustments before delivery. Analyzing all the movements of the inter-occlusal relationship, the definitive prosthesis can be fabricated in different shapes and thicknesses. This will affect the quality of the final product and will require additional time for adjustments. To the author's knowledge, no studies have tested the discrepancy of the static inter-occlusal relationship on the anterior-posterior plane.

One of the main limitations of this study was the use of an intra-oral scanner in an in-vitro setting. In this setting, the intra-oral environment, including saliva, humidity, soft tissue, anatomical factors, limited space, and the geographic location of the teeth were missing, all of which are known to affect the accuracy of the digital impressions. In addition, the bite scan was done from the side of the preparation, which was expected to affect the accuracy of recording the static inter-occlusal relationship in terms of having less surface data for bite alignment. However, Mejía et al.(37) found that the accuracy of digital impressions made with intra-oral scanning was not affected by abutment geometry.

Another limitation is that the scanned substrate material was Type IV gypsum stone. This could also affect the accuracy of the intra-oral scanner. A study by Nedelcu(86) assessed the influence of three different materials (polymethyl methacrylate [PMMA], titanium, and zirconia) on the accuracy of four intra-oral scanners (3M Lava COS, CEREC AC/Bluecam, E4D, and iTero). They reported that the substrate material influenced the outcome; specifically, scanning zirconia substrate tended to be more accurate followed by titanium and PMMA, respectively.

Finally, only one clinical scenario was tested. In this scenario, the accuracy of the inter-occlusal relationship was investigated for a three-unit tooth supported fixed dental prosthesis having the distal tooth abutment as the last tooth in the dental arch. In addition, the current study evaluated the static inter-occlusal relationship and therefore, a virtual articulator was not used. However, the virtual articulator would be mandatory if the dynamic inter-occlusal relationship was to be analyzed .[87] Thus, it would be beneficial for future studies to evaluate different clinical scenarios and different location of the arches, as well as the dynamic occlusion. Further, the fabrication of a fixed dental prosthesis over the prepared abutments would allow to assess if the accuracy of the scanned relationship fell within the clinically acceptable range.

Conclusion

Within the limitations of this study, the Trios3 scanner was significantly more accurate than the CEREC Omnicam scanner in terms of registering the static inter-occlusal relationship in all observed planes, in vertical, horizontal, and anterior-posterior orientation. The discrepancy of the occlusal relationship had similar pattern, with the mandibular arch moving coronally, buccally, and distally with both scanners.

APPENDIX A

Table 1: Mean, Standard deviation (SD), minimum, and maximum deviations (μm) by plane and scanner.

Plane	Scanner	Mean	SD	Min.	Max.	*p*
Vertical	Trios3	272.3	76.0	100.3	431.0	<0.001*
	Omnicam	365.3	34.1	293.6	419.7	
Horizontal	Trios3	323.3	30.7	253.3	365.3	0.001*
	Omnicam	353.9	28.6	308.7	403.2	
Anterior-Posterior	Trios3	388.7	51.8	306.7	543.5	<0.001*
	Omnicam	611.8	47.9	487.0	686.8	

*P-value from the independent-samples t-test.

APPENDIX B

Figure 1: A typodont (Model PRO2002, Nissin Dental, Tokyo, Japan).

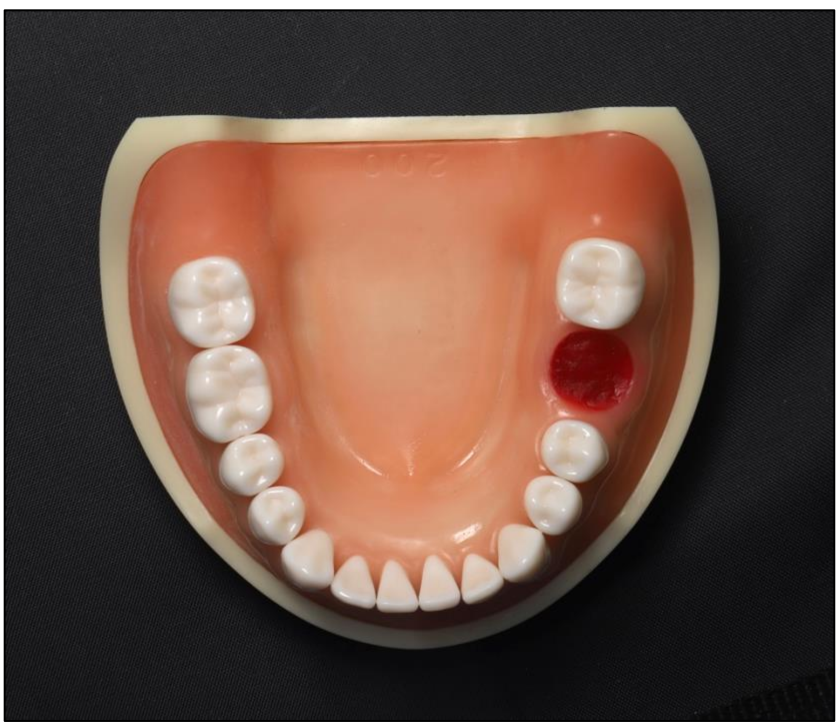

Figure 2: The Mandibular arch with missing #19.

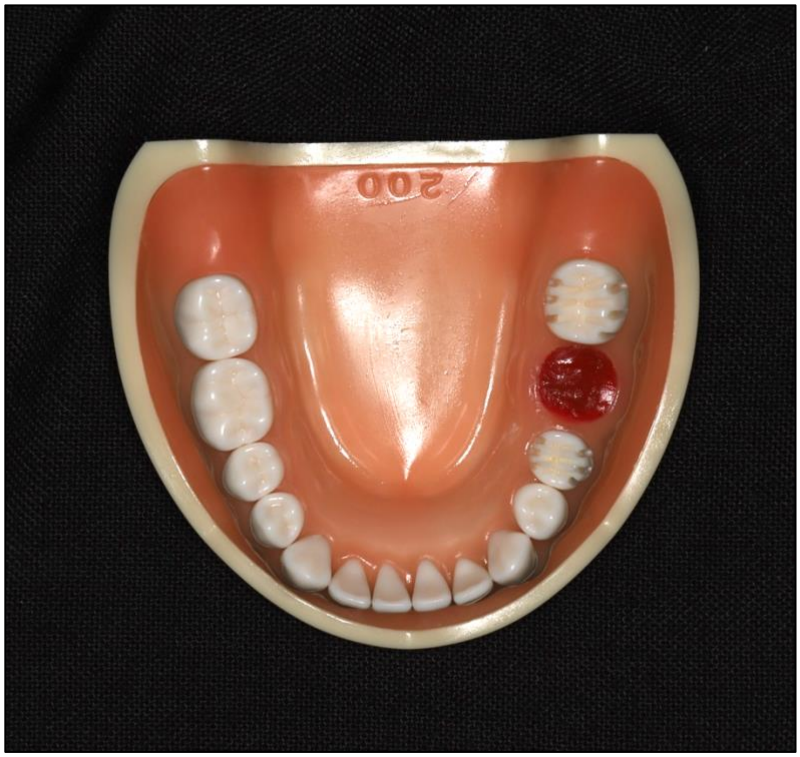

Figure 3: Depth grooves in the buccal, lingual and occlusal surfaces.

Figure 4: The depth cuts were assessed using a periodontal probe.

Figure 5: The depth cuts were marked with a graphite pencil.

Figure 6: The final tooth reduction for 3-unit FDP.

Figure 7: The static interocclusal relationship recorded with Blu-Mousse.

Figure 8: The Blu-Mousse after cutting the excess material.

Figure 9: The captured mandibular impression after preparation for pouring.

Figure 10: The captured maxillary impression after preparation for pouring.

Figure 11: The mandibular master model.

Figure 12: The maxillary master model.

Figure 13: Master models mounted using the bite registration material.

Figure 14: Activity 880 scanner; Smart Optics, Bochum, German.

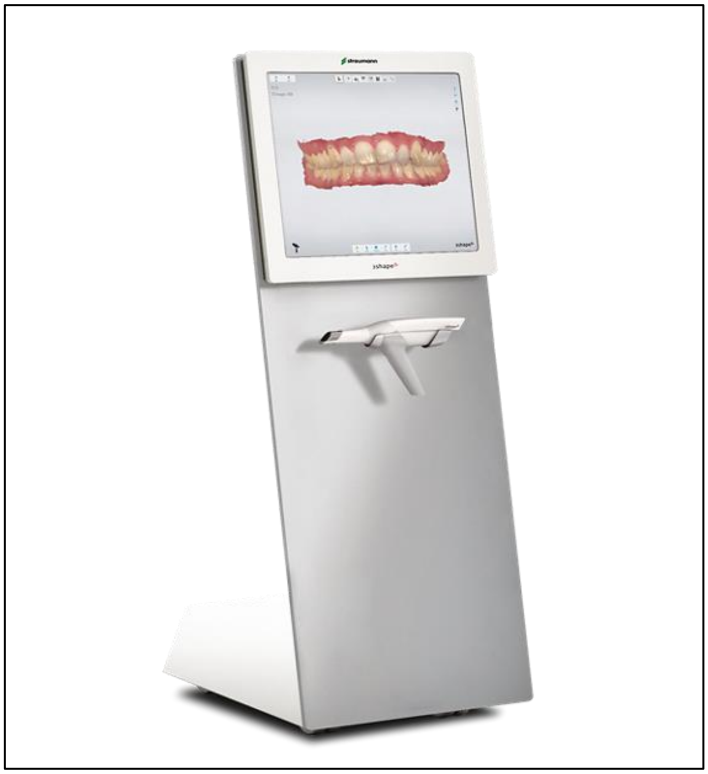

Figure 15: 3Shape Trios3® Intraoral Scanner.

Figure 16: CEREC Omnicam Intraoral Scanner.

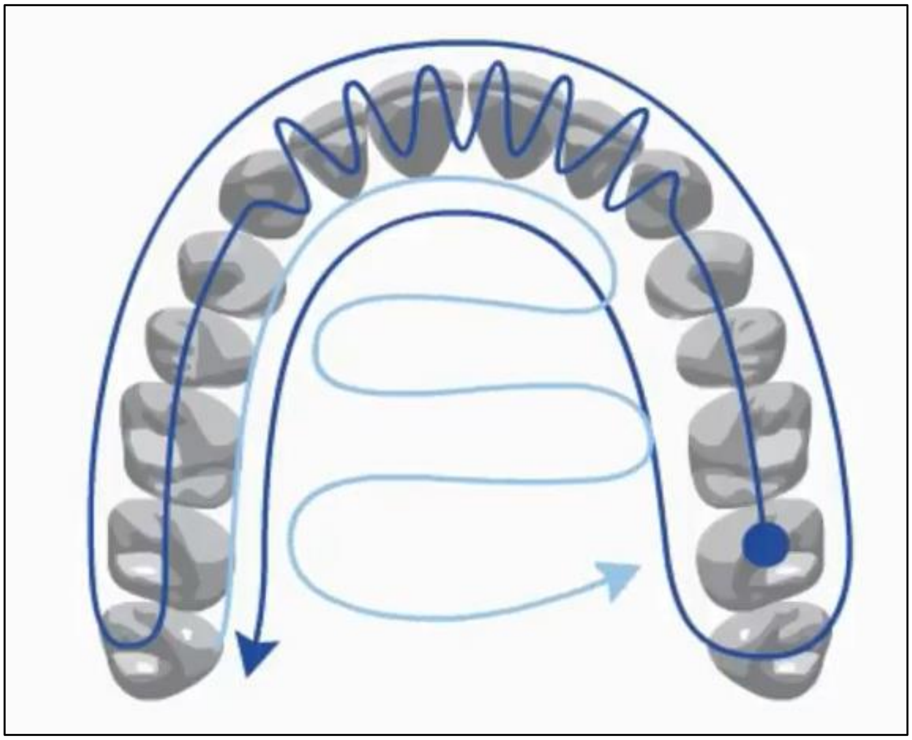

Figure 17: Scanning Protocol for 3Shape Trios3® maxillary arch.

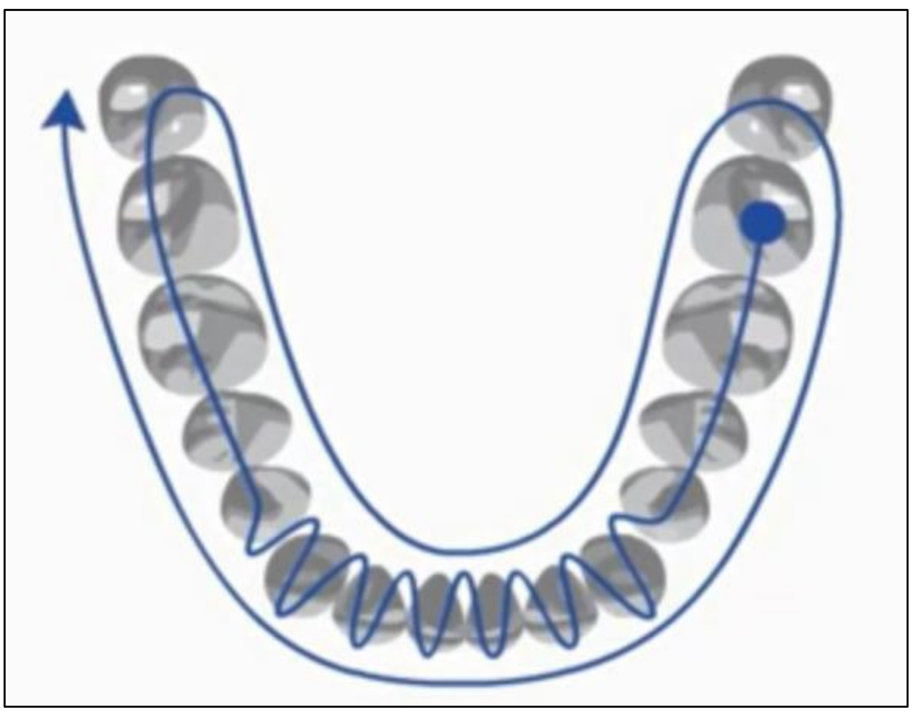

Figure 18: Scanning Protocol for 3Shape Trios3® mandibular arch.

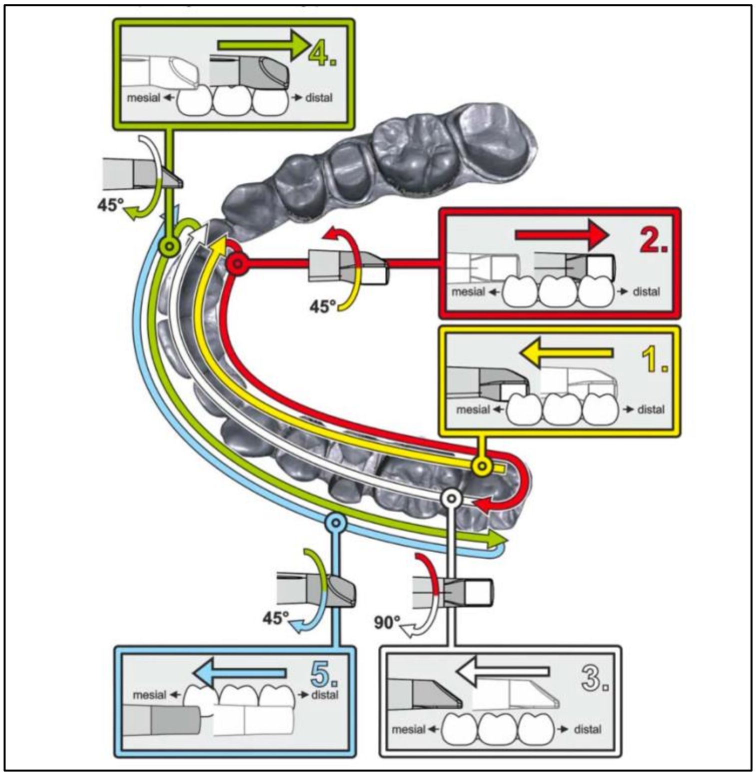

Figure 19: Scanning Protocol for CEREC Omnicam Part I.

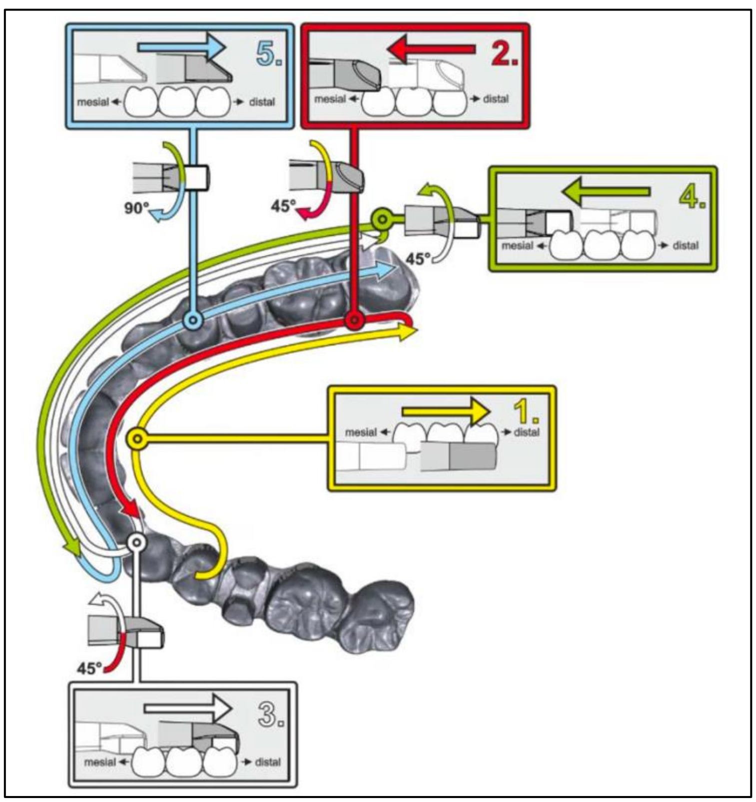

Figure 20: Scanning Protocol for CEREC Omnicam Part II.

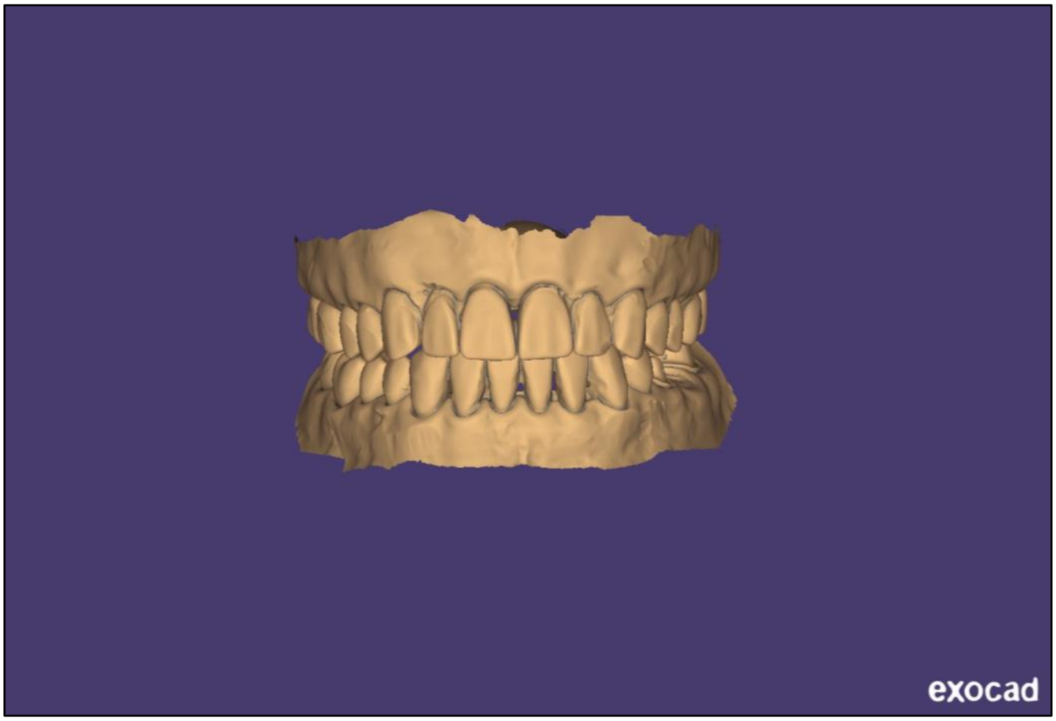

Figure 21: The STL file before exporting as one object with the recorded relationship.

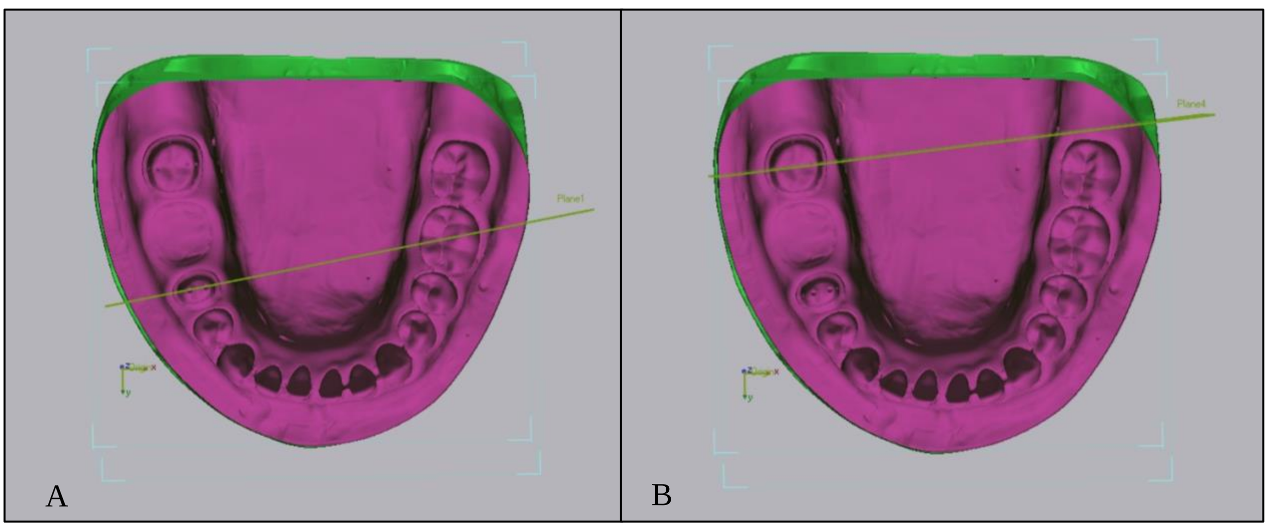

Figure 22: Virtual vertical Planes through indentation on the buccal and lingual cups. A: Vertical plane on tooth #20. B: Vertical plane on tooth #19.

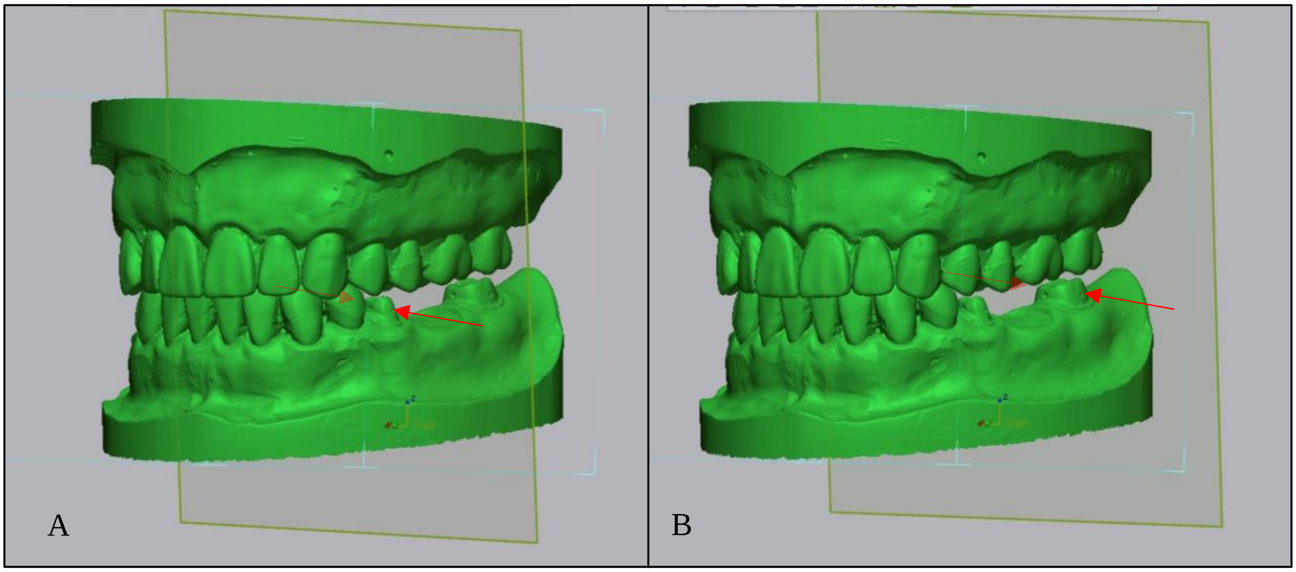

Figure 23: Virtual Horizontal Planes through indentation on the buccal and lingual surfaces. A: Horizontal plane on tooth #20. B: Horizontal plane on tooth #19.

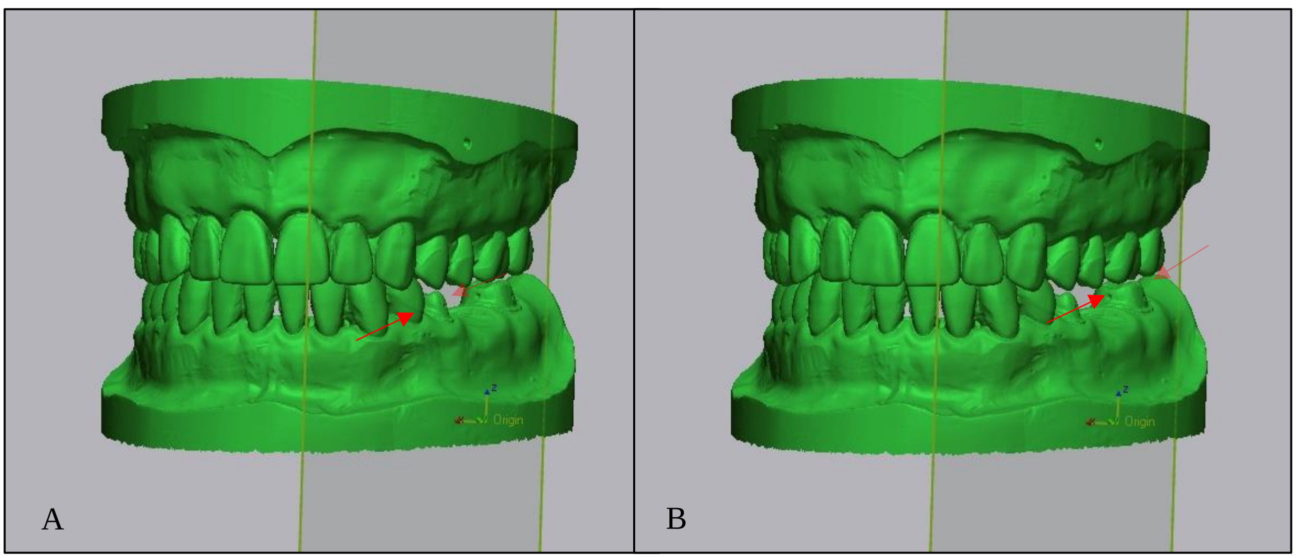

Figure 24: Virtual Anterior-Posterior Planes through indentation on the mesial and distal surfaces. A: Anterior-Posterior plane on tooth #20. B: Anterior-Posterior plane on tooth #19.

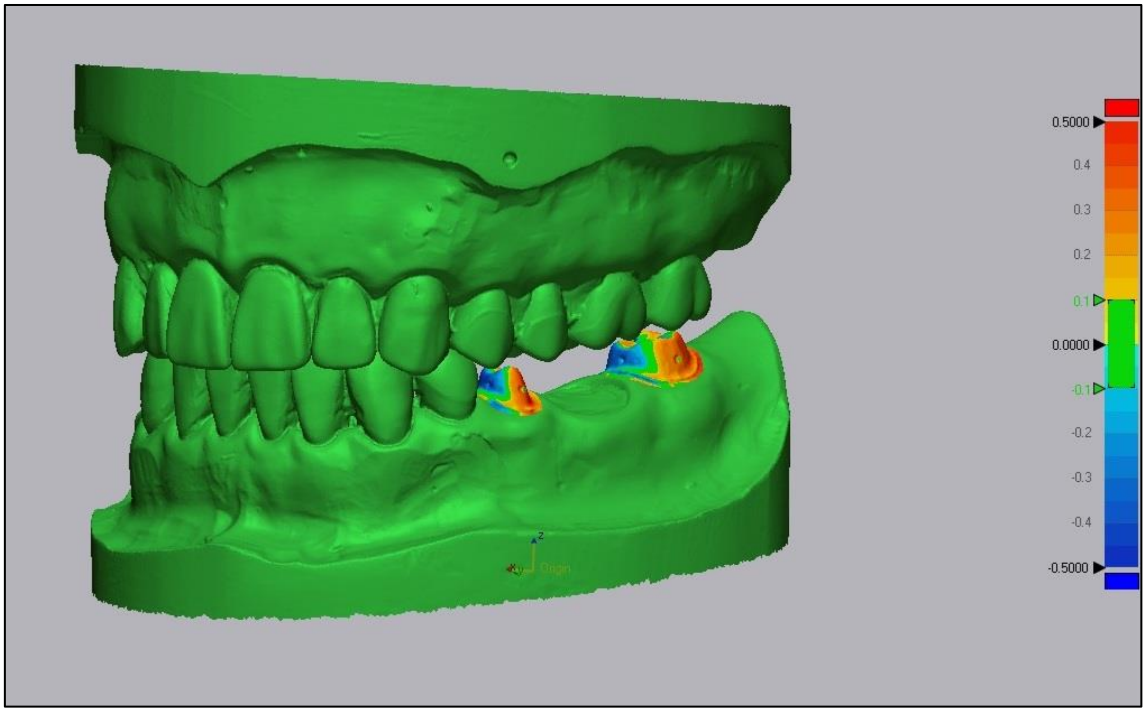

Figure 25: Superimposition of STL files of digital reference model and 3shape Trios3 scan.

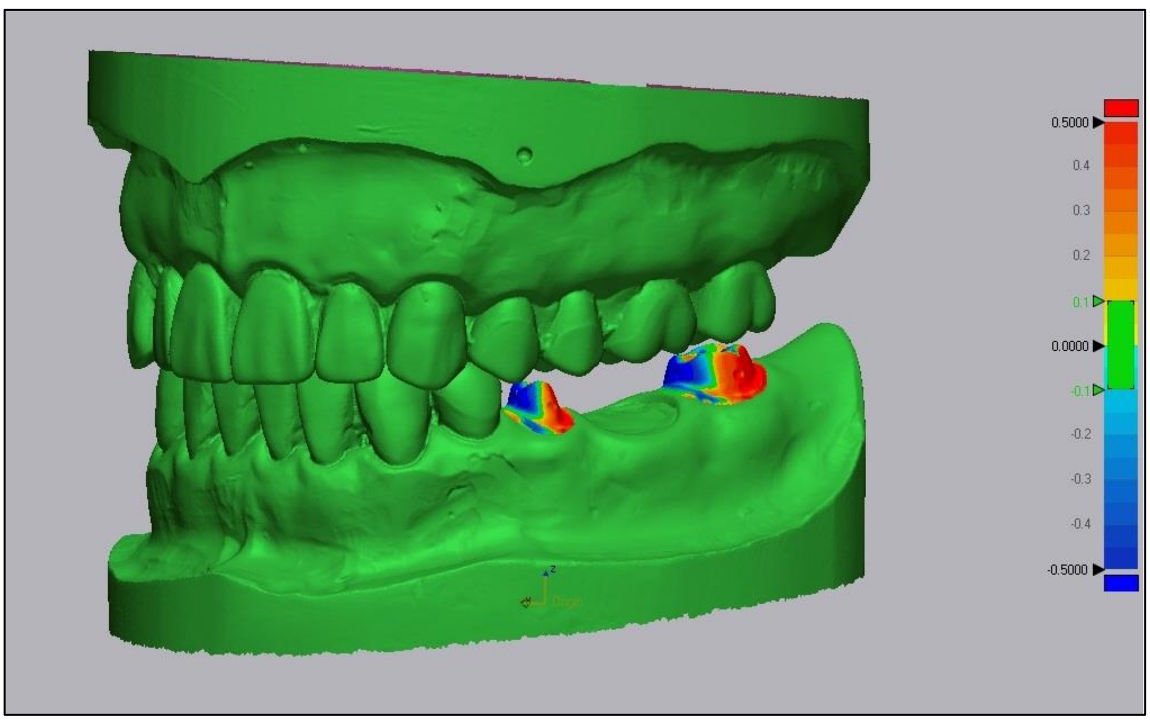

Figure 26: Superimposition of STL files of digital reference model and CEREC Omnicam scan.

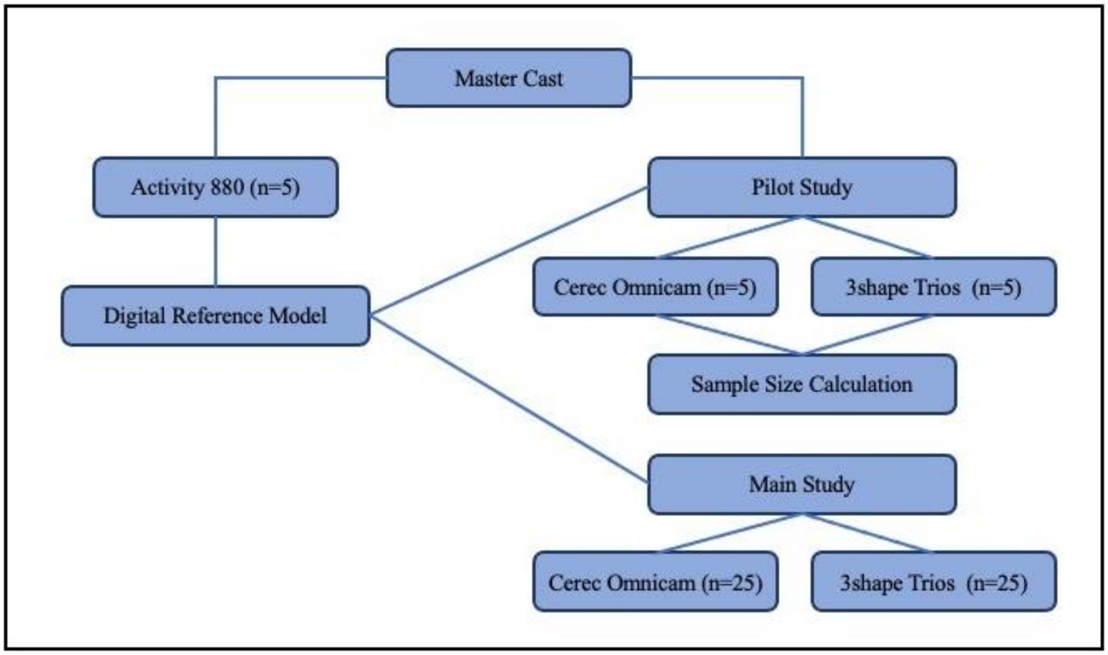

Figure 27: A flowchart of this study.

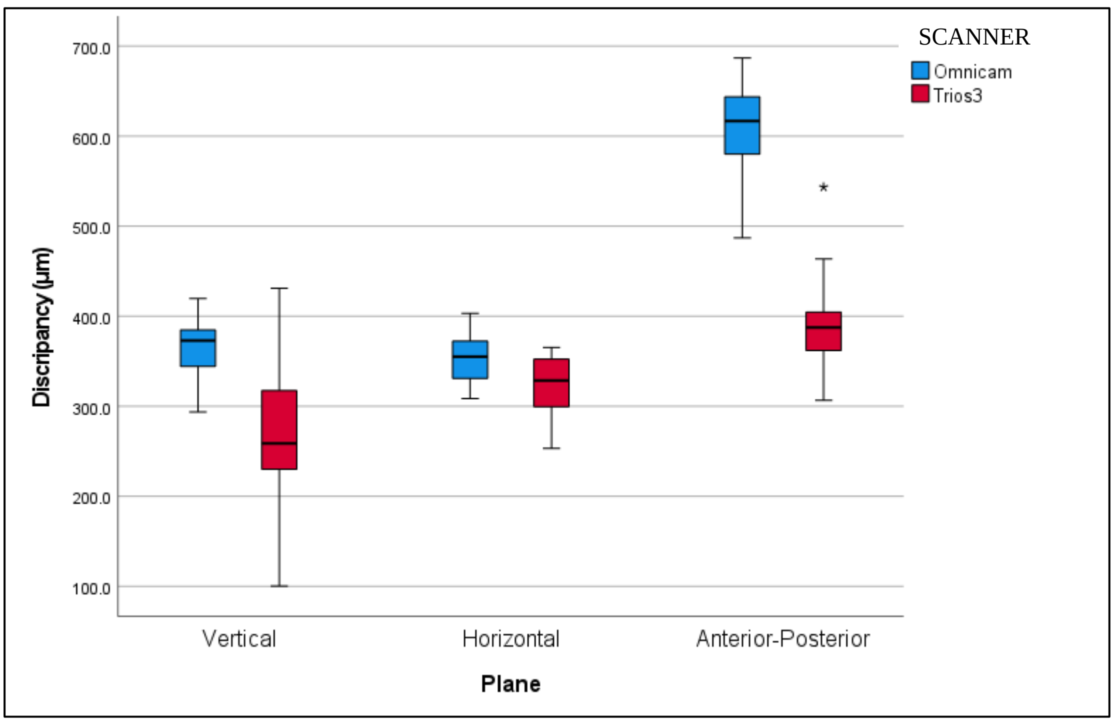

Figure 28: Side-by-side boxplots of the linear discrepancy in microns for 3Shape Trios3 and CEREC Omnicam scanners in the vertical, horizontal and anterior-posterior planes.

References

1. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. J Prosthodont Res. 2016;60(2):72-84.

2. Ender A, Mehl A. Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision. J Prosthet Dent. 2013;109(2):121-8.

3. Ting-Shu S, Jian S. Intraoral Digital Impression Technique: A Review. J Prosthodont. 2015;24(4):313-21.

4. Logozzo S, Zanetti EM, Franceschini G, Kilpela A, Makynen A. Recent advances in dental optics - Part I: 3D intraoral scanners for restorative dentistry. Optics and Lasers in Engineering. 2014;54:203-21.

5. Duret F, Blouin JL, Duret B. CAD-CAM in dentistry. J Am Dent Assoc. 1988;117(6):715-20.

6. Heitlinger P, inventorProcess for the production of dentures and device for carrying out the process.1980.

7. Marco Brandestini M, inventorMethod And Apparatus For The Three-Dmensional Registration And Display Of Prepared Teeth. United States patent 4,837,732. 1987.

8. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J. 2008;204(9):505-11.

9. Nathan S. Birnbaum HBA, Chris Stevens, Bob Cohen. 3D Digital Scanners: A High-Tech Approach to More Accurate Dental Impressions2009; 5(4). Available from: https://www.aegisdentalnetwork.com/id/2009/04/3-dimensional-digital-scanners-a-high-tech-approach-to-more-accurate-dental-impressions.

10. G DEV, Ferraris F, Arcuri L, Guzzo F, Spinelli D. A novel workflow for computer guided implant surgery matching digital dental casts and CBCT scan. Oral Implantol (Rome). 2016;9(1):33-48.

11. 5725-1:1994 I. Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions. 1994.

12. (JCGM) JCfGiM. Basic and general concepts and associated terms. VIM. BIPM: BIPM; 2012.

13. Mangano FG, Veronesi G, Hauschild U, Mijiritsky E, Mangano C. Trueness and Precision of Four Intraoral Scanners in Oral Implantology: A Comparative in Vitro Study. PLoS One. 2016;11(9):e0163107.

14. Medina-Sotomayor P, Pascual-Moscardo A, Camps I. Accuracy of four digital scanners according to scanning strategy in complete-arch impressions. PLoS One. 2018;13(9):e0202916.

15. Imburgia M, Logozzo S, Hauschild U, Veronesi G, Mangano C, Mangano FG. Accuracy of four intraoral scanners in oral implantology: a comparative in vitro study. BMC Oral Health. 2017;17(1):92.

16. Zimmermann M, Mehl A, Mormann WH, Reich S. Intraoral scanning systems - a current overview. Int J Comput Dent. 2015;18(2):101-29.

17. Wael Att SW, Jörg Sturb. Digital Workflow in Reconstructive Dentistry. 1st ed: QP Deutschland; 2019.

18. Birnbaum NS, Aaronson HB. Dental impressions using 3D digital scanners: virtual becomes reality. Compend Contin Educ Dent. 2008;29(8):494, 6, 8-505.

19. Henkel GL. A comparison of fixed prostheses generated from conventional vs digitally scanned dental impressions. Compend Contin Educ Dent. 2007;28(8):422-4, 6-8, 30-1.
20. Liu PR, Essig ME. Panorama of dental CAD/CAM restorative systems. Compend Contin Educ Dent. 2008;29(8):482, 4, 6-8 passim.
21. Kachalia PR, Geissberger MJ. Dentistry a la carte: in-office CAD/CAM technology. J Calif Dent Assoc. 2010;38(5):323-30.
22. Steinbrenner H. The new Cerec AC Bluecam recording unit: a case report. Int J Comput Dent. 2009;12(1):71-7.
23. Pieper R. Digital impressions--easier than ever. Int J Comput Dent. 2009;12(1):47-52.
24. Dental C. CS 3500 Intraoral Scanner Recognized among Dentistry Today's Top 100 Products for 2014 2014 [Available from: https://www.carestreamdental.com/en-us/training-resources/newsroom/english/americas/2014/cs-3500-intraoral-scanner-recognized-among-dentistry-todays-top-100-products-for-2014/.
25. Yoshida M, Hanaoka Y, Tsuzuki T, Ueno A, Takagi T, Iwahara K, et al. Collection of intraoral findings in corpse with small-scale color dental scanner system. Forensic Sci Int. 2009;185(1-3):e25-8.
26. Kutulakos KN, Steger E. A theory of refractive and specular 3D shape by light-path triangulation. International Journal of Computer Vision. 2008;76(1):13-29.
27. Kravitz ND, Groth C, Jones PE, Graham JW, Redmond WR. Intraoral digital scanners. J Clin Orthod. 2014;48(6):337-47.
28. Wiedhahn K, Schenk O, Fritzsche G. Cerec Omnicam - Intraoralscan 2.0. Int J Comput Dent. 2012;15(3):199-205.
29. Jeong ID, Lee JJ, Jeon JH, Kim JH, Kim HY, Kim WC. Accuracy of complete-arch model using an intraoral video scanner: An in vitro study. J Prosthet Dent. 2016;115(6):755-9.
30. Rohaly J. The development of the Lava chairside oral scanner C.O.S. technology--masterstroke of a legion of talented and committed people. Interview by Laslo Faith. Int J Comput Dent. 2009;12(2):165-9.
31. Reich S, Vollborn T, Mehl A, Zimmermann M. Intraoral optical impression systems--an overview. Int J Comput Dent. 2013;16(2):143-62.
32. Renne W, Ludlow M, Fryml J, Schurch Z, Mennito A, Kessler R, et al. Evaluation of the accuracy of 7 digital scanners: An in vitro analysis based on 3-dimensional comparisons. J Prosthet Dent. 2017;118(1):36-42.
33. Goracci C, Franchi L, Vichi A, Ferrari M. Accuracy, reliability, and efficiency of intraoral scanners for full-arch impressions: a systematic review of the clinical evidence. Eur J Orthod. 2016;38(4):422-8.
34. Patzelt SB, Lamprinos C, Stampf S, Att W. The time efficiency of intraoral scanners: an in vitro comparative study. J Am Dent Assoc. 2014;145(6):542-51.
35. Yuzbasioglu E, Kurt H, Turunc R, Bilir H. Comparison of digital and conventional impression techniques: evaluation of patients' perception, treatment comfort, effectiveness and clinical outcomes. BMC Oral Health. 2014;14:10.
36. Chochlidakis KM, Papaspyridakos P, Geminiani A, Chen CJ, Feng IJ, Ercoli C. Digital versus conventional impressions for fixed prosthodontics: A systematic review and meta-analysis. J Prosthet Dent. 2016;116(2):184-90 e12.

37. Carbajal Mejia JB, Wakabayashi K, Nakamura T, Yatani H. Influence of abutment tooth geometry on the accuracy of conventional and digital methods of obtaining dental impressions. J Prosthet Dent. 2017;118(3):392-9.
38. Ender A, Attin T, Mehl A. In vivo precision of conventional and digital methods of obtaining complete-arch dental impressions. J Prosthet Dent. 2016;115(3):313-20.
39. Ender A, Mehl A. In-vitro evaluation of the accuracy of conventional and digital methods of obtaining full-arch dental impressions. Quintessence Int. 2015;46(1):9-17.
40. Atieh MA, Ritter AV, Ko CC, Duqum I. Accuracy evaluation of intraoral optical impressions: A clinical study using a reference appliance. J Prosthet Dent. 2017;118(3):400-5.
41. Lee SJ, Betensky RA, Gianneschi GE, Gallucci GO. Accuracy of digital versus conventional implant impressions. Clin Oral Implants Res. 2015;26(6):715-9.
42. Joda T, Bragger U. Time-Efficiency Analysis Comparing Digital and Conventional Workflows for Implant Crowns: A Prospective Clinical Crossover Trial. Int J Oral Maxillofac Implants. 2015;30(5):1047-53.
43. Joda T, Katsoulis J, Bragger U. Clinical Fitting and Adjustment Time for Implant-Supported Crowns Comparing Digital and Conventional Workflows. Clin Implant Dent Relat Res. 2016;18(5):946-54.
44. Naidu D, Freer TJ. Validity, reliability, and reproducibility of the iOC intraoral scanner: a comparison of tooth widths and Bolton ratios. Am J Orthod Dentofacial Orthop. 2013;144(2):304-10.
45. Gonzalez de Villaumbrosia P, Martinez-Rus F, Garcia-Orejas A, Salido MP, Pradies G. In vitro comparison of the accuracy (trueness and precision) of six extraoral dental scanners with different scanning technologies. J Prosthet Dent. 2016;116(4):543-50 e1.
46. Bohner LOL, De Luca Canto G, Marcio BS, Lagana DC, Sesma N, Tortamano Neto P. Computer-aided analysis of digital dental impressions obtained from intraoral and extraoral scanners. J Prosthet Dent. 2017;118(5):617-23.
47. Shimizu S, Shinya A, Kuroda S, Gomi H. The accuracy of the CAD system using intraoral and extraoral scanners for designing of fixed dental prostheses. Dent Mater J. 2017;36(4):402-7.
48. Flugge TV, Schlager S, Nelson K, Nahles S, Metzger MC. Precision of intraoral digital dental impressions with iTero and extraoral digitization with the iTero and a model scanner. Am J Orthod Dentofacial Orthop. 2013;144(3):471-8.
49. Byung-hyun Kang KS, Kyu-bok Lee. Accuracy of Five Intraoral Scanners and Two Laboratory Scanners for a Complete Arch: A Comparative In Vitro Study. Appl Sci. 2020;10(74).
50. Guth JF, Runkel C, Beuer F, Stimmelmayr M, Edelhoff D, Keul C. Accuracy of five intraoral scanners compared to indirect digitalization. Clin Oral Investig. 2017;21(5):1445-55.
51. Wesemann C, Muallah J, Mah J, Bumann A. Accuracy and efficiency of full-arch digitalization and 3D printing: A comparison between desktop model scanners, an intraoral scanner, a CBCT model scan, and stereolithographic 3D printing. Quintessence Int. 2017;48(1):41-50.
52. Michalakis KX, Pissiotis A, Anastasiadou V, Kapari D. An experimental study on particular physical properties of several interocclusal recording media. Part I: consistency prior to setting. J Prosthodont. 2004;13(1):42-6.

53. Tejo SK, Kumar AG, Kattimani VS, Desai PD, Nalla S, Chaitanya KK. A comparative evaluation of dimensional stability of three types of interocclusal recording materials-an in-vitro multi-centre study. Head Face Med. 2012;8:27.
54. Freilich MA, Altieri JV, Wahle JJ. Principles for selecting interocclusal records for articulation of dentate and partially dentate casts. J Prosthet Dent. 1992;68(2):361-7.
55. Strohaver RA. A comparison of articulator mountings made with centric relation and myocentric position records. J Prosthet Dent. 1972;28(4):379-90.
56. Walls AW, Wassell RW, Steele JG. A comparison of two methods for locating the intercuspal position (ICP) whilst mounting casts on an articulator. J Oral Rehabil. 1991;18(1):43-8.
57. Eriksson A, Ockert-Eriksson G, Lockowandt P, Eriksson O. Clinical factors and clinical variation influencing the reproducibility of interocclusal recording methods. Br Dent J. 2002;192(7):395-400; discussion 391.
58. Sweeney S, Smith DK, Messersmith M. Comparison of 5 types of interocclusal recording materials on the accuracy of articulation of digital models. Am J Orthod Dentofacial Orthop. 2015;148(2):245-52.
59. Prachitee D. WAP. Comparative evaluation of linear dimensional change and resistance to the compressibility of three polyvinyl siloxane interocclusal recording materials: an in-vitro study. Int J Dent Mater. 2020;2(2):30-6.
60. Chandu GS, Khan MF, Mishra SK, Asnani P. Evaluation and comparison of resistance to compression of various interocclusal recording media: an in vitro study. J Int Oral Health. 2015;7(5):24-9.
61. Park DH, Park JM, Choi JW, Kang ES, Bae EB, Jeon YC, et al. Accuracy of several implant bite registration techniques: an in-vitro pilot study. J Adv Prosthodont. 2017;9(5):341-9.
62. Muller J, Gotz G, Horz W, Kraft E. An experimental study on the influence of the derived casts on the accuracy of different recording materials. Part I: Plaster, impression compound, and wax. J Prosthet Dent. 1990;63(3):263-9.
63. Chun JH, Pae A, Kim SH. Polymerization shrinkage strain of interocclusal recording materials. Dent Mater. 2009;25(1):115-20.
64. Molina A, Martin-de-las-Heras S. Accuracy of 3D scanners in tooth mark analysis. J Forensic Sci. 2015;60 Suppl 1:S222-6.
65. Medina-Sotomayor P, Pascual-Moscardo A, Camps AI. Accuracy of 4 digital scanning systems on prepared teeth digitally isolated from a complete dental arch. J Prosthet Dent. 2019;121(5):811-20.
66. Abduo J, Elseyoufi M. Accuracy of Intraoral Scanners: A Systematic Review of Influencing Factors. Eur J Prosthodont Restor Dent. 2018;26(3):101-21.
67. Ender A, Mehl A. Full arch scans: conventional versus digital impressions--an in-vitro study. Int J Comput Dent. 2011;14(1):11-21.
68. Patzelt SB, Emmanouilidi A, Stampf S, Strub JR, Att W. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig. 2014;18(6):1687-94.
69. Jaschouz S, Mehl A. Reproducibility of habitual intercuspation in vivo. J Dent. 2014;42(2):210-8.
70. Wong KY, Esguerra RJ, Chia VAP, Tan YH, Tan KBC. Three-Dimensional Accuracy of Digital Static Interocclusal Registration by Three Intraoral Scanner Systems. J Prosthodont. 2018;27(2):120-8.

71. Edher F, Hannam AG, Tobias DL, Wyatt CCL. The accuracy of virtual interocclusal registration during intraoral scanning. J Prosthet Dent. 2018;120(6):904-12.
72. Arslan Y, Bankoglu Gungor M, Karakoca Nemli S, Kokdogan Boyaci B, Aydin C. Comparison of Maximum Intercuspal Contacts of Articulated Casts and Virtual Casts Requiring Posterior Fixed Partial Dentures. J Prosthodont. 2017;26(7):594-8.
73. Gintaute A, Keeling AJ, Osnes CA, Zitzmann NU, Ferrari M, Joda T. Precision of maxillo-mandibular registration with intraoral scanners in vitro. J Prosthodont Res. 2020;64(2):114-9.
74. 11 ITW. Digitizing devices for CAD/CAM systems for indirect dental restorations — Test methods to assess the accuracy and precision. ISO; 2011.
75. Ren S, Morton D, Lin WS. Accuracy of virtual interocclusal records for partially edentulous patients. J Prosthet Dent. 2020;123(6):860-5.
76. Hurng JM, Kurylo MP, Marshall GW, Webb SM, Ryder MI, Ho SP. Discontinuities in the human bone-PDL-cementum complex. Biomaterials. 2011;32(29):7106-17.
77. Riise C, Sheikholeslam A. Influence of experimental interfering occlusal contacts on the activity of the anterior temporal and masseter muscles during mastication. J Oral Rehabil. 1984;11(4):325-33.
78. S Logozzo GF, A Kilpelä, M Caponi, L Governi, L Blois. A Comparative Analysis Of Intraoral 3d Digital Scanners For Restorative Dentistry. The Internet Journal of Medical Technology. 2011;5(1):1-18.
79. Patzelt SB, Bishti S, Stampf S, Att W. Accuracy of computer-aided design/computer-aided manufacturing-generated dental casts based on intraoral scanner data. J Am Dent Assoc. 2014;145(11):1133-40.
80. 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(7):1495-504.
81. Ender A, Zimmermann M, Mehl A. Accuracy of complete- and partial-arch impressions of actual intraoral scanning systems in vitro. Int J Comput Dent. 2019;22(1):11-9.
82. Hayama H, Fueki K, Wadachi J, Wakabayashi N. Trueness and precision of digital impressions obtained using an intraoral scanner with different head size in the partially edentulous mandible. J Prosthodont Res. 2018;62(3):347-52.
83. Abdulateef S, Edher F, Hannam AG, Tobias DL, Wyatt CCL. Clinical accuracy and reproducibility of virtual interocclusal records. J Prosthet Dent. 2020.
84. OKESON JP. Management of TEMPOROMANDIBULAR DISORDERS AND OCCLUSION. 7th ed2013.
85. The Glossary of Prosthodontic Terms: Ninth Edition. J Prosthet Dent. 2017;117(5S):e1-e105.
86. Nedelcu RG, Persson AS. Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-dimensional analysis. J Prosthet Dent. 2014;112(6):1461-71.
87. Koralakunte PR, Aljanakh M. The role of virtual articulator in prosthetic and restorative dentistry. J Clin Diagn Res. 2014;8(7):ZE25-8.