A comparison of the Fitting Surface Trueness and Precision of Traditionally Constructed Complete Dentures and 3D Printed Dentures.

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Submitted in accordance with the requirements for the Degree of Master of Science by Research.

The University of Leeds

The School of Dentistry December 2019

Intellectual Property and Publication Rights

Acknowledgements:

I would like to thank the following people who have supported me throughout this process. Dr Andy Keeling and Dr Paul Hyde who have been my supervisors throughout this project. Without their help and encouragement, I would not have been where I am today with this project.

Dr Andy Keeling and Cecilie Osnes who have been my technical advisors with the digital technologies if I ever needed help with anything on the digital side of this project. They helped run the batch files that enabled me to get the raw data for the denture measurements in Appendix 4 and the colour mapping of the dentures in Appendices 2 & 3

Prof Helen Whelton and Prof David Wood who secured the funding for me to be allowed to proceed with my degree.

Finally, I would like to thank my wife Helen and daughters Niamh and Erin who have put up with so much over the last 2 years enabling me to get this far.

Statistical advice was sought by the School of Dentistry statistician Jianhua Wu.

If there is anybody else who I may have omitted by accident I do apologise.

Abstract:

Introduction:

Complete denture construction was revolutionised in the 1930's when (Polymethyl Methacrylate) PMMA was developed. But it does have its drawbacks. This research compared the fitting surface trueness and precision of complete dentures against the fitting surface trueness and precision of new 3D printed dentures using additive manufacturing techniques.

Method:

10 sets of both traditional and 3-D printed dentures were constructed and assessed. Virtual digital dentures were created using scans of the master casts and try-ins from the traditional workflow. The teeth on the virtual dentures were digitally removed to produce printable denture blanks with tooth sockets. The blanks were printed. Commercially available teeth were re-inserted into the blanks. Post-print curing was completed in a light box. Scans of traditional and printed dentures were taken at each stage of production and measured for trueness and precision against the model scans.

Results:

Paired t-tests ($p \leq 0.05$) were conducted on traditional dentures and compared against

printed baseplates without and with teeth. Means and signed standard deviations distances were calculated. Mean deviations were 0.055 +/- 0.008mm for upper traditional dentures and 0.061 +/- 0.075 mm for lowers. Printed mean deviations for upper and lower dentures measured 0.109 +/- 0.007 mm and 0.076 +/- 0.013mm. P values for upper trueness was calculated at (p= 0.000) and precision p value measured (p= 0.000). For lowers trueness p value was measured at (p= 0.006) and precision p value measured (p=0.006).

Conclusion:

Traditionally constructed dentures were significantly more accurate than printed dentures. The results for printing were promising. When printed, lowers were more accurate than traditionally constructed dentures until teeth were added. Light curing and storage of baseplates prior to adding teeth may be a factor in determining trueness and precision. Further work investigating storage of light cured dentures is needed as this may affect denture trueness and precision.

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Section 5.1 Discussion of the results

List of Abbreviations:

3D	3 Dimensional
50/50	50% Dental Stone, 50% Plaster of Paris
AM	Additive Manufacturing
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CE	Conformité Européenne European Conformity
DLP	Digital Light Processing
DMD	Digital Micro-mirror Device
FDA	Federal Drugs Administration
ICP	Iterative Closest Point
ISO	International Standards Organisation
LL	Lower Left
LR	Lower Right
MIT	Massachusetts Institute of Technology
MLP file.	Meshlab Project File
MMA	Methyl Methacrylate
mW	Milliwatt
NHS	National Health Service
OVD	Occlusal Vertical Dimension
.ply	Polygon file format
PMMA	Poly Methyl Methacrylate
PVS	Polyvinyl Siloxane
RCT	Randomised Controlled Trials
RP	Rapid Prototyping
SD	Standard Deviation
SLA	Stereo Lithography

SLS	Selective Laser Sintering
SM	Subtractive Manufacturing
.stl	Stereo Lithography File/Standard Tessellation Language
UL	Upper Left
UR	Upper Right
VSE	Vinylsiloxanether

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Chapter 1

1.1 Background:

The history of acrylic resin, or, its scientific name poly methyl methacrylate (PMMA) for use in dentures dates back to its invention in 1932 by ICI (Rueggeberg, 2002). In 1936 the first commercial dentures were made using the recently invented “Veronite”, a derivative of PMMA (Rueggeberg, 2002) and by the 1940’s, 95% of all dentures were made from this material (Rueggeberg, 2002; Baba, 2016). Baba states a number of disadvantages using this material, for example its “net volumetric shrinkage” amount during its curing cycle and the promotion of dental infections, mainly Candida Albicans. It normally takes six dental appointments to have a set of complete dentures fitted from start to finish including the review appointment. While this research will not decrease this number currently, the author speculates in the future, technology may reduce patient appointments.

According to the Adult Dental Health Survey of 2009 “15% of adults aged 65–74, 30% aged 75–84 and 47% aged >85 years are edentulous and require complete dentures” (Gray et al., 2012). Traditionally acrylic resin is widely used to construct complete dentures (Powers & Wataha 2013). While it remains the material of choice with many advantages, it is not ideal material as a denture base.

While PMMA has been used successfully over the last 70 years, there remains the potential to further improve the fit of complete dentures. One way of doing this might be using new technology and CAD/CAM. This research will concentrate on one aspect of CAD/CAM, the 3D printing of dentures.

1.2 How dentures are currently made. Current technology and current workflow:

Presently dentures are made using the Lost Wax Technique. Making acrylic dentures is a time consuming process. The workflow for a patient receiving complete dentures is: (Neill & Nairn 1990)

- Primary Impressions.
- Secondary Impressions.
- Recording the occlusion.
- Try-in of the dentures.
- Possible retry of the dentures.
- Finish of the dentures.
- Review.

Normally there are at least 6 stages for a patient to receive a set of complete dentures including the review visit. This doesn't mean that the treatment will be successful as problems post insertion may take time to show. It also means that there are many opportunities for things to go wrong between the clinic and the lab. Examples of where things may go wrong between clinic and laboratory are as follows: (Basker, R., Davenport, J., & Tomlin, 2002; Allen and McCarthy, 2003).

- Impression errors clinical/technical errors.

- Recording the occlusion and articulation errors.
- Try-in and retry errors.
- Processing errors – open bites.

A wax baseplate with acrylic teeth incorporated in it is transformed into an acrylic denture. A gypsum mould of the model is made from an impression of the patient's mouth. A mould of the polished surfaces of the denture is made using gypsum in a denture flask. The flask is closed and inserted into boiling water for ten minutes to soften the wax. The mould is opened and the wax eliminated with boiling water. What is left is a negative of the wax denture. This gypsum mould is filled with Poly Methyl Methacrylate (PMMA), otherwise known as Acrylic Resin. This is cured in a hot water bath under pressure for 10 hours. It can be shorter but for the purpose of this research all dentures will be cured for this length of time. Dentsply state their products are curable for extended time polymerization techniques. (Dentsply GMBH, n.d.) This may not be commercially practical in NHS laboratories due to time constraints. After curing, the denture is removed from the mould, trimmed, polished and returned to the clinic for final fitting.

1.3 Problems with complete dentures:

1.3.1 Dental impression problems:

While McCord and Grant describe what the common problems are with fitting complete dentures and how dental impressions may affect the fit of dentures, what they are describing are impression errors and not accuracy problems with PMMA as a denture base material. (McCord & Grant. 2000) A possible way of avoiding impression and casting errors may be a digital workflow as impression storage (Chandran et al., 2010), and impression casting, may introduce errors that may affect the fit of a dental appliance (Rudd & Rudd, 2001).

According to the Adult Dental Health survey of 2009 (Gray et al., 2012) the "quality of the dental impressions is the most important issue for improving the fit and comfort of complete dentures". However, other factors in the workflow can also contribute to errors, and these may be more readily targeted for improvement. Altering clinical/behavioural habits (such as impression taking) requires a complex multi-factorial approach and may be an inefficient use of resource. For example, changing the antimicrobial prescribing habits of UK dentists is proving to be challenging, and this arguably is a simpler intervention than upskilling all clinicians in impression taking (Thompson et al., 2019). Therefore, whilst other research focusses on the potential for improving other aspects of the workflow that are more readily able to be improved, this research aims to investigate the problems of acrylic resin when constructing complete dentures. Fitting surface trueness and precision may cause a denture not to fit properly. PMMA is known to shrink during polymerisation. Acrylic shrinkage can be a problem and cause problems fitting dental appliances. Pure methyl methacrylate (MMA) can have a volumetric shrinkage of up to 21% and is a reason why an investigation into the trueness and precision of new 3D printed polymers is needed (Anusavice et al. 2013). This is reinforced by Powers and Wataha as they state "acrylics have significant polymerisation reaction shrinkage approaching 6% vol. This degree of polymerisation shrinkage poses significant problems for the fit of dental prosthesis" (Powers & Wataha 2013). This affects the fit of an acrylic denture base and can be seen when the palate pulls away from the oral mucosa usually in the middle of the palate. The author speculates that this is one reason why, post dams are needed on the fitting surfaces of complete dentures. Powers and Wataha state that residual monomer may have clinical consequences as patients can have allergic reactions to dental acrylics post insertion. This may be because the unreacted monomer reacts with the intra-oral mucosa causing inflammation of the tissues in the mouth (Powers & Wataha, 2013). Dental polymers, according to Powers and Wataha, need a high degree of polymerisation as this leads to “more rigid, less soluble polymer networks, which is desirable in clinical applications” (Powers & Wataha, 2013). With the development of new polymers this may be something that can be avoided with new construction techniques.

1.3.2 Tooth arch distortion:

An area where dentures may distort is tooth arch alignment. Salloum found that teeth moved during construction with complete dentures for various reasons both laterally and antero-posteriorally when measured using a digital calliper across the palate and from the central incisors to first molar (Salloum, A., 2016). This was put this down to:

- The use of dental stone or a 50/50 mix of stone and plaster reduced the amount of tooth movement during processing over plaster as a flasking material.
- Setting expansion of gypsum.

- Denture base thickness has been attributed tooth movement during processing.

- Flask closure attributing to tooth movement.

Other researchers found the thickness of the denture base affected the position of the teeth. Jamani and Moligoda Abuzar found thick denture bases affected cross arch accuracy of teeth compared to their thin counterparts (Jamani, K. & Moligoda Abuzar, M., 1998).

A possible way to overcome tooth movement may be to digitise the denture base. Printing a denture base with tooth sockets included for positioning of teeth and adhering these to the denture base using light cured resin. This may reduce/eliminate possible processing errors that Salloum found (Salloum, 2016).

1.3.3 Acrylic shrinkage and distortion:

The palate and its associated post dam area for upper dentures is highly important when checking for “accuracy of fit of denture bases” for complete dentures. “Accuracy of fit” is critical if an upper denture is to succeed (Sykora & Suttow., 1993). This is reinforced by Lamb et al who attributed shrinkage of the post dam area to polymerisation shrinkage (Lamb et al., 2005). This supports what Anusavice and Phillips stated regarding the shrinkage of MMA and PMMA which can be up to 21% for pure methyl methacrylate and “can be a problem for accuracy of fit” (Anusavice & Phillips., 2013). An example of accuracy of fit can be seen below in Fig 1 (Lamb et al., 2005).

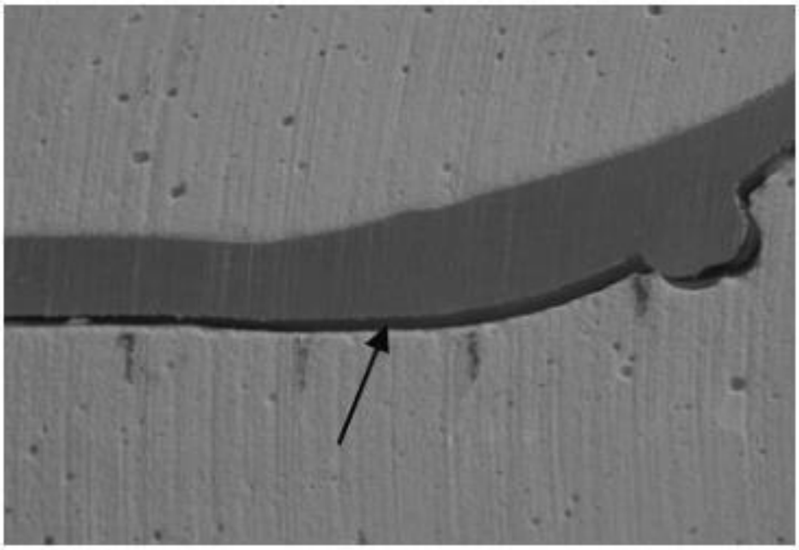


Fig. 1. Denture Base after processing. The arrow is pointing to the space between the denture base and its associated model it was processed on. (Lamb et al., 2005)

This is where this research will concentrate. Finding new materials that are cured differently and using digital technologies may reduce the chance this may happen, increasing the chance of a more accurate fit and eliminating the possible need for Post-Dams for complete dentures.

1.3.4 Lost wax technique problems:

This can affect the OVD of a denture during the processing stage (Basker et al., 2002). After trying in the denture the technician makes a negative of the denture using Plaster of Paris and Dental Stone mixture in a denture flask. Once set, the wax in the flask is removed by placing it in boiling water for 10 minutes. This softens the wax in the mould. After 10 minutes the flask is opened up and the wax is removed from the mould using boiling water. What is left is a gypsum negative of the wax try in. Acrylic resin is inserted into the mould and is compressed together until both halves of the flask contact each other.

Errors using this technique can come from the following (Basker et al., 2002):

1. Acrylic packing is excessive. This can drive the acrylic teeth into the gypsum mould moving the teeth. This may occur if the acrylic has gone beyond its dough stage requiring more pressure to close the flask
2. If there are voids in the gypsum. These may collapse under pressure when packing the acrylic into the mould resulting in tooth movement.
3. If there is insufficient pressure placed on the mould during the curing cycle. The flask may separate during processing increasing the OVD.
4. Both halves of the flask are not closed together. The excess resin from the mould is squeezed out as both halves of the flask are compressed together. This results in an increase in the OVD which may have to be corrected at the final fit stage.

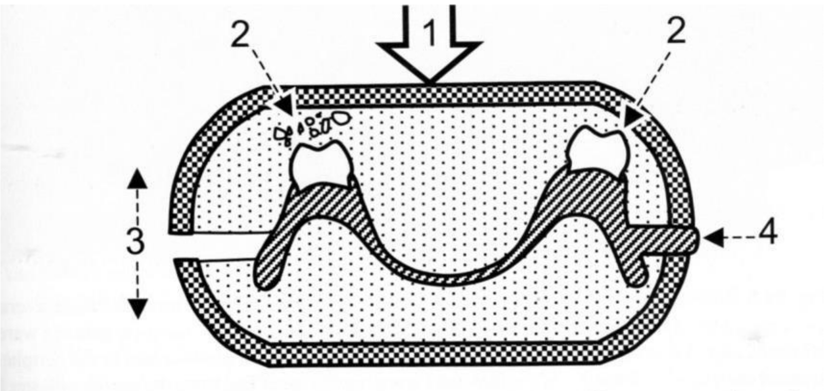


Fig. 14.2 Laboratory causes of occlusal error (for a description of the causes, see the text).

Fig 2. Cross section of a denture mould and how errors may occur. Image from Basker et al., Prosthetic Treatment of the Edentulous Patient 4th ed. Page 243.

1.3.5 Injection moulding processing:

Another way of processing dentures (other than compression moulding) is injection moulding. This differs from compression moulding as the flask is sealed together and acrylic is injected into a closed mould under pressure. With compression moulding, the flask is open when placing the acrylic into the mould the two halves of the flask are squeezed together. The excess acrylic is squeezed out of the flask is known as "flash", see Fig 2 above. Error number 4 is the flash being squeezed out. This "flash" increases the OVD as the flask is unable to close properly, leading to errors in the final denture occlusion.

Gharechahi et al. found using injection moulding as a technique to produce complete dentures to be more accurate than using compression moulding, however their study was limited to using acrylic samples rather than using denture bases (Gharechahi, et al., 2014). Nogueira et al found injection moulding was more accurate for constructing dentures. This study used denture bases rather than acrylic samples. The results showed that OVD errors were reduced using injection moulded bases but found that horizontal errors were very similar to those of compression moulded dentures (Nogueira, et al., 1999). Gharechahi also found that acrylic samples stored in water often negated the shrinkage of the acrylic as "water sorption forces the macromolecules apart and results in acrylic expansion. This expansion compensates the polymerization shrinkage of the acrylic resin and improves the adaptation of denture bases with underlying tissues" (Gharechahi, et al., 2014). However, it is conceivable that such water sorption may have an adverse effect on the mechanical properties of the denture. Furthermore, the degree of water sorption may be unpredictable.

For this study it was decided not to use injection moulding as a technique for processing dentures as the compression moulding technique is still widely used to construct complete dentures. (Gharechahi, et al., 2014)

1.4 A new way of making dentures:

Given the shortcomings in traditional denture construction, novel ways of constructing complete dentures for patients should be sought. One example is 3D printing, which may have the potential to be more true and precise. This is worth trying in dentistry as other industries have also tried using 3D printing as a way of manufacturing medical appliances, for example, 3D printing of hearing aids (Sandström, 2015; Alifui-Segbaya & George, 2018). If this is shown to be an accurate method, then dentures that fit better and are more retentive and comfortable for patients may be achieved. Furthermore if 3D printing is more true and precise it may be possible to eliminate the need for a Post Dam.

There is limited published research in the field of printed digital dentures. The use of digital technology to construct complete dentures is in its infancy and according to Steinmassl et al "represents a novelty" (Steinmassl et al., 2017). Kattadiyil and AlHelal state that before 2015, there were "no studies that evaluated clinical outcomes for computer generated complete dentures" which was stated by Kattadiyil and AlHelal and Srinivasan et al (Kattadiyil and AlHelal, 2017; Srinivasan et al., 2017). Much of the research concentrates on subtractive manufacturing of complete dentures rather than additive manufacturing (Kanazawa et al., 2011; Kattadiyil et al., 2013; Chesterman. J, 2018; Goodacre et al., 2018). Published research concentrating on printing dentures usually focusses on printing denture bases rather than the full dentures with teeth attached. (Yoon et al., 2019; Hwang et al., 2019).

1.4.1 New technologies and new workflows, 3D printing technologies: Stereo Lithography (SLA/DLP):

With development of new technologies come new materials and new workflows. Digital equipment that dental laboratories and surgeries are embracing include computers, dental scanners, 3D printers with the software that these technologies need to produce custom made dental appliances.

One area where rapid developments are taking place is 3D printing. Revilla-Leon (Revilla-Leon, M. & Ozcan, M. 2018) states that Stereo Lithography, otherwise known as SLA, works by a laser drawings a cross section of the object to form each layer. Once the layer is polymerised by the laser/light, the printed object, attached to the buildplate, lifts out of the liquid polymer attached to a moving buildplate, by one layer thickness and the process starts again until the object/appliance has been printed (Revilla-Leon, M. & Ozcan, M. 2018). They state the thickness of the layer depends on the printer used but is generally 15-150µm and that the wavelength necessary to polymerise the liquid polymer generally ranges from 200-500 nm.

The difference between SLA and DLP printers is that with an SLA printer, a laser is pointed into a vat of resin with the beam of light directed to the appropriate point using a rapidly moving mirror galvanometer and the item to be constructed is drawn by the laser. When the layer is drawn the plate holding the item to be printed is lifted from the vat of resin by one layer thickness which allows the next layer to be printed (Pires, 2019), (Gregurić, 2019).

With a DLP printer the whole layer is printed at once using a digital light projected into a vat of resin. The light projected must be shaped to correctly outline the object to be printed. This is done by masking out the light using mirrors (Digital Micro-mirror Device, DMD) to reflect the light away from areas not to be printed from that layer. When the layer is printed the plate holding the item to be printed is lifted from the vat of resin by one layer thickness which allows the next layer to be printed (Pires, 2019) (Gregurić, 2019).

According to Elsenpeter (Elsenpeter, 2016) the limitations are the materials that are currently in use. He states "it's getting the right material. Regulators must be onside ensuring no harm comes to patients as these are intra-oral appliances." There isn't any long term data regarding these materials. He continues to state that more research must be done to "satisfy regulators in various jurisdictions" (Elsenpeter, 2016).

The article states why 3D printing is an attractive developing area in dentistry. Laboratories will be able to produce some of the following: All types of gypsum models; wax patterns for casting; bite appliances; dentures, custom trays and diagnostic wax ups for crowns and bridges.

According to Bae, other advantages of 3D printing are:

- Material waste is kept to a minimum, unlike that for subtractive technologies (milling).
- 3D printing is able to get into undercut areas unlike subtractive technologies (Bae et al., 2017).

Revilla-Leon states a disadvantage of SLA/DLP is that the structures being constructed need support, “consuming additional material and increases production and post processing time” (Revilla-Leon, M. & Ozcan, M. 2018). Bae found that Additive Manufacturing (AM) technology or Rapid Prototyping (RP) was able to produce more complex dental appliances than milled devices.

They also found that additive techniques were slightly more accurate than subtractive technologies when comparing 3D printing using a light cured photo polymer, Stereo Lithography Apparatus (SLA/DLP), against Selective Laser Sintering (SLS). Both additive techniques were more accurate than their subtractive counterparts for wax and zirconia. (Bae et al., 2017) Once the object has been built in the 3D printer, it must be hardened in a light curing unit to maintain the shape of the appliance.

A factor that may affect the accuracy of complete dentures using additive manufacturing techniques is post print processing (Bennett, 2017). Examples of this would be adding teeth to the denture base or washing the print with isopropanol. Post processing may alter the accuracy of the fitting surface. If the appliance had teeth added that were heat cured to the baseplate afterwards, it may alter the fitting accuracy. This was evidenced by Chesterman for milled dentures (Chesterman. J, 2018). There has been no research done in this area yet for 3D printed dentures and this needs further investigation.

It is important to note that this new technique has not reduced the workflow as it was 5 clinical appointments or 6 if a retry was needed. What this technique may eliminate is the processing and finishing errors that may have occurred with traditional flasking and packing during compression moulding. It may also eliminate undercut areas prior to processing so that these areas are never printed into the final denture as these are digitally blocked out quickly using partial denture design construction software. However the author forecasts that other stages that make up the construction of a denture will also be digitised in the future reducing the number of visits to the clinic for the patient as well as simplifying laboratory processes and reducing the cost of manufacture.

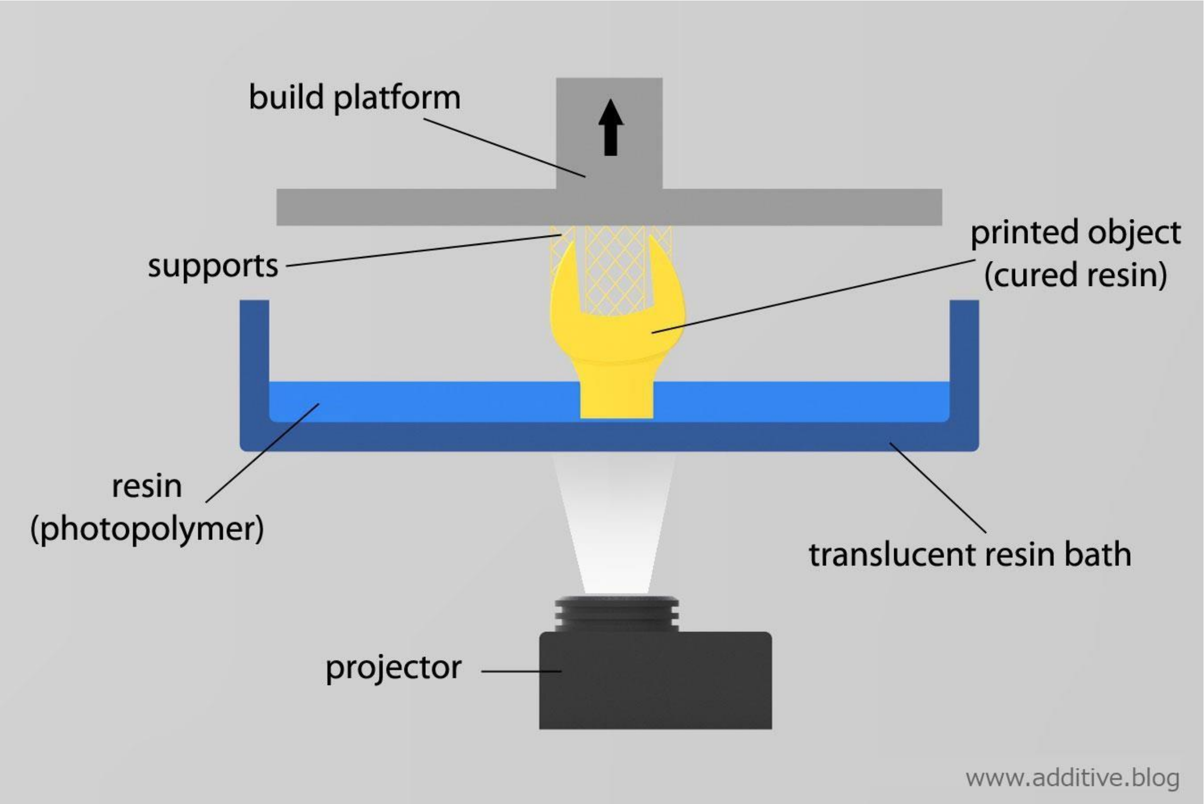


Fig 3. Image of how a 3D DLP (Digital Light Projector) printer works. Image courtesy of Additive.blog

1.4.2 Milling technologies:

While Elsenpeter advocates the use for 3D printers for future manufacturing of dental appliances, another area growing in dentistry and dental technology is milling (Elsenpeter, 2016). Otherwise known as Subtractive Manufacturing (SM), it is the opposite of 3D printing. Instead of an appliance being built up layer by layer using a laser and a liquid polymer, milling is where an appliance is made from a preformed block of acrylic, zirconia, lithium disilicate, or other suitable material. This is cut to shape in a machine to form the final appliance which is fitted to the patient's mouth.

Acquiring the data for subtractive manufacturing (SM) is done the same way as for additive technologies (SLA). A scan of the patient's mouth or scan of the patient's model is taken. From this scan, an STL is produced. This is imported into the specific software where the appliance can be designed digitally. Once designed, the file is sent to a milling machine where the appliance is constructed from what is best described as an ice hockey puck.

Perceived advantages of milling as a form of manufacturing are:

- Accurate, to a point (Bae et al., 2017; Chesterman. J, 2018).

- Shrinkage is reduced (Kattadiyil, M. & Al Helal, A. 2017).

- Less likely to be irritant to the patient. Already polymerised, less residual monomer

(P.A. Steinmassl et al., 2017).

- Control of the thickness of the appliance.

Disadvantages of milling are:

- Slow, as only one appliance can be milled at a time. However the author of this research speculates that this may change in the future

- Wasteful, as much of the puck is ground away to form the final appliance (Barazanchi et al., 2017).
- Expensive, because of the amount of waste that is produced (Barazanchi et al., 2017).
- Milling machines are expensive
- Burs can break mid mill and stop the manufacture of the appliance (Chesterman2018).
- Can be difficult to produce complex appliances as detailed corners within the internal structure may not be milled accurately due to the thickness of the burs used to construct the appliance (Chesterman, J.A.A. 2018).
- Post processing accuracy may be compromised (Chesterman, J.A.A 2018).

1.4.3 Scanning technologies:

In recent years digital scanning technologies have grown with dental practices investing in intra oral scanning equipment. The result of the digitization of dentistry is that dental laboratories will invest in digital dentistry to improve their workflow as work arriving from dental surgeries will be in digital format and laboratories need to access these files to construct the work.

1.4.3.1 The basics of how a digital scanner works:

3D scanners are made up of a number of components. These are:

1. Light source
2. Cameras, one or more
3. Motion systems enabling scanning on different positions

Looking at the components individually, the light source is usually made up of one of the following:

- Laser light source
- White light

Scanners work by projecting defined lines of light onto an object. The camera acquires the light reflected from the object and takes an image of the lines. Based on the known angle of the light source and the camera head to each other, (called the scan head), “the 3D position of the projected light reflected back to the camera is calculated using trigonometry.” (Hollenbeck et al., 2012). This is called Triangulation. Hollenbeck et al state “that it is fine with one camera however it works better with 2 cameras as the speed of the calculations can be worked out quicker, have a larger scan coverage and also be more accurate”. (Hollenbeck et al., 2012). Each projected line of light gives one 3D contour line. The more lines the light source projects, the more lines the cameras can pick up, building up a 3D contour of the object in question. This, along with the movement of the scan head or the table allows multiple scans of the object to be picked up and an image of the scanned object is built up.

They work in one of two ways:

- The light source and cameras can move in relation to the object that is to be scanned.
- The light source and cameras are fixed, and the object position is movable.

Either way the difference/change in the position of the object to the position of the light source and cameras are worked out using trigonometry. If multiple cameras are used, calculations can be worked out quicker and the items can be scanned quicker but this depends on the processor used within the scanning unit.

The images of the scanned objects are mounted on top of one another using matching or overlapping points defined by the scan. This technique, known as “Software Alignment”. This can result in errors, as small areas are prone not to be picked up accurately.

The scanner must be able to record sharply the images received from the light source on the object scanned. Scanners come with high quality sensors enabling this to happen. If a laser is used to scan an object, it is important when laser light hits the scanned object, the laser light does not scatter as this would give a reduced quality scan. If using white light on the other hand it is important that the light is not blurred. This comes from the composition of white light. Each colour gives a different refractive index leading to blurring of the light on the object to be scanned. This is called “Chromatic Aberration”.

A “Point Cloud” is formed when all images of the object are put together and broken down into its most basic form. Viewing this scanned object on a computer, it comprises of nothing but tiny dots on a screen. Each dot is a point, hence the term point cloud. From this point cloud, the images are built up into a 3D surface comprised of really fine triangles. The finer the triangles the higher the scan resolution obtained from the scanner. From this image, an STL or a Polygon File Format (PLY) file, as it is more commonly known, is produced of the appliance. This is then sent to the 3D printer to be manufactured.

1.5 Digital workflow:

With advances in technology, come new working practices. An area where this is evident is digital dentistry. Over the last few years there has been a revolution in dentistry. Intra-Oral Scanning is growing and according to Tordiglione and co-workers, it represents "the first step in a totally digital process of design and fabrication of dental prosthesis" (Tordiglione et al., 2016). The authors say that digital workflows are now present in the workplace and that clinicians should have it in their practices. According to Al-Imam and co-workers, "dental restorations can be produced with or without the use of definitive casts" which is a great advantage, as making a definitive model is time consuming, often breaks, (especially the teeth) and leads to errors with the final appliance (Al-Imam et al., 2018). If models are needed, they can be sent to the lab via e-mail and constructed using either subtractive techniques like milling or additive techniques like 3D printing and fit the appliance to the model after construction.

Advantages of digital workflows are according to Baba, and Russo and Salamini (Baba, 2016; Russo & Salamini, 2018):

- Favourable clinical outcomes.
- Reduction in chair time.

- No impression errors/ reduced impression errors.
- No gypsum casts and its associated errors.
- More time for the dental technician to work more efficiently.
- Standardisation of work techniques.
- Reduced visits for patients.
- Data storage in comparison to model storage.

For this research, using digital technologies to produce dentures, it is hoped to avoid errors that occur due to the processing of dentures. If the dentures are digitally printed and the teeth added afterwards then it is hoped this error will not occur.

Digital Workflow Flow Chart:

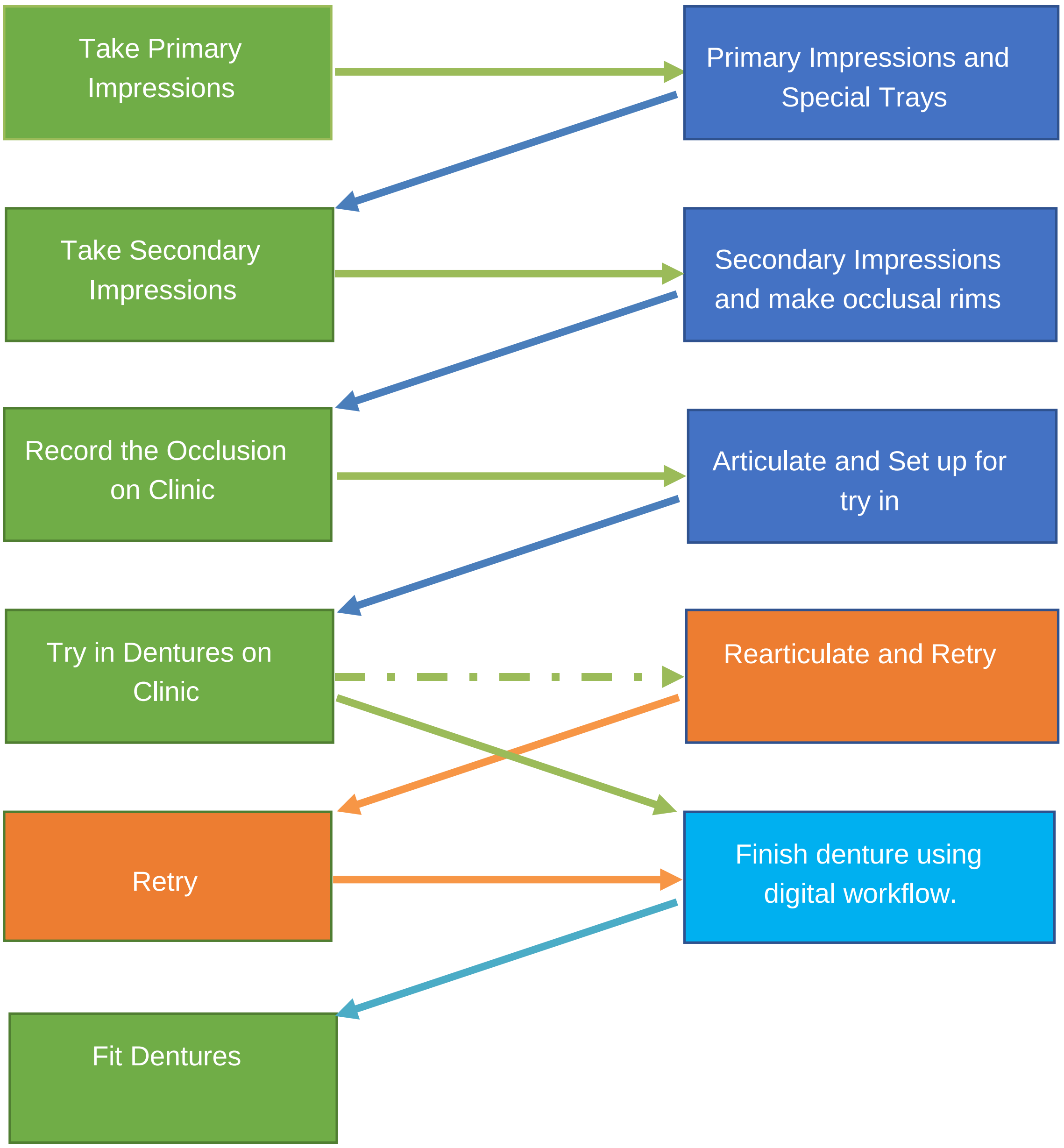


Fig 4. New digital workflow for Complete Dentures

Chapter 2 Research Aims and Objectives

2.1 Research aim:

To investigate the trueness and precision of the fitting surface of compression moulded dentures compared to the fitting surface of 3D printed denture bases.

According to ISO standards (ISO.org):

- Trueness refers to “the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted value”
- Precision refers to “refers to the closeness of agreement between test results” Accuracy refers to “both trueness and precision.”

2.2 Objectives:

To measure and report:

1. The mean fitting surface accuracy of 10 sets of conventional dentures against a master scan of its model.
2. The mean signed standard deviation of the results reported for point 1 above.

3. The mean fitting surface accuracy of 10 sets of printed denture bases without teeth against a master scan of its specific model.
4. The mean signed standard deviation of the results reported for point 3 above

5. The mean fitting surface accuracy of 10 sets of printed denture bases with teeth added to them against a master scan of its specific model.
6. The mean signed standard deviation of the results reported for point 5 above

7. Compare the mean fitting surface trueness and the mean signed standard deviation precision of 10 sets of printed denture bases without teeth against their traditional counterparts
8. Compare the mean fitting surface trueness and the mean standard deviation precision of 10 sets of printed denture bases with teeth against their traditional counterparts
9. Compare the mean fitting surface trueness and the mean standard deviation precision measurements of 10 sets of printed denture bases without and with teeth against each other.

2.3 Research questions:

Primary

Are 3D printed denture bases more true and precise than traditionally manufactured denture bases?

Secondary

Does the process of curing in the acrylic teeth to a 3D printed denture base cause additional distortion on the fitting surface?

2.4 Null hypotheses:

The first null hypothesis is there is no difference in the mean and maximal surface deviations between traditionally produced denture bases and 3D printed denture bases fitting surfaces.

The second null hypothesis is that there will be no difference in the mean and maximal fitting surface deviations between freshly printed 3D denture bases and following curing in of acrylic teeth.

Chapter 3 Method:

3.1 Method for complete dentures:

The method used for the construction of the complete dentures has been published previously (Dillon and Hyde, 2015). The method was broken down into sections. 10 sets of complete dentures were picked as the amount to research as previous studies stated this was an appropriate number to get reliable data and to “minimise errors” (Goodacre et al., 2016; Srinivasan et al., 2017; Kalberer et al., 2019).

1. Construct 10 sets of upper and lower edentulous models.

2. Construct Occlusal rims that fitted all 10 sets

3. Articulated the casts to published Protocol

4. Set up the teeth to published protocol

5. Flask pack and finish dentures to traditional methods without incorporating a post dam on the upper denture.

3.1.1 Construction of the models:

10 sets of edentulous upper and lower casts were constructed from one set of acrylic edentulous models. The acrylic models were placed into duplicating flasks, duplicated using Metrodent’s Metrosil Plus®, a PolyVinyl Siloxane (PVS) duplicating material. When set, the acrylic models were removed from the silicone moulds. The silicone moulds were then cast

up in a 50/50 mix of Dental Stone, Class 3, and Plaster of Paris, Class 2, to manufacturer's specifications. The models were duplicated 10 times for 10 upper and lower casts.

3.1.2 Construction of the occlusal rims:

Occlusal rims were constructed using wax bases. The upper model was a full occlusal rim. The lower, a Manchester rim. (Butt et al., 2018) The purpose of occlusal rims was to locate the lower jaw (mandible) in the correct relationship to the upper jaw (maxilla) (Basker et al., 2002). The rims related the upper and lower models in the correct relationship to each other (Dillon and Hyde, 2015). The occlusion was recorded to establish a relationship between the upper and lower models and sealed together using Blu Mousse® from Parkell. The original acrylic models were placed onto a plasterless articulator, and the occlusion recorded using these rims. One set of occlusal record rims was constructed to fit all 10 sets of duplicated casts.

3.1.3 Articulation of the casts:

All casts were mounted on a Denar® average value articulator using a technique used for two previous clinical trials at the School of Dentistry at Leeds. (Dillon and Hyde, 2015), (Dillon et al., 2008) The occlusal rims were placed onto set of models number 1 and articulated on a Denar® Average Value Articulator using Plaster of Paris.

Models were numbered 1-10 for both upper and lower models. The upper model 1, with the original set of occlusal rims was used to articulate all lower models to model number 1. When all lower models were articulated, all upper models were articulated against its corresponding number. For example, Upper Model 1 was articulated against Lower Model 1 normally, Then upper Model 1, articulated against Lower Model 2, 3 and so on until all 10 lower models were articulated, see Fig 5. Once Lower Model 2 was articulated then the corresponding Upper Model 2 was articulated against it using the same set of occlusal rims, see Fig 6. This enabled all models for all cases to be articulated to each other in the same way for each case. Figs 5-6.

Fig 5. Upper model 1 against Lower model 2

Fig 6. Upper and Lower model 2 with each other

3.1.4 Setting up the dentures:

Dentures were waxed up on set of Models 1. They were set up in balanced occlusion with the lower teeth over the ridge to the clinical standard for try in. Following previous RCT protocols. (Dillon et al., 2008; Dillon and Hyde, 2015), subsequent dentures were made ensuring they were similar to each other. It was important to note that for this research, this was not essential but was considered good practice. This technique would work for any denture that was set up traditionally.

A Lab Putty® matrix, by Coltene, was made from the dentures set up from Models 1 and transferred to all other cases. See Figs 7-8.

Denture teeth were inserted into the moulds. Teeth used for this project are the Delphic V® from Schottlander. The teeth were seated into position, Fig 9 and sealed with molten wax around their necks in the moulds to prevent tooth movement when pouring the mould, Fig 10. Molten wax was poured into the putty moulds and left to cool. When cold, the wax rims with teeth attached were removed from the moulds and set up. The lower tooth set up that was removed from the silicone mould was stuck to the upper completed set up using sticky wax, see Fig 11 . The gap between the alveolar ridge and the lower teeth was filled with soft modelling wax and the articulator closed so the incisal guidance pin was in contact with the incisal guidance table ensuring the Occlusal Vertical Dimension remained the same for all cases being tested, see Fig 12. This lower wax set up was tidied up, see Fig 13. The same happened for the upper. The upper rim with teeth attached was stuck to the completed lower try-in using sticky wax, see Fig 14. The gap between the upper alveolar ridge and the wax rim was filled using soft modelling wax and tidied up, see Fig 15. The articulator was closed together until the incisal guidance pin touched the incisal guidance table ensuring the OVD remains the same. This was done for all 10 complete cases. All cases were set up against the original Model 1 set up ensuring consistency. Figs 11-15.

Figs 7-15, setting up the teeth to Improvdent RCT protocols

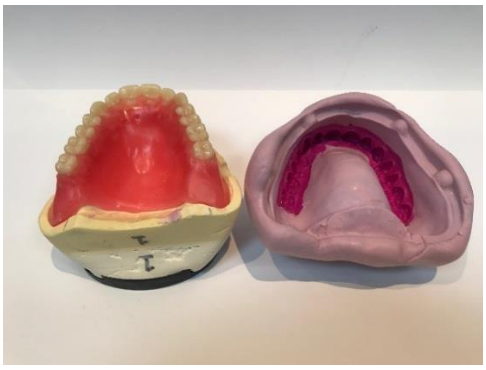


Fig 7.


Fig 8.


Fig 9.


Fig 10.


Fig 11.


Fig 12.


Fig 13.


Fig 14.

Fig 15.

After setting up the dentures the try-ins were scanned. Once scanned, they were returned to the laboratory where they were flasked, packed and finished.

3.1.5 Finishing the complete dentures:

The dentures were flasked and packed as described in previous articles published and used in previous clinical trials (Dillon et al., 2008; Dillon and Hyde, 2015). The acrylic used, Stellon QC 20® trans-veined, from Dentsply, was mixed up to manufacturer recommendations, 23g powder with 10 ml liquid, at room temperature, with excess liquid being absorbed by adding excess powder. A wax spacer was incorporated between both halves of the flask. This allowed the flasks:

1. to be separated,

2. reduce the OVD increase that is normally associated with conventional flasking (Dillon et al., 2008).

The acrylic was placed into the denture flasks, put in a hydraulic press and closed under pressure to 100 kp cm^2. These were left under pressure in the press until all excess (flash) acrylic stopped flowing out of the moulds and transferred to a denture flask clamp, which maintained the pressure achieved by the hydraulic press. The flasks were placed into a curing bath, Eclipse Multicure® by Milbro, for 10 hours at 95°C on a slow cure. Once cured, the dentures were left to cool down in the bath before removing them from the plaster moulds. These were trimmed and polished to clinical standards. Finally, the completed dentures were scanned to determine the final position of the fitting surfaces in relation to the scanned position of the models.

3.2 Digital methodology:

3.2.1 Method for constructing digital dentures:

Using 3D printing as a method for constructing complete dentures, conventional dental stone models were constructed from a duplicate of edentulous acrylic models and scanned. Conventional complete dentures were constructed as described in Section 4.1 developed for the Dunhill Randomised Controlled Trial (Dillon et al., 2008) and further refined for the Improvdent Trial (Gray et al., 2012). These dentures were scanned at the try-in and finished stages. This produced a Stereo Lithography File, otherwise known as an STL. This file produced the denture bases that were printed in the 3D printer. The digitally printed dentures were scanned and compared to the conventional dentures for trueness and precision. Both dentures were compared to the initial model and scanned for trueness and precision. Using a digital workflow, teeth were digitally removed from the try in before printing the base. The teeth were added to the final printed denture base after printing and rescanned.

3.2.2 Method for construction:

The methods for scanning were as follows:

1. Scanned the models. Using Solutionex Rexcan DS2® Scanner and EZScan® software
2. Scanned the individual teeth
3. Scanned the denture try-in's
4. Scanned the completed dentures. This was done to measure the conventional dentures and to construct and compare the printed dentures to.
5. Cleaned up and aligned the scans using Meshlab®
6. Defined the fitting surfaces from the model scans to make the fitting surface template (Cookie Cutter)
7. Aligned individual teeth to the denture try in using Denturemaker®
8. Subtracted the teeth and added the fitting surface to the try-in from the denture scans using Denturemaker®
9. Inverted the "Normals" on the fitting surface of the final denture scans
10. Merged the scans to make a final .stl file to work with
11. Added supports to the .stl's using Meshmixer®
12. Positioned the .stl to the printer build-plate using Perfactory RP®

13. Sent file to printer to print using Envisiontec® 3D Printer

14. Scanned the 3D printed base without teeth

15. Aligned the scan with the model scan.

16. Scanned the 3D printed base with teeth attached

17. Aligned the scan with the model scan

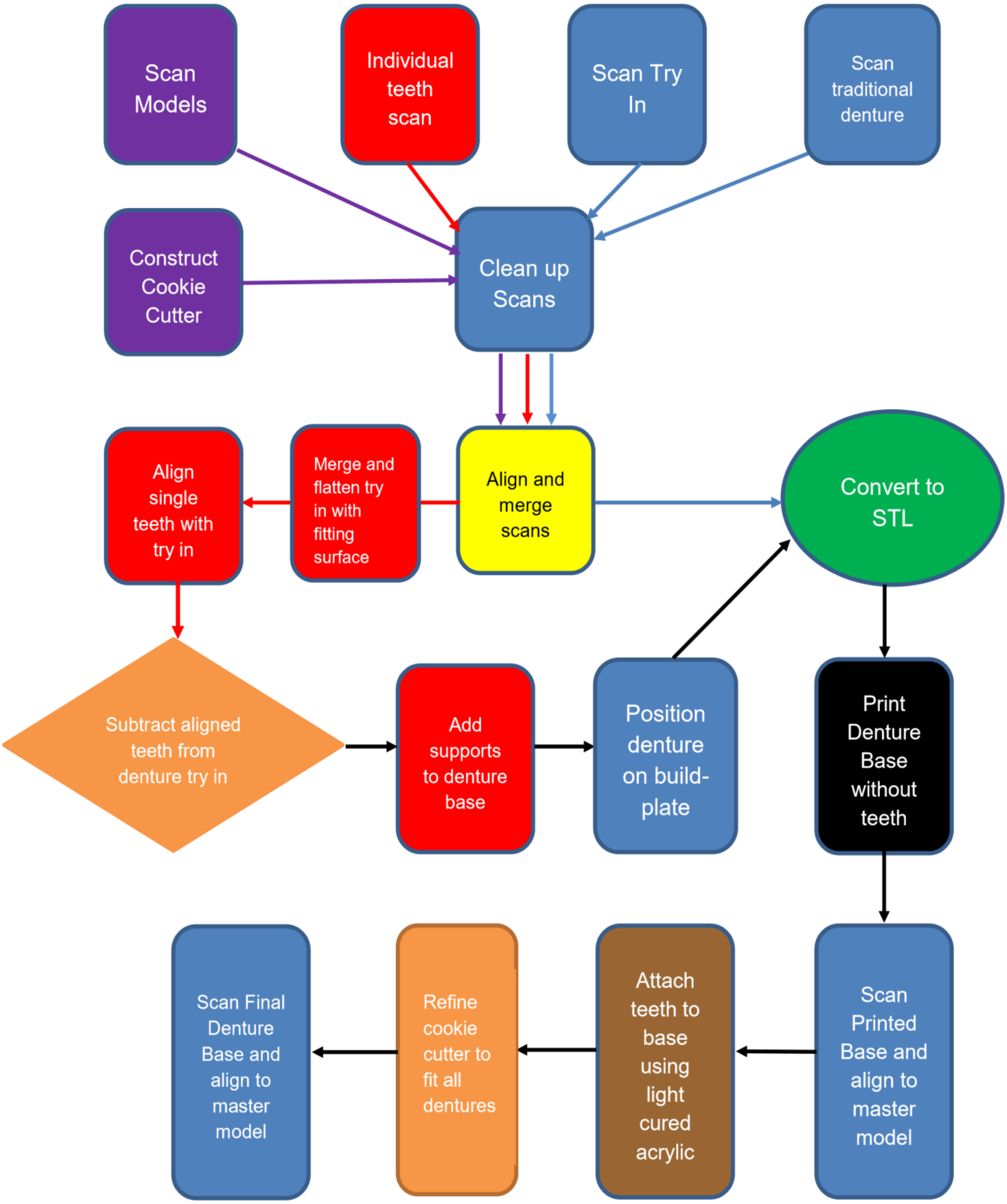


Fig 16: Flow chart of the digital process: Follow the coloured arrows

3.3. Model scanning technique:

3.3.1 Model scan with the two-axis scanner:

The scanner used for this project was the Solutionix Rexcan DS2® scanner from the MEDIT Corporation, Seoul, South Korea. It is a two axis model scanner that consisted of 2 cameras of 1.3MP resolution with a white light source which was fixed in position. The trueness and precision of the scanner was validated against the Association of German Engineers' VDI/VDE 2634 which was a bought validation.

A stone model was placed into a clamp that magnetically attached to a rotating table within the scanner. Using Solutionex ezScan®, the software for the scanner, models were initially scanned on a pre-set number of scans from different angles. As the model was scanned, a picture appeared on a computer screen showing what parts were successfully scanned. At the end of the pre-set scans, missing areas were individually scanned by the operator, ensuring all parts were scanned successfully.

When scanning an object, usually the scanned object is powdered to prevent light reflecting back to the sensor resulting in missing areas of the scan. In this case there was no need to powder the models, as gypsum absorbs light. (Hollenbeck and Poel, 2011). Scanned models were aligned and merged at high resolution. This produced a model that was surfaced and ready to be used to construct the final fitting surface of the 3D printed denture. Figs 17-18.

Figs 17-18. Scanned upper and lower models model using the Solutionex Rexcan RS with ezScan software.

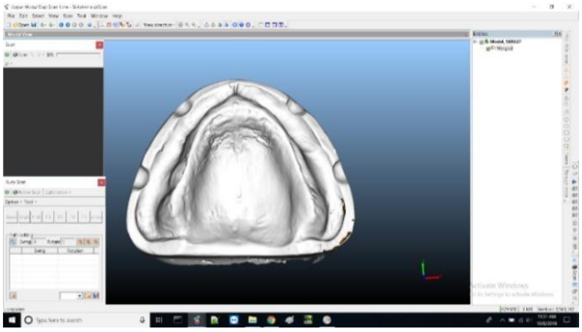


Fig 17. Upper model scan

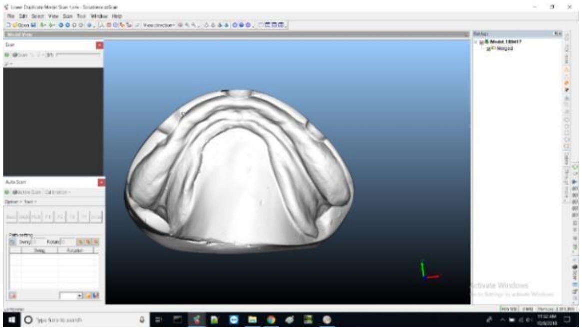


Fig 18. Lower model scan

3.3.2 Cleaning up the STL/PLY file:

Once the final scan of the models was achieved, they were cleaned up in Meshlab® producing an .stl (Stereo Lithography File) file. Cleaning up the file deleted unnecessary areas of the scan, for example, scan of the table holding the model, or any floating scans/noise attached to the file. This eliminated sending unnecessary information and reduced the file size when sending the final STL/PLY to the printer ensuring a clean print.

3.4 Individual tooth scanning and alignment:

Delphic V® acrylic teeth from Schottlander, were used to construct the wax try-ins for all dentures. To digitally subtract the teeth from the denture base it was important to have a digital file of each tooth. Each tooth was individually scanned at least twice for anterior teeth and 3 times for posterior teeth. This allowed the operator to build up images of all surfaces, incisal, labial, buccal, occlusal, lingual and underside of the teeth. Scanning acrylic teeth was problematic as these were highly reflective and difficult to scan. This was overcome using Cerec Optispray®, manufactured by Sirona. It was sprayed onto the teeth reducing the reflective glare and allowed the scanner to scan the teeth. Optispray® is a fine powder in aerosol form, CE marked for intra oral use, and used for intra oral scanning. The material is water soluble and allowed the operator to wash the powder from the teeth after scanning.

Anterior and posterior teeth were placed on the scanning table and held in position using Blue Tack® by Bostik. These were scanned at high resolution, building up an image of the teeth. Scanned teeth were removed from the Blue Tack®, repositioned in a different position into the Blue Tack® and rescanned, ensuring a surface not previously scanned was done. An image of the teeth was built up from different angles. Figs 19-20

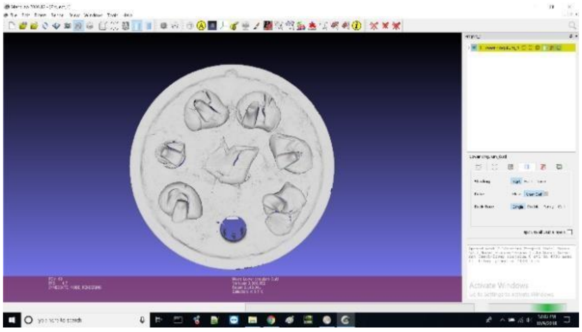


Fig 19. Lower cingulum anterior scans

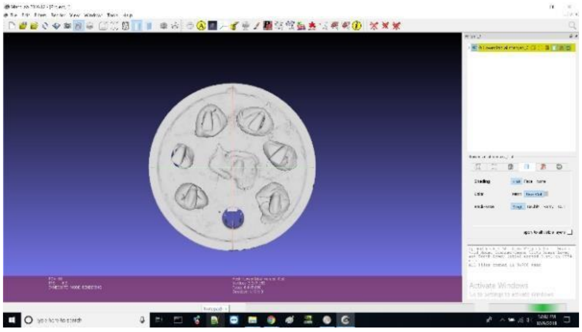


Fig 20. Lower labial anterior scans

After the teeth were scanned, each individual tooth was saved as a separate file. This file contained an image of the tooth that was scanned and an image of the Blue Tack®. The Blue Tack® was removed from the scan. This was done in Meshlab® for each individual tooth.

To build up a digital tooth, one file of a tooth was opened in Meshlab® for example the Lower Right 3. Other scans of the same tooth were imported into this open file for aligning. Using the aligning tool in Meshlab® all images of the particular tooth were aligned with each other using manual aligning. This was done by aligning the same points of the tooth to each other from different scans. The software calculated how the images were built up. When the tooth was complete, the overlaps were removed/deleted from the file ensuring a clean digital tooth scan. The matrix of each individual tooth was frozen in position and saved as an MLP file. (Meshlab® Project File) It was imported into the final denture scan which enabled removal from the denture base digitally. See Figs 21-24 on how a digital scan of a tooth is built up and merged using Meshlab®

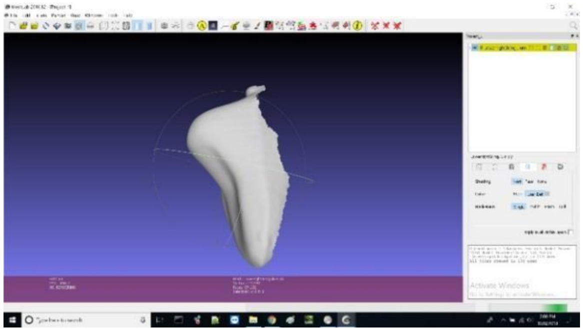


Fig 21. Incomplete scan of Lower Right 3

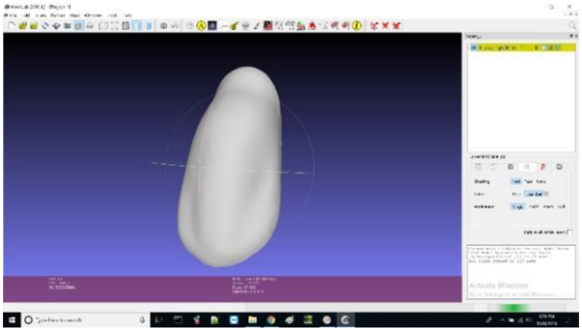


Fig 22. Incomplete scan of Lower Right 3

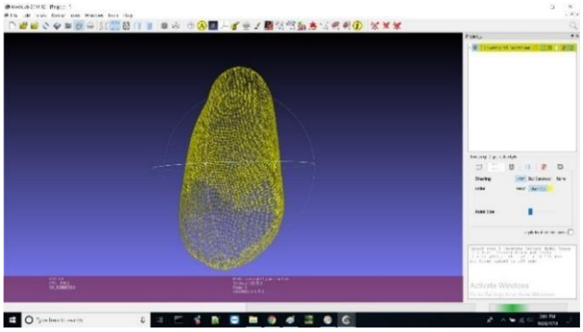


Fig 23. Lower Right 3 Pointcloud

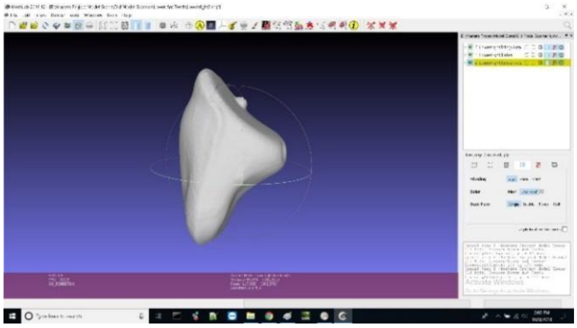


Fig 24. Lower right 3 merged scan

3.5 Scan technique for the try-in's:

The denture wax ups were scanned in the model scanner. These wax ups were scanned on their models. The denture try-ins were adhered to their models and prevented movement during scanning. This did two things:

1. Prevented the dentures from moving during the scan phase.
2. The models had location notches on their land areas as seen in Figs 17-18. This allowed correct alignment between the model scan and model with try-in scan when it came to print the dentures.

Scanning the wax try-ins created its own problems as wax is a poor reflector of white light for scanning purposes. As with the teeth, Cerec Optispray® was sprayed onto the wax try-in, creating an opaque layer over the wax. This allowed the scanner to pick up digital images of the wax try in. After scanning, the Optispray was washed off the dentures which enabled the dentures to be flasked, packed and finished. The image of the try in denture was captured using Solutionex ezScan® and turned into an .stl file. This file formed the position of the polished surfaces of the denture and the position of the teeth. See Figs 25-26.

After scanning the denture try-in's the following were obtained:

1. A scan of the model surface from the first scan.
2. A scan of the teeth from a previous scan.
3. A scan of the polished surfaces of the dentures from this scan.
4. A scan of the position of the teeth for the wax try-ins from this scan.

5. A scan of the position of the dentures and teeth to the models.

The scanned wax dentures were then processed into acrylic.

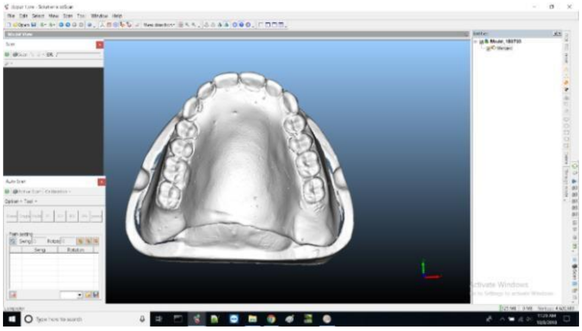


Fig 25. Upper try-in scan

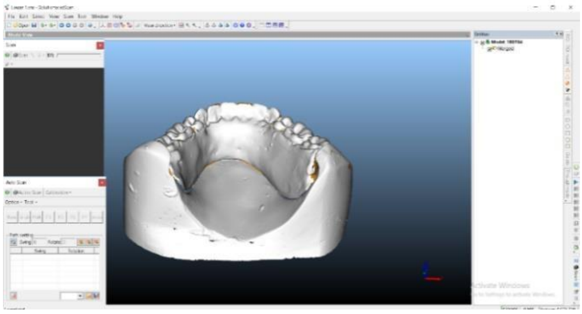


Fig 26. Lower try-in scan

3.6 Defining the fitting surface area for all models:

Deciding where the fitting surface ended, and the polished surfaces began for the denture had to be defined. Constructing a template to enable this to happen was important if the fitting surface was to be:

- Accurately calculated correctly for all dentures.
- Measured for consistency of results.

Upper and lower models 1 were used to make the templates. All measurements were aligned to these templates. From these scanned models, everything apart from the fitting surface was deleted using Solutionex ezScan and set up as a .stl file in Meshlab. ® These files were used to align all upper and lower scans to the templates, using auto alignment software contained in Meshlab®, so all models had the same fitting surface ensuring accuracy of results. For the upper template, the models were extended to just short of the hamular notch and extended to just past the deepest point of the labial and buccal sulcus. For the lower it extended past the deepest part of the buccal shelf and just short of the full sulcus depth labially and lingually. This defined where the fitting surface ended and where the reflection of the inside borders of the lips began.

These templates were further refined after construction of all dentures as it was important to ensure the templates fitted all dentures constructed. All templates were further trimmed back and checked against all upper and lower dentures. These templates would be further refined later to give a more accurate measurement template.

See Figs 27-28 below:

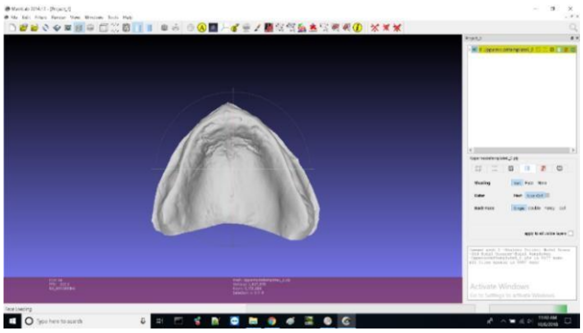


Fig 27. Upper model template

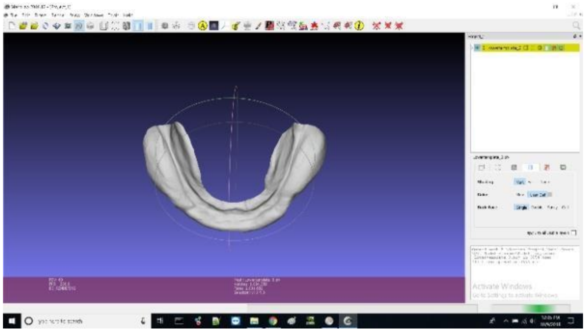


Fig 28. Lower model template

3.7 Scanning the finished dentures:

The final completed dentures were scanned using the Solutionex Rexcan DS®. The fitting surfaces of all dentures were scanned to the same resolution as all previous scans. The dentures were sprayed using Optispray, ® placed on the table of the scanner and held in position on the table using Blue Tack. ® This ensured the denture didn’t move during scanning. When scanned, the files were aligned and merged using ezScan and exported to Meshlab® as an .stl. See Figs 29-30 below.

Information gathered at the final denture scan was added to the previous scans that showed:

1. A scan of the model surface from the initial scans.
2. A scan of the teeth from a previous scan.
3. A scan of the polished surfaces of the dentures from a previous scan.
4. A scan of the position of the teeth for the wax try-ins from a previous scan.
5. A scan of the position of the dentures and teeth to the models from a previous scan.
6. A scan of the position of the completed dentures and fitting surface to the models, polished surfaces and teeth from this scan.

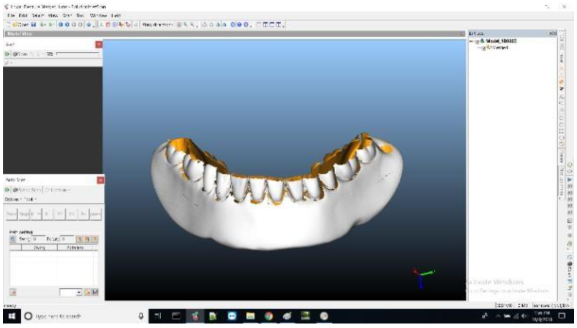


Fig 29. Lower complete denture scan

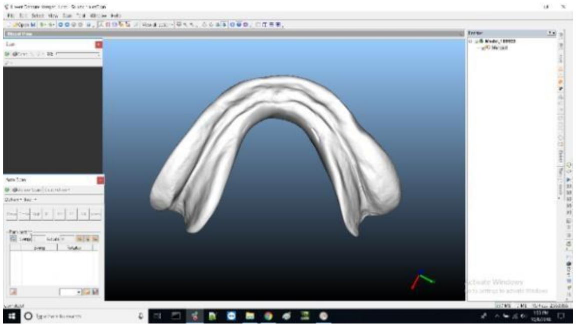


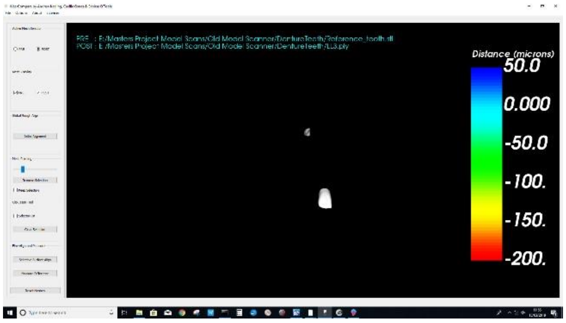
Fig 30. Lower complete denture fitting surface scan

3.8 Tooth alignment for other dentures:

After scanning and aligning the individual teeth. The next stage aligned the individual teeth on top of each other in separate quadrants. This was done to:

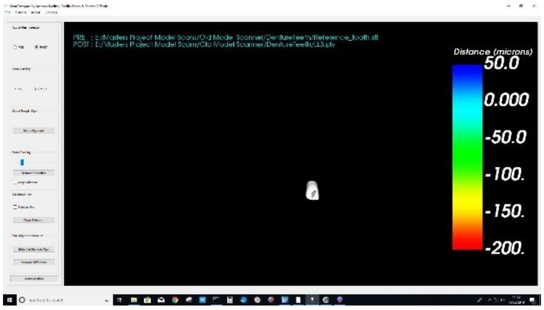
1. Determine the path of insertion of the teeth into the 3D printed denture base. This was so the denture base did not prevent the teeth from entering the sockets due to undercuts that may have been on the printed denture base from gingival contouring on the palatal/lingual aspect on the cingulum of the acrylic teeth.
2. Enabled the teeth to be individually aligned to individual teeth for other 3D printed denture projects for that particular mould of tooth.
3. Allowed the operator to make a socket ensuring a positive location of the teeth within while allowing space for the acrylic to secure the tooth into the denture socket.

This was constructed using a previously validated software called Wear Compare® from the University of Leeds. (O'Toole et al., 2019 a) An individual tooth, an Upper Right 1 in this case was imported into the software and was named the Reference Tooth. Each other tooth, 12, 13,14, etc, was imported into the software and initially aligned with the reference tooth. This made alignment of all teeth easier when opened in Meshlab when doing the next alignment. See figs 31 and 32 below



PRE : E:/Masters Project Model Scans/Old Model Scanner/DentureTeeth/Reference_tooth.stl
POST : E:/Masters Project Model Scans/Old Model Scanner/DentureTeeth/LL3.ply

Fig 31. Reference tooth and tooth to be aligned.



PRE : E:/Masters Project Model Scans/Old Mode Scanner/DentureTeeth/Reference_tooth.stl
POST : E:/Masters Project Model Scans/Old Model Scanner/DentureTeeth/LL3.ply

Fig 32. Tooth aligned in 3D space with reference tooth.

After initial aligning in Wear Compare® the aligned tooth was opened in Meshlab® where all teeth were aligned over each other in their respective quadrants, see figs 33-37. The example seen below is aligning of the Lower Left 3 with the Lower Left 1 in its respective quadrant as dictated by the visible X (red), Y (green) and Z (blue) axis lines.

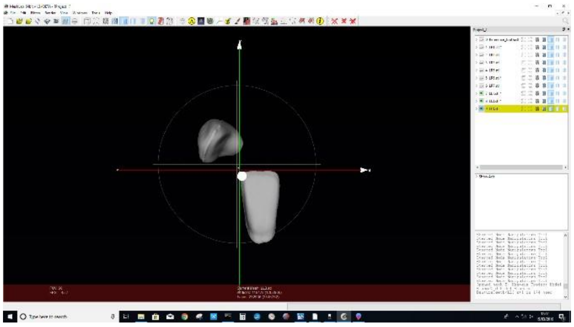


Fig 33. Initial importing of LL3 to LL1 and 2

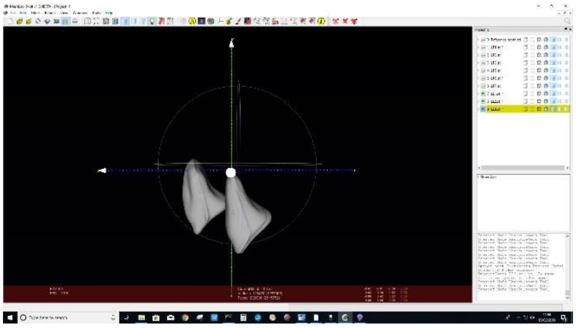


Fig 34. Orienting the tooth to the correct axis

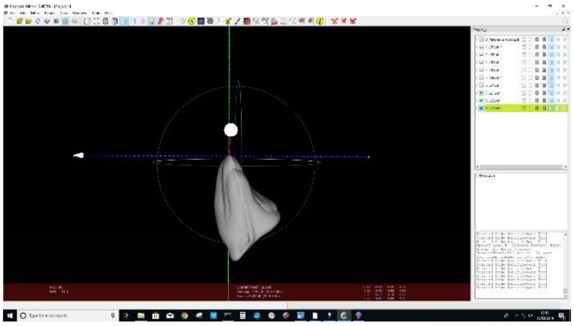


Fig 35. LL3 superimposed over LL1. Side view

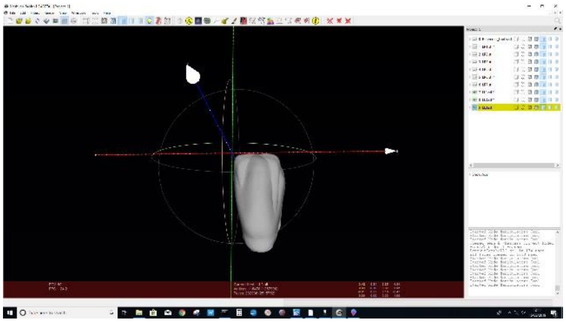
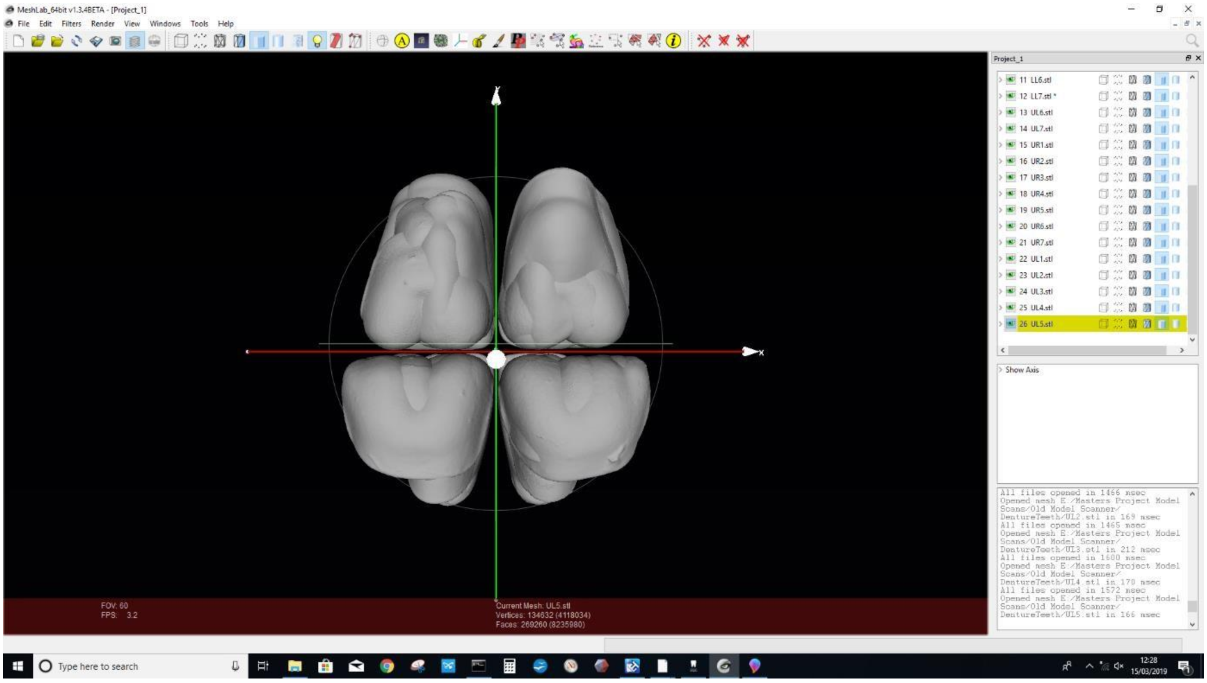


Fig 36. LL3 superimposed over LL1. Front view



```
FOV: 60
FPS:   3.2
```

```
Current Mesh: UL5.stl
Vertices: 134632 (4118034)
Faces: 269260 (8235980)
```

```
All files opened in 1466 msec
Opened mesh E:/Masters Project Model
Scans/Old Model Scanner/
DentureTeeth/UL2.stl in 169 msec
All files opened in 1465 msec
Opened mesh E:/Masters Project Model
Scans/Old Model Scanner/
DentureTeeth/UL3.stl in 212 msec
All files opened in 1600 msec
Opened mesh E:/Masters Project Model
Scans/Old Model Scanner/
DentureTeeth/UL4.stl in 170 msec
All files opened in 1572 msec
Opened mesh E:/Masters Project Model
Scans/Old Model Scanner/
DentureTeeth/UL5.stl in 166 msec
```

Fig 37. All teeth superimposed over each other in their respective quadrants'.

3.8.1 Trial socket design and construction:

To test how the denture teeth would fit inside the sockets of the denture base, a trial matrix was constructed initially to check the fit of the denture teeth within the denture base while allowing for spacing for the teeth to be cemented in. The spacing was 0.5mm for either side of molar teeth and 0.2mm for anterior teeth with a socket spacing of 0.05mm. If it was too thick a layer it may have affected the results gathered but was necessary to allow the teeth to be bonded to the denture base allowing for a thin adhesive layer between the teeth and the denture base.

After initial alignment as discussed in Section 3.8 a trial socket matrix was constructed as outlined below: How to prepare teeth to construct a Boolean socket in Meshlab® Figs 37-44.

1. Initial alignment of the teeth in their respective quadrants was done in Meshlab® See Fig 37
2. A morphed file of the teeth was constructed. This allowed a tooth to be enlarged digitally, in certain areas to allow for undercuts and spacing for the tooth cement afterwards. Not all the tooth was enlarged digitally. See Figs 38 - 41
3. Both files were aligned using a batch file to allow for quick alignment of both files.
4. A digital box to insert the digital teeth into, to make the socket. Fig 42
5. The box was aligned with both the morphed tooth and the original aligned file as shown in Figs 42- 43.

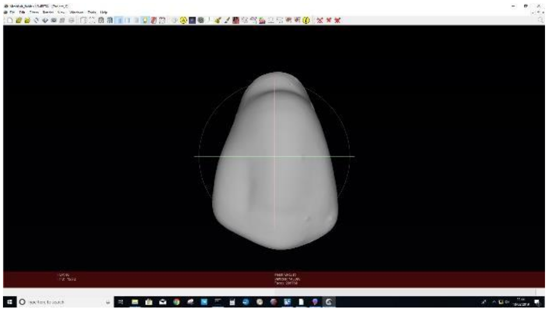


Fig 38. Original aligned tooth UR3

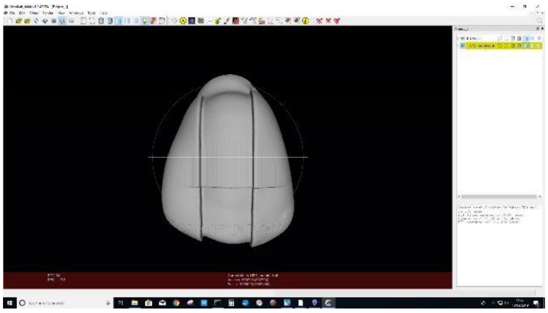


Fig 39. Morphed UR3 aligned with original UR3

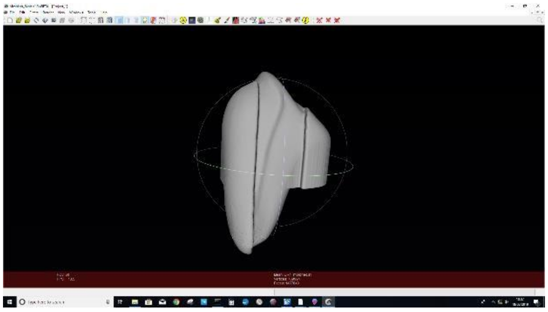


Fig 40. UR3 Side view of Fig 39

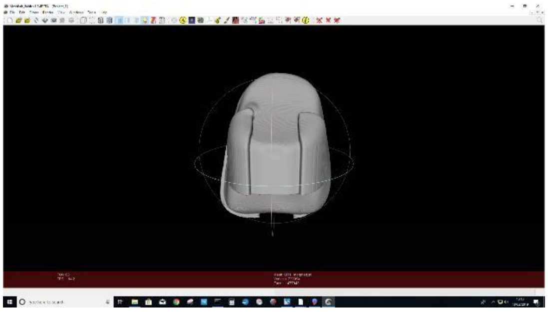


Fig 41. UR3 Rear view of Fig 39

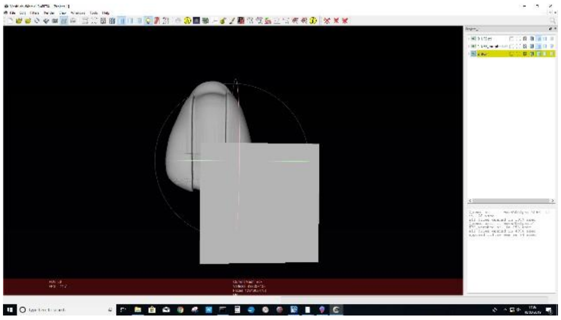


Fig 42. Morphed tooth aligning with box

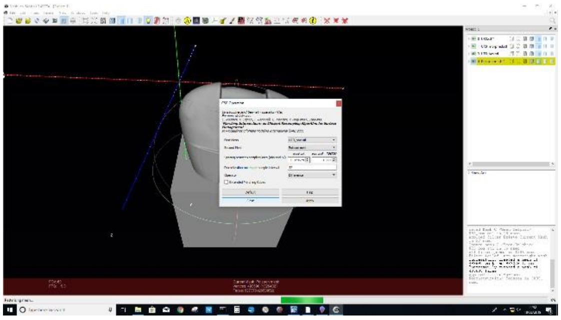
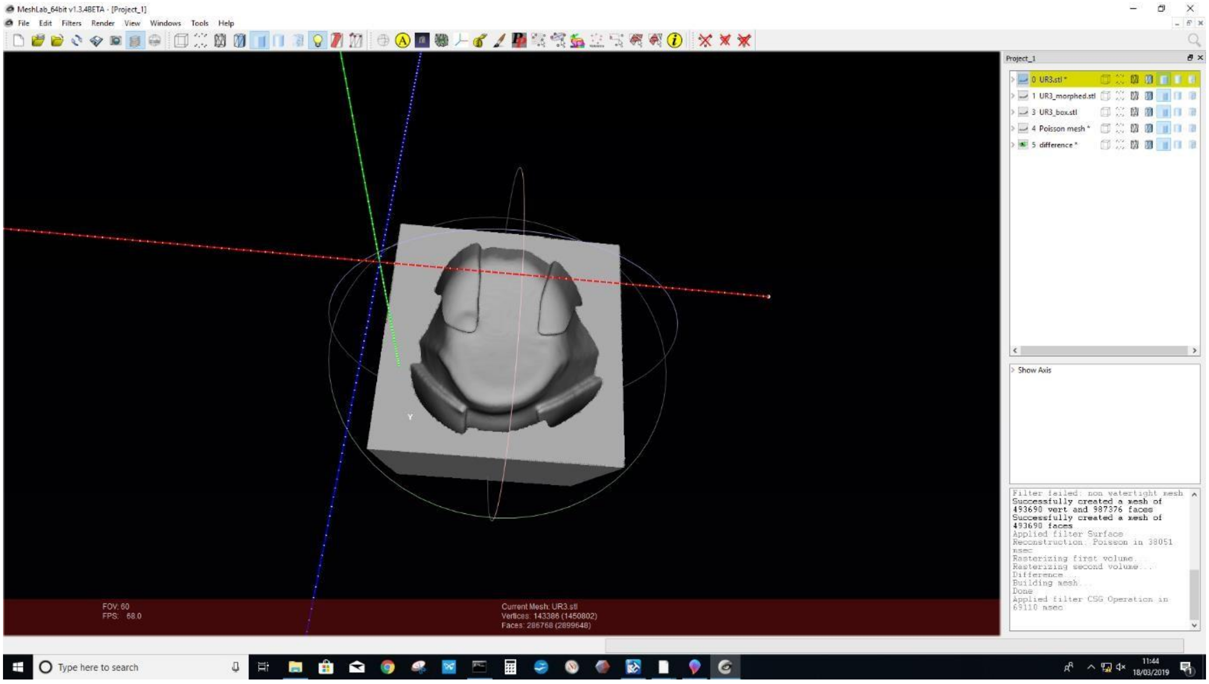


Fig 43. Aligned tooth with box and conversion tool



```
Filter failed: non watertight mesh
Successfully created a mesh of
493690 vert and 987376 faces
Successfully created a mesh of
493690 faces
Applied filter Surface
Reconstruction: Poisson in 38051
msec
Rasterizing first volume...
Rasterizing second volume...
Difference...
Building mesh...
Done
Applied filter CSG Operation in
69110 msec
```

```
FOV: 60
FPS:  68.0
Current Mesh: UR3.stl
Vertices: 143386 (1450802)
Faces: 286768 (2899648)
```

Fig 44. Trial socket for UR3. The Normals were inverted for this box to be printed

This file was sent to the 3D printer to print the matrixes. Prior to doing this, sprues/supports were connected to the print. This was done in Meshmixer. ® This software allowed positioning of the object to be printed to the build plate. It also allowed the sprues to be attached to the printed object. The spruing parameters were 1mm thick densely packed. Once generated the file was opened in Perfactory Start Centre. ® This is a rapid prototyping software designed for the Envisiontec® 3D printer that was used for this project. This file was sent to the 3D printer for printing. This was important as this was the Perfactory software is the only software the Envisiontec printer recognises as it is a closed system.

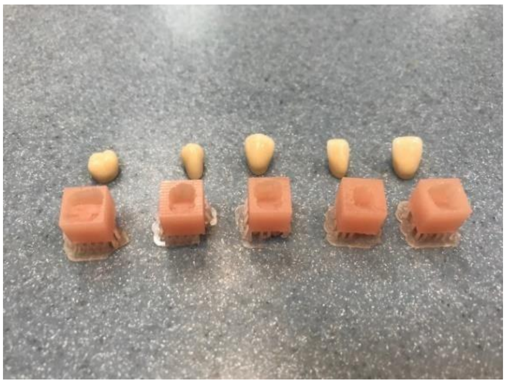
After printing the sockets, the prints were removed from the printer and placed into an ultrasonic bath with isopropanol which was used to remove the print residue from the prints for 30 minutes. It was light cured for 30 minutes after that.

The Delphic ® denture teeth were inserted into the prints to check for fit afterwards.

3.8.2 Fitting teeth to sockets:

After printing, the selected teeth used to make the trial sockets were fitted to the printed sockets. In this case the teeth were the UR1, 2, 3, 4 and 7. See Figs 45 and 46 below. Looking closely at the sockets the spacing for the acrylic to bond the teeth to the baseplate was seen. To ensure that all teeth sat accurately in relation to the denture base, a 3D printed morphed socket was constructed that accurately held the teeth within its socket while at the same time allowing enough space to flow some light cured 3D polymer into it to bond the teeth to the baseplate. This technique had not been tried before and so it was initially tested on some teeth for proof of concept. Fitting teeth into the printed Boolean sockets Figs 45-48.

An example of this technique can be seen below.



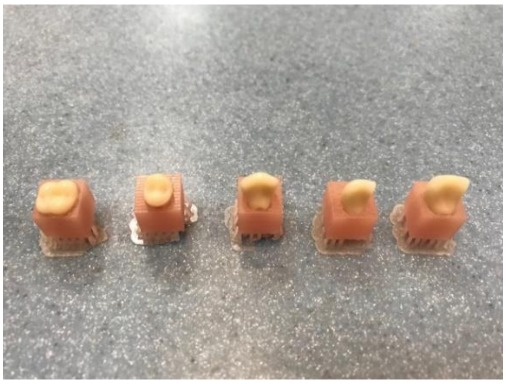


Fig 45. Printed sockets with their respective teeth. Fig 46. Tooth inserted into the sockets with spacing incorporated to allow for bonding of teeth to baseplate.

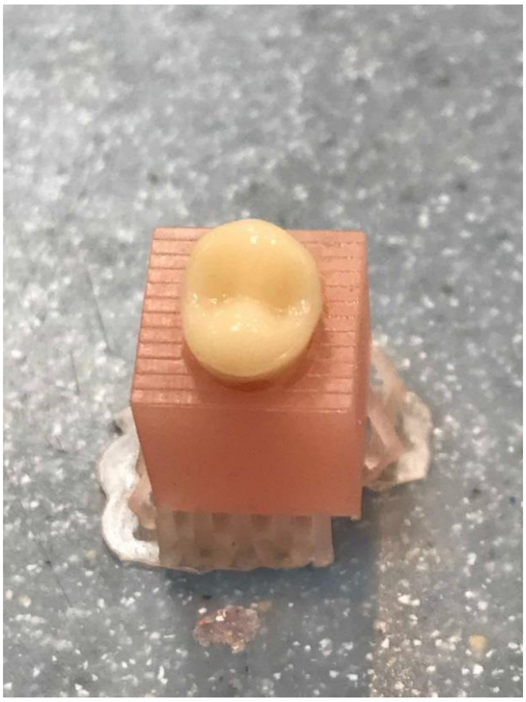


Fig 47. Socket showing space for acrylic on UR2. Fig 48. Socket showing space for acrylic on UR4

The teeth were slightly enlarged digitally using Meshlab® with cut-outs incorporated within the enlarged file back to the original tooth scan enabling the printer to construct the sockets with contact points for the teeth.

3.8.3 Cementing teeth to the sockets:

Using the 3D printed resin for this project, a small amount was inserted into the socket of each individual trail socket. The teeth were inserted into their correct position as dictated by the matrix. This created some overspill of the acrylic. This was removed using a disposable brush ensuring a clean join between the tooth and the socket. Once the tooth was in its correct position and excess acrylic cleaned up, the resin was light cured using D-Light Pro® from GC for 20 seconds on each side of the tooth. According to the manufacturers it is a “Dual Wavelength LED Curing Light”. (GC Europe, n.d.) The blue LED wavelength was between 460465nm, while the Violet LED wavelength was between 400-405nm. This gave an initial set of the acrylic and prevented the teeth from moving before it was inserted into a light curing unit, the Formlabs Form Cure® for 30 minutes, without heat, where it cured the pre-set polymer at 405nm. Figs 49-61, developing a technique to add teeth to a trial printed denture base

Fig 49. Edenture light cured polymer

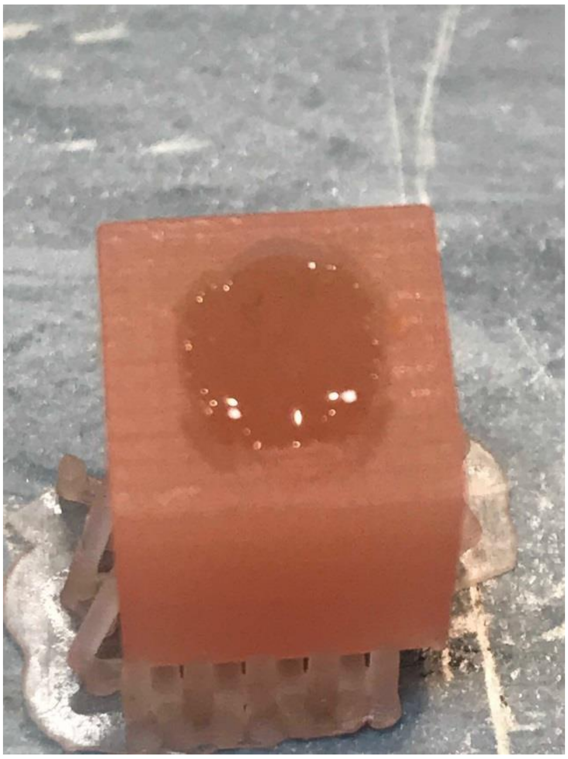
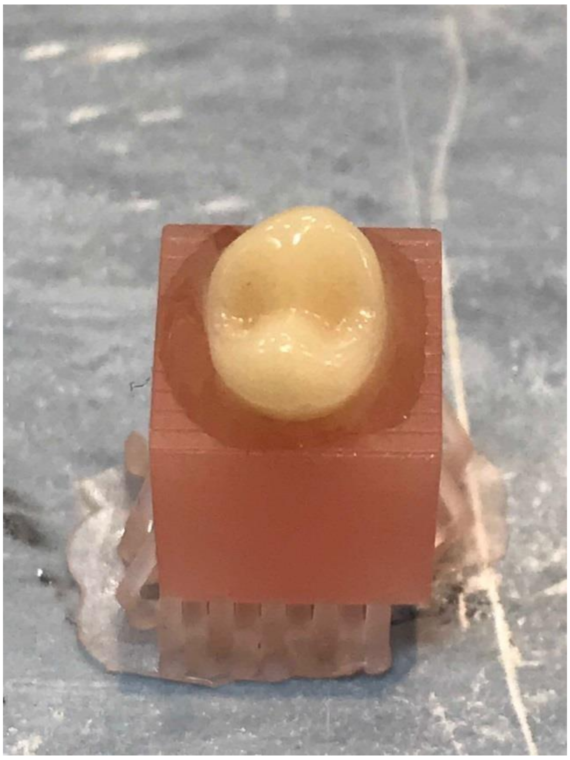


Fig 50. Liquid placed in socket



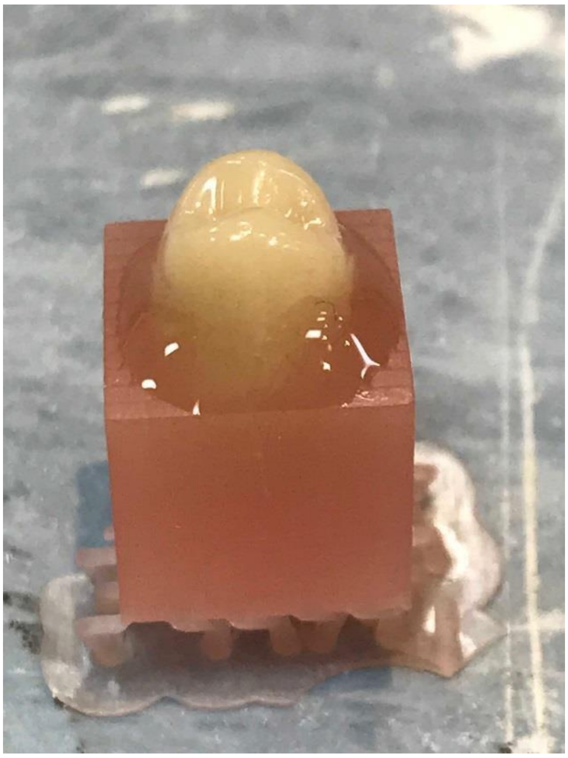


Fig 51. Tooth inserted into polymer in socket. Fig 52. Tooth inserted into polymer in socket Buccal view

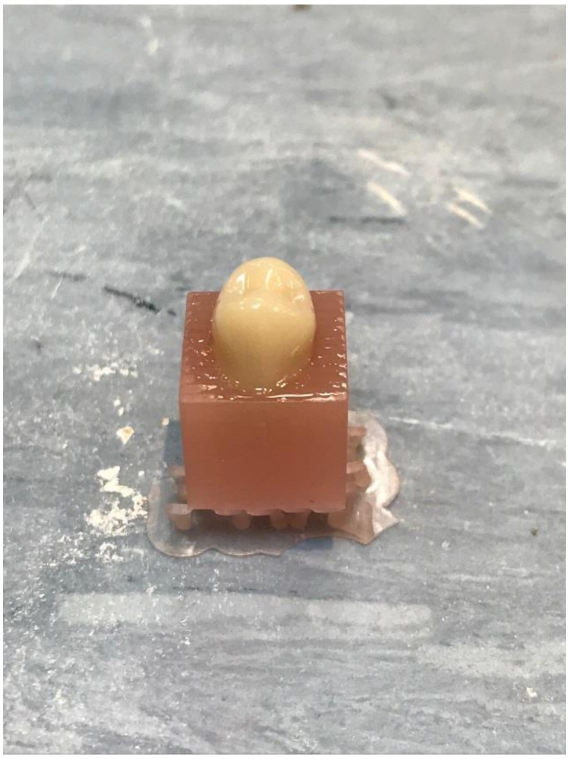


Fig 53. Polymer cleaned up occlusal view. Fig 54. Cleaned up buccal view

Fig 55. Light cured for 20 seconds on each side

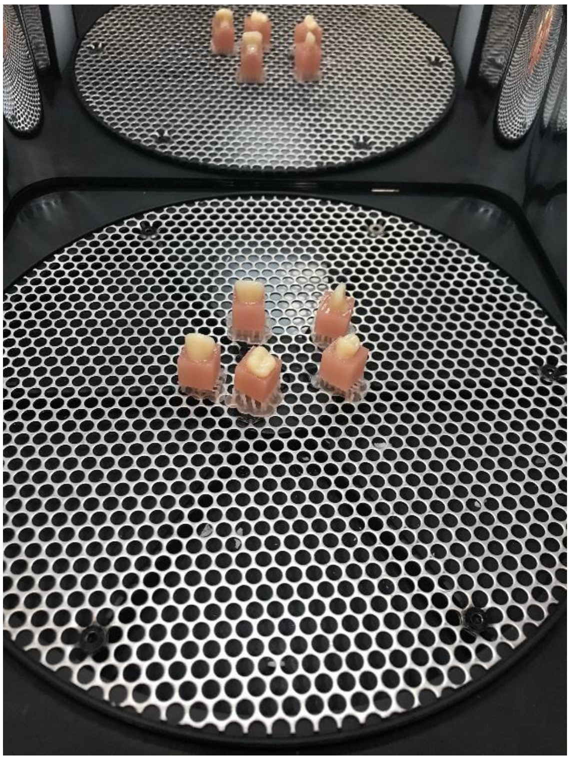


Fig 56. All samples cured for 30 mins

When this was completed a trial denture was used to cement teeth using this technique. This was for information to see if teeth could be cured to a denture without the excess acrylic flowing into other sockets which may have prevented the teeth from seating home.

Fig 57. Teeth placed in denture (not part of trial)

Fig 58. Upper 6 placed in position.

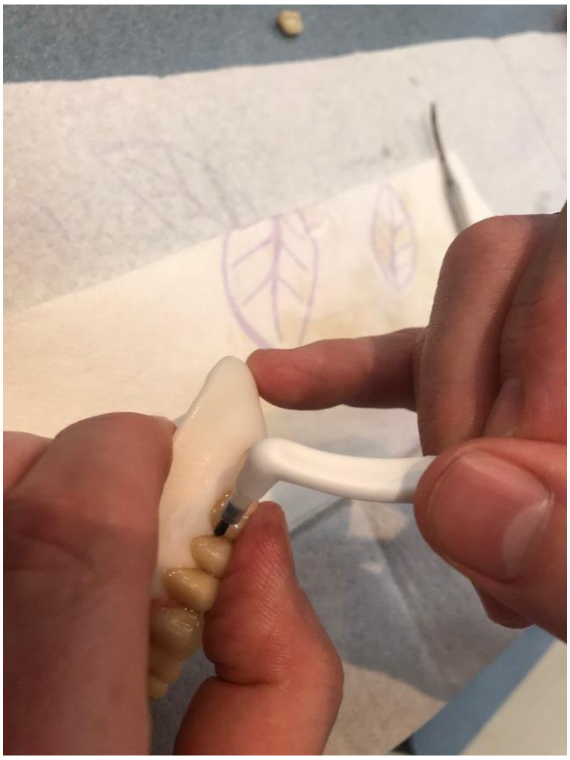


Fig 59.

Fig 60.

Figs 59 and 60. Light cured polymer margins cleaned up.

Fig 61. Polymer cured for 20 seconds each side.

3.9 Alignment of the model, cookie cutter, teeth, try-in and complete denture:

Accurate alignment of the scans was important if errors were to be avoided. This was done using a technique called Iterative Closest Point, (ICP) invented by Besl and McKay in 1992. (Xie et al., 2010; Chesterman. J, 2018). Algorithms allow multiple scans to overlap each other enabling a computer model of the object scanned to be constructed. According to Xie et al, this was important as there may have been issues with scanning that prevented the cameras seeing the object that was being scanned which had to be scanned from multiple viewpoints for the image to be acquired.

3.9.1 Iterative closest point (ICP):

As stated above the algorithm used to align scans was called ICP. Two or more data sets from different scanned point clouds were merged together to form a final object that could be constructed in a 3D printer or other machine in one of three ways:

- Point to point
- Point to projection
- Point to surface

3.9.1.1 Point to point:

Point to point according to Xie and co-workers, is good for "fine registration of partial 3D surfaces". (Xie et al., 2010) The algorithm looked for points in common from the source dataset and compared it to points in the data set to be merged with it. The advantage of this technique was that it was quick, but Xie & co-workers stated that what the algorithm acquired may not be the closest matching point between the original scan and the scan to be aligned with, and inaccuracies may have been incorporated in the final scan model (Xie et al., 2010).

3.9.1.2 Point to projection:

Point to projection according to Xie & co-workers worked by using a source point image and projected it onto a destination source image from the point of view of the destination image.

The advantage of this was that it was a quick way of merging files, but its accuracy could be questioned as the registration sacrifices accuracy for speed. (Xie et al., 2010).

3.9.1.3 Point to surface:

Point to surface was the most accurate according to Xie et al and was the most widely used because it was the most precise method. It worked by "minimising the distances from points in the source dataset to tangential planes at corresponding points in the destination dataset", as opposed to using "point to the nearest point distance" (Xie et al., 2010). He continued to state that this method was more accurate as point to surface "converged in less iterations and was less likely to be influenced by local minima so that higher accuracy and efficiency could be guaranteed" (Xie et al., 2010) as compared with the other two methods.

3.9.2 Aligning method:

In Meshlab ® all scans of the models, denture try-in's and finished dentures were aligned together (using point-to-surface alignment) so that:

1. The cookie cutters aligned to both upper and lower models.

2. The model aligned with the finished denture.

3. The try was aligned with the completed denture base

4. The individual teeth must align with the denture try-in

5. The individual teeth were aligned with the completed denture base

6. All model scans aligned with each other.

3.9.2.1 Inverting the normals:

Before the final alignment, the upper final denture scans were opened in Meshlab® and the Normals were inverted. “Normals” is a way STL/PLY files looked at the internal triangular structure of the object being constructed. For STL/PLY files the normal should always point outward from the object in question. In the case of the fitting surface of the denture, this was the inverse of the scan of the model. Therefore the “normal” of the fitting surface of the denture was pointing in the opposite direction to that of the models. This needed to be inverted so both scans were pointing in the same direction. It was important as previous scans of the try-in’s and dentures were aligned in one direction while the fitting surface of the try-ins (models) were pointed in the other. This allowed the software to calculate where the surface of the denture would be when compared to the rest of the other scans and turned the negative scan of the fitting surface of the denture into a positive so it aligned with the previous scans, and allowed the software to calculate the final position for the fitting surface for the 3D printed denture (Chakravorty, 2019).

Failure to invert the “normal” would result in a corrupt denture print file being sent to the 3D printer and printing failure.

3.9.2.2 Scan alignment:

Using model alignment software developed by MIT, Fast Global Registration, (Zhou et al., 2016) the model, try-in and tooth scans were aligned more accurately and quicker using this technique than by manually aligning specific points. The Iterative Closest Point (ICP) algorithm using the optimal point to plane metric was used during this alignment and all functions were captured into a custom software package called Denturemaker, which aligned teeth scans, wax trial scans, and fitting surface scans. At the end of the alignments the information gathered was:

- The model scan was the negative of the fitting surface of the denture.

- The try in scan gave the position of the polished surfaces and position of the teeth in relation to the model.
- The final denture scan gave the fitting surface information of the denture to be printed. This scan was inverted to normal to allow final aligning.
- The tooth scans gave the position of the fitting surface of the teeth within the denture base and gingival margin positions.

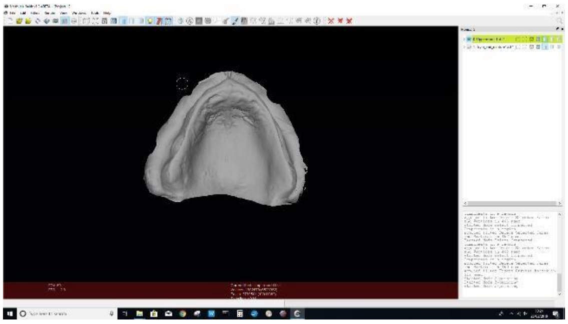
Scans had to be aligned with each other accurately to enable the denture base and tooth sockets to be printed accurately. Therefore, all scans were converted to .PLY (Polygon File Format) files and aligned against either Upper or Lower Models 1.

Using this technique meant that Upper model 1 was aligned against the measuring template/cookie cutter, as described in Section 3.6, the upper traditional denture, the upper printed denture without teeth and the 3D printed denture with teeth scans.

3.10 Constructing a digital fitting surface on the try in:

Prior to the denture printing, a solid digital model of the denture try-in to be printed had to be constructed. This was done for both upper and lower dentures for every case. The scans to be used for this were the try-in's, and models for each denture. There wasn't a surface on the fitting surface of the try-in denture. This had to be constructed. How this was done was:

1. On Upper/Lower Model 1 the .stl of the model was opened in Meshlab®.
2. Imported to this file was the try in denture.
3. The models should be aligned, if not, they were aligned now.
4. The model fitting surface was marked out using the paint tool in Meshlab®. The unnecessary parts of the model, the land area, was deleted leaving the fitting surface of the denture only. The fitting surface of this model had its normals inverted. See Fig 62
5. The denture try in was also marked out using the paint tool in Meshlab® and unnecessary elements of the denture around the periphery deleted. See Fig 63
6. Both files were flattened together in Meshlab® forming the outline of a denture.



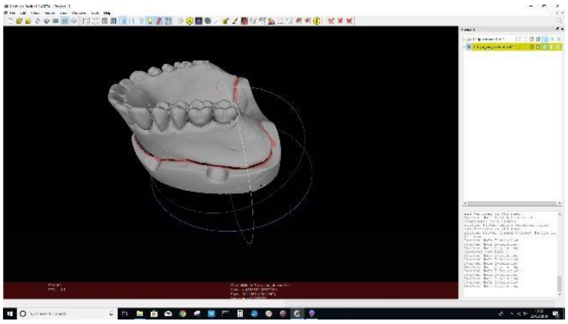


Fig 62. Cut out of fitting surface. Invert normals

Fig 63. Outline of denture using Meshlab

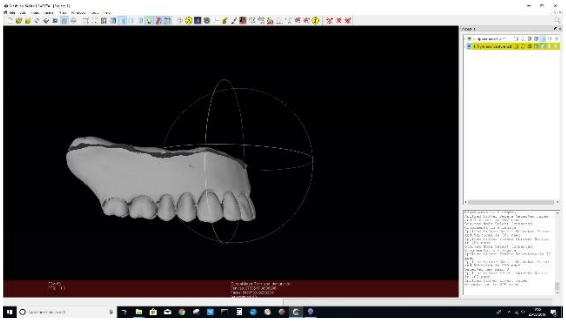


Fig 64. Model and Denture together.

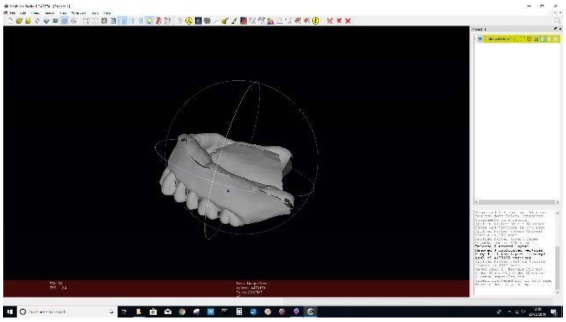


Fig 65. Models flattened together.

Adding a digital fitting surface to a virtual denture in Meshlab® Figs 62-65

There still was a gap between the upper/lower fitting surfaces and the polished surfaces of the dentures. This was filled in during the next stage of construction.

3.10.1 Digital extraction of the teeth:

The teeth were digitally extracted from the denture using in house stand-alone software called Denturemaker from the University of Leeds. It was software designed to remove teeth from try in dentures and filled in any gaps between the polished surfaces and the fitting surfaces of the dentures. Examples of this can be seen in the figures below. See Figs 66-70. This followed a technique developed in a paper to digitally extract teeth using milling as the form of construction (Kanazawa et al., 2011).

The teeth first had to be aligned using this software. The teeth were marked out using Denturemaker.

Each tooth was marked out and aligned using the alignment discussed previously in Section 3.8. The lower 1 tooth was highlighted against the lower 1 tooth position on the try in, lower 2 tooth against its counterpart on the try in denture and so on until all teeth were aligned with their tooth counterpart.

Figs 66-70. Importing the denture files to be printed in Denturemaker ®. Teeth are aligned to the try in and digitally subtracted from the denture base, creating Boolean sockets at the same time

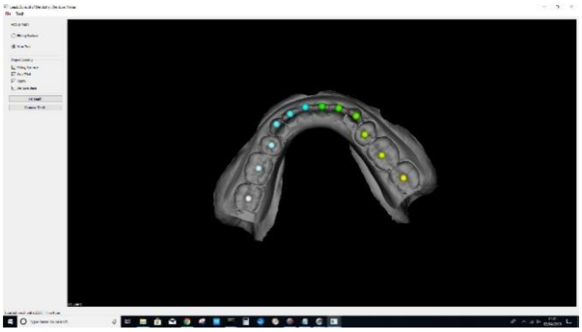


Fig 66. Teeth marked with dots to be aligned.

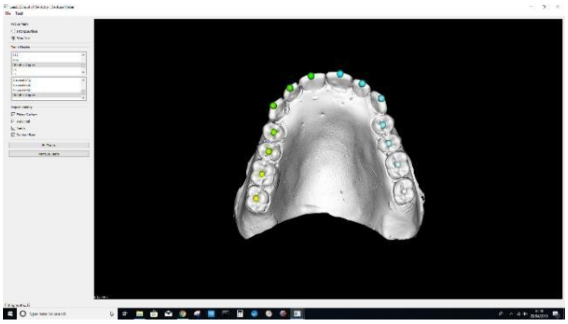


Fig 67. Upper teeth with dots to be aligned

Fig 68. Aligned teeth in white (taken from Fig 37)

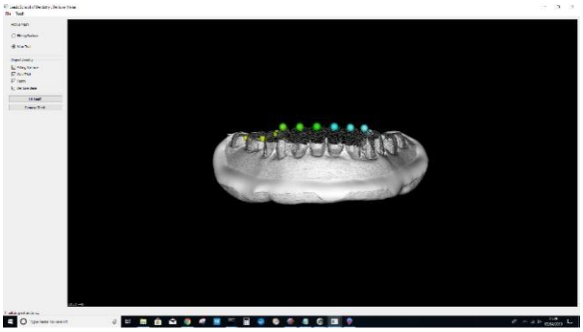


Fig 69.

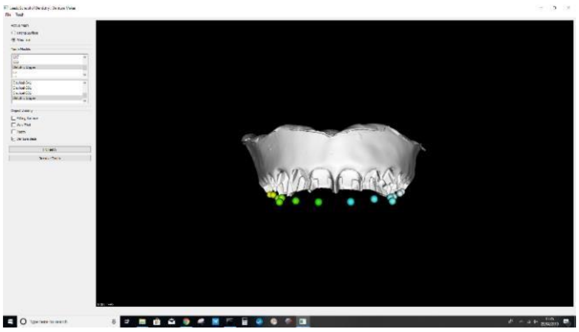


Fig 70.

Figs 69 & 70. Teeth subtracted from dentures. Fitting surface also merged with polished surfaces.

After the teeth were extracted and the sockets prepared as discussed in section 3.8.1, the files of all dentures were saved and exported as a .stl so they could be opened in a different software package that prepared the dentures for printing.

3.10.2 Adding the supports to the denture base:

After removing the teeth and filling the gap between the denture base and its respective fitting surface, the denture file was still not ready for printing. To get the denture ready for printing, printed supports had to be added to the file. The role of the supports was to:

1. Attach the denture base to the build plate of the 3D printer enabling the denture to be printed.
2. Prevent cured polymer from detaching from the main print.

To place supports on the file the denture file to be printed was opened in Meshmixer®. This was an open source 3D printing tool that enabled supports to be added to the file. The .stl file to be printed was imported into Meshmixer®

Once opened the denture had to be positioned correctly to the build plate. This was done using the Transform tool in Meshmixer®. The file was placed into the correct position over the virtual build-plate and the denture had to be rotated to ensure no supports contacted the fitting surface, or the denture tooth sockets of the denture. See Figs 71- 74.

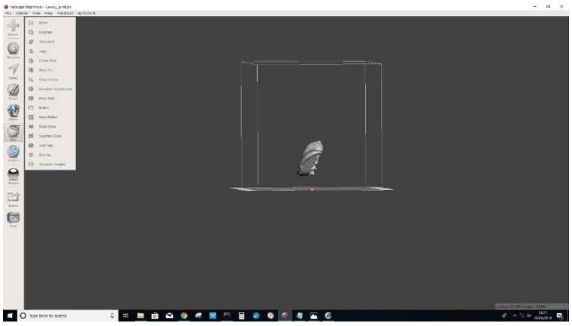


Fig 71.

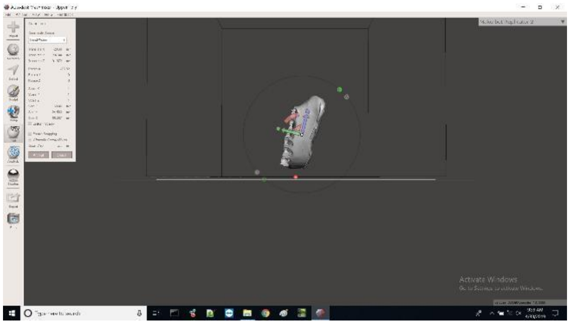


Fig 72.

Figs 71 & 72. Lower and Upper dentures positioned over build-plate (Lateral View). The anterior labial area was placed closest to the build plate

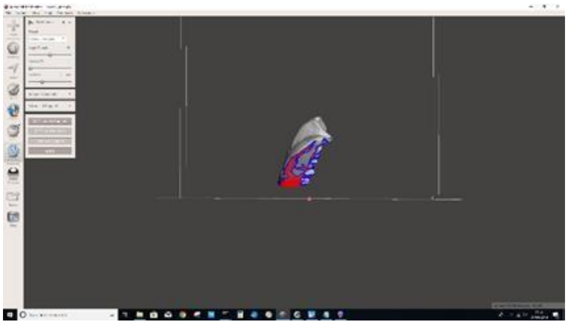


Fig 73. Overhangs (unsupported areas in Red).

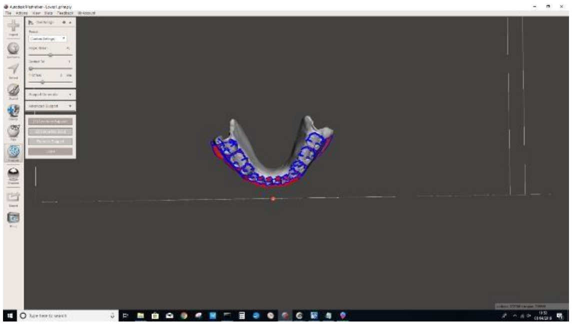


Fig 74. Unsupported areas in red

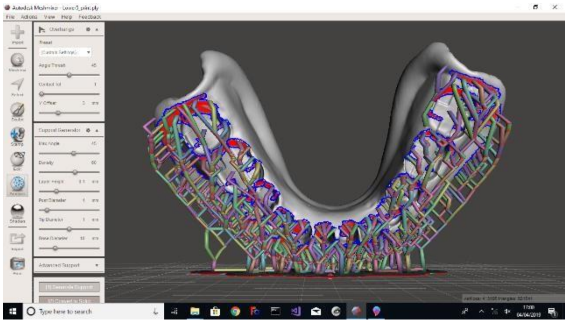


Fig 75.

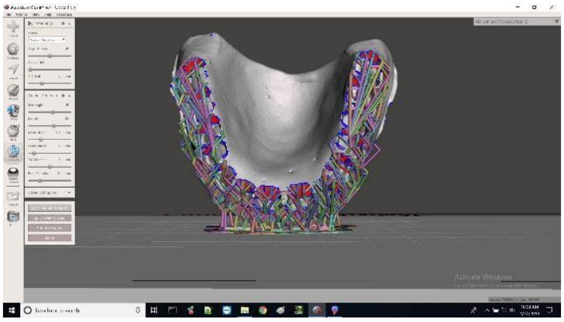


Fig 76.

Fig 75 & 76. Supports added to lower and upper dentures to be printed. Supports kept out of sockets

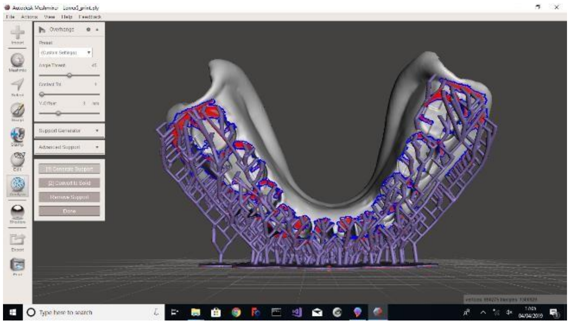


Fig 77. File converted to a .stl

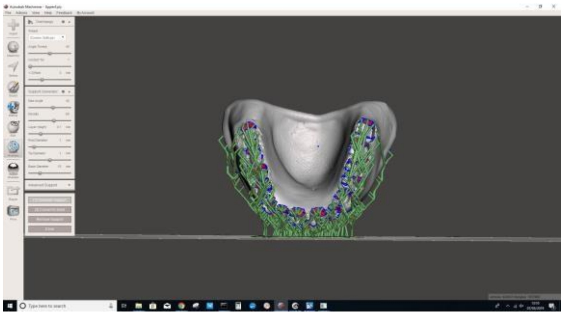


Fig 78. File converted to .stl

Figs 77-78, files converted to .stl files

The supports were auto generated once the settings had been established using trial and error from previous failed prints. The support and tip thickness were set to 1mm. The base diameter for the supports was 1cm. The density of the supports was set at 60. This was why the labial section of the dentures were densely supported. It was found from previous experience that sparse supports in this area led to print failure. See Figs 75-78.

3.10.3 Perfactory software enabling printing:

After supports were generated using Meshmixer, ® the file had to be saved as a .stl and imported into Perfactory RP ® as stated in Section 3.8.1. Perfactory converts the STL into a printable file (a series of images which the printer will project layer by layer). This was the software used to position the denture to the build-plate for the specific printer, Envisiontec® as the printer used did not recognize Meshmixer's positioning of the denture base.

Figs 79-81, importing denture print files to Perfactory RP® to position over the buildplate.

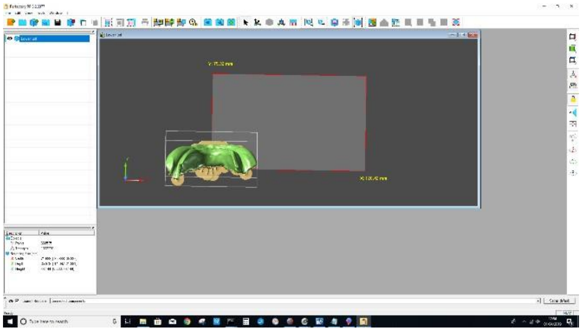


Fig 79. Positioning .stl file on build-plate.

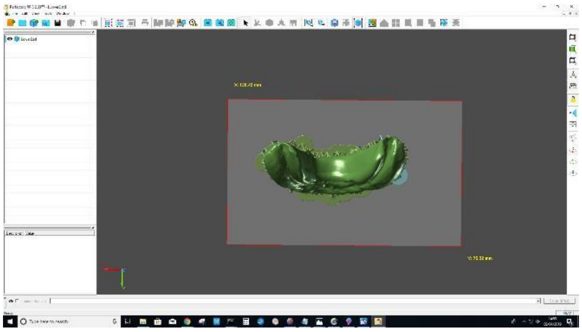


Fig 80 .stl in position on build-plate. Birds eye view.

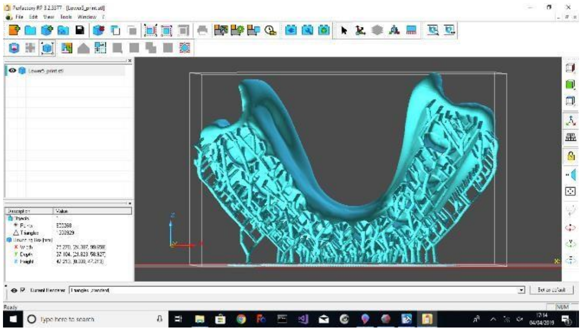


Fig 81. .stl in position occlusal view.

3.11 Printing the denture base:

The .stl file of the denture base was sent to the 3D printer. The printer used for this project was the "Envisiontec Microplus XL" ® (Envisiontec Inc., Dearborn, Michigan, USA) https://envisiontec.com/wp-content/uploads/2016/09/2017-Micro-Plus-XL.pdf. It used ultra violet light, at 405nm, to cure a liquid polymer. It can also cure it at 465nm for blue light emissions. The liquid polymer used for this project was "E-Denture." ® (Envisiontec Inc., Dearborn, Michigan, USA). It was an FDA and CE approved liquid polymer denture material that according to the manufacturers is suitable for all types of "removable denture bases." The manufacturers claim that this material has a much lower shrinkage rate to traditional PMMA denture bases and complies to the ISO standard 10993-1 for biocompatibility as it is "Non-cytotoxic, non-mutagenic, does not induce any erythema or oedema reactions, is not a sensitizer, and does not cause systemic toxicity." (https://envisiontec.com/wp-content/uploads/2017/07/2019-E-Denture-3D-Plus.pdf). The printer resolution was 82 µm (0.082 mm) on the X-axis and Y axis was 105 µm (0.105 mm). Slice resolution was set at 100 µm as per manufacturer's recommendations for this material.

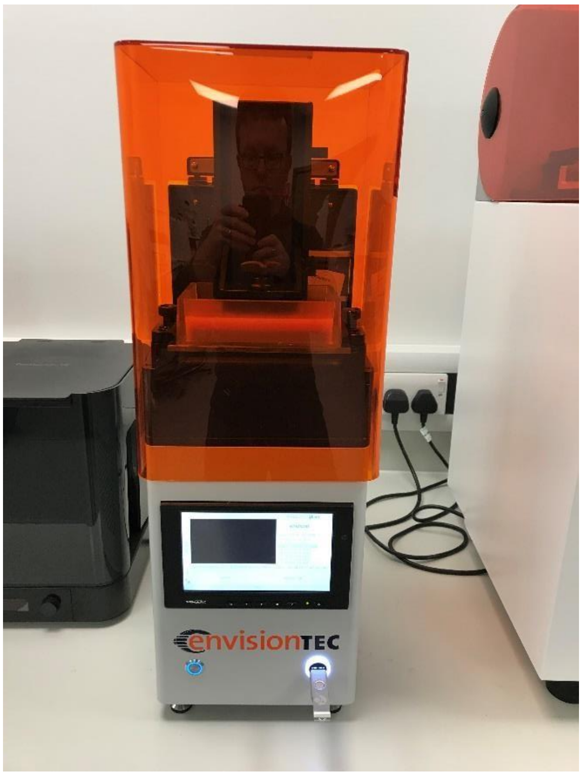


Fig 82. 3D printer resin used in this research Fig 83. 3D printer used in this research

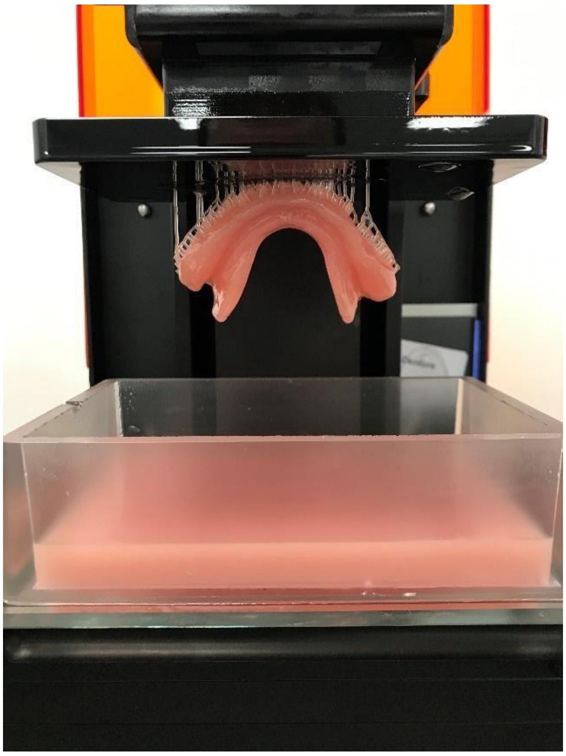


Fig 84 Lower denture attached to build plate. Note supports attached to denture base that enable the baseplate to be built.

Figs 82-84, E Denture Printing resin, Envisiontec Microplus XL 3D Printer used & lower printed denture base on printer buildplate.

3.11.1 Procedure post printing:

After printing the denture bases were removed from the build-plate, placed in isopropanol for 20 minutes to remove any uncured residue. They were not placed in a light curing unit yet until after the teeth had been attached to the denture. The supports were removed using a wax knife, scanned and stored in a sealed bag with a little moisture as per good practice for normal PMMA storage to prevent the denture from drying out (Bates et al., 1991).

3.12 Scan of the 3D printed denture base without teeth:

After successful removal of the denture supports using a wax knife, the fitting surfaces of the dentures were sprayed with Sirona's Optispray® and scanned using the Solutionex Rexcan DS2. This file was saved as a .stl and was aligned with the cookie cutter scan, model scan, try-in scan and denture scan to check trueness and precision after construction.

3.13 Scan of the 3D printed base with teeth:

Once the denture base had been scanned, Delphic® teeth were attached to the denture base, light cured into position using the method as described in sections 3.8.2 and 3.8.3 and rescanned. This was to check whether adding teeth to the denture base altered the fitting surface and to assess one of the null hypotheses of this research. After teeth were added to the denture bases, the labial, buccal and lingual surfaces were lightly trimmed with a bur to remove all traces of the support attachments and were light cured for 30 minutes in the light box described in Section 3.8.3. After curing the dentures were pumiced and polished in the normal traditional manner to clinical standards. After polishing, the dentures were rescanned in the scanner. This file was saved as a .stl and aligned with the cookie cutter scan, model scan, try-in scan, denture scan and printed denture scan without teeth to the same protocol as described in Section 3.12. It was aligned with the printed denture scan without teeth to check if adding teeth to the denture base altered the fitting surface trueness and precision of the denture bases.

3.14 Final alignment of all scans:

After dentures were constructed and initially aligned in Meshlab, as described in Section 3.9.2, a final alignment of all scans was undertaken using the method described in Section 3.9.2.2 ensuring all meshes were tightly aligned together in relation to the master model for Case 1. A computer batch file was used to do this alignment. The scans used for this alignment were:

1. Master model
2. Cookie cutter (the measuring tool for the results) describe in section 3.6
3. Traditional completed denture (fitting surface)
4. 3D printed denture without teeth attached to it (fitting surface)
5. 3D printed denture with teeth attached to it (fitting surface)
6. The CAD print file

3.14.1 Alignment of the CAD print file:

All previous files have been mentioned before 1-5 above, in Section 4.13. For point 6, the CAD print file was added to the alignments to check if shrinkage occurred during printing. This may explain some inaccuracy within the results. This was done for several reasons.

1. Aligning the CAD print file to the Model file would show how accurate the planned denture would be, compared to the original model. This was necessary because, contrary to popular belief, digital data may degrade during the CAD design process, as the various interim 3D meshes are resurfaced and recalculated.
2. Aligning the CAD file to the 3D printed denture scan (without teeth added) would show how accurate the printed denture (no teeth) was compared to the CAD file. This is an absolute measure of the ‘black box’ printing system accuracy.
3. It would show if adding teeth to the print file (i.e. print file with teeth added) would alter the accuracy of the printed denture base. This may prove or disprove one of the null hypotheses of the research.
4. If there was a difference between the CAD file and the printed denture scan it would be easier to narrow down where the error may have occurred. Could the scanner, printing software, 3D printer or light curing cause an error?
5. If there was a difference between the print file without teeth and the print file with teeth, could light curing cause the error?

3.14.2 Adjustment of the cookie cutter:

The cookie cutter constructed as described in Section 4.5 was checked to ensure that it did not extend beyond the borders of the traditional and final finished 3D printed dentures with teeth attached. If it did, the cookie cutter scan was cut back using Meshlab. Each denture scan was checked against the cookie cutter and adjusted until the cookie cutter fitted every denture it was to be measured against, ensuring accuracy of results.

3.14.3 Defining the measuring surface of the dentures to the models:

After construction of the model templates/cookie cutters, these were further refined using a lasso tool to define the actual measurement surface between the models and the dentures. This was done using in-house software called Contour Select. The purpose of this tool was to measure how accurate the dentures were to its corresponding models within 25µm or 0.025mm. This was done by redefining the cookie cutter template scan as described in section 4.5 and ensuring all triangles within the scan were no larger than 25µm. The scans of the models and the dentures were aligned against each other. The corresponding scans were aligned. These regions were then subdivided down into 25µm triangles. A Dijkstra algorithm was then run against both scans. This algorithm measures the shortest route between 2 vertices/nodes within the scans, within a 25µm area (0.025mm) in this case. (https://en.wikipedia.org/wiki/Dijkstra%27s_algorithm)

This measuring tool was fine aligned against upper or lower models 1. Once aligned against these models, and checked to ensure it worked, a batch file was used to align it against all other models. This ensured the measuring tool was in the same position against all models and all dentures ensuring consistency of results. It also ensured the same area of every denture was measured.

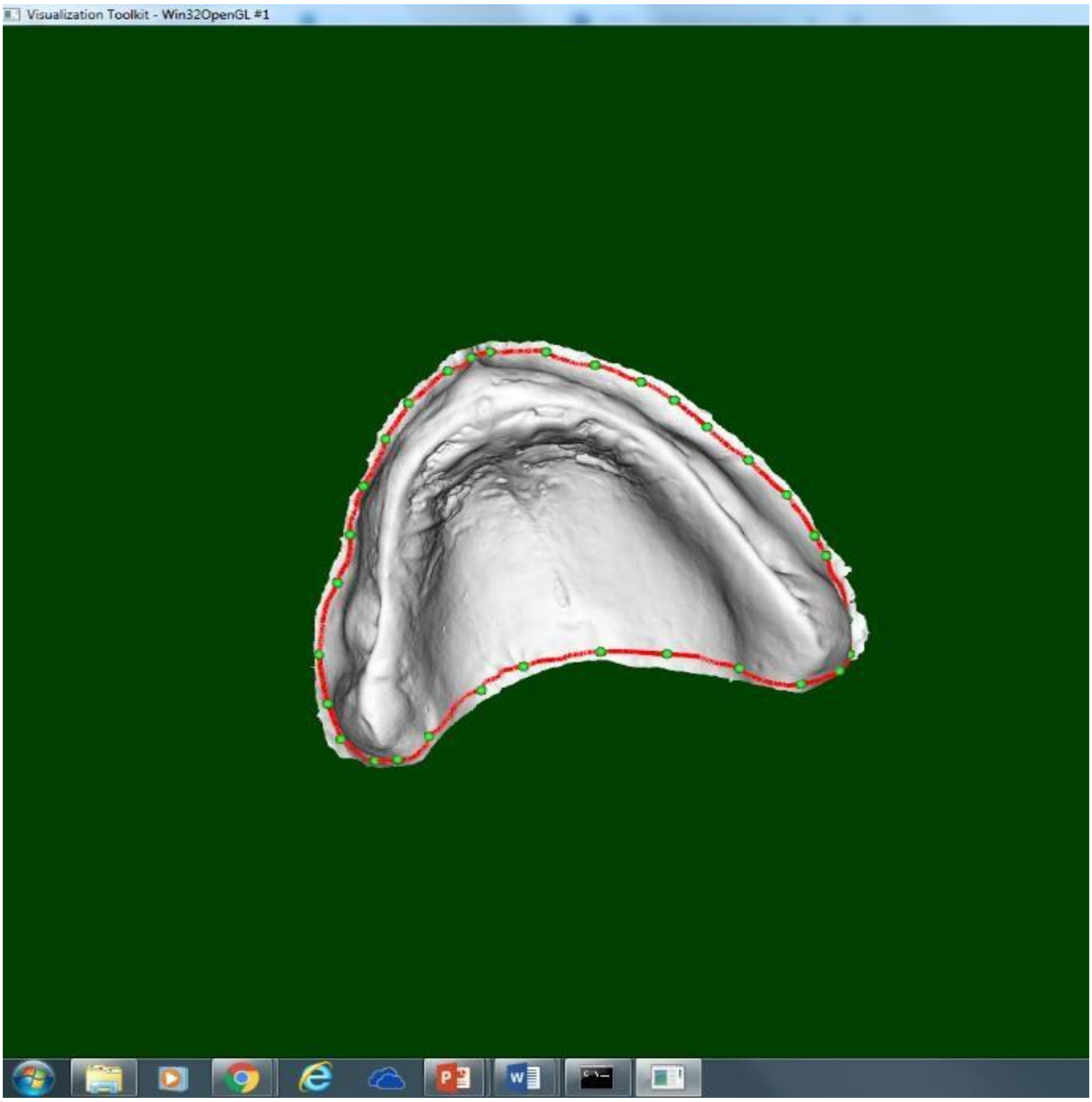


Fig 85 Final cropping of the cookie cutter to define the measuring area. This was done for the lower cookie cutter too. This figure may also show that some of the upper or lower dentures will be outside of the measuring area.

3.15 Statistical analysis of the results:

10 sets of traditional complete dentures were evaluated against its printed counterpart to check for trueness and precision. Statistical advice was sought from the University of Leeds School of Dentistry resident statistician Jianhua Wu. Using scanned models from the traditional arm of this research, 10 sets of printed complete dentures were constructed. As mentioned in Section 3.1.

The number of 10 was determined from previous studies (Kattadiyil et al., 2013; Goodacre et al., 2016; Srinivasan et al., 2017; Kalberer et al., 2019).

The cut-off point for measurement was set at 100µm. This figure was picked as there is published data on the accuracy of dental impression materials by Ender. The best figures came from Vinylsiloxanether (VSE) impression materials 17.7(5.1) µm and the poorest material, Alginate, measured 162.2(71.3) µm. 100µm was deemed to be a fair split between the worst and best fit. (Ender et al., 2016). The fitting surface trueness and precision was measured from traditional dentures to their models, and 3D printed denture bases back to their models. Normality tests were carried out prior to statistical analysis using Q-Q Plot graphs. The difference between the traditional and printed was measured and compared. Paired T Tests, using SPSS software from IBM, was carried out on the samples between 1, 2 and 3 below to measure trueness and precision. The confidence level was set at 95%, ($p \leq 0.05$) for all tests. This meant anything larger than this figure was not statistically significant. The results report the following:

3.15.1 Results collected:

The following results were collected as dictated by the objectives set in Section 2.2. These showed the following:

1. The mean fitting surface trueness of 10 sets of conventional dentures against a master scan of its model.
2. The mean signed standard deviation, precision, results reported for point 1 above.
3. The mean fitting surface trueness of 10 sets of printed denture bases without teeth against a master scan of its model.
4. The mean signed standard deviation, precision, results reported for point 3 above.
5. The mean fitting surface trueness of 10 sets of printed denture bases with teeth added to them against a master scan of its model.
6. The mean signed standard deviation, precision, results reported for point 5 above.
7. The mean fitting surface trueness and the mean signed standard deviation, precision, measurements of 10 sets of printed denture bases without teeth against their traditional counterparts
8. The mean fitting surface trueness and the mean signed standard deviation, precision, measurements of 10 sets of printed denture bases with teeth against their traditional counterparts
9. The mean fitting surface trueness and the mean signed standard deviation, precision, measurements of 10 sets of printed denture bases without and with teeth against each other.

Other results were calculated based on the primary findings above and are secondary. These will be discussed later.

1. CAD file in relation to its model.

2. The 3D dentures aligned to the CAD file

The results were also shown using colour mapping as it is an accepted way of displaying accuracy of fit information (Chesterman, J.A.A. 2018), (Srinivasan et al. 2017), (Steinmassl et al. 2018). It is important not to only rely on colour mapping as a way of displaying results (O' Toole et al., 2019 b).

Chapter 4

Results

4.1 Trueness and precision of dentures:

All data was normally distributed and so paired t-tests were conducted throughout. Normality results for these are displayed in Appendicies1.1 and 1.2. These were not needed due to the relatively low number of samples being tested (n < 15) and negated the applicability of formal normality testing but were carried out anyway and did show normally distributed data.

4.1.1 Trueness and precision of upper dentures:

The box graphs show the Mean Trueness and Precision of Upper Dentures back to the Master Model are shown in Figs 86 and 87 as well as Tables 1 & 2. Measurements are in mm.

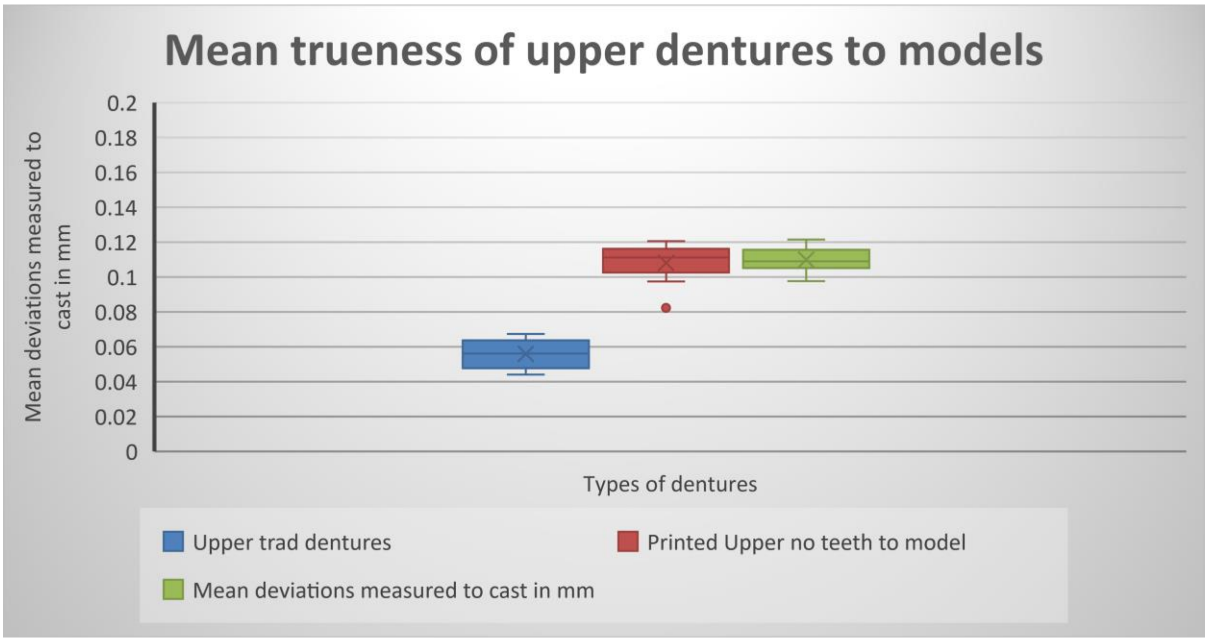


Fig 86 Mean trueness of all upper dentures.

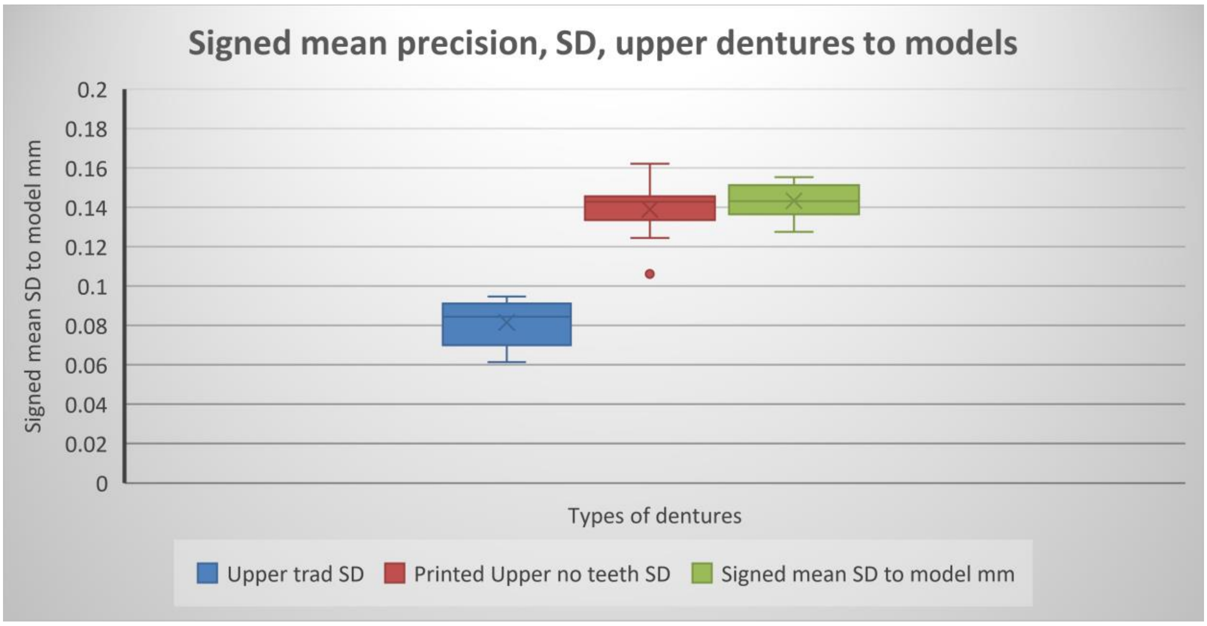


Fig 87 Signed mean SD of all upper dentures.

Trueness Uppers to model Upper traditional Versus 3D printed baseplates	Means	SD	t	Df	Sig P ≤ .05	Null hypothesis
Upper traditional dentures Printed baseplates no teeth	0.055 0.107	0.008 0.011	10.522	9	0.000	Rejected
Upper traditional dentures Printed baseplates with teeth	0.055 0.109	0.008 0.007	13.600	9	0.000	Rejected
Printed baseplates no teeth Printed baseplates with teeth	0.107 0.109	0.011 0.007	0.864	9	0.410	Accepted

Table 1. Trueness (Means) of dentures against Upper printed denture bases without and with teeth.

Means and SD results are in mm.

Precision Uppers to model Upper Traditional Versus 3D printed baseplates	SD Mean	SD	t	Df	Sig p ≤ .05	Null hypothesis
Upper traditional dentures Printed baseplates no teeth	0.081 0.138	0.017 0.015	-8.611	9	.000	Rejected
Upper traditional dentures Printed baseplates with teeth	0.081 0.143	0.017 0.008	-11.011	9	.000	Rejected
Printed baseplates no teeth Printed baseplates with teeth	0.138 0.143	0.015 0.008	-1.484	9	.172	Accepted

Table 2. Precision (Signed SD) of dentures against Upper printed denture bases without and with teeth. Means and SD results are in mm.

The results showed on average the upper traditional dentures were significantly truer to the model than the printed denture baseplates. When teeth were added to the printed denture bases the mean measurements did not deteriorate on light curing. The primary null hypothesis was therefore rejected.

Statistical analysis showed the following. The results for upper dentures traditionally made against the model shows a mean unsigned surface deviation of 0.055 +/- 0.008mm. See Fig 86 and Table 1. The signed SD mean measured at 0.081 +/- 0.017mm. The proportion of the fitting surface which deviated from the model by more than 0.1mm was 15% +/- 4%. This is a clinically useful measure and possibly easier for a dentist to relate to as 15% of the denture fit area will be poorer than 100 microns. See chart above, Fig 87 and Table 2, data for the traditional upper dentures to its respective model.

The upper printed denture bases without teeth showed significantly poorer trueness and precision compared to their traditional counterparts. From the graph above, Fig 86, the upper printed denture means unsigned surface deviation (trueness) was 0.107+/- 0.011mm. The signed mean SD (precision) measured 0.138 +/- 0.015mm in Fig 87 and Table 2. The proportion of the fitting surface of the denture with an error beyond 0.1mm was 41% +/- 4.3%.

The printed denture base results showed little difference adding teeth and curing it. The mean surface deviations measured at 0.109 +/- 0.007mm as opposed to 0.107mm mean surface deviation without teeth. The signed mean SD measured at 0.143 +/- 0.008mm. The proportion of the fitting surface of the denture with an error beyond 0.1mm was 41% +/- 2.7%. There was little change in the fitting surface accuracy by adding teeth. This was not deemed significant as the findings were (p = 0.172) and the Secondary Null Hypothesis was accepted.

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4.1.2 Trueness and precision of lower dentures:

The box graphs show the Mean Trueness and Precision of Lower Dentures back to the Master Model are shown in Figs 88 and 89 as well as Tables 3 & 4. Measurements are in mm.

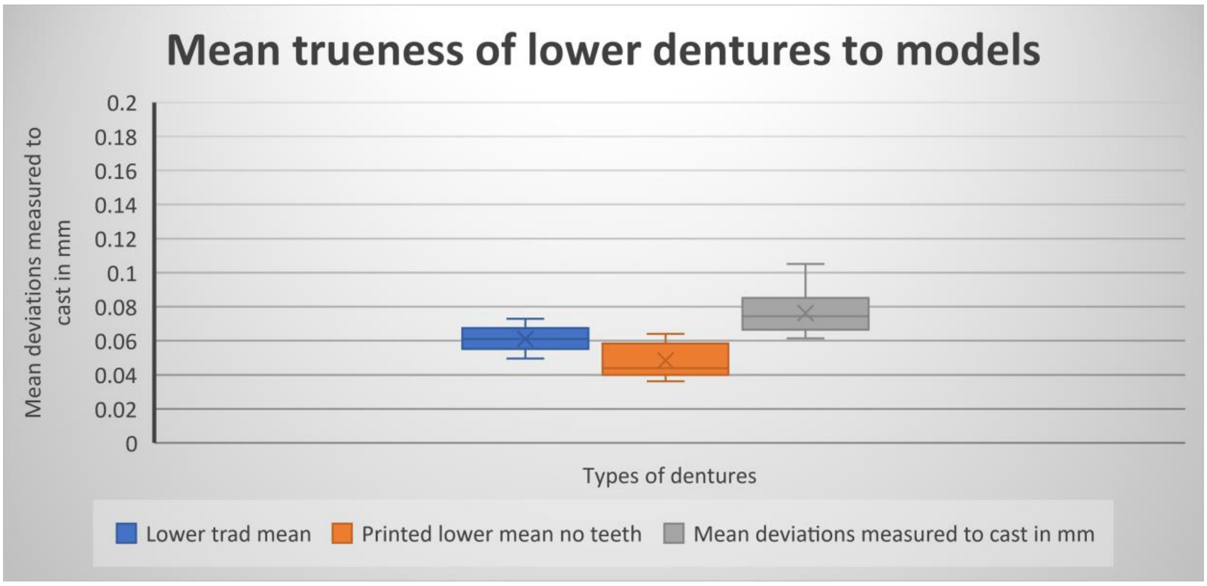


Fig 88 Trueness (Means) of dentures against Lower printed denture bases without and with teeth. Means results are in mm.

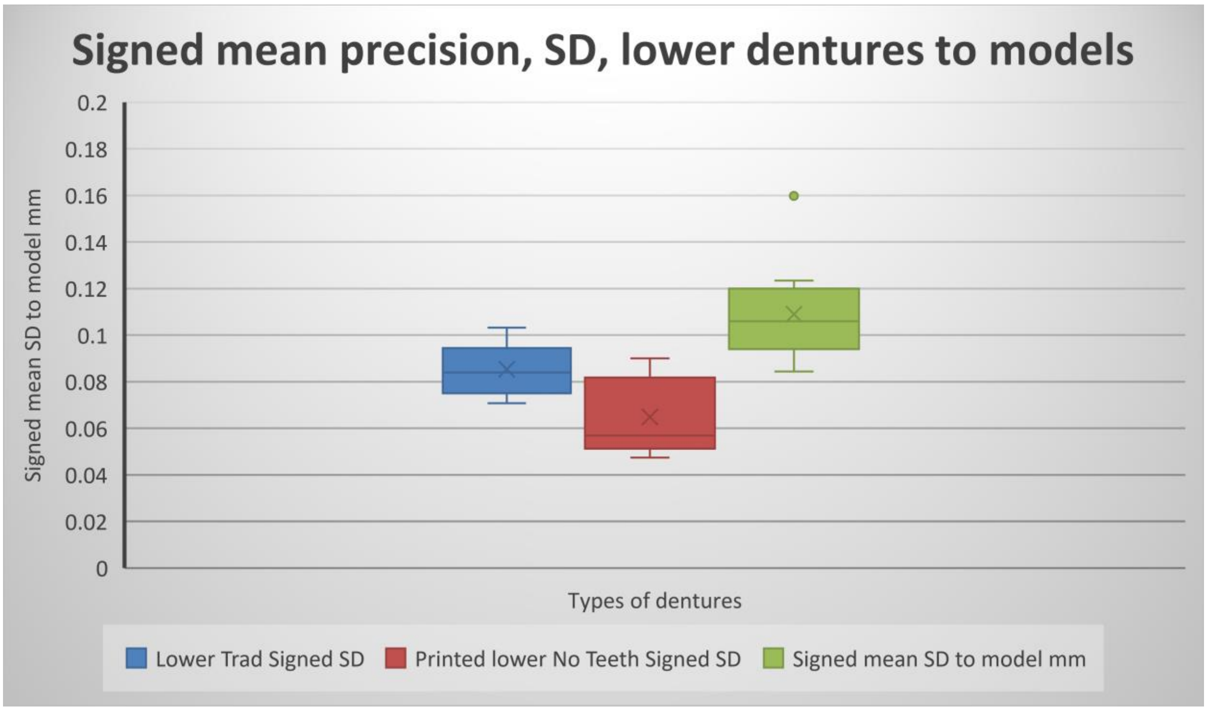


Fig 89 Precision (Signed SD) of dentures against lower printed denture bases without and with teeth.

SD results are in mm.

Trueness Lowers to model Traditional Versus 3D printed baseplates	Means	SD	t	df	Sig P ≤ .05	Null hypothesis
Lower traditional dentures Printed baseplates no teeth	0.061 0.048	0.075 0.011	2.803	9	0.021	Rejected
Lower traditional dentures Printed baseplates with teeth	0.061 0.076	0.075 0.013	-3.599	9	0.006	Rejected
Printed baseplates no teeth Printed baseplates with teeth	0.048 0.076	0.011 0.013	-5.283	9	0.001	Rejected

Table 3. Trueness (Means) of Lower dentures against printed denture bases without and with teeth

Precision Lowers to model Traditional Versus 3D printed baseplates	SD Mean	SD	t	df	Sig P ≤ .05	Null hypothesis
Lower traditional dentures Printed baseplates no teeth	0.085 0.064	0.010 0.016	3.002	9	.015	Rejected
Lower traditional dentures Printed baseplates with teeth	0.085 0.108	0.010 0.022	-3.582	9	.006	Rejected
Printed baseplates no teeth Printed baseplates with teeth	0.064 0.108	0.016 0.022	-5.122	9	.001	Rejected

Table 4. Precision (Signed SD) of Lower dentures against printed denture bases without and with teeth

The results for lower dentures can be seen in Figs 88 & 89 as well as Tables 3 & 4

The results show that lower printed baseplates were more accurate than their traditional counterpart. When teeth were added, accuracy of the baseplate significantly diminished. Traditional lower dentures were consistent to the lower models with similar amounts of distortion to their upper counterparts. Fig 88 shows mean trueness of lower dentures. Mean deviation measurements for the traditional lower dentures showed a mean trueness of 0.061 +/- 0.075 mm in relation to the model. The signed SD measured at 0.085+/- 0.010mm. The proportion of the fitting surface of the denture with an error beyond 0.1mm was 17% +/- 4.3%.

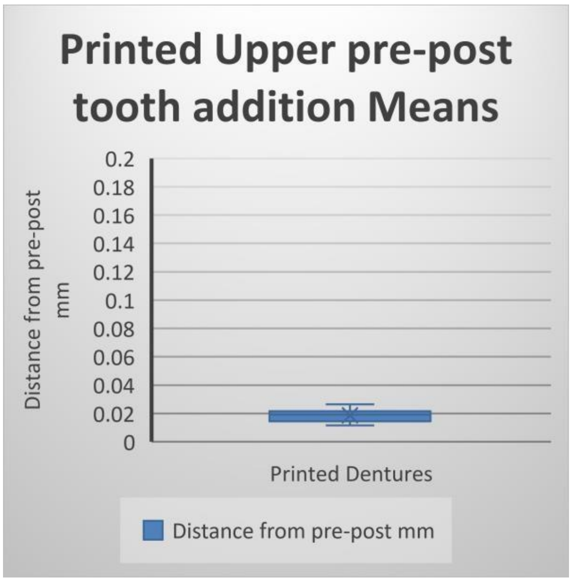
The lower printed without teeth was more accurate to its model than the lower traditional denture. The mean surface deviations measured at 0.048 +/- 0.011mm. The signed SD measured at 0.064 +/- 0.016mm. The proportion of the fitting surface of the denture with an error beyond 0.1mm was 9.9% +/- 6.5%.

Placing teeth on the denture baseplate affected the fitting surface accuracy. The mean surface deviations on average for the lowers printed with teeth was 0.076 +/- 0.013 mm as opposed to 0.048 +/- 0.011mm to the lowers without teeth. The signed SD measured at 0.108 +/- 0.022mm. The proportion of the fitting surface of the denture with an error beyond 0.1mm was 23.3% +/- 4.4%. When teeth were added to the printed denture bases the mean measurements deteriorated on light curing enough to be significant. This was not observed for the upper. Statistical analysis showed that the change was significant as (p = 0.01). The Primary and Secondary Null Hypothesis were both rejected.

4.2 Printed without teeth to printed with teeth alignment calculations:

4.2.1 Upper printed without teeth to printed with teeth alignment calculations:

The final calculations aligned the pre and post addition of teeth to the denture base. The pre teeth and post teeth scans were aligned as described in Section 4.13. This alignment directly calculated the measurement between both files pre and post tooth addition. The figures can be seen in Figs 90 and 91 below.



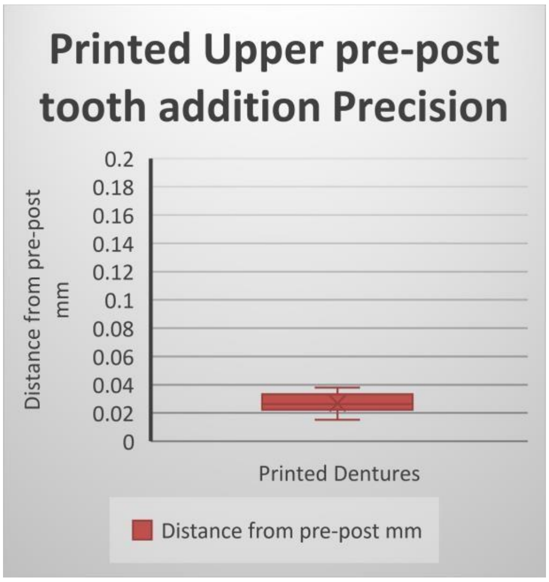


Fig 90

Fig 91

Fig 90. Mean Pre – Post Fitting Surface measurements after teeth adding to the denture bases

Fig 91. Precision Pre – Post Fitting Surface measurements after teeth adding to the denture bases.

The mean deviation measurements between upper printed dentures without teeth to with teeth compared to each other was calculated at 0.018+/-0.004mm. The signed SD was calculated at 0.026 +/-0.007mm. See Appendix 4.6.

This aligning post to pre shows very little change (20 microns or so). It contrasts with the earlier finding when the aligned the pre-to-model and post-to-model. A possible explanation is that the poor fit of the pre and post to the model scan means that the alignment is more variable naturally (a bit like there are many positions a poorly fitting crown – double die-spacer could be cemented onto a prep in).

On balance, this post-to-pre result may be more important and suggests little clinically relevant distortion from adding teeth.

4.2.2 Lower printed without teeth to printed with teeth alignment calculations:

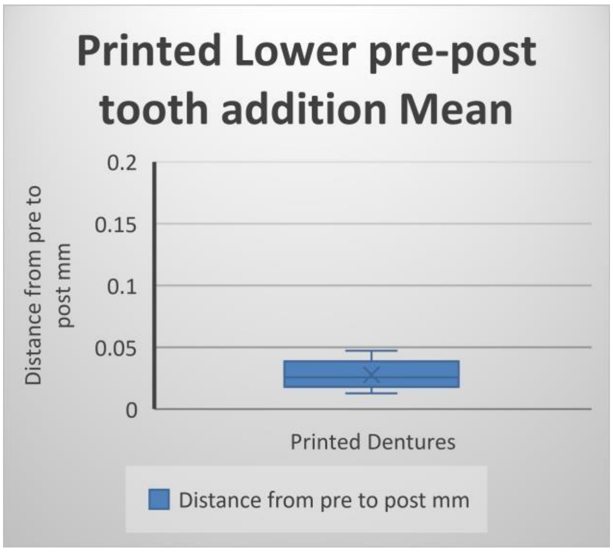


Fig 92

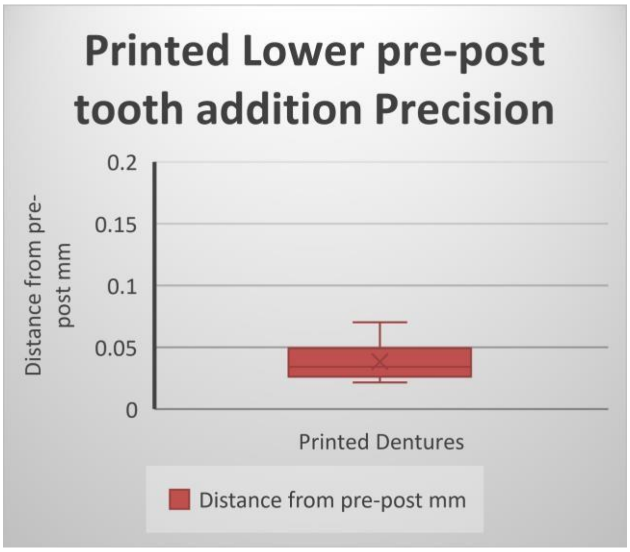


Fig 93

Fig 92 Mean Pre - Post Fitting Surface measurements after teeth adding to the denture bases

Fig 93 Precision Pre - Post Fitting Surface measurements after teeth adding to the denture bases.

The mean deviation measurements between lower printed dentures without teeth to with teeth compared to each other was calculated at 0.027 +/- 0.011mm. The signed SD was calculated at 0.038 +/- 0.016mm.

The results showed the uppers seem to outperform the lowers when adding teeth to the baseplates. The lowers outperform the uppers when the print file was printed.

4.3 Secondary results.

4.3.1 Upper CAD file to model:

The CAD file was the file sent to the printer to print the dentures. If there was an error in the printed denture files, did the error occur before the file was printed? Measuring the CAD against the model should answer this question.

The upper CAD file measured in relation to the model showed a mean deviation of 0.003 +/- 0.0001mm. The signed SD measured at 0.006 +/- 0.002mm. The proportion beyond 0.1mm that was outside of the maximum distance that was measured was on average 0.0002 +/- 0.0005mm. This is seen in Appendix 5.

4.3.2 Lower CAD file to model:

The lower print file was measured for accuracy. The results showed that the lower mean deviations measured 0.003 +/- 0.0002mm. The signed SD measured at 0.005+/- 0.002mm. The proportion outside of 0.1mm was 0.0003 +/- 0.0007mm. The results showed the CAD files were closely aligned to the model files and there was no significant difference between the model and the CAD files. These can be seen in Appendix 5.1.

4.3.3 Upper printed dentures compared to the CAD file to the models:

The final result aligned the CAD files to each of the printed dentures to check how far out from the print files each denture was. This was checked twice; the first time it was checked without the teeth attached to the baseplate and the second time was with teeth attached. See Appendices 4.4, 4.5, 5.2 and 5.3

The finding for the uppers without teeth to the CAD file means were measured at 0.123 +/- 0.017mm and with teeth was measured at 0.117 +/- 0.015mm. The signed mean SD without teeth measured 0.158 +/- 0.020mm. The signed mean SD with teeth measured 0.155 +/- 0.015mm. See Appendices 4.5 and 5.2. This reinforced the results that adding teeth didn't make a significant change to fitting surface trueness and precision.

4.3.4 Lower printed dentures compared to the CAD file to the models:

The finding for the lowers without teeth to the CAD file mean was measured at 0.046 +/- 0.009mm and with teeth measured 0.086 +/- 0.012mm. The signed mean SD without teeth measured 0.059 +/- 0.012mm. The signed mean SD with teeth measured 0.126 +/- 0.019mm. See Appendices 4.4 and 5.3. These results show that adding teeth did make a change to fitting surface trueness and precision.

These results show for sections 5.3.3 and 5.3.4 the errors occurred from the print itself and not from the CAD file sent to the printer.

4.4 Colour maps of the scans:

Colour mapping was conducted on each denture to allow identification of any patterns of distortion. From the initial scan each denture traditionally made or printed, was aligned against its own model. Colour maps showing occlusal views were produced showing accuracy of the printed or traditional dentures to their original models, and the pattern of distribution of any error. The following colour maps were conducted:

1. Traditional dentures to the model.
2. Printed with no teeth to the model.
3. Printed with teeth to the model.
4. CAD file to the model.
5. No teeth and with teeth aligned to the CAD file.
6. No teeth aligned to with teeth.

CAD files were aligned with the original model scan and the printed denture scan with and without teeth. Colour maps were produced showing accuracy of the CAD file to the model, to the printed file without teeth and with teeth. Colour maps were also produced showing no-teeth printed bases aligned to the CAD file and with teeth printed baseplates to the CAD file. Finally, no-teeth aligned to with-teeth scans. This investigated post processing errors, for example, errors caused by adding teeth and light curing, could be detected.

4.4.1 Colour mapping:

Upper and lower dentures were aligned against their corresponding model. The colour map below showed how well a traditional denture fitted against its model, upper traditional 3, Fig 94. The green areas represent the baseline measurement where no detectable change was observed using the software. The red shows a compression against the tissue in the hamular notch areas of up to -200 microns. The blue shows how much the denture has pulled away for the model of up to 200 microns. Colour maps were produced for the upper printed denture without teeth, Fig 99 and with teeth, Fig 100. A CAD print file, Fig 97 was produced to check alignment to the model and the data sent to the printer. The colour maps can be seen below in Figs 94-100.

Colour maps were conducted for the lower dentures too. An example of these are seen below. See Figs 101-107. The full colour maps for all dentures can be seen in Appendices 2 and 3.

4.4.2 Upper traditional denture colour mapping:

Fig 94 below shows a colour map of the fitting surface of a traditionally constructed upper denture. The colour map showed this denture fitted its model more accurately than the printed denture base. Every case showed an inaccuracy of up to -.200 mm in the hamular notch area. The colour map also showed a better fit over the crest of the alveolar ridge. Every case showed a slight distortion in the palatal rugae area where it showed yellow on the colour maps as compared to showing blue in the printed denture bases. See Appendix 2 for all colour maps

4.4.3 Lower traditional denture colour mapping:

Lower colour maps were constructed for all traditional dentures. Fig 101 is an example of one of the dentures constructed. All lower dentures are fairly consistent and mostly fit fairly well. All show some distortion on the patients left side on the buccal shelf up to +.200mm. 2 show some compression on the alveolar ridge of up to -.200mm. This may be down to alignment distortion. See Appendix 3

4.4.4 Upper printed denture colour mapping against the model:

Colour maps showed all upper printed dentures were inaccurate as opposed to their traditional counterparts. This compared well to the statistics that confirmed this in section

4.1.1. The upper printed files were noticeably different after printing compared to the model, but there was no real difference between the scans after adding the teeth to the denture, Figs 95-96. See Appendices 2.2 and 2.3

4.4.5 Lower printed denture colour mapping against the model:

Colour maps for the lower printed dentures are displayed below in Figs 101-107. The results showed the dentures were more accurate initially than their traditionally constructed counterparts. When teeth were added there was some deterioration in the colour maps. Most had deficiencies in the labial fitting surface, pulling away from the fitting surface of the lower model. According to the colour maps deficiencies measured up to +.200 mm in this area.

4.4.6 Upper and lower CAD files colour mapping against the model:

All upper and lower CAD colour maps were consistently green from the occlusal view, see Figs 97 and 104 for one example and Appendix 2.1 and 3.1 for all CAD file colour maps. The results showed that there was no real detectable change between the CAD file to the model.

4.4.7 Upper without and with teeth aligned to each other:

Statistical analysis showed there was not a significant difference, ($p = 0.410$) between the print no-teeth to print with-teeth upper dentures, when compared back to the master model scan. Given the large errors of both groups, it is possible that alignment to the models will have considerable ‘play’ rather like a loose-fitting crown being able to be cemented in multiple, slightly different, orientations. Therefore, a direct comparison between the no-teeth and with-teeth dentures was indicated, to gain a better understanding of the distortions that the process of adding the teeth might incur. To explain the difference, upper and lower printed files were aligned to each other and a colour maps produced. The maps showed for upper files there was little difference between both scans of printed dentures. This was reflected with the statistical analysis as this also stated there was little difference between the pre and post tooth insertion of teeth. See Figs 99 & 100 below.

4.4.8 Lower without and with teeth aligned to each other:

Lower scans showed that there was not much difference between the lower traditional dentures and the initial printed bases. Placing teeth on to the denture bases did make a significant change to the fitting surface accuracy. ($p = 0.001$). The colour maps show there was a change in the scans between these denture bases. See figs 106-107 and appendices 3.5 and 3.6.

Figs 94-100. Example of colour maps collected for upper dentures

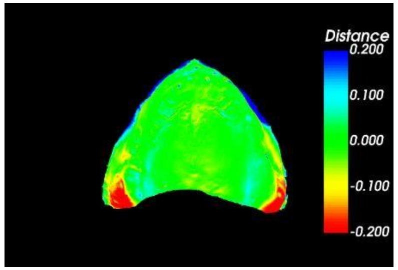


Fig 94. Upper traditional denture 3 in relation to its model

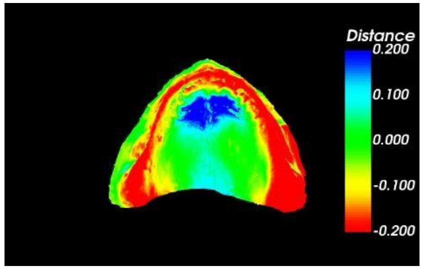


Fig 95. Upper 3 printed denture without teeth in relation to its model

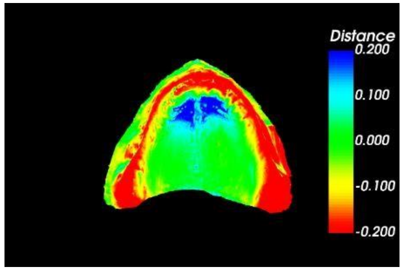


Fig 96.Upper 3 printed with teeth in relation to its model

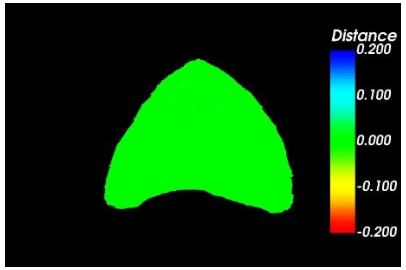


Fig 97. Upper 3 CAD file sent to the printer in relation to its model

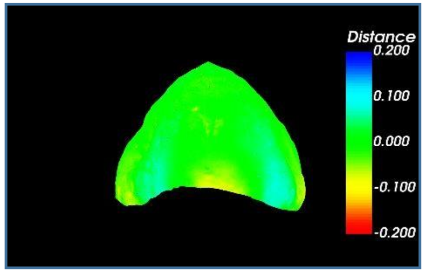


Fig 98. Upper 3 no teeth aligned with teeth

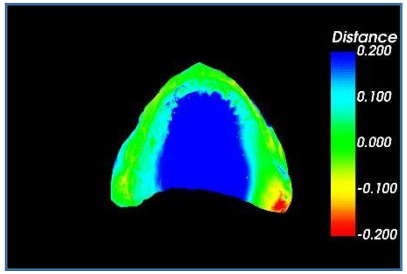


Fig 99. Upper 3 no teeth aligned to print file

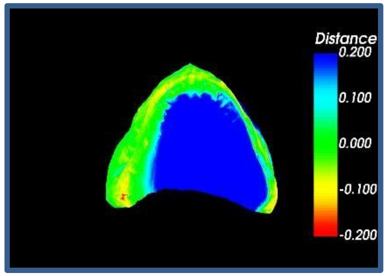


Fig 100. Upper 3 with teeth aligned to print file

Figs 101-107. Examples of colour maps collected for lower dentures

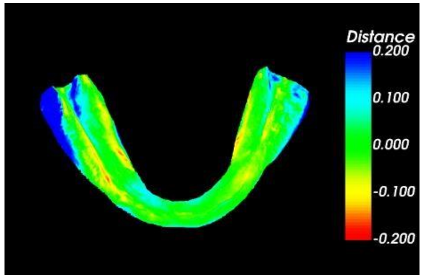


Fig 101. Lower traditional denture 5 against its model

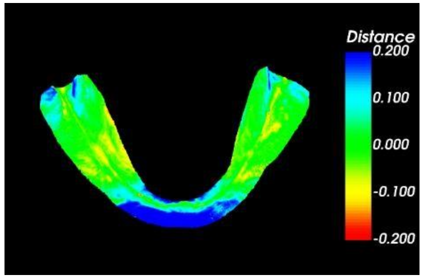


Fig 102. Lower printed denture 5 without teeth against its model

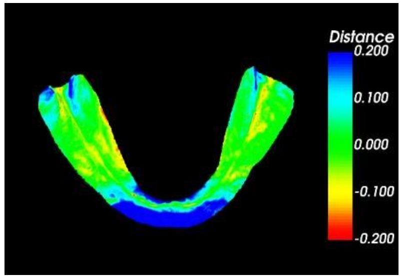


Fig 103. Lower printed denture 5 with teeth against its model

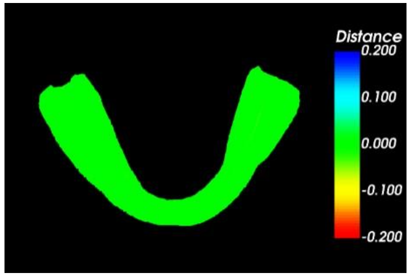


Fig 104. Lower CAD print file 5 against its model

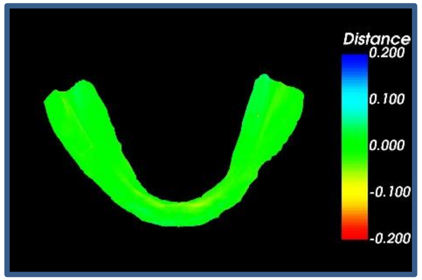


Fig 105. Lower 5 no teeth aligned to with teeth

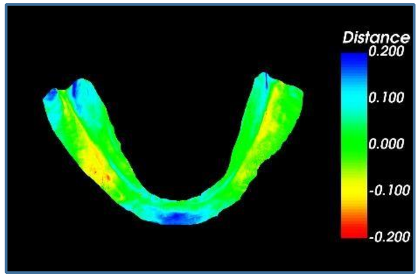


Fig 106. Lower 5 no teeth aligned to CAD file

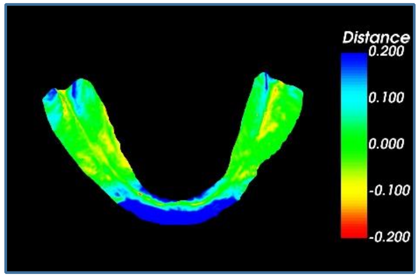


Fig 107. Lower 5 with teeth aligned to CAD file

Chapter 5

Discussion:

5.1 Discussion of the results:

5.1.1 Trueness and precision of traditional dentures:

The trueness and precision of the fitting surfaces of traditional dentures was better than with previous studies (Woelfel et al., 1960; Sykora and Sutow, 1993; Kobayashi et al., 2004; Lamb et al., 2005; Powers and Wataha, 2013). This may be down to the long slow cure of traditional dentures and the experience of the technician. There was shrinkage of the acrylic in certain areas for both upper and lower dentures. This corresponds with previous published work for shrinkage of acrylic resin in dentures as far back as the 1960's. (Woelfel et al., 1960; Sykora and Sutow, 1993; Kobayashi et al., 2004; Lamb et al., 2005). Colour maps in Appendix 1 show distortion in all cases in the hamular notch areas for the upper dentures. Appendix 2.1 shows distortions on the buccal shelf area on the left side of all lower dentures and the pear-shaped pad areas.

Statistical analysis of the upper traditional dentures showed the mean deviations, for all upper dentures was 0.055mm +/-0.008mm and signed mean surface deviations measured 0.081 +/-0.017mm. These results are better than Hwang et al's study for traditional dentures as results in this paper were very unclear as the table and written results in the published paper conflicted (Hwang et al., 2019). The author of this research believes there is an error in the published data. In table 5a in their paper the range of upper traditional dentures showed a range approximately 0.125mm and 0.205mm with an unclear signed SD (Hwang et al., 2019).

Hwang does not report how the pack and press element of his study was carried out and does not report any curing cycles for traditionally constructed dentures that may have a bearing on his results.

Another paper reports that PMMA shrinkage was about 0.9% (0.29mm) in the cross-arch dimension which is larger than this research found for upper dentures using conventional compression moulding (Parvizi et al., 2004).

For lower traditional dentures, mean surface deviations measured 0.061 +/- 0.075mm. The signed standard deviations measured 0.085+/- 0.010mm. This study is better than Yoon et al's findings for lower traditional dentures where their mean error was measured at 0.118mm +/- 0.053mm (Yoon et al., 2019). Yoon et al does not report how the pack and press element of their study was carried out and do not report any curing cycles for traditionally constructed dentures that may have a bearing on their results.

The proportion of fitting surface which deviated beyond 0.1mm averaged 15% for uppers and 17% for lowers.

While the results of this research were more accurate than that found by Hwang and Yoon (Hwang et al., 2019; Yoon et al., 2019) for traditionally constructed dentures, the author speculates that the curing cycle used for this research was the gold standard and probably not a cycle that most commercial dental laboratories may use when constructing dentures due to time and financial constraints. It does show what results can be achieved when using slow cured processes and following manufacturers mixing ratios for acrylic and the effect of reduced curing cycles is worthy of further investigation. It is entirely conceivable that 3D printing may already surpass the accuracy of ‘commercial standard’ flasking methods, based upon the results presented here in comparison with the traditional results mentioned above from previous studies.

5.1.2 Colour mapping:

Colour maps show there was distortion on all traditionally cured denture bases. Similar colour maps of upper traditional dentures can be seen in a study by Srinivasan (Srinivasan et al., 2017). The reader should be cautious when viewing colour maps, because the area where distortion may be happening may not be exactly where the colour maps are suggesting. Rigid alignment can show differently on colour maps as opposed to non-rigid alignment according to Brown. The scanned data may have tried to align itself as best as it can to the model scan. The scans may distort to give best alignment, and this may distort the colour maps (Brown, B. et al 2007). Brown researched improving accuracy of colour mapping so that non rigid alignment was used to gain better accuracy of colour mapping in relation to the scans. Colour maps cannot be relied upon on their own but must be used in conjunction with the statistical analysis of the results also. O'Toole reinforced this as they stated that "alignment processes had yet to be standardised" (O' Toole et al., 2019 b).

The results showed that when aligning 3D printed denture scans with and without teeth against their respective models, lower colour maps show large differences between them. When 3D printed denture scans with and without teeth for upper and lowers are aligned against each other, there is little difference between the maps. See Appendices 1.4 and 2.4, which reinforces what Brown and O'Toole were suggesting (Brown, 2007; O' Toole et al., 2019 b). (Upper and lower pre and post prints aligned with each other), compared to

Appendices 1.5 (Upper no teeth aligned with CAD file) and 1.6 (Upper with teeth aligned with CAD file) and 2.5 (Lower no teeth aligned to CAD file) and 2.6 (Lower with teeth aligned to CAD file).

5.1.3 Trueness and precision of 3D printed dentures:

The results for 3D printed dentures were not as straight forward. Upper printed denture baseplates, without teeth, were not as accurate at their traditional counterparts. This was reinforced with results by Kalberer and Hwang (Kalberer et al., 2019; Hwang et al., 2019). Kalberer's study showed slightly better results with mean measurements for upper baseplates at 0.095mm compared to this study at 0.109mm for the final denture. When teeth were added and light cured, the measurement deteriorated by 0.002mm, making a final measurement of 0.109 +/- 0.007mm on average. The SD mean measurements were 0.081+/- 0.017 mm for traditional to 0.143+/- 0.008mm to printed with teeth which was significant.

Hwang showed that upper denture bases printed using a DLP printer showed mean results of 0.074+/-0.005mm (Hwang et al., 2019) as compared with this study of 0.107mm for printed no teeth baseplate and 0.109mm for printed with-teeth attached. None of the studies by Kalberer, Hwang and Yoon add teeth to their denture bases and rescan for trueness and precision and this reinforces the lack of data regarding printed dentures noted by Steinmassl, Kattadiyil and Srinivasan in Section 1.4 and could alter their findings if teeth were added to their baseplates (Steinmassl et al., 2017; Kattadiyil and AlHelal, 2017; Srinivasan et al., 2017).

The results of this research are similar for upper denture prints produced by Davda in 2016 and Kalberer in 2019, where it was found that 3D printed denture bases were similar in measurements to this study. Davda's findings for 3D printed copy denture templates was measured at 0.103 +/- 0.021mm. This study didn’t compare like for like as this study used a CE marked liquid polymer for temporary intra oral use as its baseplate template for copy dentures as opposed to making a final denture base with teeth attached (Davda et al., 2017). This shows that 3D printed denture bases can fit accurately which is clinically significant and will be continued to be used by clinicians.

Lower printed dentures results showed baseplates without teeth were more accurate than traditional dentures initially. Initial mean deviations without teeth were measured at 0.048 +/- 0.011mm and standard deviations at 0.064 +/- 0.016mm. A slight improvement on traditionally cured lower denture base mean deviations of 0.061+/-0.075mm and standard deviations 0.085+/-0.010mm. Changes occurred after adding teeth to the baseplates and curing them in the light box. On rescanning, results deteriorated with the mean deviations measuring 0.076 +/- 0.013mm and standard deviations measuring 0.108+/-0.022mm. This showed a change to the surface trueness and precision of the dentures. Curing the lower dentures in the light box did affect the surface trueness and precision of the dentures but not enough to be statistically significant (though the clinical significance remains unclear). These results were better than Yoon et al’s study where lower 3D printed baseplate means measured 0.118 +/- 0.053mm. Even with processing with teeth, which Yoon and co-workers failed to do, the lowers for this study were better (Yoon et al., 2019). This research shows that the trueness and precision of the fitting surfaces for traditional dentures was more true and precise than their 3D printed counterparts. What this research did not investigate was the overall trueness and precision of traditional and 3D printed dentures (including occlusal and polished surfaces) as it was limited to the fitting surface only.

5.2 Most likely cause of errors:

5.2.1 Properties of the printed resin:

A likely cause of the differences in results between upper and lower baseplates may have been post printing errors. According to Brown, 3D printed dentures are not fully cured until they have been subjected to a light cure process and this may lead to further shrinkage of the material (Brown et al., 2018). Tahayeri et al found that the colour of printer resin may affect accuracy as the light intensity for each colour resin may need to be altered to cure each different colour resin properly as Tahayeri found that using lasers to cure photo resin there was almost a two fold intensity increase between grey resin, 20+/-0.07 (mW) and castable resin 42.3+/-1.3 (mW). Tahayeri believes it is "by rastering a laser light under a vat filled with the photo-polymerizable monomer and the emission of light on the incrementally added layers of monomer can influence the quality of the printed part" (Tahayeri et al., 2018). Kalberer et al found that washing denture prints in isopropanol for longer than 5 minutes may lead to surface defects in the print according to the manufacturer of the resin used in their study (Kalberer et al., 2019). This did happen in this study as denture prints were washed in isopropanol in an ultrasonic bath for 20 mins.

Could the lowers have warped due to the nature of the shape of complete lower dentures and the positioning and density of the supports to construct the denture? This is worth further investigation. This did not happen to the uppers due to the baseplate being totally supported throughout even though there was the same density of supports on both sets of dentures. This knowledge may have been useful when constructing the printed denture bases as Bennett found that pre knowledge of photo properties is important for successful polymerisation of printed resins. Adding further supports to the lower denture extensions may have prevented the denture from warping after adding teeth to the printed baseplates and pre knowledge of this may have altered the way the denture was designed prior to printing (Bennett, 2017).

5.2.2 Immediate scanning and storage after construction:

The upper baseplates were not scanned immediately after printing whereas the lowers were, (Scan 1). This may explain why lower baseplates fitted post printing better. Before adding teeth to the baseplates, denture bases were stored in clear polythene bags and placed in a box that was open to the ambient surrounding light. After teeth were added, the baseplates were rescanned, (Scan 2). Between initial post printing Scan 1 and Scan 2 both upper and lower denture baseplates were stored in bags between scans for a few weeks before adding teeth to the baseplates. The uppers were stored longer in these bags, up to two weeks longer than the lowers, and had longer time exposed to the surrounding ambient light. This was because the uppers were printed first. The lowers had less time exposed to the surrounding ambient light, a few weeks less, and when placed into the light box after adding the teeth, the curing cycle affected the final fit accuracy of the lower denture base more than the upper denture base. This would reinforce Bennett’s argument that some pre knowledge of photo polymerisation resins “could very likely impact the manufacturability and properties of the final product” (Bennett, 2017). In the literature there is little published evidence about post processing storage of 3D printed denture baseplates.

The results showed that upper dentures changed little and light curing did have minimal effect. For lowers it had a greater effect as described in Section 5.1.2. These are shown in Appendices 1.2, 1.3, 2.2, 2.3 as well in Sections 5.2.1 - 5.2.2.

5.2.3 Printer errors:

Other areas where the error may have occurred could be printer errors. The printer used was the Envisiontec Microplus XL DLP printer as described in Section 3.11. Faults may arise with cheap DLP printers using cheap consumables for example, flimsy film trays, according to Envisiontec. This is the tray that holds the liquid polymer in the printer. If it's flimsy, the tray may bend under the weight of the liquid distorting the light and creating an error in the print. This was not the case for this research as the film tray was of glass construction with enough thickness to withstand flexing from the weight of the liquid. The manufacturer of this printer classified the tray as a consumable to be replaced after a certain period of time, sometimes up to a week if really cheap trays are used. The glass tray was covered with a slight film of silicone. This can wear away over time after repeated prints. This may cause bubbling of the thin film on the glass surface and finally peel away from the glass (Envisiontec.com).

During this research pixel size of the printer was calculated at 133 microns on the x axis with the layout of the pixels diamond rather than square shaped. This was calculated based on the microchip specifications from Texas Instruments used in the printer. Newer microchip printer specifications may help eliminate future errors and is an area for future development. This is something that Tahayeri stated in his paper regarding the "myriad of parameters that can vary from printer to printer" and can interfere with the "quality of the printed parts" (Tahayeri et al., 2018).

Brown alluded to post processing curing errors in his paper on the accuracy of 3D printed models (Brown et al., 2018). Brown stated that some of the errors found with DLP printing may be attributed to post processing curing with most of the errors occurring in the Z axis. Another study found errors with 3D printing in the Z axis too (Hazeveld, A. et al., 2014). Tahayeri found that the orientation of the object to the build plate may also affect the accuracy of the object to be printed (Tahayeri et al., 2018). A possible way to avoid this could be aligning the denture base to the build plate differently minimising much of the denture base to z axis distortion. In this study this didn't apply as both upper and lower dentures were printed on the same axis on the build plate.

5.2.4 Projector errors:

DLP printers can cause errors as Brown found (Brown et al., 2018). Brown found that significant errors in crown height can occur when printing dental models using DLP printers but concluded that overall DLP printers would be a clinically acceptable way to produce dental models. The light is projected onto the printer reservoir. According to All3DP.com, errors arise when the light is projected onto the tray. As a ray is projected onto the tray it gets bigger. The bigger the light projected gets, the more likely the edges distort and may give a blurred image for bigger items that are printed (Greguric, 2019). It is best described as zooming into a photograph taken by a smartphone. As the image is magnified, the quality of the picture diminishes. It's the same for a DLP printer. As the upper and lower dentures were printed in the middle of the build plate, and the lower dentures were printed after the upper dentures, the initial accuracy of the lower was better than the traditional and upper printed dentures. This this may be ruled out as a source of the error.

5.2.5 Liquid resin viscosity:

Liquid viscosity may be another reason why the printed denture baseplates were inaccurate and another area for future research. The minimum layer thickness according to the manufacturers for the denture resin in this research was 100µm. According to Zhang layer thickness may affect surface accuracy of 3D printing objects (Zhang et al., 2019). Zhang found that printing using a DLP printer, best results were achieved using a layer thickness of 50µm. It was found the accuracy of all printers, SLA or DLP, tested improved using a layer thickness of 50µm. When it came to speed and accuracy of print the DLP was superior for layer thickness of 100µm compared to SLA printers. This didn't apply in this case as layer thickness was 100µm and the lower printed fitted better than traditional dentures on initial scanning. Developing resins that are less viscous may allow for future improvements in denture trueness and precision coupled with better 3D printer microchip technology.

5.3 Scanning and alignment distortions:

After constructing the dentures and observing initial results between traditionally constructed dentures and the printed dentures, the author re-examined the data acquired to explain the differences. One area investigated was the initial file sent to the printer. This may explain if the alignment software had caused an error. Aligning the CAD file to the model file and statistically analysing the distance between them, it could show if the software caused an error. The results for this were reported in section 4.3. Colour maps display this in Appendices 1.1 and 2.1, and graphs display the findings reported in section 4.3 and in Appendices 4.1 and 4.2. The data showed that the CAD files were a very good representation of the model. This eliminated the CAD design and print preparation software as a possible cause of the error. This was a point that Brown reinforced in a paper on the accuracy of 3D printers. By comparing a dental stone model with two printed dental models from different 3D printers, it was possible to evaluate "the accuracy between the digital models and the 3D printed models" Brown also said doing this also allowed the accuracy of the scanners to be assessed (Brown et al., 2018).

5.4 Clinical significance:

The results showed traditional dentures fitted better than printed dentures. The degree of difference between traditionally constructed dentures and printed ones was significant, p = 0.000 upper mean deviations, p = 0.000 upper standard deviations, p = 0.006 lower mean deviations and p = 0.006 lower standard deviations, but would the dentures be acceptable for fit clinically? This is very subjective. Hyde et al stated that the lack of RCT's in prosthodontics meant that clinically significant results were not produced in clinical trials (Hyde et al., 2014). Hazeveld et al reported this issue for printing of dental study models (Hazeveld et al., 2014). Hyde also stated that there were many "confounding variables" that may affect the fit of dentures, for example, "patient factors", "technical construction factors" and "dentist related factors" (Hyde et al., 2014). Ender found that deviations greater than 100µm may lead to " inaccurate fitting of the definitive restoration in the maxillary and mandibular jaws” and this can be “problematic in cases of large rehabilitations” (Ender et al., 2016). If it is accepted that in the laboratory defects of 0.1mm would equate to a clinical acceptance of 0.2mm then based on Ender et al’s results of alginate measured at 0.162 +/- .071mm, the printed dental appliances may be difficult to fit even factoring in the points that Hyde et al discussed were taken into account. Hazeveld et al reported for printed study models that mean errors of 0.27mm may not be clinically significance. Hazeveld research findings are different to Ender et al’s research as to what may be clinically significant as Hazeveld et al also reported that errors up to 0.3mm would be good enough for printed orthodontic study models (Hazeveld et al., 2014). O’Toole et al reported that it may be better to report the worst findings rather than the average findings for clinical significance as these are the areas that may cause clinical problems (O' Toole et al., 2019 b).

The mean results for upper printed dentures were significantly worse than traditionally produced ones but on average was only .1mm out which may fit in with Enders research. The printed lowers were statistically more accurate than the traditional and printed uppers, but adding teeth and curing, fitting surface accuracy deteriorated. This made them significantly less accurate than traditionally produced dentures.

The printed lowers were better than the printed upper dentures, possibly due to the different overall shape being somehow more readily 3D printable. Does this make it clinically acceptable? Maybe would be the answer. Further research (preferably in a clinical RCT) is required to investigate this question. The errors for the upper printed dentures are on the crest of the alveolar ridge for all printed dentures. This would probably be unacceptable in this case as the upper printed are at least -.200mm, compressing the alveolar tissue and bone prematurely and conflicting with Enders research. The lowers may be more clinically acceptable as they fit better. Factors affecting the fitting of dentures can be occlusal, raised bites, bulky polished surfaces, compressibility of mucosa, patient habituation and age of patient.

Kanazawa found errors may occur placing teeth into Boolean sockets as polymer shrinkage may occur preventing commercial teeth inserting the sockets, causing large occlusal discrepancies that may cause clinicians more problematic fitting problems. (Kanazawa et al., 2011). This research found some discrepancies between the fitting surface of the 3D printed denture, when assessed before and after insertion of the teeth. This finding agrees with Kanazawa. More clinical trials are needed to alleviate the findings of Kattadiyil and Goodacre regarding the lack of clinical data for computer generated dentures
(Goodacre et al., 2016; Kattadiyil and AlHelal, 2017).

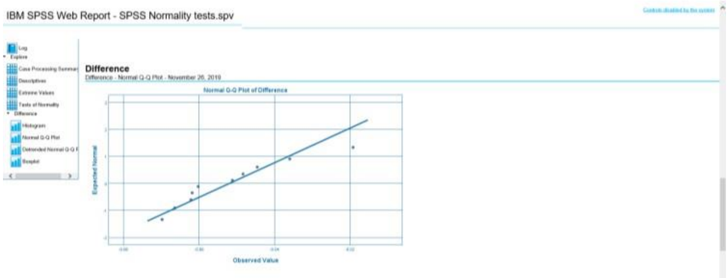
6 Conclusion:

The results showed statistically, printed dentures were significantly less true and precise than traditionally produced dentures. Small distortions happened when adding teeth to the baseplates but this probably would not be clinically significant. The majority of the error occurred between sending the CAD file to the 3D printer and the physical 3D printed result. Lower 3D printed dentures were more true and precise than upper 3D printed dentures.

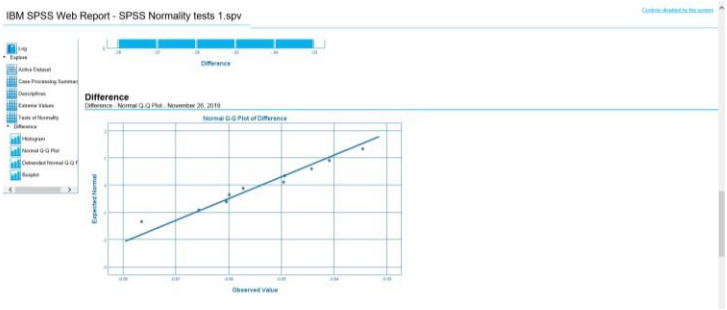
While there have been new developments in digital dentistry over the last few years, the results here show that there is still much work yet to be done. Long term data handling, processing and storage techniques need further investigation to improve technical and clinical results as this research discovered. Further research is needed to improve the technology (resins and hardware) to ensure a more accurate denture from the CAD file. Investigations into the effect of the shape of the printed object and the resulting accuracy are also indicated.

Support design for dentures needs to be further investigated as it may be the position and density of the supports that led to the alteration of the lower denture when teeth were attached to the baseplate. Improving denture resin properties regarding impact strength and bond strength between teeth and denturebase is absolutely necessary as this research has discovered. Further investigation is also needed regarding tooth addition to printed denture bases using commercially available denture teeth, especially if denture teeth have to be altered to fit the denturebase.

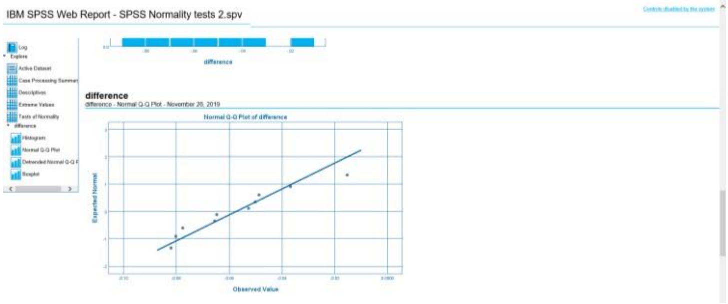
Appendix 1.1 Upper Dentures Q-Q Graphs:



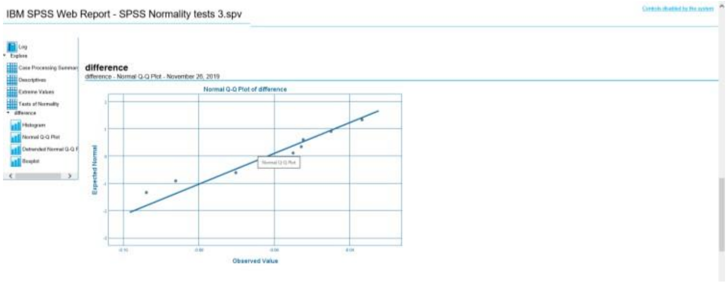
Q-Q Plot. Upper traditional dentures to printed no teeth means



Q-Q Plot. Upper traditional denture to printed with teeth means

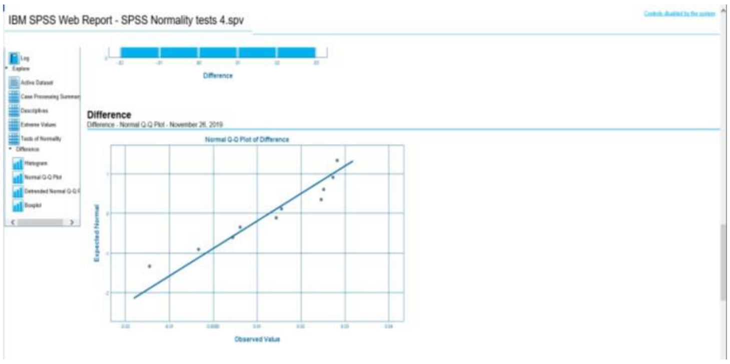


Q-Q Plot. Upper traditional dentures and printed no teeth signed SD

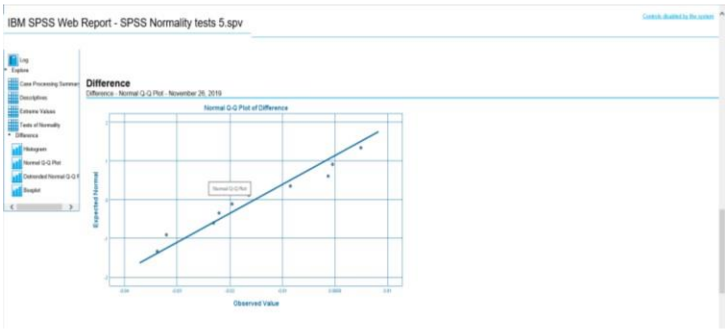


Q-Q Plot. Upper traditional dentures and printed with teeth signed SD

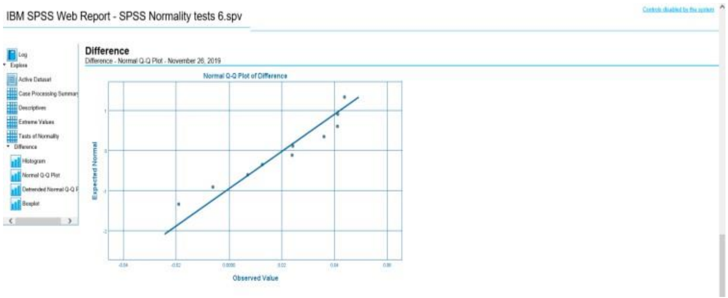
Appendix 1.2 Lower dentures Q-Q Graphs:



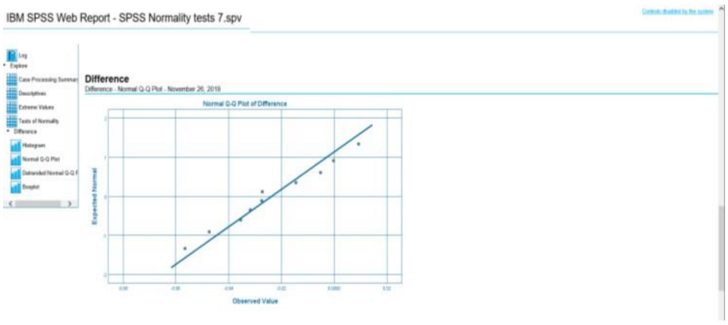
Q-Q Plot. Lower traditional dentures and printed no teeth means



Q-Q Plot. Lower traditional dentures and printed with teeth means



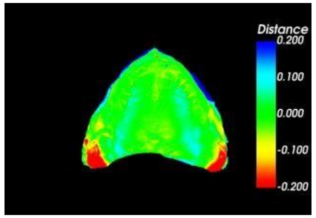
Q-Q Plot. Lower traditional dentures and printed no teeth signed SD



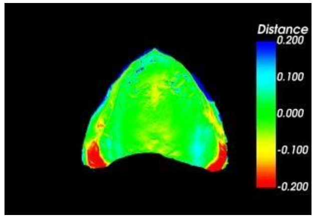
Q-Q Plot. Lower traditional dentures and printed with teeth signed SD

Appendix 2

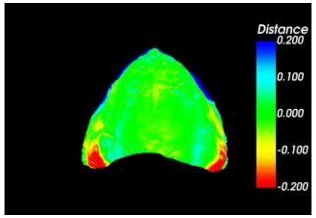
Upper Traditional Dentures aligned against its model



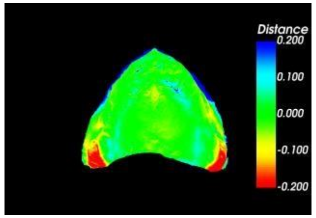
Upper 1



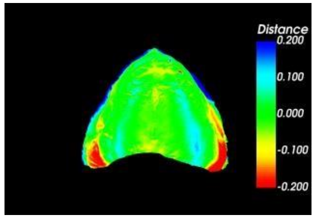
Upper 2



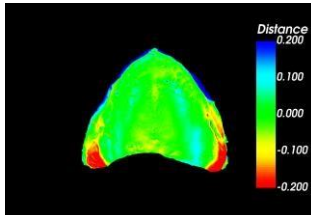
Upper 3



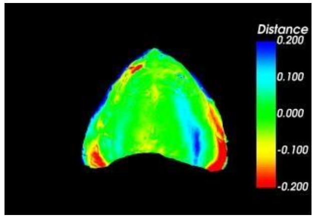
Upper 4



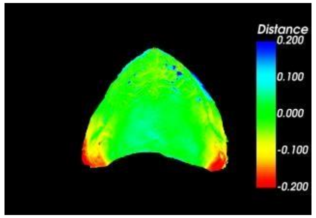
Upper 5



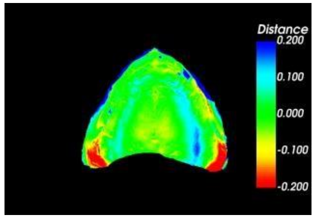
Upper 6



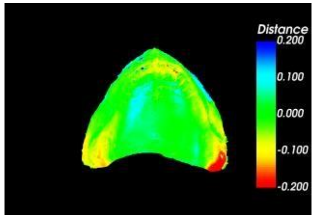
Upper 7



Upper8



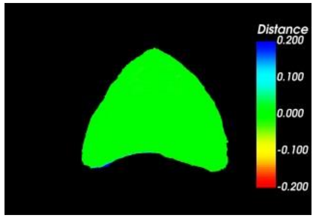
Upper 9



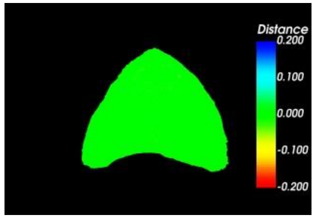
Upper 10

Appendix 2.1

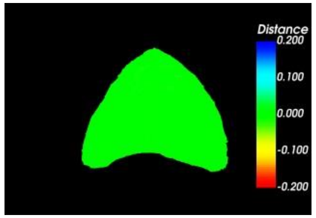
Upper CAD file against its model



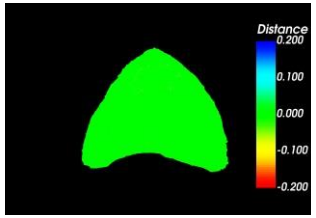
Upper 1



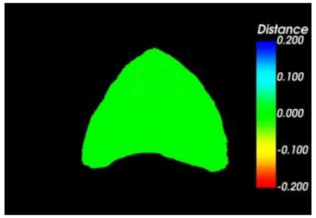
Upper 2



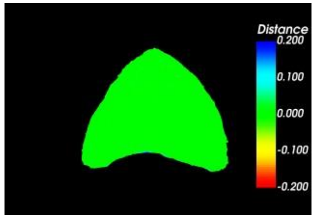
Upper 3



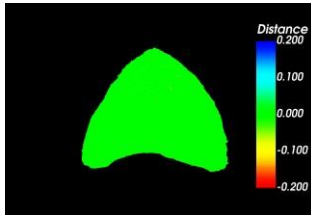
Upper 4



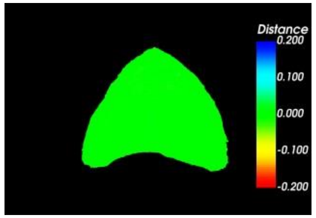
Upper 5



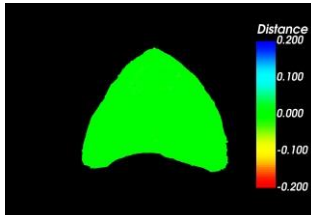
Upper 6



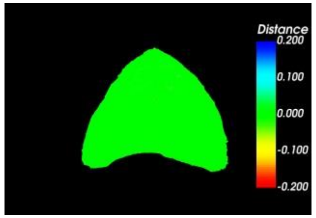
Upper 7



Upper8



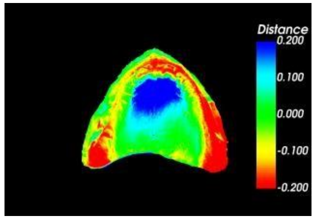
Upper 9



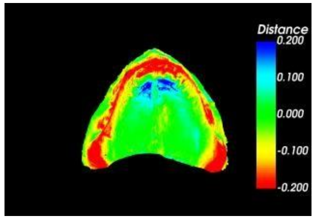
Upper 10

Appendix 2.2

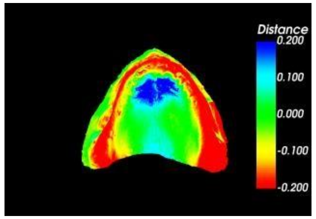
Upper print without teeth against its model



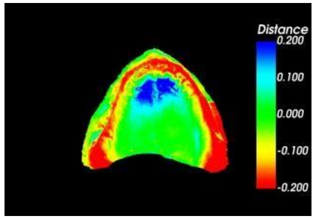
Upper 1



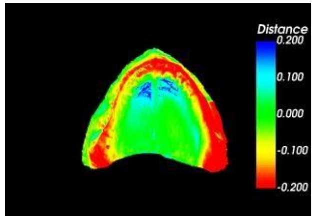
Upper 2



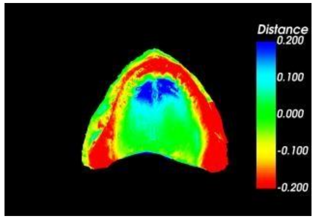
Upper 3



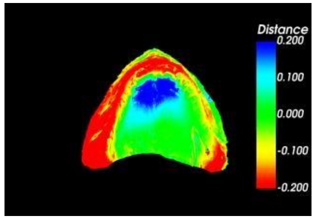
Upper 4



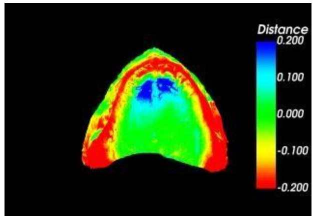
Upper 5



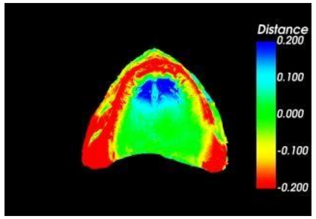
Upper 6



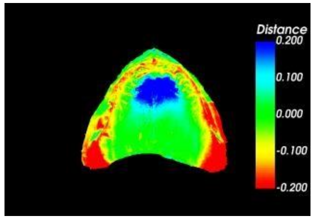
Upper 7



Upper8



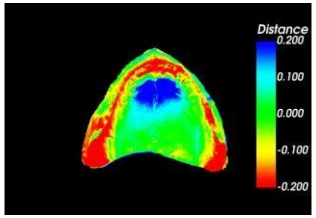
Upper 9



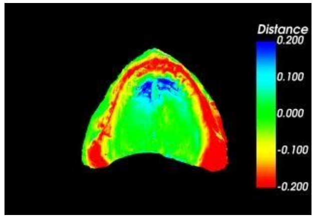
Upper 10

Appendix 2.3

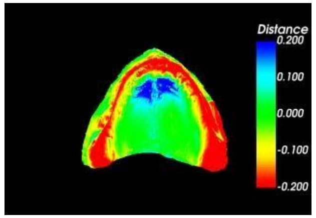
Upper print with teeth against its model



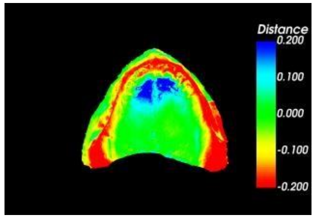
Upper 1



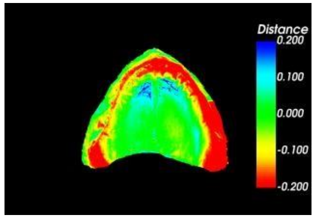
Upper 2



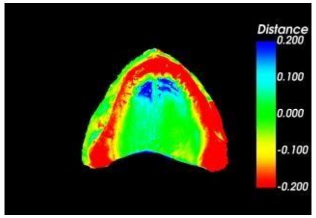
Upper 3



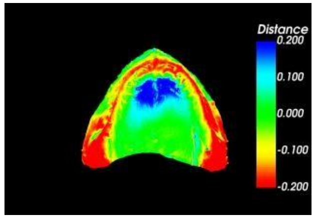
Upper 4



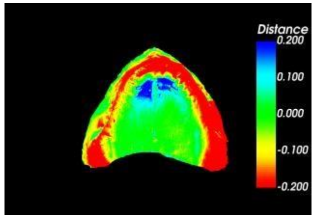
Upper 5



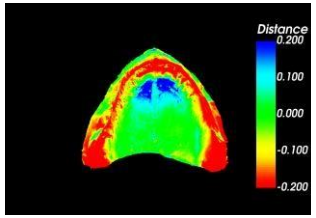
Upper 6



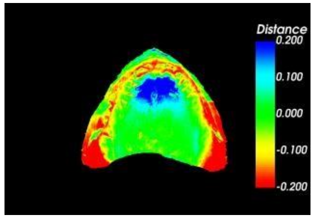
Upper 7



Upper8



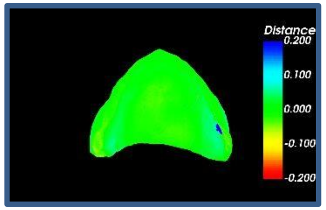
Upper 9



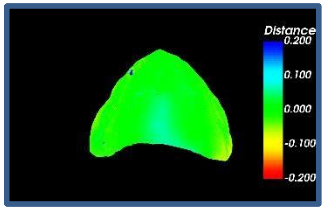
Upper 10

Appendix 2.4

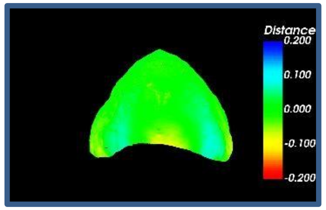
Upper pre and post print aligned with each other



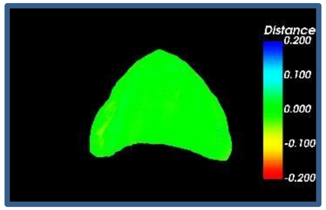
Upper 1



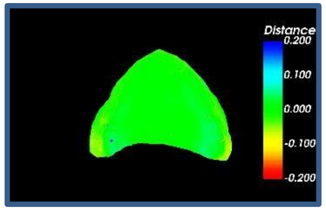
Upper 2



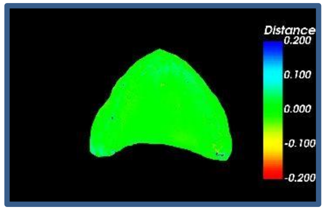
Upper 3



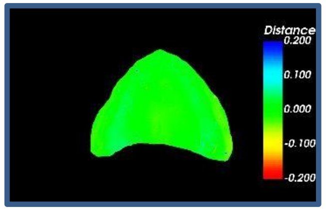
Upper 4



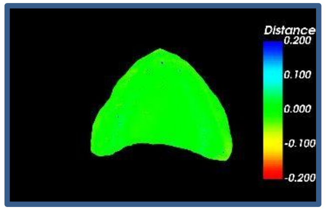
Upper 5



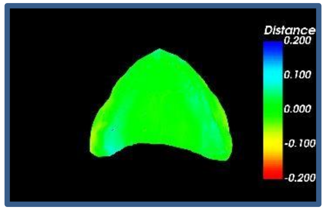
Upper 6



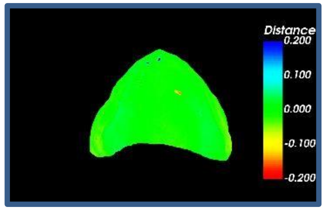
Upper 7



Upper8



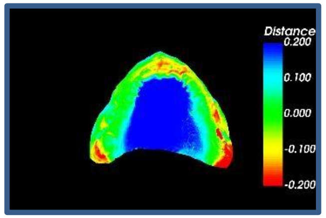
Upper 9



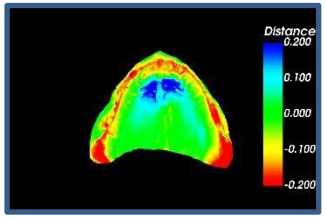
Upper 10

Appendix 2.5

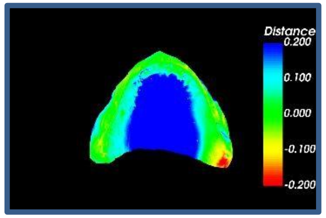
Upper no teeth aligned with CAD file



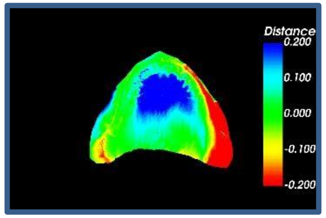
Upper 1



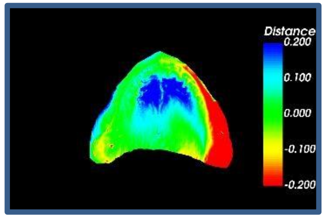
Upper 2



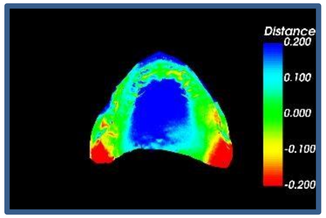
Upper 3



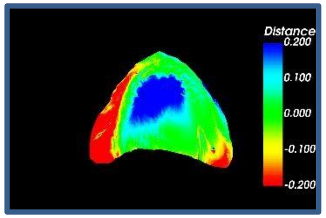
Upper 4



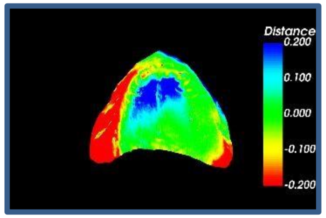
Upper 5



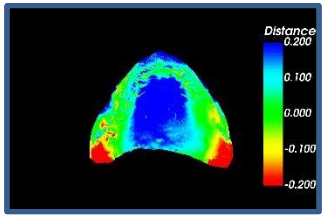
Upper 6



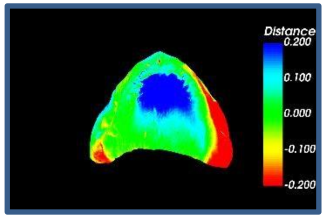
Upper 7



Upper8



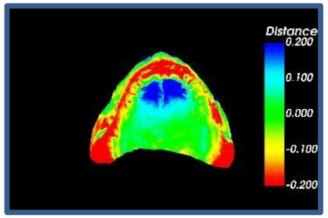
Upper 9



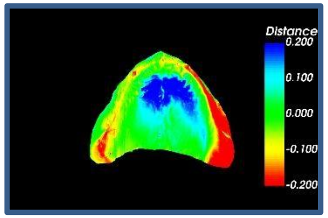
Upper 10

Appendix 2.6

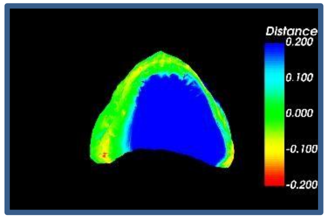
Upper with teeth aligned with CAD file



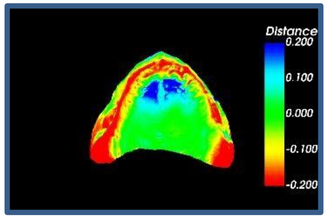
Upper 1



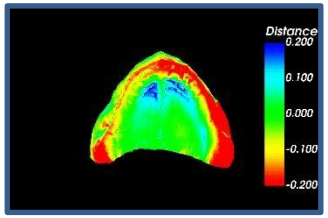
Upper 2



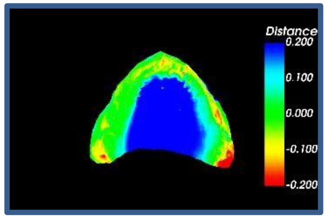
Upper 3



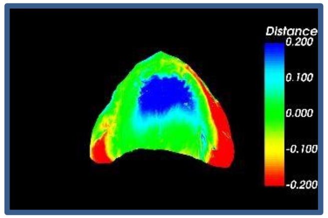
Upper 4



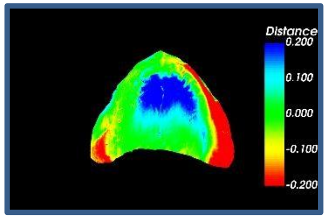
Upper 5



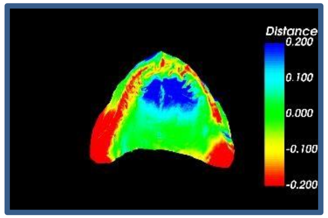
Upper 6



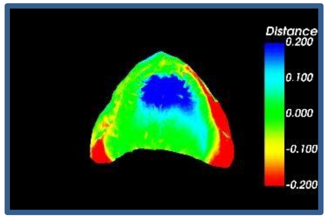
Upper 7



Upper8



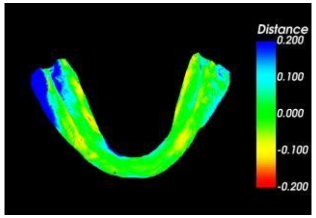
Upper 9



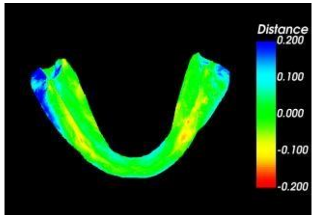
Upper 10

Appendix 3

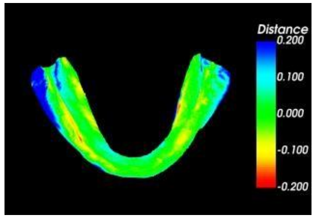
Lower Traditional denture aligned against its model



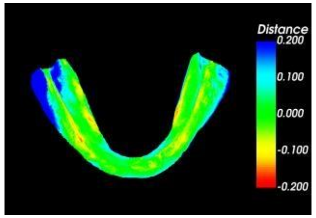
Lower 1



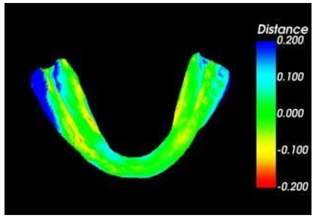
Lower 2



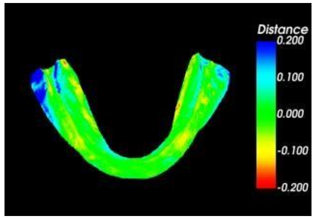
Lower 3



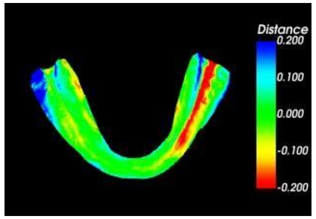
Lower 4



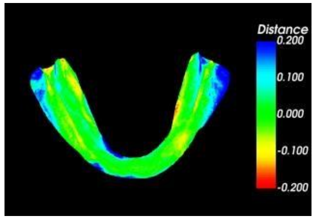
Lower 5



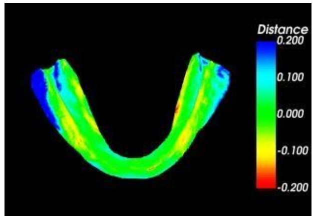
Lower 6



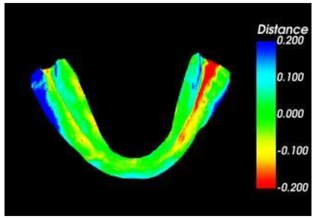
Lower 7



Lower 8



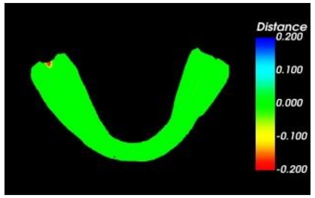
Lower 9



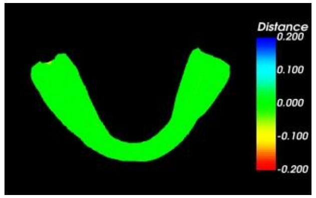
Lower 10

Appendix 3.1

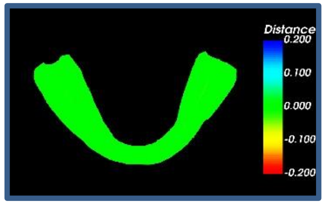
Lower CAD file against its model



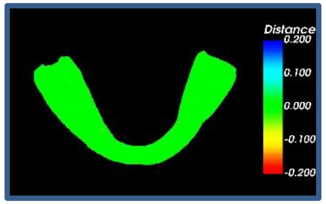
Lower 1



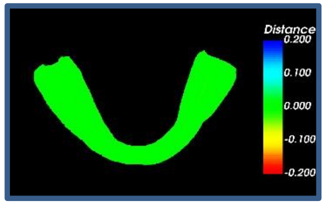
Lower 2



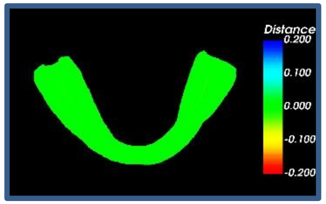
Lower 3



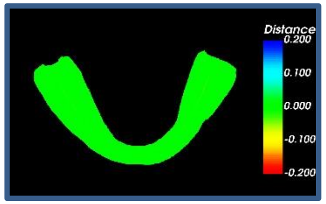
Lower 4



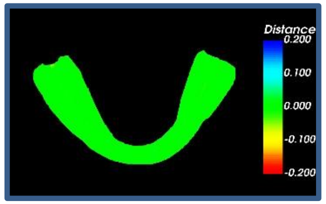
Lower 5



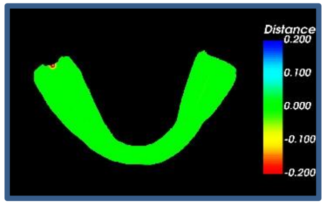
Lower 6



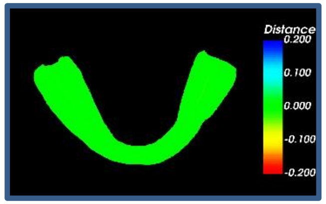
Lower 7



Lower 8



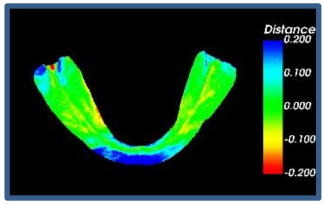
Lower 9



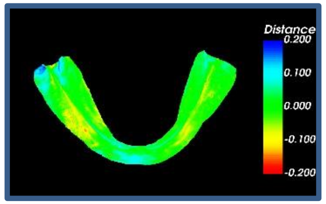
Lower 10

Appendix 3.2

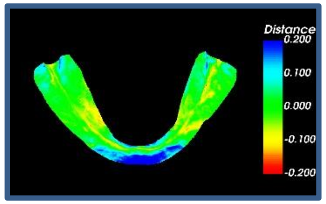
Lower Print without teeth against its model



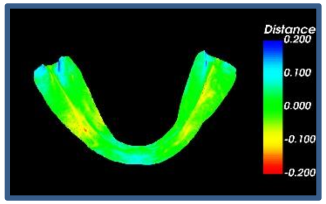
Lower 1



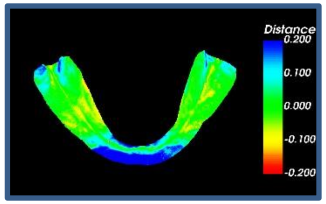
Lower 2



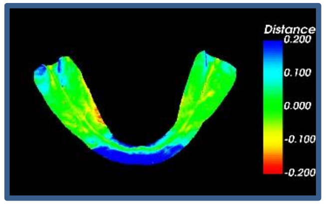
Lower 3



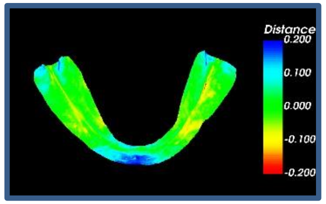
Lower 4



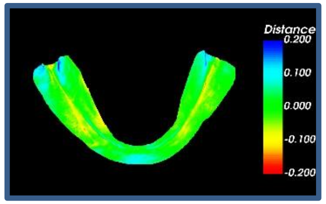
Lower 5



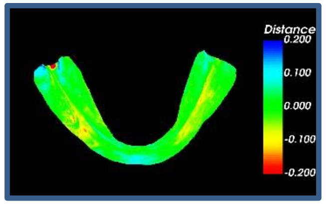
Lower 6



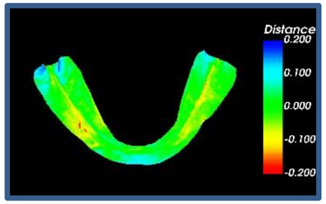
Lower 7



Lower 8



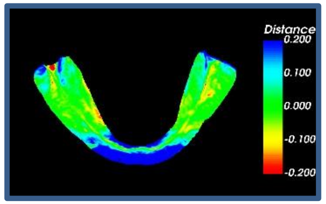
Lower 9



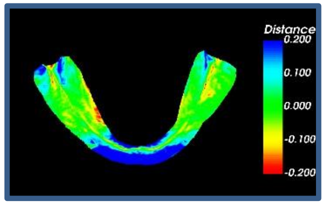
Lower 10

Appendix 3.3

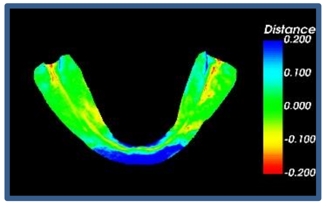
Lower printed with teeth against its model



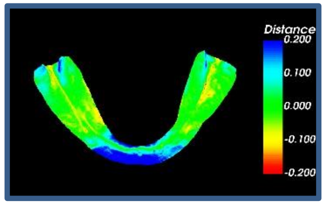
Lower 1



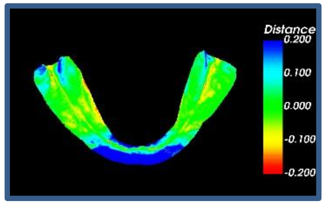
Lower 2



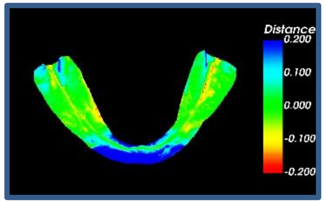
Lower 3



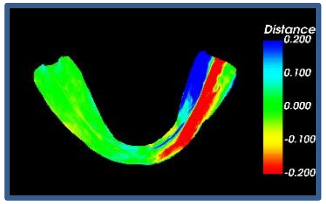
Lower 4



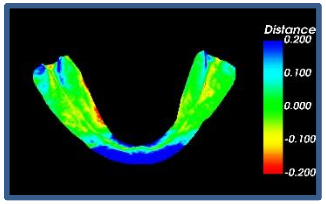
Lower 5



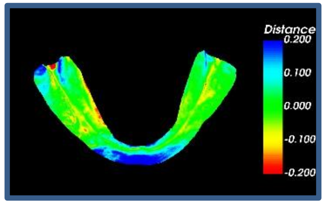
Lower 6



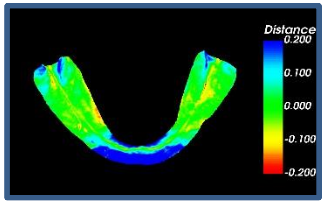
Lower 7



Lower 8



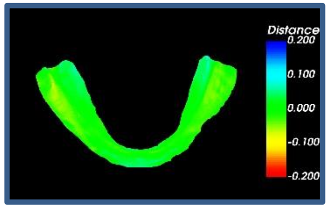
Lower 9



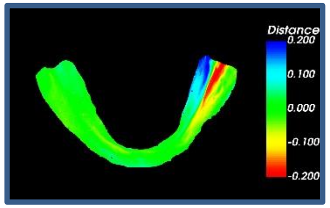
Lower 10

Appendix 3.4

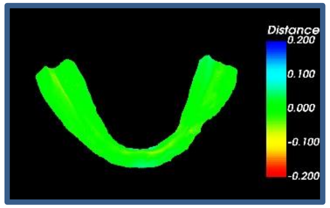
Lower pre and post print aligned with each other



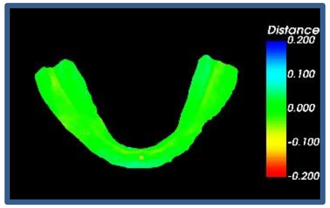
Lower 1



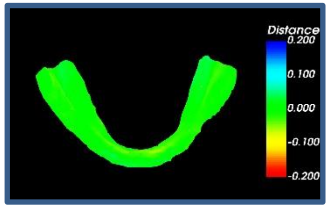
Lower 2



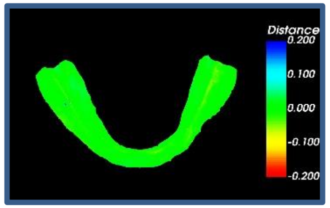
Lower 3



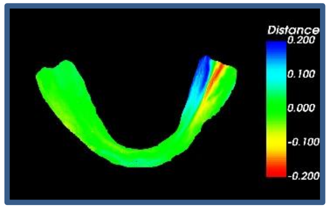
Lower 4



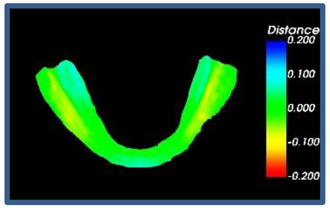
Lower 5



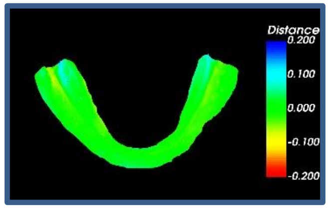
Lower 6



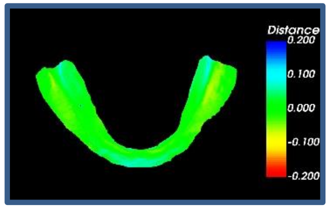
Lower 7



Lower 8



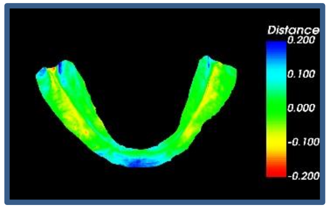
Lower 9



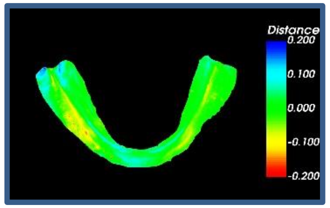
Lower 10

Appendix 3.5

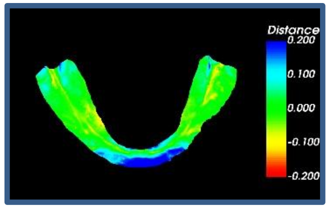
Lower no teeth aligned with CAD file



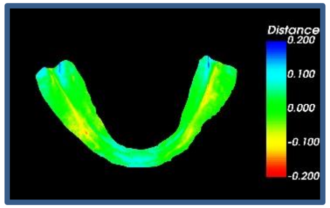
Lower 1



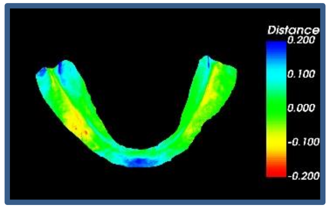
Lower 2



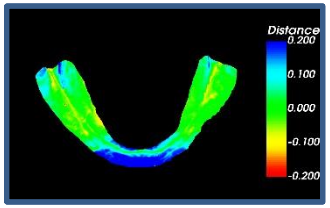
Lower 3



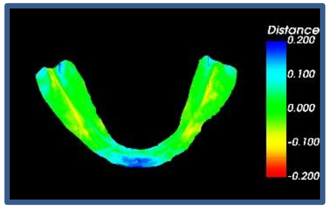
Lower 4



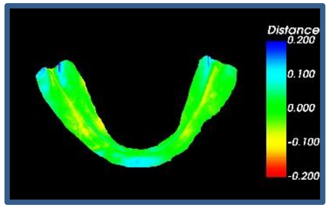
Lower 5



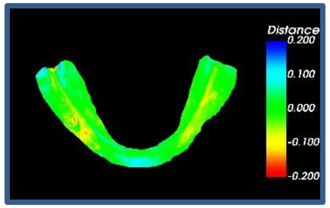
Lower 6



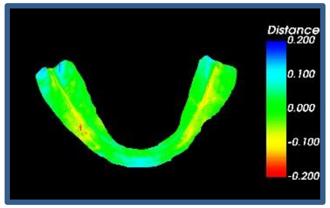
Lower 7



Lower 8



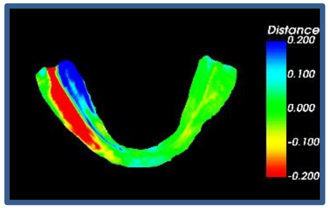
Lower 9



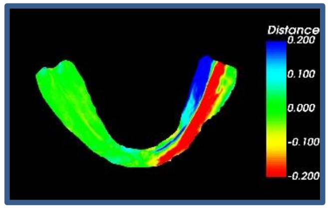
Lower 10

Appendix 3.6

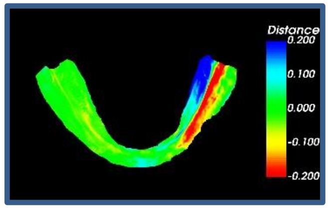
Lower with teeth aligned to CAD file



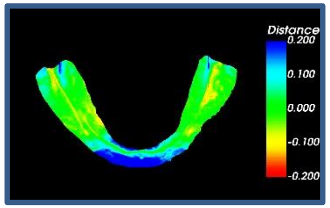
Lower 1



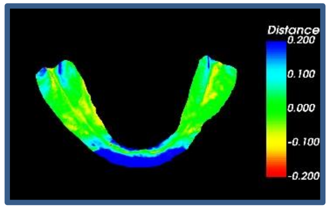
Lower 2



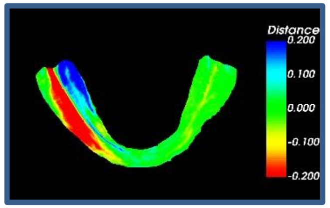
Lower 3



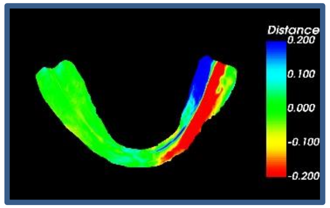
Lower 4



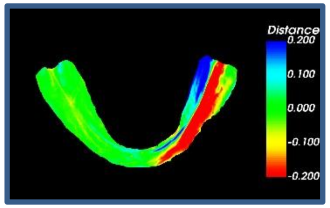
Lower 5



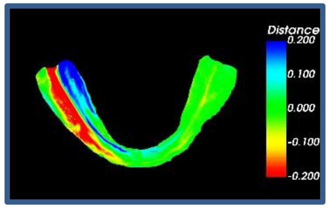
Lower 6



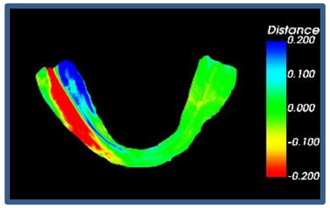
Lower 7



Lower 8



Lower 9



Lower 10

Appendix 4

Conventional Lowers and Upper Dentures to Models

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Lowers\Lower1\Lower1_denture.vtp	0.0626237	0.070278	0.0835982	0.0896893	-0.0412848	0.0296129	0.0216946	0.0915973	0.1	0.163896
E:\Masters_AK\Lowers\Lower2\Lower2_denture.vtp	0.0511259	0.0505231	0.0588796	0.0634767	-0.0434246	0.0310937	0.00755444	0.0714799	0.1	0.123647
E:\Masters_AK\Lowers\Lower3\Lower3_denture.vtp	0.0594723	0.0589575	0.0742454	0.0740281	-0.0447614	0.0323497	0.0146165	0.0824578	0.1	0.160543
E:\Masters_AK\Lowers\Lower4\Lower4_denture.vtp	0.0663182	0.0698339	0.0864567	0.0884539	-0.0459441	0.0327039	0.0206416	0.0940681	0.1	0.181638
E:\Masters_AK\Lowers\Lower5\Lower5_denture.vtp	0.0607032	0.0593919	0.07605	0.0751378	-0.0461941	0.0330388	0.013213	0.083891	0.1	0.159938
E:\Masters_AK\Lowers\Lower6\Lower6_denture.vtp	0.0495384	0.0509454	0.061708	0.0644883	-0.0391661	0.0320809	0.00724967	0.070689	0.1	0.117067
E:\Masters_AK\Lowers\Lower7\Lower7_denture.vtp	0.0729303	0.0733495	0.0705507	0.0768503	-0.0750073	0.0700852	-0.00717026	0.103187	0.1	0.25593
E:\Masters_AK\Lowers\Lower8\Lower8_denture.vtp	0.056468	0.0541808	0.071409	0.0659984	-0.0401869	0.0296584	0.0180059	0.0761576	0.1	0.164644
E:\Masters_AK\Lowers\Lower9\Lower9_denture.vtp	0.0612667	0.0598099	0.072477	0.0735489	-0.0483735	0.034047	0.0162705	0.0840601	0.1	0.161235
E:\Masters_AK\Lowers\Lower10\Lower10_denture.vtp	0.0703963	0.0642362	0.073159	0.0677192	-0.0678816	0.0607839	-0.000676165	0.0952967	0.1	0.235177
	0.0610843	**0.0611506**	**0.0728534**	**0.0739391**	**-0.0492224**	**0.0385454**	**0.011139979**	**0.08528845**		**0.1723715**
	0.0075526	**0.0081132**	**0.0084312**	**0.0092457**	**0.0121699**	**0.0144086**	**0.009395059**	**0.01072937**		**0.043455164**

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Uppers\Upper1\upper1_denture.vtp	0.0541158	0.0662193	0.0480144	0.0555694	-0.0586751	0.0728395	-0.0130475	0.084518	0.1	0.141682
E:\Masters_AK\Uppers\Upper2\upper2_denture.vtp	0.0629876	0.0686563	0.0512015	0.0595794	-0.071171	0.0732015	-0.021023	0.0907698	0.1	0.17721
E:\Masters_AK\Uppers\Upper3\upper3_denture.vtp	0.0485499	0.0550224	0.0418826	0.0494117	-0.0530629	0.0580828	-0.0147379	0.0718843	0.1	0.129814
E:\Masters_AK\Uppers\Upper4\upper4_denture.vtp	0.0533085	0.0650898	0.0506977	0.0679453	-0.0554511	0.0625679	-0.00760495	0.0837893	0.1	0.147258
E:\Masters_AK\Uppers\Upper5\upper5_denture.vtp	0.0613939	0.0640829	0.0539284	0.0576013	-0.0670854	0.0680664	-0.0147364	0.0875138	0.1	0.185527
E:\Masters_AK\Uppers\Upper6\upper6_denture.vtp	0.058137	0.0632599	0.0489512	0.0539721	-0.0647677	0.0684318	-0.0170936	0.0841994	0.1	0.177524
E:\Masters_AK\Uppers\Upper7\upper7_denture.vtp	0.0673007	0.0681662	0.0586594	0.0533475	-0.0742617	0.0773859	-0.0149583	0.0946164	0.1	0.228274
E:\Masters_AK\Uppers\Upper8\upper8_denture.vtp	0.0448314	0.0456743	0.036092	0.0372947	-0.0498845	0.0491776	-0.0183856	0.0613022	0.1	0.107518
E:\Masters_AK\Uppers\Upper9\upper9_denture.vtp	0.0650625	0.0649595	0.0632343	0.0585305	-0.0667852	0.0704398	-0.00370477	0.0918647	0.1	0.202892
E:\Masters_AK\Uppers\Upper10\upper10_denture.vtp	0.044048	0.0485884	0.0347431	0.0435272	-0.0507211	0.0508778	-0.0150276	0.0638375	0.1	0.085822
	0.0559735	**0.0609719**	**0.0487405**	**0.0536779**	**-0.0611866**	**0.0651071**	**-0.014031962**	**0.08142954**		**0.1583521**
	0.0083413	**0.0082252**	**0.0091212**	**0.0086329**	**0.0087691**	**0.0096398**	**0.00504395**	**0.01171668**		**0.043962923**

Appendix 4.1

Lowers printed without and with teeth to models

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Lowers\Lower1\Lower1_noteeth.vtp	0.0565097	0.059548	0.073338	0.0715798	-0.036961	0.031656	0.0223123	0.079003	0.1	0.169387
E:\Masters_AK\Lowers\Lower2\Lower2_noteeth.vtp	0.0367958	0.0297816	0.0383826	0.0328363	-0.035388	0.026702	-0.000702622	0.0473327	0.1	0.0309089
E:\Masters_AK\Lowers\Lower3\Lower3_noteeth.vtp	0.0550485	0.0537551	0.0691634	0.0665743	-0.040442	0.029561	0.0152991	0.0754048	0.1	0.146975
E:\Masters_AK\Lowers\Lower4\Lower4_noteeth.vtp	0.0417623	0.0326351	0.0429219	0.0353204	-0.04067	0.029844	-0.000119731	0.0530012	0.1	0.0452903
E:\Masters_AK\Lowers\Lower5\Lower5_noteeth.vtp	0.0640523	0.0711157	0.0852223	0.0856845	-0.036401	0.026903	0.0324832	0.0900277	0.1	0.179622
E:\Masters_AK\Lowers\Lower6\Lower6_noteeth.vtp	0.06404	0.0693961	0.0860042	0.0842641	-0.037969	0.029185	0.0293168	0.0897634	0.1	0.192619
E:\Masters_AK\Lowers\Lower7\Lower7_noteeth.vtp	0.0456865	0.0388112	0.0541633	0.0467144	-0.037425	0.026631	0.00778156	0.0594392	0.1	0.0952812
E:\Masters_AK\Lowers\Lower8\Lower8_noteeth.vtp	0.0409532	0.0324953	0.0445763	0.0376942	-0.037947	0.027078	-0.000525483	0.0522765	0.1	0.0461529
E:\Masters_AK\Lowers\Lower9\Lower9_noteeth.vtp	0.0361475	0.031857	0.0334133	0.0294244	-0.038879	0.033895	-0.00274936	0.0481036	0.1	0.0360845
E:\Masters_AK\Lowers\Lower10\Lower10_noteeth.vtp	0.0421957	0.0339569	0.0429445	0.0362317	-0.041521	0.031752	-0.0014742	0.0541422	0.1	0.0569835
	0.0483192	**0.0453352**	**0.057013**	**0.0526324**	**-0.03836**	**0.029321**	**0.010162156**	**0.06484943**		**0.09993043**
	0.0106961	**0.0164594**	**0.0197588**	**0.0221202**	**0.0019932**	**0.00253**	**0.013682548**	**0.01698373**		**0.0654584**
Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Lowers\Lower1\Lower1_print_with_teeth.vtp	0.0857117	0.10246	0.117068	0.12064	-0.041633	0.03836	0.0511002	0.123423	0.1	0.258567
E:\Masters_AK\Lowers\Lower2\Lower2_print_with_teeth.vtp	0.0849042	0.0926627	0.115826	0.11226	-0.048225	0.03665	0.0407862	0.118876	0.1	0.262381
E:\Masters_AK\Lowers\Lower3\Lower3_print_with_teeth.vtp	0.0679794	0.0720184	0.0857291	0.0895271	-0.049266	0.039017	0.0200154	0.0969909	0.1	0.201671
E:\Masters_AK\Lowers\Lower4\Lower4_print_with_teeth.vtp	0.0614517	0.0625681	0.0791912	0.0747012	-0.041586	0.036091	0.0222171	0.084838	0.1	0.186658
E:\Masters_AK\Lowers\Lower5\Lower5_print_with_teeth.vtp	0.0770949	0.0883926	0.103341	0.104299	-0.044923	0.046657	0.036729	0.111391	0.1	0.22335
E:\Masters_AK\Lowers\Lower6\Lower6_print_with_teeth.vtp	0.0691149	0.0755424	0.0916191	0.0914883	-0.042742	0.036005	0.0297556	0.09797	0.1	0.212043
E:\Masters_AK\Lowers\Lower7\Lower7_print_with_teeth.vtp	0.104968	0.121224	0.110335	0.126478	-0.101171	0.117217	-0.0135434	0.159781	0.1	0.338114
E:\Masters_AK\Lowers\Lower8\Lower8_print_with_teeth.vtp	0.0785124	0.0875612	0.107245	0.106261	-0.044958	0.036666	0.0370338	0.111623	0.1	0.233013
E:\Masters_AK\Lowers\Lower9\Lower9_print_with_teeth.vtp	0.0617684	0.0600971	0.0769564	0.0697989	-0.045523	0.041869	0.0177768	0.0843267	0.1	0.196788
E:\Masters_AK\Lowers\Lower10\Lower10_print_with_teeth.vtp	0.0717397	0.0785533	0.0986952	0.0948829	-0.040058	0.03137	0.0349109	0.100491	0.1	0.218347
	0.0763245	**0.084108**	**0.0986006**	**0.0990336**	**-0.050009**	**0.04599**	**0.02767816**	**0.10897106**		**0.2330932**
	0.0131794	**0.0185853**	**0.0146525**	**0.0185178**	**0.0182139**	**0.025349**	**0.017739728**	**0.02218036**		**0.044413719**

Appendix 4.2

Uppers printed without and with teeth to models

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Uppers\Upper1\upper1_noteeth.vtp	0.120547	0.110336	0.109689	0.111516	-0.129638	0.108505	-0.020577	0.162118	0.1	0.446821
E:\Masters_AK\Uppers\Upper2\upper2_noteeth.vtp	0.0821736	0.0756306	0.0593725	0.0604298	-0.097292	0.080735	-0.0348299	0.10611	0.1	0.321023
E:\Masters_AK\Uppers\Upper3\upper3_noteeth.vtp	0.110365	0.0965861	0.0809511	0.0786115	-0.12633	0.101556	-0.0534046	0.136592	0.1	0.428953
E:\Masters_AK\Uppers\Upper4\upper4_noteeth.vtp	0.104462	0.097526	0.0768198	0.0774575	-0.123197	0.104988	-0.0423973	0.136478	0.1	0.40437
E:\Masters_AK\Uppers\Upper5\upper5_noteeth.vtp	0.0973549	0.0917926	0.0607271	0.0538994	-0.12125	0.102865	-0.0494032	0.124351	0.1	0.362906
E:\Masters_AK\Uppers\Upper6\upper6_noteeth.vtp	0.120282	0.107498	0.0772558	0.0698619	-0.147692	0.117802	-0.0601545	0.149683	0.1	0.44888
E:\Masters_AK\Uppers\Upper7\upper7_noteeth.vtp	0.111874	0.100369	0.0824854	0.0837784	-0.13181	0.105655	-0.0451968	0.143342	0.1	0.433892
E:\Masters_AK\Uppers\Upper8\upper8_noteeth.vtp	0.114624	0.104716	0.0757362	0.0757396	-0.136752	0.112209	-0.0596898	0.143322	0.1	0.450195
E:\Masters_AK\Uppers\Upper9\upper9_noteeth.vtp	0.113406	0.100225	0.0758749	0.0766445	-0.138704	0.106146	-0.0523033	0.142022	0.1	0.446927
E:\Masters_AK\Uppers\Upper10\upper10_noteeth.vtp	0.104267	0.102517	0.0917214	0.10982	-0.113802	0.095502	-0.0250525	0.144062	0.1	0.401925
	0.1079356	**0.0987196**	**0.0790633**	**0.0797759**	**-0.126647**	**0.103596**	**-0.04430089**	**0.138808**		**0.4145892**
	0.0115888	**0.0097435**	**0.0144026**	**0.0185625**	**0.0141178**	**0.010031**	**0.013697342**	**0.01501478**		**0.043202073**
Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Uppers\Upper1\upper1_print_with_teeth.vtp	0.114007	0.106677	0.100694	0.102212	-0.125396	0.109071	-0.0211573	0.154693	0.1	0.418677
E:\Masters_AK\Uppers\Upper2\upper2_print_with_teeth.vtp	0.0975671	0.0963748	0.0642538	0.0651327	-0.116728	0.105758	-0.0506432	0.127447	0.1	0.376201
E:\Masters_AK\Uppers\Upper3\upper3_print_with_teeth.vtp	0.105799	0.0974876	0.0726734	0.072386	-0.127546	0.105403	-0.0481963	0.135552	0.1	0.409763
E:\Masters_AK\Uppers\Upper4\upper4_print_with_teeth.vtp	0.102905	0.100595	0.0714752	0.0759288	-0.124115	0.109275	-0.0453061	0.136587	0.1	0.39192
E:\Masters_AK\Uppers\Upper5\upper5_print_with_teeth.vtp	0.105687	0.109609	0.0589282	0.0601321	-0.134927	0.122652	-0.060342	0.139795	0.1	0.367495
E:\Masters_AK\Uppers\Upper6\upper6_print_with_teeth.vtp	0.118579	0.107938	0.0730034	0.0660251	-0.144484	0.118081	-0.0656657	0.146286	0.1	0.447087
E:\Masters_AK\Uppers\Upper7\upper7_print_with_teeth.vtp	0.108228	0.0971396	0.0839193	0.0797909	-0.124448	0.104052	-0.0410572	0.139512	0.1	0.431551
E:\Masters_AK\Uppers\Upper8\upper8_print_with_teeth.vtp	0.121322	0.120252	0.0701072	0.0733814	-0.149686	0.131262	-0.0713477	0.155207	0.1	0.434975
E:\Masters_AK\Uppers\Upper9\upper9_print_with_teeth.vtp	0.114433	0.105069	0.0802622	0.0804543	-0.136897	0.113001	-0.0507604	0.146825	0.1	0.443877
E:\Masters_AK\Uppers\Upper10\upper10_print_with_teeth.vtp	0.109685	0.106917	0.0922672	0.103092	-0.122567	0.107866	-0.031231	0.149956	0.1	0.416252
	0.1098212	**0.1048059**	**0.0767584**	**0.0778535**	**-0.130679**	**0.112642**	**-0.04857069**	**0.143186**		**0.4137798**
	0.007315	**0.0073078**	**0.0127114**	**0.0145687**	**0.0104808**	**0.008801**	**0.015195374**	**0.00894513**		**0.027605941**

Appendix 4.3

Lower and Upper CAD files to models

Mesh	U_Mean	U_SD	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Lowers\Lower1\Lower1_print.vtp	0.00388617	0.00903461	0.00324762	0.00361789	-0.00437504	0.0115561	-0.00106969	0.00977661	0.1	0.00179885
E:\Masters_AK\Lowers\Lower2\Lower2_print.vtp	0.00397098	0.00422199	0.0031861	0.00345865	-0.00433292	0.00448483	-0.00195991	0.00545459	0.1	9.98E-05
E:\Masters_AK\Lowers\Lower3\Lower3_print.vtp	0.00352477	0.00340195	0.0030659	0.0032052	-0.00378473	0.00348179	-0.00130723	0.00472106	0.1	0
E:\Masters_AK\Lowers\Lower4\Lower4_print.vtp	0.00320731	0.0039655	0.00287108	0.00354043	-0.00340106	0.00417865	-0.00110804	0.00497838	0.1	0.00011386
E:\Masters_AK\Lowers\Lower5\Lower5_print.vtp	0.00348074	0.0033523	0.00313721	0.00339495	-0.00369142	0.00330828	-0.00109553	0.00470673	0.1	0
E:\Masters_AK\Lowers\Lower6\Lower6_print.vtp	0.0034851	0.0035024	0.00309566	0.00342571	-0.00371477	0.00352674	-0.00118837	0.00479589	0.1	0
E:\Masters_AK\Lowers\Lower7\Lower7_print.vtp	0.00355804	0.003421	0.00300221	0.00310865	-0.0038676	0.00354559	-0.00141019	0.00473014	0.1	0
E:\Masters_AK\Lowers\Lower8\Lower8_print.vtp	0.00370183	0.00377423	0.00340418	0.00355029	-0.00391488	0.00391281	-0.000861543	0.00521595	0.1	0
E:\Masters_AK\Lowers\Lower9\Lower9_print.vtp	0.00405339	0.0091182	0.00333893	0.00336002	-0.00454496	0.0114885	-0.00133154	0.00988931	0.1	0.00158066
E:\Masters_AK\Lowers\Lower10\Lower10_print.vtp	0.00364862	0.00343968	0.00314438	0.00317765	-0.0039337	0.00354777	-0.00137734	0.00482149	0.1	0
	0.0036517	**0.00472319**	**0.00314933**	**0.00338394**	**-0.003956108**	**0.00530311**	**-0.001270938**	**0.00590902**		**0.000359313**
	0.00025823	**0.00231153**	**0.0001567**	**0.00017166**	**0.000355907**	**0.00329727**	**0.000294884**	**0.00208226**		**0.000704447**

Mesh	U_Mean	U_SD	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Uppers\Upper1\upper1_print.vtp	0.00379841	0.0134211	0.00479637	0.0209531	-0.00315965	0.0036556	-5.47E-05	0.0139481	0.1	0.00168586
E:\Masters_AK\Uppers\Upper2\upper2_print.vtp	0.00323355	0.00423002	0.00330711	0.00468826	-0.00318583	0.00390331	-0.000630825	0.00528687	0.1	3.17E-06
E:\Masters_AK\Uppers\Upper3\upper3_print.vtp	0.00314038	0.00395635	0.00323993	0.00447113	-0.00307512	0.00357748	-0.000574766	0.0050184	0.1	1.10E-05
E:\Masters_AK\Uppers\Upper4\upper4_print.vtp	0.00324695	0.00417603	0.00329214	0.00468072	-0.00321736	0.0038092	-0.00064153	0.00525075	0.1	2.03E-05
E:\Masters_AK\Uppers\Upper5\upper5_print.vtp	0.00325825	0.00424281	0.0033336	0.00487672	-0.00321056	0.00378632	-0.000673843	0.00530694	0.1	3.15E-05
E:\Masters_AK\Uppers\Upper6\upper6_print.vtp	0.00321783	0.00551027	0.00348305	0.00775164	-0.00304675	0.00333385	-0.000486328	0.00636246	0.1	0.000489849
E:\Masters_AK\Uppers\Upper7\upper7_print.vtp	0.0031682	0.0040415	0.00326341	0.00454252	-0.00310551	0.00367318	-0.000577037	0.00510277	0.1	0
E:\Masters_AK\Uppers\Upper8\upper8_print.vtp	0.00317702	0.00407383	0.00325851	0.00469376	-0.00312917	0.00366035	-0.000765935	0.0051091	0.1	2.60E-05
E:\Masters_AK\Uppers\Upper9\upper9_print.vtp	0.00317528	0.00402414	0.00327588	0.00485993	-0.00312241	0.00350472	-0.000918107	0.00504314	0.1	3.69E-06
E:\Masters_AK\Uppers\Upper10\upper10_print.vtp	0.00312769	0.00397341	0.00321915	0.00463327	-0.00307364	0.00352478	-0.000736227	0.00500284	0.1	0
	0.00325436	**0.00516495**	**0.00344692**	**0.00661511**	**-0.0031326**	**0.00364288**	**-0.000605928**	**0.00614314**		**0.000227132**
	0.00019622	**0.00293675**	**0.00047979**	**0.00513094**	**5.94672E-05**	**0.00016675**	**0.000227673**	**0.00277131**		**0.000534209**

Appendix 4.4

Lowers without and with teeth aligned to CAD files

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Lowers\3d_aligns\Lower1\Lower1_printednoteeth_aligned.vtp	0.052039	0.0400762	0.0575188	0.0464298	-0.045548	0.0296218	0.0103347	0.0648638	0.1	0.110981
E:\Masters_AK\Lowers\3d_aligns\Lower2\Lower2_printednoteeth_aligned.vtp	0.03763	0.0295468	0.037746	0.0306839	-0.0374969	0.0281901	0.00263819	0.0477708	0.1	0.0355505
E:\Masters_AK\Lowers\3d_aligns\Lower3\Lower3_printednoteeth_aligned.vtp	0.053745	0.0560798	0.0685959	0.0682808	-0.0351453	0.0249509	0.0225373	0.0743337	0.1	0.145573
E:\Masters_AK\Lowers\3d_aligns\Lower4\Lower4_printednoteeth_aligned.vtp	0.041945	0.0318019	0.0421016	0.0331749	-0.041771	0.0302103	0.00226892	0.0525886	0.1	0.0425738
E:\Masters_AK\Lowers\3d_aligns\Lower5\Lower5_printednoteeth_aligned.vtp	0.057759	0.0419354	0.0648313	0.0460091	-0.0485987	0.0338511	0.0154092	0.0696936	0.1	0.144924
E:\Masters_AK\Lowers\3d_aligns\Lower6\Lower6_printednoteeth_aligned.vtp	0.06181	0.0657959	0.0802512	0.0759587	-0.0326563	0.0257708	0.036503	0.0825655	0.1	0.19191
E:\Masters_AK\Lowers\3d_aligns\Lower7\Lower7_printednoteeth_aligned.vtp	0.044714	0.0378604	0.0513929	0.0438933	-0.0369853	0.0274092	0.0104254	0.0576549	0.1	0.0888922
E:\Masters_AK\Lowers\3d_aligns\Lower8\Lower8_printednoteeth_aligned.vtp	0.03872	0.0317439	0.0441218	0.0372208	-0.0338079	0.0247686	0.00331001	0.0499599	0.1	0.0442614
E:\Masters_AK\Lowers\3d_aligns\Lower9\Lower9_printednoteeth_aligned.vtp	0.035153	0.0280064	0.0331051	0.0282552	-0.0371775	0.0276092	-0.00223415	0.0448897	0.1	0.0280294
E:\Masters_AK\Lowers\3d_aligns\Lower10\Lower10_printednoteeth_aligned.vtp	0.040993	0.0325282	0.039742	0.0330289	-0.0422051	0.0319893	-0.00189248	0.0522969	0.1	0.0486732
	0.046451	**0.0395375**	**0.0519407**	**0.0442935**	**-0.0391392**	**0.0284371**	**0.009930009**	**0.05966174**		**0.08813685**
	0.009229	**0.0123581**	**0.0154182**	**0.0160856**	**0.0052118**	**0.003**	**0.012197102**	**0.01260326**		**0.057495546**
Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Lowers\3d_aligns\Lower1\Lower1_printedwithteeth_aligned.vtp	0.097098	0.0975588	0.100696	0.0958711	-0.0944061	0.0987173	-0.0108977	0.137212	0.1	0.347896
E:\Masters_AK\Lowers\3d_aligns\Lower2\Lower2_printedwithteeth_aligned.vtp	0.096706	0.112443	0.10096	0.114116	-0.0942081	0.111373	-0.0220035	0.146667	0.1	0.3266
E:\Masters_AK\Lowers\3d_aligns\Lower3\Lower3_printedwithteeth_aligned.vtp	0.069352	0.078341	0.0825787	0.0896661	-0.0621786	0.0704198	-0.0112736	0.104019	0.1	0.242833
E:\Masters_AK\Lowers\3d_aligns\Lower4\Lower4_printedwithteeth_aligned.vtp	0.062574	0.0648544	0.0808329	0.0770791	-0.0412112	0.0364629	0.0245921	0.0866999	0.1	0.193359
E:\Masters_AK\Lowers\3d_aligns\Lower5\Lower5_printedwithteeth_aligned.vtp	0.078259	0.0936327	0.107006	0.110591	-0.0416389	0.04429	0.0416354	0.114709	0.1	0.223158
E:\Masters_AK\Lowers\3d_aligns\Lower6\Lower6_printedwithteeth_aligned.vtp	0.089066	0.0937527	0.0851331	0.0834987	-0.091925	0.100455	-0.0173973	0.128139	0.1	0.343714
E:\Masters_AK\Lowers\3d_aligns\Lower7\Lower7_printedwithteeth_aligned.vtp	0.098317	0.11525	0.0977372	0.115862	-0.0986837	0.11486	-0.0225155	0.149806	0.1	0.322249
E:\Masters_AK\Lowers\3d_aligns\Lower8\Lower8_printedwithteeth_aligned.vtp	0.088365	0.0990514	0.0764153	0.0880985	-0.0961863	0.104872	-0.0279062	0.129772	0.1	0.313554
E:\Masters_AK\Lowers\3d_aligns\Lower9\Lower9_printedwithteeth_aligned.vtp	0.090287	0.0961283	0.0952002	0.087854	-0.0868994	0.101303	-0.0125775	0.131279	0.1	0.345006
E:\Masters_AK\Lowers\3d_aligns\Lower10\Lower10_printedwithteeth_aligned.vtp	0.094779	0.100288	0.0921605	0.0909127	-0.0966889	0.106568	-0.0170311	0.136933	0.1	0.347109
	0.08648	**0.09513**	**0.091872**	**0.0953549**	**-0.0804026**	**0.0889321**	**-0.00753749**	**0.12652359**		**0.3005478**
	0.012398	**0.0147424**	**0.0101522**	**0.0135011**	**0.0230481**	**0.0283062**	**0.02245185**	**0.0195453**		**0.058097703**

Appendix 4.5

Uppers without and with teeth aligned to CAD files

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Uppers\3d_aligns\Upper1\Upper1_printednoteeth_aligned.vtp	0.131249	0.116152	0.152925	0.126025	-0.0880682	0.0769902	0.0723816	0.159619	0.1	0.494486
E:\Masters_AK\Uppers\3d_aligns\Upper2\Upper2_printednoteeth_aligned.vtp	0.080117	0.0722356	0.0626005	0.0619516	-0.0950155	0.076869	-0.0225702	0.105486	0.1	0.316083
E:\Masters_AK\Uppers\3d_aligns\Upper3\Upper3_printednoteeth_aligned.vtp	0.131399	0.12814	0.16334	0.134545	-0.0462626	0.0443584	0.106157	0.149721	0.1	0.415893
E:\Masters_AK\Uppers\3d_aligns\Upper4\Upper4_printednoteeth_aligned.vtp	0.120379	0.119392	0.105975	0.10472	-0.140741	0.134887	0.00375853	0.169503	0.1	0.4141
E:\Masters_AK\Uppers\3d_aligns\Upper5\Upper5_printednoteeth_aligned.vtp	0.112657	0.113137	0.0863002	0.0737561	-0.14757	0.142865	-0.0143059	0.159019	0.1	0.387058
E:\Masters_AK\Uppers\3d_aligns\Upper6\Upper6_printednoteeth_aligned.vtp	0.141171	0.106626	0.146607	0.0969635	-0.127957	0.126115	0.0665813	0.163907	0.1	0.561847
E:\Masters_AK\Uppers\3d_aligns\Upper7\Upper7_printednoteeth_aligned.vtp	0.126886	0.114661	0.111422	0.104131	-0.150454	0.125455	0.00766932	0.170846	0.1	0.469295
E:\Masters_AK\Uppers\3d_aligns\Upper8\Upper8_printednoteeth_aligned.vtp	0.128384	0.12608	0.110378	0.0966829	-0.144561	0.145693	-0.0239115	0.178345	0.1	0.448312
E:\Masters_AK\Uppers\3d_aligns\Upper9\Upper9_printednoteeth_aligned.vtp	0.137207	0.10463	0.144064	0.0995052	-0.119249	0.115073	0.0713018	0.157128	0.1	0.559746
E:\Masters_AK\Uppers\3d_aligns\Upper10\Upper10_printednoteeth_aligned.vtp	0.121595	0.126925	0.119937	0.132033	-0.123595	0.120447	0.00954066	0.175512	0.1	0.417756
	0.123104	**0.1127979**	**0.1203549**	**0.1030313**	**-0.1183473**	**0.1108753**	**0.027660261**	**0.1589086**		**0.4484576**
	0.017222	**0.0163971**	**0.0316954**	**0.0235729**	**0.033085**	**0.0334919**	**0.046932957**	**0.02075049**		**0.076209891**

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Uppers\3d_aligns\Upper1\Upper1_printedwithteeth_aligned.vtp	0.116175	0.10931	0.100597	0.099621	-0.130093	0.115528	-0.0212371	0.158095	0.1	0.430551
E:\Masters_AK\Uppers\3d_aligns\Upper2\Upper2_printedwithteeth_aligned.vtp	0.101976	0.0983333	0.0916572	0.0840455	-0.110633	0.108127	-0.0183444	0.140471	0.1	0.378625
E:\Masters_AK\Uppers\3d_aligns\Upper3\Upper3_printedwithteeth_aligned.vtp	0.154887	0.1396	0.207837	0.14236	-0.0533149	0.0479544	0.118348	0.171673	0.1	0.492731
E:\Masters_AK\Uppers\3d_aligns\Upper4\Upper4_printedwithteeth_aligned.vtp	0.100306	0.0965234	0.0734488	0.0752454	-0.122335	0.106008	-0.0341118	0.134961	0.1	0.390532
E:\Masters_AK\Uppers\3d_aligns\Upper5\Upper5_printedwithteeth_aligned.vtp	0.102562	0.10586	0.0614539	0.0582794	-0.131213	0.121041	-0.0520817	0.137887	0.1	0.360033
E:\Masters_AK\Uppers\3d_aligns\Upper6\Upper6_printedwithteeth_aligned.vtp	0.122426	0.107967	0.153114	0.117061	-0.068962	0.0599404	0.0721286	0.146433	0.1	0.44226
E:\Masters_AK\Uppers\3d_aligns\Upper7\Upper7_printedwithteeth_aligned.vtp	0.113215	0.112491	0.102232	0.103079	-0.124348	0.120269	-0.0102882	0.159267	0.1	0.416387
E:\Masters_AK\Uppers\3d_aligns\Upper8\Upper8_printedwithteeth_aligned.vtp	0.12514	0.128703	0.104327	0.102622	-0.145	0.146675	-0.0232579	0.177999	0.1	0.427951
E:\Masters_AK\Uppers\3d_aligns\Upper9\Upper9_printedwithteeth_aligned.vtp	0.123384	0.114877	0.101935	0.0985452	-0.144501	0.125416	-0.0222437	0.167109	0.1	0.451863
E:\Masters_AK\Uppers\3d_aligns\Upper10\Upper10_printedwithteeth_aligned.vtp	0.114934	0.119473	0.110126	0.123621	-0.119276	0.115428	-0.0104247	0.165454	0.1	0.407948
	0.117501	**0.1133138**	**0.1106728**	**0.100448**	**-0.1149676**	**0.1066387**	**-0.00015129**	**0.1559349**		**0.4198881**
	0.015991	**0.0132303**	**0.0417686**	**0.0241936**	**0.0304851**	**0.0300595**	**0.052833532**	**0.01513203**		**0.038455707**

Appendix 4.6

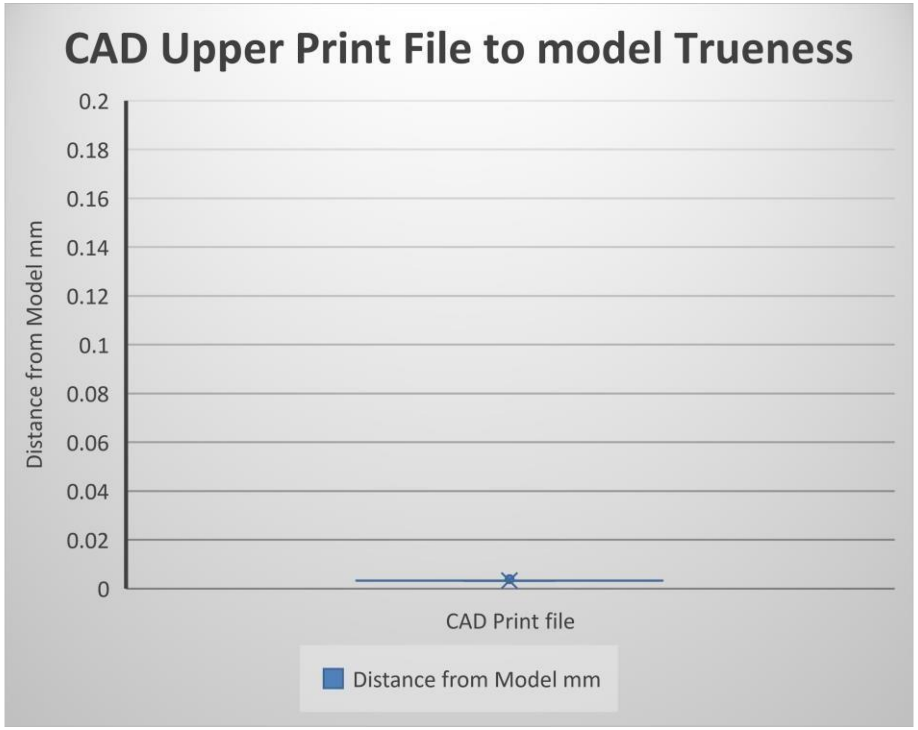
Lowers and Uppers no teeth to with teeth directly aligned

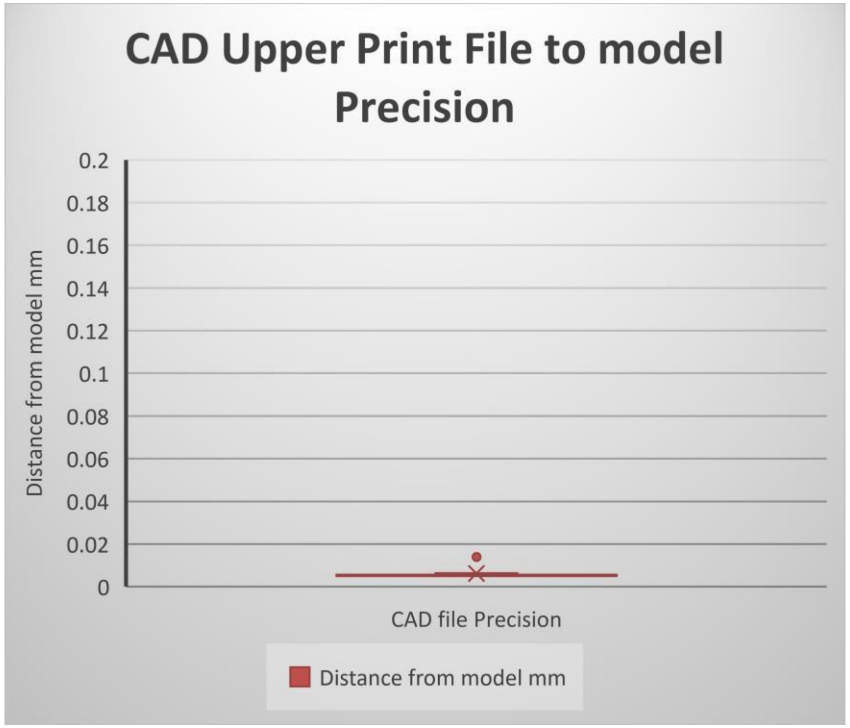
Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower1\Lower1_printednoteeth_aligned.vtp	0.0259068	0.0163402	0.0272855	0.0179596	-0.0249216	0.0149995	-0.00316475	0.0304655	0.1	0.00223685
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower2\Lower2_printednoteeth_aligned.vtp	0.0470521	0.0519786	0.0492238	0.0543679	-0.0452587	0.0498479	-2.52E-03	0.0700664	0.1	0.145789
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower3\Lower3_printednoteeth_aligned.vtp	0.016663	0.0168069	0.0152769	0.0160151	-0.0175017	0.0172143	-0.00514565	0.0231009	0.1	0.00266359
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower4\Lower4_printednoteeth_aligned.vtp	0.0216516	0.0168637	0.0210884	0.0163055	-0.0220577	0.0172435	-0.00398065	0.0271538	0.1	0.00202824
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower5\Lower5_printednoteeth_aligned.vtp	0.0181684	0.0292075	0.0176935	0.0313013	-0.0184929	0.0276813	-0.0038041	0.0341862	0.1	0.00540922
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower6\Lower6_printednoteeth_aligned.vtp	0.0128232	0.0173245	0.0112843	0.0165924	-0.0141011	0.0178089	-0.00258454	0.0213984	0.1	0.00344346
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower7\Lower7_printednoteeth_aligned.vtp	0.0434771	0.0475414	0.0486598	0.0533025	-0.0383315	0.040376	0.00500789	0.064229	0.1	0.141366
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower8\Lower8_printednoteeth_aligned.vtp	0.0370195	0.0241118	0.0362194	0.0240641	-0.0378336	0.0241331	-0.000484277	0.0441767	0.1	0.00489186
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower9\Lower9_printednoteeth_aligned.vtp	0.025363	0.0230848	0.0276136	0.0240643	-0.0235284	0.0220854	-0.000561245	0.034291	0.1	0.00875448
E:\Masters_AK\Lowers\3d_aligns_prepost\Lower10\Lower10_printednoteeth_aligned.vtp	0.0284686	0.0204634	0.0320759	0.0233441	-0.0253741	0.0170222	0.00115327	0.0350412	0.1	0.0075798
	0.02765933	**0.02637228**	**0.02864211**	**0.02773168**	**-0.02674013**	**0.02484121**	**-0.001608849**	**0.03841091**		**0.03241625**
	0.011499247	**0.013026044**	**0.013137188**	**0.014566559**	**0.010278815**	**0.011576656**	**0.002998839**	**0.016538638**		**0.05863825**

Mesh	U_Mean	U_Sd	Mean_Pos	SD_Pos	Mean_Neg	SD_Neg	Signed_Mean	Signed_Dev	Maximum_distance	Proportion_beyond
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper1\Upper1_printednoteeth_aligned.vtp	0.0200895	0.0321913	0.0235266	0.0470166	-0.0178983	0.0165939	-0.00177117	0.0379042	0.1	0.00641716
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper2\Upper2_printednoteeth_aligned.vtp	0.0201711	0.0260989	0.0208939	0.0333989	-0.0194942	0.0165382	3.60E-05	0.0329852	0.1	0.00385824
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper3\Upper3_printednoteeth_aligned.vtp	0.026438	0.02145	0.0276686	0.0227888	-0.0253778	0.0201656	-0.000828703	0.034035	0.1	0.00235804
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper4\Upper4_printednoteeth_aligned.vtp	0.0114634	0.0107913	0.00975163	0.0115798	-0.0124417	0.0101852	-0.00437091	0.0151247	0.1	0.00131738
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper5\Upper5_printednoteeth_aligned.vtp	0.0210938	0.0202926	0.0163376	0.0172462	-0.0244751	0.0215773	-0.00751672	0.0282885	0.1	0.0028305
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper6\Upper6_printednoteeth_aligned.vtp	0.0147439	0.0193488	0.0171546	0.0253841	-0.0126505	0.0114241	0.00120202	0.0242963	0.1	0.00399628
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper7\Upper7_printednoteeth_aligned.vtp	0.0182307	0.0147878	0.0187336	0.0177527	-0.0178544	0.0120906	-0.00219774	0.0233711	0.1	0.00246537
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper8\Upper8_printednoteeth_aligned.vtp	0.013459	0.01439	0.0123302	0.0164152	-0.0141552	0.0129353	-0.00405074	0.0192823	0.1	0.0027189
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper9\Upper9_printednoteeth_aligned.vtp	0.0227118	0.0176071	0.0243871	0.0189321	-0.021171	0.0161409	0.000654905	0.0287299	0.1	0.00188233
E:\Masters_AK\Uppers\3d_aligns_prepost\Upper10\Upper10_printednoteeth_aligned.vtp	0.0172883	0.0162351	0.0154615	0.0169794	-0.0186196	0.0155358	-0.00425362	0.0233318	0.1	0.00270221
	0.01856895	**0.01931929**	**0.018624533**	**0.02274938**	**-0.01841378**	**0.01531869**	**-0.002309665**	**0.0267349**		**0.003054641**
	0.004513251	**0.006210588**	**0.005577107**	**0.010420338**	**0.004492517**	**0.003713652**	**0.002734372**	**0.007013366**		**0.001427937**

Appendix 5

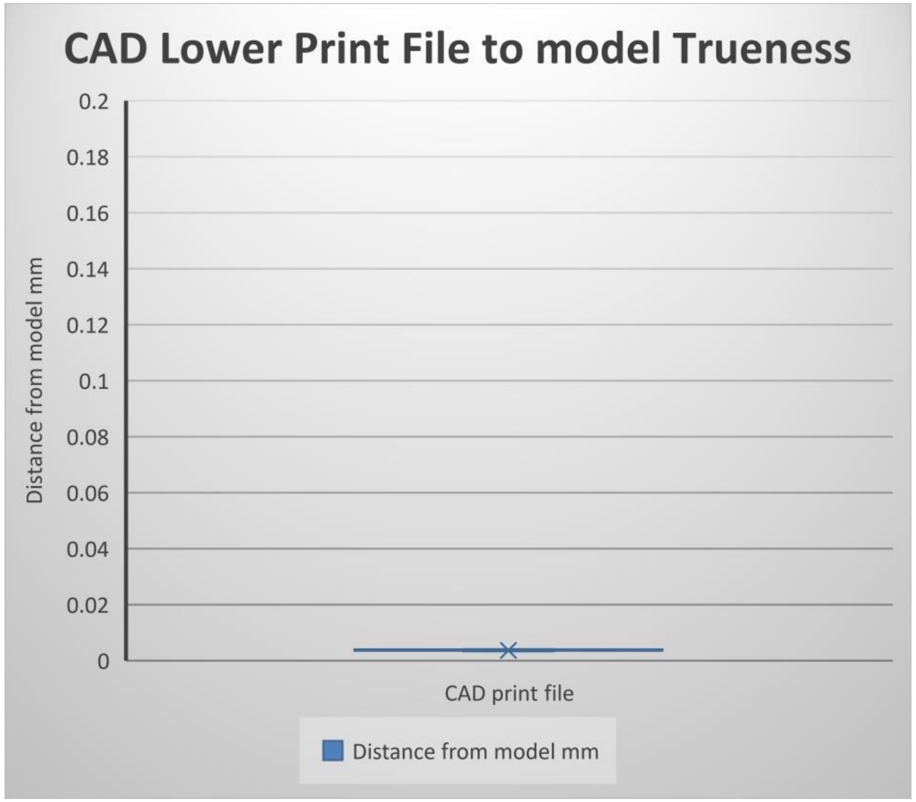
Upper CAD Files Trueness and Precision Graphs

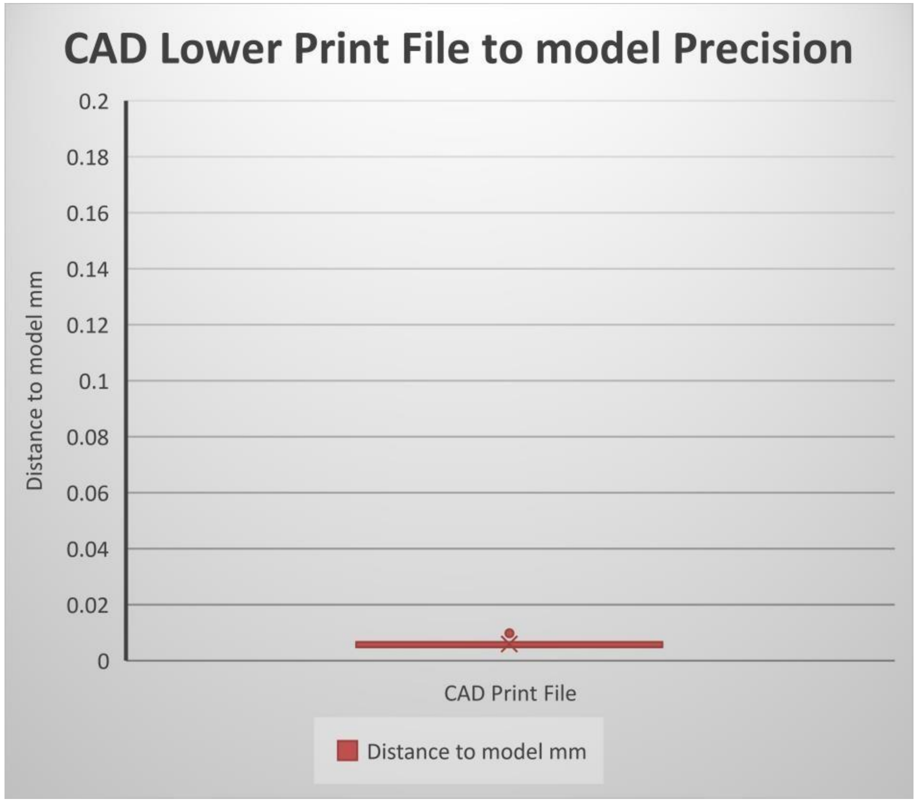




Appendix 5.1

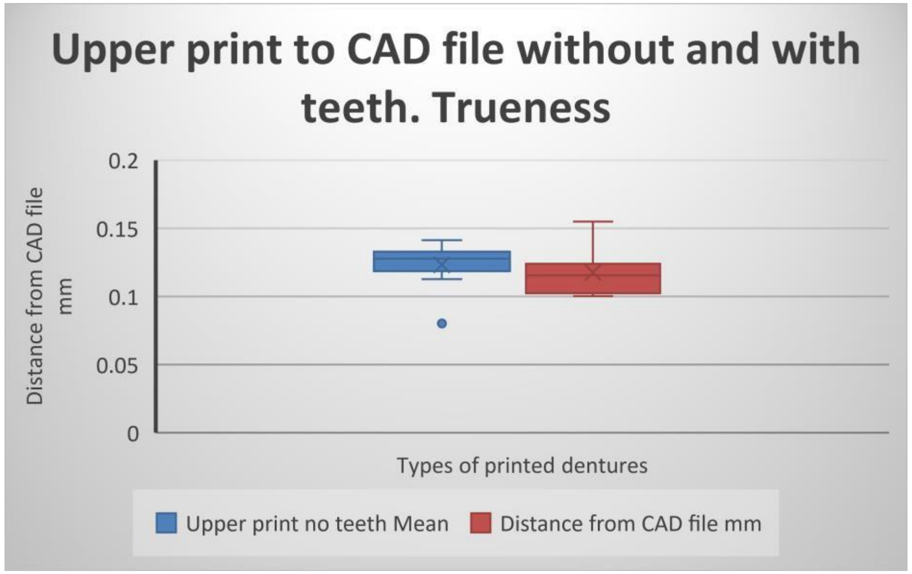
Lower CAD Files Trueness and Precision Graphs

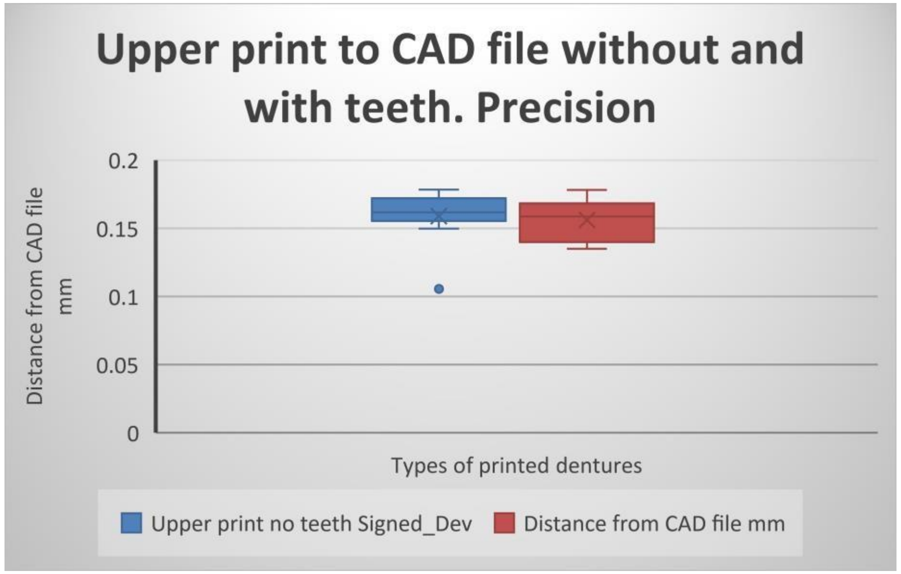




Appendix 5.2

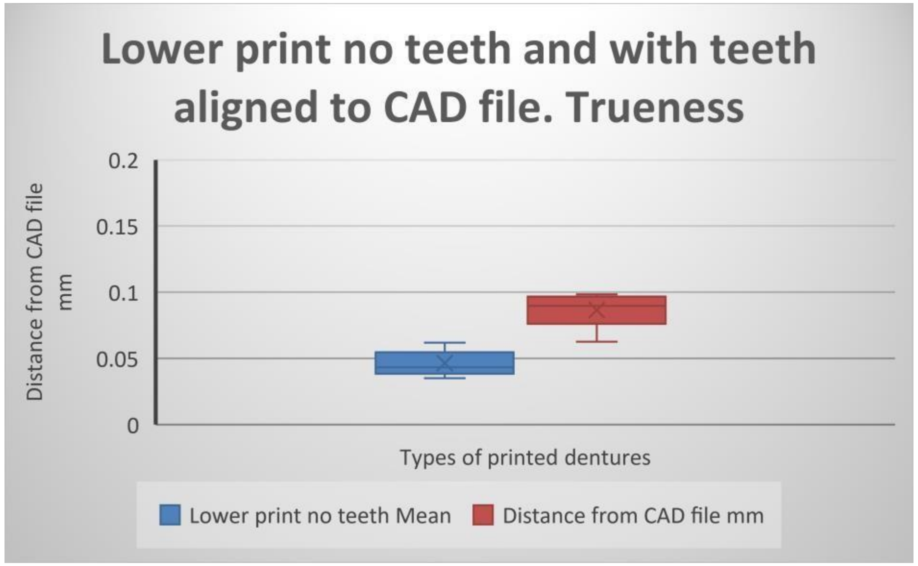
Upper print without teeth and with teeth to CAD file Trueness and Precision graphs

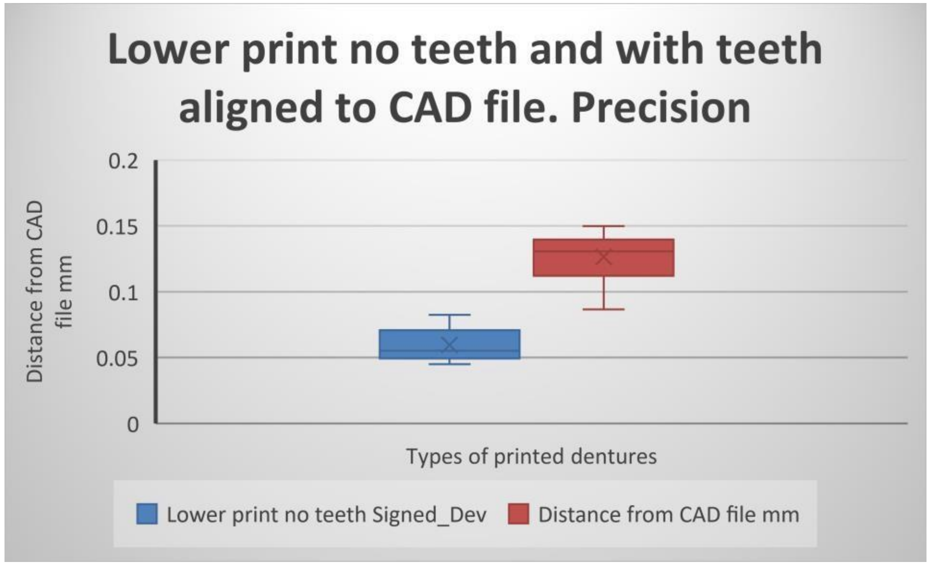




Appendix 5.3

Lower print without teeth and with teeth to CAD file Trueness and Precision graphs





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