Curriculum Vitae

Name: Sara Reanne Satin

Contact Information: srsatin@gmail.com

Degree and Date to be Conferred: Master of Science, 2022

Education:

2019-2022	University of Maryland School of Dentistry, Baltimore, MD Anticipated Degrees Awarded: Master of Science – May 2022 Certificate in Prosthodontics – June 2022
2015-2019	Boston University School of Dental Medicine, Boston, MA Degree Awarded: Doctor of Dental Medicine – May 2019
2011-2015	University of Michigan, Ann Arbor, MI Degree Awarded: Bachelor of Science – May 2015 Major: Movement Science Minor: History of Medicine

Poster Presentations:

February 2022	American Academy of Fixed Prosthodontics, Annual Session Chicago, IL Poster: Complex Rehabilitation with Dental Implants Utilizing a Digital Workflow
March 2019	American Dental Education Association, Annual Session Chicago, IL Poster: Restorative Guide for Predoctoral Students Utilizing CAD/CAM

Awards:

May 2019	Brasseler USA Award for Excellence in Removable Prosthodontics

Licensure:

	Maryland State Dental License – *pending*
April 2019	ADEX Examination

November 2018	NBDE Examination

Certifications:

July 2021	BLS
May 2019	CEREC
May 2019	Invisalign

ABSTRACT

Title of Dissertation: Comparing the Accuracy of Occlusal Vertical Dimension Transfer in Cad-Cam Dentures

Sara R Satin, DMD
Master of Science Candidate 2022

Dissertation directed by: Radi Masri BDS, MS, PhD, Professor, Department of Advanced Oral Sciences and Therapeutics

This laboratory-based study investigated the accuracy of transferring the VDO of the maxillary/mandibular relationship when designing and fabricating digital dentures by evaluating two commonly used workflows: duplicate dentures (DD) and occlusion rims (OR). 15 STLs were obtained for each workflow. Three measurements in deviation (mm) were obtained, then 3D-deviation values were averaged for each workflow at each location. A two-way ANOVA was used for the statistical analysis to evaluate differences between the methods and location of measurement. The average deviation for OR was higher than DD at all locations of measurement. There was a statistically significant difference between the DD and OR workflows [$F=46.00$, $p<0.0001$]. There was no statistically significant difference in deviation between the points of measurement [$F=0.15$, $p<0.86$] or between the location and method [$F=0.02$, $p<0.98$]. The DD workflow exhibited less deviation in transfer of VDO than the OR workflow. The location of the measurements had no significance.

Comparing the Accuracy of Occlusal Vertical Dimension Transfer in Cad-Cam Dentures

by
Sara Reanne Satin

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, Baltimore in partial fulfillment
of the requirements for the degree of
Master of Science
2022

Table of Contents

List of Tables

List of Figures

List of Abbreviations

CAD	Computer-aided design
CAM	Computer-aided manufacturing
DD	Duplicate denture workflow
OR	Occlusion rim workflow
VDO	Vertical dimension of occlusion
STL	Standard tessellation language
VPS	Vinylpolysiloxane
CBCT	Cone-beam computed tomography
mm	Millimeter

Chapter 1: Introduction

Overview

A removable complete denture is defined as a removable dental prosthesis that replaces the entire dentition and associated anatomy of the maxillae or mandible; the removable complete denture can be readily inserted and removed from the mouth by the patient [1]. Complete dentures can be fabricated in several different ways such as pack-and-press, injection molding, and digitally.

Computer-aided design (CAD) and computer-aided manufacturing (CAM) software has been integrated into digital dentistry, allowing for virtual design and fabrication of removable complete dentures. CAD is defined as the use of computer programs to create two- or three-dimensional graphical representations of physical objects [2]. CAD can be specialized for specific applications [2]. CAD software defines the geometry of an item while CAM programming directs the fabrication process [3]. In dentistry, CAD-CAM technology is used to fabricate different types of prosthetics including crowns, veneers, onlays, inlays, fixed dental prostheses, removable dental prostheses, dental implant prostheses, orthodontic appliances, and many other items [1].

History

The first dentures ever made were carved from ivory or wooden blocks, contoured to the intraoral environment. Soon after, wax was introduced, followed by the first impression material, Plaster of Paris in 1844. As denture fabrication evolved, different methodologies and theories were proposed to enhance denture retention, stability, and esthetics. In the early 1900's, the practice of border molding was introduced as well as the importance of developing a posterior palatal seal on the maxillary denture. As time went on, more and more materials were introduced both for impression making and for denture prosthesis fabrication. As far as CAD-CAM technology, the CAM component was developed prior to CAD technology [3]. In the 1950s, manufacturers first adopted tools controlled by a system of numbers and letters to produce objects with complex shapes. This was referred to as computer numerical control machining (CNC) [1,2]. This system consisted of paper tapes that fed numerical data into machines that then positioned and directed tools to create the shape of the item(s) in production. CNC machining is the integration of CAD-CAM technology, and it can be performed both in an additive and a subtractive manner to create 3D objects [1,2].

The first CAM software program was named PRONTO, which was developed in 1957 by the "father of CAD-CAM technology", Dr. Patrick J Hanratty. Introduction of CAD had little impact until more advanced applications were developed years later. In the 1980s, CAM technology was used to produce clinical dental restorations by combining spark erosion and copy milling, which sparked the further development of the CAD fabrication process [4]. Also in the 1980s, *Mörmann* developed a prototype CAD-CAM device that allowed for intraoral cavity scans and fabrication of durable ceramic inlay restorations chairside [5]. This prototype became the CEREC 1 system. In 1990, the first Procera crown was fabricated from a computer file rather than conventionally from a gypsum die [5,6]. *Andersson et al.* evaluated the accuracy of the CAM fabrication process, as it related to marginal fit of crown abutments, demonstrating that this CAD fabrication process could produce restorations to a degree of accuracy that was clinically acceptable (less than 100 microns) [4].

As the technology became more advanced, research expanded to fabricate removable denture prostheses digitally. In 1994, *Maeda et al.* manufactured the first removable prosthesis using 3D laser stereolithography, utilizing a computer aided design system for determining artificial tooth arrangement, occlusion, and denture borders [7]. Shortly thereafter, *Kawahata et al.* used a computerized numeric control (CNC) machine to mill a duplicate set of complete dentures from a block of modeling wax [8]. *Busch and Kordass* digitally scanned edentulous models then digitally arranged teeth with anatomic average measurements provided by their specific software [9]. In 2011, *Zhang et al.* developed a prototype multi-manipulator tooth-arrangement robot system that could automatically design and manufacture a set of complete denture teeth suitable for a patient according to the provided jaw arch parameters [10]. *Zhang et al.* used shape and occlusion equations matching the relationship between the upper and lower jaw arch curves with the following four principles[10]. First, the distance from the occlusal plane of dentition to the upper alveolar ridge should be the same as the distance to the lower alveolar ridge. For esthetics, the occlusal plane should be located 2 mm posterior to the lower edge of the upper lip. Second, artificial teeth should be arranged on the alveolar ridge, if possible. Third, the arc of the dentition should be consistent with the jaw arc. Lastly, the dentition should have a balanced occlusion [10].

Kanazawa et al. used CBCT scans of patients' complete dentures to digitally arrange denture teeth and fabricate denture bases from blocks of acrylic resin with CNC subtractive milling, followed by manual bonding of denture teeth into the recesses on the base [11]. Many studies reported that one of the benefits of CAD-CAM technology for fabrication of dentures was a reduction in time and associated costs [12]. In 2012, *Goodacre et al.* published the first clinical report of patient treatment using a proof of concept, where CAD-CAM dentures were milled from clear resin with a 3-axis milling machine, then later milled from pre-polymerized polymethylmethacrylate (PMMA) resin with a 5-axis milling machine [3].

<u>*Digital Denture Manufacturing*</u>

Dentists have taken a growing interest in the fabrication of digital dentures due to the promise of a decrease in the amount of chair time required as well as a decrease in the number of visits required to fabricate a set of complete dentures [12]. Different systems and workflows allow for a varying number of visits required to design and fabricate the dentures. CAD-CAM prostheses can be fabricated with either additive or subtractive manufacturing [1,2]. Additive manufacturing is the process of making a 3D object by joining materials from 3D model data layer upon layer [1,2, 13]. Some other terminology used to describe additive manufacturing includes stereolithography (SLA), rapid prototyping, three-dimensional (3D) printing, fused-deposition modeling, etc. [1, 2, 13]. SLA was developed in 1988 by 3D Systems, Inc. (Rock Hill, SC, USA) based on the research and inventions done by Charles Hull, who filed the original patent for SLA in 1986 [13, 14, 15, 16]. Charles Hull was also the co-founder of 3D Systems. 3D printing is commonly used for fabrication of surgical guides or printing patient models. 3D printing is also currently being used for fabrication of complete dentures. With stereolithography, a photosensitive polymer resin liquid is exposed to a pattern of ultraviolet light or laser to selectively draw and solidify a cross section of a designed object [13, 14]. The cured cross-section is then dipped back into the resin liquid below the surface, which allows the liquid to backfill for curing and bonding of subsequent cross-sections [13, 14]. SLA is possible because a CAD model is taken and converted into a standard tessellation language (STL) file, which is then split into slices or layers [14]. An STL is the file format native to the SLA CAD software created by 3D Systems Inc., but also supported by several other software packages for CAM use [2]. An STL is a 3D file format that describes only the surface geometry of a 3D object without all CAD model attributes (i.e., color). STLs are generally open source [2]. A build platform in SLA systems provides the base portion that is being printed, providing support for otherwise drooping components [14]. There are two main kinds of SLA systems: top-down and bottom-up [15]. In the top-down system, the ultraviolet laser beam is placed above the build platform, which submerges into the tank of photosensitive polymer [15]. The light focal spot's diameter can be programmable, and the optical transmission path can have multiple designs to allow for rapid, accurate tracing [13]. Both the layer thickness in the vertical direction, as well as the resolution in the horizontal plane are programmable with a high resolution up to 20 µm depending on the resin utilized [13]. The bottom-up system uses a light source consisting of an LED lamp in conjunction with a liquid crystal display panel or a deformable mirror device to expose an entire layer of photopolymer at once [15]. Most of these machines have build platforms that suspend above the resin tank, with the light source located below [13, 15]. One benefit of the bottom-up system is that only a shallow tank of photopolymer resin is necessary, therefore limiting potential waste [15].

Subtractive manufacturing is the process of grinding or shaping a physical object from a block or disc into the desired 3D model. Sharp cutting power-driven machine tools, such as saws, lathes, milling machines, and drill presses, are used to physically remove material to create a desired 3D object [1,2]. It is one of the most used processes to fabricate dental restorations with high precision [2]. Milling can be used to fabricate wax patterns, inlays, onlays, crowns, occlusal splints, surgical guides, and complete dentures. Mills have multiple axes (i.e., 3-axis, 4-axis, 5-axis) that determine the ability of the milling process to create objects with fine detail and complex geometries with undercuts, concavities, and holes [2]. The most advanced milling machines have multiple axes, some with more than just in the x, y, and z directions [2]. Horizontal milling machines have an additional C or Q axis that allows the mounted block to be rotated. The fifth (B) axis allows for the mounted block to be tilted [2]. When all these axes are combined, complex geometries can be milled using CAD-CAM technologies [2].

There are two main types of milling processes: dry milling and wet milling. Dry milling is the process where a material is machined without the need for a liquid for cooling and lubrication [2]. Wet milling is the process using diamond or carbide cutters, with a protective cooling liquid spray, that prevents overheating of the mounted block [2]. Wet milling is used for metals and glass ceramics because it prevents damage due to heat development [2].

Milled dentures are fabricated using subtractive processing from pre-polymerized polymethylmethacrylate (PMMA) acrylic resin blocks. Current research shows that there is minimum to no polymerization shrinkage after milling since the pucks are pre-polymerized [17,18]. Current research also shows that mechanical properties of milled dentures are superior to those of conventionally fabricated dentures in terms of both strength and fit [18]. CAD-CAM denture teeth are either prefabricated, milled, or printed then bonded to the denture base.

Comparison of Fit

Conventionally processed dentures have volumetric shrinkage as well as linear shrinkage, which can affect the denture base adaptation, cuspal interdigitation, and overall vertical dimension of occlusion (Phillips 11th ed.). *Goodacre et al.* compared the fit of maxillary denture bases fabricated by conventional pack and press, pour, injection molding and CAD-CAM methods. CAD-CAM produced the most accurate overall adaptation of the denture base to the stone cast. *McLaughlin et al.* compared fit of denture base between compression molded, injection molded, and CAD-CAM, concluding that there was 41-47% more space beneath conventionally processed dentures versus CAD-CAM denture bases [18]. Shallow palates showed the greatest discrepancy with the compression molding technique, due to the greater susceptibility of acrylic shrinkage [18]. CAD-CAM denture bases showed significantly better adaptation than compression molded bases [18]. Denture bases with better adaptation have better support and stability of the removable prosthesis. *AlHelal et al.* evaluated retention of CAD-CAM versus conventional denture bases in edentulous patients with a custom device that measured vertical pulling force. Retention of milled complete denture bases were significantly higher than conventional heat-polymerized bases [19]. In one study, trueness was evaluated between milled and printed denture bases, and they concluded that while the milled denture bases had superior trueness, both were still clinically acceptable [20].

Comparison of Strength

The denture base must be able to withstand masticatory forces. *Pacquet et al.* evaluated the strength of three different base materials from Ivoclar Vivadent: conventional pack and press, high impact resin for injection molding, and CAD-CAM discs [23]. Ivobase CAD (CAD-CAM disc) exhibited the greatest fracture toughness of the three [23]. *Srinivasan et al.* evaluated traditional heat-processed PMMA versus CAD-CAM milled removable complete dentures, finding that while both were biocompatible, the CAD-CAM resin presented with superior mechanical properties [29].

Comparison of Tooth Arrangement

Denture tooth displacement can occur with both conventional and digital modes of fabrication [17]. Processing dentures with CAD-CAM has the potential to reduce deviations in tooth arrangement, that would in turn affect the patient's occlusion and VDO [11]. Milled CAD-CAM dentures have been reported to have better accuracy and reproducibility in terms of tooth arrangement, as compared to conventionally fabricated dentures [22].

Digital Denture Systems

There are presently 7 main systems for digital denture fabrication [17, 26, 27].

AVADENT® (Global Dental Science LLC, Scottsdale, AZ)

AvaDent® utilizes computer-aided engineering (CAE) and subtractive manufacturing for fabrication of complete dentures. AvaDent® offers both printed and milled dentures as restorative options. The milled denture is fabricated in one of two ways: one, the denture base is milled from a pre-polymerized puck with individual teeth bonded in place, or two, the complete denture is milled from a monoblock. The monolithic denture blocks come in a variety of forms, with teeth in monochromatic or polychromatic shades [17, 26, 27, 58].

The AvaDent® system can fabricate dentures based on four clinical techniques: duplicate denture technique, AvaDent-Wagner EZ guide, intraoral scanning, or conventional interocclusal records [17, 26, 27]. The Wagner tray is printed or milled and contains teeth in wax to allow for movements and changes in tooth arrangement. This technique requires three measurements: inter-pupillary line, inter-alar distance, and incisal papilla measurements [17, 58].

The AvaDent® system also requires a series of extraoral photographs to be captured in addition to the digital files of the impressions, which are all sent out to design the digital denture(s) [17, 26, 27]. The clinician can request tooth position, shape, size desired occlusal scheme, etc. at this time. The clinician receives an electronic preview of the digitally designed dentures to be approved of or modified prior to fabrication. Following design approval, the clinician can opt to do a milled try-in or proceed straight to definitive denture fabrication[17]. AvaDent® offers multiple trial denture options: a monolithic trial denture, an advanced try-in (ATI) denture, and the Wagner EZ guide. The monolithic trial denture is either printed or milled from a monochromatic tooth-colored shade. The ATI denture is a milled denture base with limited wax at the tooth margins to allow for small movement modifications [17, 26, 27]. Following the trial denture stage, definitive dentures can be milled from a monolithic puck or the bases can be milled and either monochromatic or polychromatic teeth can be bonded into place[17, 26, 27, 58].

DENTCA™ (DENTCA, Inc. Torrance, CA, USA)

The Dentca™ denture system currently fabricates digital complete dentures using additive manufacturing (3D printing) [17, 26, 27, 59]. The denture base is printed and the Dentca™ teeth are bonded into place [17]. The impressions are made in company specific two-piece impression trays where the posterior portions are removed for the centric relation record by slicing through the impression with a scalpel blade [17, 26, 27]. The Dentca™ system utilizes a gothic arch tracer attached to the impression trays for centric relation recording and requires a papillometer measurement to digitally design the dentures [17]. For this system, the central bearing plate is attached to the maxillary tray. Once the vertical dimension of occlusion is locked with the centric pin, registration material can be injected. After design approval, trial dentures are printed [17]. Following any adjustments, the definitive dentures are 3D printed in two pieces: denture base with gingival recesses in a pink resin, and denture teeth printed in a tooth shade [17]. The teeth are bonded into place with PMMA [26, 27, 59].

Ivoclar Vivadent (Ivoclar Vivadent, Amherst, NY, USA)

Ivoclar Vivadent utilizes both additive and subtractive manufacturing in their digital denture protocols [60]. Ivoclar Vivadent can support digital workflows with as few as two appointments [17, 26, 27, 60]. The clinician can either go through the initial procedures of border molding, impressions, and occlusion rims, or they can utilize the company's scannable alginate impression material [17]. Ivoclar Vivadent provides alginate and centric trays used for making the impressions and aligning the digital scans of the impressions. This system requires the use of a UTS CAD to record Camper's line and measure the interpupillary line to virtually position the maxilla [17]. Inter-alar and papillometer measurements are also required for CAD design [17]. Trial dentures can either be milled from monolithic PMMA block or printed as separate bases and teeth, bonded in place with resin [17, 26, 27, 60].

Amann Girrbach® (AG, Koblach, Austria)

Amann Girrbach offers a digital denture system for the laboratory technician using the Ceramill® full denture system (FDS) [17, 26, 27, 61]. This provides the clinician with two workflow options: Baltic Denture System or Vita Vionic®, both of which are compatible with the Ceramill system [61]. The Ceramill® system takes conventional analog records (impressions, record bases with occlusion rims, facebow transfer and centric relation record) to transfer to digital software [17]. The laboratory technician mounts the master casts on the Amann Girrbach Artex articulator. The casts are scanned as well as the record bases with wax rims. Ceramill® system designs the dentures based on anatomic landmarks to arrange teeth. The trial denture bases are milled in wax then the selected manufactured denture teeth are set in place with wax. Once the wax set up is confirmed, the dentures are processed conventionally [17, 26, 27, 61].

Baltic Denture System (Merz Dental GmbH, Lutjenburg, Germany)

The Baltic Denture system works with Amann Girrbach® Ceramill® FDS to fabricate dentures in a 2-appointment protocol [61]. The first appointment collects all records, then the prostheses are delivered at the subsequent visit [17, 26, 27]. Baltic Denture system requires the use of a company-specific kit, containing trays of different sizes (small, medium, large) that already contain teeth in place [61]. Trays are adjusted to accommodate the patient then the impressions are made by relining with the kit's impression material. Tooth position on the trays cannot be altered at the impression stage. Baltic Denture system also requires a BDKEY device to aid in jaw relation records, which acts as a trial denture by allowing the patient to essentially try in denture teeth [17, 26, 27]. Once all acquired data is scanned by the laboratory technician, the dentures are milled from blocks of pre-polymerized PMMA that already contain the teeth in a lingualized occlusion [26, 27, 61].

Vita Vionic®

Vita Vionic® digital denture system works with the Amann Girrbach® Ceramill FDS, with the main difference being the denture teeth and bases are made by VITA materials [17, 26, 27, 61]. Trial denture options include a monolithic white denture milled from a PMMA puck, a milled denture base with gingival recesses for VITA denture teeth or milled wax denture bases with gingival recesses for VITA teeth to be set in wax [17, 26, 27].

For milled bases, the VITA teeth are bonded into place. For the wax trial denture, the denture is processed conventionally after any adjustments are made [26, 27, 61].

Dentsply Sirona (York, Pennsylvania, USA)

Dentsply solely utilizes additive manufacturing to fabricate digital dentures utilizing their Lucitone Digital Print 3D denture resin [17, 26, 27, 62]. Denture bases are printed, and the company-specific designed denture teeth (IPN 3D Digital denture teeth) are bonded into the gingival recesses and sealed into place before the dentures are light-polymerized [17, 26, 27, 62].

Advantages of Digital Dentures

After review of the literature, digitally fabricated dentures can offer certain advantages over conventionally fabricated dentures. Digital dentures have increased dimensional stability and exhibit a superior fit of denture bases. Digital dentures also demonstrate improved physical properties such as increased surface wettability, less residual monomer, smoother surface texture, improved stain resistance, increased flexural strength and higher fracture toughness. Digital dentures can allow for reduced number of patient visits, therefore reduced clinical chair time.

Existing Limitations of Digital Dentures

Regardless of the fabrication process of the dentures, the delivery appointment always requires the same steps. The intaglio of the denture is checked with an indicating paste or fit checker. Once the intaglio surface has been adjusted, occlusion can be checked and adjusted until desired occlusal scheme is achieved. Sometimes a clinical remount procedure is required.

Despite all the technological advances in digital dentures, there are still some limitations. Digital impressions often cannot capture functional borders and extensions of the dentures, especially in areas of undercuts. If analog impression materials are used, the materials must be dimensionally stable and scannable. There are different ways to record interocclusal records, which each of the digital systems having their own requirements. Often, adjustments are still required at the delivery appointment. Sometimes a clinical remount is required due to a lack of bilateral balanced occlusion.

Currently, digital denture technology is most often used in combination with analog methods. Due to the difficulties of making digital impressions of maxillary and mandibular border extensions, digital technology is often used after a final analog impression is made. Intraoral scanner heads often cannot extend into the entirety of the vestibules and capture all undercuts, especially in areas such as the retromylohyoid fossae. Interocclusal records are typically evaluated and recorded before converting a case to a digital workflow.

Purpose

There are multiple ways to capture and record a patient's occlusal vertical dimension, and this study seeks to compare the accuracy of the vertical dimension transfer to a digital setting. After review of the literature, there have not been any studies conducted comparing the accuracy of transferring the correct occlusal vertical dimension of the maxillary-mandibular relationship when designing and fabricating digital dentures. This study aims to investigate the accuracy of transferring the correct occlusal vertical dimension based on three of the current digital denture workflows:

1) Control: edentulous casts mounted on an articulator then scanned at a fixed vertical dimension.
2) First experimental workflow: duplicate denture functionally relined on the control edentulous casts (described above) then scanned at the same vertical dimension.
3) Second experimental workflow: final impressions and occlusion rims fabricated on the control edentulous casts then scanned at the same vertical dimension.

The null hypothesis is there will be no difference in occlusal vertical dimension between the different workflows.

Chapter 2: Materials and Methods

Overview

This study will test two groups to determine the accuracy of the digital transfer of occlusal vertical dimension in fabricating digital dentures. The two groups are based on the two commonly used clinical workflows to fabricate digital dentures. The control is the "patient" which was a set of edentulous casts, mounted on an Artex CR articulator. The first experimental group will be dentures relined functionally on the "patient" at the same vertical dimension. The second experimental group was analog impressions and wax occlusion rims fabricated on the "patient" at the same vertical dimension. The casts used to evaluate the transfer of the vertical dimension have fiduciary markers embedded on each to provide locations to measure the vertical dimension. The entire study was completed by the same dentist.

Fabrication of edentulous ridge analogs

A set of edentulous rubber molds were obtained (Nissin Dental Products INC, Kyoto, Japan). Yellow, type III dental microstone (Whip Mix, Louisville, KY, USA) was combined with water in a 3:1 ratio and mixed under vacuum (Whip Mix, Louisville, KY, USA). The dental stone was vibrated and flowed into the silicone molds and allowed to set. Once set, the stone casts were digitized to incorporate fiduciary markers embedded on each cast. The edentulous casts were digitized utilizing the 3Shape D/R2000 desktop scanner (3shape A/S, Copenhagen, Denmark) by placing the casts on the magnetic scan plates. A new order form was opened in 3Shape Dental Manager software, and the following parameters were selected to set up the order. Under scan settings, “model” was selected as the object type. “Antagonist model” was selected under antagonist. “Sectioned” was selected for neighborhood scan. No additional scans were added. A tooth on one arch was selected to register the scan and the desktop scan was completed. The scan was inspected to make sure all critical areas were captured. The scan file was saved and exported as an STL file.

Autodesk MeshMixer (Autodesk, Inc.) was opened, and the edentulous casts were imported into a new project file to modify them to include the fiduciary markers. Fiduciary markers were added to the digital casts by using the “Meshmix – Primitives” feature, where a cube was selected and opened with the edentulous casts. “Transform” tool was used to move the first cube in x, y, and z directions and place it on the edentulous cast. Once the cube was placed in the proper location, copy/paste was used to add two more identical cubes. The cubes were moved in x and z directions until they were placed in the correct locations on the edentulous cast. Three identical 2.25 mm cubes were digital added to the maxillary cast (one anteriorly on the ridge and one posteriorly on the ridge of both the left and right sides) and three on the mandibular cast (one the anterior ridge and one posteriorly on the ridge of both the left and right sides, Figure 1). These markers provide distinctive points to measure the 3D deviation in vertical dimension. Once the cubes were placed, the individual files needed to be combined into a single STL file for each arch. The individual meshes were selected using the “select” tool, and then the “combine” tool was used to produce a single digital model for each arch. These digitally modified edentulous casts were exported as STLs by clicking “export” and selecting STL as the file option. PreForm 3D Printing Software (Formlabs, Somerville, MA, USA) was opened on the desktop and the STLs of the new edentulous casts were dragged and dropped into the virtual build platform. Once in the printing software, the models were rotated and oriented so that they were not overlapping, then support struts were added with the “automatic generate” feature. These casts were 3D printed in Grey Pro Resin (Formlabs, Somerville, MA, USA) on the Form3 printer (Formlabs, Somerville, MA, USA) at the highest resolution of 25 µm. Grey Pro Resin was selected to generate these models because it offers high precision and is recommended for use for parts that will be repeatedly handled [42]. After the printing process was completed, the build platform was removed from the Form3 printer, and placed in the wash tank. The platform with the resin models still attached were washed in a 99% isopropyl alcohol bath for 10 minutes, per the manufacturer guidelines [42]. Then, the dentures were removed from the wash and light cured at 60 degrees Celsius for 60 minutes. After light curing, the support struts were removed from the printed dentures, and they were smoothed using acrylic finishing burs.

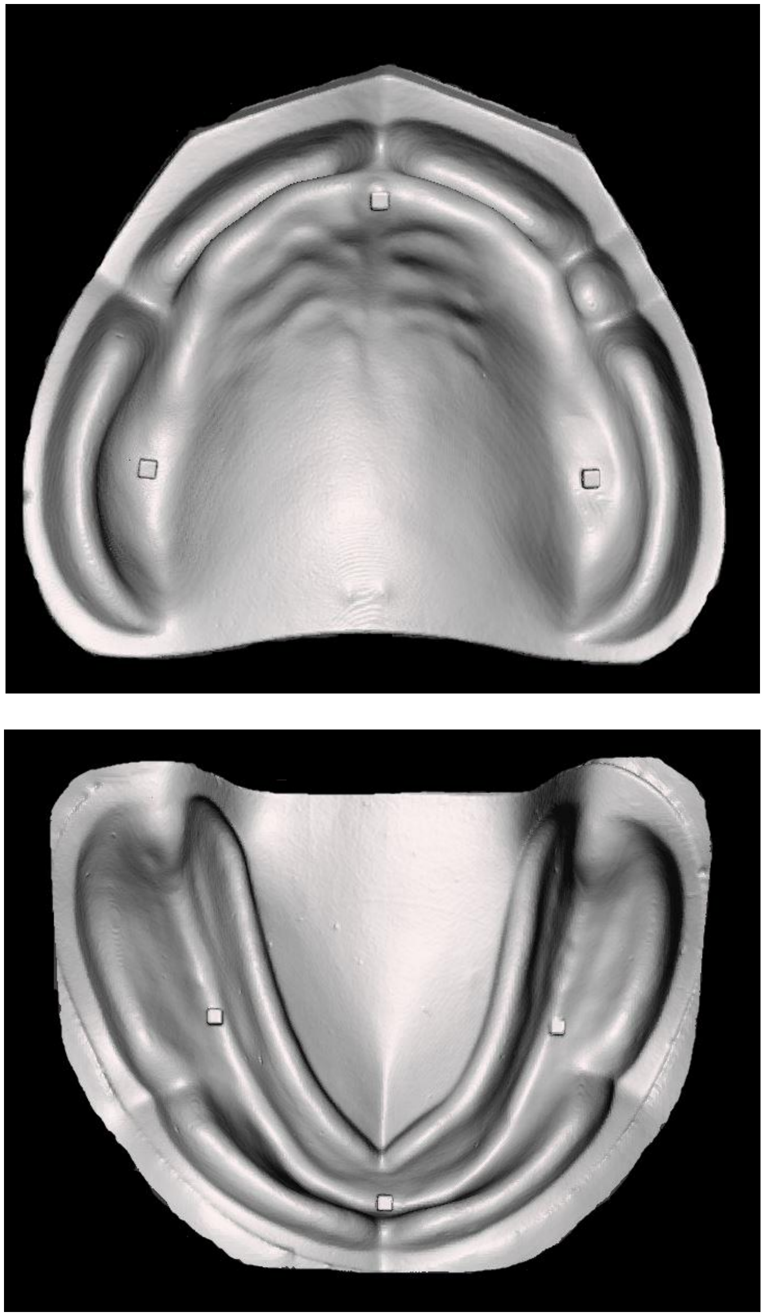


Figure 1: STLs of maxillary and mandibular edentulous casts with embedded fiduciary markers.

The meshes were combined in Meshmixer and exported as an STL. Fiduciary markers were embedded digitally to prevent damage of the casts or movement of the markers throughout the course of this experiment.

Edentulous "patient" set up

Once the printed casts were completed, they were mounted on an Artex® CR articulator (Amann Girrbach AG, Germany). The casts were mounted arbitrarily in a Class I jaw relationship using fast set mounting plaster (Whip Mix, Louisville, KY, USA) and magnetic Artex® mounting plates. The excess plaster was cleaned and smoothed with a sponge and sandpaper. Once mounted, the edentulous casts were scanned again with the 3Shape D/R2000 desktop scanner, but this time with the magnetic Artex® digital mounting plates. To set up the simulated edentulous patient that was used as the control, a new order form was opened in 3Shape Dental Manager. The teeth were selected from second molar to second molar. In the Anatomy function, artificial tooth type was selected. In the gingiva function, dentures gingiva was selected. The case was set up with the following scan parameters. Object type: Model, Antagonist: Antagonist model, and no neighborhood scan was needed. The casts were scanned with D/R2000, and the scans were inspected to ensure all aspects of the casts were captured. Once the mounted casts were scanned, the files were exported in the same manner as before. This STL was used as the control "patient". This STL was imported into the 3D inspection software, Geomagic Control X (Geomagic Inc, 3D Systems, NC), as the reference data (Figure 2). The same vertex point on each fiduciary marker will be used to measure the deviation in vertical dimension for each scan. A vertex is defined as the smallest component of a polygon model, also known as a 3D point in space [2]. Once the edentulous patient was converted from analog casts to a virtual relationship, it was used to design a set of digital dentures and a set of custom trays, as described in detail in workflow one and two.

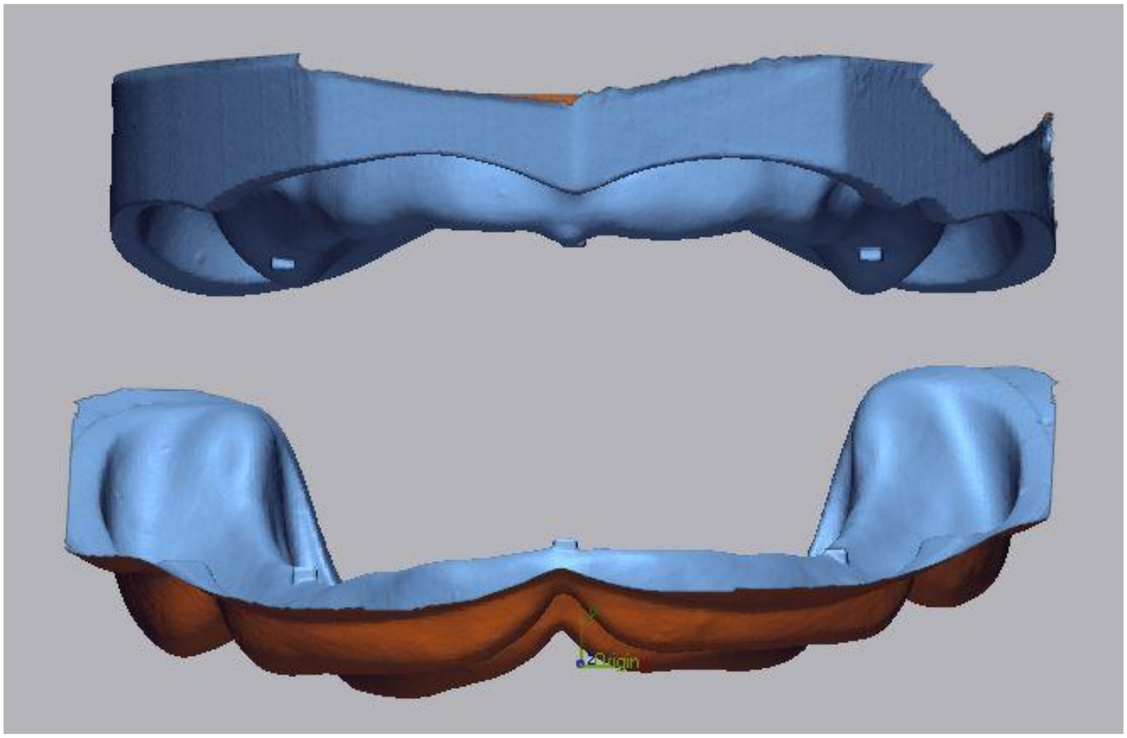


Figure 2: Edentulous casts digitally articulated in a class I jaw relationship. This is the control STL that was used to compare the digital transfer of the jaw relationship.

Experimental Groups

Workflow #1: Duplicate Dentures (DD)

One common workflow that clinicians utilize in fabricating dentures is to use a patient's existing, Ill-fitting, or worn set of dentures, reline them with impression material, and make a centric occlusal registration at the desired occlusal vertical dimension[21, 26]. A set of dentures were designed digitally on 3Shape design software, from the control. A new order was opened in 3Shape Dental Manager. The teeth were selected from second molar to second molar. The case was set up with the scan parameters (Table 1). Unlike with the control edentulous patient set up, this time scans were imported instead of scanning edentulous casts already at the desired vertical dimension. Once the order was created, the patient scans were imported by selecting the order, right-clicking, and selecting Import scan. Here, a window opened asking for uploading of the maxillary scan and mandibular scan (STL) files. There is an option to trim the generated base, but no trimming was necessary. For interface plate, the ACR (Artex™ compatible) plates were selected. This imported the edentulous scans at the same virtual relationship as the control. After the scans were inspected, the design window was opened. The occlusal plane was set by using the point placement feature in the design software; three points were placed with one on each of the fiduciary markers on the maxillary arch. Once the horizontal plane was established, the plane was lowered to halfway between the maxillary and mandibular arches. Next, the software required characteristic points to be selected on the edentulous casts. For the maxillary arch, both tuberosities, the incisive papilla, and both canine points were selected and defined. For the mandibular arch, both retromolar pad centers, buccal, and lingual aspects were marked. Also, the central ridge point and the canine points. Next, the upper and lower jaw boundaries were defined by manually tracing the borders. Next, there was an option to set an insertion direction and block out angle. However, no block out angle was used. The subsequent step entailed selecting a tooth library in the Smile Composer® stage. Candulor NFC+ was the provider for the tooth library that was used. The teeth used were labeled as Physiostar NFC Plus_552 and Physiostar NFC Plus_990. The teeth were placed in the middle, between the maxillary and mandibular arches. After the teeth were placed, the denture base was designed with selected parameters (Table 1). Natural gingival esthetics were selected. No drill compensation was used for the manufacturing. No additional sculpting was completed. The pre-manufacturing settings selected included no drill compensation, no glue space, and an assembly type of base with artificial teeth. Once designed, the digital complete dentures were saved, and the window was closed (Figure 3). The dentures were exported by selecting and right-clicking on the design file in the design manager, clicking “Advanced” and selecting “Generate CAM Output”. Once the output was generated, the output was exported by clicking “Advanced” and this time selecting “Explore CAM”. There were multiple CAM files to choose from; the “monoblock” STLs were selected because they included the assembled denture with both teeth and gingival base. These STLs were imported into PreForm and arranged on the virtual build platform. The build platform on the Form3 printer was large enough to accommodate printing two sets of complete dentures at one time. Once the dentures were placed on the platform, support struts were added by automatic generation. Each print duration was approximately 26 hours. Dental Model Resin (Formlabs, Somerville, MA, USA) was selected to print the dentures at the highest resolution of 25 µm. Model Resin was developed to print dental models and dies since it produces high-quality results in fast-paced timeframes [44]. Digital dentures were used to help standardize the process and reduce sources for potential variability. Printed dentures were utilized instead of milled dentures due to reduced material cost of printed resin. Fifteen sets of dentures were printed. After each print was completed, the resin models were washed in a 99% isopropyl alcohol bath for 10 minutes, per the manufacturer guidelines [44]. Then, the dentures were removed from the wash and light cured at 60 degrees Celsius for 60 minutes [44]. After light curing, the support struts were removed from the printed dentures, and they were smoothed using acrylic finishing burs.

Each set of printed dentures were labeled with a marker (#1-15) and tried on the edentulous casts and adjusted when needed to ensure the articulator pin remained completely closed (pin: 0). The denture seating was evaluated by applying Quickcheck white indicating spray (Vacalon, Pickerington, OH, USA) to the intaglio of the dentures and then placing them on their respective edentulous casts. Any areas where the indicating spray was rubbed or wiped off, was relieved using acrylic burs. This was repeated several times until no areas of show through remained.

VPS universal adhesive (GC America Inc., Alsip, IL, USA) was applied to the intaglio surfaces with a disposable brush. Printed dentures were relined by applying a thin layer of 3M™ Imprint light viscosity vinylpolysiloxane (LV VPS) (3M™, MN, USA) to the denture intaglios and placing them on the mounted edentulous casts. Once the impressions were fully set, occlusion was checked with articulating paper, to ensure there were no premature contacts that prevented the articulator from closing fully (pin: 0). If premature contacts were present, they were removed with acrylic burs. An occlusal registration was made with Regasil Rigid (3M™, MN, USA) by applying a small amount to the occlusal surfaces of the dentures, then closing the articulator, making sure the indicator pin was touching the incisal table. Rubber bands were wrapped around the articulator to ensure the articulator pin remained closed fully until the registration material was set. The samples were collected with the pin always fixed at 0 to preserve the vertical dimension. The same articulator was used throughout the entire experiment to provide consistency and remove potential source for error. Once set, the articulator was opened, and the dentures were removed. The denture intaglios were inspected to ensure complete capture of the fiduciary markers without any show through. Excess material was trimmed from the facial surfaces and from the borders.

Then, the records were digitized. This was completed by creating a new order for each DD set (Figure 4). In 3Shape Dental Manager, a new order was created with the following scan settings. Object type: Model, Antagonist: None. Teeth were selected on the order page and "Appliance – Copy Denture" was selected in the designer to scan the DD. Each DD set was scanned using the 3Shape D/R2000. The maxillary and mandibular dentures were placed on magnetic plates in the scanner, with the intaglio surface face-up first. The desired area was marked, and adaptive scanning was completed to ensure complete capture of the intaglio surface with the fiduciary markers. Next, the maxillary and mandibular dentures were flipped and placed on magnetic scan plates with the cameo surface face-up. The desired area was marked. No adaptive scanning was needed. Then, the intaglio and cameo surfaces were combined using three-point alignment; this created a virtual model of the individual dentures. Lastly, the dentures were placed together using their occlusal registration and glued together to prevent movement. The occlusion was scanned by fixating the articulated dentures to one of the magnetic scan plates. Point alignment was used to align the individual maxillary and mandibular dentures with the dentures in occlusion. The scans and alignment were all inspected, then the window was closed prior to beginning the design stage. The DD file was selected in 3Shape Dental Manager, the CAM was generated, and the CAM was exported as STLs. The STLs were imported into Meshmixer and combined using the "combine" tool. Each DD set was exported from Meshmixer and saved as a single, combined STL (Figure 5).

Measures	**Group**	**Settings**	**Notes**
Digital Denture	Teeth: - Anatomy – Artificial Tooth Type Gingiva: - Dentures Gingiva	Scan set up - Object type: Model - Antagonist: Antagonist model - Neighborhood scan: None Design - Teeth: Physiostar NFC Plus_552 and Physiostar NFC Plus_990 - Denture base thickness: 2.00 mm - Relief space: 0.35 mm - Natural gingival esthetics - No drill compensation or glue space - Assembly type: base with artificial teeth	*0.35 mm is the maximum relief space 3Shape allows for in the digital denture workflow*
Custom Tray	Appliance – Customized Impression Tray	Scan set up - Object type: Model - Antagonist: None - Neighborhood scan: Sectioned Design - Automatic block out - Base thickness: 2.00 mm - Impression gap: 1.50 mm - Attachment: Finger stop (impression tray handle) - No drill compensation	*Maxillary and mandibular trays were designed in separate files, 3Shape only allows for one tray to be designed per order*

Table 1: 3Shape design parameters

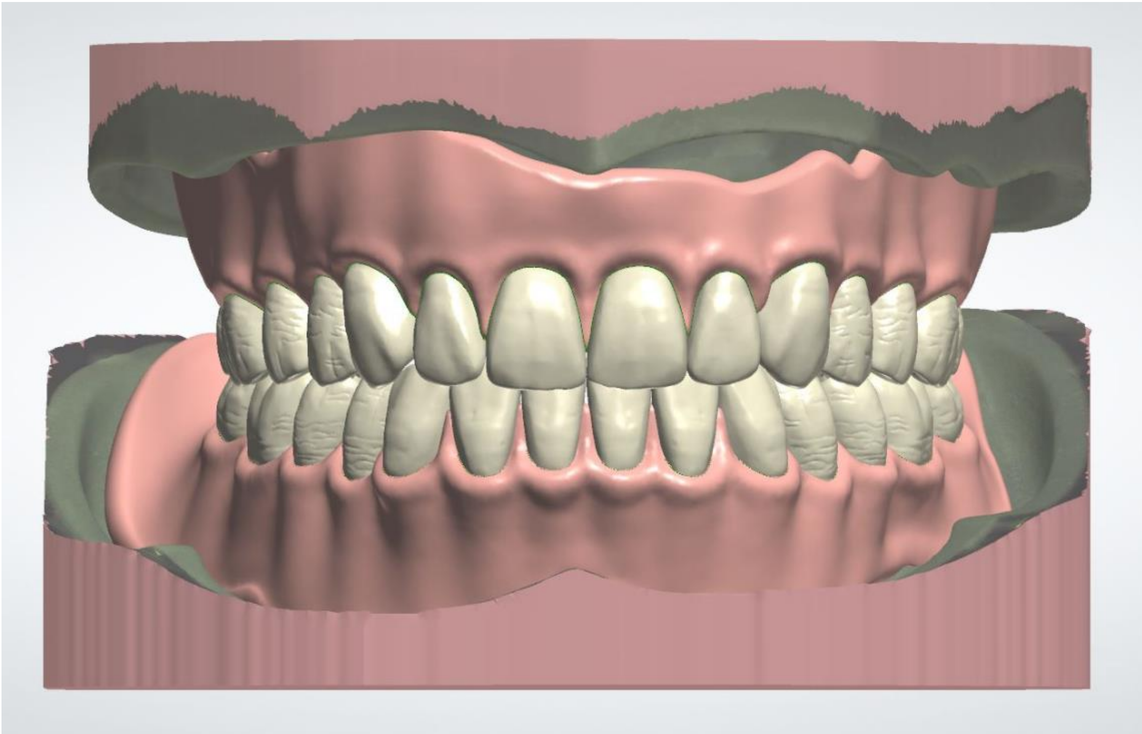


Figure 3: Digital dentures

These were designed in 3Shape using the control STL. As a result, the dentures were designed at the control vertical dimension. The CAM output generated STLs for the maxillary and mandibular dentures, which were then printed for the DD experimental workflow #1.

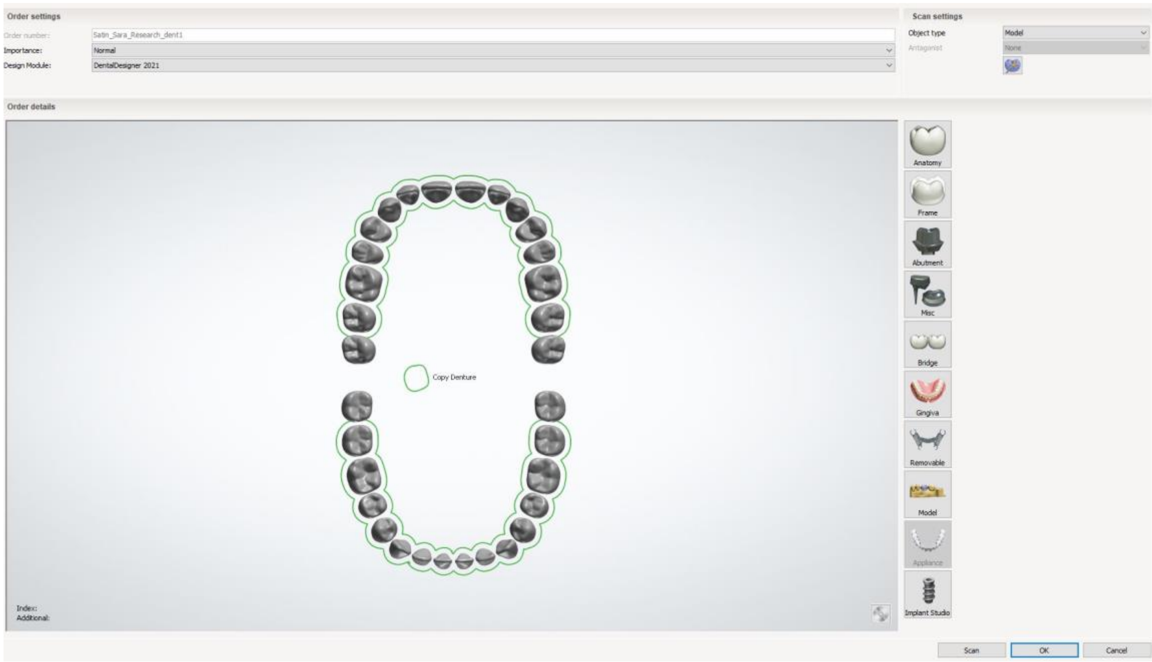


Figure 4: DD order form set up.

DD were digitally articulated in 3Shape using the “copy denture” order form option. The cameo and intaglio surfaces were scanned, aligned, and exported as STLs.

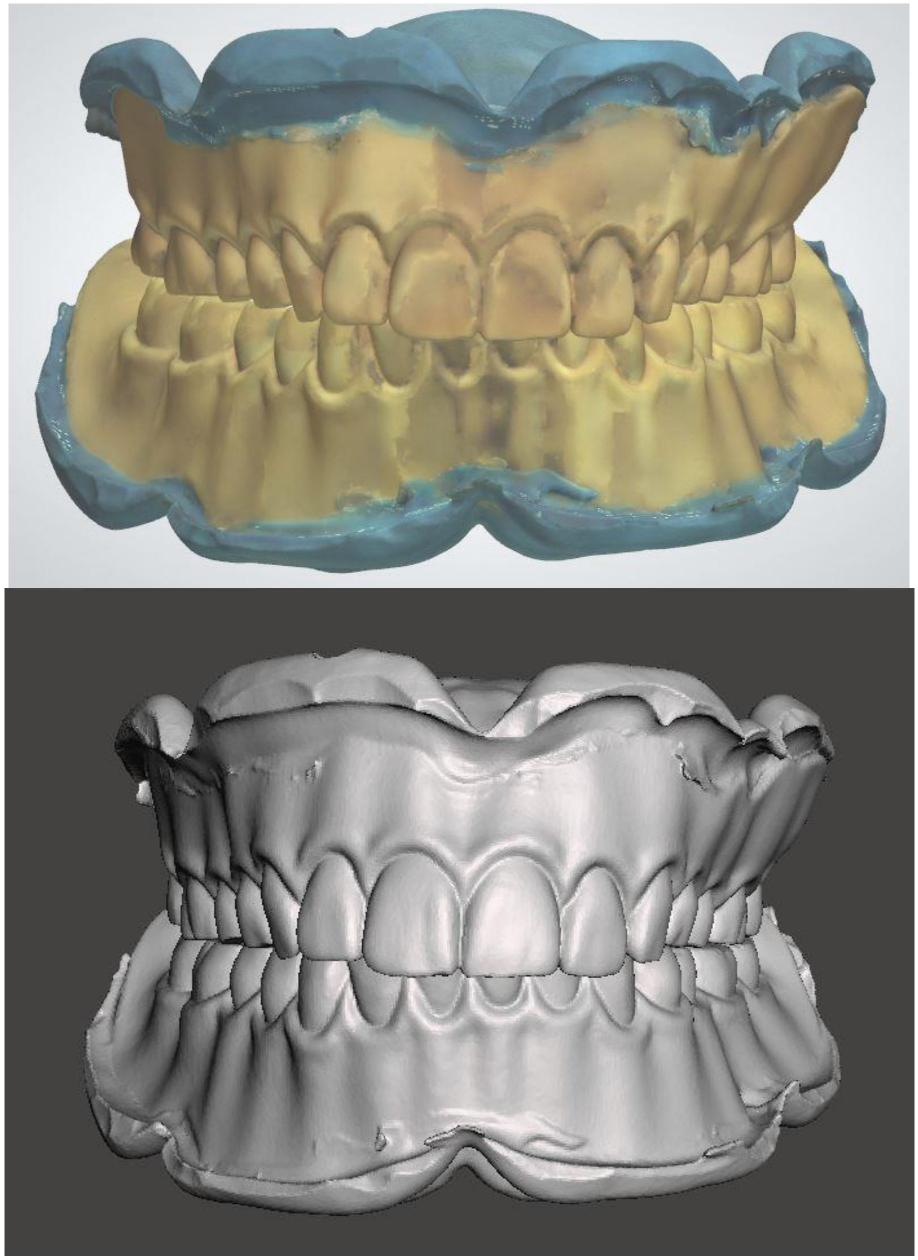


Figure 5: DD sample.

The (top) color photo shows the scanned DD sample in 3Shape. The DD STLs were imported into Meshmixer, and the individual meshes were combined and exported as an STL (bottom).

Workflow #2: Impressions and Occlusion Rims

Another workflow that clinicians use to fabricate dentures is to use custom impression trays to border mold the denture extensions, record the edentulous arches with an impression material (i.e., LV VPS), and fabricate record bases with wax occlusion rims to determine the jaw relationship [3]. Fifteen sets of final impressions were fabricated off the printed edentulous models. Since there is no musculature or movable tissue on a model, border molding was not required for this study. Custom impression trays were designed in 3Shape design software from the control patient. In 3Shape Dental Manager, the control scan was copied twice using "Standard Copy". Then, the order was modified by clearing previous selections, and instead selecting "Appliance – Customized Impression Tray" design tool was selected. The control patient scans were used to design the custom impression trays. 3Shape only allows one custom tray to be fabricated per order, which was why two copies were made – one order was for designing the maxillary custom tray, and the other for the mandibular custom tray. Parameters were selected, and the design was initiated (Table 1). The insertion direction was set automatically with a block out angle of 3.0 degrees. 3.0 is the automatic setting when designing a custom tray, so it was utilized for this experiment's design. The custom tray outline was traced. The custom tray was designed with selected parameters (Table 1). To finalize the custom tray, a small handle was added. In the Sculpt step, there was a sculpt toolkit which allowed for selection of attachments. An attachment was added with the following specifications. Group: Customized tray, Attachment: Finger stop, and Default orientation: View direction. The attachment was inspected, ensuring it was flush with the tray. No perforation settings were utilized in the Pre-manufacturing step. The design was completed and saved. The same process was repeated to design and create a mandibular custom tray (Figure 6).

The impression tray STLs were imported into Preform. The build platform allowed room for two sets of impression trays per print. The custom trays were arranged on the build platform and support struts were added via automatic generation. The custom trays were printed in Dental Model Resin using the Form3 printer. The impression trays were washed, cured, and finished in the same manner as the printed dentures.

VPS Adhesive was applied to the custom trays and wash impressions were made using LV VPS. Excess was trimmed. Then, prior to separating the impressions from the casts, wax occlusion rims were constructed and added to the cameo surface of the impression trays. Pink medium-soft baseplate wax (Corning Rubber Co, Inc., USA) was softened over a Bunsen burner flame and folded to create a wax rim. The wax was luted to the custom trays with a hot wax spatula. A flat, square hot plate was used to smooth the surfaces of the wax rims.

The wax rims were flush with each other, and the pin remained fixed at 0. Then, two triangular notches were cut into the buccal and occlusal surfaces of both the left and right sides of the maxillary and mandibular occlusion rims. Occlusal registration material (Regasil Rigid) was injected to lock the wax rims in a stable bite position on the articulator, with the pin maintained at 0. Then, the custom trays with the attached occlusion rims were carefully removed. Excess impression material and occlusal registration material was trimmed. The impressions and wax occlusion rims were scanned with the 3Shape D/R2000 desktop scanner in the same manner as the duplicate dentures and exported as STLs (Figure 7). The STL files were imported into Meshmixer and the meshes were combined into a single STL (Figure 8).

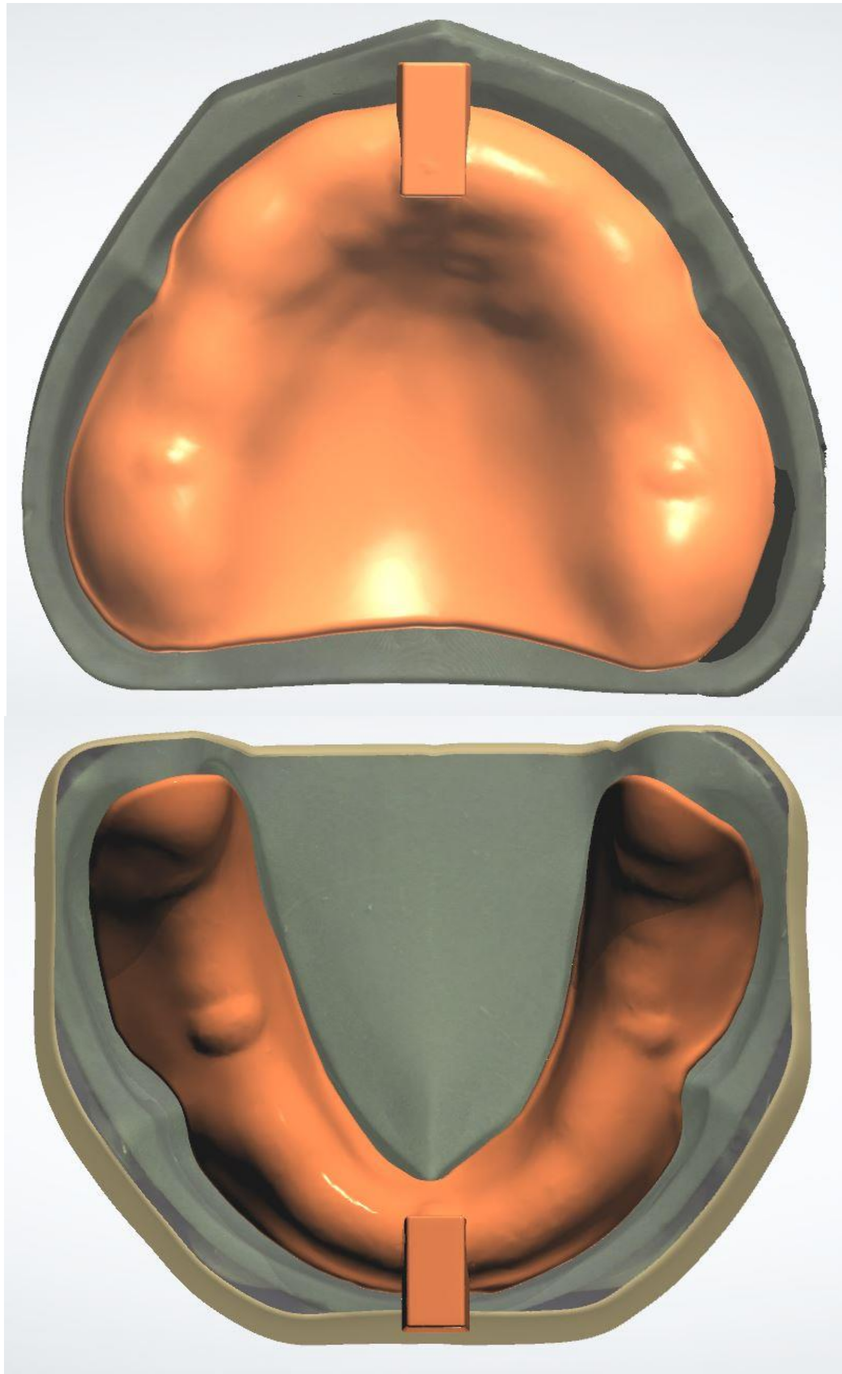


Figure 6: Digitally designed maxillary and mandibular custom trays.

The trays were designed in 3Shape. Using the control STL, the custom impression trays were designed and exported as individual STLs.

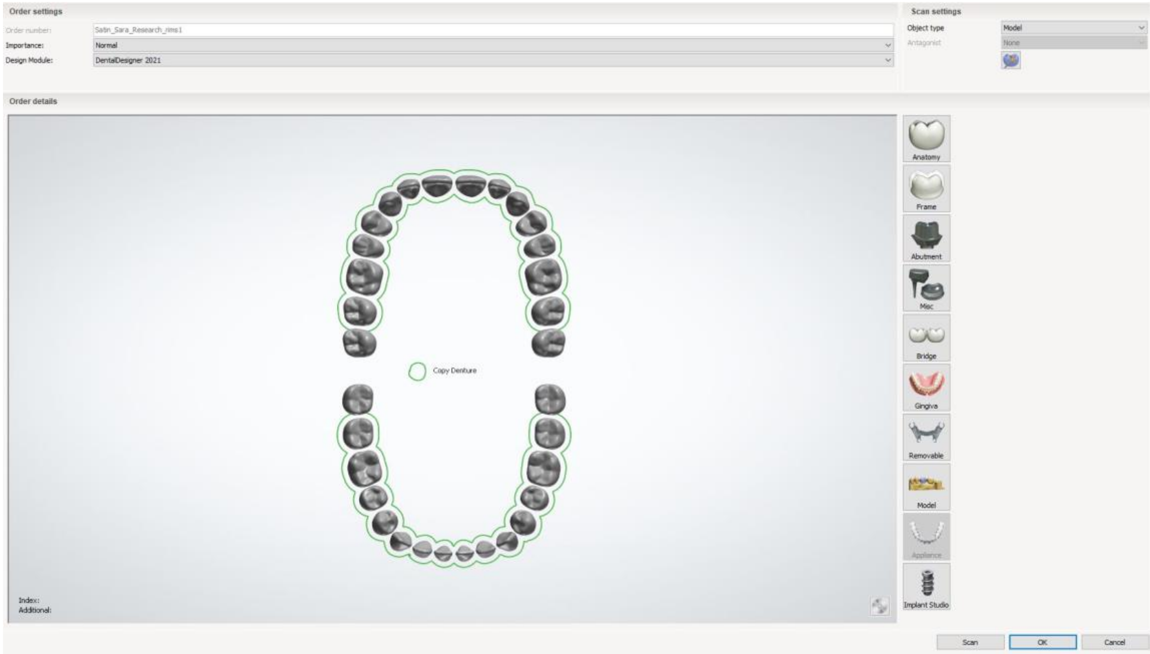
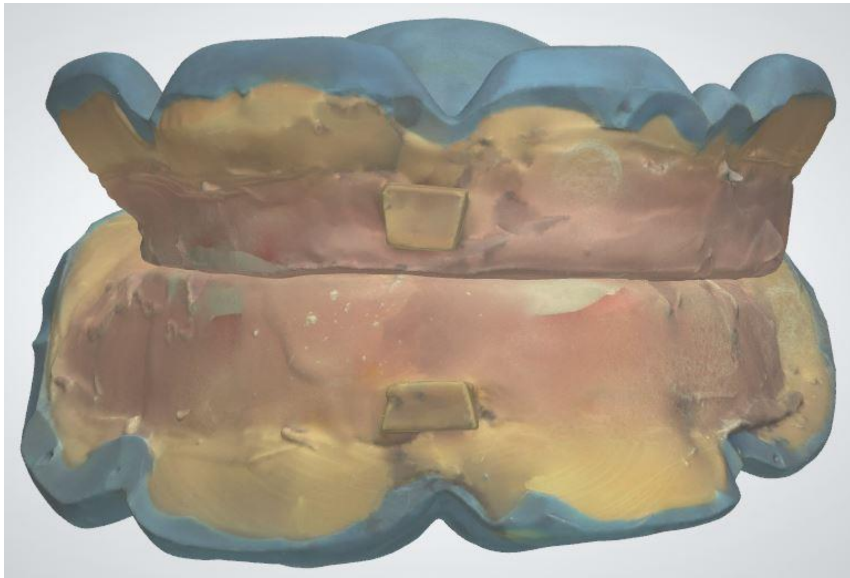


Figure 7: OR order form set up using the Copy Denture design.

The cameo and intaglio surfaces were scanned, aligned, and exported as STLs.



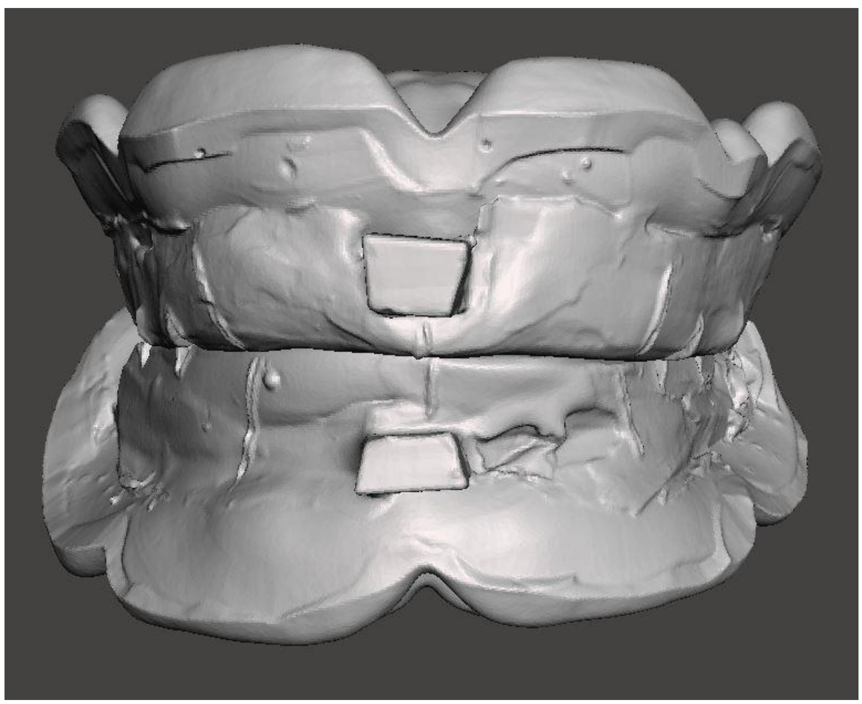


Figure 8: OR sample.

Color (top) photo shows OR sample after scanning in 3Shape. The STLs were imported into Meshmixer and combined into a single STL (bottom).

Digital Articulation

First, the control STL, consisting of the virtually articulated edentulous casts, was imported into Geomagic Control X (Geomagic Inc, 3D Systems, NC) and assigned as the Reference Data. The control STL was used as the baseline virtual articulation, that each sample was compared to, to obtain definitive values or measurements of the 3D deviation in the jaw relationships.

Second, the control STL was imported again, but this time as Result Data 1. This automatically aligns to the control STL present in the Reference data. Then, in the "Home" tab, the three points of measurement were selected by using the "Point" feature. This feature constructs a reference point on the reference or measured data, which can be useful for finding intersections, deviations, and defining positional information. The three points were added by clicking "Point – Add Point". The reference geometry was defined on the control STL. Points were added with the "pick multiple points" method. Point1 (Point A), Point2 (Point B), and Point3 (Point C) were selected, one on each fiduciary marker as seen in Figure 9. Once the points were selected, they were added and locked to define the reference geometry. The points then showed as "Constructed Geometries" under "Measured Data". Screen captures were taken, so that the point location could be identified by the specific vertex (Figure 10). As previously stated, each point was placed on a vertex since it is the smallest identifiable point in an STL. Once point selection was completed, the three points gave an identifiable location in the x, y, and z directions (Table 2).

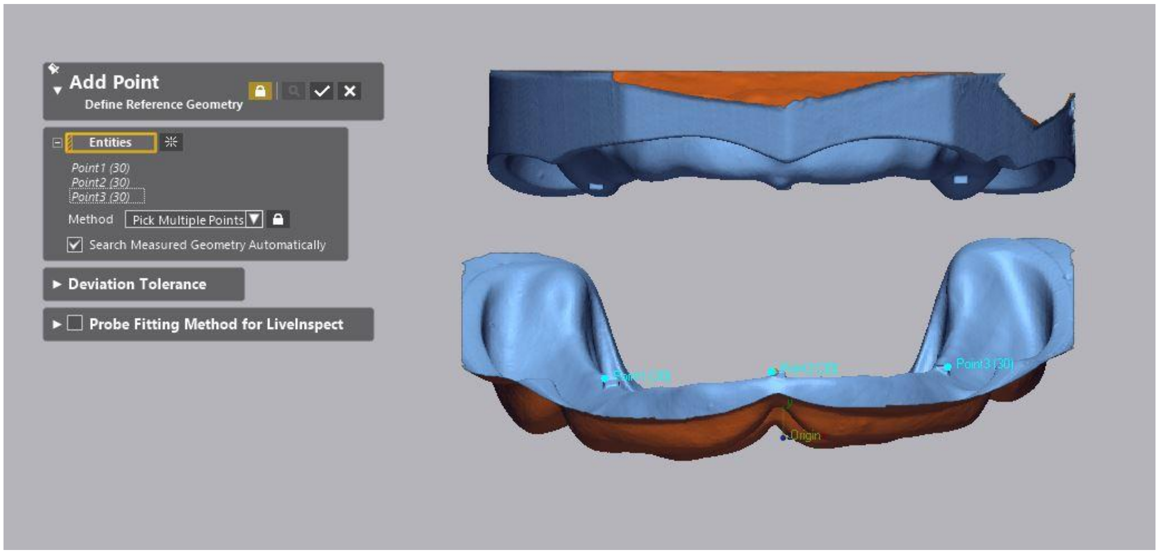


Figure 9: Reference point selection.

Points A, B, and C were identified in Geomagic on the Reference Data (control STL), with Point A on the mandibular right fiduciary marker, Point B on the mandibular anterior fiduciary marker, and Point C on the mandibular left fiduciary marker. These points were added, defining the reference geometry, and locking their location. These points were used to measure and compare deviations in x, y, z directions.

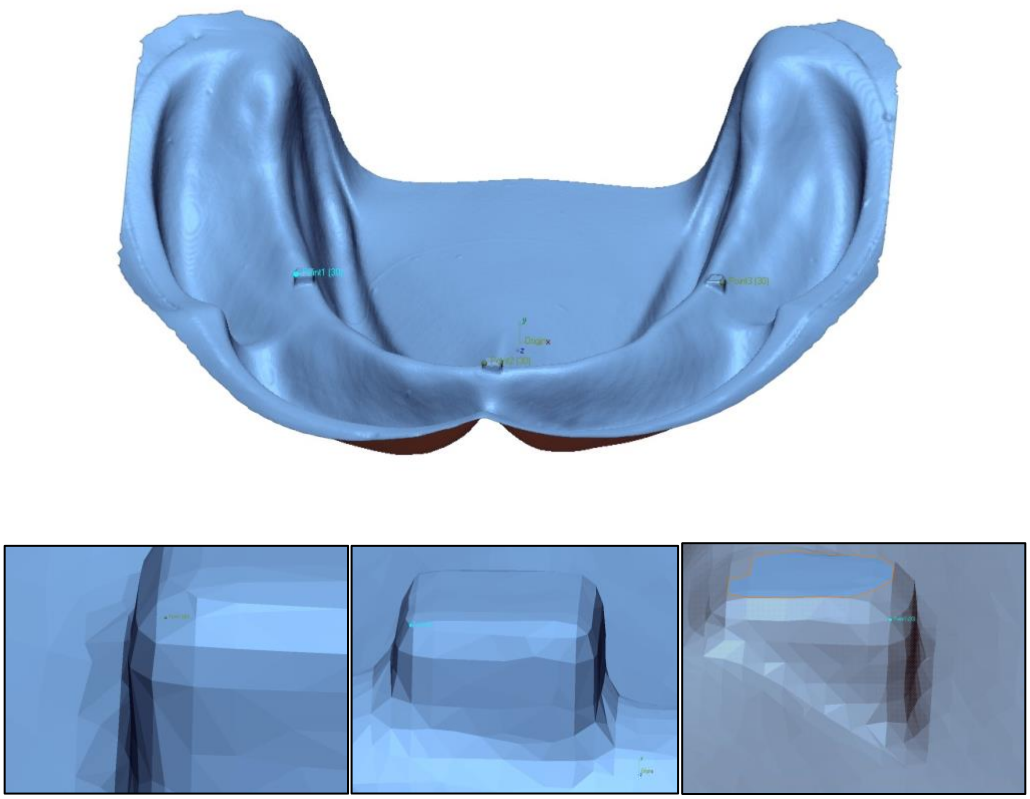


Figure 10: Location of points A, B, and C

Point selection was used to measure the 3D deviation. The same triangular mesh was selected each time, as shown in the figure below. Point A (left), B (center) and C (right) were the points of measurement used in this experiment.

	Position		
Name	X	Y	Z
Point A	-24.0103	8.0072	2.4485
Point B	-1.4897	8.9251	26.3517
Point C	22.1518	9.5234	3.3979

Table 2: Reference point location in x, y, z directions.

These locations were identified and established in Geomagic Control X.

After the reference points were identified, the following additional STLs were imported into Result Data 1: control STL – maxillary only and control STL – mandibular only. Prior to importing any experimental groups, Result Data 1 was duplicated repeatedly, to produce a total of 30 Result Data. Result Data #1-15 were the DD samples, while Result Data #16-30 were the OR samples. One experimental sample was evaluated in each Result Data tab, for a total of 15 measurements per experimental group. The reference data with points A, B, and C were then present in each tab, to measure the deviation in x, y, and z directions between the control and the experimental sample.

The first DD sample was imported into Result Data 1. Initial automatic alignment was declined. Instead of using the alignment tool in the "Home" tab, the "Measured" tab was clicked, and a manual registration was performed to get an initial superimposition of the casts. First, the DD STL needed to have its directionality changed to align the impression surface to the model surface. This was completed by selecting "Measured – Fix normal," which reversed the directionality of the DD STL. Once the normal direction was changed, the DD STL color changed, indicating that the flip had been completed. Then, the manual registration was continued. This was completed by clicking "Measured – Align to measured data". This feature allows the STLs to be aligned to each other, independently from the Reference data. The control STL – maxillary only was assigned as the reference, and the DD STL was assigned to move. The initial alignment was done with 3-point alignment. The fiduciary markers were selected from both the maxillary ridge and the maxillary impression. This produced an initial alignment (Figure 11). Then, "global and refine" was selected to enhance the alignment, while maintaining the maxillary control STL as the reference and the DD STL as moving. Next, the mandibular control STL was aligned to the DD STL. In "Measured – Align to measured data," a global registration was completed to align the mandibular control STL to the mandibular impression. However, unlike the previous step, this time the DD STL was set as the reference and the mandibular control STL was set as the moving part (Figure 12). This kept the DD STL fixated to the maxillary cast, so that the mandibular cast could be compared to that of the control. As a result, this created a virtually articulated set of casts based on the DD sample. This was performed for each STL in both groups to create 30 virtually articulated sets of casts, with all maxillary casts in the exact same position. This created 30 digital patients to compare to the control STL, and determine what deviation, if any, occurred at each of the three points in any of the samples. Workflow #1 (DD) samples were assigned Result Data 1-15. Workflow #2 (OR) samples were assigned Result Data 16-30.

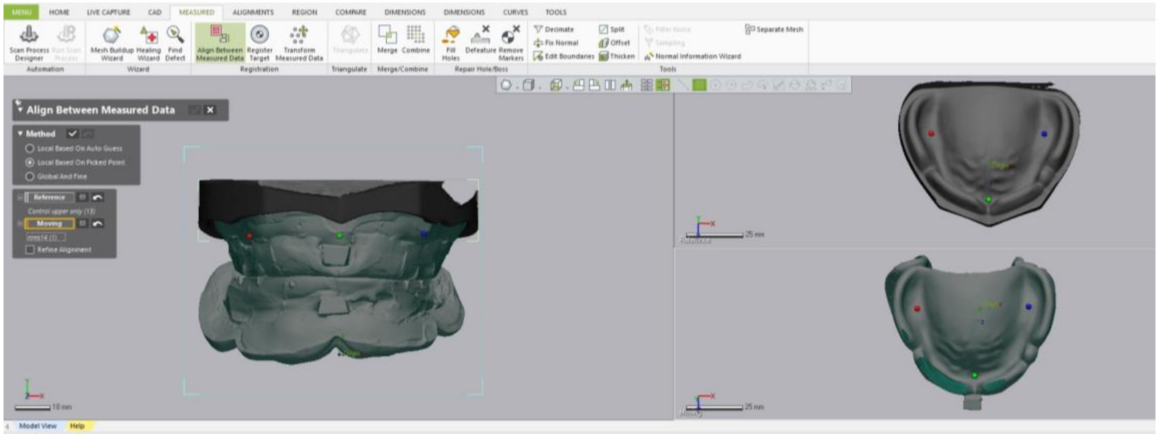


Figure 11: The OR and DD STLs aligned in Geomagic Control X.

The experimental STLs were aligned to the maxillary arch of the control patient, using point alignment followed by global registration. The control was the “reference”, and the OR/DD was the “moving” component. This aligned the intaglio surface of the experimental sample to the maxillary cast of the control patient.

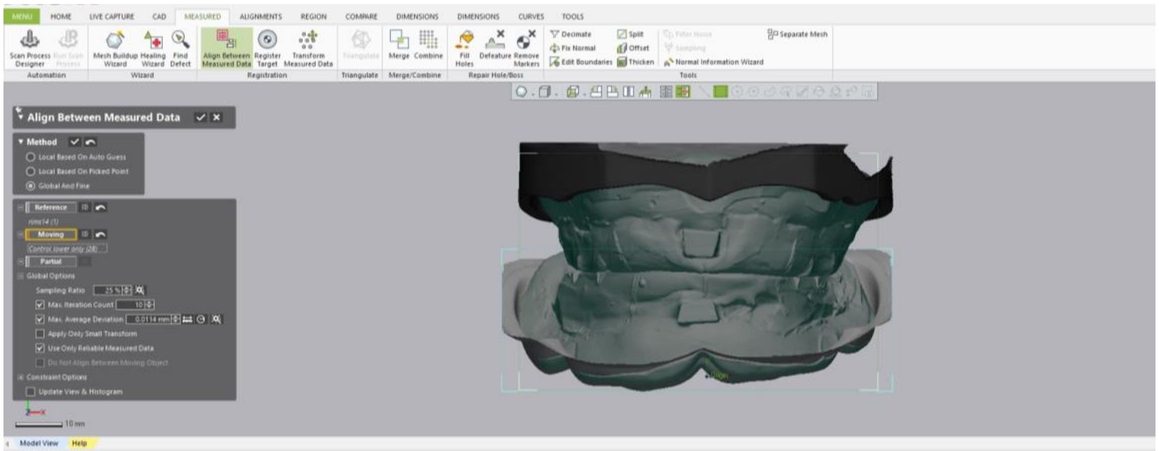


Figure 12: Global registration in Geomagic Control X

This was used to align the mandibular edentulous cast to the DD/OR experimental sample. This produced a digitally articulated set of casts, where the maxillary casts were all in alignment; therefore, all the discrepancies were noted on the mandibular cast.

Comparing Discrepancies in Digital Transfer of Vertical Dimension

Each experimental STL was superimposed with the control STL and aligned to the maxillary arch. The deviations were measured on the mandibular arch, utilizing point selection in Geomagic Control X, and constructing geometries of paired points. Reference points had been selected on the fiduciary markers of the control STL as shown previously. The same corresponding points were selected on the superimposed experimental DD/OR STL. The corresponding points on the control and the sample were paired under "constructed geometries" by highlighting the points and grouping them. Three sets of paired points or constructed geometries were created for each Result Data set. After, the calculations were automatically generated, producing deviations that were automatically produced in XYZ directions, recorded to the nearest hundredth millimeter. Each scan was compared to that of the control patient scan. A positive or negative deviation value was obtained for x, y, and z directions. A 3D deviation value was also automatically generated in Geomagic for Point A, B, and C using the 3D distance formula (Figure 13).

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Image courtesy of CalculatorSoup [68]

Figure 13: 3D Distance Formula

Formula used to calculate the 3D distance between two points in space, where d is the linear distance between point 1 (X_1, Y_1, Z_1) and point 2 (X_2, Y_2, Z_2) [68].

Figure 14: Superimposition of the control and experimental sample

This superimposition example is viewed from the occlusal view of the mandibular cast. The two colors represent the different scans and the deviation in the transfer of the jaw relationship. The lighter blue color is the control STL, whereas the darker purple color is the superimposed STL. The darker color indicates increased values.

Statistical analysis

3D deviations were averaged separately for each of the two groups, workflow one and workflow two. Mean, standard deviation, minimum, and maximum values were obtained for each workflow at each of the three locations. Differences between the groups at the different points were determined using a two-way ANOVA. A $p<.05$ was considered significant.

Chapter 3: Results

Descriptive Results

15 STL files were obtained for each workflow and superimposed against the control, for a total of 30 STLs (Figure 14). The deviation was measured in three dimensions (x, y, z) at each of the three points (A, B, C) to the nearest hundredth millimeter. The 3D deviation was computed using the 3D distance formula. A total of 90 3D deviation measurements were made. An average 3D deviation was calculated for each of the three points for each workflow (Table 3). The results are also displayed in Figure 15. For the detailed information regarding each measurement made, see Appendix (Appendix 1). For point A, the deviation was 0.47 ±0.22 mm in the DD workflow and 0.73 ±0.13 mm in the OR workflow. For point B, the deviation was 0.44 ±0.22 mm in the DD workflow and 0.71 ±0.13 mm in the OR workflow. For point C, the deviation was 0.45 ±0.26 mm in the DD workflow and 0.73 ±0.12 mm in the OR workflow. Looking at the locations of measurement, only 1/90 had a negative deviation along the Z-axis (Appendix 1). All 3D deviations were positive values, indicating an overall increase in VDO for 100% of the test samples.

Analysis

Two-way ANOVA revealed significant differences in the main factor of the method of transferring VDO [F=46.00, p=0.0001] but not the location main factor [F=0.15, p=0.86] (Table 4). There was also no significant interaction between the two main factors [F=0.02, p=0.98]. For the methods, VDO transfer using OR results in higher deviation at all three points assessed compared to the DD method.

Workflow	Point			
Duplicate Dentures	A	B	C	
	0.47	0.44	0.45	**Average**
	0.22	0.22	0.26	**Standard Deviation**
	0.33	0.36	0.34	**Median**
	0.22	0.16	0.21	**Minimum**
	0.84	0.95	1.14	**Maximum**
Occlusion Rims	A	B	C	
	0.73	0.71	0.73	**Average**
	0.13	0.13	0.12	**Standard Deviation**
	0.72	0.75	0.76	**Median**
	0.47	0.43	0.50	**Minimum**
	1.12	0.84	0.89	**Maximum**

Table 3: Results showing the average 3D deviation to the nearest hundredth mm.

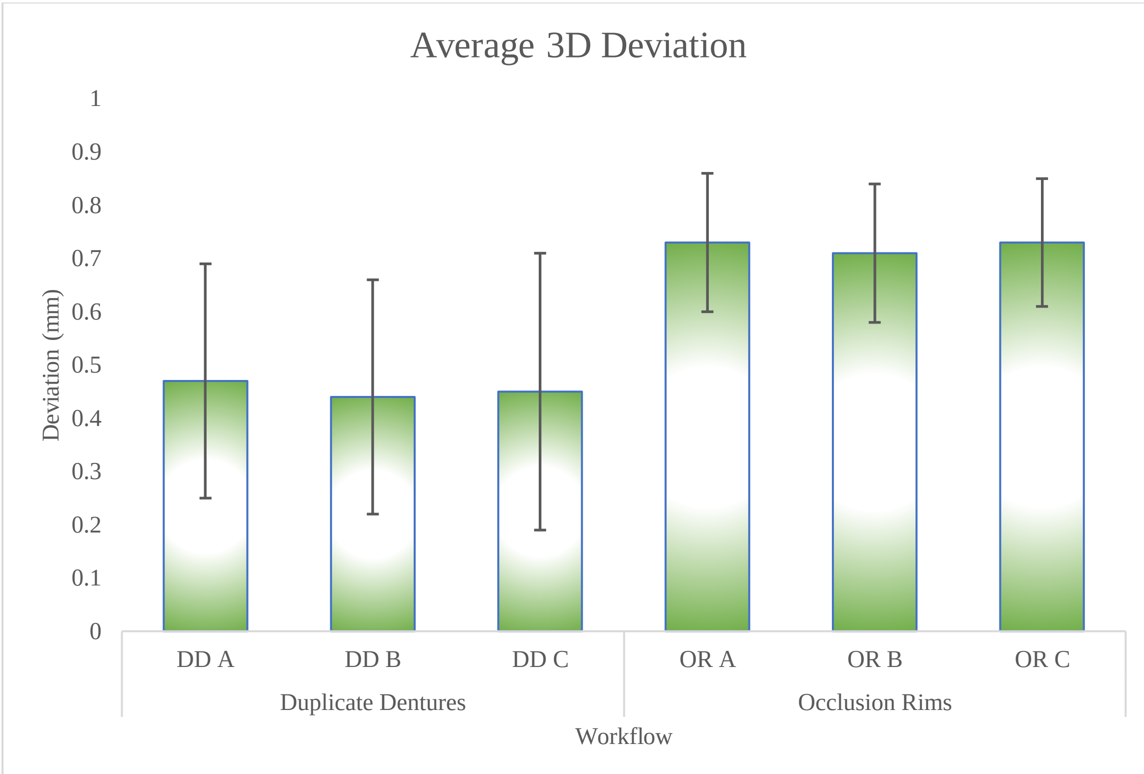


Figure 15: Graph of results, showing average three-dimensional deviation ±SD.

	Number of obs	= 90		R-squared	= 0.3555
	Root MSE	= 0.188578		Adj R-Squared	= 0.3171
Source	Partial SS	df	MS	F	Prob > F
Model	1.6477	5	0.3295	9.27	0.0000
Method	1.6359	1	1.6359	46.00	0.0000
Location	0.01036	2	0.00518	0.15	0.8647
Method*Location	0.00144	2	0.00072	0.02	0.9799
Residual	2.9871	84	0.03556		
Total	4.6349	89	0.05207		

Table 4: Two-way ANOVA

The ANOVA revealed a significant difference in the method of transfer of VDO. There was no significant difference in transfer of VDO at the location, and there was no significant interaction between the methods and locations. The method refers to either the duplicate denture or occlusion rim workflow. The location is the point at which the measurement was taken (A, B, C).

Chapter 4: Discussion

Summary of Results

Based on the results of the study, the null hypothesis was rejected. There was a significant difference in transfer of the VDO between the methods. There was significantly greater deviation in the transfer of VDO in the OR workflow as compared to the DD workflow ($p = 0.0001$). There was no significant difference in transfer of VDO between the locations. There was also no significant interaction between the methods and locations. Comparing the average three-dimensional deviation between the workflows, the OR workflow had more than 60% greater deviation. The 3D deviations were all positive values, indicating that there was an increase in VDO in both methods at all locations.

Interpretation of Results

The statistically significant difference in deviation between the two workflows can be clinically significant, especially when all potential errors are compounded. While the present study only evaluated the accuracy of transfer of VDO, some other aspects of digital dentures may influence the accuracy of VDO transfer as well.

Potential Sources of Error

While CAD-CAM can produce 3D objects with fine detail and high accuracy, there are many components involved. For additive manufacturing, there are different types of 3D printers, different resins, and different washing and curing protocols [45]. For subtractive manufacturing, there are different types of milling machines (i.e., multi-axis, wet vs. dry mill) that can handle different materials. Some milled materials require additional post-machining processing such as sintering. The combination of materials used, parameters, set and post-processing procedures has shown to significantly affect the properties and quality of the resulting product [46, 47, 48]. There are multiple studies that refer to this combination as the manufacturing trinomial, which is composed of the technology, machine, and material [45, 46].

Overall Processing Errors

Most clinicians complete a trial denture appointment prior to finalizing the dentures [17, 26]. At this time, occlusion can be adjusted, and vertical dimension can be assessed and altered if needed. If there is a minor discrepancy or deviation, the adjustment can be made, and a new occlusal registration can be obtained to capture the occlusal vertical dimension. Also, at the denture delivery appointment, regardless of the mode of manufacturing, there are almost always adjustments made. The denture intaglio is disclosed for potential pressure spots and adjusted as needed. A clinical remount is often performed to finalize the occlusion, which would adjust for any positive deviations that effect the patient's occlusion.

Denture Base

One research study by *Ishinabe* found that the denture base sinks 0.3 mm after insertion, due to occlusal forces and deformation of the soft tissue [41]. *Deng et al.* also confirmed that this 0.3 mm deviation is deemed clinically acceptable [42]. While these studies focused on the deviation between the denture base and the intaglio, by having 0.3 mm deviation in each arch on average, that can translate as well to a deviation in occlusal vertical dimension [41,42].

Wax

Wimmer et al. compared the occlusion between wax trial dentures fabricated conventionally versus digitally and found that the occlusion was not reproducible [38]. They concluded that the milled subjects showed less deviation in occlusion, but also stated that whenever wax was involved in trial dentures, there was opportunity for introducing discrepancies [38]. They also looked at the composition of the wax used and concluded that depending on the type of baseplate wax utilized, there were differences in the amount of contracture, which may result in greater deviation over time [38]. There are multiple studies that examine the effect of wax on denture accuracy. This could also explain why the OR group from the present study demonstrated greater deviation than the DD group. *Shetty & Udani* investigated the movement of artificial teeth in trial dentures at selected points over multiple time intervals. They found that there were discrepancies and deviations in all wax trial dentures[39]. Again, they attributed all discrepancies to the baseplate wax present [39]. In another study by *Sykora & Sutow*, they discussed the properties of baseplate waxes which could lead to tooth movement or distortion. Different baseplate waxes have different components, and there can even be variations between batches [40]. Unsurprisingly, in hotter temperatures with greater humidity, there was more distortion of baseplate wax regardless of composition [40]. However, this study did not find significant differences in tooth distortion between the different baseplate waxes [40]. Regardless, heating and cooling of wax can introduce stress and strain, which causes deviations in tooth position; therefore, affecting the occlusion in three-dimensions [40]. In the present study, discrepancies due to the properties of wax were minimized and controlled for by allowing the wax to fully cool while still on the articulator at the desired vertical dimension. Also, the samples were maintained in a climate-controlled environment, to not introduce heat or humidity.

Tooth Arrangement and Occlusion

There have been reports of denture tooth displacement during processing, both with conventional and digital methods [17, 63]. With digital denture systems, there are several options for the final prosthesis. Digital dentures can either be milled or printed as a monoblock, or the bases and teeth can be fabricated separately, then bonded together [17, 63]. When the denture teeth are fabricated separately, there can be discrepancies in the attachment to the base. When digital dentures are designed this way, the design software has different parameters for “glue space”. The greater the space between the teeth and the base, the greater potential for error. Conventionally processed dentures can also have errors in occlusion due to the polymerization shrinkage and potential for denture teeth to move during processing [66]. Granted, a laboratory remount would be completed to adjust for this processing error (polymerization shrinkage) [63]. However, if teeth move during heat-processing, then those can affect the occlusal scheme. Also, the laboratory and clinical adjustments required can significantly alter the tooth anatomy and even the VDO[64, 65].

One of the goals of denture fabrication via CAD-CAM, is to minimize the tooth movement by eliminating errors that occur during conventional processing [11]. *Goodacre et al.* reported superior accuracy and reproducibility in milled dentures versus conventional dentures[22]. One study by *Lo Russo et al.* evaluated the accuracy of tooth position in digital dentures that were fabricated by bonding milled teeth to denture bases [63]. They found significant displacement of the bonded teeth in the Z direction, which can produce an altered VDO [63].

Impressions

Another possible explanation for the discrepancy in deviation between OR and DD groups, could be resulting from differing impression space. The DD workflow only allowed for a built-in 0.35 mm impression gap, whereas the OR workflow allowed for 1.50 mm impression gap. *Rajapur et al.* examined the influence of tray space on impression accuracy, finding that impressions made with less space yielded more accurate stone models [69]. For digital dentures, impressions can be made with intraoral scans or conventionally with impression materials [70]. *Lo Russo et al.* evaluated 3D differences between digital impressions and conventional impressions, finding a statistically significant difference between the impression types when they were not digitally trimmed [70]. However, there was no significant difference between the digital or conventional impressions when the STLs were trimmed [70]. These findings may contribute to potential sources of error in fabricating digital dentures.

Result of Incorrect VDO

While some patients may adapt to a vertical dimension that is slightly off, some patients may not. Insufficient or excessive VDO can affect speech and function. In the classical articles written by *Pound* and *Silverman*, they describe the closest speaking spaces and its value in helping determine VDO [49, 50, 51, 52, 53, 54, 55]. According to Silverman, the closest speaking space is defined as the distance between the occlusion rims or artificial teeth during /s/ or /ch/ sounds, and that there should be 1-2 mm of interocclusal space when these words are spoken [49, 50, 51, 52]. During /s/ and /ch/ sounds, the teeth should be close together but not touching. In patients with excessive VDO, the closest speaking space is violated, and the teeth will contact during speech. This would result in a production of clicking sounds [49, 50, 51, 52].

In one classical study by *Ramfjord and Blankenship*, they evaluated the effect of an increased VDO on monkeys [56]. While this study was done on dentate monkeys, it revealed that the increased VDO caused muscle contracture, leading to intrusion of the teeth [56]. However, in those whose teeth do not intrude, the excessive muscle contracture puts excessive forces on the temporomandibular joints, which can lead to joint dysfunction (TMD) and pain [56]. In a review by *Moreno-Hay & Okeson*, they cited numerous studies with instances where altering OVD resulted in some patients with pain and discomfort, unable to adapt to the increased OVD[57].

Limitations of This Study

One potential limitation of this study is that the entire workflow was not evaluated to completion. The experiment only evaluated the transfer of the OVD at the jaw relations phase. It is possible that the amount of deviation would have been even greater, had digital dentures been designed and fabricated from the samples.

Summary

While there are laboratory and clinical adjustments that can be made to dental prostheses to refine and correct VDO, when all the potential sources for error are compounded, it may result in prostheses with too much error for a patient to tolerate. The present study evaluated the accuracy of transfer of VDO in the fabrication of digital dentures, which revealed that OR had significantly greater deviation in the transfer than DD at all three locations of measurement. The location of measurement did not pose any significance in the accuracy of the transfer of VDO, and there was no significant interaction between the methods and the location.

Future Research

Digital dentistry is a rapidly advancing component of dentistry today. With that, digital dentures are becoming more and more popular for clinicians to use. There are a currently several studies that compare CAD-CAM dentures to conventional dentures in terms of accuracy of denture base fit, strength, and color stability. After conducting this experiment, discovering that there is a significant difference between the workflows regarding the accuracy of transferring the jaw relationship, it would be interesting to further examine the direction of the deviations. For instance, comparing the amount of deviation in different scanners (intraoral versus desktop). Also, it may be interesting to evaluate the angle or degree of deviation in transfer of the jaw relationship as well.

Appendix 1

Raw measurements

Duplicate Dentures				
Point A	X	Y	Z	Total
1	-0.103	0.016	0.772	0.779
2	-0.014	0.001	0.297	0.297
3	-0.029	-0.049	0.322	0.327
4	-0.113	-0.418	0.635	0.768
5	-0.043	-0.060	0.296	0.305
6	0.002	0.019	0.215	0.215
7	0.019	-0.070	0.277	0.286
8	-0.015	-0.110	0.259	0.282
9	0.004	-0.019	0.287	0.288
10	0.004	-0.065	0.355	0.361
11	-0.016	-0.043	0.324	0.327
12	0.025	0.084	0.840	0.845
13	0.027	-0.018	0.675	0.676
14	-0.073	0.090	0.609	0.620
15	-0.069	0.094	0.605	0.616
Average	-0.026	-0.037	0.451	0.466
Standard Deviation	0.045	0.122	0.212	0.222
Median	-0.015	-0.019	0.324	0.327
Minimum	-0.113	-0.418	0.215	0.215
Maximum	0.027	0.094	0.840	0.222

Point B	X	Y	Z	Total
1	-0.244	0.068	0.917	0.952
2	0.016	-0.028	0.285	0.287
3	-0.039	-0.022	0.280	0.283
4	0.024	-0.053	0.438	0.442
5	-0.048	0.001	0.248	0.253
6	0.010	-0.021	0.158	0.160
7	0.042	0.013	0.201	0.206
8	-0.140	-0.400	0.217	0.476
9	-0.093	-0.268	0.218	0.358
10	0.034	-0.105	0.306	0.325
11	0.037	-0.106	0.226	0.253
12	0.060	-0.006	0.641	0.644
13	-0.085	0.021	0.609	0.615
14	-0.167	0.121	0.527	0.566
15	-0.179	0.212	0.653	0.710
Average	-0.051	-0.038	0.395	0.435
Standard Deviation	0.095	0.147	0.224	0.223
Median	-0.039	-0.021	0.285	0.358
Minimum	-0.244	-0.400	0.158	0.160
Maximum	0.060	0.212	0.917	0.952

Point C	X	Y	Z	Total
1	-0.058	-0.286	1.101	1.139
2	0.031	-0.008	0.298	0.299
3	0.015	-0.049	0.334	0.338
4	-0.081	0.043	0.334	0.346
5	-0.001	0.013	0.297	0.297
6	0.049	-0.066	0.198	0.214
7	0.066	-0.130	0.223	0.266
8	0.030	-0.123	0.282	0.309
9	0.050	-0.046	0.253	0.262
10	0.039	-0.293	0.406	0.502
11	0.030	-0.014	0.221	0.224
12	0.078	-0.023	0.540	0.546
13	0.070	0.048	0.650	0.656
14	-0.029	0.121	0.550	0.564
15	-0.028	0.042	0.806	0.808

Average	0.017	-0.051	0.433	0.451
Standard Deviation	0.047	0.117	0.256	0.258
Median	0.030	-0.023	0.334	0.338
Minimum	-0.081	-0.293	0.198	0.214
Maximum	0.078	0.121	1.101	1.139

Occlusion Rims				
Point A	X	Y	Z	Total
1	-0.147	-0.125	1.098	1.115
2	0.112	-0.079	0.693	0.706
3	-0.605	0.309	0.322	0.752
4	-0.102	0.095	0.680	0.694
5	0.100	0.175	0.614	0.646
6	-0.063	0.130	0.448	0.471
7	0.213	0.071	0.682	0.718
8	-0.432	0.175	0.483	0.671
9	-0.076	0.227	0.754	0.791
10	0.090	0.250	0.676	0.726
11	0.125	0.157	0.614	0.646
12	-0.018	0.171	0.727	0.747
13	0.021	0.115	0.745	0.754
14	0.053	0.131	0.669	0.684
15	0.104	0.205	0.724	0.759
Average	-0.042	0.134	0.662	0.725
Standard Deviation	0.219	0.114	0.172	0.132
Median	0.021	0.157	0.680	0.718
Minimum	-0.605	-0.125	0.322	0.471
Maximum	0.213	0.309	1.098	1.115

Point B	X	Y	Z	Total
1	0.155	0.329	0.737	0.822
2	0.029	0.284	0.705	0.760
3	-0.414	0.141	0.096	0.448
4	-0.099	0.425	0.612	0.751
5	0.052	0.248	0.605	0.656
6	-0.172	0.203	0.498	0.565
7	0.119	0.287	0.711	0.776
8	-0.294	-0.032	0.309	0.428
9	-0.067	0.365	0.690	0.783
10	0.046	0.462	0.657	0.805
11	0.072	0.355	0.605	0.705
12	-0.038	0.253	0.693	0.739
13	-0.033	0.412	0.733	0.841
14	-0.009	0.378	0.667	0.767
15	0.095	0.305	0.678	0.750
Average	-0.037	0.294	0.600	0.706
Standard Deviation	0.156	0.125	0.177	0.128
Median	-0.009	0.305	0.667	0.751
Minimum	-0.414	-0.032	0.096	0.428
Maximum	0.155	0.462	0.737	0.841

Point C	X	Y	Z	Total
1	-0.103	0.122	0.470	0.497
2	0.150	0.015	0.825	0.839
3	-0.548	0.094	-0.042	0.558
4	-0.064	0.291	0.645	0.710
5	0.139	0.268	0.696	0.758
6	-0.020	0.029	0.652	0.653
7	0.252	0.116	0.846	0.890
8	-0.369	-0.322	0.226	0.539
9	-0.028	0.133	0.725	0.737
10	0.132	0.271	0.742	0.801
11	0.164	0.265	0.698	0.764
12	0.025	0.193	0.757	0.781
13	0.062	0.166	0.826	0.845
14	0.090	0.258	0.767	0.814
15	0.150	0.164	0.731	0.764

Average	0.002	0.137	0.638	0.730
Standard Deviation	0.213	0.155	0.245	0.118
Median	0.062	0.164	0.725	0.764
Minimum	-0.548	-0.322	-0.042	0.497
Maximum	0.252	0.291	0.846	0.890

Bibliography

1. The Glossary of Prosthodontic Terms: Ninth Edition. *The Journal of prosthetic dentistry*. 2017;117(5):C1, e1-C1, e105.
2. American College of Prosthodontists and ACP Education Foundation. Glossary of Digital Dental Terms, 2nd Edition: American College of Prosthodontists and ACP Education Foundation. *Journal of prosthodontics*. 2021;30(S3):172-181.
3. Goodacre CJ, Garbacea A, Naylor WP, Daher T, Marchack CB, Lowry J. CAD/CAM fabricated complete dentures: concepts and clinical methods of obtaining required morphological data. *The Journal of prosthetic dentistry*. 2012;107(1):34-46.
4. Andersson M, Carlsson L, Persson M, Bergman B. Accuracy of machine milling and spark erosion with a CAD/CAM system. *The Journal of prosthetic dentistry*. 1996;76(2):187-193.
5. Mörmann WH. The origin of the Cerec method: a personal review of the first 5 years. *International journal of computerized dentistry.* 2004;7(1):11-24.
6. Mörmann WH. The evolution of the CEREC system. *The Journal of the American Dental Association (1939).* 2006;137(1):7S-13S
7. Maeda Y, Minoura M, Tsutsumi S, Okada M, Nokubi T. A CAD/CAM system for removable denture. Part I: Fabrication of complete dentures. *The International journal of prosthodontics.* 1994;7(1):17-21.
8. Kawahata N, Ono H, Nishi Y, Hamano T, Nagaoka E. Trial of duplication procedure for complete dentures by CAD/CAM. *Journal of oral rehabilitation.* 1997;24(7):540-548.

9. Busch M, Kordass B. Concept and development of a computerized positioning of prosthetic teeth for complete dentures. *International journal of computerized dentistry.* 2006;9(2):113-120.

10. Zhang Y, Jiang J, Liang T, Hu W. Kinematics Modeling and Experimentation of the Multi-manipulator Tooth-Arrangement Robot for Full Denture Manufacturing. *J Med Syst.* 2010;35(6):1421-1429.

11. Kanazawa M, Inokoshi M, Minakuchi S, Ohbayashi N. Trial of a CAD/CAM system for fabricating complete dentures. *Dental materials journal.* 2011;30(1):93-96.

12. Srinivasan M, Schimmel M, Naharro M, O' Neill C, McKenna G, Müller F. CAD/CAM milled removable complete dentures: time and cost estimation study. *Journal of dentistry*. 2019; 80:75-79.

13. Kazmer D. 28 - Three-Dimensional Printing of Plastics. Kutz M, ed. 2nd ed. William Andrew Publishing; 2017:617-634.

14. Kumar SA, Prasad RVS. Chapter 2 - Basic principles of additive manufacturing: different additive manufacturing technologies. Manjaiah M, Raghavendra K, Balashanmugam N, Davim JP, eds. Woodhead Publishing; 2021:17-35.

15. Moritz T, Maleksaeedi S. 4 - Additive manufacturing of ceramic components. Additive Manufacturing. 2018:105-161.

16. Hull CW, inventor; 3D Systems Inc., assignee. Apparatus for production of three-dimensional objects by stereolithography. US patent US4575330A. Mar 11, 1986.

17. Baba NZ, Goodacre BJ, Goodacre CJ, Müller F, Wagner S. CAD/CAM Complete Denture Systems and Physical Properties: A Review of the Literature. *Journal of prosthodontics.* 2021;30(S2):113-124.

18. McLaughlin JB, Ramos V, Dickinson DP. Comparison of Fit of Dentures Fabricated by Traditional Techniques Versus CAD/CAM Technology. *Journal of prosthodontics*. 2019;28(4):428-435.

19. AlHelal A, AlRumaih HS, Kattadiyil MT, Baba NZ, Goodacre CJ. Comparison of retention between maxillary milled and conventional denture bases: A clinical study. *The Journal of prosthetic dentistry.* 2016;117(2):233-238.

20. Lo Russo L, Guida L, Zhurakivska K, Troiano G, Chochlidakis K, Ercoli C. Intaglio surface trueness of milled and 3D-printed digital maxillary and mandibular dentures: A clinical study. *The Journal of prosthetic dentistry.* 2021.

21. Baba NZ. Materials and Processes for CAD/CAM Complete Denture Fabrication. *Curr Oral Health Rep.* 2016;3(3):203-208.

22. Goodacre BJ, Goodacre CJ, Baba NZ, Kattadiyil MT. Comparison of denture tooth movement between CAD-CAM and conventional fabrication techniques. *The Journal of prosthetic dentistry.* 2017;119(1):108-115.

23. Pacquet W, Benoit A, Hatège-Kimana C, Wulfman C. Mechanical Properties of CAD/CAM Denture Base Resins. *The International journal of prosthodontics.* 2019;32(1):104-106.

24. Inokoshi M, Kanazawa M, Minakuchi S: Evaluation of a complete denture trial method applying rapid prototyping. *Dental materials journal.* 2012;31(1):40-46.

25. Bilgin MS, Erdem A, Aglarci OS, Dilber E. Fabricating Complete Dentures with

CAD/CAM and RP Technologies. Journal of prosthodontics. 2015;24(7):576-579.

26. Baba NZ, AlRumaih HS, Goodacre BJ, Goodacre CJ. Current techniques in CAD/CAM denture fabrication. *General dentistry.* 2016;64(6):23-28.
27. Steinmassl PA, Klaunzer F, Steinmassl O, et al: Evaluation of currently available CAD/CAM denture systems. *Int J Prosthodont* 2017; 30:116-122.
28. Steinmassl O, Dumfahrt H, Grunert I, Steinmassl P-. Influence of CAD/CAM fabrication on denture surface properties. *Journal of oral rehabilitation.* 2018;45(5):406-413.
29. Srinivasan M, Gjengedal H, Cattani-Lorente M, et al: CAD/CAM milled complete removable dental prostheses: An in vitro evaluation of biocompatibility, mechanical properties, and surface roughness. *Dental materials journal.* 2018;37(4):526-533.
30. Prpić V, Schauperl Z, Ćatić A, Dulčić N, Čimić S. Comparison of Mechanical Properties of 3D-Printed, CAD/CAM, and Conventional Denture Base Materials. *Journal of prosthodontics.* 2020;29(6):524-528.
31. Perea-Lowery L, Minja IK, Lassila L, Ramakrishnaiah R, Vallittu PK. Assessment of CAD-CAM polymers for digitally fabricated complete dentures. *The Journal of prosthetic dentistry.* 2021;125(1):175-181.
32. Steinmassl O, Dumfahrt H, Grunert I, Steinmassl P. CAD/CAM produces dentures with improved fit. *Clin Oral Invest.* 2018;22(8):2829-2835.
33. Goodacre BJ, Goodacre CJ, Baba NZ: Using Intraoral Scanning to Capture Complete Denture Impressions, Tooth Positions, and Centric Relation Records. *Int J Prosthodont*. 2018 July/August;31(4):377–381.

34. Kanakaraj S, K HK, Ravichandran R. An update on CAD/CAM removable complete dentures: A review on different techniques and available CAD/CAM denture systems. *International Journal of Applied Dental Sciences.* 2021;7(1):491-498.

35. Woelfel JB, Paffenbarger GC, Sweeney WT: Dimensional changes occurring in dentures during processing. J AM Dent Assoc 1960; 61:413-30.

36. Wang C, Shi Y, Xie P, Wu J. Accuracy of digital complete dentures: A systematic review of in vitro studies. *The Journal of prosthetic dentistry.* 2021;125(2):249-256.

37. Matsuda T, Goto T, Yagi K, Kashiwabara T, Ichikawa T. Part-digitizing system of impression and interocclusal record for complete denture fabrication. *Journal of prosthodontics.* 2016;25(6):503-509.

38. Wimmer T, Eichberger M, Lümkemann N, Stawarczyk B. Accuracy of digitally fabricated trial dentures. *The Journal of prosthetic dentistry*. 2018;119(6):942-947.

39. Shetty NS, Udani TM. Movement of artificial teeth in waxed trial dentures. *The Journal of prosthetic dentistry*. 1986;56(5):644-648.

40. Sykora O, Sutow EJ. Comparison of the dimensional stability of two waxes and two acrylic resin processing techniques in the production of complete dentures. *Journal of oral rehabilitation*. 1990;17(3):219-227.

41. Ishinabe S. Mucosal thickness of the denture foundation under occlusal force. *Nihon Hotetsu Shika Gakkai zasshi.* 1991;35(1):111-124.

42. Deng K, Chen H, Zhao Y, Zhou Y, Wang Y, Sun Y. Evaluation of adaptation of the polylactic acid pattern of maxillary complete dentures fabricated by fused deposition modelling technology: A pilot study. *PloS one.* 2018;13(8):e0201777.
43. Formlabs. Grey Pro Resin for Versatile Prototyping Datasheet. Formlabs. 2020:1-2.
44. Formlabs. Dental Resin Model. Formlabs. 2021.
45. Anadioti E, Kane B, Zhang Y, Bergler M, Mante F, Blatz MB. accuracy of dental and industrial 3d printers. *Journal of prosthodontics.* 2022;31(S1):30-37.
46. Piedra-Cascón W, Krishnamurthy VR, Att W, Revilla-León M. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. *Journal of dentistry.* 2021; 109:103630.
47. Unkovskiy A, Bui PH, Schille C, Geis-Gerstorfer J, Huettig F, Spintzyk S. Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin. *Dental materials.* 2018;34(12):e324-e333.
48. Shim JS, Lee JS, Lee JY, Choi YJ, Shin SW, Ryu JJ. Effect of software version and parameter settings on the marginal and internal adaptation of crowns fabricated with the CAD/CAM system. *Journal of applied oral science.* 2015;23(5):515-522.
49. Silverman MM. Accurate measurement of vertical dimension by phonetics and the speaking centric space. Part I. *Dental digest.* 1951;57(6):261-265.

50. Silverman MM. Accurate measurement of vertical dimension by phonetics and the speaking centric space: Part two. *Dental digest*. 1951;57(7):308-311.

51. Silverman MM. Determination of vertical dimension by phonetics. *The Journal of prosthetic dentistry*. 1956;6(4):465-471.

52. Silverman MM. Vertical dimension must not be increased. *The Journal of prosthetic dentistry*. 1952;2(2):188-197.

53. Pound E. Let /S/ be your guide. *The Journal of prosthetic dentistry*. 1977;38(5):482-489.

54. Pound E. Controlling anomalies of vertical dimension and speech. *The Journal of prosthetic dentistry*. 1976;36(2):124-135.

55. Pound E. Utilizing speech to simplify a personalized denture service. *The Journal of prosthetic dentistry*. 1970;24(6):586-600.

56. Ramfjord SP, Blankenship JR. Increased occlusal vertical dimension in adult monkeys. *The Journal of prosthetic dentistry*. 1981;45(1):74-83.

57. Moreno-Hay I, Okeson JP. Does altering the occlusal vertical dimension produce temporomandibular disorders? A literature review. *Journal of oral rehabilitation*. 2015;42(11):875-882.

58. AvaDent Clinical Educational Tools. AvaDent Website. https://www.avadent.com/clinical/education-tools/.

59. Dentca Instructions for Use. Dentca Website. https://dentca.com/blog/home/resources/dentca-design-denture-step-by-step-guide.

60. Digital Denture User's Guide. *Ivoclar*.

61. Full Denture Solutions in the Ceramill System. *Amann Girrbach.*

62. Dentsply Sirona Digital Dentures. Dentsply Sirona Web site. https://www.dentsplysirona.com/en-us/categories/lab/digital-denture.html

63. Lo Russo L, Park J, Troiano G, Salamini A, Lo Muzio E, Guida L. Assessment of tooth displacement during the cast-free digital processing of milled dentures. *The Journal of prosthetic dentistry.* 2021.

64. Mahler DB. Inarticulation of complete dentures processed by the compression molding technique. *The Journal of prosthetic dentistry.* 1951;1(5):551-559.

65. Babu S, Manjunath S, Vajawat M. Effect of palatal form on movement of teeth during processing of complete denture prosthesis: An in-vitro study. *Contemporary clinical dentistry.* 2016;7(1):36-40.

66. Lorton L, Phillips RW. Heat-released stress in acrylic dentures. *The Journal of prosthetic dentistry.* 1979;42(1):23-26.

67. Atkinson HF, Grant AA. An investigation into tooth movement during the packing and polymerizing of acrylic resin denture base materials. *Australian dental journal.* 1962;7(2):101-108.

68. Furey E. 3D Distance Calculator. CalculatorSoup Website. https://www.calculatorsoup.com/calculators/geometry-solids/distance-two-points.php.

69. Rajapur A, Dixit S, Hoshing C, Raikar SP. The influence of tray space and repeat pours on the accuracy of monophasic polyvinylsiloxane impression. *The journal of contemporary dental practice*. 2012;13(6):824-829.

70. Lo Russo L, Caradonna G, Troiano G, Salamini A, Guida L, Ciavarella D. Three-dimensional differences between intraoral scans and conventional impressions of edentulous jaws: A clinical study. *The Journal of prosthetic dentistry*. 2020;123(2):264-268.