PRELIMINARY INVESTIGATIONS INTO MEASUREMENTS AND PAR SCORES TAKEN FROM PLASTER AND TWO TYPES OF DIGITAL STUDY MODEL

by

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ABSTRACT

Aim

To determine if digital study models are a satisfactory alternative to plaster study models.

Digital models were created by two methods; laser scanning of a plaster model or an alginate dental impression.

Method

The study was undertaken in three parts:

1. A pilot study of ten sets of study models using linear measurements to compare plaster models with both types of digital model.
2. A study of thirty sets of study models using PAR scoring to compare plaster models with digital models created from scans of dental impressions.
3. A pilot study of ten sets of study models using PAR scoring to compare plaster models with 3D printed models created from laser scans of dental impressions.

Results

The majority of linear measurements from digital models were indicated to be comparable with plaster models. A mean difference of less than 0.5mm (range 0.02–0.51mm) for all single measurements, for example overjet, was shown. A mean difference of less than 3.0mm (0.47–3.03mm) for multiple linear measurements, for example arch length, was indicated.

Digital models created from plaster models, had a higher level of agreement with plaster models, than those created from dental impressions.

A mean difference of 0.03 PAR points with a standard deviation of 3 PAR points was demonstrated between PAR scores for plaster models and digital models.

A mean difference of 1 PAR point with a standard deviation of 3 PAR points was demonstrated between PAR scores for plaster models and 3D printed models.

Conclusions

Both types of digital study model may be comparable with plaster models when used for linear measurements.

Digital models created from scans of dental impressions appear to be comparable with plaster models for PAR scoring.

3D printed models may be comparable to plaster models for PAR scoring.

Further research using a larger sample size is required to confirm the above conclusions with regard to validity and reliability.

DEDICATION

With heartfelt thanks to my family and also Anita.

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CHAPTER ONE

LITERATURE REVIEW

1. LITERATURE REVIEW

1.1 Introduction

Computer based patient management systems and digital records are a part of current orthodontic practice. Plaster study models are however still used routinely as occlusal records.

With the drive towards electronic records increasing; the future may well bring the ‘plasterless’ orthodontic practice. For this to become a reality however, digitally produced study model images would need to be ‘accurate as’ plaster models and be able to be used in clinical situations, such as case evaluation using the Peer Assessment Rating.

Manufacturers’ and developers’ claims for technological advances with the current generation of technology for digital imaging and 3D printing suggest that these systems may now be ready for use in the clinical situation.

1.2 Dental Study Models

Dental study models are used throughout dentistry as the standard method for recording a patient’s dentition. The dental study model has been defined as, ‘a direct replica of the surfaces of the oral cavity created from an impression taken of the oral anatomy’ (Van Noort, 1994).

Study models provide a three-dimensional view of the patient’s occlusion and allow the clinician to analyse the dentition more thoroughly than during a clinical examination (Quimby *et al*., 2004).

Dental study models are also used to diagnose or monitor anomalies, record key treatment stages, assist clinical decision-making and in the construction of restorations, orthodontic appliances and prostheses.

Plaster study models created from dental impressions in heated wax were first developed in the early 1700s. Alginate impression materials revolutionised the process in the early 1900s by improving accuracy and ease of use (Peluso *et al*., 2004).

1.3 Orthodontic Study Models

Orthodontic study models are normally taken pre and post treatment. Additional study models may be cast at the end of specific stages of treatment, such as for functional appliance therapy.

Orthodontic study models differ from dental study models in that they are trimmed with the occlusal plane parallel to both the upper and lower bases, with the heels and sides symmetrical and flush (Mitchell, 2001). This enables the occlusion to be correct from whichever position the study models are viewed. The study models should include all erupted teeth and soft tissue details including extension into the buccal sulci and palatal vault (Cobourne and DiBiase, 2010).

Articulated study models are not routinely used in orthodontic diagnosis and treatment planning. The value of articulation remains unproven, although it is accepted that a discrepancy between retruded contact position and intercuspal position is commonplace (Ellis and Benson, 2003).

1.4 Conventional Materials

1.4.1 Plaster

Plaster or Type II Dental Stone remain the most common materials used to construct orthodontic study models (Peluso *et al.*, 2004). Plaster or dental stone is created from calcium sulphate dihydrate [$CaSO_4.2H_2O$], more commonly known as gypsum. Heating gypsum to 150ºC drives off water and produces calcium sulphate hemihydrate [$(CaSO_4)_2.H_2O$]. This material has large, irregular, porous particles and is also known as Plaster of Paris or β-hemihydrate. If gypsum is autoclaved calcium sulphate hemihydrate is produced with smaller, regular, less porous particles. This product is known as dental stone or α-hemihydrate (Van Noort, 1994).

When either type of hemihydrate is mixed with water an exothermic chemical reaction occurs and the calcium sulphate hemihydrate reverts to calcium sulphate dihydrate prior to setting (Combe, 1992).

$$[(CaSO_4)_2.H_2O] \; + \; [3H_2O] \longrightarrow [2CaSO_4.2H_2O] \; + \; \text{Heat}$$

The ratio for a plaster mixture satisfactory for dental models is 50ml of water to 100grams of powder. Setting time is 5-10 minutes. Less water (20ml) is required for a dental stone mixture. Additives such as potassium sulphate and sodium chloride speed up setting, whereas potassium citrate and borax slow the setting process (Van Noort, 1994).

The calcium sulphate dihydrate forms crystals with a spherulitic structure once set. During setting there is minimal expansion in the order of 0.2% – 0.3%. This is especially helpful as construction of appliances on slightly enlarged models ensures they are will not be too tight when fitted (Van Noort, 1994).

1.4.2 Alginate

Alginate is commonly used as an impression material to construct orthodontic study models. It is suitably flowable to record adequate detail of the dental and soft tissue anatomy using a standard perforated stock tray technique. Alginate is stored as a dry powder and is easily mixed with water to provide a working material with a short setting time that can be readily disinfected. The elastic nature of alginate allows most undercuts present within the oral cavity to be satisfactorily recorded in an impression that is easily removed. It is non-irritant and may be flavoured to improve patient tolerance. Alginate provides good quality impressions at low cost (Van Noort, 1994).

Syneresis is a process where internal stresses force water to the surface of the impression, which evaporates causing shrinkage. Imbibition is the reverse problem, if an impression dries out the alginate may take up water if re-exposed, causing further distortion (Van Noort, 1994). These processes can compromise the dimensional stability of an alginate impression if it is not covered with damp gauze and there is a delay prior to casting (Combe, 1992).

1.5 Advantages of Plaster Study Models (Van Noort, 1994; Combe, 1992)

- Minimal changes following setting ensuring good dimensional stability and allows storage of models for extended periods of time.
- Excellent reproduction of surface detail.
- Inexpensive and easy to work with.

1.6 Disadvantages of Plaster Study Models (Van Noort, 1994; Combe, 1992)

- A 12MPa compressive strength makes models unsuitable for some types of appliance construction.
- A 2MPa tensile strength makes models brittle and susceptible to fracturing or chipping. Damage tends to occur as study models are retrieved and returned to storage multiple times.
- Hardness and abrasion resistance is low so that the material may become damaged or marked through regular use.
- Some plasters contain silica and are an irritant if inhaled.
- Storage costs and space; 88.5% of hospital orthodontic departments store their study models on site, but most found difficulties in accommodating them all (McGuinness and Stephens, 1992).

- Disposal of study models must be done in a confidential and secure manner. Plaster study models should not be disposed of in normal clinical waste. Disposal of gypsum in landfill with biodegradable waste causes production of hydrogen sulphide, which is detrimental to the local environment.

1.7 Medico-Legal Factors: Storage and Disposal

Dental professionals have an ethical obligation to keep accurate and complete records. The National Health Service (General Dental Services Contract) Regulations 2005 confirm that patient records must include all radiographs, photographs and study models.

Patients are entitled to have access to their complete dental records (Data Protection Act, 1998; General Dental Council Standards for Dental Professionals, 2005).

In an attempt to review the need to retain study models, a previous study concluded that good quality photographs provided sufficient orthodontic information for medico-legal purposes but that assessment of overbite was not as accurate as from dental study models (Malik *et al*., 2009).

The Department of Health document ‘Code of Practice on Retention / Disposal of Records under the NHS’ (2006), recommends that orthodontic records and study models should be retained dependent on location as follows:

- Community Records
    - 11 years for adults
    - Up to the age of 25 years for children or 11 years (whichever is the longest)

- Hospital Records
    - 8 years for adults
    - Up to the age of 25 years (or 26 if patient age is 17 at conclusion of treatment)

The code also states the maximum period practitioners should retain records should be no longer than 30 years.

Requirements to keep dental / orthodontic treatment records for both NHS and private practice are covered by: The Consumer Protection Act (1987) and the Medical Devices Directive (Directive 93/42/EEC). In addition, the Health and Social Care Act (2008), led to the formation of the Care Quality Commission which details requirements for records to be held securely, accurately and fit for purpose, located promptly as required, retained for the appropriate length of time and destroyed securely on disposal (Care Quality Commission Regulations, 2009).

Digital images must be stored securely and access to the images is subject to an audit trail to ensure no allegations could be made that the images have been manipulated. Any patient information, which is transmitted electronically, should be encrypted and databases should be adequately protected with firewalls to ensure security and data protection.

1.8 Digital Study Models

Digital study models are a way of recording all the features evident on a plaster study model but as an electronic record. Computer software allows a pseudo three-dimensional image of the study models to be viewed on a two-dimensional computer screen and the models can be manipulated on screen by rotation or tilting (Mayers *et al*., 2005). Measurements in all three planes of space can be undertaken and models can be sectioned to assist with this if required. Digital diagnostic set ups and proposed tooth movements can also be performed.

Further advantages of digital models are that data can be linked to other records such as radiographs, patient notes and clinical photographs using systems such as Dolphin Imaging and Management Solutions (Chatsworth, CA 91311-5807, USA). With adequate computer backup systems in place there is less chance of records being mislaid or damaged and hence compromised. Instant access to all records within the clinical area can improve efficiency and eliminate study model retrieval time from storage areas, which may be significant for a large, busy practice or department. In addition, case discussions can occur remotely and sharing information among colleagues can enhance teaching, presentations, research and treatment planning, potentially worldwide (Veenema *et al*., 2009).

Communication of treatment options to patients can also be aided by illustrations with digital study model simulations such as incisor retraction and extraction patterns, which will enhance understanding and may improve patient compliance with the chosen treatment option (Hajeer *et al*., 2004b).

Professional bodies have also started to realise the benefits of digital records. The American Board of Orthodontics currently accepts pre-treatment digital study models for pre-treatment records, although physical models are still needed for finishing records (Mah, 2007).

Most companies who offer digital study models accept dental impressions mailed overnight. The plaster models are made and then scanned to create digital models , which are returned electronically to the clinician (Mayers *et al.*, 2005).

Although the initial set up costs for digital study models are higher than the equipment needed to produce plaster models, storage needs are considerably less since thousands of cases are accommodated on a computer hard drive. One set of digital study model records typically requires 5Mb of space and hence a 60-Gb hard drive can store on average 12,000. An orthodontic clinic seeing 1000 new cases per year would require storage space of $17m^3$ to accommodate plaster models (Hajeer *et al*., 2004b).

There are three currently recognised methods for the production of digital 3D study models (Wiranto *et al*., 2013):

1. Laser scanning of plaster study models or dental impressions.
2. Cone-beam computed tomography scanning of plaster study models or dental impressions.
3. Intra-oral scanning of the dentition directly at the chairside.

Laser scanning is the current industry standard for the creation of digital study models and there are two main commercial systems available: OrthoCAD^{TM} (Cadent, Inc, Fairview,NJ, USA) and EModels^{TM} (GeoDigm, Corp, Chanhassen, MN, USA) (Peluso *et al*., 2004).

OrthoCAD^{TM} introduced the first digital study model system in 1999. Plaster casts are made from alginate impressions and then scanned using a proprietary destructive process. The company stores the digital models for 10 years prior to deleting (Peluso *et al*., 2004).

EModels^{TM} became available in 2001. This company fabricates plaster models from dental impressions and these are scanned by a non-destructive laser scanning technique. A wax bite is used to articulate the study models. The electronic study models are available in five days and stored indefinitely by the company (Peluso *et al*., 2004).

A further company, Digimodel^{TM} from Orthoproof (Albuquerque, NM, USA) have more recently started direct scanning of dental impressions to produce digital study models with cone beam computed tomography and are currently the main provider in this field (Fleming *et al*., 2011); (Wiranto *et al*., 2013).

1.9 Overview of the 3D Image and Acquisition

A 3D image is composed of three Cartesian coordinates: an *x*-axis in the transverse dimension, a *y*-axis in the vertical dimension and a *z*-axis in an antero-posterior dimension. These coordinates together are used to construct the 3D image and a layer of pixels creates a surface. Further shading, lighting and 'rendering' adds realism to the object (Hajeer *et al*., 2004a).

Projective imaging is the most commonly used 3D approach and measurements may be orthogonal or by triangulation. Orthogonal means the object is sliced into layers measured by *x* and *y* dimensions and the *z* dimension is measured by calculating the number of slices in the area of interest e.g. CT scans. Triangulation uses two images from different views (Hajeer *et al*., 2004a).

There are two different methods for 3D surface imaging, contact scanning where a measuring probe is used to record surface detail and non-contact scanning where a laser beam and cameras capture surface detail through triangulation (Ireland *et al*., 2008).

1.10 3D Laser Scanning of Plaster Models and Dental Impressions

Laser scanners analyse a real object and use this data to construct digital three-dimensional images.

Digital orthodontic study models are created by scanning the plaster models or impressions. An additional scan of the plaster study models in occlusion is required to articulate them. The bite registration can be either a polyvinylsiloxane material or wax bite reinforced with a foil inner layer to provide adequate thickness and avoid distortion (Barry, 2011). A typical scan time for a plaster model is 2-3 minutes and for an impression it is 7 minutes.

A laser scanner has 4 main components: 2 high-resolution CCD (charge couple device) cameras, a laser projector and an articulating table. The articulating table rotates, tilts and translates during the scanning process so that the cameras can view all surfaces and no areas are left obscured.

Figure 1.10.1 Internal view of a 3D Laser Scanner

(Courtesy of ESM Digital Solutions, Swords, Ireland, 2011)

The laser beam is projected onto the surface of the model and both cameras observe the profile of the line. The laser and cameras sweep over the object and snapshots of the laser profile are taken at defined spatial increments. The object is re-orientated so the cameras can see every detail such as undercuts on an impression surface. A basic scan is done quickly and the software then re-directs the scanner to rescan deficient areas in a process known as ‘adaptive scanning’. The acquired data are then aligned and used to produce a 3D digital representation of the object.

A two camera scanner reduces scan times as less re-orientation of the model is required to capture the surface detail in ‘shadowed’ areas. Discrepancies between points lead to data being ignored or averaged as appropriate to enhance overall accuracy (Barry, 2011).

It is more challenging to scan dental impressions than plaster models since the morphology of an impression surface is deep and narrow with a higher degree of undercuts. Surface detail is captured by scanning the impression from several different angles (Hajeer *et al*., 2004b). This scan is essentially a ‘negative surface’ model technique and the impression surface is transformed in to a positive surface to represent the digital study model (Dalstra and Melsen, 2009).

Figure 1.10.2 Schematic Diagram of a 3D Laser Scanner: illustrating 2 cameras capturing the laser projection on to the object

(Courtesy of ESM Digital Solutions, Swords, Ireland, 2011)

The scanned image is composed of thousands of points, each with *x, y* and *z* coordinates, which produce a 'point cloud'.

As the position of the cameras and the laser is known, the point at which the laser hits the surface of the object can be calculated using triangulation to produce data regarding length, width and depth of the object (Ireland *et al*., 2008); (Kusnoto and Evans, 2002).

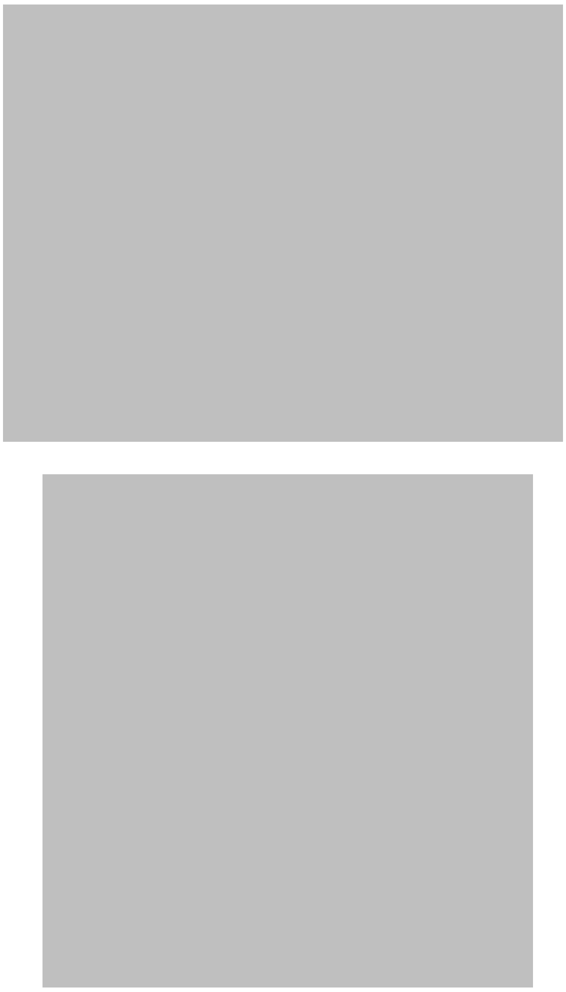


Figure 1.10.3 Construction of the Digital Model from a Point Cloud and 30% Decimation (Courtesy of ESM Digital Solutions, Swords, Ireland, 2011)

Figure 1.10.4 Illustration of Final Processing of the Digital Study Model

(Courtesy of ESM Digital Solutions, Swords, Ireland, 2011)

Laser scanning lends itself to the production of digital images of plaster study models and dental impressions. The method does not have to be as quick as required with a live subject and the laser is safely accommodated within the scanner away from the operator's eyes (Hajeer *et al.*, 2004a).

Both alginate or polyvinylsiloxane impressions can be scanned but there are limitations. The laser produces a line of red light and this will not produce a clear scan of a model or impression made of red material. Impressions that are wet reflect the laser beam causing inaccuracies. This is overcome by removing residual water with compressed air. Highly polished plaster models may not allow the laser line to be clearly projected onto the shiny surface, leading to a reduction in scan quality (Barry, 2011).

1.11 Other 3D Imaging Methods

Stereophotogrammetry like laser scanning also uses the concept of triangulation to create a 3D image but instead of a laser a series of photographs are used (Ireland *et al*., 2008). This technique although useful for imaging human faces is thought to be less suitable for capturing details from study casts although one study showed an average difference of only 0.27mm between plaster and digital images generated by stereophotogrammetry (Hajeer *et al*., 2004b); (Bell *et al*., 2003).

Optical scanning is more suited to facial imaging rather than for study models. Surface detail can be captured on average in 17 seconds, reducing errors due to movement (Halazonetis, 2001).

3D digital images produced by scanning with a holographic sensor are inaccurate when compared with conventional plaster models (Redlich *et al*., 2008).

Moire topography aims to produce successive contour lines directly onto an object but suffers from poor resolution as the lines are not fine enough to capture details of the dentition (Bell *et al*., 2003).

1.11.1 Intra-Oral Scanning

Intra-oral scanning has the potential to remove the need to take dental impressions. However, this technology needs refinement and is subject to problems such as the length of time required to capture all the dental and soft tissue surfaces and address the issue of patient movement. Structured light is used to capture details of the dentition by a camera which needs light distortions as it is moved over the dentition. The images are merged to form a 3D structure (Hajeer *et al*., 2004b).

More recent intra-oral scanners work by capturing 3D data in a video sequence and then constructing digital models. The maxillary and mandibular arches are first scanned separately and then together in occlusion (Wiranto *et al*., 2013).

Some intra-oral scanning systems require coating of the teeth with titanium dioxide prior to scanning (Barry, 2011). This compromises the overall accuracy (Persson *et al*., 2009). The Lava Chairside Oral Scanner (3M ESPE, Seefeld, Germany) requires all tooth surfaces to be coated in this manner (Wiranto *et al*., 2013). Coating is not required with newer scanners such as the 3Shape TRIOS intra-oral scanner (3Shape, Copenhagen, Denmark).

One study showed patients to prefer intra-oral scanning to impression taking. Although scanning took 26 minutes, patients felt more engaged by the experience as they could watch the scan monitor (Vasudavan *et al*., 2010).

An intraoral scanner has been used to produce digital study models and stereolithographic models from human skulls. Linear measurements of tooth widths and arch lengths showed statistical differences between the methods but these were not clinically significant (Cuperus *et al.*, 2012).

1.11.2 Cone-Beam Computed Tomography Scanning

Cone-beam computed tomography (CBCT) enables 3D visualisation of the entire craniofacial complex. The relationship between the face, hard tissues, temporomandibular joint and dentition can be visualised. The dentition can be further represented by digital 3D study models with trimmed bases. The study model bases can be made transparent to allow 3D visualisation of root morphology and position (Mah, 2007).

However, for orthodontic purposes alone, the radiation dosage needed to achieve an adequate level of detail is excessive for clinical use (Barry, 2011). Also the cost of CBCT limits its applications in routine orthodontic practice (Hajeer *et al*., 2004b). Metal artefacts such as amalgam restorations may also distort the image (Hajeer *et al*., 2004a).

However, one study using computed tomography found that measurements in all three planes of space were of a high level of accuracy. The study used CT slices with a thickness of 1.25mm to maintain detail but reduce the high radiation dose (El-Zanaty *et al.*, 2010).

1.12 Digital Study Model Measurements

1.12.1 Digital Study Models created from Scans of Dental Impressions

Only two studies have used digital study models generated directly from dental impressions.

The first study compared dental crown preparations cut on plastic teeth mounted in a typodont study model with digital models produced by two methods: the direct scanning of plaster models created from the master model with a touchprobe contact scanner and laser scanning the polyvinyl siloxane dental impressions of the master model. Best fit alignment of the point clouds created by each method were compared and illustrated by colour difference maps. There was no significant difference between digital models created either from plaster models or dental impressions and both methods could be relied on clinically. The impression method obviated the need for plaster models (Persson *et al*., 2009).

The second study compared study models generated by 3 different methods: conventional plaster models, digital study models created from cone-beam computed tomography scans of alginate impressions and digital models created from intra-oral scans. Bolton's analysis and tooth width measurements were taken. An intra-oral scan took on average 23 minutes. Tooth-width measurements did not differ significantly between the 3 methods, however Bolton's analyses did, but not by more than 1.5% and this was deemed clinically insignificant. All methods were identified to be valid, reliable and reproducible. Digital study models were found to be a satisfactory alternative to plaster models (Wiranto *et al*., 2013).

1.12.2 Digital Study Models created from Scans of Plaster Study Models

Multiple studies have shown acceptable levels of agreement between individual tooth dimensions, intra and inter-arch measurements taken from plaster models compared to those from digital models generated from scans of the plaster models (Zilberman *et al*., 2003); (Quimby *et al*., 2004); (Bootvong *et al*., 2010).

A number of studies have suggested measurement errors from both types of study model to be in the range of 0.05mm and 0.5mm concluding both methods to be accurate and reliable (Kuroda *et al*., 1996); (Santoro *et al*., 2003); (Asquith *et al*., 2007); (Sousa *et al*., 2012).

Measurements on digital models were shown to be more accurate than those from plaster models and an easy alternative to plaster models only taking 2.03 minutes to record compared to 4.15 minutes and were suggested for use in future research (Kusnoto and Evans, 2002); (Horton *et al*., 2010).

Although not clinically significant, measurements for overbite and tooth width showed the largest mean difference with digital model measurements being smaller than those from plaster models (Santoro *et al*., 2003).

Digital models were also shown to produce marginally smaller measurements and although not clinically significant may be too large for research purposes (Abizadeh *et al*., 2012). Plaster models were recommended for scientific work as reproducibility of measurements were superior to digital models (Sjogren *et al*., 2010).

1.13 Systematic Reviews of Digital Study Model Measurements

In a systematic review of digital versus plaster study models (Fleming *et al*., 2011) assessed the validity of measurements for tooth size, arch length, irregularity index, arch width and crowding. Overall, 283 papers were identified but only 17 studies were reported with sufficient accuracy to be included in the review. A high degree of validity was found between the two methods.

Another systematic review of linear measurements from digital and plaster study models compared to plaster study models to assess both validity and reliability included 17 out of 278 papers. Clinically relevant mean differences were set at 0.5mm for two-landmark linear measurements e.g. overjet and 2.0mm for linear measurements based on more than two landmarks e.g. Bolton analyses. Reliability and validity were high for all measurements and acquisition type did not alter this, making digital study models clinically acceptable for use when compared with plaster models (Luu *et al*., 2012).

1.14 Treatment Planning and Digital Study Models

Laser scans of dental study models combined with 3D images of the facial skeleton can be effective in assisting treatment planning for orthognathic surgery cases. This has allowed advantageous visualisation of skeletal and occlusal changes both in unison (Motohashi and Kuroda, 1999); (Okumura *et al*., 1999).

Treatment planning on digital and plaster models was investigated using 30 sets of both types of models. Replacement of plaster models with digital models resulted in treatment plan changes in only 6 percent of cases. Treatment plan differences were all of a minor clinical nature and it was agreed any differences or changes detected could have been decided on at a clinical appointment (Rheude *et al*., 2005).

Another study involved twenty clinicians who assessed ten Class II cases using both digital and plaster models on two separate occasions. Kappa statistics showed good agreement for treatment plans and suggested that digital models were as reliable as plaster models for treatment planning (Whetten *et al*., 2006).

1.15 Tooth Movement and Digital Study Models

Tooth movement was assessed by comparing measurements from 50 conventional and 50 digital models. Pre and post treatment digital models were superimposed on screen to assess tooth movement. The digital models generated by laser scans were accurate to 0.0235mm for antero-posterior measurements and 0.0071mm for bucco-lingual movements. The study also investigated molar anchorage loss by superimposing pre and post treatment lateral cephalogram radiographs and then compared this to the same measurements from superimposed digital models. It was possible to measure individual tooth movement in all planes and the method obviated the need for a post-treatment cephalogram (Thiruvenkatachari *et al.*, 2009).

1.16 Impression Material Stability and Digital Study Models

Impressions poured immediately were compared with those poured 3-5 days later, as would be the case in posting impressions to a scanning company. Six linear measurements were taken from the plaster models and then again on the corresponding digital models. There were no differences between the measurements made on either type of model from either of the alginate impressions, suggesting that alginate is a stable impression material over a few days (Dalstra and Melsen, 2009).

Another investigation into alginate stability found dimensional differences between linear measurements made on plaster and digital models obtained from impressions poured immediately and those not poured up to 4 days. However, the differences were not deemed to be clinically significant and not to affect the production of digital study models (Alcan *et al*., 2009).

Plaster study models poured from two types of alginate impressions and two types of alginate substitutes were compared after 72 hours, 120 hours and 1 week. Cone-beam computed tomography scans of each type of impression were also taken at 72 hours to construct digital study models. Statistical and clinically significant dimensional changes were found after 72 hours for alginate impressions but alginate substitutes showed no significant changes. Digital models were dimensionally smaller compared to plaster models by 0.5mm. A suggested explanation for this may be due to radiation sources producing a burnout effect at the periphery. Immediate pouring of models would be recommended in light of these findings (Torassian *et al*., 2010).

1.17 3D Printing

A 3D physical model can be manufactured from 3D data by two different methods; either rapid prototyping or via a computer numerical aided manufacturing. This technology is currently used in all fields of manufacturing to produce complete objects or component parts. In the last decade this technology been applied to use in medicine.

1.17.1 Additive Manufacturing

'Additive manufacturing' is another term used to describe rapid prototyping systems or 3D printing. Previous materials used to 'print' models via rapid prototyping have included wax, starch and plaster (Mah, 2007).

The most frequently used types of rapid prototyping used in medical applications are stereolithography and 3D printing. 3D printed models are one third of the cost of stereolithographic models and production can be fully automated. 3D printed models are recognised as more suitable and the industry standard for printing small complex structures (Cohen *et al*., 2009).

In 3D printing an ultrathin layer of liquid light cure resin polymer is sprayed onto a build platform from a jet head and is cured by an ultraviolet light. The platform then drops down to accommodate the next increment of material. Individual layers are polymerised together by crosslinking. The finished models are accurate to 0.016mm and build time is 1cm in height per hour (Cohen *et al*., 2009).

Figure 1.17.1 Illustration of the 3D Printing Process

(Courtesy of Objet Geometries Limited, Israel, 2012)

The drawback of 3D printing is a stepped or staircase surface is produced which can introduce surface error. By reducing the layer thickness to address this problem this increases production time and costs. ‘Adaptive slicing’ is being researched to help reduce costs and control surface detail as required. This allows more layers to be added to certain areas of the model where more detail is required to replicate surface morphology (Martorelli *et al.*, 2013).

1.18 3D Printing and Reconstructed Study Models

Digital models confer many advantages, however if a physical hardcopy is required this may pose a problem. To overcome this difficulty it is possible to reconstruct a digital model via 3D printing or rapid prototyping.

In a comparison of 30 plaster models, digital models and 3D reconstructed models, the digital models were created by laser scanning the plaster models and the reconstructed models were created from the digital images (Keating *et al*., 2008). Dimensional accuracy was assessed via linear measurements and they concluded there were no significant differences between the digital and plaster models. However there were statistically significant differences between plaster, digital and reconstructed models for measurements in the ‘z’ plane. They suggested that digital models were reliable when compared to plaster models but that study models reconstructed from digital images were not.

Current 3D printers use layer thicknesses in the range 0.03 – 0.20mm. The use of thinner layers in the building process causes a less ‘stepped’ surface profile and hence the amount of material used to construct the 3D model is similar to the volume specified by the digital image. This improves accuracy with regard to dimensions and the quality of the model surface finish (Martorelli *et al*., 2013).

Retainer appliances made on stereolithographic models produced from digital models compared to plaster models did not differ significantly from those made on plaster models (Vasudavan *et al*., 2010).

1.19 Peer Assessment Rating Index

The Peer Assessment Rating (PAR) Index was developed by the British Standards Working Party in 1987, to provide an objective system to summarise the severity of a case in a single score. It does this by acknowledging the malocclusion severity by the level of dental anomalies found in the malocclusion pre-treatment and the outcome post-treatment. The index assesses and quantifies how far the malocclusion is from an ideal occlusion. An ideal occlusion has been defined by Andrews Six Keys (Andrews, 1972). To use the index a PAR score is given for the case both pre-treatment and post-treatment. Each component, which contributes to the overall score pre and post treatment, is weighted to reflect the importance of the component. The difference between the scores allows a judgement to be made as to the success of the treatment outcome (Richmond *et al*., 1992a).

The Peer Assessment Rating Index is made up of five components. Each component score is weighted prior to adding the five scores together to give an overall score. A score of zero would indicate perfect alignment and occlusion (Richmond *et al*., 1992a).

An orthodontic practitioner's scores may be used to audit quality of the service being delivered per individual or collectively for the entire caseload. PAR scores may also allow comparison with other practitioners (Richmond *et al*., 1992b).

The index has been shown to also be highly correlated with practitioners' subjective assessment of treatment need, even in a setting free of financial incentives and patient desires (McGorray *et al*., 1999). Orthodontic opinions of malocclusion severity according to the PAR Index have also been shown to correlate highly with public opinion (Arruda, 2008).

Treatment methods have no significant differences on PAR outcome scores in a study assessing correction of Class II malocclusions (King *et al*., 2003).

A further validation study by 74 clinicians included 320 study models representing a range of malocclusions and treatment plans and found an intraclass correlation coefficient of R>0.91, indicating excellent reliability between examiner scores (Richmond *et al*., 1992a).

The PAR Index is now used in over fifty countries worldwide and has proved to be both robust and reliable for both clinical and research use (Richmond, 2008).

The five components are shown below:

- Upper and lower anterior segments
    - amount of crowding or spacing is quantified and impacted teeth are also accounted for
    - weighted by x1

- Left and right buccal occlusion
    - antero-posterior, vertical and transverse relationships are recorded
    - weighted by x1

- Overjet
    - positive and negative overjets are assessed for all incisor teeth
    - weighted by x6

- Overbite / Openbite
    - are recorded for all incisor teeth
    - weighted by x2

- Centreline
    - shifts compared to the lower midline are assessed
    - weighted by x4

A PAR ruler acts as an aide memoir for the rater in systematic, quick and accurate measurement taking.

Differences between pre and post treatment PAR scores can be analysed in three different ways. Either by assessing the points difference, the percentage change or plotting the pre and post treatment scores against each other on a PAR nomogram. A case is considered as 'greatly improved' if there has been a reduction of 22 PAR points and 'improved' if there has been a percentage reduction of at least 30% (Richmond *et al.*, 1992b). Alternatively the nomogram will indicate the outcome to fall in one of three categories: Worse/No Different, Improved, and Greatly Improved.

An orthodontist with PAR scores showing a high percentage reduction and also outcomes within the 'Greatly Improved' range on the PAR nomogram would demonstrate good assessment of the need for treatment and that outcomes were of a good standard (Richmond *et al*., 1992b).

Calibration of examiners is a requirement to use the Peer Assessment Rating Index properly and ensure reproducibility. The accepted level of agreement is no more than ± 12 (Brown and Richmond, 2005).

The Peer Assessment Rating Index has many advantages, it is quick, taking 2-4 minutes and it is simple, systematic and informative (Richmond, 2008).

The index also has limitations, mainly related to the different weightings of components. The weighting for overjet is high and reflects a British population but it may not be applicable to other populations. However the index has been validated for use in the United States of America (DeGuzman *et al*., 1995). The overjet weighting makes the index overly sensitive to any malocclusion with this feature. Conversely, the weighting for overbite is low, so complex treatment to correct a deep and traumatic overbite is not recognised sufficiently in the overall score. There is also zero weighting for displacements in the buccal segments including impacted units (Hamdan and Rock, 1999). The index also does not take account of restorative work and it may not be sufficiently critical of final outcome to be used for cost-effectiveness analyses (Richmond, 2008).

1.20 Occlusal Indices and Digital Study Models

No studies to date have used digital models generated from impressions for PAR scoring. The studies discussed in the following sections were generated by scans of plaster models.

1.20.1 Peer Assessment Rating Index

Two studies have compared PAR Index scoring using both digital and plaster study models.

The first by (Mayers *et al*., 2005), included 48 pairs of plaster and digital pre-treatment models. No significant differences were found between scores from digital and conventional study models, P=0.82. PAR scores were also highly correlated with an intraclass correlation coefficient, ICC= 0.95. The study assessed the reliability of all PAR components against those originally described by Richmond (1992) and found all scores generated on digital models to be comparable except for buccal occlusion. PAR scores from digital models were confirmed to be both valid and reliable measures of occlusion. The study also found that PAR scoring of digital models took longer than with plaster study models. This did not significantly reduce with experience.

In the second study where PAR scores of 24 sets of pre-treatment digital and plaster models were compared to include 8 malocclusion types as defined by the American Board of Orthodontics, the use of digital models produced similar results to those for plaster models. Diagnosis and treatment planning were not compromised (Stevens *et al*., 2006).

1.20.2 Other Occlusal Indices

Comparison of the Index of Complexity, Outcome and Need (ICON) scores on 30 sets of plaster and digital models found no statistical differences between total ICON scores (Veenema *et al*., 2009).

Twenty-four sets of digital and plaster study models were graded using the American Board of Orthodontics objective grading system (ABO OGS) to evaluate accuracy and reliability. Out of the total seven occlusal criteria there were no significant differences for marginal ridges, occlusal contacts, occlusal relationships, overjet and interproximal contacts. However, there were significant differences for tooth alignment and buccolingual inclination and scoring between the two examiners. Re-evaluation for both types of study model and adequate calibration of examiners was suggested prior to accepting ABO examination on digital models (Costalos *et al*., 2005).

The ABO OGS was investigated further when 30 sets of digital and plaster study models were compared. Significant differences between plaster and digital models for occlusal contacts, occlusal relationships and total scores were found and it was felt that digital study models were not adequate for scoring all components of the ABO OGS (Okunami *et al*., 2007).

Other workers have also found significant differences between three of the seven components in the grading system and suggested that digital models were not an adequate substitute for plaster models (Hildebrand *et al*., 2008).

Digital models have been shown to be as accurate as plaster models when performing a Bolton space analysis. Digital models were also shown to be significantly faster in performing a Bolton analysis (Stevens *et al*., 2006); (Mullen *et al*., 2007). The latter study found that scoring from digital models was faster.

Space analysis conducted on 25 sets of digital and plaster models in a different study found a statistically significant difference between mean measurements on the maxillary models of 0.40mm but not on mandibular models where the mean difference was 0.33mm, however this was not deemed to be clinically significant (Leifert *et al.*, 2009).

Peer Assessment Rating Index scores from digital models generated from scanning dental impressions and their 3D printed models have not to date yet been shown to be comparable to plaster study models.

1.21 Aims

The aim of this study was to compare accuracy of measurements and PAR scoring of conventional orthodontic plaster study models with digital study models and 3D printed plastic study models.

Digital study models were generated in two different ways; either by laser scanning of the plaster models, or by laser scanning of the alginate dental impressions.

CHAPTER TWO

METHOD

2. METHOD

2.1 Objectives

1. To determine the accuracy of measurements taken from both types of digital study model (derived from plaster models and directly from alginate impressions) with that from plaster study models.

2. To compare pre-treatment Peer Assessment Rating (PAR) scores for digital study models created from dental impressions with plaster study models.

3. To compare pre-treatment PAR scores taken from 3D printed plastic study models generated from a digital study model created from a dental impression, with scores from plaster study models.

2.2 Null Hypotheses

- There is no difference in the accuracy of measurements taken from both types of digital study model and plaster study models.

- There are no differences in pre-treatment PAR scores obtained from digital study models created from dental impressions compared with plaster study models.

- There are no differences in pre-treatment PAR scores obtained from 3D printed plastic study models generated from digital models created from dental impressions compared with plaster study models.

2.3 Study Design

The study was located in three centres:

- Birmingham Dental Hospital, Birmingham, England.
- Queen's Hospital, Burton-upon-Trent, England.
- ESM Digital Solutions, Dublin, Ireland.

Data were collected from four sources:

- Plaster orthodontic study models.
- Digital study models created by laser scanning of the above plaster orthodontic study models.
- Digital study models created by laser scanning dental impressions of the same plaster models.
- 3D printed plastic study models generated from digital study models by laser scanning of dental impressions.

The study was divided into three sections:

2.3.1 Section One

The first section of the study was a pilot study to support existing literature and determine the validity of measurements taken on digital study models as compared to traditional plaster study models; the current gold standard.

10 sets of study models were randomly selected from the study model box storage area in the Orthodontic Department at Birmingham Dental Hospital. Duplicates were made of the selected models to avoid treatment being disturbed.

The selection criteria were:

- Pre-treatment orthodontic study models.
- Permanent dentition erupted.

The 10 sets of models were taken to ESM Digital Solutions, Dublin, Ireland and two types of digital study models were created; either via a laser scan of the plaster study models, or using a laser scan of alginate dental impressions taken of the plaster study models.

The plaster models were soaked for approximately two minutes prior to impression taking to assist in impression removal and prevention of breakage of the plaster model. Standard plastic, perforated impression trays with a tray fixative were used.

For each of the 10 sets of actual or digital study models, seven different landmark measurements were recorded to represent vertical, horizontal and transverse dimensions.

Measurements recorded were:

- Overjet (OJ) – the maximum horizontal distance (mm) between the upper and lower incisors measured parallel to the occlusal plane.
- Overbite (OB) – the maximum vertical overlap (mm) of the lower incisors by the upper incisors in occlusion.
- Upper inter-canine width (UIC) – the horizontal distance (mm) between the maxillary canine cusp tips.
- Lower inter-molar width (LIM) – the horizontal distance (mm) between the centre of the mandibular first permanent molar mesio-lingual cusps.
- Upper left central incisor height (UL1) – the maximum vertical height (mm) from the gingival margin to the incisal edge.
- Upper arch length (UAL) – sum of posterior and anterior chord lengths for left and right side of the arch.
- Lower arch length (LAL) – sum of posterior and anterior chord lengths for left and right side of the arch.

Distal chord length was measured from the distal aspect of the first permanent molar to the mesial aspect of the first premolar.

Anterior chord length was recorded from the distal aspect of the canine to the mesial aspect of the central incisor.

Plaster model measurements were recorded with Mahr Callipers 16EX (Mahr GmbH, Esslingen, Germany) with a measurement resolution of 0.01mm.

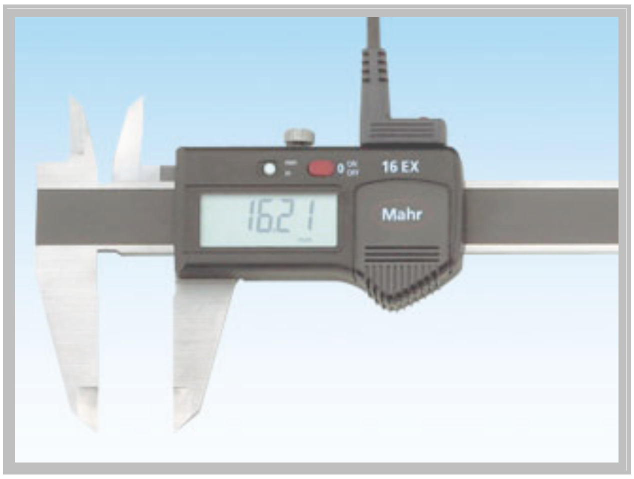


Figure 2.3.1a Mahr 16EX Callipers

Digital model measurements were viewed and recorded via OrthoAnalyser™ 3Shape computer software which was used in conjunction with the 3Shape R700 laser scanner (3Shape, Copenhagen, Denmark). Measurement resolution was 0.01mm. Images of the digital study models were rotated on screen and magnified as required to assist viewing whilst recording measurements.

Figure 2.3.1b 3Shape R700 Laser Scanner (3Shape, Copenhagen, Denmark)

Figures 2.3.1c – 2.3.1g illustrate the measurements recorded from the digital study models.

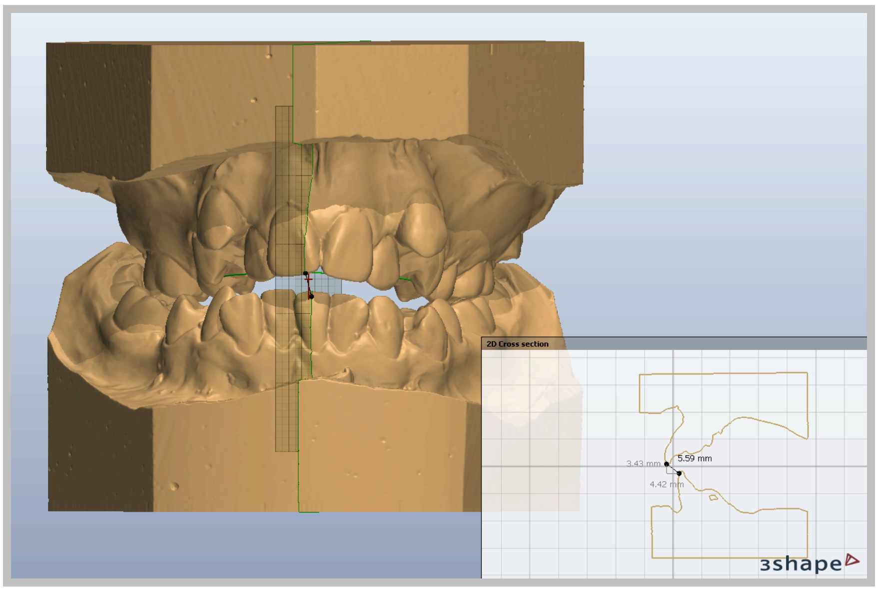


Figure 2.3.1c Overjet measurement assisted by a sagittal cross-section view through the study models as shown on the inset graph

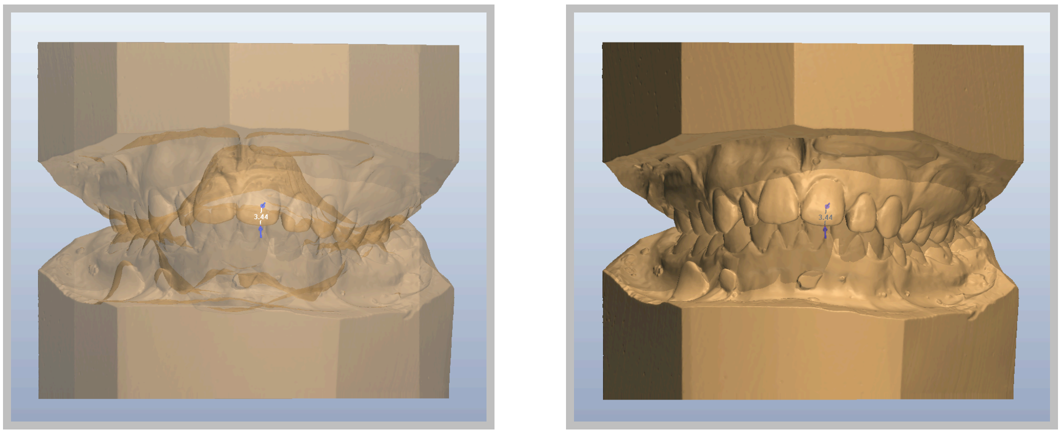


Figure 2.3.1d Overbite measurement assisted by software feature of making study models translucent to visualise overbite

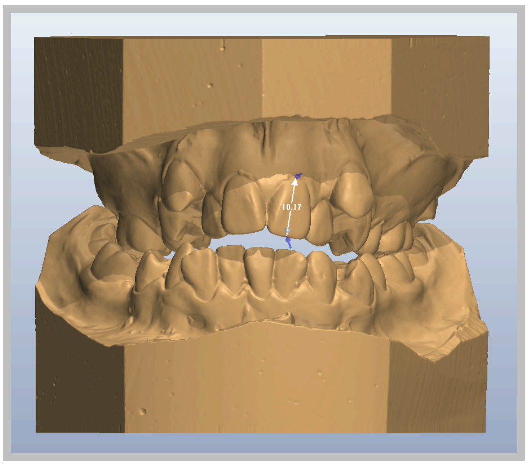


Figure 2.3.1e Upper central incisor height measurement

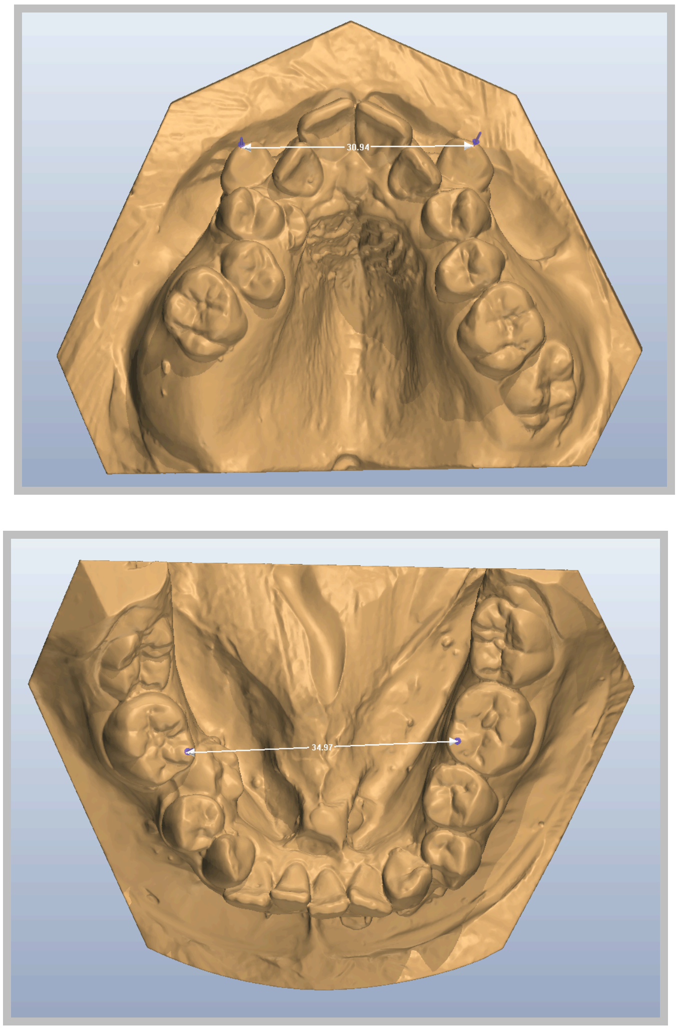


Figure 2.3.1f Upper inter-canine width and lower inter-molar width measurements

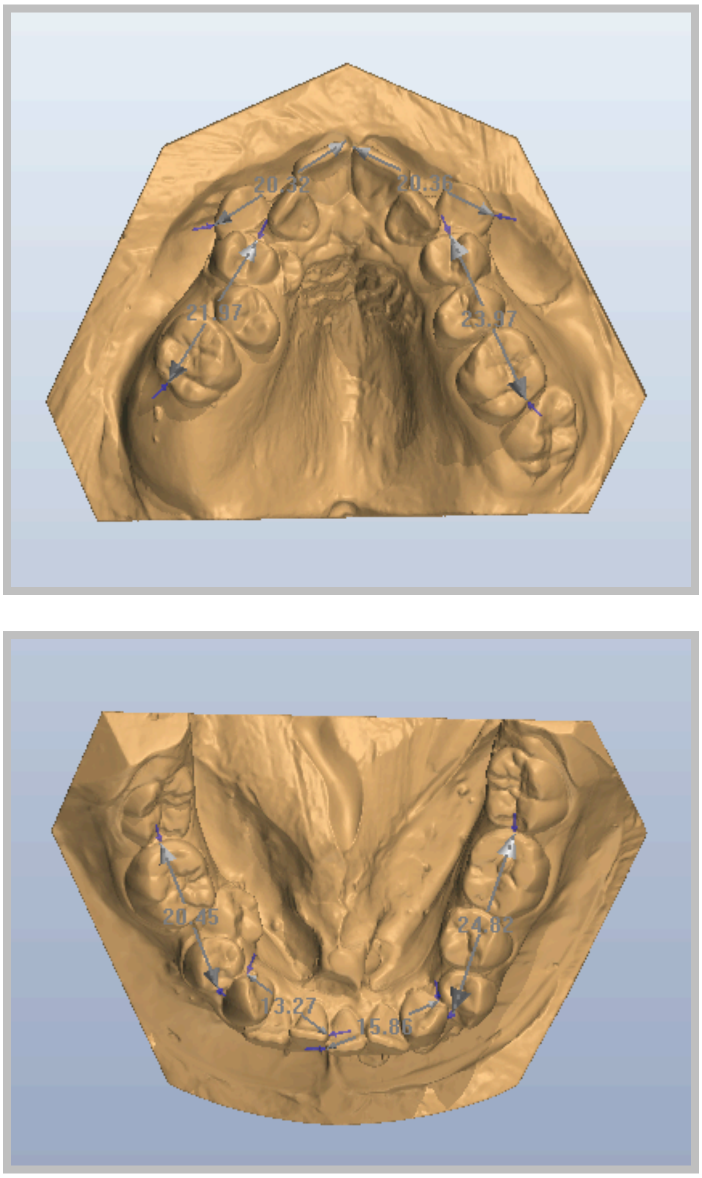


Figure 2.3.1g Upper and lower arch lengths, as measured by the sum of the anterior and posterior chords bilaterally per arch

The plaster study model group was used as a gold standard reference / control group as plaster models are used routinely in orthodontic practice. The plaster study model group was compared against both groups of digital study models with regard to measurement accuracy.

2.3.2 Section Two

Pre-treatment PAR scores from plaster study models were compared with those from digital study models created from dental impressions.

The examiner (SG) underwent calibration for use of the Peer Assessment Rating Index.

The sample consisted of 30 sets of orthodontic plaster study models from the study model archive storage area of the Orthodontic Department at Queen's Hospital, Burton-upon-Trent. Study model boxes that had been in storage for 10 years were selected by hand at random. No duplications were made of the study models as they were due to be disposed of in the near future.

The 30 sets of study models, which were all pre-treatment, were PAR scored.

These study models were taken to ESM Digital Solutions, Dublin. As in the first section of the study, models were soaked in water for approximately five minutes prior to alginate dental impressions being taken. Standard plastic, perforated impression trays with a tray fixative were used. The impressions were then scanned. The scanned image was then converted into an orthodontic based and trimmed digital on-screen study model. A wax bite of the original plaster models in occlusion was also scanned to allow articulation of the digital models.

The 30 sets of digital study models generated in this way were PAR scored using OrthoAnalyser^{TM} Software (3Shape, Copenhagen, Denmark).

The images were rotated on screen using magnification to assist with viewing whilst recording measurements.

The key stages of digital study model construction are illustrated in Appendix One.

2.3.3 Section Three

The final section of the study assessed if 3D printed plastic study models generated from digital study models created from dental impressions were comparable to plaster study models when used for PAR scoring.

From Section 2 of the study, 10 sets of models were chosen by hand at random. These plaster models had previously had alginate impressions taken of them and had been scanned to produce a digital model. 3D models were printed out using a plastic polymer material via an Objet Eden 260V 3D printer (Objet Geometrics Ltd, Israel). This printer had a high resolution of 28 micron per layer. The study models were printed in a cream colour to best represent a traditional white plaster study model.

Figure 2.3.3a Objet Eden 260V 3D Printer (Objet Geometrics Ltd, Israel)

Only 10 sets of study models were chosen due to a budget limit of £500, each set of study models cost £50.

The plastic 3D printed study models were PAR scored. PAR scores from the original plaster study models used in Section 2 were then compared with the scores from the 3D printed models.

Figure 2.3.3b 3D Printed Orthodontic Study Models

(Courtesy of Objet Geometrics Ltd, Israel, 2012)

2.4 Selection criteria

2.4.1 Inclusion criteria

- Pre-treatment orthodontic study models.
- A full permanent dentition erupted including at least the first molars, premolars, canines and incisors.

2.4.2 Exclusion criteria

- Presence of retained deciduous teeth.
- Dentitions with missing units or additional supernumerary teeth.
- Dentitions with gross caries or fractures that would compromise natural tooth morphology.
- Previous orthodontic treatment.
- Damaged or fractured models.
- Cleft palate.

The sample was not to be matched for gender, age or malocclusion.

2.5 Ethical approval

Ethical approval was not deemed necessary for this study as there was no direct patient involvement and all study models were treated anonymously throughout the study.

2.6 Reproducibility study

Intra-examiner reliability was performed by repeating Section One measurements after one month, for plaster study models and both types of digital models.

The Wilcoxon signed – rank test was used to assess intra-examiner reliability.

The Wilcoxon signed – rank test assessed if the two sets of data originating from the same set of study models generated at two different time points have the same distribution. This test illustrated any differences between the two sets of data and allowed a comparison to be made with regard to the accuracy of the landmark measurements taken by the examiner (SG).

If there were no differences between each of the examiner measurements at both time points then the mean difference in the sample would be equal to zero.
The differences within the sample are accounted for by observing if they are greater or less than zero i.e. positive or negative and also with regard to their magnitude. The differences are then placed in order of size and are ranked accordingly.

If there is no difference between examiner measurements then the sums of the ranks relating to positive and negative differences should be the same (Petrie and Sabin, 2010).

A Bonferonni correction was used *post hoc* to account for multiple hypothesis testing.

Statistical tests were performed using statistical software IBM SPSS Statistics 21.

2.7 Data analysis

Data analysis was undertaken via Bland Altman Plot statistics to compare levels of agreement between the results of the different study model groups in all three sections of the study including landmark measurements and Peer Assessment Rating scores.

Bland-Altman Plots were used to assess correlation of the results. The mean of the two (paired) measurements was plotted on the x-axis and the difference between the pair of measurements on the y-axis. Assuming a normal distribution of differences it would be expected that 95% of the differences within the sample population to lie between two standard deviations from the mean of the observed differences (Bland and Altman, 1986); (Bland and Altman, 2012).

The upper and lower limits of these intervals; two standard deviations or 'limits of agreement', can be used to determine if paired measurements from two different methods are acceptable. The magnitude by which there is a difference between the pair is illustrated on the plot, along with any outliers present.

A random scatter of points evenly distributed above and below zero is evident if there is no systematic difference between the pairs and then agreement is deemed acceptable and the null hypothesis is accepted. Alternatively, if there is a funnel effect e.g. with the variation of differences being greater for larger mean values, then this would indicate a significant difference between the pairs
(Petrie and Sabin, 2010).

Minitab 16 Statistical Software was used to perform the above statistical tests.

2.8 Sample size calculation

Since the present study was designed as a preliminary investigation numbers were kept small. Guidance sought from statistical support services at the University of Birmingham deemed a sample size calculation not necessary for this study.

Post hoc power calculations have since been undertaken with the assistance of supervisory mentors for Section One and Section Two as follows:

The measurement differences found in Section One were generally less than 1mm between groups, indicating that measurements taken from digital study models were closely comparable to those obtained from actual plaster models. With the encouragement of this degree of accuracy a *post hoc* power calculation was carried out using the Altman Nomogram. To provide 90% power the 20 sample sizes used (10 per group) in the present study support a standardised difference of 1.45. Given a standard deviation of 0.4mm this suggests a clinically relevant difference of 0.6mm: very acceptable for clinical application.

In Section Two, the Altman Nomogram was used to undertake a *post hoc* power calculation. To provide 80% power and to detect a PAR score difference of 2 with a standard deviation of 2, a standardised difference of 1 with a significance level of 5% would indicate a sample size of 30 to be appropriate.

CHAPTER THREE

RESULTS

3. RESULTS

3.1 Intra-examiner reliability

Examiner reliability was performed by repeating Section One measurements one month apart.

Raw data for landmark measurements for each of the three groups at both time points is presented in Appendix Two.

The Wilcoxon signed – rank test data table showing positive and negative ranks for the paired data is presented in Appendix Three.

Wilcoxon signed – rank test results for intra-examiner reliability are shown in Table 3.1.

The key to abbreviations used in the table are listed below:

- P1 = Measurement taken from a plaster study model taken at time point 1.
- P2 = Measurement taken from a plaster study model taken at time point 2.
- DSM1 = Measurement from a digital study model created from a scanned plaster study model taken at time point 1.
- DSM2 = Measurement from a digital study model created from a scanned plaster study model taken at time point 2.
- Imp1 = Measurement taken from a digital study model created from a scanned dental impression of the plaster study model taken at time point 1.
- Imp2 = Measurement taken from a digital study model created from a scanned dental impression of the plaster study model taken at time point 2.

Table 3.1 Wilcoxon signed – rank test for intra-examiner reliability taken from each of the three study groups

	Pairs		
	OJ P2 – OJ P1	OJ DSM2 – OJ DSM1	OJ Imp2 – OJ Imp1
Z Asymp. Sig. (2-tailed)	-.357[a] .721	-.765[a] .444	-.204[a] .838

	Pairs		
	OB P2 – OB P1	OB DSM2 – OB DSM1	OB Imp2 – OB Imp1
Z Asymp. Sig. (2-tailed)	-.059[b] .953	-1.355[a] .176	-2.253[b] .024

	Pairs		
	UIC P2 – UIC P1	UIC DSM2 – UIC DSM1	UIC Imp2 – UIC Imp1
Z Asymp. Sig. (2-tailed)	-.770[a] .441	-.153[b] .878	-1.274[a] .203

	Pairs		
	LIM P2 – LIM P1	LIM DSM2 – LIM DSM1	LIM Imp2 – LIM Imp1
Z Asymp. Sig. (2-tailed)	-2.547[a] .011	-.204[b] .838	-.237[b] .812

	Pairs		
	UL1 P2 – UL1 P1	UL1 DSM2 – UL1 DSM1	UL1 Imp2 – UL1 Imp1
Z Asymp. Sig. (2-tailed)	-1.123[a] .262	-.718[a] .473	-1.785[a] .074

	Pairs		
	UAL P2 – UAL P1	UAL DSM2 –UAL DSM1	UAL Imp2 – UAL Imp1
Z Asymp. Sig. (2-tailed)	-1.173[b] .241	-.714[a] .475	-.714[b] .475

	Pairs		
	LAL P2 – LAL P1	LAL SM2 – LAL SM1	LAL Imp2 – LAL Imp1
Z Asymp. Sig. (2-tailed)	-1.172[a] .241	-2.497[a] .013	-.459[a] .646

Statistically significant differences were found between measurements taken at the two time points for:

OB Imp (p value=0.02)

LIM P (p value=0.01)

UL1 Imp (p value=0.07)

As the sample size was small a Bonferonni correction was used post hoc to account for multiple hypothesis testing.

The p-value was set at a conventional 0.05 significance level and as there were 21 sets of data (7 sets of paired data per each of the 3 study groups) then the calculation was performed by dividing 0.05 by 21 to give a significance level of 0.0024.

The Bonferonni correction confirmed there was no statistically significant difference between measurements taken for the two time points. Intra-examiner reliability was therefore acceptable.

3.2 Section One

3.2.1 Comparison of measurements taken in the three groups

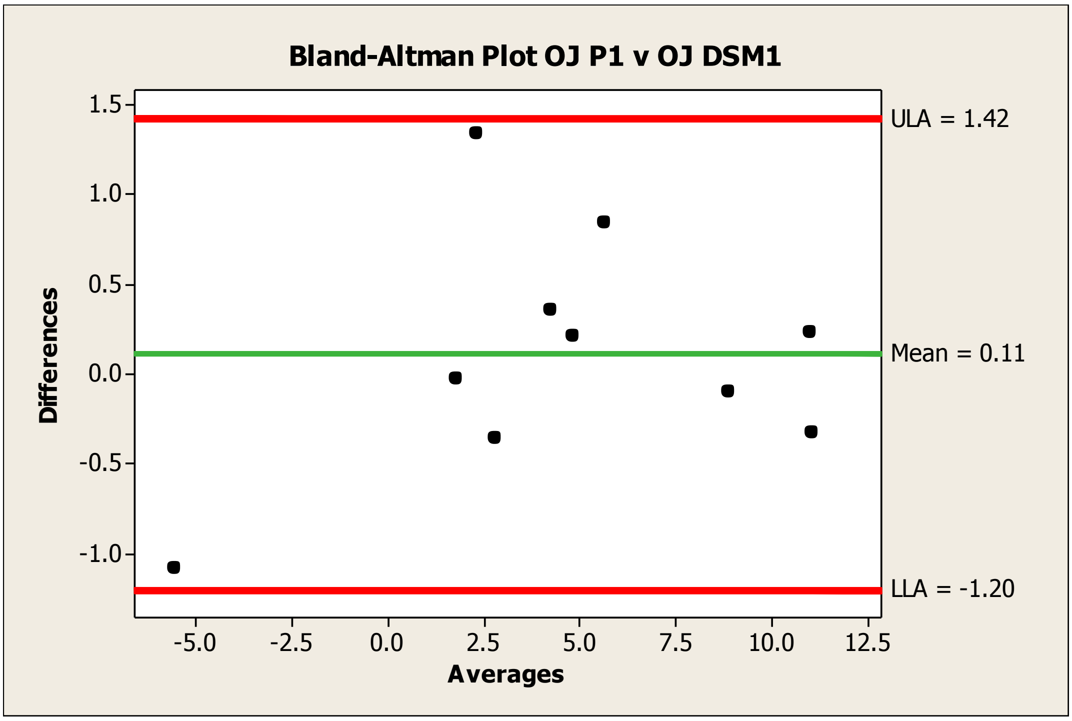
The plaster study model group was used as a gold standard reference group against which to compare both groups of digital study models with regard to measurement accuracy.

The following Bland-Altman Plots illustrate each of the measurements recorded between:

- Plaster study models as compared to digital study models created from scanned plaster study models.
- Plaster study models as compared to digital study models created from scanned dental impressions of the plaster study models.

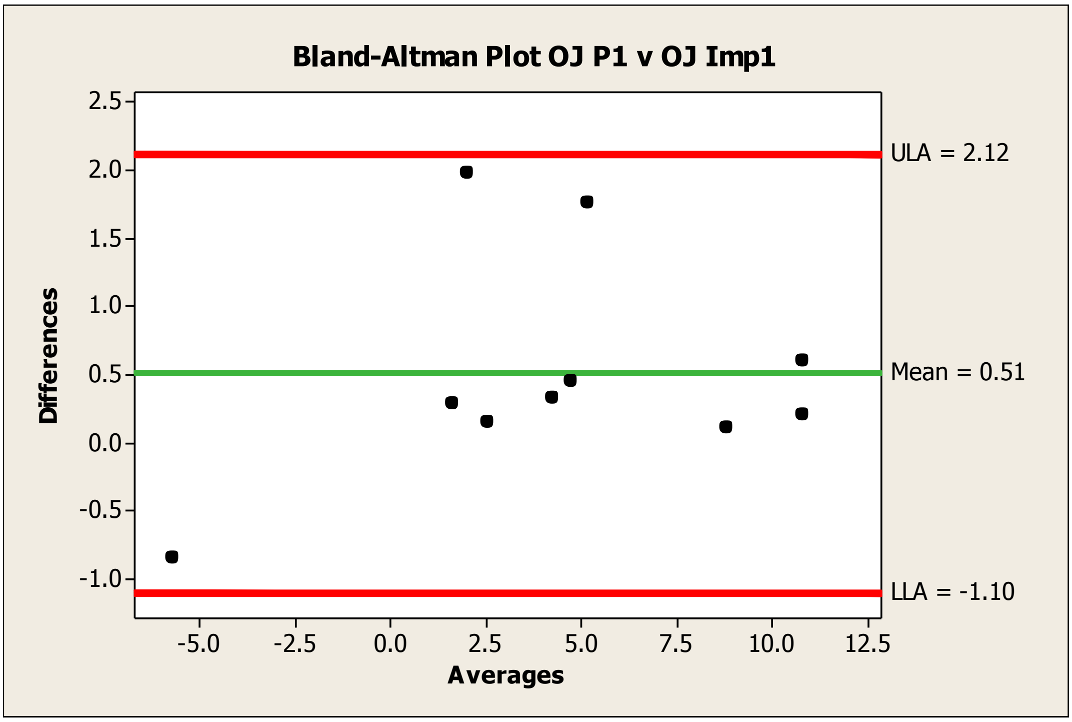
The graph titles have been abbreviated as follows:

- P1 = Plaster study model.
- DSM1 = Digital study models created from scanned plaster study models.
- Imp1 = Digital study models created from scanned dental impressions of the plaster study models.



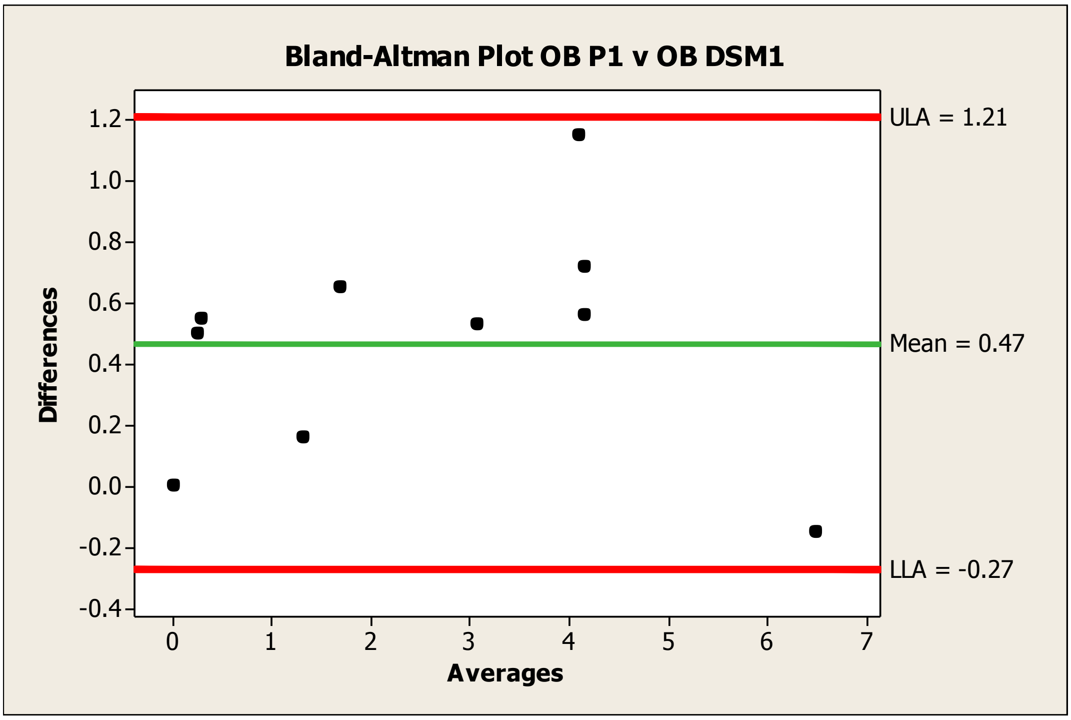
Est. mean of the differences: 0.11 Est. stdev of the differences: 0.67

Figure 3.2.1a Bland – Altman Plot for Overjet



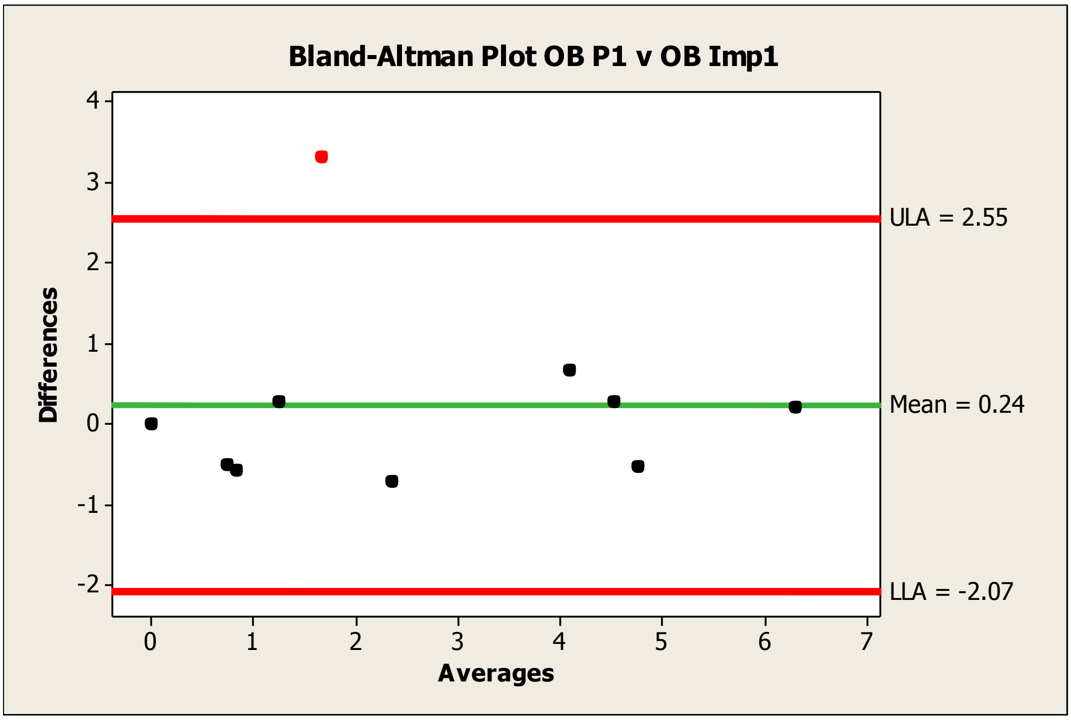
Est. mean of the differences: 0.51 Est. stdev of the differences: 0.82

Figure 3.2.1b Bland – Altman Plot for Overjet



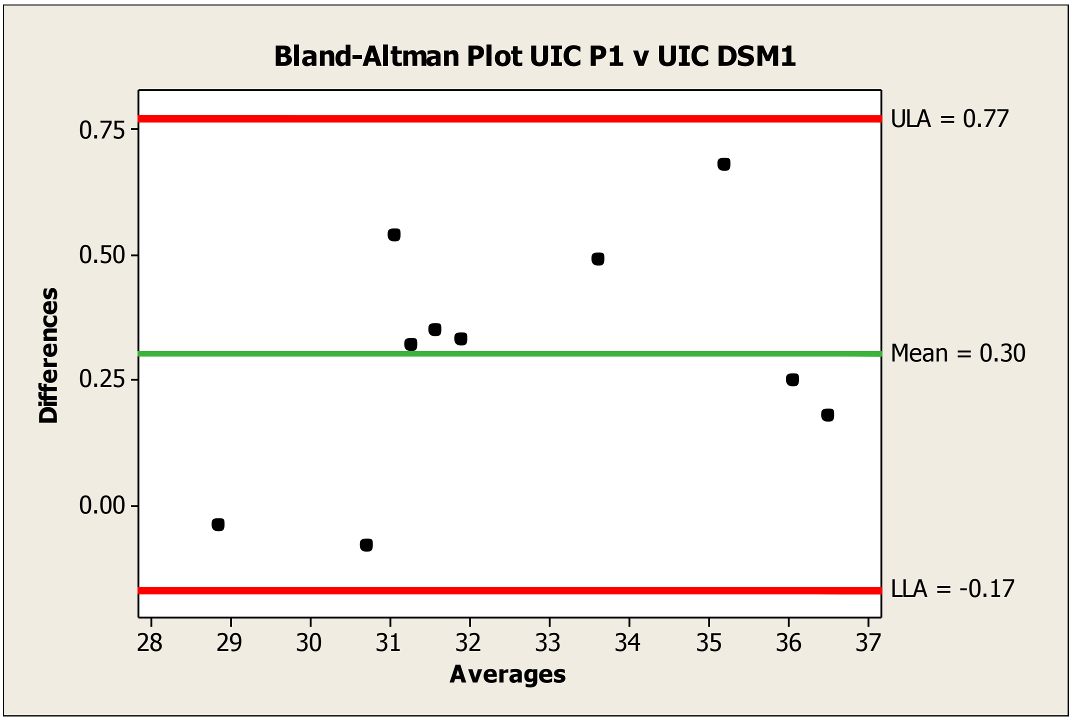
Est. mean of the differences: 0.47 Est. stdev of the differences: 0.38

Figure 3.2.1c Bland – Altman Plot for Overbite



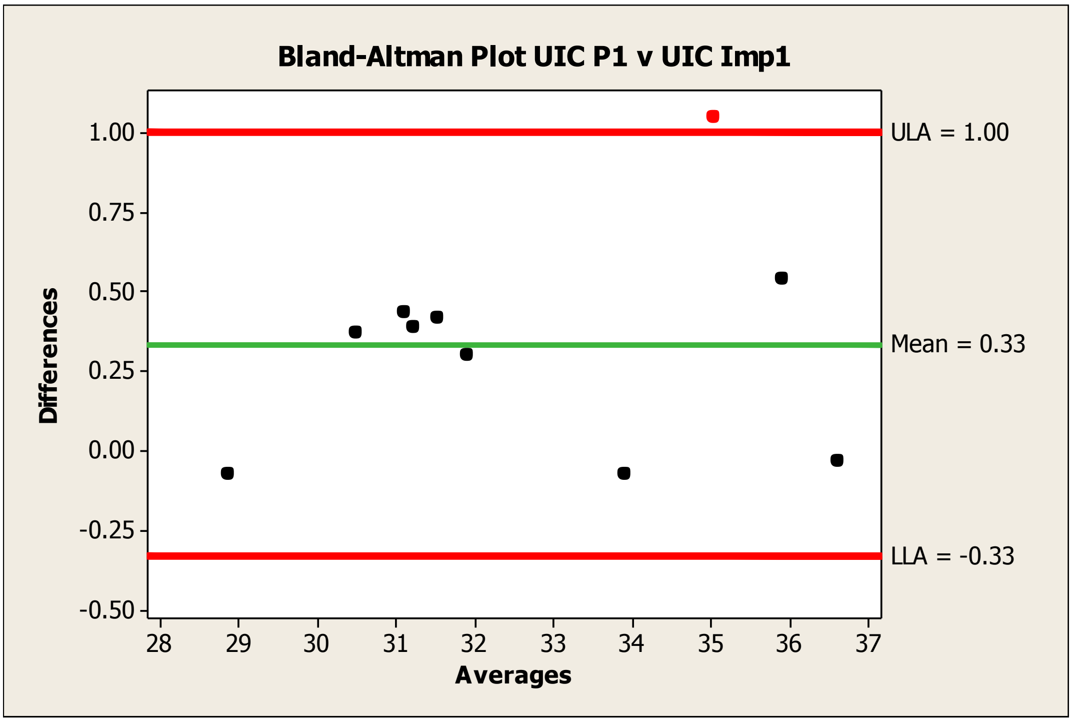
Est. mean of the differences: 0.24 Est. stdev of the differences: 1.18

Figure 3.2.1d Bland – Altman Plot for Overbite



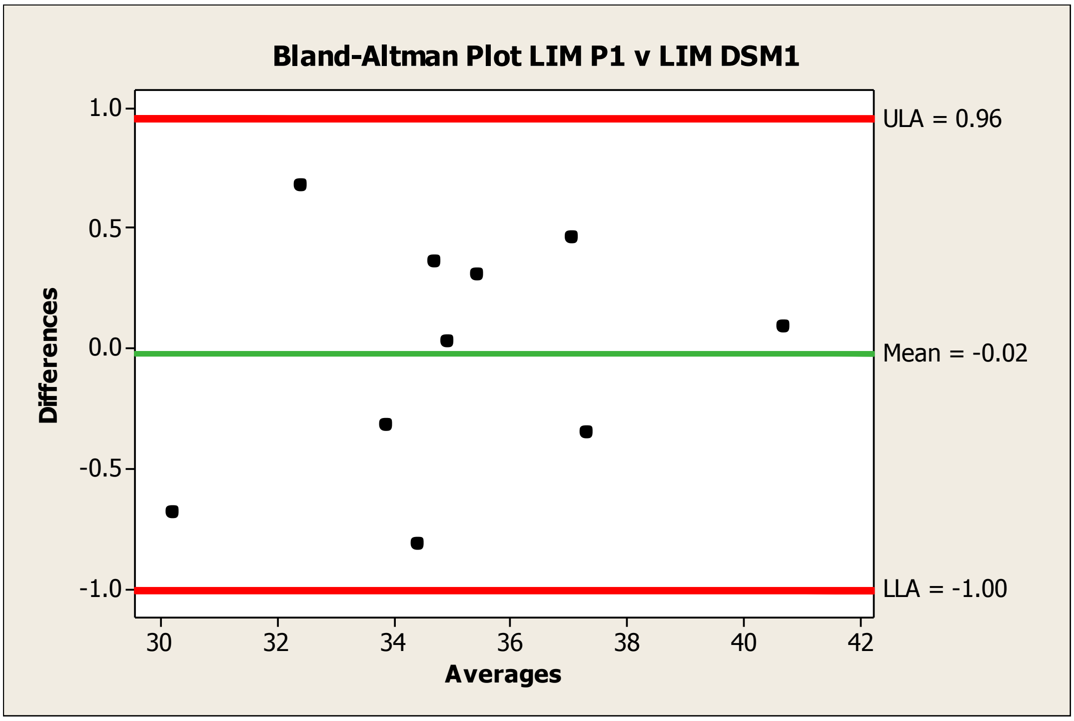
Est. mean of the differences: 0.30 Est. stdev of the differences: 0.24

Figure 3.2.1e Bland – Altman Plot for Upper Inter-canine Width



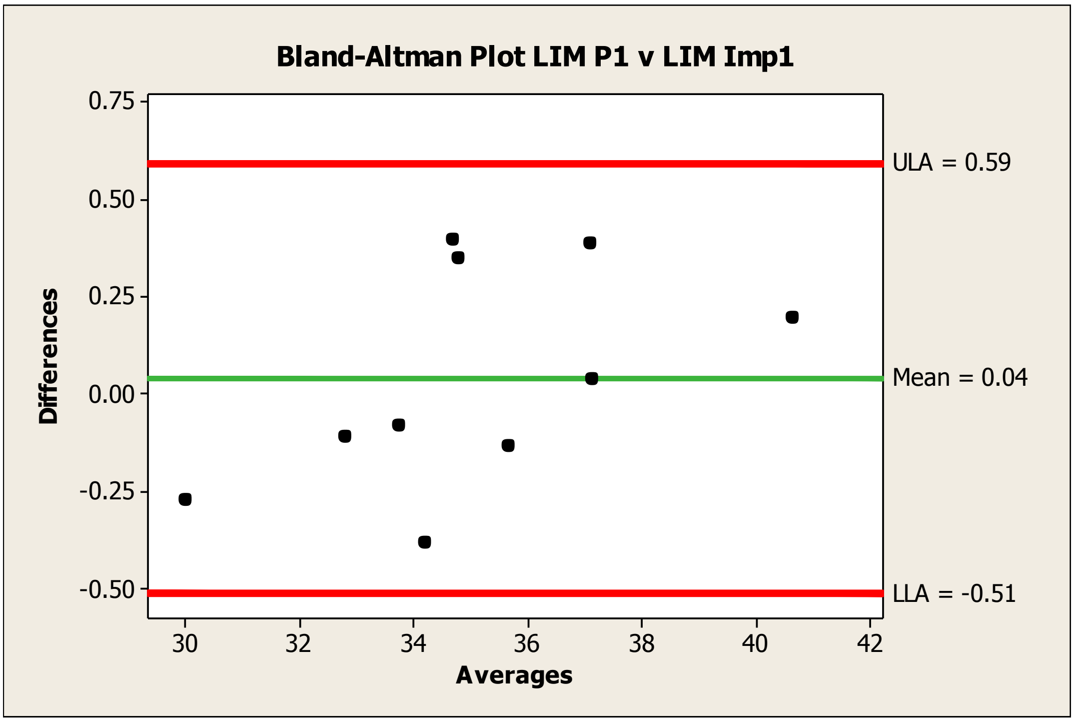
Est. mean of the differences: 0.33 Est. stdev of the differences: 0.34

Figure 3.2.1f Bland – Altman Plot for Upper Inter-canine Width



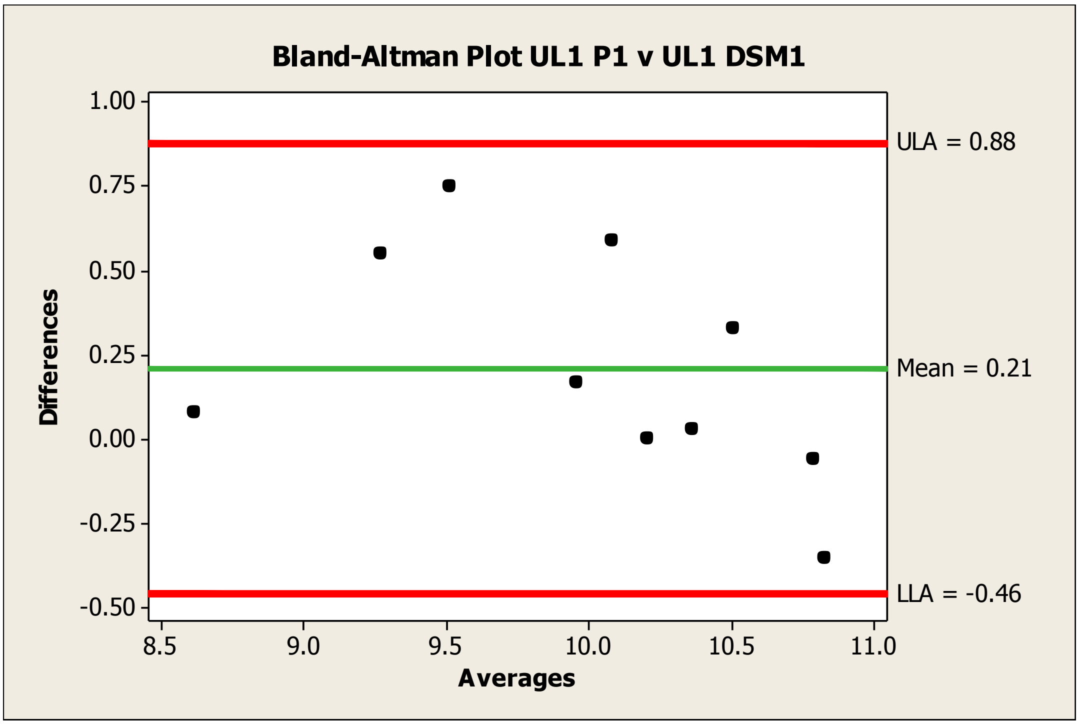
Est. mean of the differences: -0.02 Est. stdev of the differences: 0.50

Figure 3.2.1g Bland – Altman Plot for Lower Inter-molar Width



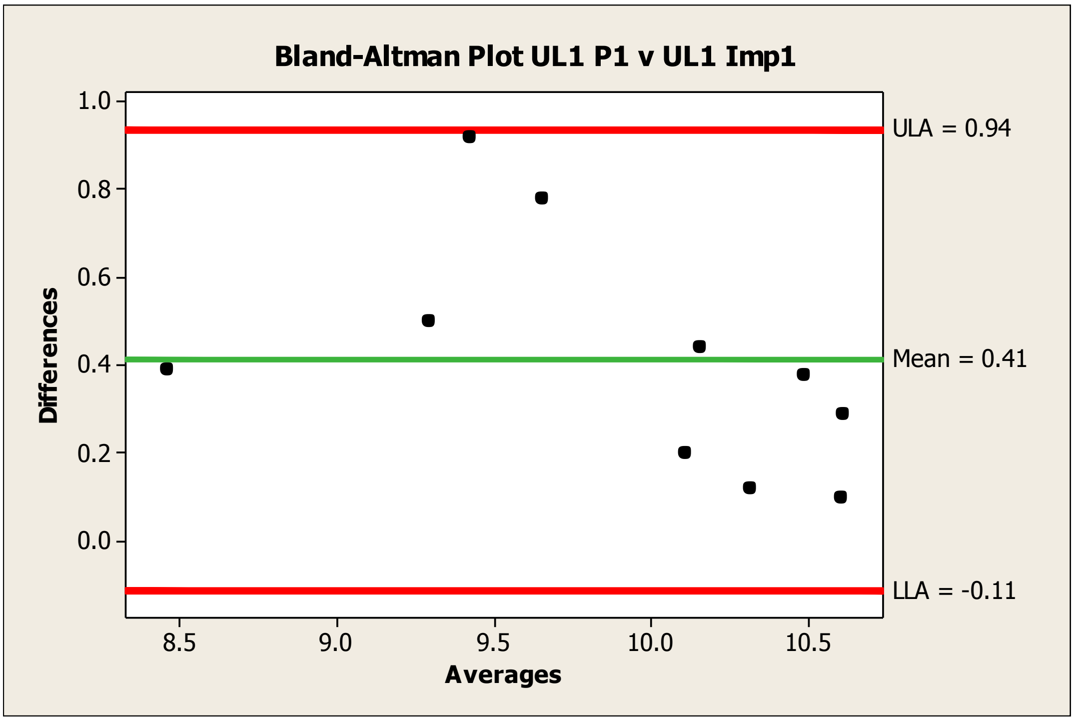
Est. mean of the differences: 0.04 Est. stdev of the differences: 0.28

Figure 3.2.1h Bland – Altman Plot for Lower Inter-molar Width



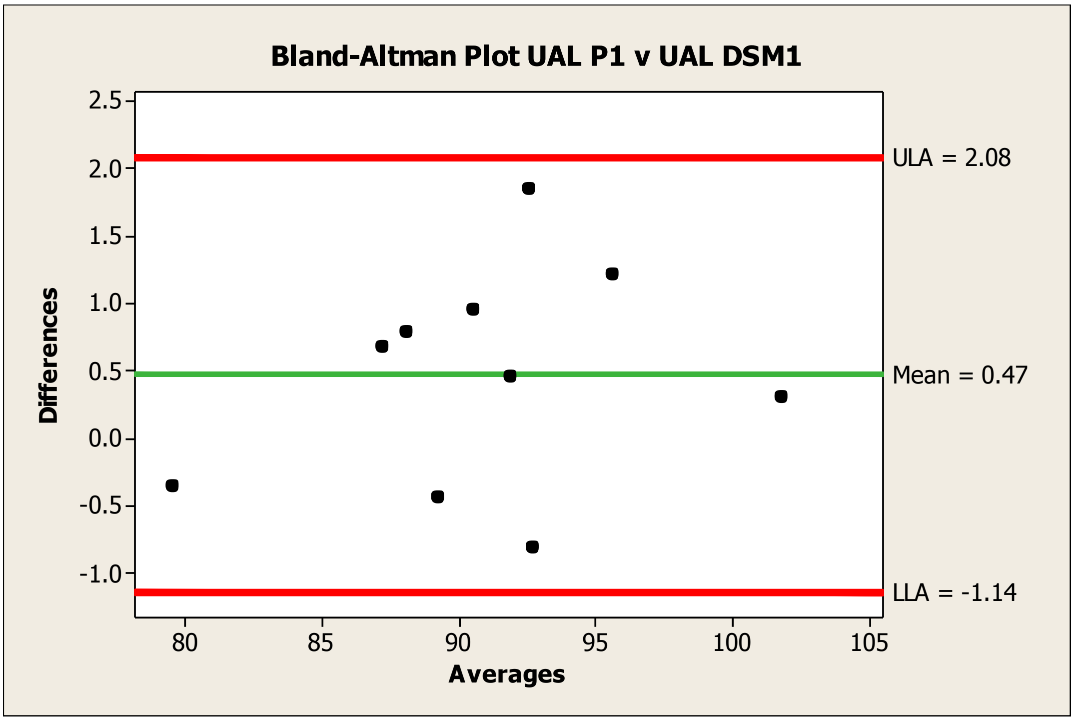
Est. mean of the differences: 0.21 Est. stdev of the differences: 0.34

Figure 3.2.1i Bland – Altman Plot for Upper Central Incisor Height



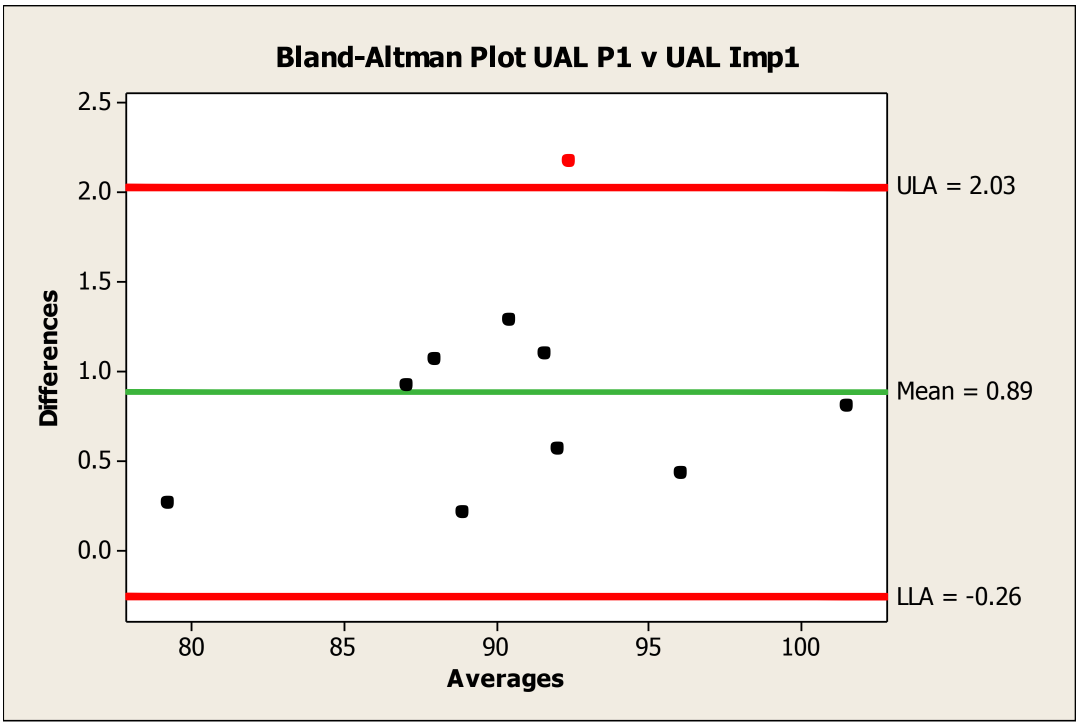
Est. mean of the differences: 0.41 Est. stdev of the differences: 0.27

Figure 3.2.1j Bland – Altman Plot for Upper Central Incisor Height



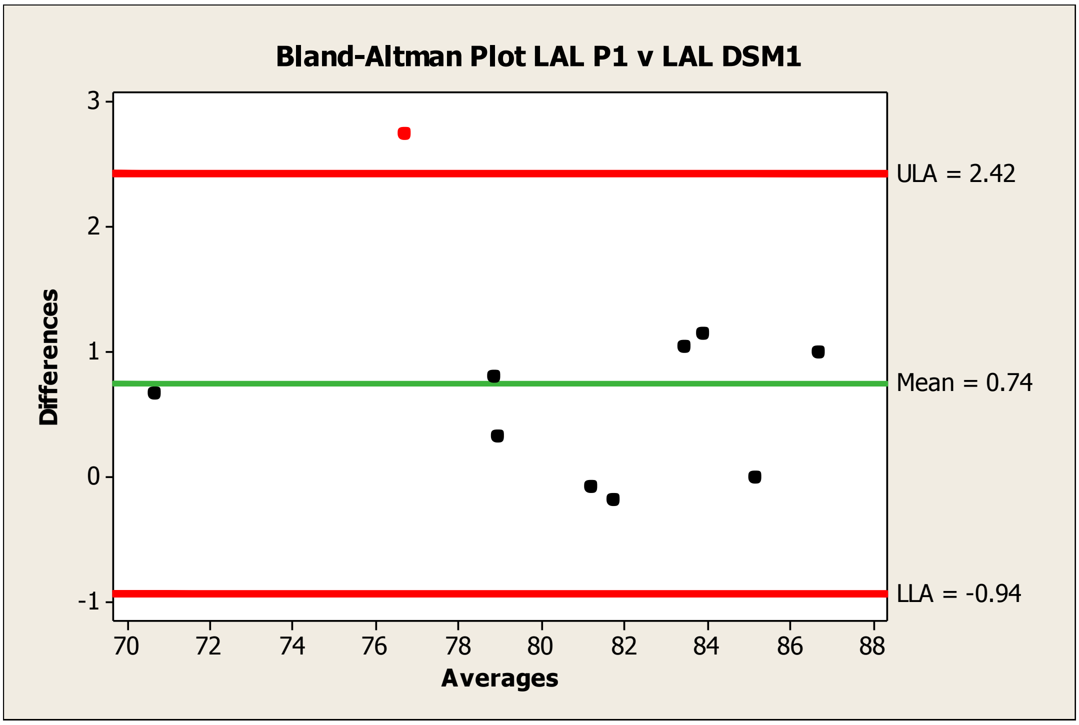
Est. mean of the differences: 0.47 Est. stdev of the differences: 0.82

Figure 3.2.1k Bland – Altman Plot for Upper Arch Length



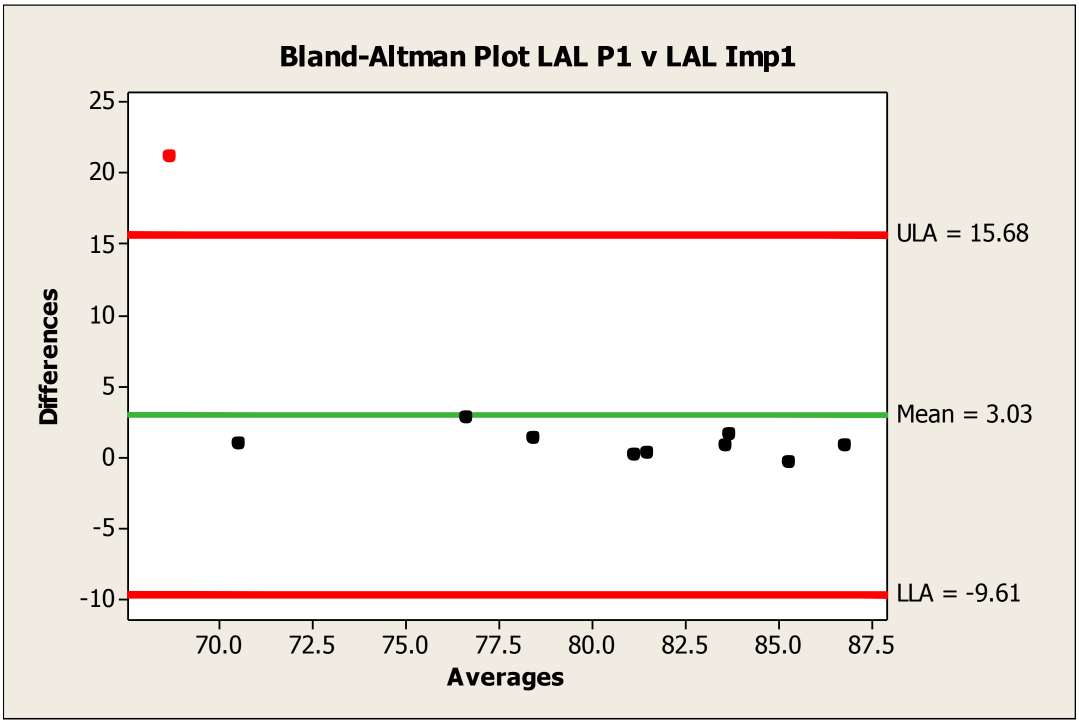
Est. mean of the differences: 0.89 Est. stdev of the differences: 0.58

Figure 3.2.1l Bland – Altman Plot for Upper Arch Length



Est. mean of the differences: 0.74 Est. stdev of the differences: 0.86

Figure 3.2.1m Bland – Altman Plot for Lower Arch Length



Est. mean of the differences: 3.03 Est. stdev of the differences: 6.45

Figure 3.2.1n Bland – Altman Plot for Lower Arch Length

3.2.2 Plaster Study Models as compared to Digital Study Models created from a Scan of the Plaster Study Models

The Bland – Altman Plots show that for the digital study models created by a scan of plaster models, for all landmark measurements, the sample fell within the 'limits of agreement' except for 'lower arch length'. (Figure 3.2.1m).
Lower arch length is outside the upper 'limit of agreement' by 0.25mm.

The mean for each plot as shown by the central green line, ranged from -0.02mm for overjet up to 0.74mm for lower arch length. The smallest limit of agreement was -0.17mm for upper inter-canine width and the largest limit of agreement was 2.42mm for lower arch length.

There was no pattern evident from the scatter of points which were distributed evenly above and below the mean. This suggests no systematic differences between the two methods.

3.2.3 Plaster Study Models as compared to Digital Study Models created from a Scan of the Dental Impressions of the Plaster Study Models

The Bland – Altman Plots show that for the digital study models created by a scan of dental impressions the majority of measurements fell between the upper and lower 'limits of agreement'. There were four outliers in this group, compared to only one in the digital study model group created by scanning plaster models.

When there were outliers present it was only one per landmark measurement and it was always above the upper 'limit of agreement'. The following outliers were noted for Overbite by 1.0mm (Figure 3.2.1d) / Upper inter-canine width by 0.06mm (Figure 3.2.1f) / Upper arch length 0.13mm (Figure 3.2.1l) / Lower arch length 2.0mm (Figure 3.2.1n).

The mean for each plot as shown by the central green line ranged from 0.04mm for lower inter-molar width up to 3.03mm for lower arch length.

The smallest limit of agreement was -0.11mm for upper central incisor length and the largest limit of agreement was 15.68mm for lower arch length but this was due to the outlier in the measurement sample.

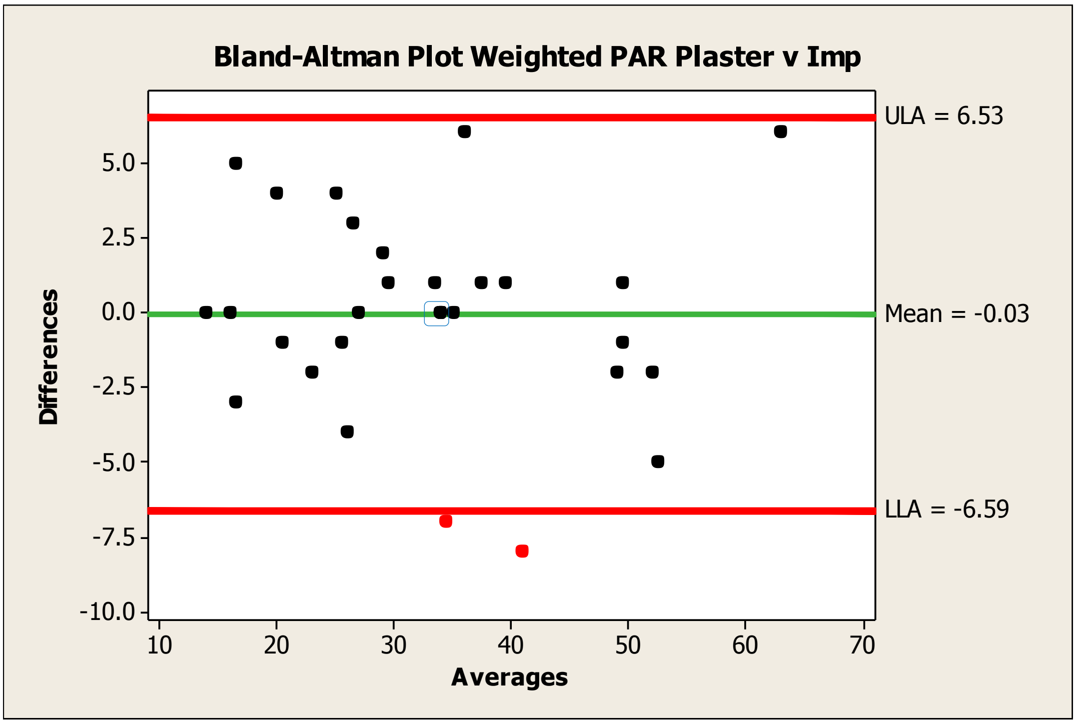
For all plots the scatter of points was distributed evenly both above and below the mean, suggesting that there were no systematic differences between the two methods. There was one exception to this for lower arch length as shown in (Figure 3.2.1n), with all the points being just below the mean, apart from the one outlier.

3.3 Section Two

Thirty sets of plaster study models were given a Peer Assessment Rating score (Appendix Four).

One month later digital study models were created from alginate dental impressions of the plaster study models. The digital study models were PAR scored using OrthoAnalyser^{TM} PAR Scoring Software (3Shape, Copenhagen, Denmark).

A Bland – Altman Plot was used to analyse if there was a systematic difference between plaster and digital study models with regard to PAR scores (Figure 3.3).



Est. mean of the differences: -0.03 Est. stdev of the differences: 3.35

Figure 3.3 Bland – Altman Plot for the Pre-Treatment Weighted PAR Scores for Plaster and Digital Study Models

Most points fell within the upper and lower 'levels of agreement' and there were only two outliers which were below the lower 'level of agreement'. One of the outliers was only just outside the level of agreement at 0.5. The second outlier was further away from the 'level of agreement' at 1.5. Both of these are unlikely to affect the PAR score grade.

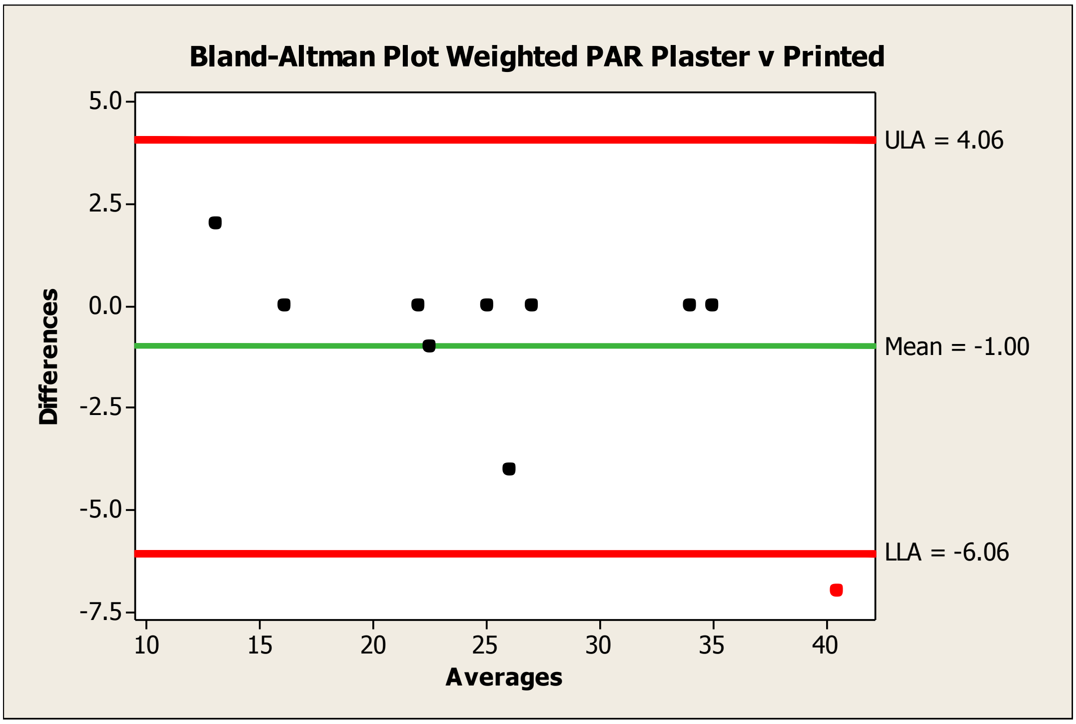
The mean difference for the sample was -0.03. The upper level of agreement was 6.53 and the lower -6.59.

The highlighted point on the plot represents 3 points all with the same value which explains why there are only 28 points on the plot but 30 sets of data in total.

The plot showed there was no pattern evident with the scatter of points being distributed relatively evenly both above and below the mean thus supporting there to be no systematic differences between the two methods.

3.4 Section Three

Ten plaster study models were randomly selected from the sample used in Section Two. These study models had already had alginate dental impressions taken of them, which had been used to create digital study models also used in Section Two. From these ten digital study models, physical hard copy study models were generated by 3D printing of the digital images. PAR scores were obtained for the ten 3D printed study models.



Est. mean of the differences: -1.00 Est. stdev of the differences: 2.58

Figure 3.4 Bland – Altman Plot for Pre-Treatment Weighted PAR Scores for Plaster and 3D Printed Study Models

The Bland – Altman Plot shows the entire sample fell between the upper and lower ‘levels of agreement’ bar one outlier. The outlier was 1.0 under the lower ‘limit of agreement’. This is unlikely to be significant clinically.

The mean difference for the plot was -1.00. The upper ‘level of agreement’ was 4.06 and the lower -6.06.

The plot showed there was no pattern evident indicating there was no systematic difference between the plaster PAR scored study models and the 3D printed PAR scored study models.

The outlier in Figure 3.4 (Section Three) and the furthest outlier in Figure 3.3 (Section Two) were from the same study model; number 16.
This may have been due to a technical error or through examiner error. Study model number 16 was not involved in the Section One sample so will not have impacted on these results.

CHAPTER FOUR

DISCUSSION

4. DISCUSSION

4.1 Comparison of measurement accuracy of Plaster and Digital Models

Bland – Altman Plots to illustrate each of the landmark measurements for plaster study models as compared to digital study models created from scanned plaster study models are shown in (Figures:3.2.1a, 3.2.1c, 3.2.1e, 3.2.1g, 3.2.1i, 3.2.1k, 3.2.1m).

All plots, except for Figure 3.2.1m illustrating lower arch length, show the levels of agreement between the two types of study models to be satisfactory with all differences falling within the levels of agreement and with a random scatter of points around the mean. The plot for lower arch length shows one outlier outside the levels of agreement. However, this is only just outside the upper level of agreement by 0.25mm and hence unlikely to be clinically significant.

Bland – Altman Plots used to illustrate each of the landmark measurements for plaster study models compared to digital study models created by scans of alginate dental impressions are shown in (Figures: 3.2.1b, 3.2.1d, 3.2.1f, 3.2.1h, 3.2.1j, 3.2.1l, 3.2.1n).

The majority of the differences between both methods fell between the levels of agreement for all the landmark measurements and there was no pattern evident with the scatter of points being relatively evenly distributed around the mean. Both these observations support no systematic differences between the two methods. However, one outlier was detected outside the levels of agreement for overbite by 1.0mm, upper inter-canine width by 0.0625mm, upper arch length by 0.125mm and lower arch length by 2.0mm. Most of the outliers were outside the levels of agreement by such a small amount it is unlikely to be of any clinical significance.

Previous systematic reviews by (Fleming *et al*., 2011) and (Luu *et al*., 2012); have also concluded a high degree of validity between linear measurements on plaster and digital study models created from laser scans of plaster models. They confirmed differences between both methods to be minimal and not clinically significant.

Multiple recent studies conducted have also confirmed agreement between linear landmark measurements made with plaster and digital study models. Greatest mean differences were typically demonstrated to be just below 2mm with the majority of measurements differing by less than 1mm. Any differences detected were deemed by the authors not to be clinically significant although statistical significance was demonstrated in some instances (Sousa *et al*., 2012); (Abizadeh *et al*., 2012); (Bootvong *et al*., 2010); (Horton *et al*., 2010); (Asquith *et al*., 2007); (Quimby *et al*., 2004).

However, other workers have highlighted inconsistencies between some measurements such as overbite, performed on plaster and digital study models (Sjogren *et al*., 2010); (Zilberman *et al*., 2003); (Santoro *et al*., 2003). They recommended further research is necessary before digital models can be used confidently for scientific work, but still felt digital models to be adequate for routine clinical work.

The present study suggests that digitised records from plaster models are essentially accurate enough to replace the physical models for clinical applications.

The digital models used in the above mentioned studies were created from laser scans of plaster models. Only one previous study has used digital models created from dental impression laser scans and compared them to plaster models. No significant difference between digital models created in this manner and plaster models were found when comparing crown preparations with both methods (Persson *et al*., 2009).

Another study (Wiranto *et al*., 2013), also using digital models created from CBCT scans of dental impressions showed no clinically significant difference between tooth width measurements and plaster models.

The obvious advantage of scanning dental impressions to create digital study models is there is no need to fabricate a plaster model, hence saving on time and material costs.

The present study agrees that digitised records derived from scans of impressions are also accurate enough to be comparable to plaster casts.

4.2 Comparison of PAR Scoring with Plaster and Digital Models

The level of agreement between PAR scores from both methods was indicated to be satisfactory, as illustrated in the Bland – Altman Plot shown in (Figure 3.3). This was demonstrated by the scatter of points being relatively evenly distributed above and below the mean and also the majority of scores falling within two standard errors of the mean. The two outliers evident were just outside the levels of agreement at 0.5 and 1.5 PAR score points, both of which are unlikely to be clinically significant.

The mean difference for the sample was just 0.03 PAR score points. However, the magnitude of differences between the upper level of agreement was 6.53 PAR points and the lower level of agreement was 6.59 PAR points.

The suggested level of agreement for PAR scoring should be a difference of no more than ± 12 PAR points from the gold standard, for calibration of 50 models overall (Brown and Richmond, 2005). On this basis, the present results suggest that PAR scoring with digital versus plaster models is on the borderline for acceptable agreement.

Previous studies comparing pre-treatment PAR scores of digital and plaster study models confirmed this study's findings from using Bland-Altman statistics, that digital models were an acceptable replacement for plaster models. A mean difference of two PAR scores was shown between both methods (Mayers et al., 2005); (Stevens *et al*., 2006).

Conversely, one study found PAR scoring digital models took longer than conventional plaster models, however this was not experienced during this study (Mayers *et al*., 2005).

PAR scoring takes into account five occlusal components which are also assessed during treatment planning. Previous studies have confirmed good agreement between treatment plans made on both digital and plaster study models (Rheude *et al*., 2005); (Whetten *et al*., 2006).

The studies discussed above all used digital models created from laser scans of plaster models, no studies were identified where study models created from dental impressions were assessed for PAR scoring, hence, further research is warranted in this area. Although the present study suggests this method of PAR scoring would be acceptable for use.

4.3 Comparison between Plaster and 3D Printed Study Model Peer Assessment Rating Index Scores

A satisfactory level of agreement between both methods is shown in the Bland – Altman Plot (Figure 3.4). The distribution of points was concentrated around the mean and all but one point was within two standard errors of the mean. There was only one outlier beyond the levels of agreement and by only 1.0 PAR score point, which is unlikely to be clinically significant.

This outlier was analysed further from the raw data and was identified as also an outlier in the results from Section Two. It is possible there may be other factors causing this anomaly such as a technical or examiner error rather than a systematic error.

The mean difference in the sample was 1.0 PAR score point and the magnitude of differences was 4.06 PAR points for the upper level of agreement and 6.06 PAR points for the lower level of agreement. It is possible the lower level of agreement was increased in Section Two and Section Three results because of the anomalous outlier identified. A larger sample size is needed to refute or confirm the findings of this study.

There were no studies identified in the literature comparing 3D printed models with plaster models for PAR scoring. However, a study comparing retainer appliances constructed on stereolithographic models produced from digital models created from alginate dental impressions as compared to plaster models, concluded both methods did not differ significantly (Vasudavan *et al*., 2010).

The present study results indicate used of 3D printed models may be adequate for PAR scoring as compared with conventional plaster models.

4.4 Additional Comments

Operator experience during this study found undertaking linear measurements and PAR scoring with digital models to be both intuitive and efficient. However, it is possible measurement differences within the compared methods may be the result of operator inexperience with the new method. Intra-examiner reliability for PAR scoring would be indicated in future studies.

Suggestions have been made previously for a separate calibration to be conducted when using digital models rather than traditional plaster models for occlusal indices and this could also be applied to the Peer Assessment Rating Index.

A busy practice may find purchase of their own laser scanner advantageous as current concerns over impression distortion in transit will be eliminated along with courier costs and delay in access to the electronic digital models. Operator experience during this study found both scanning and using the associated software to create the digital study models was straightforward to use. The 3Shape R700 Laser Scanner is small enough to place on a desktop this technology could easily be accommodated.

Digital study models of the dentition are only one element of digital records allowing analysis, diagnosis and treatment planning for the orthodontic patient. 3D imaging technologies are now being applied to both cranio-maxillofacial hard and soft tissues to enable the development of the ‘digital orthodontic patient’. Combining data for all these components has the potential to revolutionise how treatment is planned and delivered.

CHAPTER FIVE

CONCLUSIONS

5. CONCLUSIONS

This study indicates that linear measurements taken from digital study models created by laser scanning of plaster study models or of alginate impressions, may be comparable in accuracy to plaster models and should be suitable for clinical use. In clinical practice, measurements are routinely taken to the nearest 1mm or 0.5mm increment.

Digital study models created from laser scanning alginate dental impressions are indicated to be adequate for clinical use as compared to conventional plaster study models, for scoring pre-treatment study models with the Peer Assessment Rating Index.

3D printed study models generated from digital study models created from laser scanning alginate dental impressions, may be comparable to plaster study models for scoring pre-treatment study models with the Peer Assessment Rating Index.

Suggestions for further research would be to undertake a larger sample to confirm the above conclusions from this study with regard to validity and reliability. A power calculation would be needed to determine the size of the sample.

Additional studies could also involve assessing efficiency of this new method by assessing time differences between PAR scoring digital and plaster models.

REFERENCES

REFERENCES

ABIZADEH, N., MOLES, D. R., O'NEILL, J. & NOAR, J. H. 2012. Digital versus plaster study models: how accurate and reproducible are they? *Journal of Orthodontics,* 39**,** 151-9.

ALCAN, T., CEYLANOGLU, C. & BAYSAL, B. 2009. The relationship between digital model accuracy and time-dependent deformation of alginate impressions. *Angle Orthodontist,* 79**,** 30-6.

ANDREWS, L. F. 1972. The six keys to normal occlusion. *American Journal of Orthodontics,* 62**,** 296-309.

ARRUDA, A. O. 2008. Occlusal indexes as judged by subjective opinions. *American Journal of Orthodontics and Dentofacial Orthopedics,* 134**,** 671-5.

ASQUITH, J., GILLGRASS, T. & MOSSEY, P. 2007. Three-dimensional imaging of orthodontic models: a pilot study. *European Journal of Orthodontics,* 29**,** 517-22.

BARRY, M. 2011. In-office digital study models. *Journal of Clinical Orthodontics,* 45**,** 385-9.

BELL, A., AYOUB, A. F. & SIEBERT, P. 2003. Assessment of the accuracy of a three-dimensional imaging system for archiving dental study models. *Journal of Orthodontics,* 30**,** 219-23.

BLAND, J. M. & ALTMAN, D. G. 1986. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet,* 1**,** 307-10.

BLAND, J. M. & ALTMAN, D. G. 2012. Agreed statistics: measurement method comparison. *Anesthesiology,* 116**,** 182-5.

BOOTVONG, K., LIU, Z., MCGRATH, C., HAGG, U., WONG, R. W., BENDEUS, M. & YEUNG, S. 2010. Digital model analysis as an alternative approach to plaster model analysis: reliability and validity. *European Journal of Orthodontics,* 32**,** 589-95.

BROWN, R. & RICHMOND, S. 2005. An update on the analysis of agreement for orthodontic indices. *European Journal of Orthodontics,* 27**,** 286-91.

COBOURNE, M., DIBIASE A. *A Handbook of Orthodontics*, Mosby, 2010.

COHEN, A., LAVIV, A., BERMAN, P., NASHEF, R. & ABU-TAIR, J. 2009. Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontology,* 108**,** 661-6.

COMBE, E. *Notes on Dental Materials*, Churchill Livingstone,1992.

COSTALOS, P. A., SARRAF, K., CANGIALOSI, T. J. & EFSTRATIADIS, S. 2005. Evaluation of the accuracy of digital model analysis for the American Board of Orthodontics objective grading system for dental casts. *American Journal of Orthodontics and Dentofacial Orthopedics,* 128**,** 624-9.

CUPERUS, A. M. R., HARMS, M. C., RANGEL, F. A., BRONKHORST, E. M., SCHOLS, J. G. J. H. & BREUNING, K. H. 2012. Dental models made with an intraoral scanner: A validation study. *American Journal of Orthodontics and Dentofacial Orthopedics,* 142**,** 308-313.

DALSTRA, M. & MELSEN, B. 2009. From alginate impressions to digital digital models: accuracy and reproducibility. *Journal of Orthodontics,* 36**,** 36-41; discussion 14.

DEGUZMAN, L., BAHIRAEI, D., VIG, K. W., VIG, P. S., WEYANT, R. J. & O'BRIEN, K. 1995. The validation of the Peer Assessment Rating index for malocclusion severity and treatment difficulty. *American Journal of Orthodontics and Dentofacial Orthopedics,* 107**,** 172-6.

EL-ZANATY, H. M., EL-BEIALY, A. R., ABOU EL-EZZ, A. M., ATTIA, K. H., EL-BIALY, A. R. & MOSTAFA, Y. A. 2010. Three-dimensional dental measurements: An alternative to plaster models. *American Journal of Orthodontics and Dentofacial Orthopedics,* 137**,** 259-65.

ELLIS, P. E. & BENSON, P. E. 2003. Does articulating study casts make a difference to treatment planning? *Journal of Orthodontics,* 30**,** 45-9; discussion 22-3.

FLEMING, P. S., MARINHO, V. & JOHAL, A. 2011. Orthodontic measurements on digital study models compared with plaster models: a systematic review. *Orthodontics and Craniofacial Research,* 14**,** 1-16.

HAJEER, M. Y., MILLETT, D. T., AYOUB, A. F. & SIEBERT, J. P. 2004a. Applications of 3D imaging in orthodontics: part I. *Journal of Orthodontics,* 31**,** 62-70.

HAJEER, M. Y., MILLETT, D. T., AYOUB, A. F. & SIEBERT, J. P. 2004b. Applications of 3D imaging in orthodontics: part II. *Journal of Orthodontics,* 31**,** 154-62.

HALAZONETIS, D. J. 2001. Acquisition of 3-dimensional shapes from images. *American Journal of Orthodontics and Dentofacial Orthopedics,* 119**,** 556-60.

HAMDAN, A. M. & ROCK, W. P. 1999. An appraisal of the Peer Assessment Rating (PAR) Index and a suggested new weighting system. *European Journal of Orthodontics,* 21**,** 181-92.

HILDEBRAND, J. C., PALOMO, J. M., PALOMO, L., SIVIK, M. & HANS, M. 2008. Evaluation of a software program for applying the American Board of Orthodontics objective grading system to digital casts. *American Journal of Orthodontics and Dentofacial Orthopedics,* 133**,** 283-9.

HORTON, H. M., MILLER, J. R., GAILLARD, P. R. & LARSON, B. E. 2010. Technique comparison for efficient orthodontic tooth measurements using digital models. *Angle Orthodontist,* 80**,** 254-61.

IRELAND, A. J., MCNAMARA, C., CLOVER, M. J., HOUSE, K., WENGER, N., BARBOUR, M. E., ALEMZADEH, K., ZHANG, L. & SANDY, J. R. 2008. 3D surface imaging in dentistry - what we are looking at. *British Dental Journal,* 205**,** 387-92.

KEATING, A. P., KNOX, J., BIBB, R. & ZHUROV, A. I. 2008. A comparison of plaster, digital and reconstructed study model accuracy. *Journal of Orthodontics,* 35**,** 191-201; discussion 175.

KING, G. J., MCGORRAY, S. P., WHEELER, T. T., DOLCE, C. & TAYLOR, M. 2003. Comparison of peer assessment ratings (PAR) from 1-phase and 2-phase treatment protocols for Class II malocclusions. *American Journal of Orthodontics and Dentofacial Orthopedics,* 123**,** 489-96.

KURODA, T., MOTOHASHI, N., TOMINAGA, R. & IWATA, K. 1996. Three-dimensional dental cast analyzing system using laser scanning. *American Journal of Orthodontics and Dentofacial Orthopedics,* 110**,** 365-9.

KUSNOTO, B. & EVANS, C. A. 2002. Reliability of a 3D surface laser scanner for orthodontic applications. *Amercian Journal of Orthodontics and Dentofacial Orthopedics,* 122**,** 342-8.

LEIFERT, M. F., LEIFERT, M. M., EFSTRATIADIS, S. S. & CANGIALOSI, T. J. 2009. Comparison of space analysis evaluations with digital models and plaster dental casts. *American Journal of Orthodontics and Dentofacial Orthopedics,* 136**,** 16 e1-4; discussion 16.

LUU, N. S., NIKOLCHEVA, L. G., RETROUVEY, J. M., FLORES-MIR, C., EL-BIALY, T., CAREY, J. P. & MAJOR, P. W. 2012. Linear measurements using digital study models. *Angle Orthodontist,* 82**,** 1098-106.

MAH, J. 2007. The evolution of digital study models. *Journal of Clinical Orthodontics,* 41, 557-61; quiz 424.

MALIK, O. H., ABDI-OSKOUEI, M. & MANDALL, N. A. 2009. An alternative to study model storage. *European Journal of Orthodontics,* 31, 156-9.

MARTORELLI, M., GERBINO, S., GIUDICE, M. & AUSIELLO, P. 2013. A comparison between customized clear and removable orthodontic appliances manufactured using RP and CNC techniques. *Dental Materials,* 29, e1-10.

MAYERS, M., FIRESTONE, A. R., RASHID, R. & VIG, K. W. 2005. Comparison of peer assessment rating (PAR) index scores of plaster and computer-based digital models. *American Journal of Orthodontics and Dentofacial Orthopedics,* 128, 431-4.

MCGORRAY, S. P., WHEELER, T. T., KEELING, S. D., YURKIEWICZ, L., TAYLOR, M. G. & KING, G. J. 1999. Evaluation of orthodontists' perception of treatment need and the peer assessment rating (PAR) index. *Angle Orthodontist,* 69, 325-33.

MCGUINNESS, N. J. & STEPHENS, C. D. 1992. Storage of orthodontic study models in hospital units in the U.K. *British Journal of Orthodontics,* 19, 227-32.

MITCHELL, L. *An Introduction to Orthodontics*, Oxford University Press, 2001.

MOTOHASHI, N. & KURODA, T. 1999. A 3D computer-aided design system applied to diagnosis and treatment planning in orthodontics and orthognathic surgery. *European Journal of Orthodontics,* 21, 263-74.

MULLEN, S. R., MARTIN, C. A., NGAN, P. & GLADWIN, M. 2007. Accuracy of space analysis with emodels and plaster models. *American Journal of Orthodontics and Dentofacial Orthopedics,* 132, 346-52.

OKUMURA, H., CHEN, L. H., TSUTSUMI, S. & OKA, M. 1999. Three-dimensional digital imaging of facial skeleton and dental morphologic condition for treatment planning in orthognathic surgery. *American Journal of Orthodontics and Dentofacial Orthopedics,* 116, 126-31.

OKUNAMI, T. R., KUSNOTO, B., BEGOLE, E., EVANS, C. A., SADOWSKY, C. & FADAVI, S. 2007. Assessing the American Board of Orthodontics objective grading system: digital vs plaster dental casts. *American Journal of Orthodontics and Dentofacial Orthopedics,* 131, 51-6.

PELUSO, M. J., JOSELL, S. D., LEVINE, S. W. & LOREI, B. J. 2004. Digital models: An introduction. *Seminars in Orthodontics,* 10, 226-238.

PERSSON, A. S., ODEN, A., ANDERSSON, M. & SANDBORGH-ENGLUND, G. 2009. Digitization of simulated clinical dental impressions: digital three-dimensional analysis of exactness. *Dental Materials,* 25**,** 929-36.

PETRIE, A., SABIN, C. *Medical Statistics at a Glance*, Wiley-Blackwell, 2010.

QUIMBY, M. L., VIG, K. W., RASHID, R. G. & FIRESTONE, A. R. 2004. The accuracy and reliability of measurements made on computer-based digital models. *Angle Orthodontist,* 74**,** 298-303.

REDLICH, M., WEINSTOCK, T., ABED, Y., SCHNEOR, R., HOLDSTEIN, Y. & FISCHER, A. 2008. A new system for scanning, measuring and analyzing dental casts based on a 3D holographic sensor. *Orthodontics and Craniofacial Research,* 11**,** 90-5.

RHEUDE, B., SADOWSKY, P. L., FERRIERA, A. & JACOBSON, A. 2005. An evaluation of the use of digital study models in orthodontic diagnosis and treatment planning. *Angle Orthodontist,* 75**,** 300-4.

RICHMOND, S., SHAW, W. C., O'BRIEN, K. D., BUCHANAN, I. B., JONES, R., STEPHENS, C. D., ROBERTS, C. T. & ANDREWS, M. 1992a. The development of the PAR Index (Peer Assessment Rating): reliability and validity. *European Journal of Orthodontics,* 14**,** 125-39.

RICHMOND, S., SHAW, W. C., ROBERTS, C. T. & ANDREWS, M. 1992b. The PAR Index (Peer Assessment Rating): methods to determine outcome of orthodontic treatment in terms of improvement and standards. *European Journal of Orthodontics,* 14**,** 180-7.

RICHMOND, S. *Evaluating Effective Orthodontic Care*, FIRST Numerics Ltd, 2008.

SANTORO, M., GALKIN, S., TEREDESAI, M., NICOLAY, O. F. & CANGIALOSI, T. J. 2003. Comparison of measurements made on digital and plaster models. *American Journal of Orthodontics and Dentofacial Orthopedics,* 124**,** 101-5.

SJOGREN, A. P., LINDGREN, J. E. & HUGGARE, J. A. 2010. Orthodontic study cast analysis--reproducibility of recordings and agreement between conventional and 3D digital measurements. *Journal of Digital Imaging,* 23**,** 482-92.

SOUSA, M. V., VASCONCELOS, E. C., JANSON, G., GARIB, D. & PINZAN, A. 2012. Accuracy and reproducibility of 3-dimensional digital model measurements. *American Journal of Orthodontics and Dentofacial Orthopedics,* 142**,** 269-73.

STEVENS, D. R., FLORES-MIR, C., NEBBE, B., RABOUD, D. W., HEO, G. & MAJOR, P. W. 2006. Validity, reliability, and reproducibility of plaster vs digital study models: comparison of peer assessment rating and Bolton analysis and their constituent measurements. *American Journal of Orthodontics and Dentofacial Orthopedics,* 129**,** 794-803.

THIRUVENKATACHARI, B., AL-ABDALLAH, M., AKRAM, N. C., SANDLER, J. & O'BRIEN, K. 2009. Measuring 3-dimensional tooth movement with a 3-dimensional surface laser scanner. *American Journal of Orthodontics and Dentofacial Orthopedics,* 135**,** 480-5.

TORASSIAN, G., KAU, C. H., ENGLISH, J. D., POWERS, J., BUSSA, H. I., MARIE SALAS-LOPEZ, A. & CORBETT, J. A. 2010. Digital models vs plaster models using alginate and alginate substitute materials. *Angle Orthodontist,* 80**,** 662-669

VAN NOORT, R. *Introduction to Dental Materials*, Mosby, 1994.

VASUDAVAN, S., SULLIVAN, S. R. & SONIS, A. L. 2010. Comparison of intraoral 3D scanning and conventional impressions for fabrication of orthodontic retainers. *Journal of Clinical Orthodontics,* 44**,** 495-7.

VEENEMA, A. C., KATSAROS, C., BOXUM, S. C., BRONKHORST, E. M. & KUIJPERS-JAGTMAN, A. M. 2009. Index of Complexity, Outcome and Need scored on plaster and digital models. *European Journal of Orthodontics,* 31**,** 281-6.

WHETTEN, J. L., WILLIAMSON, P. C., HEO, G., VARNHAGEN, C. & MAJOR, P. W. 2006. Variations in orthodontic treatment planning decisions of Class II patients between digital 3-dimensional models and traditional plaster study models. *American Journal of Orthodontics and Dentofacial Orthopedics,* 130**,** 485-91.

WIRANTO, M. G., ENGELBRECHT, W. P., TUTEIN NOLTHENIUS, H. E., VAN DER MEER, W. J. & REN, Y. 2013. Validity, reliability, and reproducibility of linear measurements on digital models obtained from intraoral and cone-beam computed tomography scans of alginate impressions. *American Journal of Orthodontics and Dentofacial Orthopedics,* 143**,** 140-7.

ZILBERMAN, O., HUGGARE, J. A. & PARIKAKIS, K. A. 2003. Evaluation of the validity of tooth size and arch width measurements using conventional and three-dimensional digital orthodontic models. *Angle Orthodontist,* 73**,** 301-6.

APPENDICES

APPENDIX I

KEY STAGES OF DIGITAL STUDY MODEL CONSTRUCTION

Figures 2.3.2a – 2.3.2m illustrate the key stages of digital study model construction.

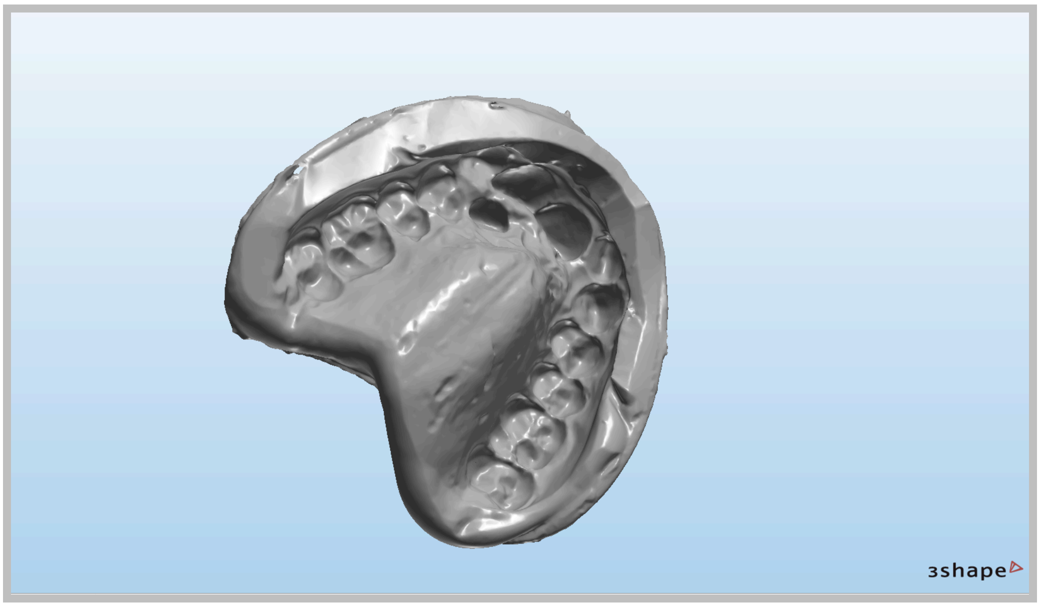


Figure 2.3.2a Scan of a maxillary alginate dental impression on screen.

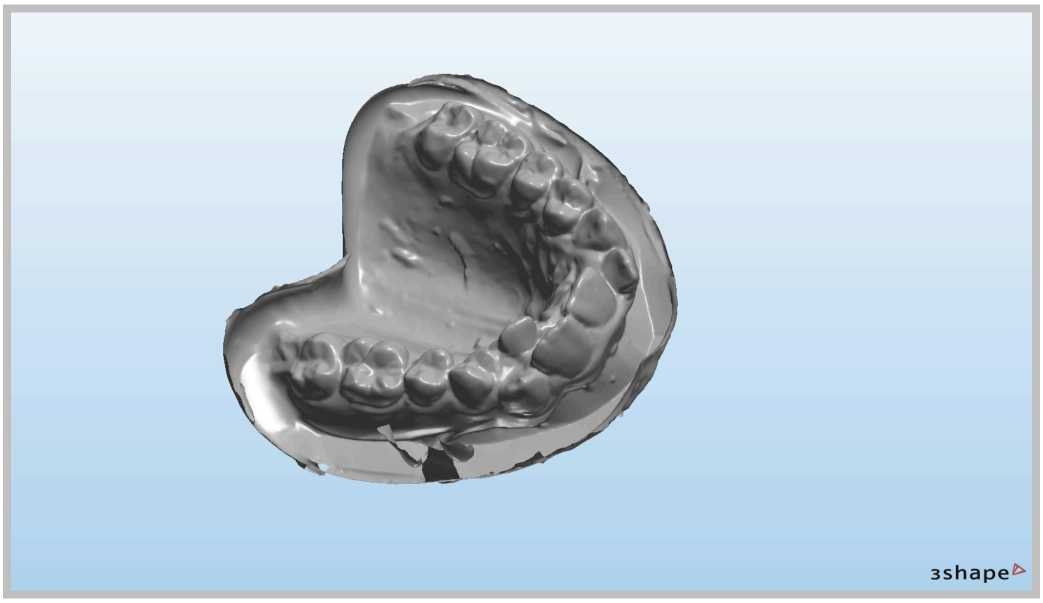


Figure 2.3.2b Scanned maxillary alginate dental impression reverse side on screen following rotation. This illustrates the positive image constructed from the negative impression surface shown in Figure 2.4.2a.

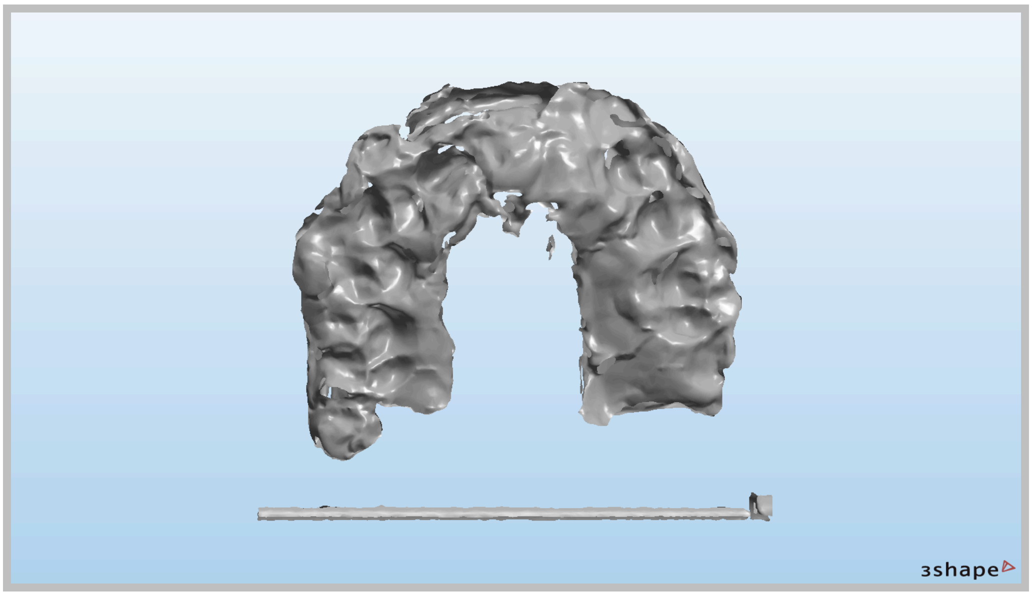
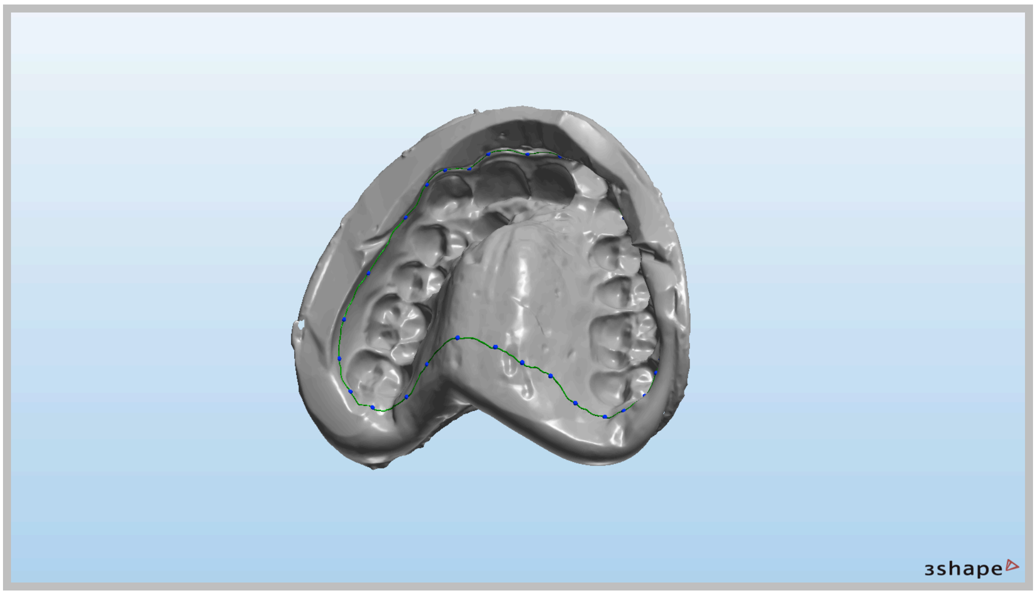


Figure 2.3.2c Scan of a wax bite occlusal registration.



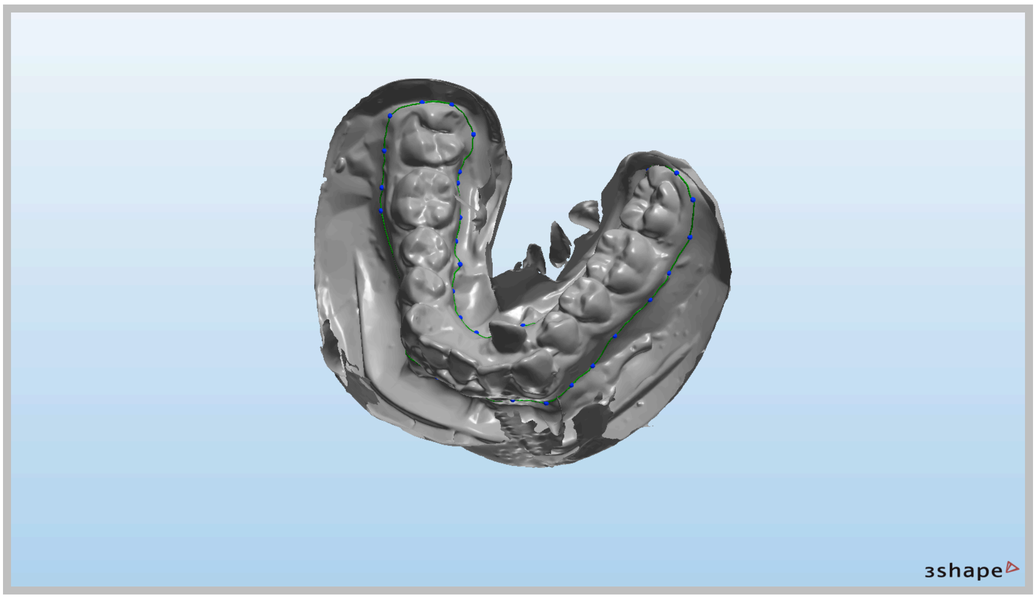


Figure 2.3.2d ‘Trimming’ of maxillary and mandibular digital study models on screen, as seen by the linear border around the working area of the impression.

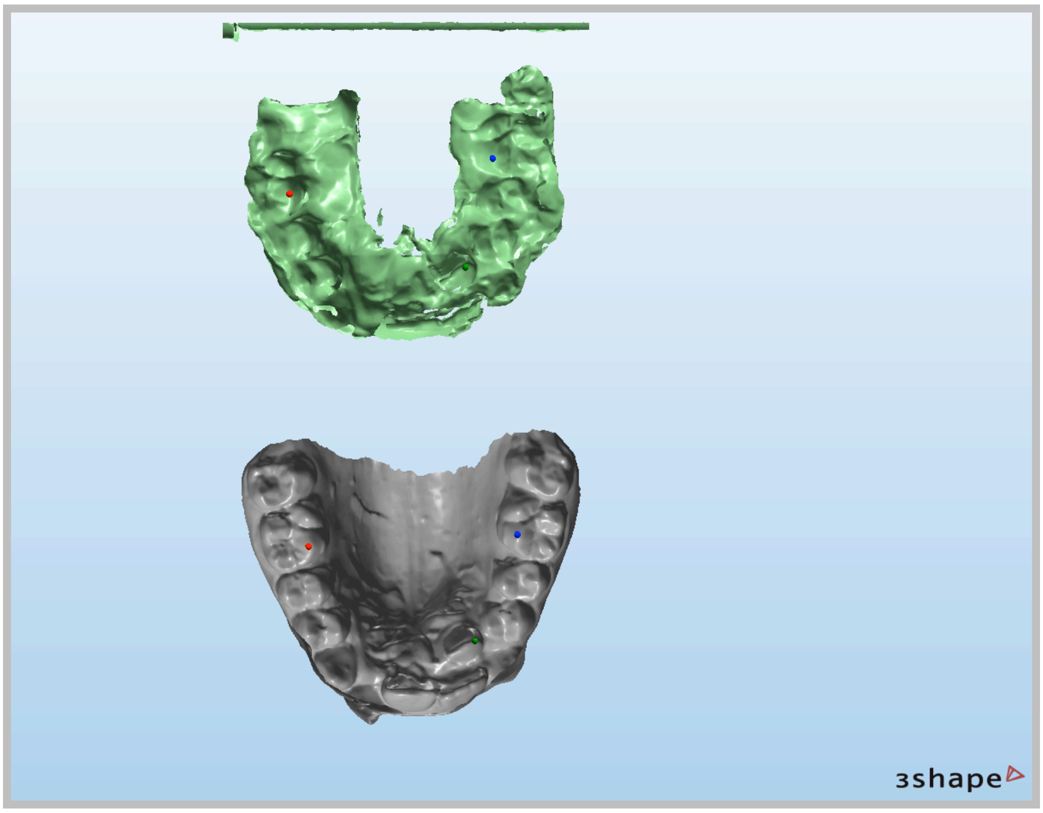


Figure 2.3.2e Alignment of the maxillary digital study model to the digital wax bite prior to articulation of the study models. This is aided by marking coincident points on the model and wax bite to optimise accurate positioning. Three points were used to articulate the digital study models.

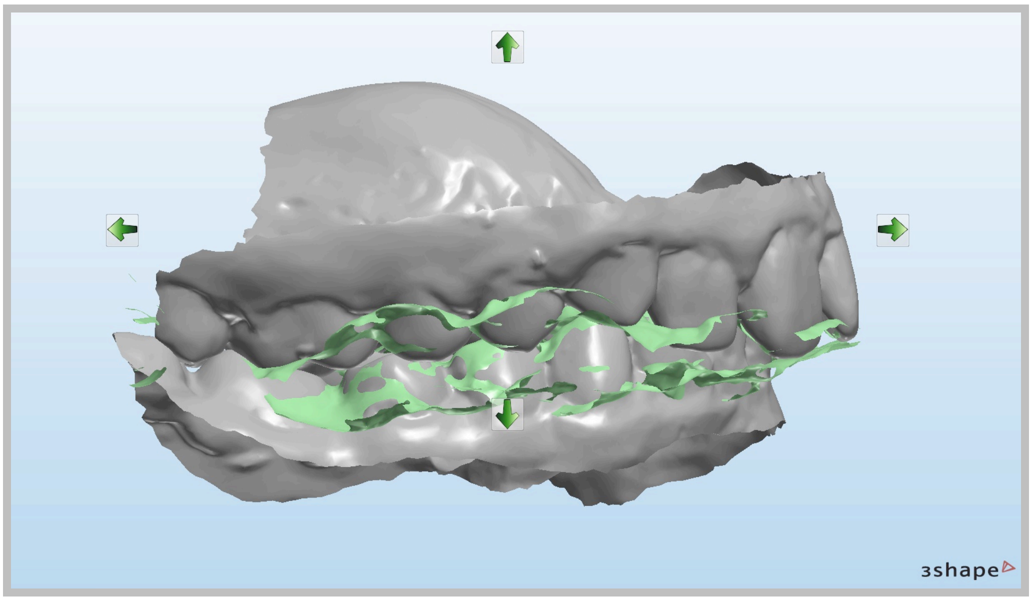


Figure 2.3.2f Adjustments for fine occlusal detailing were made by further alignment of the maxillary and/or mandibular model to the wax bite manually in all three planes of space.

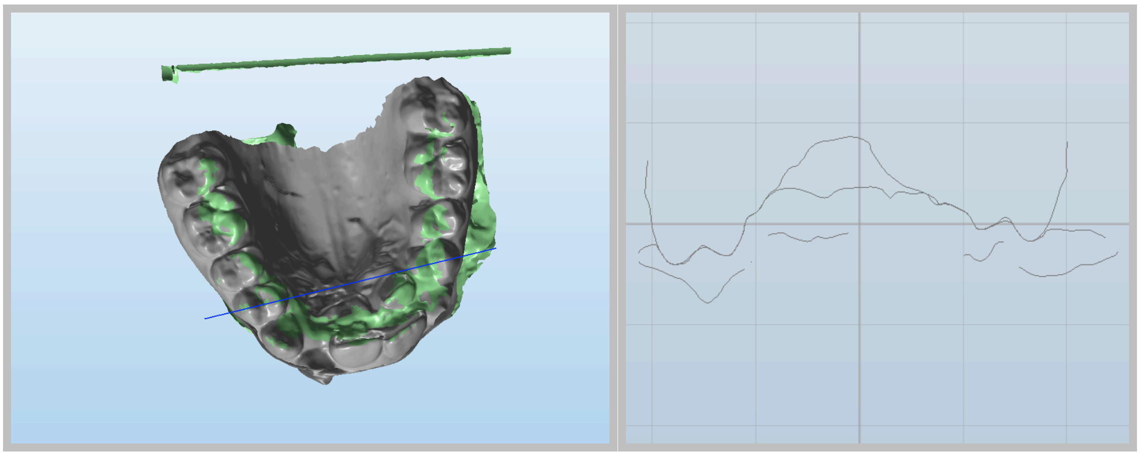


Figure 2.3.2g Adaptation of the wax bite to the maxillary study model can be demonstrated or checked by taking a cross-section through the wax bite in situ on the study model as shown by the inset graph. In this example there is good adaptation of the wax bite to the study model.

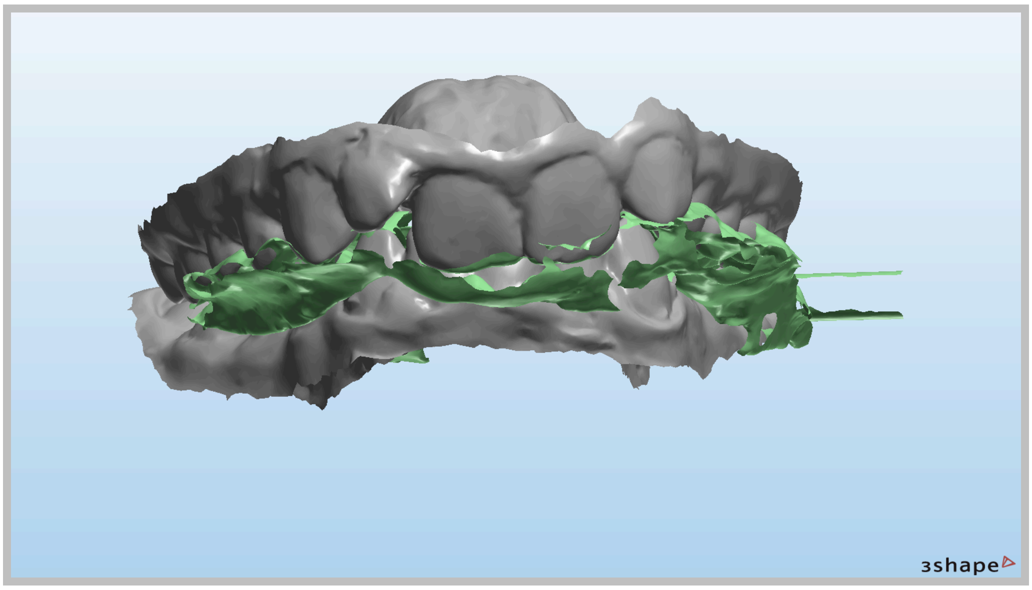


Figure 2.3.2h Final checking of maxillary and mandibular study model position prior to occlusion approval. This can be thoroughly checked from all angles by rotating the study models on screen.

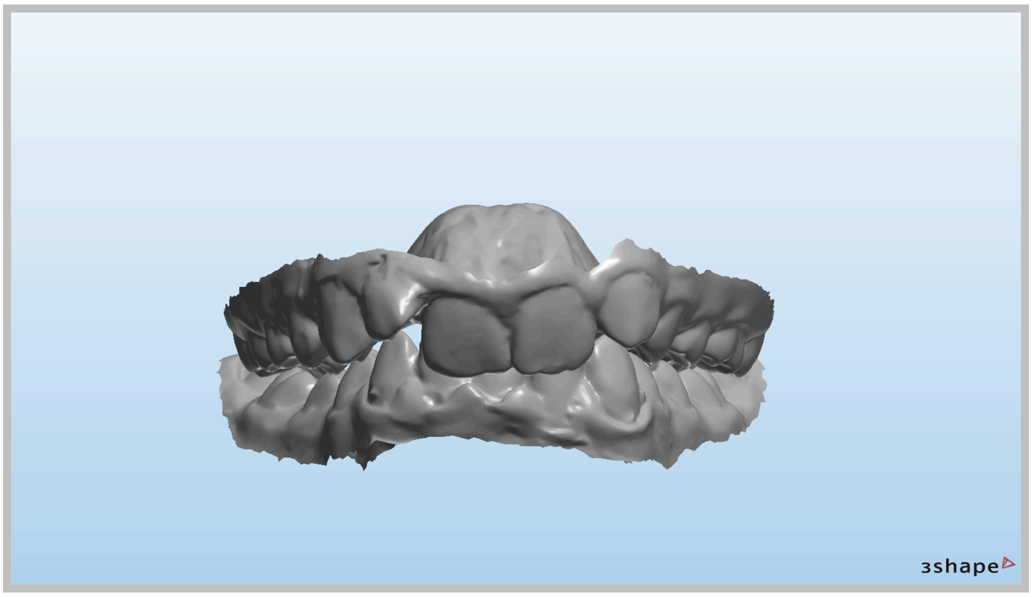


Figure 2.3.2i Final occlusion following approval and removal of wax bite.

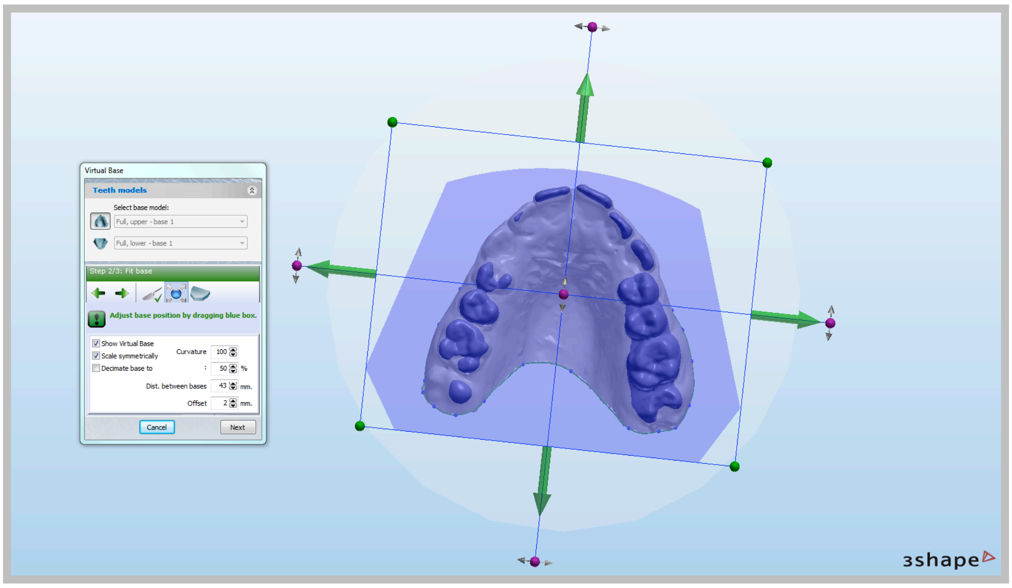


Figure 2.3.2j Prior to finishing the digital set of study models, digital bases for the study models are created. This illustration shows the base dimensions being set and centred to the maxillary study model.

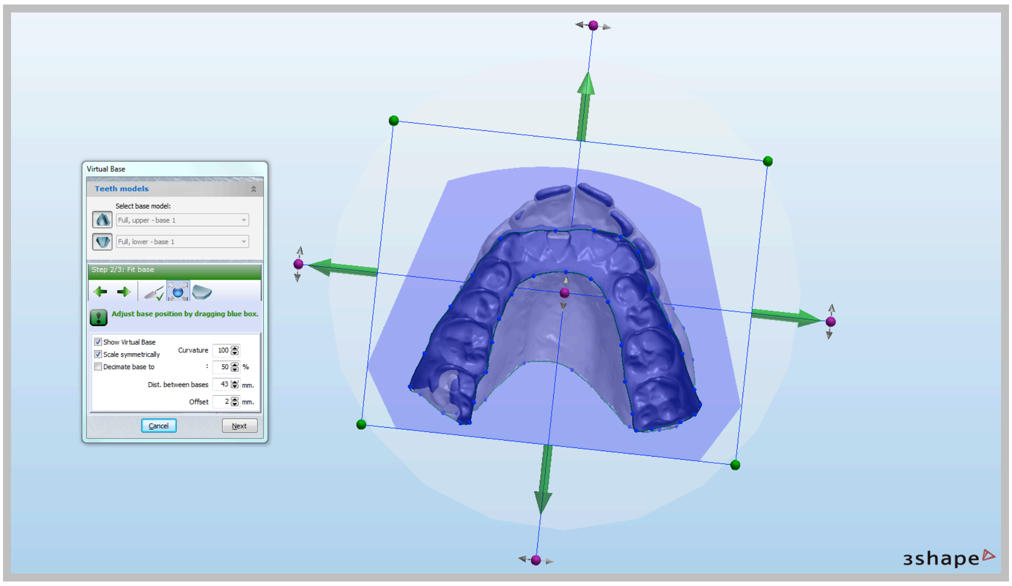


Figure 2.3.2k The mandibular study model is then added and the digital bases adjusted as necessary.

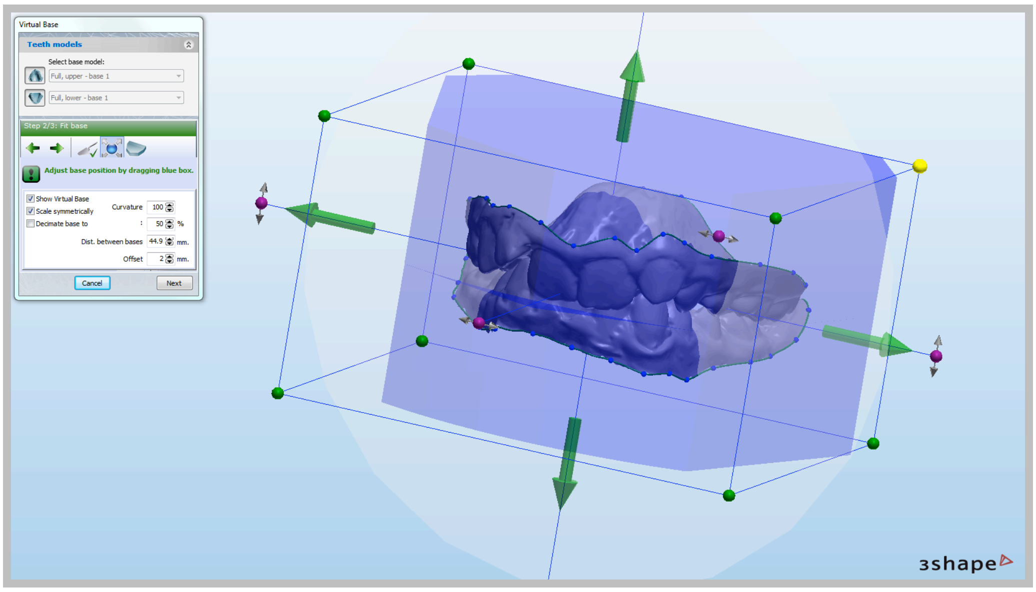


Figure 2.3.2l Alterations to the bases can be made in all three planes of space by viewing the models from any angle on screen.

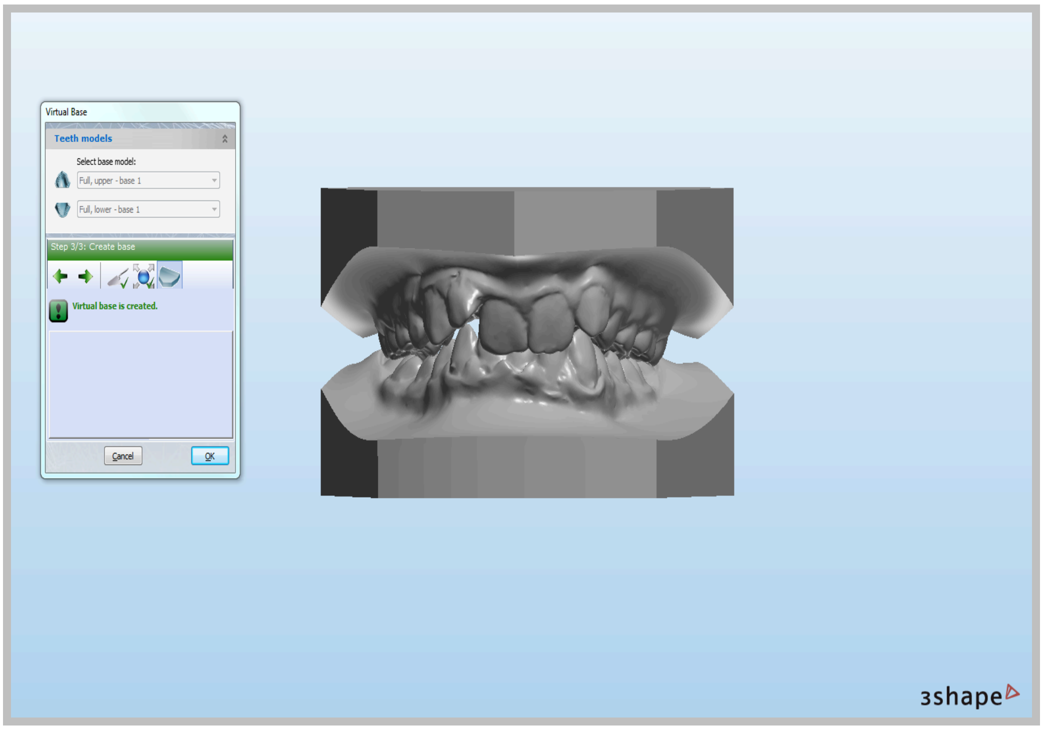


Figure 2.3.2m Final completed digital study models created from alginate dental impressions.

APPENDIX II

RAW DATA FOR ALL LANDMARK MEASUREMENTS

Pt No	OJ P1	OJ SM1	OJ Imp1	OB P1	OB SM1	OB Imp1	UIC P1	UIC SM1	UIC Imp1	LIM P1	LIM SM1	LIM Imp1	UL1 P1
1	8.79	8.89	8.68	6.4	6.55	6.2	36.57	36.39	36.6	29.84	30.52	30.11	10.75
4	1.73	1.75	1.44	2	1.35	2.72	36.16	35.91	35.62	40.71	40.62	40.51	10.2
41	-6.16	-5.08	-5.32	0.55	0	1.13	33.85	33.36	33.92	35.57	35.26	35.7	10.37
44	4.37	4.01	4.03	4.43	3.87	3.76	35.53	34.85	34.48	37.26	36.8	36.87	10.65
45	2.93	1.59	0.94	0	0	0	30.66	30.74	30.29	37.13	37.48	37.09	8.65
50	2.57	2.93	2.41	1.39	1.23	1.12	28.82	28.86	28.89	32.72	32.04	32.83	10.37
58	6.02	5.17	4.25	3.33	2.8	0	31.31	30.77	30.87	34.93	34.9	34.58	10.67
72	10.85	11.18	10.64	4.67	3.52	4.39	31.41	31.09	31.02	34.88	34.52	34.48	9.54
74	11.05	10.82	10.44	4.5	3.78	5.03	32.04	31.71	31.74	33.7	34.02	33.78	9.88
77	4.89	4.68	4.43	0.5	0	1	31.73	31.38	31.31	33.98	34.79	34.36	10.04

Pt No	UL1 SM1	UL1 Imp1	UAL P1	UAL SM1	UAL Imp1	LAL P1	LAL SM1	LAL Imp1	OJ P2	OJ SM2	OJ Imp2	OB P2
1	10.81	10.46	101.85	101.54	101.04	84.45	83.3	82.79	9.27	8.46	8.65	6.85
4	10.2	10	93.43	91.57	91.25	87.15	86.16	86.27	1.43	1.6	1.48	2.16
41	9.78	9.93	92.07	91.6	90.97	81.15	81.23	80.96	-5.26	-4.9	-5.31	0.9
44	11	10.55	92.22	93.03	91.65	85.12	85.13	85.35	4.32	4.12	4.06	4.38
45	8.57	8.26	79.31	79.66	79.04	70.98	70.32	69.97	1.49	1.6	1.13	0
50	10.34	10.25	88.46	87.66	87.39	79.09	78.76	77.63	2.86	2.55	2.59	1.37
58	10.34	10.29	87.49	86.8	86.56	78.04	75.3	75.15	5.46	4.79	4.29	1.99
72	8.99	9.04	90.99	90.03	89.7	79.25	78.45	58.02	10.95	11.75	10.24	4.24
74	9.13	8.96	96.18	94.95	95.75	83.96	82.92	83.1	11	10.66	10.08	4.44
77	9.87	9.26	88.96	89.4	88.75	81.64	81.83	81.25	4.73	4.61	3.82	0.71

Pt No	OB SM2	OB Imp2	UIC P2	UIC SM2	UIC Imp2	LIM P2	LIM SM2	LIM Imp2	UL1 P2	UL1 SM2	UL1 Imp2	UAL P2
1	6.42	6.27	36.57	36.03	36.5	29.5	30.26	29.59	10.91	11.05	10.58	101.52
4	1.19	2.7	36.51	35.81	35.87	40.11	40.31	40.83	10.09	9.76	9.73	92.58
41	0	1.4	33.6	34.02	33.24	34.84	35.57	35.44	10.16	9.99	9.97	92.15
44	3.88	3.71	34.81	34.58	34.19	36.82	37.12	36.8	10.76	10.58	10.17	92.07
45	0	1.04	30.53	30.49	30.16	36.89	37.49	37.26	8.39	8.52	7.96	80.19
50	1.1	1.17	28.76	28.95	28.98	31.87	32.57	32.76	10.23	10.08	9.73	89.13
58	2.92	0	31.43	30.94	30.8	34.38	35.04	34.95	10.53	10.29	10.11	87.27
72	3.14	4.48	31.48	31.26	31.1	34.52	34.54	34.48	9.63	8.94	9.18	91.66
74	3.8	5.51	31.88	31.69	31.53	33.9	33.84	33.61	9.59	9.33	9	97.68
77	0	1.06	31.77	31.72	31.3	33.98	34.21	34.64	10.22	9.92	9.11	90.4

Pt No	UAL SM2	UAL Imp2	LAL P2	LAL SM2	LAL Imp2
1	101.05	101.14	83.61	82.19	82.06
4	92.03	91.58	86.42	85.82	85.86
41	91.96	90.83	79.15	79.88	79.89
44	91.59	91.74	84.77	83.54	83.72
45	79.46	78.95	71.88	70.22	70.42
50	87.28	87.44	78.21	78.2	77.51
58	86.44	85.89	76.67	73.93	74.78
72	89.97	90.68	79.73	77.81	78.19
74	95.53	96.03	84.19	83.47	81.79
77	89.25	88.69	82.26	81.18	85.17

APPENDIX III

WILCOXON SIGNED-RANK TEST DATA TABLE

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
OJ P2 - OJ P1	Negative Ranks	6[a]	5.17	31.00
	Positive Ranks	4[b]	6.00	24.00
	Ties	0[c]		
	Total	10		
OJ SM2 - OJ SM1	Negative Ranks	6[d]	5.83	35.00
	Positive Ranks	4[e]	5.00	20.00
	Ties	0[f]		
	Total	10		
OJ Imp2 - OJ Imp1	Negative Ranks	4[g]	7.38	29.50
	Positive Ranks	6[h]	4.25	25.50
	Ties	0[i]		
	Total	10		
OB P2 - OB P1	Negative Ranks	5[j]	4.40	22.00
	Positive Ranks	4[k]	5.75	23.00
	Ties	1[l]		
	Total	10		
OB SM2 - OB SM1	Negative Ranks	4[m]	5.50	22.00
	Positive Ranks	3[n]	2.00	6.00
	Ties	3[o]		
	Total	10		
OB Imp2 - OB Imp1	Negative Ranks	2[p]	1.75	3.50
	Positive Ranks	7[q]	5.93	41.50
	Ties	1[r]		
	Total	10		
UIC P2 - UIC P1	Negative Ranks	5[s]	5.80	29.00
	Positive Ranks	4[t]	4.00	16.00
	Ties	1[u]		
	Total	10		
UIC SM2 - UIC SM1	Negative Ranks	5[v]	5.20	26.00
	Positive Ranks	5[w]	5.80	29.00
	Ties	0[x]		
	Total	10		
UIC Imp2 - UIC Imp1	Negative Ranks	7[y]	5.71	40.00
	Positive Ranks	3[z]	5.00	15.00
	Ties	0[aa]		

	Total	10		
LIM P2 - LIM P1	Negative Ranks	8[ab]	5.50	44.00
	Positive Ranks	1[ac]	1.00	1.00
	Ties	1[ad]		
	Total	10		
LIM SM2 - LIM SM1	Negative Ranks	4[ae]	6.38	25.50
	Positive Ranks	6[af]	4.92	29.50
	Ties	0[ag]		
	Total	10		
LIM Imp2 - LIM Imp1	Negative Ranks	5[ah]	4.10	20.50
	Positive Ranks	4[ai]	6.13	24.50
	Ties	1[aj]		
	Total	10		
UL1 P2 - UL1 P1	Negative Ranks	6[ak]	6.42	38.50
	Positive Ranks	4[al]	4.13	16.50
	Ties	0[am]		
	Total	10		
UL1 SM2 - UL1 SM1	Negative Ranks	6[an]	5.75	34.50
	Positive Ranks	4[ao]	5.13	20.50
	Ties	0[ap]		
	Total	10		
UL1 Imp2 - UL1 Imp1	Negative Ranks	6[aq]	7.50	45.00
	Positive Ranks	4[ar]	2.50	10.00
	Ties	0[as]		
	Total	10		
UAL P2 - UAL P1	Negative Ranks	4[at]	4.00	16.00
	Positive Ranks	6[au]	6.50	39.00
	Ties	0[av]		
	Total	10		
UAL SM2 - UAL SM1	Negative Ranks	7[aw]	4.93	34.50
	Positive Ranks	3[ax]	6.83	20.50
	Ties	0[ay]		
	Total	10		
UAL Imp2 - UAL Imp1	Negative Ranks	4[az]	5.13	20.50
	Positive Ranks	6[ba]	5.75	34.50
	Ties	0[bb]		
	Total	10		
LAL P2 - LAL P1	Negative Ranks	6[bc]	6.50	39.00
	Positive Ranks	4[bd]	4.00	16.00
	Ties	0[be]		

	Total	10		
LAL SM2 - LAL SM1	Negative Ranks	9[bf]	5.78	52.00
	Positive Ranks	1[bg]	3.00	3.00
	Ties	0[bh]		
	Total	10		
LAL Imp2 - LAL Imp1	Negative Ranks	7[bi]	4.57	32.00
	Positive Ranks	3[bj]	7.67	23.00
	Ties	0[bk]		
	Total	10		

a. OJ P2 < OJ P1

b. OJ P2 > OJ P1

c. OJ P2 = OJ P1

d. OJ SM2 < OJ SM1

e. OJ SM2 > OJ SM1

f. OJ SM2 = OJ SM1

g. OJ Imp2 < OJ Imp1

h. OJ Imp2 > OJ Imp1

i. OJ Imp2 = OJ Imp1

j. OB P2 < OB P1

k. OB P2 > OB P1

l. OB P2 = OB P1

m. OB SM2 < OB SM1

n. OB SM2 > OB SM1

o. OB SM2 = OB SM1

p. OB Imp2 < OB Imp1

q. OB Imp2 > OB Imp1

r. OB Imp2 = OB Imp1

s. UIC P2 < UIC P1

t. UIC P2 > UIC P1

u. UIC P2 = UIC P1

v. UIC SM2 < UIC SM1

w. UIC SM2 > UIC SM1

x. UIC SM2 = UIC SM1

y. UIC Imp2 < UIC Imp1

z. UIC Imp2 > UIC Imp1

aa. UIC Imp2 = UIC Imp1

ab. LIM P2 < LIM P1

ac. LIM P2 > LIM P1

ad. LIM P2 = LIM P1

ae. LIM SM2 < LIM SM1

af. LIM SM2 > LIM SM1

ag. LIM SM2 = LIM SM1

ah. LIM Imp2 < LIM Imp1

ai. LIM Imp2 > LIM Imp1

aj. LIM Imp2 = LIM Imp1

ak. UL1 P2 < UL1 P1

al. UL1 P2 > UL1 P1

am. UL1 P2 = UL1 P1

an. UL1 SM2 < UL1 SM1

ao. UL1 SM2 > UL1 SM1

ap. UL1 SM2 = UL1 SM1

aq. UL1 Imp2 < UL1 Imp1

ar. UL1 Imp2 > UL1 Imp1

as. UL1 Imp2 = UL1 Imp1

at. UAL P2 < UAL P1

au. UAL P2 > UAL P1

av. UAL P2 = UAL P1

aw. UAL SM2 < UAL SM1

ax. UAL SM2 > UAL SM1

ay. UAL SM2 = UAL SM1

az. UAL Imp2 < UAL Imp1

ba. UAL Imp2 > UAL Imp1

bb. UAL Imp2 = UAL Imp1

bc. LAL P2 < LAL P1

bd. LAL P2 > LAL P1

be. LAL P2 = LAL P1

bf. LAL SM2 < LAL SM1

bg. LAL SM2 > LAL SM1

bh. LAL SM2 = LAL SM1

bi. LAL Imp2 < LAL Imp1

bj. LAL Imp2 > LAL Imp1

bk. LAL Imp2 = LAL Imp1

APPENDIX IV

DATA FOR ALL PLASTER AND DIGITAL STUDY MODEL PAR SCORES

Study Model Number	Plaster Unweighted PAR Score	Plaster Weighted PAR Score	Digital Unweighted PAR Score	Digital Weighted PAR Score
1	11	22	14	24
2	15	34	15	34
3	25	49	26	50
4	9	25	10	26
5	10	16	10	16
6	16	34	15	33
7	7	15	7	18
8	20	50	20	55
9	17	27	14	23
10	27	48	29	50
11	19	34	16	34
12	17	38	16	37
13	8	14	8	14
14	19	35	19	35
15	14	31	18	38
16	20	37	23	45
17	10	27	10	27
18	10	19	8	14
19	16	30	13	28
20	10	22	9	18
21	18	40	15	39
22	11	24	11	28
23	26	51	25	53
24	12	20	13	21
25	30	50	28	49
26	14	30	12	29
27	38	66	30	60
28	12	28	10	25
29	16	39	13	33
30	12	34	12	34

APPENDIX V

DATA FOR ALL 3D PRINTED STUDY MODEL PAR SCORES

Digital Models: 1, 2, 4, 5, 13, 14, 16, 17, 20, 22 from Section Two of the study were used for generating 3D printed models for Section Three.