

**COMPARISON OF OCCLUSAL CONTACTS ON  
MOUNTED DENTAL MODELS TO CONTACTS IDENTIFIED  
ON DIGITAL 3D MODELS USING A NEW VIRTUAL  
ALIGNMENT METHOD**

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D.D.S., The University of Alberta, 2004

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF  
THE REQUIREMENT FOR THE DEGREE OF

MASTER OF SCIENCE

in

The Faculty of Graduate Studies

(Dental Science)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2009

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## **ABSTRACT**

As 3D imaging of dental models becomes more common in clinical dentistry, the need for accurate images will increase. In order for these 3D models to be of greatest benefit, they will need to be aligned to accurately represent the given presentation of the individuals they represent. This is an important step, since the acquisition of digital models results in two unrelated image files. This study evaluated a new technique for aligning 3D digital dental models using a 3D scan of the anterior teeth in occlusion of articulator mounted models as a “virtual bite registration.”

Three-dimensional digital models of one set of epoxy dental models were created using a commercially available 3D laser scanner (Konica Minolta Vivid 910) and Geomagic software. Ten mountings of these same epoxy models were made, and a 3D scan of the anterior teeth in occlusion was made for each mounting. The 3D digital models were registered to the anterior 3D scan, and virtual occlusal contacts were recorded and compared to the actual occlusal contacts recorded on the epoxy models using shimstock and articulating film. Comparison of the new technique to the standards was made using sensitivity, specificity, positive predictive value and negative predictive value analyses.

Specificity was high when using both shimstock and articulating film contacts as standards and digital contacts as tests, 0.97 and 0.98 respectively. When comparing the traditional methods of recording contacts to the new digital technique

the sensitivity with shimstock as the standard was 0.63 and with articulating film as the standard the sensitivity was 0.54. Positive predictive value and negative predictive value of the digital technique compared to shimstock was 0.52 and 0.98 respectively. Compared to articulating paper the values were 0.76 and 0.96 respectively.

Using a scan of the anterior teeth in occlusion as a virtual bite registration represents an appropriate method for aligning 3D digital dental models in an anatomically correct position. The technique described may represent a good technique for future comparison of the alignment of digital models to the alignment found on articulator mounted models or in the patient regardless of hardware and software being used.

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## **ACKNOWLEDGMENTS**

I would like to thank Dr. Alan Hannam for giving me the opportunity to explore an aspect of dentistry that my periodontal training would otherwise not have exposed me to. Because digital technology can often be a mystery to those not exposed to the inner-workings of it, the opportunity that I received from Dr. Hannam to work with 3D imaging hardware and software will no doubt benefit my clinical career if, for no other reason than the familiarity that I developed with this emerging aspect of dentistry.

# 1 INTRODUCTION

## 1.1 Background

Clinical dentistry involves the gathering of a great deal of information about each patient in order to diagnose problems and formulate a treatment plan that will result in the most benefit to the patient. Much of this information is gathered through the clinical examination, radiographs, and record taking. As with most other professions there is a continued increase in the use of digital technologies within dentistry in order to improve diagnosis and treatment and shorten required time involved (Calberson, Hommez, & DeMoor, 2008) Use of computers for patient booking and billing is almost universal. Use of digital radiography is also becoming very commonplace. As dental offices become more computerized, other opportunities for use of digital technologies become available. Because much of the digital technology that is entering dental offices is replacing older traditional methods of carrying out some process, the new technology must be compared to the old in order to know if implementing it is beneficial or simply for the sake of technology. A practitioner who is considering switching over to a new digital technology must ask the following: What will the cost be initially and over the long term? Is the new technology easier or harder to use than the old? Does the new technology give any additional information that will allow better patient care? Is the new technology at least as accurate or more accurate than the current technology, or in other words, is the new technology sufficiently accurate? An

example is digital radiography. The cost may involve sensors, scanners, software, computer systems, and monitors but also the eliminated cost of film, chemicals, wet developer, and possibly dedicated darkroom space. The digital radiography system may also require retraining of staff and involves a certain degree of learning curve both in acquiring and viewing the image, depending on the computer literacy of the staff being trained (Farman, Levato, Gane, & Scarfe, 2008; Ramamurthy, Canning, Scheetz, & Farman, 2006). Additional information gained from the new technology can be a key point when deciding to switch. With digital radiographs, software manipulation programs can correct poorly exposed images and calculate changes over time through subtraction radiography software which cannot be done with film (Reddy & Jeffcoat, 1999; Wenzel, Warrer, & Karring, 1992). Finally, the information gained from the new technology must be true. Using the old technique as a gold standard, the line pair resolution of the digital system can be evaluated. If the digital sensor has a higher resolution than the human eye can detect, which is around 11 lp/mm, (Kunzel, Scherkowski, Willers, & Becker, 2003) the degree to which this will be beneficial to diagnosis must be considered.

## **1.2 Conventional Dental Models**

The thought process above can be used with any new technology introduced in dentistry, and should be, in order to prevent new technology from being introduced just for the sake of technology. One technology that is gaining

momentum in dentistry is the use of digital models in place of traditional stone models (Birnbaum & Aaronson, 2008; Christensen, 2008). Dental models are used for many purposes such as treatment planning (study models), surgical planning, fabrication of fixed and removable prostheses, fabrication of night guards, and treatment assessment (such as in orthodontics) (Beuer, Schweiger, & Edelhoff, 2008; Hajeer, Millett, Ayoub, & Siebert, 2004b; Lauren & McIntyre, 2008; Lin, Zhang, Chen, & Wang, 2006; Rekow, Erdman, Riley, & Klamecki, 1991). The accuracy needed for each of these purposes varies and so do the new technologies being used, but regardless of this, they all need to be compared to the current standard being used. The first step in acquiring dental models is taking an intraoral impression of the teeth and adjacent tissue. This can be accomplished using various traditional materials such as reversible or irreversible hydrocolloid, polyether, polyvinylsiloxane materials, and can be done using stock metal or plastic trays or rigid custom trays. The choice of which technique and materials are used is often based on the accuracy needed in the final result. The American Dental Association (ADA) has stated that the elastomeric materials used for impressions for fabrication of precision castings must be able to reproduce fine detail of 25 $\mu$ m or less (Revised American, 1977). This level of accuracy may not be needed if the impression is being used for a different purpose but is a good best case scenario standard to use to compare emerging technology. The gypsum die materials used to pour up the impression into a usable stone model have less ability to reproduce fine detail than

the impression material itself, so they are the limiting factor in the process of creating stone models (Donovan & Chee, 2004). The ADA specification for fine detail replication for gypsum die material is 50 $\mu$ m (Donovan & Chee, 2004). In addition to these quantifiable accuracies in specific materials, the technique used will also affect the accuracy, as will the type of impression tray used. Carrotte, Johnson, and Winstanley (1998) found that when comparing impressions of single crown and three unit bridge preparations using a polyvinylsiloxane impression material, the least discrepancy was found when a rigid impression tray was used (50 $\mu$ m) and the greatest discrepancy was with a flexible impression tray (180-210 $\mu$ m). Set impression materials can also change over time. Alginate, for example, can imbibe (gain) or lose water depending on the environment it is stored in and the length of time it is stored (Peutzfeldt & Asmussen, 1989; Sedda, Casarotto, Raustia, & Borracchini, 2008). This property will further affect the accuracy of the final stone models and must be kept in mind when working with the materials or reading literature that use these materials. As mentioned above, the need for a certain degree of accuracy is dependent on the purpose for the dental casts. Generally, alginate is used for study models and for orthodontic purposes because of the ease of use, low cost and adequate accuracy. Various alginates were shown to have accuracy between 44-180 $\mu$ m compared to elastomeric materials which showed accuracy between 39-130 $\mu$ m with the elastomeric materials being

statistically more accurate as a whole compared to the alginates.(Peutzfeldt & Asmussen,1989).

### **1.3 Articulation of Dental Models**

Dental models that will be used for the fabrication of a fixed or removable prosthesis or other dental appliance will often need to be mounted on an articulator in order to reproduce as closely as possible the correct maxillo-mandibular relationship. This process can introduce additional error in the system (Breeding, Dixon, & Kinderknecht, 1994). The first aspect that can introduce additional error is the interocclusal record. If the maxillary and mandibular cast have good intercuspation and have a tripod of adequately spaced contacts, the most accurate technique for mounting the casts is by hand articulation without an interocclusal record (Dixon, 2000; Squier, 2004). No interocclusal record material has demonstrated absolute dimensional accuracy, and most have dimensional change over time (Freilich, Altieri, & Wahle, 1992). In addition, the interocclusal record, regardless of material, may have differences in surface detail compared to the stone models that were obtained from various impression materials. These differences may add to the error in mounting of casts.(Breeding et al., 1994).

## 1.4 Digital Dental Models

All dental materials used for the reproduction of the dental arch have inherent limits to accuracy and resolution, but the majority of error introduced in traditional techniques is from the inappropriate use of the materials and techniques (Donovan & Chee, 2004). Despite all these steps that can and do introduce error into the final outcome, the use of impressions and stone models for fabrication of precise fixed restorations has shown to have very good long-term success for the life of the final prosthesis (Goodacre, Bernal, Rungcharassaeng, & Kan, 2003; Palmqvist & Swartz, 1993). With an established level of success and acceptance in the dental profession, what is the benefit of trying to change this system to a digital one? There are many advantages to digital casts over traditional stone models. There is a decreased need for storage space. A model box used to store four models takes up about the space taken up by a modern one Terabyte external hard drive which could hold up to 100,000 models (assuming 10 Megabytes/model), which is a reasonable size depending on the file format used (in this study models saved as .obj files required just under 10mb/cast). This physical storage space can be completely eliminated by storing the data offsite and accessing it through an internet or local area network connection (Farman, et al., 2008). Another advantage of digital casts is that they do not change. Once the file is saved it can be accessed an infinite number of times without affecting the original data. It can also be easily manipulated without losing the original data. The process can be non-destructive. Stone models, on the

other hand, can be broken or the occlusal surfaces can be worn by repeatedly bringing the maxillary and mandibular model in contact. No adjustments can be done on the original models in a non-destructive way, but instead, additional impressions must be taken of the original models and poured up. Digital files can just as easily be shared between two dentists in the same office as with a dentist in another country. This can be a benefit if several practitioners are involved in a single case and all want to base decisions on the same information.

Despite the advantages of digital casts, there are still some disadvantages. The biggest disadvantage is the lack of tactile sensation. In treatment planning cases many dentist have grown accustomed to manually handling casts to check articulation or to do bench top adjustments to the teeth. This may only be a relative disadvantage of digital models since hard copies of the digital models can be produced when needed, although the cost is currently much greater than impressing and pouring up traditional duplicate models. Issues related to accuracy of digital models compared to traditional stone models are still being investigated but may represent a disadvantage depending on the system used for digitizing and the purpose of the digitized cast (Bell, Ayoub, & Siebert, 2003; Brusco, Andreetto, Lucchese, Carmignato, & Cortelazzo, 2007; DeLong, Heinzen, Hodges, Ko, & Douglas, 2003; Kuroda, Motohashi, Tominaga, & Iwata, 1996). Other concerns that practitioners may have include loss of data, systems crashes, and privacy issues related to security of digital records. These are valid concerns, but other digital

systems have demonstrated that they are of limited threat when properly addressed. (Brian & Williamson, 2007).

These advantages and disadvantages of digital models cannot be simply considered on their own but must be taken in context of the final purpose of the dental model. Digital models being used solely for linear measurements for space analysis that lack tactile sensation may not be an issue to the dentist compared to models that a dentist wants to use to do an ideal wax-up. Similarly, a model that is solely used as a record of the initial presentation of an individual will have a significantly different requirement in resolution and accuracy compared to a model being used for fabrication of a fixed prosthesis. Therefore, in analyzing the technologies available, they must be compared to techniques that represent the current standard accepted in the specific discipline. As mentioned, the ADA requires 25 $\mu$ m resolution for elastomeric impression materials used for cast restorations and 50 $\mu$ m resolution for the stone in which those impressions are poured up in. Therefore, 50 $\mu$ m is the very best resolution required by traditional methods for 3-dimensional (3D) replication of dental structures and would represent a good goal for digital methods. Although this would be a good goal, it is obviously more than is required in some disciplines; for example, orthodontics, which has shown that in a Bolton analysis by trained individuals there is a final range of  $\pm 2.2$ mm in outcomes (Shellhart, Lange, Kluemper, Hicks, & Kaplan, 1995). This would represent a needed accuracy in the millimetre range compared to the micrometre

range in order to have an acceptable outcome. Similarly, it is known that humans can only detect occlusal discrepancies of greater than 20 $\mu$ m between teeth, so demanding an accuracy greater than this is probably unreasonable from a clinical standpoint (Karlsson & Molin, 1995)

These arguments represent one of the weaknesses in digital imaging used in dentistry. There are no established standards or ranges of what accuracy is acceptable for most clinical uses. Nevertheless, digital 3-dimensional imaging is a growing area of clinical dentistry.

### **1.5 Acquisition of Digital 3D Data**

Presently there are established clinical tools for acquiring and manipulating 3D images in use in orthodontics, prosthodontics, restorative dentistry, implant dentistry, and radiology. Examples of these are Orthocad, Procera, Cerec, Simplant, Nobelguide, and I-cat, and recently two new intraoral 3-D scanners, iTero and 3M ESPE Lava scanner, have been released with the ability to image the entire arch intra-orally. When considering the process of 3D imaging and modeling, one must understand the steps required to produce a complete 3D model and also be aware of the different technologies that can accomplish this goal. The first step is image acquisition. Acquiring a 3D image requires some type of image capture device capable of imaging in more than two dimensions. There are currently several major classes of such devices available commercially.

Computed tomography (CT) is one type or modality used for 3D image capture. CT uses ionizing radiation to build, in layers, a 3D image (White & Pharoah, 2008). There are variations of this technology such as cone beam CT (CBCT) and micro CT which are used for specific purposes. Cone beam CT is used most frequently in dentistry because of the lower radiation exposure to the patient and the small window that is used in this type of imaging which is adequate to image the jaws compared to the more extensive standard medical CT scanners (Chau & Fung, 2009; White & Pharoah, 2008). Cone beam CT scans vary in radiation exposure from one manufacturer to another but range from as low as 12-477 $\mu$ Sv depending on the field of view compared to over 2200 $\mu$ Sv from a medical CT scan of the mandible and maxilla (White, 2008). In comparison, a digital panoramic radiograph is between 6-7 $\mu$ Sv (Howerton & Mora, 2008). Computed tomography produces true 3D images, which is an advantage over some other scanning technologies available. Disadvantages of CBCT technology are the radiation exposure to a patient, the relatively low resolution (except the micro CT), and the inability to image metal restorations which can result in streak artefacts that can obstruct the surrounding anatomy. (Howerton & Mora, 2008) The accuracy of linear measurements of CBCT scans of skulls compared to measurements from the actual skulls has been shown to be within 1mm in absolute value, or a percentage difference of less than 5% for most measurements (Brown, Scarfe, Scheetz, Silveira, & Farman, 2009).

Another group of scanners that can also produce true 3D images are touch probe scanners or contact profilers. These use a spherical tipped stylus that is placed in contact with the object being scanned as the object is rotated in order to record all surfaces of the object. Contact scanners tend to be highly accurate but the resolution of complex free-form surfaces is limited by the size of the stylus tip, which tends to be 0.1mm or greater. An example of this type of scanner is the Nobel Biocare Procera scanner, which is used for scanning crown preparations. Due to the size of the stylus tip, crown preparations must meet certain design criteria or else they cannot be properly scanned. This fact eliminates the possibility of scanning full dental arches, which can have acute angles and complex anatomy, with this machine.

Non-contact scanners use light instead of a contact stylus to determine the surface anatomy of an object. They come in two general varieties - structured white light or laser light. Laser scanners use a line of laser light that sweeps across an object while a camera records the shape of the reflected laser light. Through triangulation the three dimensional location of each surface point is calculated. (Bernardini & Rushmeier, 2002; Lane & Harrell, 2008) This can be done because a fixed, known angle exists between the laser source and the capture lens, and any deviation or deflection of the straight line of laser light represents a surface variation of the object. Structured light scanners use a similar technique, except that instead of a line of laser light they use a pattern of white light projected on the image and

use triangulation, interferometry, phase shifting, Moiré fringe patterns or, several of these, to determine surface points. (Bell et al., 2003; Brusco et al., 2007; Hajeer, Millett, Ayoub, & Siebert, 2004a; Kuroda et al., 1996)

A new intraoral 3D scanner, iTero (Cadent Inc., Carlstadt, NJ) uses similar principles to that used in confocal microscopy to create a 3D image. Briefly, it projects 100,000 beams of parallel laser light through a filter onto an object surface which then reflects the light back. Only objects at the right focal distance will reflect light that will pass back through the filter, all other reflected light will be blocked (Garg, 2008; Henkel, 2007). In addition, 3M has released a new intraoral scanner that uses a novel structured light technique developed at MIT (Rohaly & Hart, 2000). Both scanners have been in development for several years, but the commercial products are both still very new, so very little information is currently available.

The advantage of non-contact scanners is that they do not need to touch the surface of the image they are capturing, which is a benefit if intraoral scanning is the goal or if the object has fine details that are smaller than a touch probe scanner. In addition, no radiation is involved and they are much faster than contact scanners (Brusco et al., 2007). One disadvantage is that non-contact scanners do not produce a true 3D image but instead are often called 2.5D scanners because shadowing occurs when undercuts are present or anywhere that the surface is hidden from the laser source or the lens. (Xiaoguang Lu, Jain, & Colbry, 2006) To overcome this

limitation, multiple scans must be taken at different angles in order to sample the entire surface and also to ensure that there is enough overlap in each scan for aligning each image into the complete 3D model (Bernardini & Rushmeier, 2002; Levoy, 1999). Alignment or registration of the multiple scans is a necessary step in the process of creating a complete 3D image with this type of scanner (Lane & Harrell, 2008).

## **1.6 Image Registration**

Registration is the alignment of two or more 3D surfaces based on similarity of the overlapping surfaces or by means of aligning common fiducial markers and is generally carried out in two broad steps - pairwise registration of scans followed by registration of all scans, or global registration. The first step is carried out in two steps - rough and fine alignment. Rough alignment is often done by manually selecting one or more corresponding points on pairs of images and allowing the software to rotate and translate the two images until the points are as closely aligned as possible (Brusco et al., 2007). Alternately, this process can be done completely manually by identifying surface markers or surface features and through trial and error, moving the images until they appeared aligned. Software advances and increased computational power has made this time-consuming manual method almost completely obsolete. A completely automatic technique for rough alignment also exists, and uses specific forms of 3D images called spin images. As long as

pairs of scans have at least 30% overlap and the surfaces are characterized by adequate geometric features they will have similar spin images (Johnson & Hebert, 1999). These can be rotated and translated by the software until the spin images are aligned, which results in a good alignment of the actual image if the same rotation and translation is applied.

Fine registration is accomplished by the iterative closest point algorithm or one of its variants (Besl & McKay, 1992; Kapoutsis, Vavoulidis, & Pitas, 1999; Rusinkiewicz & Levoy, 2001). The general idea of this technique is to find a set of matching points on the overlapping surface of two scans and minimize the distance between each of these points. Once all scans have been registered or aligned they are merged into one surface in order to decrease the file size and simplify further manipulation of the model (DeLong et al., 2003). If this final merged image has holes these can be filled at this time by the software but will not be a representation of true surface of the object (Brusco et al., 2007)

## **1.7 Accuracy**

As with any recording technique or device, the accuracy, precision, and resolution must be acceptable for the application it is used for. Accuracy is defined as how well a measured value represents the truth, precision is the repeatability of the measurement system, and resolution is the degree of detail visible in an image (Brosky, Major, DeLong, & Hodges, 2003; Persson, Andersson, Oden, &

Sandborgh-Englund, 2008) Resolution is the number of pixels per unit area, points per unit area, or in CT scans the size of voxel (volume pixel) used. These values are given by most manufacturers and depend on the number of pixels present on the sensor. They increase as sensor size or density increases.

Accuracy is a much more difficult measure to define when describing non-contact 3D scanners and free form shapes because there is no established standard for measuring accuracy on these machines. The only standard has been established for contact scanners using the substitution method in which repeated measures are carried out on calibrated objects and measurements are compared to the calibrated data (Brusco et al., 2007; Savio, De Chiffre, & Scmitt, 2007). Metrological standards for optical scanners and free-form shapes is still an open research area (Brusco et al., 2007). In addition to the measuring device, error can come from the measuring strategy, the item being measured, the environment (such as ambient light), the operator, and other sources (Brusco et al., 2007).

Determining the accuracy of 3-D scans of complete dental arches has been published extensively in the orthodontic literature (Bell et al., 2003; Hildebrand, Palomo, J., Palomo, L., Sivik, & Hans, 2008; Kuroda et al., 1996; Okunami et al., 2007; Quimby, Vig, Rashid, & Firestone, 2004; Santoro, Galkin, Teredesai, Nicolay, & Cangialosi, 2003; Zilberman, Huggare, & Parikakis, 2003). The general technique that is used in this literature is to measure linear distances between points and compare the results from the digital model to those from the actual stone model.

Because orthodontics is concerned with space availability, and traditionally measurements on dental casts involve the measurement of tooth width and arch length, this technique gives a sufficient measure of accuracy for orthodontic purposes. A brief review of these studies and their findings follows.

Many of these studies have used digital models produced from a commercial provider, Orthocad (Cadent Inc, Carlstadt, NJ), in order to determine the accuracy of that particular system and to determine if it is a valid alternative to stone models. Error can come from several sources along the line when producing digital dental casts, such as impression material, impression technique, methods and materials for pouring up the stone models, scanning system, etc. In studies using Orthocad services only the total error can be roughly determined because Orthocad does not release detailed information on either the process of producing the cast or the scanning method (Quimby et al., 2004) In addition, the final digital cast can only be viewed in the company's proprietary software, which is mainly aimed at linear measurements and not measuring free-form surfaces. Despite these limitations most studies come to similar conclusions that digital casts produced by Orthocad are adequate substitutes for stone models in orthodontics.

Zilberman et al. (2003) compared individual tooth widths on an original dentoform and stone model of the dentoform using digital calipers to the individual tooth widths measured in Orthocad software. They found the highest correlation between the original dentoform teeth and the stone models ( $R=0.929-0.998$ ) and

lower correlation between dentoform and computer models ( $R=0.784-0.976$ ) and stone and computer models ( $R=0.763-0.975$ ) but no statistically significant difference between any measuring method. They concluded that measuring stone casts with digital calipers is better than using Orthocad but that Orthocad is clinically acceptable.

Instead of dentoform teeth which can be removed and measured, Santoro et al. (2003) used actual patients to carry out a very similar study. Seventy-six patients were involved and tooth width measurements were compared between stone models and Orthocad digital models. They found statistically significant differences between the two methods of measuring for most teeth measured. The digital models always measured smaller than the stone models with a mean difference ranging between 0.16-0.38mm per tooth. The authors conclude that although the difference is statistically significant, the magnitude of the difference does not seem to be clinically significant. One difference between these two studies that may have contributed to the different findings was the impression material used. Zilberman et al. (2003) used polyvinylsiloxane whereas Santoro et al. (2003) used alginate. This may play a role because the impressions were mailed to Orthocad for pouring up. This likely results in a delay of greater than 12 hours before pouring up of the models, which may affect the water content of the alginate impressions and therefore their size (Alcan, Ceylanoglu, & Baysal, 2009; Sedda et al., 2008).

If individual teeth widths are different between stone and digital models, even if by a very small amount, this may result in significant differences in total arch length or total space needed. Instead of individual teeth, Quimby et al. (2004) measured arch lengths and space required, in addition to several cross arch measurements, to compared dentoform and stone models to digital models produced by Orthocad. They found statistically significant differences for arch length, space required, and all cross-arch measurement when comparing stone to digital models. Measurements made on the digital models were larger than those made on the stone models, and the difference was generally less than 1mm except for maxillary space required and mandibular space available which were 2.23mm and 2.88mm greater on the digital models respectively. The question arises whether or not these statistically significant differences are clinically significant. The authors concluded that it was questionable if the measured differences would lead to a significantly different treatment outcome.

Other authors have taken a similar approach as those mentioned above, to determine accuracy of digital casts for orthodontic purposes, but have used various in-lab scanning systems versus a scanning service. (Bell et al., 2003; Kuroda et al., 1996). Bell et al. (2003) used a structured light non-contact scanner and in-house software for model reconstruction. Instead of measuring tooth widths or arch length, they placed 6 points along the arch and made 15 measurements between these various points. They found no statistically significant difference between the

measurements made on the stone and the digital models. The differences ranged between 0.16-0.38mm. This value, the authors felt, would not be clinically significant and that digital models offer a valid alternative to long-term storage of stone models.

Instead of making linear measurements to determine accuracy of digital models, some authors have used interocclusal contact points as a surrogate marker of how accurate digital models are (DeLong, Knorr, Anderson, Hodges, & Pintado, 2007; DeLong, Ko, Anderson, Hodges, & Douglas, 2002a; Maruyama, Nakamura, Hayashi, & Kato, 2006). In general, these authors have compared contact points marked on mounted stone models, using some form of articulating ribbon or shimstock, to the contacts that appeared on digital models after aligning them. Whenever a new technology is developed and tested, the results need to be compared to the established gold standard. This becomes a little difficult when using contact points because of the discrepancy between techniques and materials.

## **1.8 Occlusal Contacts**

Marking occlusal contacts is a very common procedure in clinical dentistry. It is used to diagnose occlusal interferences, check for appropriate height of new restorations, and as an initial screening for most new patients. The procedure is most commonly accomplished using thin, inked paper or film, which is placed on the occlusal surface of a patient's teeth. When the patient bites or grinds the teeth

together, coloured marks are left where the contact or where there are areas of near contact. More recently, various types of computer controlled devices (T-Scan system, Sentek Corp, Boston, Mass.) have been developed for recording occlusal contact forces.

Whenever new technology is developed for detecting occlusal contacts, it should be compared to the existing “gold standard” to establish validity, accuracy, etc. This usually means that the new technique is compared to occlusal film or paper, although this has not been established as a “gold standard” due to the varying thicknesses, inks, and plasticity of the marking films and papers and because of the various operator techniques in obtaining occlusal markings.

Marking occlusal contacts is not a precise science. Although there are many types of articulating film and paper ranging in thickness from  $8\mu\text{m}$  up to  $200\mu\text{m}$  which results in differences in results between brands and types, there has also been shown to be significant differences in results with the same material on the same casts. Millstein and Maya (2001) found that between brands there was as much as a  $9\text{mm}^2$  difference in surface area marked on the same tooth ( $2.16\pm 0.56\text{mm}^2$  vs  $11.16\pm 2.57\text{mm}^2$ ). In addition to surface area, they found the number of contact areas varied from a mean of 1.24/tooth up to 6.68/tooth for the same tooth using different brands of articulating paper or film. These results may be expected because of the differences between brands, but even within the same film or paper type the authors found significant differences in surface area marked as well as number of contact

areas/tooth. The results of Saad, G. Weiner, Ehrenberg, and S. Weiner (2007) support Millstein and Maya's (2001) findings that the number of occlusal contacts recorded clinically depend greatly on the type of articulating paper or film being used.

Saraçoğlu and Özpınar (2002) also compared various types of articulating paper and film as well as the T-Scan system and found that all lost sensitivity after multiple uses, or, stated differently, showed fewer occlusal markings for the same teeth after each additional use. They concluded that the most accurate material was the one that resulted in the most occlusal markings. There is no evidence in their study that in fact more markings represented greater accuracy than fewer markings because there was no standard that all others were being compared to. One finding they reported that is of clinical value is that there was a significant decrease in occlusal markings in wet conditions compared to dry conditions for all the materials they tested except for the T-Scan system.

Gazit, Fitzig, and Lieberman (1986) concluded that neither a novel photo-occlusion technique nor the standard colour marking technique was reproducible. They marked occlusal contacts in subjects at two separate times, one month apart. Although the new technique they used was reported to be more reproducible, between 20-50% of markings were only seen at one of the two time points. This they attributed to the non-standardized biting of the subjects as well as natural

changes over time and stated that marking on articulated models may avoid these errors.

Both accuracy and validity are difficult to assess for occlusal markings because there is no test that is known to give an accepted true value (DeLong et al., 2007). Because most studies use mounted casts as the experimental subjects, one comparison to assess validity would be to compare the markings made on mounted casts to those made in the actual patient. Once again, there are a few variables that must be considered when making this comparison, such as the quality of the casts and the accuracy of the mounting.

In a recent study, the authors compared the markings obtained from occlusal film and the T-Scan system on mounted casts to the markings made in the actual patients. They found that the quantity of marks was lower on the articulated casts compared to in the mouth but that the location of the marks present were similar (Cabral, Andrade, Buarque, Landulpho, & Buarque, 2006). Unfortunately, statistical significance was not reported for the difference in quantity of markings. Several recent studies have examined the role that force plays on the quantity and quality of occlusal markings. (Carey, Craig, Kerstein, and Radke, 2007; Saad et al., 2007). Both groups found that the size of the occlusal mark is not directly related to the force of closing, although Carey et al. (2007) found that there was a non-linear relationship between force and size of occlusal marks in some instances. Both

authors emphasized that from their results equal sized markings on adjacent teeth do not necessarily represent similar occlusal forces.

Until a gold standard for marking occlusal contacts is established dentists will continue to use a variety of articulating papers and techniques for marking occlusion in both clinical dentistry and dental research. There are very few studies reporting on the validity, accuracy, precision, and repeatability of occlusal marking techniques. More research is necessary in order to establish a gold standard so that when new technology for marking occlusal contacts is developed, both researchers and clinical dentists will be able to critically evaluate the value of the new technology. Despite this shortcoming, the use of occlusal contacts as a surrogate measure for accuracy of digital casts may be justified just as the use of contacts on traditional mounted casts acts as a measure of mounting accuracy.

Just as articulator mounted casts must reproduce the occlusal contacts noted clinically, so too digital casts must be able to reproduce the clinical contacts. Not only do occlusal contacts act as a method for verification of the mounting of stone models and digital models, but the occlusal contacts are an important clinical record (Harrel, Nunn, & Hallmon, 2006; Kim, Oh, Misch, & Wang, 2005) and can play a role in diagnosis and treatment planning in various disciplines in dentistry.

## 1.9 Accuracy of Digital Models

Delong et al. (2002a, 2003, 2007) have published several papers that all use a very similar experimental design to test the accuracy of aligned digital models by comparing occlusal contacts. Briefly, stone dental casts are scanned using a non-contact 3D scanner and digital models are created using commercial software. Standard interocclusal records are taken on the articulator mounted casts and these are also scanned. Using in-house software, the maxillary and/or mandibular digital models are aligned with the scanned bite record, and a limit is set whereby any two points on the mandibular and maxillary model that are within a given distance are considered contact points. Alternately, the bite record alone can be used to determine contact points using the same technique, where any point on the maxillary and mandibular surface are considered a contact point if they are within a given distance.

Delong et al., (2002a) compared digital contacts from the digitized bite record and the aligned digital models to actual mounted models and found that regardless of alignment technique, the resultant specificity and sensitivity was adequate for clinical requirements - 0.95-0.98 and 0.76-0.89 respectively. Also, digital dental casts could produce contacts equivalent to those noted on mounted stone models. Although they compared several alignment procedures, some automatic and one manual, all aligned casts were manually “refined to correct for penetration...or for separation of the 2 virtual surfaces.” (Delong et al., 2002a, p. 626)

In a separate study, the same group again compared occlusal contacts on aligned digital casts, scanned bite records, and using a technique of transillumination of bite records to the contacts determined on mounted stone models that using shimstock. They allowed for a separation of up to 0.350mm to be considered a contact in the two digital methods, casts and bite record. They found that aligned digital casts, scanned bite record, and transillumination, all had better agreement than when any of those were compared to shimstock, although agreement between all methods was greater than 80% (DeLong et al., 2007).

Although this direction of research may validate the use of digital models from a generic or specific source for use in clinical dentistry, it does not address the issue of absolute accuracy of the final digital model. The manufacturers of most commercially available 3-D scanners give a value for accuracy, but this refers to a single scan under ideal conditions (DeLong et al., 2006). In order to create a complete digital model of a dental cast, several scans are required, as is software reconstruction of those scans into a complete 3D model. Each of these steps will introduce additional error into the final outcome (Brusco et al., 2007; DeLong et al., 2003; Hirogaki, Sohmura, Satoh, Takahashi, & Takada, 2001).

A couple of groups have attempted to measure the overall surface accuracy of free-form dental models acquired from non-contact scanners and apply this to the accuracy required in dental applications (Brusco et al., 2007; DeLong et al., 2003) . With regards to full arch models, the most stringent accuracy requirement in dental

practice is likely for interocclusal contacts, since patients are sensitive to a change of 0.020mm in their occlusal anatomy. (DeLong et al., 2003; Karlsson and Molin, 1995). DeLong et al. (2003) used a calibrated standard (7 steel ball bearings positioned in a steel arch) from which impressions were taken and stone models made. Three-dimensional scans were made of the stone models as well as the vinyl polysiloxane impressions and were compared to a mathematical model of the standard, which was produced by a calibration service with the aid of a coordinate measuring machine. Creation of the digital models required 20 individual scans of the stone models or impressions to be filtered, aligned, and merged into one final object. Accuracy after each step was determined. They found the single scan accuracy of their system to be 0.018mm and final accuracy after processing to be  $0.013\text{mm}\pm 0.003\text{mm}$  for the scanned impression and  $0.024\pm 0.002\text{mm}$  for the scanned stone models. The alignment step created the greatest improvement in accuracy throughout the process, and the other processing steps had minimal effect on accuracy. The accuracy was deemed adequate for dental uses including accurately determining the location of occlusal contacts (DeLong et al., 2003).

Brusco et al. (2007) followed a slightly different direction in determining the accuracy of a dental cast scanning system. One advantage of their system was that it was completely automated, in other words no human input was required for the processing of individual scans into the final 3-D model. This saves both time and the need for specially trained personnel for the digitization of dental casts. Their

entire system, both hardware and software, was produced in-house and is not available commercially, as compared to most similar studies. Accuracy was determined using the substitution method (Savio, Hansen, & De Chiffre, 2002) where a calibrated block was glued to a dental cast for scanning and measurements were made from this block. They found that positioning of the object, ambient light, and calibration of the imaging system all resulted in changes in accuracy. In addition, as the number of voxels increased, the standard deviation, decreased with little change in mean error values (no change in accuracy), but, as the number of scans increased, the mean error increased. This means that in order to produce a digital model of the greatest precision and accuracy, the smallest number of scans possible and the greatest resolution should be used. The final models built using 11 scans had a mean error of  $0.0175 \pm 0.228$ mm. The mean error is comparable to the results of DeLong (2003), but the standard deviation is much greater. These authors felt that this result was well within the range needed for use in orthodontics (Brusco et al., 2007)

The volume of dental literature that is addressing the overall accuracy of dental casts is very limited, as is the determination of what accuracy is needed for dental applications. This is understandable, since the standards for determining accuracy of free-form surfaces using non-contact scanners is still an open research area in the engineering field, and until there are accepted standards, the dental research will continue to use surrogates such as the linear measurements used in

orthodontics or comparing the location of occlusal contacts. These surrogate measurements are not inherently bad for determining accuracy of digital models for clinical applications because they allow the clinician to understand the accuracy in a real life measurement that they are familiar with from clinical experience.

Production of digital models in various forms is continuing to increase in dentistry despite the limitations and questions regarding accuracy. Although digital models alone are useful in various aspects of dentistry, such as measuring tooth widths and arch length as is done in orthodontics or as an initial record of tooth location, the full advantage of digital models will only be reached when an accurate static and dynamic relationship between maxillary and mandibular teeth can be incorporated into the digital process. This is especially true for any prosthetic work, since, if the occlusal relationship is not accurate, any prosthetic work done by a dental technician will be off (Henkel, 2007). When stone dental models are mounted in an articulator, tooth contacts can be determined in both excursive and protrusive movements as well as maximal intercuspation or centric relation depending on the mounting. The advantage that this offers is that dental restoration and prostheses can be fabricated and tested in a dynamic environment that will limit or eliminate the amount of intraoral adjustment of the restoration. Most articulators are limited because they do not replicate exactly the jaw motion of a patient but instead use average values that can approximate jaw movement. Despite this limitation articulator use is essential for major dental reconstruction. A digital

system that can incorporate 3D models of a patient's teeth into a dynamic model of the patient's jaw motion may allow for even more accurate occlusal relationships in the final restorations than is possible with current articulator mounted casts.

Evaluating this type of system for accuracy will be a significant challenge to researchers due to a lack of gold standard comparisons. The first step in validating this type of model will be validating the static relationship of the maxillary and mandibular models in a pre-determined starting point.

## **2 STATEMENT OF THE PROBLEM**

As 3-D imaging becomes more common in clinical dentistry, the need for accurate and high resolution images will increase. In order for these highly accurate 3-D models to be of greatest benefit, they will need to be aligned accurately to represent the given presentation of the individuals they are acquired from. This is especially true for 3-D dental casts, since the acquisition of maxillary and mandibular models results in two unrelated image files. This is in contrast to CBCT images of the maxilla and mandible that, although of lower resolution, are aligned anatomically correctly because of the nature of the scan. Unlike traditional models that can often be positioned to accurately represent the static relationship between maxillary and mandibular teeth based on tactile feedback, this is not possible with digital models. Therefore, a simple, accurate, and reproducible technique for aligning digital models is necessary. It is hypothesized that 3D maxillary and mandibular digital models can be aligned using a 3D image of the anterior teeth in occlusion. This alignment will result in the visualization on the digital models of the occlusal contacts as seen on the articulator mounted casts

The purposes of this study are:

- 1) Demonstration of a technique for 3D digital acquisition of stone dental models using a commercially available 3D scanner.

2) Alignment of the maxillary and mandibular models in an anatomically correct position relative to each other with a “virtual bite registration” instead of a traditional interocclusal record.

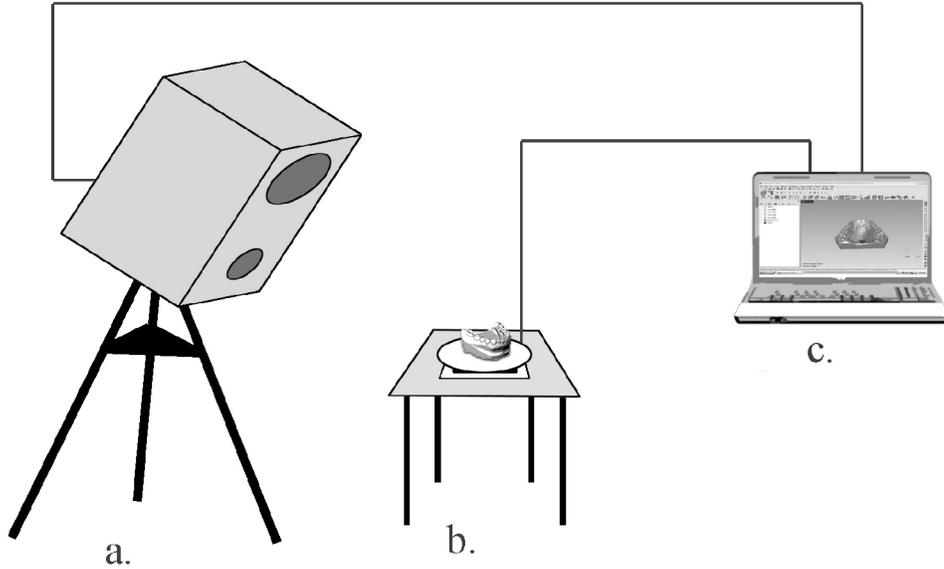
3) Validation of the method by comparing the reproducibility of occlusal contacts between the digital models and the actual occlusal contacts recorded by traditional techniques on the mounted dental models.

### **3 MATERIALS AND METHODS**

#### **3.1 Virtual Model Acquisition**

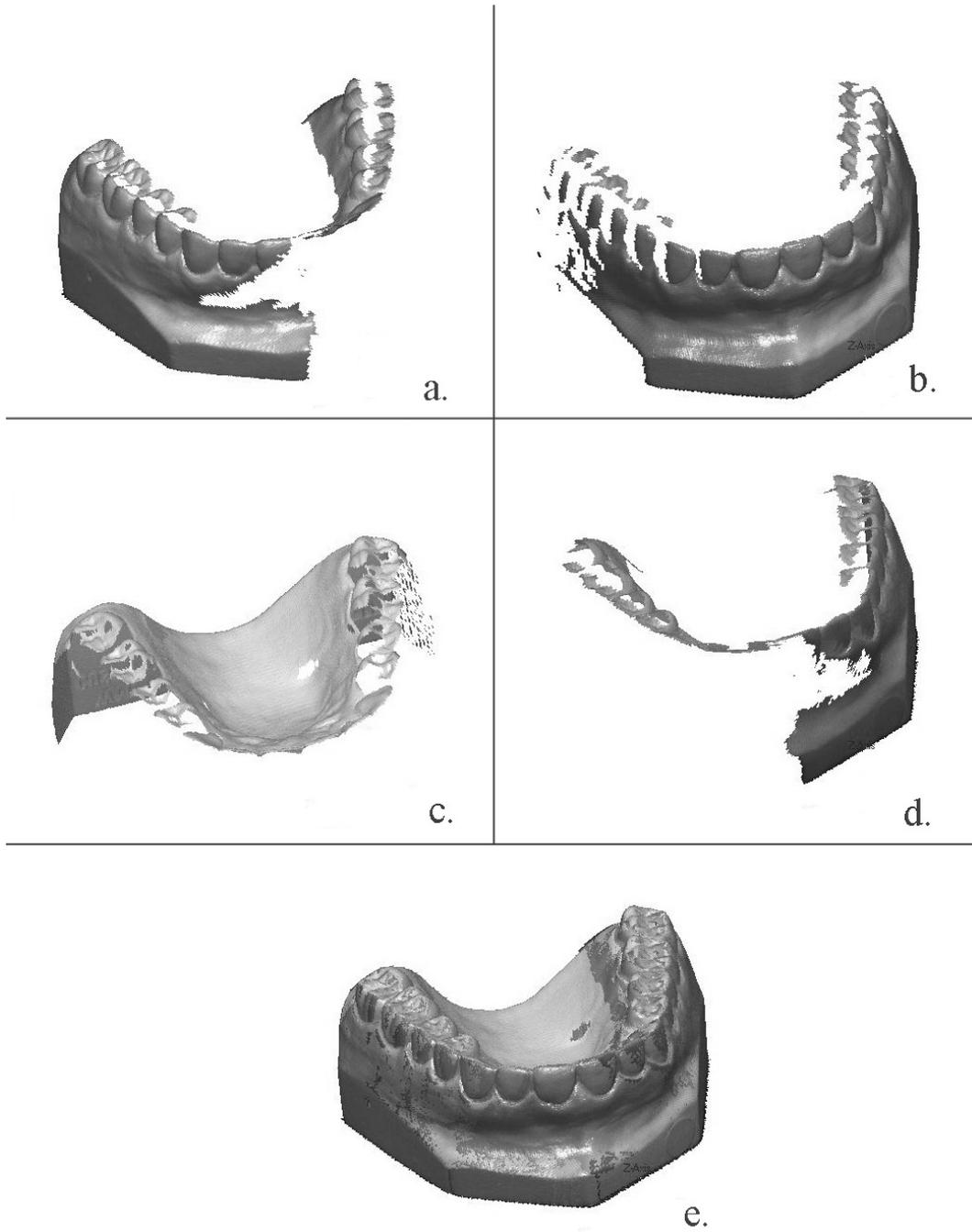
Throughout the study a single set of generic epoxy dental casts was used (Denar). A Minolta VIVID 910 non-contact laser scanner (Konica Minolta Sensing, Ramsey, NJ) was used for scanning the dental casts and for scanning the anterior teeth with the models in occlusion. The Minolta VIVID 910 has a reported accuracy in each axis of  $X\pm 0.22\text{mm}$ ,  $Y\pm 0.16\text{mm}$ , and  $Z\pm 0.10\text{mm}$ . All scanning was done using the tele lens at a distance between 600-750mm on the fine scanning setting, which takes 2.5 seconds/scan. Cast acquisition was accomplished by placing one of the casts on a rotating stage controlled by the same computer that controlled the scanner, occlusal surface up (Figure 1). The scanner was angled at 45 degrees down from the horizontal in order to eliminate undercuts. Four separate images were acquired by the scanner with the stage rotating 90 degrees between each scan. This resulted in four images that were roughly aligned due to the fact that the software rotated each image the same angle that the stage rotated, but in the opposite direction. The goal was to limit the number of scans necessary to have complete imaging of the occlusal surfaces. Brusco et al. (2007) showed that the error in the completed model was greater with an increased number of scans. Since only the occlusal surface was of concern, additional scans to correct holes that resulted because of undercuts hidden from view of the scanner were not done. Incidentally,

using the method described resulted in very few and only small voids, most commonly in the interproximal region at the gingival margin.



**Figure 1.** Set-up for acquiring 3D digital images of dental casts. The 3D scanner (a) was angled down to eliminate undercuts and to adequately image the occlusal surface of the stone dental model that was placed on the rotating stage (b), both the scanner and stage were controlled by a personal computer (c) which also contained the software for 3D image manipulation and registration.

After acquisition of the four scans, further image handling was carried out in Geomagic Studio software (Geomagic, Research Triangle Park, NC). By using the rotating stage, the four images were roughly aligned so no further manual alignment was needed (Figure 2). Instead they were finely aligned using the global registration function in the software. This was accomplished by selecting all four images and then allowing the software algorithm to calculate a translation and rotation that

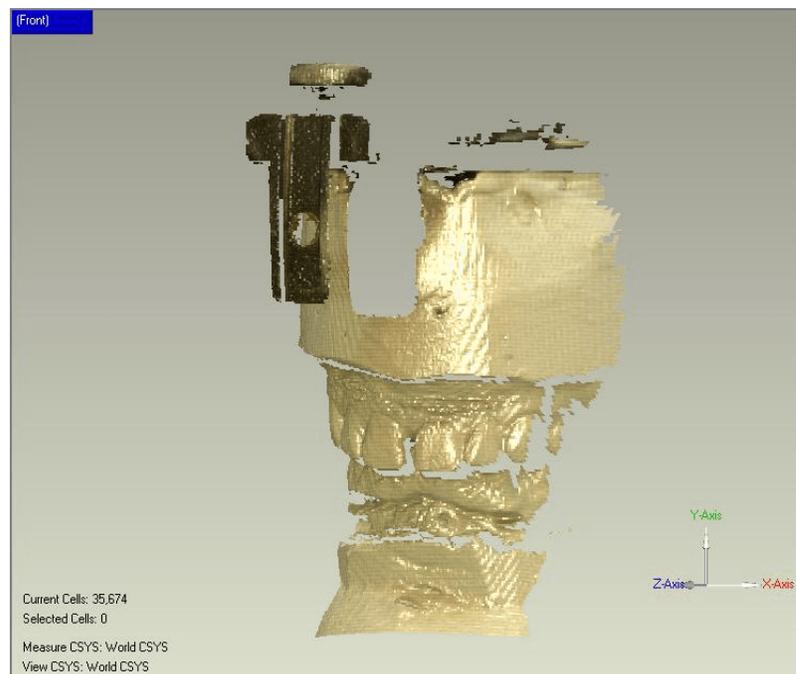


**Figure 2.** Each individual scan only captured a portion of the full dental cast due to the fact that laser scanners can only image the surfaces facing the lens and laser source. Areas hidden from the lens or laser result in holes in the image (a-d). Global registration results in all four images being aligned with respect to each other and gives the appearance of a complete 3D model (e).

resulted in the least difference between overlapping regions. Once all four images were aligned manual cleaning was carried out which involved erasing areas of each scan that were clearly not part of the epoxy model. This can be either surrounding surfaces that were captured or shadowing artifact from the scanner (Figure 3).

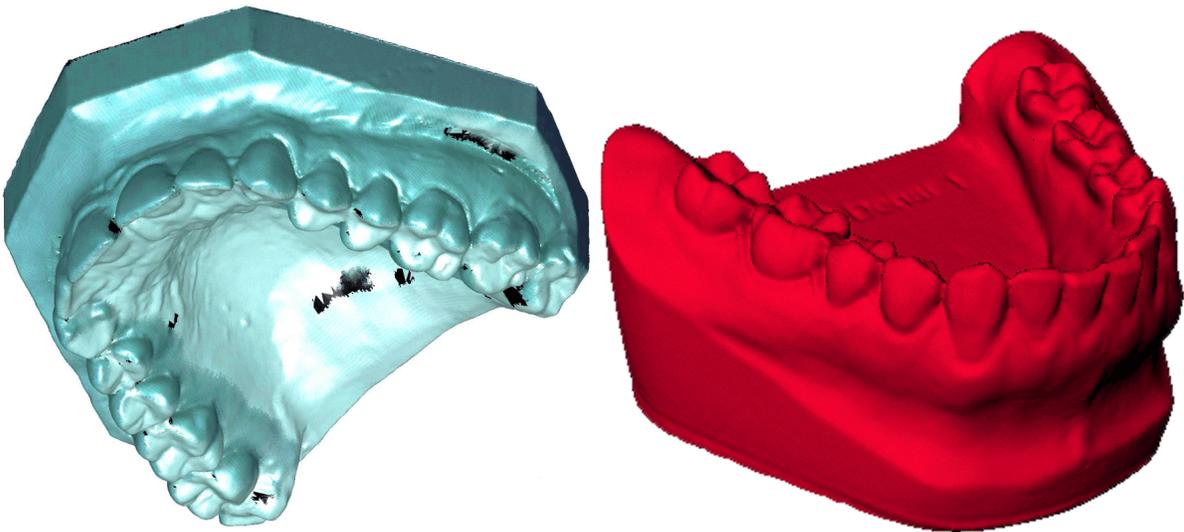
Another global registration was carried out prior to merging the four images.

Merging created a single complete model out of the four scans. After merging, holes may be present in the models as was described previously. These holes could be filled by the software for esthetic purposes, but in the case of this study, as long as the holes were not present on the occlusal surface, they were be left open. If holes were noted on the occlusal surface new scans were necessary to capture this region.



**Figure 3.** Screen capture from Geomagic showing part of the articulator captured by the scan. The articulator is clearly not part of the dental cast and is deleted during as one of the first steps in registration.

One weakness of all structured light scanners, as well as laser scanners, is the limited ability to correctly scan shiny surfaces (Bernardini & Rushmeier, 2002). Epoxy models have a slight sheen compared to standard stone dental models and it was found that this resulted in detectable artefact in the images (Wheeler, Sato, & Ikeuchi, 1998). In order to avoid this, a washable matte spray, Spotcheck SKD-S2 Developer (Magnaflux, Glenview, IL), was used on the surface of the epoxy models prior to scanning and on the anterior views prior to scanning. These sprayed models were the only ones used in the final analysis (Figure 4). Only one set of virtual models was used for all mountings (below).



**Figure 4.** Example of a complete maxillary and mandibular digital 3D model.

### **3.2 Mounting of Dental Casts**

The epoxy models were mounted on a Denar articulator using snow white stone and allowed to set for 30 minutes. Ten arbitrary mountings were performed

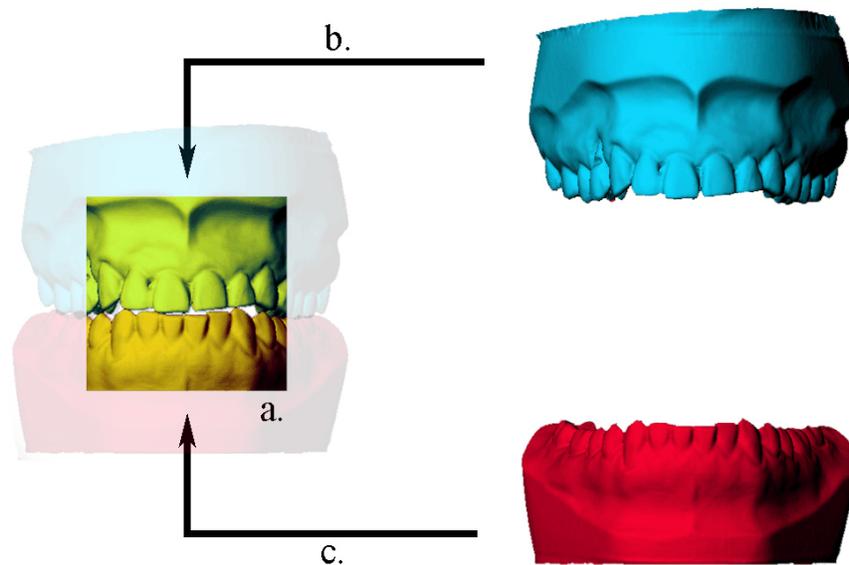
and each time only the maxillary model was remounted. The anterior view of each mounting was scanned as described below.

### **3.3 Acquisition of Digital Bite Registration**

In order to align standard stone dental models, an interocclusal bite record is used such as a wax wafer, vinyl polysiloxane registration material, etc. In this study the aim was to eliminate that step since it represents an additional clinical step (additional time) and may introduce additional error (Breeding et al., 1994). Instead, an image of the anterior maxillary and mandibular casts was acquired while in occlusion (virtual bite registration). This was accomplished by placing the epoxy models in a Denar articulator and aligning the facial surfaces of the anterior teeth parallel to the scanner's lens. Two identical images were acquired, registered using the global registration function, and merged into a single image. Two scans were used instead of one in order to create a merged file which eased subsequent steps (see below).

### **3.4 Alignment of Maxillary and Mandibular Digital Models**

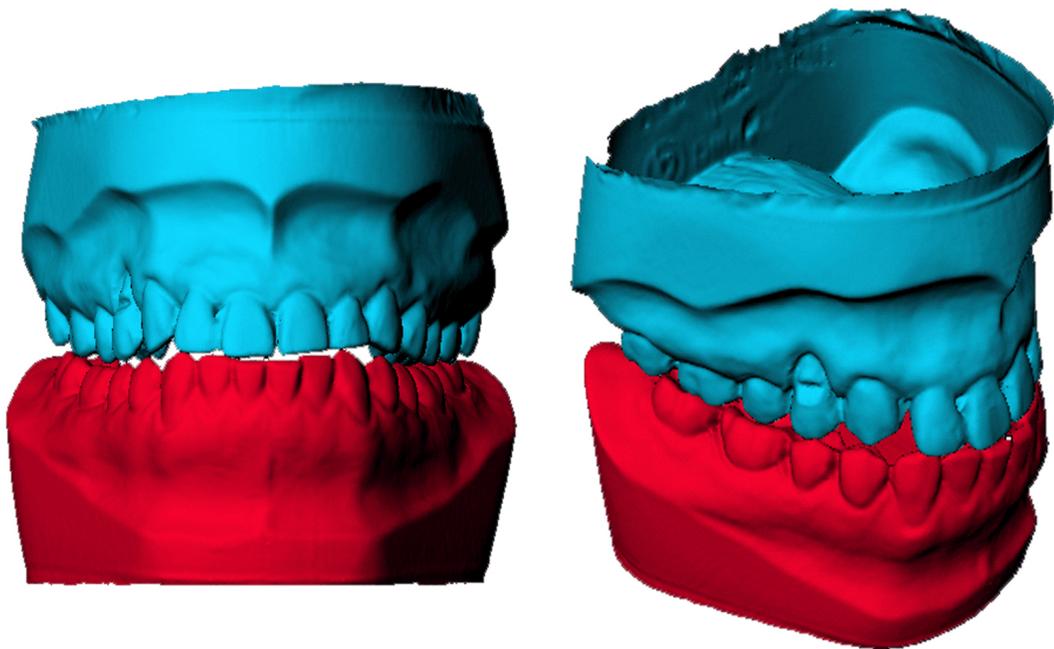
Alignment of the virtual maxillary and mandibular models to the virtual bite registration was accomplished in Geomagic software (Figure 5). This alignment was carried out in two steps for the maxillary and two steps for the mandibular virtual models. Because the initial alignment of the virtual models and virtual bite



**Figure 5.** 3D scan of the anterior teeth in occlusion (a) acted as the virtual bite registration. The complete maxillary digital model was registered with the corresponding maxillary teeth captured by the anterior scan (b). The step was repeated for the complete mandibular digital model (c). This resulted in the digital models being in the correct relationship with respect to each other.

registration may be significantly off, a coarse manual alignment needed to be carried out first. In the software this was accomplished by the manual alignment function. The two images to be aligned were first chosen and aligned in two separate windows so that the images viewed on the monitor were at roughly the same angle. The next step was selection of one or more points on the first image and the corresponding points on the second image in the other window. The software then roughly aligned those points as well as the matching surfaces on the images. If there was good overlap between the two images then selecting a single point was sufficient to

roughly align the models. This was carried out separately for the maxillary and mandibular virtual models using the virtual bite registration as the fixed image. After this was accomplished, the images could then be aligned using the global registration function. This was again done in separate steps for the maxillary and mandibular models by “pinning” (Geomagic function) the virtual bite registration in place so that the only translation and rotation was of the virtual models. These final aligned images were not merged as was performed in creation of the final models but were left as separate images (Figure 6).



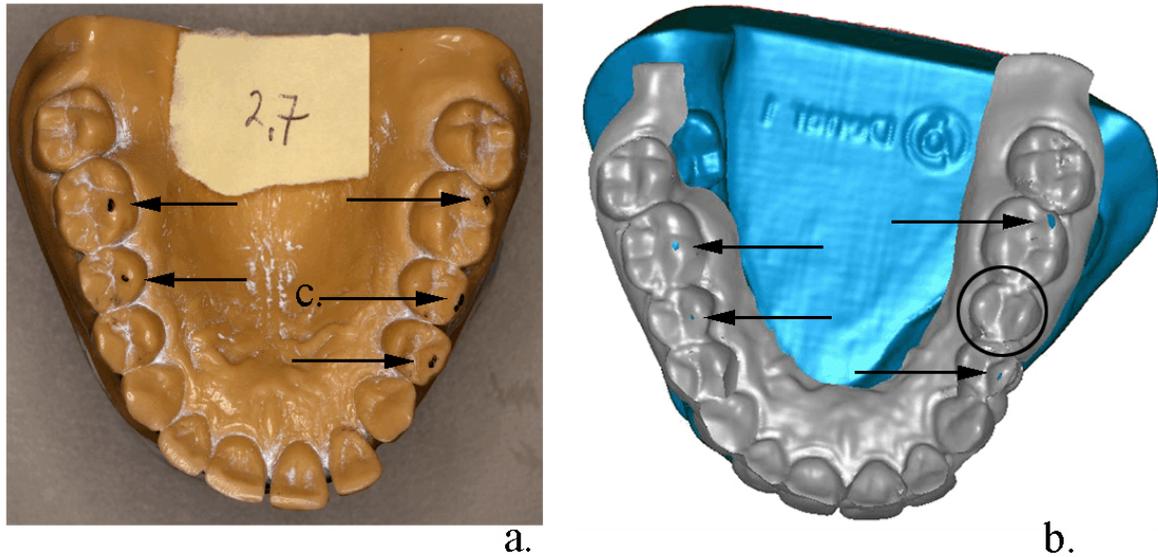
**Figure 6.** Two views of 3D digital maxillary and mandibular aligned casts. Since mountings were arbitrary there was not always good intercuspation of teeth, but this was not important since the key measurement was similarity between occlusal contacts marked digitally and those marked on the actual casts.

### **3.5 Detection of Contacts**

Unlike other studies that calculated contacts as regions of the maxillary and mandibular casts that were within a certain proximity, in the present study contacts were identified as areas where the two virtual models were actually in contact (DeLong et al., 2007; DeLong et al., 2002a) . These areas could be visualized by cutting the top of the maxillary virtual model and the bottom of the mandibular model off and looking at the inside occlusal surface of the virtual models. By making the two models contrasting colours these contacts were readily visible.

Actual contacts were determined on the articulated models using a new piece of Accufilm II articulating film (Parkell Products Inc., Farmingdale, NY) which has a thickness of 21µm for each mounting and firmly tapping the maxillary model against the mandibular model three times. Marked contacts were then checked with 8µm shimstock (Hanel Shimstock, Almore International Inc., Portland, OR). Digital photographs were taken of the marked models using an Olympus Evolt E-300 with a 50mm Olympus macro lens and ring flash. (Olympus Imaging America, Center Valley, PA)

For the analysis, no refinement of the alignment of the models was performed even in cases that showed no occlusal contacts. This was because one of the goals of the study was to determine how predictably the virtual models would replicate the actual clinical situation without a knowledge of the clinical situation beforehand (Figure 7).



**Figure 7.** Representative pairing of epoxy (a) and corresponding digital model (b). Contacts are indicated by arrows on both images. Alignment of the digital models resulted in four out of the five contacts being visible digitally. The only contact not indicated on the digital model that is present on the epoxy model is the 15 buccal cusp tip (c). This pairing represent good agreement between actual and digital contacts.

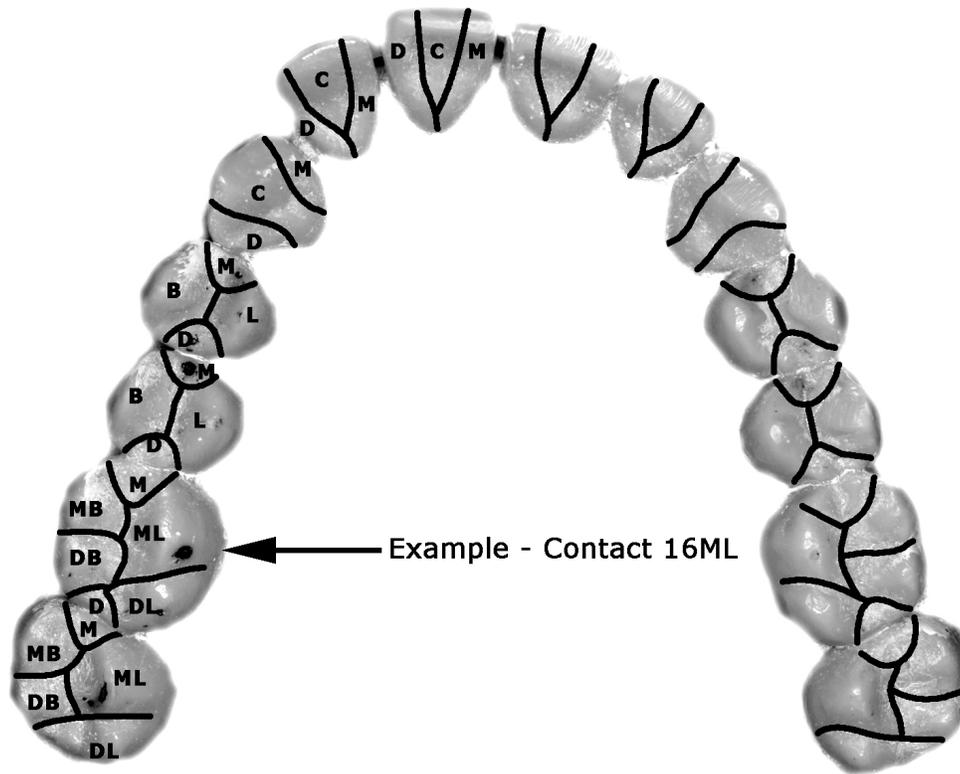
### 3.6 Independent Examiner Validation

Two additional experienced dental clinicians reviewed the photographs of the marked dental casts and the images of the occluding digital models in order to verify the findings of the principal investigator. Each one recorded which regions they thought represented clinical contacts from photos of the marked epoxy casts as well as from the images of the digital casts. The examiners also compared each corresponding epoxy and digital set of images to determine which contacts they considered, in their clinical judgement, to be coincident between the articulating paper markings and the digital contacts. This data was recorded on a standard form

for both examiners. All examiners were blind to the results of the other examiners at the time of recording.

### **3.7 Data Analysis**

The location of all occlusal contacts noted using articulating film and shimstock on the actual mounted models were recorded, as were all the digitally produced contacts. Sensitivity and specificity were calculated twice, first using shimstock as the standard, and then using articulating paper as the standard. Contacts were considered similar based on location and clinical judgement. Location of contacts was determined by dividing the occlusal surfaces on the arch into 56 regions as demonstrated by DeLong et al. (2002a) (Figure 8). Each maxillary/mandibular contact pair was recorded as a single contact for analysis purposes since using two values will artificially increase the number of data points despite the fact that each point in a contact pair is not independent.



**Figure 8.** Anatomic contact regions. Contacts were defined qualitatively based on location on tooth anatomy. Region and tooth number identified contacts (arrow). B, Buccal; C, Central; L, Lingual; M, Mesial.

### 3.8 Statistical Analysis

Virtual contacts from the digital models were compared to the standard shimstock and articulating paper contacts according to sensitivity, specificity, positive predictive value, and negative predictive value (Figure 9). All data from each group (digital, shimstock, or articulating paper) was combined to give a single value comparing total digital contacts to shimstock and articulating paper. This was done because the models in each series were identical, and the only difference was

the mounting. Contact location was based on anatomic regions as described and used by DeLong et al (2002a, 2007). Percent positive agreement between examiners for each set of images was calculated from the data gathered from the additional independent examiners.

	positive (occlusal contact truly exists)	negative (occlusal contact truly not present)
positive (occlusal contact appears on new test - digital alignment)	<b>true positives</b>  <b>a</b>	<b>false positives</b>  <b>b</b>
negative (occlusal contact does not appear on new test - digital alignment)	<b>false negatives</b>  <b>c</b>	<b>true negatives</b>  <b>d</b>

**Figure 9.** Comparison of the new test to the gold standard. In the present study the digital contacts were always the test and either shimstock or articulating film marks were considered the standard. Sensitivity =  $a/a + c$ , specificity =  $d/b + d$ , positive predictive value (PPV) =  $a/a + b$ , negative predictive value (NPV) =  $d/c + d$ .

## 4 RESULTS

The mean number of contacts per model pair recorded by shimstock, articulating paper, and digital, were  $2.7 \pm 1.34$ ,  $4.9 \pm 1.58$  and  $3.3 \pm 2.53$  respectively. The total number of contacts for each recording technique and each mounting pair, as well as the number of contacts that were considered coincident between the various recording techniques are shown in table 1.

Cast Mounting Pair	Shimstock (total number of contacts recorded by method)	Articulating paper (total number of contacts recorded by method)	Digital (total number of contacts recorded by method)	Number of contacts coincident between all three methods	Number of contacts coincident between digital and articulating paper only	Number of contacts coincident between shimstock and articulating paper only	Number of contacts unique to only one recording method
1	1	1	1	1	0	0	0
2	3	6	4	1	1	2	4
3	3	6	6	3	1	0	4
4	2	7	9	2	4	0	4
5	2	4	1	1	0	1	2
6	1	4	1	0	1	1	2
7	5	5	4	4	0	1	0
8	4	6	2	2	0	2	2
9	2	5	1	0	1	2	2
10	4	5	4	3	0	1	2
TOTALS	27	49	33	17	8	10	22

**Table 1.** The table demonstrates the number of contacts present on each cast mounting pair and the number of contacts that were considered identical between recording methods. Since each mandibular contact had a coinciding maxillary contact, each mandibular/maxillary pair was considered as a single contact. There is no column for coincident contacts between digital and shimstock methods only because all shimstock contacts were also identified with articulating paper.

Using shimstock as the standard and digital markings as the test the specificity was 97%, the sensitivity was 63% and the negative predictive value and positive predictive value were 98% and 52% respectively. When articulating paper markings were used as the standard and digital contacts as the test the corresponding values were 98%, 54%, 96% and 76% respectively. (Table 2)

Standard	Specificity	Sensitivity	PPV	NPV
Shimstock	0.97	0.63	0.52	0.98
Articulating paper	0.98	0.54	0.76	0.96

**Table 2.** Comparison of occlusal contacts determined using virtual models and two traditional techniques. The table shows the specificity, sensitivity, positive predictive value (PPV), and negative predictive value (NPV) of the digital contact method when using the two standards (shimstock and articulating paper) used in the present study. Digital contacts were always used as the test for calculations.

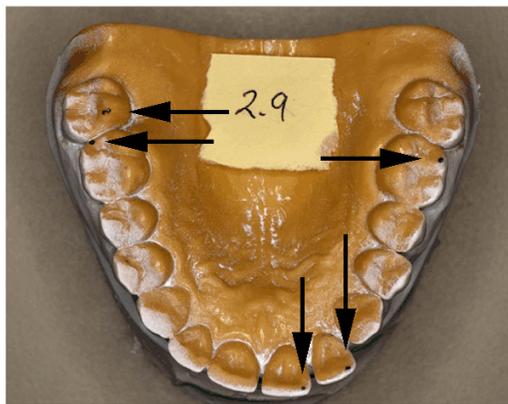
Overall positive examiner agreement for articulating paper marked casts was 83%, for digital casts was 86%, and for coincident contacts between actual and digital casts was 85%. Pair wise agreement between examiners is shown in table 3.

Pairings	Articulating paper	Digital	Coincident
A-B	84%	89%	89%
A-C	94%	89%	92%
B-C	93%	94%	92%

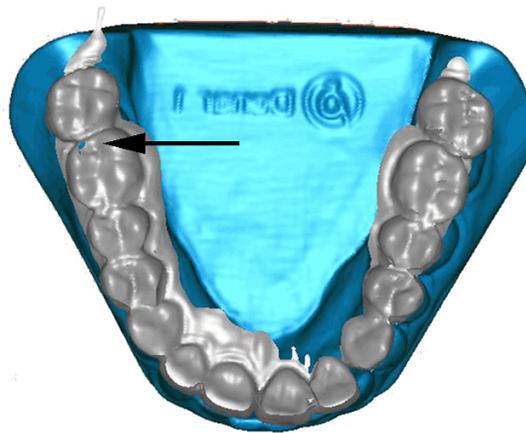
**Table 3.** Percent (positive) examiner agreement. The table shows the pair-wise percent positive agreement for the three examiners for the two contact methods used. In addition percent positive agreement between examiners for the contacts considered to be coincident between the two marking methods is shown. The total number of contacts for all cast pairs in each marking method were combined to calculate percent agreement.

After analyzing the data it was noted that some mountings had very good agreement of occlusal contacts between the epoxy and digital models while other digital models showed almost no contacts. It was decided to test whether or not better agreement could be obtained by closing the digital models through a path of rotation representing the motion of the articulator. This step was only carried out on one set of mountings where the digital model showed poor agreement with the epoxy model due to lack of contacts present digitally. This step was similar to the manual adjustments made in other studies (DeLong et al. 2007; DeLong et al., 2002a), except instead of simply moving the mandibular cast perpendicular to the maxillary cast, a rotational axis was created and the mandibular cast was rotated into the maxillary cast in an attempt to simulate a jaw closing motion. The axis was determined by using a coordinate measuring machine (MicroScribe-3DX) and

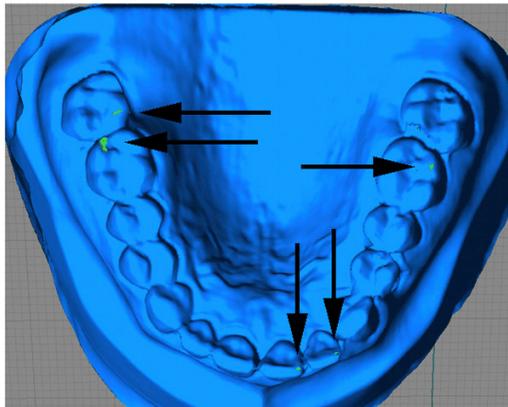
marking points at three locations on the mandibular teeth and at the two points along the hinge axis of the articulator. These points were imported into Rhino 3D modeling software and aligned with the mandibular cast, which was already aligned with the maxillary cast from the original registrations. An axis of rotation was created through the two points from the articulator hinge axis, and the mandibular cast was rotated through various known angles. The original alignment had produced only a single virtual contact compared to the five contacts achieved with articulating film. A rotation of only 0.15 degrees achieved all five contacts on the virtual casts with no false positive contacts. This amount of rotation represented a translation of just over 0.2mm at the anterior teeth and approximately 0.14mm at the posterior teeth (Figure 10).



a.



b.



c.

**Figure 10.** Maxillary cast with contacts indicated by arrows (a). Digital cast of same mounting showing only one contact present (arrow) (b). Same digital cast after being rotated through axis representing articulator hinge axis. All true contacts (arrows) are now present with no false positives (c).

## 5 DISCUSSION

Acquisition of digital models is the first step in creating a virtual patient, and this can be accomplished with a variety of scanners. The accuracy and resolution of the scanner chosen will affect any results further down the line. In this study, the scanner used was a Konica Minolta 910 with a stated accuracy in the X, Y, and Z axes of  $\pm 0.22\text{mm}$ ,  $\pm 0.16\text{mm}$ , and  $\pm 0.10\text{mm}$  respectively. DeLong et al. (2003, 2007, 2002a) used a Comet 100 optical digitizing system with a stated accuracy of  $\pm 0.040\text{mm}$ . These accuracies are for a single scan under ideal conditions, so the accuracy of the final 3-D model would also depend on the number of scans required to produce the full model, since increasing the number of scans results in a decrease in overall accuracy of the model (Brusco et al., 2007). Regardless of the number of scans, one of the limitations in this study was the accuracy of the scanner used. Since the manufacturer's stated accuracy is for a single scan, the creation of a complete 3-D model from four scans will result in even less accuracy, and therefore it can be assumed that the average point accuracy for the final models in the present study is less than  $0.22\text{mm}$ . Although for linear measurements this value may be adequate, it could potentially represent either large interocclusal gaps between the maxillary and mandibular teeth when in fact a contact should be present, or conversely, pass through between the maxillary and mandibular teeth when in fact no contact is present. Shimstock contacts represent gaps between the maxillary and mandibular teeth of  $8\mu\text{m}$  or less, and articulating film represent gaps of  $21\mu\text{m}$  or less. These values are at least

an order of magnitude finer than the accuracy of the scanner used in the present study. Despite this large discrepancy, the digital contacts correlated moderately well with both the shimstock and the articulating film contacts. Use of a higher accuracy scanner may have resulted in improved values in this study while still maintaining the same protocol. Konica Minolta has recently released a new 3-D laser scanner (Konica Minolta Range 7) with a stated accuracy of  $40\mu\text{m}$  in all three axes and a precision of  $4\mu\text{m}$ . This represents an accuracy improvement of roughly five times over the scanner used in the present study.

False negative values will directly affect the sensitivity value of a test. For acceptance as a diagnostic test, sensitivity should be  $>0.70$  and specificity  $>0.90$  (DeLong et al., 2002a). Sensitivity values in this study fell just short the value needed for a test to be considered clinically acceptable, although the sensitivity when using shimstock as the standard did approach the needed value. This differs from the results of DeLong et al. (2002a) that found sensitivities for different alignment protocols to range between 0.76 and 0.89.

Despite the fact that the specificity values in the present study reached levels that are considered acceptable for new clinical tests, the value of this result in the present study is limited. This is because specificity represents the ability of the test to identify true negatives. Since the number of contacts present on each model pair was very small, ranging from one to nine, the total number of regions without contacts was always much greater than those with contacts. This results in the numerator being

consistently large in comparison to the denominator in the calculation of specificity as shown in figure 9.

There are several reasons that the results in the present study were just short of the necessary sensitivity value whereas the results of Delong et al. (2002a) did surpass a sensitivity of 0.70. The first being the accuracy of the scanner used as mentioned previously. The second is related to the way contacts were recorded. Comparison of the digital contacts was made to two different standards since in occlusal marking there is no universally accepted gold standard (DeLong et al., 2002a). Shimstock and articulating film were both used as standards since both are commonly used in clinical dentistry. The shimstock thickness was  $8\mu\text{m}$  and the thickness of the articulating paper was  $21\mu\text{m}$ . Since the greatest accuracy of the scanner was 0.1mm in the Z axis and this represents 5X the thickness of the articulating paper, it is possible that areas of the actual model that should be within the limits to be marked with articulating paper are lost during the digitization process, and the result is a false negative on the aligned digital models. This type of error would be expected to be even greater when comparing to shimstock since it is less than 1/10th the thickness of the upper end of accuracy of the scanner. This was not found in this study since the sensitivity was actually slightly greater (0.63) when shimstock was used as the standard compared to articulating paper (0.54).

The reason for this may be due to how contacts were determined on the digital models. Unlike other studies (DeLong et al., 2007; Delong et al., 2002a) and software

(Orthocad) that use a tolerance range to determine contact areas, in this study a contact was only recorded digitally if the actual 3D maxillary and mandibular surfaces came into contact. This technique has not been used previously, and there are some limitations to it but also some benefits. If the maxillary and mandibular surfaces are even within  $1\mu\text{m}$  but not contacting no contact will show up on the digital model but clinically if only  $1\mu\text{m}$  space exists between teeth, either intraorally or mounted on an articulator, they will hold an  $8\mu\text{m}$  thick piece of shimstock, and therefore the digital model will show a false negative.

In one study, Delong et al. (2002a) used a range of 0.050mm of separation to determine occlusal contacts. This meant that any areas of the maxillary and mandibular digital models that were within 0.050mm of each other were marked as contacts. This value was chosen because it was slightly larger than the accuracy of the scanner being used. In another study, they used a value of 0.350mm as the tolerance range (Delong et al., 2007). This second value that was used seems clinically inappropriate since it is over 40 times the thickness of a piece of shimstock.

Allowing for a range of separation in the present study would likely have resulted in a greater number of contacts recorded on the digital casts, but it is not known if these would have been true contacts or false positive contacts. Also, in a true clinical situation, allowing for a tolerance range is justified since, unlike stone models, teeth are not rigidly positioned. Due to the periodontal ligament attachment, teeth can move both horizontally and vertically in the socket. This movement ranges

from 25-100 $\mu$ m axially and up to 200 $\mu$ m in a horizontal direction for healthy teeth (Kim et al., 2005).

The advantage of not using a tolerance range, especially if shimstock is being used as the standard to compare to, is the decrease of false positives that can be created by using an inappropriately large tolerance range. Future studies could overcome this problem by using a range of tolerances from zero, as was used in this study, up to some arbitrary value, and compare the results in order to determine, in the context of their system, what the ideal range of tolerance would be for determining contacts.

One of the goals of the method used in this study was to limit the amount of operator input necessary to output results. An additional goal was that the method would be able to predict the contacts without prior knowledge of location or number. Both these goals were achieved to varying degrees. Some operator input is necessary with any system, whether that be simply placing the stone model in a scanner and pushing a button or manually scanning each view of the casts, aligning the scans, and orienting the maxillary and mandibular casts. In the method described here, the operator is required during each step to push a button, but the software carries out the vital tasks. This is an important point because a digitizing system that requires skilled operators will increase the cost to the dentist and limit the use of the system within a dental practice. In addition, a digital technique that requires significant user input and decision making will introduce bias into the final outcome, a system that is automatic

limits the user bias and provides for a more standardized output. A major difference between the present study and that of DeLong et al. (2007, 2002a) is the elimination of any manual adjustments to the alignment of the casts. DeLong et al. (2007, 2002a) manually refined the alignment of the maxillary and mandibular casts after automatic alignment in order to correct for separation or excessive penetration beyond the tolerance range used by moving the mandibular virtual cast perpendicular to the maxillary cast. In addition, the positions of the contacts were visible on the 3-D models, whereas in this study the contact points were not visible on the 3-D models because only one set of scanned models was used for all 10 mountings and they were scanned before any mounting or occlusal marking was carried out.

The use of automatic alignment and a single set of unmarked casts eliminated the bias that may have been introduced if manual adjustments were made. It also provides a system that can be carried out by anyone with basic knowledge of the hardware and software used. In this study all the tests were carried out by a single investigator, who also developed the method. An interesting and valuable test would be for someone unfamiliar with the system to be trained in the basic steps necessary to create and align 3-D models to see if the outcome is dependent on the skill or knowledge of the operator. Ideally, the more automatic the method is, the less the result will depend on the operator, and therefore, the more consistent the results will be between operators.

For this reason the additional testing using the created path of rotation determined from the articulator was only carried out on a single model set as a point of interest and as a test to see whether or not manual manipulation would improve the results in this method. Although this test was not carried out on all the mountings, it does demonstrate within the methods described here that if manual adjustments are carried out on the automatically aligned digital models, the comparison between actual and digital contacts may improve. The reasons that this procedure was not carried out on all the models are varied. First, not all models had poor agreement between articulating film and digital contacts. In fact, some mounting sets had perfect agreement after automatic alignment, and therefore, any manual adjustments could not have improved the agreement. The second reason for only one application of this technique relates to the first in that it increases the technique sensitivity of the method, and since it may only be needed on some models, the decision to make manual adjustments introduces bias into the method. The decision to do this step was only made after comparison of contacts between the epoxy and the digital models and only because the actual contact points were known to be different from those represented digitally. In a clinical situation where only digital models are obtained with, for example an intraoral 3D scanner, and there is no recording made of the actual occlusal contacts for comparison, the clinician would not know if manual adjustment of digitally aligned models was necessary or not. Therefore, adding it as a step within the methods when one is assessing accuracy of digital model alignment may result in

improved results but represents a step which is clinically inappropriate. Additionally, although it is a trivial step to determine the hinge axis on articulator mounted casts, it is not trivial in the human.

The use of virtual dental models leads to the idea of a “virtual articulator” where the aligned casts can be “mounted” and moved to represent the patient’s movement just as is done on a traditional articulator. The static alignment of dental casts has been demonstrated by several methods by a variety of authors, including this one, and appears to be quite reliable. Introduction of dynamic capabilities to the models involves several new challenges that have been approached in different ways.

Mandibular movements involve both translations and rotations, and the easiest way to incorporate these movements into a dynamic virtual model is to program them in. This approach could truly be called a “virtual articulator” because the geometries and constraints of an actual articulator are simply programmed into a software package into which the 3-D virtual dental models can be “mounted”(Maruyama et al., 2006). The advantage of this type of system is the ability to visualize contact paths and locations during dynamic processes such as excursive and protrusive movements. This system could also be used for automatic designing of interference-free restorations. Limitations to this type of system are similar to the limitations with a standard articulator. Most notably, the settings are somewhat arbitrary and will not exactly match the movements of the patient. In addition, the virtual dental models need to be aligned with respect to each other statically before being inserted into the

virtual articulator. This is where the process described in the present study could be applied to this type of virtual articulator. Just as stone models need to be aligned with respect to each other using a bite registration or hand articulation, digital models need to be aligned with respect to each other in a static relationship before being mounted in a virtual articulator. If the static relationship is not established and accurate between the digital models, any dynamic relationship that is produced on a virtual articulator will also be inaccurate.

Various systems that allow for 3-dimensional recording of the patient's actual jaw movements have been developed (Bisler, Bockholt, Kardass, Suchan, & Voss, 2002; Bisler, Bockholt, & Voss, 2002; Fang & Kuo, 2008; Gartner & Kordass, 2003). The most reported system uses the Jaw Motion Analyzer from the Zebris company to record patient jaw movements (Bisler et al., 2002; Bisler et al., 2002; Gartner & Kordass, 2003). This system uses ultrasound to measure the position of three tracking sensors which are attached to the lower jaw. The position of these trackers is also used for the alignment of the virtual dental models into the dynamic path. As with the preset virtual articulator, this system allows for visualization of dynamic occlusal contact paths in any jaw movement. The advantage is that the movement of the model represents the patient's actual movements. Although this system has been described in several papers, the accuracy of the system has not been reported, nor has the clinical practicality of the system.

As mentioned above, any articulating system, whether bench top or digital, requires an accurate static relationship between the maxillary and mandibular models prior to mounting in order for the dynamic relationship produced by the articulator to be accurate. The technique described in the present study outlines a technique that requires minimal user input, uses commercial 3D imaging hardware and software that exports files in common multi-platform formats, and achieves near clinical sensitivity despite the limited accuracy of the scanner for statically aligning digital models.

An important limitation that is often mentioned in regards to this area of dental research is the rigidity of the system. (DeLong et al., 2002a; Maruyama et al., 2006). Just as stone dental models and mechanical articulators are rigid, so too are the 3-D virtual models used in all the studies. When using virtual models for orthodontic treatment planning, the rigidity of the system is not a concern but if the goal is occlusal assessment or fabrication of a fixed restoration, then the lack of tooth movement and jaw flexure could affect the results (DeLong, Ko, Olson, Hodges, & Douglas, 2002b; Koriath & Hannam, 1994).

Despite the current limitations with 3D digital imaging, it continues to increase in use in clinical dentistry. Any digital system that will involve articulation of teeth will require accurate static alignment of the maxillary and mandibular casts as one of the primary steps. This step will be necessary if the digital models are used for fabrication of machined restorations, recording static occlusal contacts, or measuring dynamic contacts between teeth. The method describe in the present study can act as

a blueprint for a formal method for testing any new digital system that provides a static or dynamic relationship between digital maxillary and mandibular models.

It is perceivable that it will be possible to incorporate into the “virtual articulator” individual viscoelastic properties for each tooth that would be measured clinically, as well as a measure of the flexure of the mandible. Add to this collision properties that would not allow the maxillary cast to penetrate the mandibular cast, but instead allow for displacement of teeth depending on their individual viscoelastic properties, and provide recordings of forces experienced by the teeth and the result would be more appropriately called a “virtual patient” instead of a “virtual articulator.”

## **6 FUTURE DIRECTIONS**

Several directions of research could follow from the present study. Initially, the most beneficial direction would be to try to obtain results with clinically acceptable sensitivity. The sensitivity results in the present study fell just below the level considered acceptable for new clinical tests. Performing the identical procedure with the higher accuracy 3D scanner, such as the Konica Minolta Range 7, may result in acceptable sensitivity levels. An additional important step would be to determine the level of reproducibility between different operators provided by the present method. For this method to be useful clinically, it should provide similar results regardless of the individual operating the system.

Once the method is considered clinically consistent between operators and consistently achieves sensitivity levels that are clinically acceptable the next step in developing the method would be to incorporate movement of the digital casts that represents the patient's own movements in order to visualize dynamic occlusal contacts.

## 7 CONCLUSIONS

The present study was a demonstration of acquisition and alignment of digital 3D dental models. Several conclusions can be made from the results obtained:

- 1) Digital dental models can be created and aligned with the use of commercial, non-dental specific hardware and software with minimal user input.
- 2) Sensitivity of the method and/or system used did not quite reach levels that are considered clinically acceptable but specificity did reach clinically acceptable levels.
- 3) A 3D scan of the anterior teeth in occlusion can be used as a virtual bite registration in place of traditional bite registration materials for aligning digital dental models.

## REFERENCES

- Alcan, T., Ceylanoglu, C., & Baysal, B. (2009). The relationship between digital model accuracy and time-dependent deformation of alginate impressions. *The Angle Orthodontist*, 79(1), 30-36.
- 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(3), 219-223.
- Bernardini, F., & Rushmeier, H. (2002). The 3D model acquisition pipeline. *Computer Graphics Forum*, 21(2), 149-172.
- Besl, P. J., & McKay, H. D. (1992). A method for registration of 3-D shapes. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 14(2), 239-256.
- Beuer, F., Schweiger, J., & Edelhoff, D. (2008). Digital dentistry: An overview of recent developments for CAD/CAM generated restorations. *British Dental Journal*, 204(9), 505-511.
- Birnbaum, N. S., & Aaronson, H. B. (2008). Dental impressions using 3D digital scanners: Virtual becomes reality. *Compendium of Continuing Education in Dentistry (Jamesburg, N.J.: 1995)*, 29(8), 494, 496, 498-505.
- Bisler, A., Bockholt, U., Kordass, B., Suchan, M., & Voss, G. (2002). The virtual articulator. *International Journal of Computerized Dentistry*, 5(2-3), 101-106.
- Bisler, A., Bockholt, U., & Voss, G. (2002). The virtual articulator - applying VR technologies to dentistry

- Breeding, L. C., Dixon, D. L., & Kinderknecht, K. E. (1994). Accuracy of three interocclusal recording materials used to mount a working cast. *The Journal of Prosthetic Dentistry*, 71(3), 265-270.
- Brian, J. N., & Williamson, G. F. (2007). Digital radiography in dentistry: A survey of Indiana dentists. *Dento Maxillo Facial Radiology*, 36(1), 18-23.
- Brosky, M. E., Major, R. J., DeLong, R., & Hodges, J. S. (2003). Evaluation of dental arch reproduction using three-dimensional optical digitization. *The Journal of Prosthetic Dentistry*, 90(5), 434-440.
- Brown, A. A., Scarfe, W. C., Scheetz, J. P., Silveira, A. M., & Farman, A. G. (2009). Linear accuracy of cone beam CT derived 3D images. *The Angle Orthodontist*, 79(1), 150-157.
- Brusco, N., Andreetto, M., Lucchese, L., Carmignato, S., & Cortelazzo, G. M. (2007). Metrological validation for 3D modeling of dental plaster casts. *Medical Engineering & Physics*, 29(9), 954-966. doi:10.1016/j.medengphy.2006.10.011
- Cabral, Cláudio Wilson Lima Ferro, Andrade, e. S., Buarque, e. S., Landulpho, A. B., & Buarque, e. S. (2006). Comparison between two methods to record occlusal contacts in habitual maximal intercuspatation. *Braz.j.Oral Sci*, 5(19), 1239-1243.
- Calberson, F. L., Hommez, G. M., & De Moor, R. J. (2008). Fraudulent use of digital radiography: Methods to detect and protect digital radiographs. *Journal of Endodontics*, 34(5), 530-536.

- Carey, J. P., Craig, M., Kerstein, R. B., & Radke, J. (2007). Determining a relationship between applied occlusal load and articulating paper mark area. *The Open Dentistry Journal*, 1, 1-7.
- Carrotte, P. V., Johnson, A., & Winstanley, R. B. (1998). The influence of the impression tray on the accuracy of impressions for crown and bridge work--an investigation and review. *British Dental Journal*, 185(11-12), 580-585.
- Chau, A. C., & Fung, K. (2009). Comparison of radiation dose for implant imaging using conventional spiral tomography, computed tomography, and cone-beam computed tomography. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics*,
- Christensen, G. J. (2008). Will digital impressions eliminate the current problems with conventional impressions? *Journal of the American Dental Association* (1939), 139(6), 761-763.
- DeLong, R. (2006). Intra-oral restorative materials wear: Rethinking the current approaches: How to measure wear. *Dental Materials : Official Publication of the Academy of Dental Materials*, 22(8), 702-711. doi:10.1016/j.dental.2006.02.003
- DeLong, R., Heinzen, M., Hodges, J. S., Ko, C. C., & Douglas, W. H. (2003). Accuracy of a system for creating 3D computer models of dental arches. *Journal of Dental Research*, 82(6), 438-442.
- DeLong, R., Knorr, S., Anderson, G. C., Hodges, J., & Pintado, M. R. (2007). Accuracy of contacts calculated from 3D images of occlusal surfaces. *Journal of Dentistry*, 35(6), 528-534. doi:10.1016/j.jdent.2007.02.004

- DeLong, R., Ko, C. C., Anderson, G. C., Hodges, J. S., & Douglas, W. H. (2002a). Comparing maximum intercuspal contacts of virtual dental patients and mounted dental casts. *The Journal of Prosthetic Dentistry*, 88(6), 622-630.
- DeLong, R., Ko, C. C., Olson, I., Hodges, J. S., & Douglas, W. H. (2002b). Helical axis errors affect computer-generated occlusal contacts. *Journal of Dental Research*, 81(5), 338-343.
- Dixon, D. L. (2000). Overview of articulation materials and methods for the prosthodontic patient. *The Journal of Prosthetic Dentistry*, 83(2), 235-247.
- Donovan, T. E., & Chee, W. W. (2004). A review of contemporary impression materials and techniques. *Dental Clinics of North America*, 48(2), vi-vii, 445-70.
- Fang, J. J., & Kuo, T. H. (2008). Modelling of mandibular movement. *Computers in Biology and Medicine*, 38(11-12), 1152-1162.
- Farman, A. G., Levato, C. M., Gane, D., & Scarfe, W. C. (2008). In practice: How going digital will affect the dental office. *Journal of the American Dental Association* (1939), 139 Suppl, 14S-19S.
- Freilich, M. A., Altieri, J. V., & Wahle, J. J. (1992). Principles for selecting interocclusal records for articulation of dentate and partially dentate casts. *The Journal of Prosthetic Dentistry*, 68(2), 361-367.
- Garg, A. K. (2008). Cadent iTero's digital system for dental impressions: The end of trays and putty? *Dental Implantology Update*, 19(1), 1-4.
- Gartner, C., & Kordass, B. (2003). The virtual articulator: Development and evaluation. *International Journal of Computerized Dentistry*, 6(1), 11-24.

- Gazit, E., Fitzig, S., & Lieberman, M. A. (1986). Reproducibility of occlusal marking techniques. *The Journal of Prosthetic Dentistry*, 55(4), 505-509.
- Goodacre, C. J., Bernal, G., Rungcharassaeng, K., & Kan, J. Y. (2003). Clinical complications in fixed prosthodontics. *The Journal of Prosthetic Dentistry*, 90(1), 31-41.
- Hajeer, M. Y., Millett, D. T., Ayoub, A. F., & Siebert, J. P. (2004). Applications of 3D imaging in orthodontics: Part I. *Journal of Orthodontics*, 31(1), 62-70.
- Hajeer, M. Y., Millett, D. T., Ayoub, A. F., & Siebert, J. P. (2004). Applications of 3D imaging in orthodontics: Part II. *Journal of Orthodontics*, 31(2), 154-162.
- Harrel, S. K., Nunn, M. E., & Hallmon, W. W. (2006). Is there an association between occlusion and periodontal destruction?: Yes--occlusal forces can contribute to periodontal destruction. *Journal of the American Dental Association* (1939), 137(10), 1380, 1382, 1384 passim.
- Henkel, G. L. (2007). A comparison of fixed prostheses generated from conventional vs digitally scanned dental impressions. *Compendium of Continuing Education in Dentistry* (Jamesburg, N.J.: 1995), 28(8), 422-4, 426-8, 430-1.
- 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 : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 133(2), 283-289.

- Hirogaki, Y., Sohmura, T., Satoh, H., Takahashi, J., & Takada, K. (2001). Complete 3-D reconstruction of dental cast shape using perceptual grouping. *Medical Imaging, IEEE Transactions on*, 20(10), 1093-1101.
- Howerton, W. B., Jr, & Mora, M. A. (2008). Advancements in digital imaging: What is new and on the horizon? *Journal of the American Dental Association* (1939), 139 Suppl, 20S-24S.
- Johnson, A. E., & Hebert, M. (1999). Using spin images for efficient object recognition in cluttered 3D scenes. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 21(5), 433-449.
- Kapoutsis, C. A., Vavoulidis, C. P., & Pitas, I. (1999). Morphological iterative closest point algorithm. *Image Processing, IEEE Transactions on*, 8(11), 1644-1646.
- Karlsson, S., & Molin, M. (1995). Effects of gold and bonded ceramic inlays on the ability to perceive occlusal thickness. *Journal of Oral Rehabilitation*, 22(1), 9-13.
- Kerstein, R. B. (2008). Articulating paper mark misconceptions and computerized occlusal analysis technology. *Dental Implantology Update*, 19(6), 41-46.
- Kim, Y., Oh, T. J., Misch, C. E., & Wang, H. L. (2005). Occlusal considerations in implant therapy: Clinical guidelines with biomechanical rationale. *Clinical Oral Implants Research*, 16(1), 26-35.
- Kunzel, A., Scherkowski, D., Willers, R., & Becker, J. (2003). Visually detectable resolution of intraoral dental films. *Dento Maxillo Facial Radiology*, 32(6), 385-389.

- 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 : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 110(4), 365-369.
- Lane, C., & Harrell, W., Jr. (2008). Completing the 3-dimensional picture. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 133(4), 612-620.
- Lauren, M., & McIntyre, F. (2008). A new computer-assisted method for design and fabrication of occlusal splints. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 133(4 Suppl), S130-5.
- Levoy, M. (1999). The digital michelangelo project. *3-D Digital Imaging and Modeling. Proceedings. Second International Conference on*, 2-11.
- Lin, Y., Zhang, S., Chen, X., & Wang, C. (2006). A novel method in the design and fabrication of dental splints based on 3D simulation and rapid prototyping technology. *The International Journal of Advanced Manufacturing Technology*, 28(9), 919-922.

- Maruyama, T., Nakamura, Y., Hayashi, T., & Kato, K. (2006). Computer-aided determination of occlusal contact points for dental 3-D CAD. *Medical & Biological Engineering & Computing*, 44(5), 445-450. doi:10.1007/s11517-006-0046-0
- Millstein, P., & Maya, A. (2001). An evaluation of occlusal contact marking indicators. A descriptive quantitative method. *Journal of the American Dental Association* (1939), 132(9), 1280-6; quiz 1319.
- 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 : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 131(1), 51-56.
- Palmqvist, S., & Swartz, B. (1993). Artificial crowns and fixed partial dentures 18 to 23 years after placement. *The International Journal of Prosthodontics*, 6(3), 279-285.
- Persson, A. S., Andersson, M., Oden, A., & Sandborgh-Englund, G. (2008). Computer aided analysis of digitized dental stone replicas by dental CAD/CAM technology. *Dental Materials : Official Publication of the Academy of Dental Materials*, 24(8), 1123-1130. doi:10.1016/j.dental.2008.01.008
- Peutzfeldt, A., & Asmussen, E. (1989). Accuracy of alginate and elastomeric impression materials. *Scandinavian Journal of Dental Research*, 97(4), 375-379.
- 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. *The Angle Orthodontist*, 74(3), 298-303.

- Ramamurthy, R., Canning, C. F., Scheetz, J. P., & Farman, A. G. (2006). Time and motion study: A comparison of two photostimulable phosphor imaging systems used in dentistry. *Dento Maxillo Facial Radiology*, 35(5), 315-318.
- Reddy, M. S., & Jeffcoat, M. K. (1999). Methods of assessing periodontal regeneration. *Periodontology 2000*, 19, 87-103.
- Revised american dental association specification no. 19 for non-aqueous, elastomeric dental impression materials.(1977). *Journal of the American Dental Association* (1939), 94(4), 733-741.
- Rohaly, J., & Hart, D. P. (2000). High-resolution ultrafast 3D imaging. *Proc.SPIE*, 3958(1), 2-10.
- Rusinkiewicz, S., & Levoy, M. (2001). Efficient variants of the ICP algorithm. In: *Proceedings of the third international conference on 3D digital imaging and modeling*, 145-152.
- Saad, M. N., Weiner, G., Ehrenberg, D., & Weiner, S. (2008). Effects of load and indicator type upon occlusal contact markings. *Journal of Biomedical Materials Research.Part B, Applied Biomaterials*, 85(1), 18-22.
- 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 : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 124(1), 101-105.

- Saracoglu, A., & Ozpinar, B. (2002). In vivo and in vitro evaluation of occlusal indicator sensitivity. *The Journal of Prosthetic Dentistry*, 88(5), 522-526.
- Sedda, M., Casarotto, A., Raustia, A., & Borracchini, A. (2008). Effect of storage time on the accuracy of casts made from different irreversible hydrocolloids. *The Journal of Contemporary Dental Practice*, 9(4), 59-66.
- Shellhart, W. C., Lange, D. W., Kluemper, G. T., Hicks, E. P., & Kaplan, A. L. (1995). Reliability of the bolton tooth-size analysis when applied to crowded dentitions. *The Angle Orthodontist*, 65(5), 327-334.
- Squier, R. S. (2004). Jaw relation records for fixed prosthodontics. *Dental Clinics of North America*, 48(2), vii, 471-86.
- Wenzel, A., Warrer, K., & Karring, T. (1992). Digital subtraction radiography in assessing bone changes in periodontal defects following guided tissue regeneration. *Journal of Clinical Periodontology*, 19(3), 208-213.
- Wheeler, M. D., Sato, Y., & Ikeuchi, K. (1998). Consensus surfaces for modeling 3D objects from multiple range images
- White, S. C. (2008). Cone-beam imaging in dentistry. *Health Physics*, 95(5), 628-637.
- White, S. C., & Pharoah, M. J. (2008). The evolution and application of dental maxillofacial imaging modalities. *Dental Clinics of North America*, 52(4), 689-705, v.
- Xiaoguang Lu, Jain, A. K., & Colbry, D. (2006). Matching 2.5D face scans to 3D models. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 28(1), 31-43.

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 virtual orthodontic models. *The Angle Orthodontist*, 73(3), 301-306.