University of Alberta

Clinical Use of Virtual Study Models versus Traditional Plaster Study Models for Orthodontic Treatment Diagnosis

by

©

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A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfillment of the requirements for the degree of Master of Science
in
Orthodontics

Department of Dentistry
Edmonton, Alberta
Spring 2004

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Abstract

The purpose of this study is to compare the current gold standard plaster model with the digital counterpart made by Emodel for the analysis of tooth sizes and occlusal relationships—specifically the Bolton analysis and the PAR index and their components. The study sample consists of 24 randomly selected patients with varying malocclusions.

There was no statistically significant difference of *intra*-examiner measurements with digital and plaster orthodontic study models. Reliability was high (average concordance correlation coefficient 0.923 for plaster and 0.883 for Emodels.) The average difference of repeated tooth width measurements was clinically insignificant at 0.10 mm (range = 0.05 to 0.18 mm) for plaster and 0.19 mm (range = 0.14 to 0.24 mm) for Emodels. PAR index scores ranged from a mean difference of repeated Raw PAR score = 0.50 (range = 0.00 - 4.67), US weighted PAR score = 0.89 (rang e= 0.00 - 7.33), and UK weighted PAR score = 1.86 (range = 0.00 - 12). Inter-examiner reliability was consistent.

The orthodontic profession should accept the precision and reliability of digital orthodontic study models as the new gold standard of dentition replication and benefit from their ease of storage and virtual transport without diminished precision.

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Dedication

To my wife Shonni who continues to be my best friend through the endless trials of school and life. To my two children Maryn and Luke for adding immeasurable joy and endless excitement. I love you and thank you!

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Acknowledgements

I would like to thank my supervisor, Dr. Paul Major for his direction and wisdom and would also like to thank my committee members, Dr. Giseon Heo, and Dr. Don Raboud for their insight and feedback throughout this project.

I would also like to thank Dr. Carlos Flores-Mir and Dr. Brian Nebbe for their selfless time commitment to the data collection for my thesis.

I would like to thank all of the clinical instructors Dr. Pawliuk, Dr. Swanson, Dr. Cox, Dr. Major, Dr. Williamson, Dr. Lee-Knight, and Dr. Boychuk for their patience and friendship, as they provided me with an excellent clinical orthodontic education.

I would like to thank Gail, Susan, Wendy, Jacalyn, Laurie, Pat, Kim, Francisca, and Margaret for all their help over the past two and half years. They made the orthodontic clinic a great place to work. I would also like to thank Joanne and especially Cindy for their dedication and hard work for keeping the program running as a smooth operation.

I would like to thank my fellow residents Keith, Mariano, Josh, Kurt, Farah, Darcy and especially Neal and Nadja Klum, for their friendship and support throughout my program. They are truly good friends.

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Table of Contents

Chapter One – Introduction and Literature Review **Page**

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Table of Contents (Continued)

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Table of Contents

Chapter Two – Research Paper **Page**

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Table of Contents

Chapter Three – General Discussion **Page**

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List of Tables

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List of Figures

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Chapter One

Introduction
And
Literature Review

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1.1 General Introduction:

Like most areas of our lives, orthodontics is ‘going digital’. Many orthodontists are joining other health professionals by utilizing a paperless patient information system including virtual chart notes, health histories, digital photographs and radiographs. However, one major obstacle for orthodontists going completely digital is the necessity of using a plaster study model of the patient’s dentition when treatment planning and while performing a patient’s orthodontic treatment.

In late 1999 OrthoCAD (Cadent, Carlstadt, NJ, www.orthocad.com) developed and released to market a *virtual* digital patient study model. Then, in early 2001, Emodels (Geodigm Corporation, Chanhassen, MN, www.geodigmcorp.com) came to market. The technology of digital patient study models allows orthodontists to send a patient’s alginate impression or existing plaster study model to one of these companies for processing of a virtual 3-D computerized image. This image is then available to the orthodontist for download from the company’s website within five days. Software provided by the imaging companies allows the orthodontist to then view the image.

Because of the recent breakthrough in this 3-D imaging technology not much is known about it. However, it would be revolutionary if plaster orthodontic models could be replaced with these new virtual counterparts. This would potentially enable orthodontists to benefit in the following areas:

- Efficiency of having paperless patient records instantly accessible on the computer screen vs. paper chart filing,
- Saving money on the monthly cost of storage space needed for the thousands of traditional plaster models accumulated by each orthodontist over his career,
- Efficiency, and ease in measurement of tooth and arch sizes as well as dental crowding,
- Simple diagnostic set-ups of various extraction patterns,
- The ability to send the virtual image anywhere in the world for instant referral/consultation as needed or for internet study clubs,
- Objective rather than subjective model grading analysis for ABO certification.

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Despite these potential advantages, only a small percentage of orthodontists currently utilize these virtual images. One reason might be limited research regarding their clinical applicability—although the literature review that is to follow identifies several studies that have tested the accuracy of OrthoCAD (but not Emodels.) If these virtual images can clinically replace their plaster counterparts—as claimed by the imaging companies—orthodontists would most likely start using the technology more readily. This would help make a tremendous leap in the exchange of information and collection of accurate orthodontic data through easily transferred digital means.

The purpose of this study is to compare the current gold standard plaster model with the digital counterpart made by Emodels for the analysis of tooth sizes and occlusal relationships—specifically the Bolton analysis and the PAR index.

1.2 Literature Review

1.2.1 Introduction

Computerized surface scanning is the process of digitizing a physical image. There are multiple methods for acquiring a virtual image such as holography, Moire topography, photostereometrics, and laser scanning to name a few. However, a thorough literature review reveals that these four imaging techniques are the main methods that have been employed for use in orthodontic study model fabrication and measurement. Undoubtedly the future will bring improvements to the present methods that are cheaper, faster and more accurate.

Although computerized surface scanning is used in other industries such as automobile and aircraft fabrication, its introduction to orthodontic study models of teeth is relatively new; thus, there are relatively few articles that exist on the subject. This literature review will cover the articles that have been published on this digital study model technology as well as give an understanding of the general topics associated with this thesis such as the Bolton analysis and PAR index.

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1.2.2 Computerized Surface Scanning

Computerized surface scanning is possible in many different ways. In the following, four will be discussed. All surface scanning methods seem to stem from four basic methods of acquiring 3-D shapes from images, which are summarized by Halazonetis[19]:

1. Stereo Analysis
2. Shape From Shading (SFS)
3. Photometric Stereo
4. Structured Lighting

As with all these methods, computer software programs that assimilate the information through the use of algorithms process the information from the imagery.

1.2.2.1 Stereo Analysis

Stereo analysis might be the easiest method to understand as it is modeled after human sight, which uses stereopsis, or binocular vision through two eyes to combine the two slightly different images into one that creates depth of field (see figure 1.1). The difference in imagery of each eye is a phenomenon called parallax (which Webster's dictionary defines as "the apparent change in the position of an object resulting from a change in the viewer's position".) Dentistry commonly uses this concept to locate radiographic images by means of Clarke's rule—or commonly referred to as the S.L.O.B. rule (Same = Lingual, Opposite = Buccal)—whereby one can determine an object's buccal or lingual position to neighboring objects by the use of two radiographs taken from differing angles.

The application of stereopsis is transparent to the human brain. However, to program a computer algorithm that can match one point from two different images can be difficult—especially when one is scanning objects without well-defined edges such as teeth. Also, the depth resolution of stereo analysis is dependant on the separation between 2 cameras. The larger the camera separation and the shorter the camera to object distance the higher the depth resolution. However, increasing the separation of the

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cameras at relatively close object to camera distances also results in an increase in image difference, which results in increased difficulty for the computer to combine the two images.

1.2.2.2 Shape From Shading (SFS)

Aside from stereopsis, the human brain also uses shape from shading (SFS) to visualize in 3-D. Object shading is dependant on three main factors:

1. Global illumination (intensity of the light source)
2. Albedo (reflecting properties of the object)
3. Slope (of the surface of the object in relation to the eye and the light source)

Assuming the object has a uniform finish (no varying dull or shiny surfaces), the brightness of the object is dependant on the angle of the object's surface to the light source. Figure 1.2 shows the trigonometry involved in this relationship. SFS calculates depth by a known direction and intensity of the light source. However, the reality is that most real objects have surfaces of varying albedo and color. Intraobject and interobject interreflections also compromise accuracy.

1.2.2.3 Photometric Stereo

As a variation of SFS, photometric stereo is basically the reverse of stereo analysis. Instead of using two cameras and one light source, it uses two (or more) light sources and one camera. The camera is not moved which avoids the correspondence problems of stereo analysis and the computer easily combines the two (or more) pictures of varying brightness. The differences in brightness between the images provide the necessary information to calculate depth and object shape despite varying albedo and color. Some photometric methods exist that are albedo-independent.

1.2.2.4 Structured Lighting

Structured lighting methods project known patterns of light onto an object in either a point of light (see Figure 1.3) or in a stripe of light (see Figure 1.4). The camera is stationary and either the light source scans the stationary object or the object is rotated

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on a turntable. Simple trigonometry using the known geometry of the setup allows for simple calculation of the objects shape. Resolution of structured lighting is a direct function of the fineness of the light pattern used. The SureSmile OraScanner by Orametrix (Dallas, TX, www.orametrix.com) is an example of this type of scanning. Although Emodel (Geodigm Corporation, Chanhassen, MN, www.geodigmcorp.com) and OrthoCAD (Cadent, Carlstadt, NJ, www.orthocad.com), the types of digital models used in this thesis, highly guard their proprietary secret methods, they too most likely use structured lighting techniques to produce their products. Emodel's official statement on their process is:

> *Emodels are created using a patented and proprietary scanning process that utilizes a 5 axis digital scanner. The scanning process is non-destructive in nature. The laser probes accuracy is to the micron level*

OrthoCAD most likely uses the same or similar type of scanning method as Emodels; however, OrthoCAD claims to use a "destructive scanning" process. Rather than combine images of varying angles as Emodels does, OrthoCAD seems to have a stationary model and a stationary laser that takes multiple scans of the model in roughly 0.10mm or smaller increments. Once the initial scan is made of the model, a 0.10 mm or smaller incremental slice is shaved off the model and another scan is made. This is repeated until the entire model has been shaved and scanned. Thus the end result is a typical OrthoCAD file of 3000 KB (or 3 MB or megabytes) because the internal aspects of the model are scanned—even though the internal information is completely unusable. Compare this to an Emodel file of roughly 800 KB (kilobytes) due to surface scanning only. From a storage and data transfer standpoint it is clear that the smaller file size of the Emodel is more ideal. Also, because destructive scanning done by OrthoCAD requires so much useless intrastructure information it is more difficult to increase surface scanning quality without making the file size exponentially so large that it is impractical from a storage and image manipulation standpoint compared to Emodels. With the smaller Emodel file size more surface detail can be processed while maintaining a small file size.

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For research purposes when comparing the accuracy of a digital study model versus the actual plaster model, the scanned image should be compared with the manually measured image. With Emodels this is possible as the model is not destroyed in the scanning process; however, with OrthoCAD one must produce two different models—one for manual measurements and one for the destructive scanning process. It is true one could measure a model and then send it off to OrthoCAD for destructive scanning, but then the plaster model would not be available for data verification later on. And although polyvinyl siloxane impressions are accurate enough to make model duplication error non-contributory on a clinical and research level from a material standpoint[8 30], the possibility of error from physical distortion not contributed to the material properties cannot be eliminated. To date, all research on the commercially available digital models has been performed with OrthoCAD. This is probably due to the initial software of OrthoCAD being more esthetic and easy to use. However Emodels has had time to update their software to where in the author's opinion, the Emodel software is just as esthetic but more importantly more advanced and easier to use.

The following is a brief explanation of the fabrication and use of the digital orthodontic study model[32]. An impression is made of the patient's teeth with typically used alginate material. This impression and a wax bite are sent to the company (Emodel or OrthoCAD) via overnight courier. Within a week, models are ready for download via the internet to the orthodontic office. Doctors can then store, retrieve, diagnose and communicate their cases electronically. The system requires the use of free proprietary software available for download on the company website. The digital model is easily manipulated into any orientation on screen. Easy-to-use measuring and viewing devices make it easy to measure Bolton discrepancies, overjet, overbite, arch length, occlusal interferences, etc.

1.2.3 Digital Model Measurement Methods

Although laser scanning appears to be the only method used by commercially available digital orthodontic study model companies, there are several other digital model measuring methods that have been studied. The most popular being:

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- Photo Copying
- Holography
- Moire topography
- Photostereometrics

A brief introduction into these techniques will follow. The scope of this thesis is not to prove that laser scanning is the most accurate, the fastest, or the most cost effective method of 3-D imaging and computer digitization. However, for completeness the other main methods of computer measurement of orthodontic study models are discussed.

1.2.3.1 Photocopying

Photocopying or direct flatbed scanning of plaster models has been tested as an alternative to vernier caliper measurement on plaster models. Yen[60] was the first to use this method. Although this is not technically a digital replication of the model, it does allow for an image to be put onto a computer screen for computerized digital measurement. The basic process involves placing a plaster model onto a scanner (or onto a copy machine, then placing the photocopied image onto a scanner) and acquiring a still image of the occlusal surface of the model. Computer software is then used to measure distances on the model.

Shirmer and Wiltshirel[50] compared computer aided measurements of photocopied models with measurements of the actual plaster model made by a vernier gauge. On the plaster model, intraexaminer and interexaminer reliability was determined to be 0.2 mm. Intraexaminer digitized measurements were almost identical and differed for only one measurement. However, interexaminer manual and digitized measurements differed significantly for 20 of 24 teeth. Nineteen of these digitized tooth measurements were smaller. Shirmer et al thought that maybe the inability to accurately measure a 3-D study cast that has been duplicated in 2-D may play a role in the difference between a photocopy and the plaster model. They concluded that the computer-aided measuring system is reliable, but the accurate mesiodeistal measurements cannot be made from photocopies of dental models. Photocopies will most likely not be a method of choice in the future due to their still nature and lack of precision[10].

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1.2.3.2 Holography

Holography is another method of virtual model replication introduced in 1948[17] and involved microscopy by reconstructed wave fronts. Measurement differences between holograms and plaster were first made by Ryden et al[48]. A description of holographic images fabrication is found in Figure 1.5 made by Martensson and Ryden[33].

The hologram technique's major problem is the poor quality of recording the details of the study models, especially the incisor region. Although an advantage of holography is that films may be stored with paper medical record files and are more cost effective archiving, the still imagery is one of the main reasons it cannot replace the original models[5].

Martensson and Ryden[33] tested holographic images of metal test objects with sharp well-defined contours which were easily reoriented and found precision to be 0.02 to 0.11 mm for x, y, and z coordinates (transverse, longitudinal, and vertical planes.) When dental casts that have less distinct contours were used, precision was reduced to 0.03 to 0.43 mm. Due to photo copy inaccuracies, holographic images offer a more practical solution to storage issue problems by replacing bulky plaster casts with an accurate replication; however, like photo copies they are a still image and cannot be rotated or manipulated to view the study models from all angles.

Romeo et al[47] did a follow up study to Martensson and Ryden to measure the accuracy of the hologram compared to the gold standard plaster model measured with a vernier caliper. Both canine distance from the mid palatal raphe as well as maxillary depth (center of the palatine raphe to maxillary canine) were measured. They found the precision obtained from holographic image measurements to fall between 0.05 and 0.2 mm and termed them clinically insignificant.

1.2.3.3 Moire Topography

Moire topography is yet another studied method of digital model replication[58]. This is a contour mapping technique designed to produce successive contour lines directly on an image through a process called grating. A computer to produce an image

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like a topographical map then records these lines. According to Bell et al[5] this technique is not used much today because of the poor resolution. However, Brosky et al[8] report that the Steinbichler Comet 100 Optical Digitizer, which is a device that uses a Moire fringe pattern analysis, has an accuracy of 40 microns or better over its entire measurement volume of 80 x 80 x 65 mm^3 and a resolution of 130 microns in the x and y directions and 5 microns in the z directions.

1.2.3.4 Photostereometrics

The most promising method of computerized model digitization aside from laser scanning appears to be photostereometrics or stereophotogrammetry introduced by Ayoub et al[4]. This technique uses stereo pairs of video cameras connected to a computer and special colored illumination to record dental study models in digital format. Like other digital formats, the stored data can then be converted into a stereolithographic format for the reconstruction of the study model. This method has also been used to image the face for use in maxillofacial assessment and surgical planning[3]. Due to the potential damaging effects of laser scanning on the face and eyes, photostereometrics may become the most dominant method of facial scanning if all other quality and usability factors are proven to be even in the future.

Bell et al[5] conducted a comparative assessment between direct measurements of plaster study models with vernier calipers and measurements of computer generated 3D images (via photostereometrics) of the same study models. 6 points on the 22 study models were made on the cusp tips of various teeth for a total of 15 distances between points. These distances between the points were measured on both the plaster and 3D digital models 8 times for each cast with at least a 10 day interval between measurements. The mean differences in measurements were calculated to assess the error of the method (intra-operator error.) A power value of 0.90 was chosen so that there was a high probability of detecting a significant difference should it exist. The results showed an average difference between plaster and the 3D image to be 0.27 mm, which is within the range of operator error (0.10-0.48 mm) and was not found to be statistically significant ($P<0.05$). The variation in measurement related to the operator positioning the measuring

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points on the digitized models was 0.02—0.14 mm. However, this was a smaller value than the variation observed when measuring with a vernier caliper directly onto plaster models, which was 0.14—0.48 mm.

1.2.4 Laser Surface Scanning Accuracy

Kusnoto and Evans[29] measured the reliability and validity of laser surface scanning (using the Minolta Vivid700 3D surface laser scanner (Minolta USA, Ramsey, NJ)) with three different objects: a geometric calibrated cylinder, a dental study model (measuring intermolar width and palatal vault depth), and a plaster facial model. Tests were conducted with laser surface scanning at both 70 and 90 cm object-to-scanner lengths; however no difference in accuracy between these two distances was detected. These laser-scanned images were measured on a computer and then compared to direct manual measurements with a caliper accurate to 0.5 mm. The calibrated cylinder was 141 mm high and 46 mm wide with spatial distance measurement accurate to 0.5 mm (+/- 0.1 mm) in the vertical dimension and 0.3 mm (+/- 0.3 mm) in the horizontal dimension. The dental study cast was found to be accurate to 0.2 mm (+/- 0.1 mm, $P>0.05$) for intermolar width and to 0.7 m (+/- 0.2 mm, $P>0.05$) for palatal vault depth. The same dental cast was used for both the scanning as well as the direct measurements to reduce error of multiple casts. For the facial model, an accuracy of 1.9 mm (+/- 0.8 mm) was obtained. Kusnoto and Evans' findings led to the following conclusions about surface laser scanning:

- 3D data can be obtained accurately by using the surface laser scanner
- Laser scanning has very low distortion regardless of object-to-scanner distance
- The spread of the laser beam over the object actually makes the scanner work more accurately for smaller objects than for larger objects
- Studies involving dental casts can be performed with ease and wire-frame diagrams allow models to be cut, superimposed, and measured on the computer
- Measuring changes in area and length of curves allows the potential for more insight into data sets

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The author's critique about this article is that computer images were measured to the nearest 0.1 mm whereas the direct manual measurements with a caliper were measured to 0.5 mm increments. The article does not mention if they made any adjustment for this; however, such a discrepancy in measuring device accuracy when the results report differences within 0.5 mm is not ideal.

Sohmura et al[57] also measured the accuracy of the Minolta Vivid700 3D surface laser scanner (Minolta Inc, Osaka, Japan) at an object-to-scanner distance of 70 cm. Although a dental cast was scanned and pictured in the article, there were no measurements made on the dental cast. Instead, a "cast reconstruction" was made for measurements on three different objects of known inclines that represented the different types of surface measurements found on a dental study cast (see Figure 1.6). The intent of this article was to detect any digital image distortion in the laser scanning process. As noted earlier, laser scanning is done with either a stationary laser scanning an object on a rotating stand or a rotating laser around a stationary object. The subsequent multiple scanned images are then combined by an algorithm with computer software. Because any given point on a digitized dental cast will be the product of one or more scanned data sets, it seems logical that there could exist a potential for inconsistencies in the combining process. Keep in mind Emodels appear to be the product of 5 different scanned images (although the process is proprietary) combined to eliminate undercuts—or shadows—in the scanning process. Sohmura et al[57] used 4 different angles varying by 30 to 60 degrees (see Figure 1.7) to complete a scan. They found that the non-curved area of a model was "only" accurate to 0.015 mm in the z-axis at 0.070 m in the 75-degree inclined plane. However, the x- and y-axes' accuracy was about 0.4 mm and thus too large to reproduce complicated structures such as fissures in occlusal surfaces. They concluded "This data will be applicable in...orthodontics to replace stone casts by computerized 3-dimensional shape data information."

In 1996 Kuroda et al[28] used a slit-ray laser scanner (3D-VMS250R, UNISN Inc., Osaka, Japan) to measure the scanning accuracy. Although their method of measurement was not stated, they claim to have found a measurement error of 0.05 mm. One interesting thing about this article was their application of using the scanned information

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to produce a digital image of the oral cavity (see Figure 1.8). This type of information could be useful for observations in tongue thrusting or sleep apnea research that until the advent of scanning and digitization would not be possible.

In 1999 Motohashi and Kuroda[36] published a paper using the same laser scanner. They measured the digitized tooth crown dimensions 5 times (from second molar to second molar in both arches) in the x, y, and z coordinates on a computer and compared them to the 5 manual vernier caliper (measuring accuracy to 0.05 mm) measurements on the plaster model. They found no significant difference in each measurement at the 1 per cent level, and the maximum difference between the graphic and dental models was 0.2mm.

Hirogaki et al[22] used a non-contact 3D measuring apparatus with a line laser (Cubesper, Topcon Inc., Tokyo, Japan). This article is helpful in visualizing the process of piecing multiple laser-scanned images together to form a final product. In a previous article[23] by these authors they found laser scanning accuracy to be 250 microns in X and Y directions and 40 microns in the Z direction. This accuracy was measured prior to the multiple scanned images being combined to reconstruct the image in whole to avoid any decrease in accuracy due to the reconstruction of the image. Hirogaki et al[22] present article four distance measurements were made (intermolar, intercanine, and canine to molar) between the highest points of the canine cusp tips and distolingual cusp tips of the first molars. The software uniquely detected and measured the cusps' tip without requiring human input so multiple measurements were not necessary. However the manual measurements were made 10 times with a digital caliper and compared. Results showed differences within 0.3 mm. Hirogaki et al[22] stated that the accuracy required on orthodontic case models is thought to be about 0.3 mm but did not justify this number. They concluded that the surface laser scanner at this amount of error is considered to be satisfactory for the present purpose of orthodontic study model use in assessing dental arch shape, Spee's and Wilson's curvatures, crowding, inter-arch relations, etc. The author's opinion is this 0.3 mm value is well within a clinically acceptable range for study cast observation.

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1.2.5 Commercial Laser Surface Scanning

Since the commercialization of laser surface scanning orthodontic study models by OrthoCAD and Emodels, numerous articles have been published on this topic. Most of the articles focus on topics such as the basics of how to use them, how they are helpful in storage, informatics exchange, etc, however very few articles have been published on the accuracy of the commercialized scanning process and software. It is assumed by the author that these companies are using the same if not similar laser scanning processes as have been mentioned here that produce equal or better results in accuracy. However trade secrets prevent one from knowing what type of laser is being used and how they are using it. The use of digitized orthodontic study models is in its infancy of being measured against the gold standard of plaster. The following will summarize the articles that have been published in the major orthodontic journals pertaining to OrthoCAD. Again, all articles used the OrthoCAD software to date.

Tomassetti et al[59] compared Bolton tooth-size analyses (overall 12-tooth analysis and anterior-6 tooth analysis) of three methods to the gold standard of vernier caliper on plaster. The three methods tested were: QuickCeph, Hamilton Arch Tooth System (HATS), and OrthoCAD. The QuickCeph system uses a video captured image with a 1:1 scale and then has software to digitally measure the tooth widths and calculate the Bolton analysis. The HATS uses digital calipers wired to a computer to measure on a plaster model with instantaneous calculation of the Bolton analysis. And finally, the OrthoCAD system, which is the laser surface scan and is measured much like the QuickCeph software program. The measurements were made on 22 (11 pretreatment and 11 post treatment) sets of models with no more than 3 mm of crowding. The article did not specify but it is assumed that one examiner took the measurements as no interexaminer reliability was mentioned. An analysis using vernier calipers on plaster study models was completed three times and averaged to set a gold standard. Measurements were completed within a 1-month period with at least 2 weeks between measurements, and the order in which the casts were presented varied.

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All three digital methods were only measured once. The results of the study for the QuickCeph overall analysis showed a mean difference of 1.84 mm (range = 0.2 to 7.7 mm, with 52.4% within 1.4 mm and 81.0% within 2.5 mm). The anterior analysis mean difference was 1.07 mm (range = 0.0 to 3.2 mm, with 77.3% within 1.4 mm and 90.9% within 2.5 mm). The HATS system overall analysis showed a mean difference of 0.99 mm (range = 0.3 to 2.4 mm, with 86.4% within 1.5 mm and 90.9% within 1.8 mm). The anterior analysis mean difference was 0.55 mm (range = 0.1 to 1.5 mm, with 86.4% within 1.0 mm and 100% within 1.5 mm). OrthoCAD's overall analysis showed a mean difference of 1.20 mm (range = 0.0 to 5.6 mm, with 72.0% within 1.4 mm and 90.9% within 2.2 mm). The anterior analysis mean difference was 1.02 mm (range = 0.1 to 4.2 mm, with 81.8% within 1.5 mm and 90.9% within 1.9 mm). Pearson correlation coefficients for OrthoCAD vs. plaster were calculated to be 0.715 and 0.574 for the overall and anterior discrepancies respectively. When the three plaster measurements were compared amongst each other the overall average mean differences were 0.77, 0.95, and 0.86 mm (range = 0.0 to 2.8 mm). The anterior analysis mean differences were 0.58, 0.47, and 0.5 mm (range = 0.0 to 2.9 mm). Pearson coefficients between time trials were 0.805, 0.900, and 0.824. The time necessary for each of the three computer methods were: QuickCeph=1.85 minutes, HATS=3.40 minutes, OrthoCAD=5.37 minutes compared to vernier calipers on plaster being 8.06 minutes. Since vernier calipers are the only method that does not automatically calculate a Bolton analysis, it's the author's opinion that it would have been interesting to break down the vernier caliper time into measurements taken and calculation time.

The study by Tomassetti et al[59] had two deficiencies worth noting. For the OrthoCAD measurements two different models were used—one cast sent to OrthoCAD and one kept to measure. Alginate was most likely the impression material used in order to avoid breaking the teeth (although the article did not state what was used) while duplicating these models. Although the effect of using alginate is probably negligible, it would have been more accurate to use two polyvinyl impressions. The second critique would be that multiple measurements of the various methods would have added reliability.

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Santoro et al[49] performed a study with OrthoCAD comparing it to plaster study models on 76 randomly selected pretreatment patients for mesiodistal tooth size, overbite and overjet. Bolton analysis was not evaluated. No guidelines for crowding existed in subject selection. Two independent examiners measured both the plaster and digital model twice. Results showed a statistically significant difference between the two groups for tooth size and overbite, with the digital measurements smaller than the manual measurements. Digital models are measured by a point and click method allowing one to measure without the physical hindrance of a vernier caliper. This potentially allows one to measure a tooth width where one visualizes the greatest width of the tooth which may not be accessible with a vernier caliper due to physical constraints. The smaller digital size found in the Santoro article could be a result of the examiner clicking within the tooth dimension rather than on the border of it so care must be taken in this regard. Nevertheless, the magnitude of these differences ranged from 0.16 mm to 0.49 mm and was considered clinically insignificant. No statistically or clinically significant difference was found for overjet (mean difference 0.098 mm.) Interexaminer reliability was consistent for both the plaster and digital models.

Two major critiques of this article would first include the method of measuring overjet and overbite. On the plaster models a calibrated periodontal probe in 0.5 mm increments was used whereas the OrthoCAD software was measuring to the nearest 0.1 mm but then rounded to the nearest 0.5 mm. Although this would technically compare apples with apples, it would have been easy and more accurate to measure the plaster with a digital caliper to the nearest 0.1 mm like OrthoCAD. The other critique would be their use of consecutive alginate impressions instead of the more accurate polyvinyl siloxane elastomeric material.

Zilberman et al[61] compared both mesiodistal tooth size as well as arch width measurements (intercanine and intermolar at both the cusp tips and gingival margins) on OrthoCAD and plaster. They took a unique approach of comparing the gold standard of plaster with an even more gold standard of the actual tooth. Twenty setups using artificial teeth corresponding to various malocclusions (with a variety of spacing conditions and curve of Spee depths) were created. Impressions (alginate) were taken of

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the setups, providing 20 plaster and 20 virtual orthodontic models. Then polyvinyl siloxane impressions were taken of the plaster models and sent to OrthoCAD for destructive scanning. Measurements of mesiodistal tooth dimensions on plaster, OrthoCAD and the actual teeth (removed from the setup) with a vernier caliper (accurate to 0.1 mm) revealed a difference of 0.2 mm or less between plaster, OrthoCAD, and the actual tooth. Zilberman et al claimed that Pearson correlations between the three groups showed that tooth widths were all highly correlated—plaster and actual teeth measurements (R = 0.929—0.998) being the most correlated followed closely by digital to actual (R = 0.784—0.976) and then digital to plaster (R = 0.763—0.975). When the intercanine and intermolar widths were compared at both sites (cusps and gingival margins) high correlation values were found with all methods (R = 0.998—1). Zilberman et al concluded:

- Within a confidence interval of 95%, they could not prove that measurements carried out with the three methods differed from each other.
- Measurements with digital calipers on plaster models produced the most accurate and reproducible results.
- The OrthoCAD measurement tool showed high accuracy and reproducibility but was inferior to measurements done on plaster models with digital calipers.
- Digital calipers seem to be a more suitable instrument for scientific work. However, OrthoCAD's accuracy is clinically acceptable, and it is likely, taking into consideration its present advantages and future possibilities, that the examined or an equivalent 3D virtual model procedure would become the day-to-day standard for orthodontic use.

Garino and Garino[18] did a study comprising 40 patients ages 8-16 years (24 boys and 16 girls) in different stages of dentition. The patients had two silicon impressions taken by the same operator on the same day with one impression sent to OrthoCAD for digitization and the other poured in stone for direct measurement. For both digital and plaster casts, two examiners measured intermolar, intercanine, and mesiodistal tooth widths at two different times at least two weeks apart. This article was found to have several typographical errors pertaining to the data's results. They also used a digital caliper on the plaster models with an accuracy of 0.5 mm while comparing it to OrthoCAD's 0.1 mm accuracy measuring tool. The authors conclude that the digital

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casts (relative to the stone casts) presented a reduced difference from one time trial to the next amongst examiners as well as a variance of minor dispersion of the values.

There are several articles that are published in the major orthodontic journals that are not scientific but informative in nature. Most of the ideas are the author's opinion about the advantages and implications of digital model use in orthodontics as well as 'how to' articles on this new technology. Redmond[41-43] points out the shortcomings of plaster casts and other physical records pertaining to storage, transferability and diagnosis. In his opinion the advent of digital models was the final missing link to a completely digital office.

Marcel[32] touches on the same topics as well as explaining how a 650-MB compact disk costing less than $1 can hold over 200 OrthoCAD models (or over 800 Emodels per disk) vs. the cost of storage space for a lifetime of storing the models in plaster. For example, the cost of physical storage space for 20,000 plaster casts would be considerably higher *each month* than the total cost of storage for the same 20,000 casts in a digital format (100 disks for OrthoCAD and only 25 disks for Emodels.) Storage disks are already in the 1,000-MB or 1-GB range so in the future even more models could be stored per disk to the point where any given orthodontists entire life's work (digital radiographs, charting, study models, photographs) could be stored on one small disk. This is useful as it is unsure how long an orthodontist must preserve their records for legal reasons, with some suggesting an indefinite amount of time[51].

As with all technology, it does not come with a small price. Scholz[52] wrote an article where his focus was to remind people we need to ask ourselves some basic questions before accepting new technology and changing our current approach or method—Is it better? Faster? More efficient? Less expensive? He points out that as new technology presents itself to orthodontics, "our job in evaluating them will become increasingly difficult, not only in understanding new technologies, but in understanding their clinical applications. We will have to devote considerable time and energy to keep our practices on the cutting edge of technolocity." The key is to make sure technology works for us—not just make us work in a new, fancy, more expensive way.

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Mah and Sachdeva[31] describes the intra-oral scanners that are just now coming to market in the form of the SureSmile process (OraMetrix, Dallas, TX) which uses an intra-oral laser scanner (OraScanner by OraMetrix) passed over the teeth in a rocking motion to allow visualization of all tooth surfaces, including undercut areas. The process takes about a minute and a half per arch. Of course saliva isolation and patient cooperation can be a problem, however this technology or something like it in the future could completely eliminate the use of impressions for orthodontics and dentistry in general.

There are technologies that compete with surface laser surface scanning that could even supercede it in the future for orthodontic study cast 3D imaging. Harrell et al[20] point out radiographic methods of reproducing the dental arches by means of computed tomography (CT) scans, magnetic resonance imaging, ultrasound, and NewTom technology. The future undoubtedly will bring an accurate 3D virtual patient by any one or a combination of these and other techniques spoken of here. Ackerman and Proffit[1] speak of a day not far off when 3D images of teeth are seamlessly integrated with other 3D objects such as photographs and radiographs. This will create a virtual patient's face, teeth, and jaws rendering the articulator a historical curiosity. The virtual replication of a patient's face will, with the click of a button, be able to duplicate range of motion, show muscles, nerves, etc through this marriage of surface scans, photographs and radiographic images. Harrell et al[20] points out the benefits of digital virtual patients that apply to laser surface scanning as well:

- Improved clinical and research outcomes (due to computerized measurements and calculations reducing human error)
- Ability to share images and 3D models through the internet with other doctors and patients
- Treatment planning and 3D simulation on the basis of the patient's 3D morphologic anatomy (virtual tooth setups)
- Accurate 3D visualization with binocular vision for qualitative and quantitative analysis
- Virtual reality capabilities to enhance visual depth information (occlusiograms)
- The ability to interact with individual anatomic parts (i.e., facial soft tissue, muscles, bone, and teeth) and to analyze their 3D spatial relationships (which will be possible when Emodels are able to merge with photographs and radiographs for surgical treatment planning)

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1.2.6 PAR Index and Bolton Analysis

For this thesis, plaster and digital study models are compared using both the Bolton Analysis with its associated tooth-size measurements as well as the PAR index. The scope of this literature review is not to validate the Bolton analysis or the PAR index but rather to provide a basic explanation of what these measurements are and why they are used for orthodontic measurements—especially in research settings.

1.2.6.1 PAR Index

In order to quantify the traits of a malocclusion to assess treatment need or outcome in either a numerical or categorical form, an orthodontic index is necessary. Multiple orthodontic indices have been developed to accomplish this task[14 40]. Although Roberts and Richmond[46] go into great detail on the requirements of such an index, basic necessities are that it be reliable, valid, easy to use, and amenable to modification[54]. The strengths and limitations of the various indices are well documented[14 40 53 54] with one index—the peer assessment rating (PAR)—having achieved considerable acceptance[9 13 25 27].

In 1992, Richmond et al[44 45] developed the PAR index. The PAR index measures occlusal characteristics and is weighted with a combination of seven occlusal traits: maxillary and mandibular anterior alignment, right and left buccal occlusion, overjet, overbite and midlines. Weightings for the separate components are a derivation from validated studies in which panel assessments serve as the "gold standard". These weighted scores for each occlusal trait are then combined to formulate a single score—the PAR index.

Today there are two variations of the PAR index—the British UK[37 38 45] weighted PAR index and the American US[12 34] weighted PAR index. The US weighted PAR places more emphasis on overbite, the buccal segments, and the midline. Mandibular anterior segment alignment is excluded, as it is not thought to influence the perception of treatment outcome. The UK weighted PAR however includes the mandibular anterior

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segment alignment and places heavier emphasis on overjet.[35] Both UK and US weighted PAR indices have been accepted as valid orthodontic occlusal assessments[15].

1.2.6.2 Bolton Analysis

The Bolton tooth size analysis is frequently used as a research and clinical diagnostic tooth in orthodontics[59]. Achieving a proper occlusion with ideal overbite and overjet requires that the maxillary and mandibular teeth be proportional in size. If there is a discrepancy in tooth sizes between the two arches, an ideal occlusion may not be possible. In 1958, Bolton[6] studied tooth sizes in relation to malocclusion. His study of 55 patients with excellent occlusions produced ratios for the mesiodistal sizes of maxillary and mandibular teeth—both the anterior 6 teeth and the first molar to first molar overall 12 teeth. The formula in its basic form for the anterior 6 teeth is: (sum of the mandibular widths)/(sum of the maxillary widths) = 77.2%; and for the overall 12 teeth: (sum of the mandibular widths)/(sum of the maxillary widths) = 91.3%. The difference found from this calculation is now commonly referred to as the Bolton discrepancy and is expressed as either maxillary or mandibular excess indicating where the larger segment exists. In 1962, Bolton[7] revisited his original study and with several clinical cases determined that by using his analysis there would rarely be a need for diagnostic setups.[59] Since then numerous articles[2 16 21 24 55 56] have validated the Bolton analysis for incidence and reliability as well as how it relates to different racial groups resulting in a nearly unanimous conclusion that Bolton is valid for clinical and research settings.

1.3 Statement of Problem

The Emodel product was officially released at the 2000 AAO meeting in Toronto. Emodels is a virtual 3-D image of plaster orthodontic study models. Such technology allows for many clinical improvements. As Redmond[9 39 41-43] and Scholz[52] point out, it is a great advancement to go paperless in the orthodontic office for reasons such as: patient information availability, ability to consult with others in the profession instantly, and storage management. Previous to Emodels, a patient's health history, clinical exam, and

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radiographs could be put into a digital format. The one thing lacking was the 3-D orthodontic study model. Emodels and OrthoCAD have made this completely possible.

1.3.1 Digital Advantages

Ackerman and Proffit[1] point out other advantages to this era of 3-D virtual models in that they are easily used to rearrange teeth on the computer screen rather than having to cut the teeth off a plaster model and resetting them in wax. They also believe these virtual counterparts will eventually replace today's physical articulator.

Computers are changing our lives. Sometimes they make things easier (when they're working properly) as they have the capability of reducing human error and making our tasks more reliable, organized, and accurate. Aside from their convenience, using computers for measurement of orthodontic study models allows us to make precise measurements to the hundredth or thousandth of a millimeter[5 13 28 29 31 36 57]. From a clinical standpoint such precision is not currently necessary for model analysis. Nevertheless, this high degree of precision means that digital models should be unquestionably acceptable replacements of their plaster counterparts which themselves have inherent inaccuracies and shortcomings[26 26 39].

Some people may think that holding a traditional set of plaster models or looking at a traditional set of radiographs is the one and only Gold Standard of treatment diagnosis and treatment planning. Orthodontists who have become accustomed to the use of plaster study models for diagnosis and treatment planning might have a learning curve to go through to use a computer image in its place. However, with minimal effort they should be capable of learning the skills to use digital models as a substitute for plaster, however future studies are needed to assess this.

Radiographs are a prime example of an acquired learning curve. Many orthodontists still think that looking at and holding traditional radiograph paper up to a light board is better than a digital image on a screen. However, Chen et al[11], showed that cephalometrics on a computer is just as, if not more accurate than traditional radiograph paper due to the human error and bias being eliminated in computerized measurements of

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the angles. That's simply it. We're not talking about a new radiographic method but simply a means of viewing the information on a well-contrasted computer screen versus a sheet of black and white radiograph paper over the top of a light board to produce the same contrasts seen on a computer monitor.

No one would have been able to imagine the scope of computer *use* and *availability* in today's society as little as 20 years ago. In orthodontics, we are seeing computers used for customized orthodontic brackets for each patient[31], and Invisalign. It is likely that today's orthodontic residents will reminisce 20 years from now thinking about how their profession used to use non-prescription brackets, non-superelastic wires, and worst of all plaster models that they had to file and then store for decades in large storage areas instead of on little digital disks that fit in one's coat pocket.

In order to exemplify the ease in which plaster can be replaced by 3-D images, it is helpful to focus on three principles that must exist for any type of information (in this case a patient's dentition/malocclusion) to be beneficial:

- Information must be *accurate*
- Information must be *available*
- Information must be *decipherable*

Truth does not change—only its interpretation varies in *accuracy*. Christopher Columbus revealed the truth of the world being round rather than flat. This correction of information allowed the knowledge base of scientists to increase, which led to yet more discoveries and improvements.

Information must be *available*. What good is a library whose doors are shut to the public? Undeniably the internet's ability to share information has boosted the ability of science to help find "the truth".

Computers' use 0's and 1's in groups of eight known as binary code as a basis to record graphics. How useful would it be if all we saw were these codes of two numbers? No matter its truth and availability, we need software to make this information *decipherable*.

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The use of orthodontic study models is a means of transferring a particular patient's information to those that see them. Comparing Emodels to plaster we assume that:

- Emodels is just as accurate as its plaster counterpart in form[19 49 49 59 59 61 61]
- Emodels is superior in availability as it can be sent instantly in its digital format
- Emodels is identical or superior to plaster when deciphering the information a study model provides.

The purpose of this study is to test the measurable accuracy and validity of the Emodel versus plaster (the Gold Standard of today for orthodontic diagnosis and treatment planning.) This study compares the two mediums with Bolton[6 7 28] discrepancy measurements, PAR[15] indices[9 12 15 45], and the associated measurements necessary to derive them.

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1.4 Figures

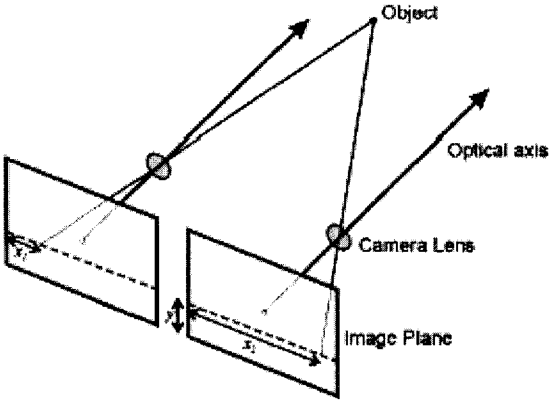

Figure 1.1 Stereo Analysis
Simple setup for stereo analysis. A point on the object produces 2 corresponding image points that lie on the same row of the image (y) but at different horizontal offsets (x_1, x_2). (Halazonetis DJ, AJODO 2001; 119(5):556-60)

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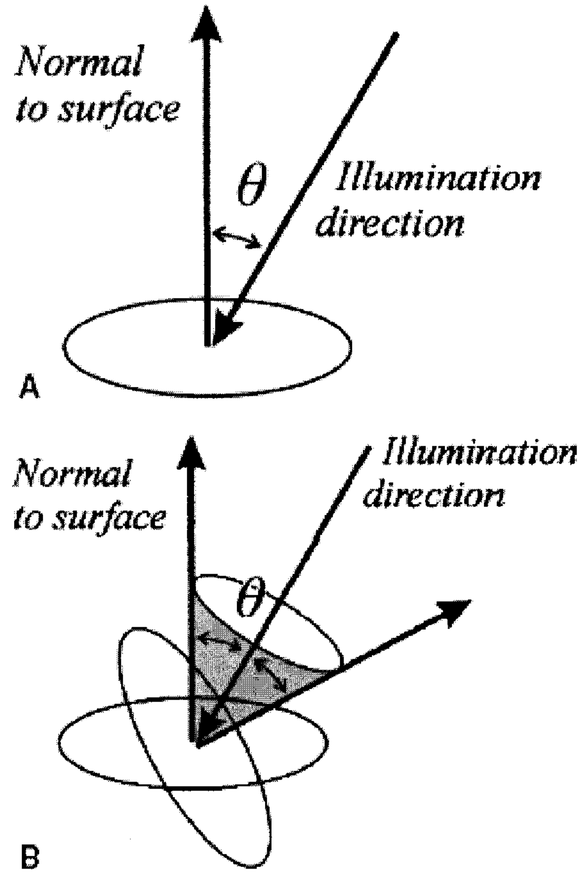

Figure 1.2 Shape From Shading (SFS)
A, Brightness of object is proportional to cosine of angle between illumination direction and surface normal. B, Same brightness can be produced by infinite surface orientations (only 2 shown here), all having same angle between their normal and direction of illumination. Normals of these surfaces sweep a cone around direction of illumination. (Halazonetis DJ, AJODO 2001; 119(5):556-60)

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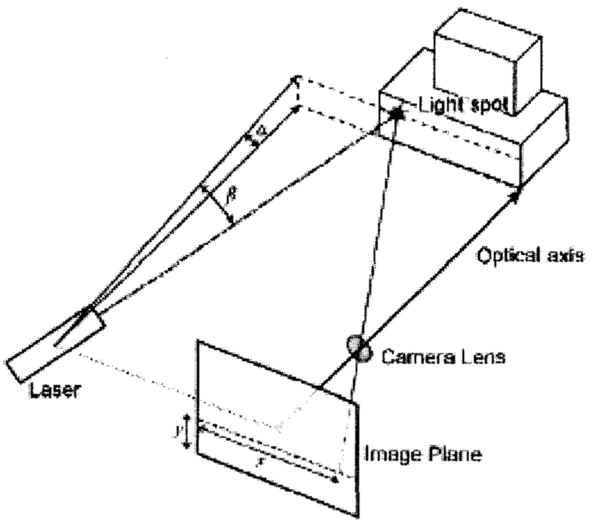

Figure 1.3 Structured Lighting—Light Point
Structured lighting with laser that projects light spot. Knowledge of geometry of system allows calculation of depth of object. (Halazonetis DJ, AJODO 2001; 119(5):556-60)

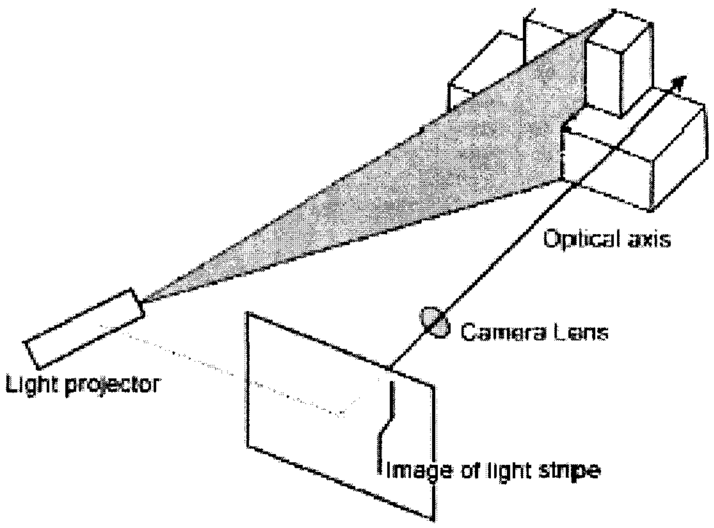

Figure 1.4 Structured Lighting—Light Stripe
Structured lighting with use of light stripe. (Halazonetis DJ, AJODO 2001; 119(5):556-60)

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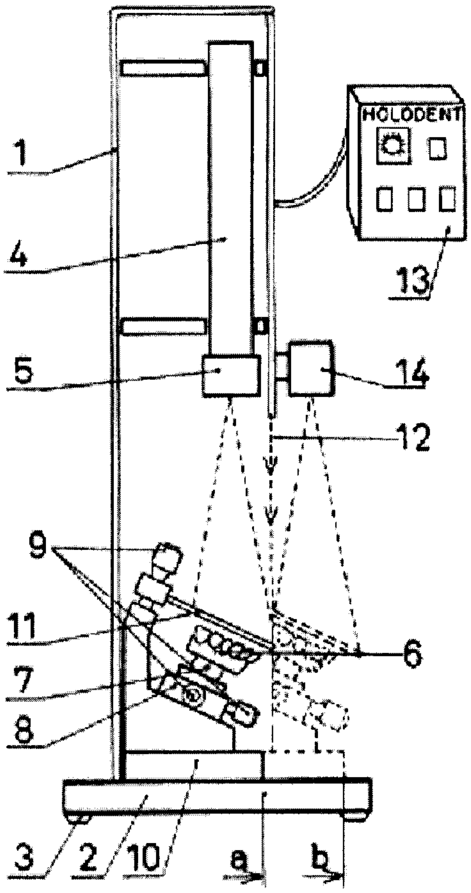

Figure 1.5 Holography
The object was fixed to the coordinate table. In dark room lighting an unexposed holographic plate (AGFA 8 E 75 HD NAH) was put into the holder (11) above the object. The coordinate table was set in position *a* and the shutter (12) was closed to minimize the risk for air turbulence affecting the laser light during exposure. The holographic glass plate was exposed to the laser beams with an exposure control (13). After exposure, the plate was transferred to a developing unit. This unit carried out developing, water-rinsing, bleaching, and wetting procedures. By using different bleaching agents, the holograms could be made green or red. The total time for producing a hologram was about 30 minutes. (Martensson B, Ryden H, AJODO 1992; 102(2):113-9)

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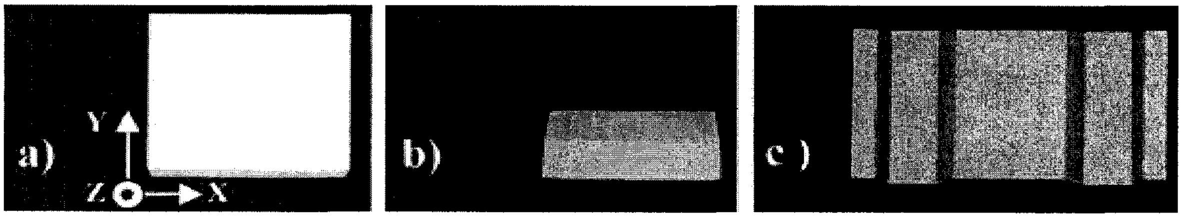

Figure 1.6 Digital Model Accuracy of X, Y, and Z planes
Stone model for calibration. (a) Model 1 flat plate; (b) model 2 with double trapezoid; and (c) model 3 with steep edge. (Sohmura T, et al., Journal of Prosthetic Dentistry 2000; 84(3):345-52.)

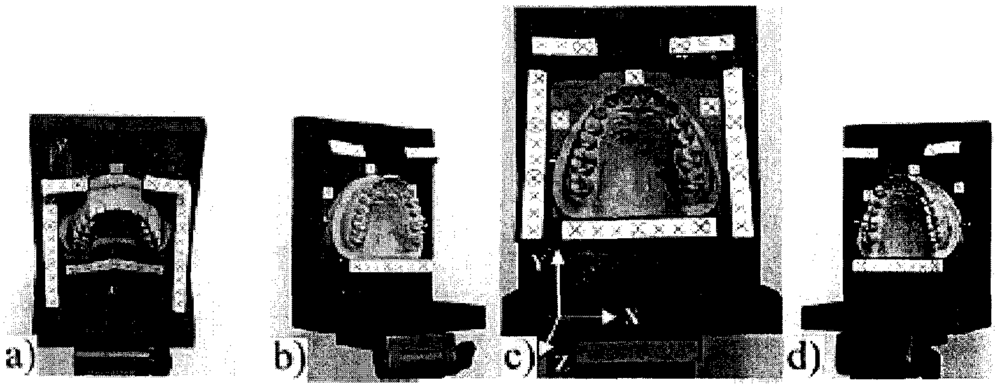

Figure 1.7 Eliminating Undercut Voids with 4 Different Varying Angles
Arrangement of goniometer for measurements from 4 directions. Tilted about 60 degrees to measure anterior teeth (a). (b) and (d) Rotated about +/-30 degrees to measure buccal and lingual surfaces in posterior teeth. (c) Occlusal direction to measure occlusal plane and palate. (Sohmura T, et al., Journal of Prosthetic Dentistry 2000; 84(3):345-52.)

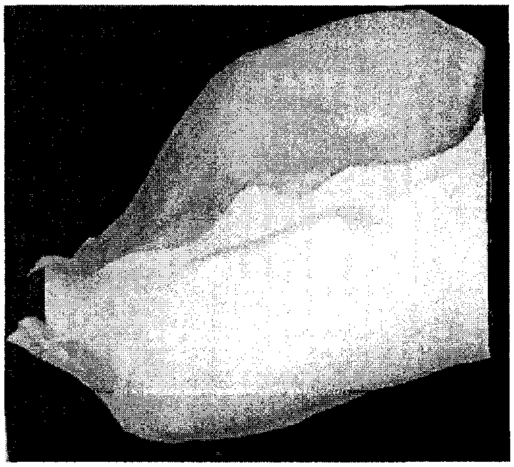

Figure 1.8
Digital Image of the Oral Cavity
Lateral view of oral cavity (61153.S mm3) (Kuroda T, et al., AJODO 1996; 110(4):365-9.)

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1.6 Research Questions

The objective of this study is to examine if orthodontists can quantify the same diagnostic information on a digital study model as they can on a plaster study model. The following research questions specifically address this objective:

1. Is there a difference in diagnostic measurements made by orthodontists between Emodels vs. plaster orthodontic study models?
2. Is there an *intra* examiner difference in reliability of repeated measures used to assess orthodontic study models between Emodels vs. plaster?
4. Is there an *inter* examiner difference in reliability of repeated measures used to assess orthodontic study models between Emodels vs. plaster?

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1.7 Null Hypotheses

1. There is no difference in diagnostic measurements made by orthodontists between Emodels vs. plaster orthodontic study models.
2. There is no *intra* examiner difference in reliability of repeated measures used to assess orthodontic study models between Emodels vs. plaster.
3. There is no *inter* examiner difference in reliability of repeated measures used to assess orthodontic study models between Emodels vs. plaster

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Chapter Two

Research Paper

Plaster Study Models versus Digital Study Models: Comparison of PAR, Bolton, and Their Constituent Measurements

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2.1 Introduction:

Like most areas of our lives, orthodontics is 'going digital'. Many orthodontists are joining other health professionals by utilizing a paperless patient information system including virtual chart notes, health histories, digital photographs and radiographs. However, one major obstacle for orthodontists going completely digital is the necessity of using a plaster study model of the patient's dentition when treatment planning and while performing a patient's orthodontic treatment.

In late 1999 OrthoCAD (Cadent, Carlstadt, NJ, www.orthocad.com) developed and released to market a *virtual* digital patient study model. Then, in early 2001, Emodels (Geodigm Corporation, Chanhassen, MN, www.geodigmcorp.com) came to market. The technology of digital patient study models allows orthodontists to send a patient's alginate impression or existing plaster study model to one of these companies for processing of a virtual 3-D computerized image. This image is then available to the orthodontist for download from the company's website within five days. Software provided by the imaging companies allows the orthodontist to then view the image.

Replacement of plaster orthodontic models with these new virtual counterparts could potentially benefit orthodontics in the following areas[1]:

- Efficiency of having patient records instantly accessible on the computer screen vs. retrieving plaster models from a storage area
- Saving money on the monthly cost of storage space needed for the thousands of traditional plaster models accumulated by each orthodontist over their career
- Accuracy, efficiency, and ease in measurement of tooth and arch sizes as well as dental crowding
- Accurate and simple diagnostic set-ups of various extraction patterns
- The ability to send the virtual image anywhere in the world for instant referral/consultation as needed or for internet study clubs
- Objective rather than subjective model grading analysis for ABO certification

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A review of published literature did not identify any studies that tested the clinical applicability of the use of Emodels vs. plaster; however previous studies have shown the dimensional accuracy of laser surface scanned digital models to be within roughly 0.05mm accuracy[2-5]. Several studies[6-9] have tested the accuracy of OrthoCAD vs. plaster but to date there have been no comparisons between Emodels and plaster.

Emodel and OrthoCAD guard their proprietary secret methods of model fabrication. Although their products appear similar on the computer screen, the two companies have fundamental differences in their laser surface scanning techniques. Emodel scans the surface of a complete plaster model whereas OrthoCAD uses a "destructive scanning" process that takes multiple scans of a model in thin slices. This is repeated until the entire model has been shaved and scanned. Thus the end result is a typical OrthoCAD file of 3000 KB (or 3 MB or megabytes) because the internal aspects of the model are scanned and recorded—even though the internal information is completely unusable. Compare this to an Emodel file of roughly 800 KB (kilobytes) due to surface scanning only. Emodel then uses software to "slice through" the image vs. OrthoCAD actually slicing through the model and imaging it. From a storage and data transfer standpoint it is clear that the smaller file size of the Emodel is more ideal.

To date, all research on the commercially available digital models has been performed with OrthoCAD.

The purpose of this study is to compare the current gold standard plaster model with the digital counterpart made by Emodel for the analysis of tooth sizes and occlusal relationships—specifically the Bolton analysis and the PAR index and their components.

Several terms in this paper are defined as the following and taken from Roberts and Richmond[10]:

- **Reliability**: the extent to which a measurement is repeatable under identical conditions. The term intra-examiner reliability referring to consistency of repeated observation by an observer with himself while inter-examiner reliability relates to observations being consistent amongst a group of observers. Athanasiou et al state reliability is a synonym for *reproducibility* or *precision.*[11]

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- **Validity**: the extent to which the new diagnostic test (Emodels) measures against the 'gold' standard (plaster).
- **Accuracy**: a synonym for *validity*. Assumes one knows the truth. The extent to which the diagnostic test identifies truth in the absence of measeurment error[11]. According to Colton[12] the term *accuracy* encompasses both *unbiasedness* (the tendency to arrive at the true or correct value) and *precision* (the degree of spread of a series of observations). Thus, medical data may be unbiased but imprecise, and vice versa.

2.2 Materials and Methods

Approval to conduct this study was obtained from the University of Alberta Health Research Ethics Board. The study sample consisted of pretreatment diagnostic study models of 24 randomly selected subjects, subdivided into 3 subjects in each of 8 malocclusion categories. Statistics from a pilot study estimated the sample size of the main project should be 10-13 subjects with alpha = 0.05 and power 95%. However, because of the interest in the subjects representing the broad spectrum of malocclusion categories, a sample size of 24 was chosen to allow adequate representation of each category.

The sample was selected from the initial patient records at the University of Alberta Orthodontic Clinic. 225 records were categorized into the 8 groups and then selected by a random number generator within each group. Each subject was in permanent dentition from first molar to first molar with no existing orthodontic appliances. The 8 categories were based on the following criterion, which closely resembles the various categories found in the Case Report Category Specifications of The American Board of Orthodontics Information for Candidates Phase III clinical examination publication 6th Edition[13]. The following selection criteria were used as an attempt to sufficiently represent the entire range of subjects treated by orthodontists:

1. **Class I Malocclusion** with <4mm crowding in both arches **(non-extraction)**
2. **Class I Malocclusion** with 4.1-8mm crowding in either or both arches **(borderline extraction)**
3. **Class I Malocclusion** with >8.1mm crowding in either or both arches **(extraction necessary)**

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4. **Class II* Division 1 Malocclusion (<4mm crowding):** FMA ≥30 degrees and/or an SNa G0-Gn angle ≥37 degrees
5. **Class II* Division 1 Malocclusion (>5mm crowding):** mandibular arch length discrepancy that requires extraction of permanent teeth *in at least the mandibular arch*
6. **Anteroposterior Skeletal Discrepancy:** Class II* malocclusion with (ANB≥6) or a Class III* malocclusion with an ANB angle not less than -2 degrees.
7. **Deep Overbite Malocclusion:** overbite ≥100%, retroclined maxillary central incisors, and an FMA ≤22 degrees and/or an SNa G0-Gn angle ≤29 degrees, no specifications for crowding
8. **Transverse Discrepancy:** posterior cross-bite malocclusion that requires complete appliance treatment. Prior to treatment, at least one (1) posterior quadrant must be in complete lingual or buccal cross-bite.

*** Definitions of Class II and III malocclusions found in Appendix 3.1 and 3.2 of Chapter 3**

The diagnostic study models from the subjects included in this study were duplicated by taking alginate impressions of the models and pouring the impressions in plaster. No positive or negative bubbles in the plaster or digital models were present. The bite was recorded using a wax wafer. Once the duplicate models were properly trimmed, they were sent to Emodel for scanning into digital models via overnight courier (it should be noted that although Emodel donated their services for this research there is no collaboration between the author or the Univeristy for this project.) The same plaster models were then returned from Emodels via overnight courier so they could be used for the direct measurement segment of the experiment. By using the same plaster cast for direct measurement and digital replication, any distortion or variation amongst multiple alginate impressions was avoided. Any variance in measurements between plaster and Emodels would then be attributable to operator variation or an inherent distortion that might exist in the Emodel image.

Three examiners working independently, consisting of a senior orthodontic resident as the primary examiner and two fully licensed orthodontists with a minimum 5 years of orthodontic experience as secondary examiners, recorded measurements on the plaster and digital models (each plaster and digital model was measured three times by the primary examiner and once by each secondary examiner.) Measurements included

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tooth size from first molar to first molar in both arches, which were used for a Bolton analysis, as well as all measurements necessary for the PAR index (see tables). Rather than solely using a traditional incremental approximation for PAR measurements (0-1mm, 1-2mm, 2-3mm, etc), actual millimeter measurements along with approximations were recorded for things such as contact displacements greater than 1mm, overjet (OJ), overbite (OB), millimeters from ideal posterior interdigitation, and millimeters of midline deviation on both casts. Maximum mesiodistal width was recorded for each tooth based on the anticipated contact point if the teeth were properly aligned. Overbite was measured in millimeters as the greatest amount of maximum vertical overlap found between a maxillary central and mandibular central incisor. Overjet was also measured in millimeters from the labial surface of the most anterior mandibular central incisor to the labial surface of the most anterior maxillary central incisor despite differences in labial inclinations of the maxillary incisors (see Appendix 3.3 for further measurement clarifications.)

All plaster measurements were made with an electronic digital Boley gauge (Sealey, Bury St Edmunds, UK) to the nearest 0.01mm.

Tooth size was measured on the digital models with the analysis tools provided by Emodels (software version 6.0), to the nearest 0.01mm. All teeth were measured from the direct occlusal view (using the Emodels 'Auto Center' feature) for consistency of object measurement between plaster and Emodels.

In the case of severely malpositioned anterior teeth, the images were rotated on-screen, and the measurements were made from the occlusal view to provide better visibility. For ease and accuracy of measurements, the images were enlarged on-screen as needed using the magnifying feature. Overjet and overbite were also measured using the analysis tools. Millimeters of displacement in the posterior as well as midlines were measured using the 'Grid: 1mm Crosshair' feature. Posterior displacement from ideal interdigitation was assessed with a view perpendicular to the posterior quadrant as slight rotation of the model quickly changed the operator's perception (see Figure 2.1)

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2.2.1 Statistics

All measurements were recorded in a Microsoft Excel 2000 spreadsheet (Microsoft Corporation, Redmond, Washington) and analyzed with SPSS version 11.5 (SPSS Inc., Chicago, Illinois). Individual variables were graphed and assessed for normal distribution.

Reproducibility of measurement for both *intra* an *inter*-examiner measurements were tested with a correlation coefficient (specifically the Concordance Correlation Coefficient (CCC)). Also, a Paired Samples T-Test was used to compare reliability between plaster and Emodels for both *intra* and *inter*-examiner measurements. The validity of Emodel measurements was assessed using a Paired Samples T-Test to compare the mean Emodel and plaster model measurements for all five trials for all 24 subjects. A non-parametric Kruskal-Wallis Test was used to detect differences amongst the 8 malocclusion groups.

2.3 Results

2.3.1 Reliability of Digital Models via Concordance Correlation Coefficient (CCC)

Intra and *inter* examiner reproducibility (Table 2.1) was generally high with the average *intra* examiner CCC being 0.923 (range 0.618—0.993) for plaster and 0.882 (range 0.591—0.990) for Emodels and the *inter* examiner CCC being 0.851 for plaster (range 0.427—0.975) and 0.835 (range 0.573—0.976) for Emodels.

46/50 and 47/50 CCC values exceeded 0.750 for *intra* examiner plaster and Emodels respectively. 43/50 and 41/50 CCC measurements exceeded 0.750 for *inter* examiner plaster and Emodels respectively. No CCC value was lower than 0.400.

The highest CCC values for *intra* examiner measurements were for maxillary 12 lengths and mandibular 6 & 12 lengths for plaster (CCC= 0.993) and overjet measurements on Emodels (CCC = 0.990). The lowest CCC values for *intra* examiner

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measurements were for the number of posterior contact displacements counted for plaster (CCC = 0.618) and quantitative centerline measurements on Emodels (CCC = 0.591).

The highest CCC values for *inter* examiner measurements were for posterior crossbite assessment for plaster (CCC = 0.975) as well as Emodels (CCC = 0.976). The lowest CCC values for *inter* examiner measurements were for the right quadrant millimeter measurement from "good interdigitation" for plaster (CCC = 0.427) and quantitative centerline measurements on Emodels (CCC = 0.573).

Thus the 5 sets of measurements made by the 3 independent examiners were found to be statistically correlated, both for the plaster and digital models, via the concordance correlation coefficient indicating good to mostly excellent *intra* and *inter* examiner reliability for both media.

2.3.2 Reliability of Digital Models via the Average Mean of Absolute Differences of Repeated Measurements

2.3.2.1 Tooth Size Measurements

Table 2.2 and Table 2.3 provide the average difference between measurement values and standard deviations for repeated *intra* and *inter* examinations. Most of the mean differences were not statistically significant ($P < 0.0021 = 0.05/24$. The individual mean tooth measurement differences are significant at significance level $\alpha = 0.05$. However, it was necessary to adjust the significance level to control overall probability since 24 teeth were compared simultaneously. Other *P*-values in this article are adjusted according to the group of measurements they are in.) The average *intra*-examiner difference of tooth width measurements was 0.10mm (range = 0.05 to 0.18mm) for plaster and 0.19mm (range = 0.14 to 0.24mm) for Emodels. The average *inter*-examiner difference of tooth width measurements was 0.17mm (range = 0.12 to 0.24mm) for plaster and 0.22mm (range = 0.17 to 0.33mm) for Emodels.

Differences in repeated tooth width measurements between plaster and Emodels for *intra*-examiner resulted in mostly statistically insignificant *P*-values ($P < 0.0021 =$

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0.05/24) except teeth #'s 1.4, 1.1, 2.2, 3.5, 4.5, 4.4, 4.2, and 4.1, all of which are premolars and incisors—no molars.

2.3.2.2 Bolton Analysis and Associated Measurements

Paired samples T-tests reveal *intra*-examiner Bolton 6 ratios between plaster and Emodels to differ by an average of -0.38mm (P<0.000) and Bolton 12 ratios to differ by – 0.50mm (P=0.001) showing the average difference being slightly larger in the digital format. The difference between repeated plaster and digital models' sums of lengths for the maxillary 6, mandibular 6, maxillary 12 and mandibular 12 dentition lengths were statistically significant (*P*-values ranging from <0.000 to 0.001). *Inter*-examiner Bolton 6 ratios differed by an average of –0.36mm (*P*=0.001) and Bolton 12 ratios differed by – 0.22mm (*P*=0.185).

2.3.2.3 PAR Index and Associated Measurements

A Paired Samples T-Test for *intra*-examiner results shows a statistically significant difference in reliability of overjet measurement between the plaster and digital models (0.24mm, $P < 0.000$). Overbite differences were also statistically significant with 20/24 digital overbite measurements smaller than plaster with the mean difference being 0.27mm ($P = 0.012$). As PAR index scores range from a mean difference of Raw PAR score= 0.50 (range= 0.00 - 4.67), US weighted PAR score= 0.89 (range= 0.00 - 7.33), and UK weighted PAR score= 1.86 (range= 0.00 - 12)—again, ranges are taken from the raw data set not included in with this article but included here for comparison capability. *Inter*-examiner results were similar (Table 2.3).

2.3.3 Validity of Digital Models

Table 2.4 provides a comparison of all five recordings for digital and plaster models.

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2.3.3.1 Tooth Size Measurements

Mean plaster and Emodels' tooth-size measurement differences for all five time trials combined (the difference between the measurements means for plaster and Emodels) was 0.01 to 0.21mm. The greatest mean difference was found for the maxillary left central incisor (0.21mm.) One half of the tooth-size measurements were statistically significant with almost equal representation of plaster measurement means being both larger and smaller than Emodel measurement means.

2.3.3.2 Bolton Analysis and Associated Measurements

Bolton 6 and Bolton 12 ratios between plaster and Emodels were not significantly different (P=0.790 and P=0.084 respectively). The difference between repeated plaster and digital models' sums of lengths for the maxillary and mandibular 6 teeth (0.59mm and 0.40mm) were statistically significant ($P < 0.0125$ (0.05/4)) with P-values of <0.000 and 0.004 respectively. Maxillary and mandibular 12 dentition length differences (both 0.20mm) were statistically insignificant ($P < 0.0125$ (0.05/4)) with P-values of 0.226 and 0.256 respectively.

2.3.3.3 PAR Index and Associated Measurements

A Paired Samples T-Test did not identify statistically significant differences ($P < 0.0167$ (0.04/3)) for PAR measurements. Overjet differences of mean measurements were not statistically significant; however overbite differences of mean measurements were statistically significant ($P < 0.025$ (0.05/2)) with a P-value of 0.001 and difference of 0.30mm, with plaster measurements being larger. Digital model measurements for anterior crowding (Total contact displacement in millimeters) were statistically significantly larger (-2.71 mm, P = 0.003).

2.3.4 Differences Amongst 8 Groups via Kruskal-Wallis Measurements

(Table 2.5) A non-parametric Kruskal-Wallis Test for all measurements reveals that there was no statistically significant difference amongst the 8 malocclusion groups for any measurement.

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2.4 Discussion

2.4.1 Reliability of Digital Model Measurements

The Concordance Correlation Coefficient (CCC)[14-16] showed that all 50 *intra*-examiner measurements were of excellent reliability for both plaster and Emodels except 7 measurements (4 plaster and 3 Emodels) which were good. The CCC was used because the intraclass correlation coefficient (ICC or also refered to as the reliability coefficient) measures reliability under the model of equal marginal distributions; however, when the marginal distributions are not equal (inaccuracy), the ICC captures the deviations and considers those as unreliable. Furthermore, the commonly used Pearson correlation coefficient only provides an expression of the linearity between values for repeated measures if the data is plotted while ignoring the inaccuracy component. In contrast, the CCC can segregate the inaccuracy from the unreliability[17].

To generalize an acceptable level of orthodontic reliability, Roberts[10] et al. suggests that ICC values for R below 0.4 constitutes poor reliability, between 0.4 and 0.75 fair to good, and above 0.75 is excellent. Lin[17] states that the CCC, ICC, and Pearson correlation coefficient depend largely on the analytical range and the intrasample variation and can be compared as long as they have similar clinical interpretations. Thus the ranges put forth in Roberts' paper are applied in this paper.

The present study did not detect any clinically significant difference in reliability between plaster and Emodel tooth-size or PAR index measurements. Amongst *intra*-examiner tooth-size measurement differences between plaster and Emodels, two thirds resulted in statistically insignificant *P*-values; however all measurement differences were clinically insignificant (range = 0.01 to 0.16mm). *Inter*-examiner results revealed that none of the tooth-size measurement differences were statistically or clinically significant (mean measurement differences ranging from 0.00 to 0.09mm).

Bolton 6 measurements fell within a clinically insignificant mean difference of *intra* = -0.38 and *inter* = -0.36 again showing that the digital measurement was less reliable, which is to be expected with the individual tooth widths being such. There were

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no other consistent correlations of this type amongst the other measurements in this study.

There appears to be no clinically relevant difference in reliability when switching between digital and plaster models. Although the range of the US and UK PAR weighted scores are higher, this is due to the multiplication factor placed on various aspects of each individual score. The important fact is that the raw PAR score only varies by 0.5 of a point (not clinically significant) on average with a range of less than 6 points for either plaster or Emodels. *Inter*-examiner results were similar.

Aside from tooth-size and related Bolton analysis results there were no correlations amongst the other measurements being consistently higher or lower for plaster and Emodels.

2.4.2 Validity of Digital Model Measurements

No difference of mean measurement was clinically significant for Bolton 6 and 12 (0.04mm and 0.38mm respectively), any arch length (range = 0.20 to 0.59mm), PAR (range = 0.04 to 0.83), overjet (0.01mm) or overbite (0.30mm). Emodels are clinically valid for study model measurement of Bolton, PAR and their constituents.

Santoro[8] et al reported findings that include OrthoCAD digital tooth-width measurements being smaller 100% of the time. The present study did not identify consistent tooth-width bias with digital models; however, the range of differences was similar to Santoro in that they were clinically insignificant.

Possible reasons for this study (using Emodels) and the Santoro (using OrthoCAD) study differing include:

- OrthoCAD and Emodels may have differing distortion in the fabrication process
- Minimum number of repeated time trials in their study (1 time trial by each of 2 examiners—negating the possibility of *intra*-examiner analysis)
- Potential operator difference when clicking the mouse pointer on tooth location for width

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- Differences in model detail between OrthoCAD and Emodel software around tooth borders or contact points to see an accurate point of measurement

A non-parametric Kruskal-Wallis Test for all measurements revealed that no statistically or clinically significant difference was detected amongst the 8 groups.

Any difference between plaster and digital models in this study cannot be attributed to alginate impression distortion as all digital models were made by the same plaster casts used in this study. If one assumes the digital model is accurate (a near-exact replica of a plaster model) in size, the most likely explanation for the difference is that digital models result in a more valid measurement than plaster due to the lack of physical barrier of the caliper dictating placement of measurement points; however this also allows one to click the mouse pointer either within or on the outside surface of the teeth. As long as a careful measuring point is selected on the computer screen, it would reasonable to believe that digital measurements are more valid than those made by calipers on plaster.

Another contributing factor to the difference between plaster and Emodel measurement might also be the learning curve of the operator precisely measuring with the computer mouse on the screen. Once this learning curve was achieved, it is easier to make the measurement on the computer screen.

Slight differences in measurement for overjet and overbite are most likely attributed to the intimate contact points achieved on the digital image compared to the bulky Boley gauge on a plaster cast—again, the differences were of no clinical significance (<0.30mm difference).

2.4.3 Limitations of Emodels

Digital models present several unique challenges compared to plaster models. Due to the 3D computer image being displayed on a two-dimensional screen, the biggest challenge was observing crossbites. Especially in the posterior, teeth can falsely appear in crossbite on the screen. Or inversely, they will look to have positive overjet in the posterior when the reality is they do not. This phenomenon seems to be dependent on the

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amount of zoom and rotation; however the author found that one of the 'Standard' preset views of the buccal or anterior segments proves to be correct after rotating the model in various positions for verification. However, if there is any question on crossbites, it can easily be cross-checked with the 'vertical' or 'horizontal' cross section function, but this is somewhat time consuming and frustrating.

Detail for midlines, occlusal anatomy, wear facets, etc is not as clear on the digital Emodel. However, in the case of deep overbite, it is easier and reliable to check the midline and measure overbite and overjet in most cases by using the software's cross-sectioning tool.

It is more difficult to quantify the precise interdigitation of a digital model than it is with plaster. Maybe this would improve with future software releases, but the picture on the screen seems to reveal more open bites than its plaster counterpart. This could be a function of zoom. More zoom exaggerates things that wouldn't normally be noticeable in plaster. This may be for good or bad—as long as this phenomena is recognized, one needs to calibrate themselves as to what is clinically significant when viewing the computer image as it may be magnifying an otherwise insignificant problem on the computer screen and make it appear like something that needs to be dealt with clinically when it clearly does not when viewed with plaster. It is possible that Emodels will allow clinicians to see imperfections and make other aspects of a patient's malocclusion better which in turn will raise the bar in clinical outcome of patient treatment.

The practitioner should be aware of the potential for distortion in the shipment of alginate impressions when using Emodels as they suggest. Obviously this would be translated into the digital image. Further studies are necessary to determine this important aspect of distortion with the shipment of alginate impressions, which could in turn negate some or all of the results found in this article.

The average age of the examiners used in this study was 33.3 (range = 31-38). The learning curve for the use of the product was steep and short-lived. As with most computer-related activities, those more familiar with computers in general will probably

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experience very little learning curve with Emodels and be able to achieve precise measurements without complication.

2.5 Conclusions

1. No measurement associated with a Bolton Analysis or PAR index made on plaster vs. digital models revealed any clinically significant differences.
2. Digital models are a clinically acceptable replacement of plaster casts for routine measurements made in most orthodontic practice.
3. Due to the PAR analysis and its constituent measurements not being significantly different clinically between plaster and Emodel media and preliminary results showing no indication that digital models would render an orthodontist to make a different diagnosis of malocclusion compared to plaster models, digital models are not a compromised choice for treatment planning or diagnosis.

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Figure 2.1

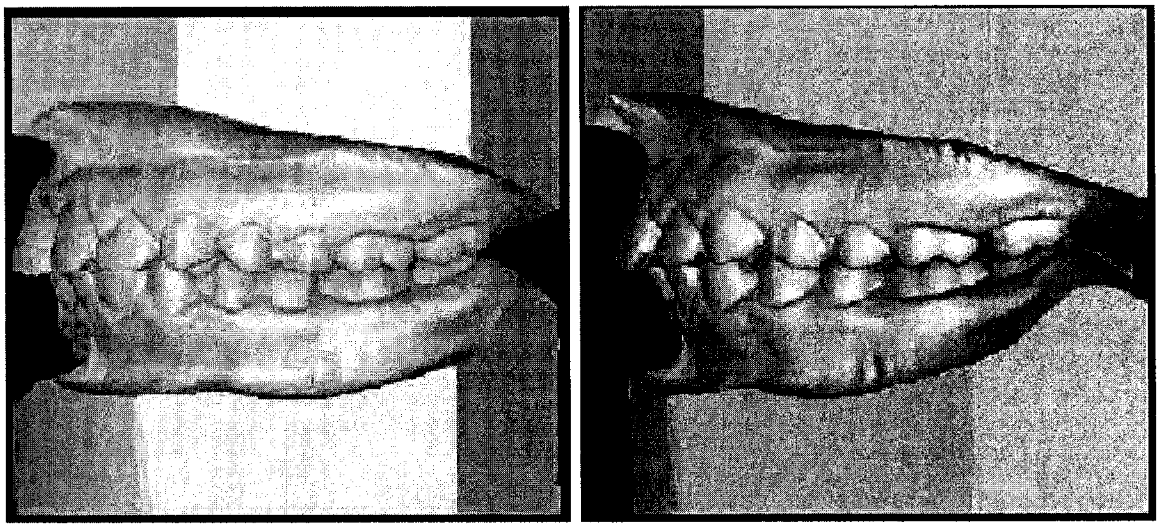

Figure 2.1 Emodel Molar Relationship Rotated on Z-axis
Model on left shows a patient with relatively solid Class I molar relationship when shown in Emodels' preset 'Left Buccal' view. Model on right shows the same model appearing to be in an end-to-end molar relationship. Special care must be taken when assessing a digital model for molar and canine relationship as slight rotation around the Z-axis of only a few degrees can quickly affect diagnosis of molar and canine relationships. This phenomenon requires one to rotate the model on screen as one would rotate a plaster model in hand to diagnose the proper molar relationship. (still images from Emodel software)

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Table 2.1

***Intra* & *Inter** Examiner Concordance Correlation Coefficient (CCC) to Evaluate Reproducibility of Measurement Between Plaster and Emodel**

	***Intra* Examiner**						***Inter* Examiner**					
	Plaster			**Emodel**			**Plaster**			**Emodel**		
		Confidence Interval			**Confidence Interval**			**Confidence Interval**			**Confidence Interval**	
Measurement	**CCC**	**Lower**	**Upper**	**CCC**	**Lower**	**Upper**	**CCC**	**Lower**	**Upper**	**CCC**	**Lower**	**Upper**
Bolton 6	0.976	0.940	0.991	0.916	0.814	0.963	0.918	0.822	0.963	0.874	0.752	0.938
Bolton 12	0.945	0.861	0.979	0.885	0.742	0.951	0.863	0.710	0.938	0.875	0.735	0.944
6 Max Length mm	0.992	0.989	0.995	0.972	0.939	0.987	0.965	0.926	0.983	0.963	0.909	0.985
6 Man Length mm	0.993	0.990	0.995	0.944	0.873	0.976	0.955	0.909	0.978	0.913	0.830	0.956
12 Max Length mm	0.993	0.981	0.997	0.963	0.929	0.980	0.948	0.912	0.969	0.949	0.912	0.971
12 Man Length mm	0.993	0.986	0.997	0.971	0.941	0.986	0.957	0.930	0.974	0.954	0.923	0.973
PAR (raw score)	0.943	0.881	0.973	0.916	0.827	0.960	0.920	0.817	0.966	0.897	0.778	0.954
PAR US	0.939	0.870	0.972	0.868	0.723	0.939	0.876	0.750	0.941	0.731	0.489	0.868
PAR UK	0.964	0.922	0.984	0.872	0.734	0.941	0.911	0.814	0.958	0.763	0.538	0.886
OJ mm	0.980	0.956	0.991	0.990	0.978	0.996	0.887	0.779	0.944	0.878	0.770	0.937
OB mm	0.891	0.774	0.950	0.984	0.963	0.993	0.797	0.604	0.902	0.957	0.895	0.983
OB quantitative	0.871	0.719	0.943	0.823	0.633	0.920	0.856	0.703	0.934	0.887	0.780	0.944
Total contact displacement mm	0.859	0.708	0.935	0.803	0.614	0.905	0.803	0.591	0.911	0.756	0.533	0.881
Post. contact displacement mm	0.798	0.595	0.905	0.808	0.619	0.909	0.740	0.510	0.871	0.776	0.572	0.889
Ant. contact displacement mm	0.902	0.795	0.954	0.853	0.701	0.931	0.807	0.604	0.912	0.761	0.520	0.890
Total contact displacement #	0.746	0.539	0.868	0.813	0.625	0.912	0.796	0.559	0.913	0.699	0.470	0.840
Post. contact displacement #	0.618	0.331	0.800	0.698	0.439	0.850	0.699	0.458	0.844	0.604	0.358	0.772
Ant. contact displacement #	0.873	0.747	0.939	0.903	0.783	0.958	0.822	0.606	0.925	0.816	0.603	0.921
Right interdig. quantitative	0.649	0.349	0.828	0.785	0.591	0.893	0.561	0.230	0.775	0.589	0.302	0.779
Left interdig. Quantitative	0.728	0.465	0.873	0.776	0.571	0.890	0.569	0.235	0.782	0.665	0.385	0.832
Right interdig. mm from “good”	0.826	0.639	0.921	0.830	0.687	0.912	0.427	0.144	0.646	0.739	0.490	0.876
Left interdig. mm from "good"	0.795	0.573	0.908	0.853	0.700	0.931	0.541	0.313	0.710	0.756	0.517	0.886
Centerline mm	0.822	0.647	0.915	0.971	0.929	0.988	0.671	0.430	0.822	0.728	0.466	0.872
Centerline quantitative	0.938	0.845	0.976	0.591	0.261	0.797	0.782	0.557	0.900	0.573	0.224	0.792
Posterior x-bite severity	0.991	0.982	0.996	0.988	0.973	0.994	0.975	0.946	0.988	0.976	0.948	0.989
Anterior x-bite severity	0.962	0.916	0.983	0.618	0.351	0.791	0.954	0.909	0.977	0.632	0.352	0.809
1.6 size mm	0.941	0.856	0.977	0.912	0.822	0.958	0.896	0.751	0.959	0.850	0.680	0.933
1.5 size mm	0.963	0.909	0.985	0.915	0.812	0.963	0.864	0.721	0.936	0.853	0.691	0.933
1.4 size mm	0.984	0.964	0.993	0.876	0.744	0.942	0.865	0.736	0.934	0.848	0.704	0.925
1.3 size mm	0.915	0.794	0.966	0.878	0.709	0.952	0.889	0.766	0.950	0.854	0.682	0.936
1.2 size mm	0.978	0.952	0.990	0.925	0.844	0.964	0.900	0.809	0.949	0.910	0.826	0.955
1.1 size mm	0.980	0.971	0.986	0.910	0.783	0.964	0.953	0.888	0.980	0.872	0.709	0.947
2.6 size mm	0.928	0.837	0.970	0.886	0.743	0.952	0.873	0.714	0.946	0.806	0.654	0.895
2.5 size mm	0.975	0.946	0.988	0.932	0.865	0.966	0.850	0.713	0.925	0.896	0.803	0.946
2.4 size mm	0.964	0.908	0.986	0.935	0.848	0.973	0.859	0.741	0.925	0.917	0.829	0.960
2.3 size mm	0.966	0.916	0.986	0.924	0.837	0.966	0.934	0.864	0.968	0.881	0.755	0.944

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2.2 size mm	0.984	0.962	0.993	0.891	0.780	0.948	0.927	0.850	0.965	0.887	0.770	0.947
2.1 size mm	0.980	0.971	0.987	0.940	0.887	0.969	0.970	0.954	0.981	0.923	0.811	0.970
3.6 size mm	0.959	0.914	0.980	0.952	0.899	0.977	0.963	0.909	0.985	0.923	0.820	0.968
3.5 size mm	0.972	0.959	0.981	0.911	0.796	0.963	0.860	0.687	0.941	0.858	0.688	0.939
3.4 size mm	0.956	0.899	0.981	0.896	0.768	0.955	0.926	0.831	0.969	0.870	0.715	0.944
3.3 size mm	0.955	0.898	0.980	0.915	0.811	0.963	0.897	0.776	0.955	0.906	0.800	0.957
3.2 size mm	0.980	0.948	0.992	0.866	0.727	0.937	0.886	0.783	0.942	0.797	0.633	0.892
3.1 size mm	0.928	0.842	0.968	0.921	0.816	0.968	0.918	0.825	0.962	0.895	0.784	0.950
4.6 size mm	0.961	0.913	0.983	0.964	0.913	0.986	0.940	0.863	0.974	0.945	0.884	0.975
4.5 size mm	0.976	0.936	0.991	0.930	0.833	0.971	0.903	0.798	0.955	0.919	0.823	0.964
4.4 size mm	0.984	0.964	0.993	0.930	0.850	0.968	0.907	0.825	0.952	0.902	0.805	0.952
4.3 size mm	0.956	0.904	0.980	0.878	0.767	0.938	0.889	0.787	0.943	0.894	0.785	0.949
4.2 size mm	0.971	0.931	0.988	0.797	0.610	0.900	0.811	0.645	0.904	0.803	0.603	0.908
4.1 size mm	0.991	0.987	0.994	0.834	0.633	0.930	0.876	0.729	0.946	0.822	0.656	0.912
Averages	**0.923**			**0.882**			**0.851**			**0.835**		
Tooth sizes: First number quadrant, second number tooth. Quad 1, UR; Quad 2, UL; Quad 3, LL; Quad 4, LR. Example: 4.1 is lower right central incisor.												
Values closest to 1.00 are the most reproducible. **Time trial #2 of Primary examiner randomly selected for comparison*												

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Table 2.2 (Comparing Reliability Between Plaster and Emodels)										
Intra Examiner: Average Mean of Absolute Difference of Repeated Measurements										
	Descriptives				**Descriptives**				**Paired Samples T-Test**	
Measurement	**Plaster** Ave [Diff]				**Emodel** Ave [Diff]				**Diff** (+/-) Plaster (-) Emodel	
	Mean	S.D.	Range (Min/Max)		Mean	S.D.	Range (Min/Max)		Diff (+ value = plaster is larger)	P value
Bolton 6	0.32	0.17	0.04	0.78	0.69	0.32	0.23	1.31	**-0.38**	0.000
Bolton 12	0.58	0.37	0.10	1.37	1.08	0.51	0.39	1.99	**-0.50**	0.001
6 Max Length mm	0.31	0.16	0.04	0.62	0.58	0.38	0.09	1.47	**-0.27**	0.001
6 Man Length mm	0.21	0.12	0.04	0.57	0.62	0.38	0.05	1.41	**-0.41**	0.000
12 Max Length mm	0.51	0.28	0.03	1.27	1.13	0.67	0.11	2.27	**-0.62**	0.000
12 Man Length mm	0.48	0.27	0.07	1.19	1.07	0.53	0.23	2.10	**-0.59**	0.000
PAR (raw score)	2.42	1.58	0.67	6.00	2.92	1.47	0.67	6.67	**-0.50**	0.307
PAR US	2.83	2.04	0.00	6.67	3.72	2.97	0.00	12.00	**-0.89**	0.201
PAR UK	2.69	2.03	0.67	6.67	4.56	4.00	0.67	14.67	**-1.86**	0.047
OJ mm	0.49	0.31	0.08	1.29	0.25	0.29	0.02	1.32	**0.24**	0.000
OB mm	0.47	0.57	0.06	2.85	0.20	0.21	0.03	0.98	**0.27**	0.012
OB quantitative	0.17	0.41	0.00	1.33	0.28	0.48	0.00	2.00	**-0.11**	0.444
Total contact displacement mm	3.07	1.95	0.95	8.61	3.42	3.14	0.49	12.89	**-0.35**	0.524
Post contact displacement mm	2.36	1.27	0.75	6.46	2.16	1.61	0.42	6.23	**0.20**	0.611
Ant. contact displacement mm	1.33	1.14	0.15	4.85	1.80	1.56	0.26	7.67	**-0.47**	0.046
Total contact displacement #	1.64	0.88	0.67	4.00	1.53	0.77	0.00	3.33	**0.11**	0.597
Post. contact displacement #	1.50	0.82	0.00	3.33	1.11	0.70	0.00	2.67	**0.39**	0.027
Ant. contact displacement #	0.61	0.59	0.00	2.00	0.69	0.42	0.00	1.33	**-0.08**	0.479
Right interdig. quantitative	0.33	0.39	0.00	1.33	0.22	0.32	0.00	0.67	**0.11**	0.162
Left interdig. quantitative	0.22	0.38	0.00	1.33	0.19	0.31	0.00	0.67	**0.03**	0.788
Right interdig mm from "good"	0.38	0.45	0.00	1.45	0.43	0.41	0.00	1.67	**-0.05**	0.608
Left interdig mm from "good"	0.37	0.50	0.00	2.19	0.40	0.43	0.00	1.33	**-0.04**	0.791
Centerline mm	0.33	0.57	0.00	2.89	0.14	0.17	0.00	0.33	**0.19**	0.090
Centerline quantitative	0.06	0.19	0.00	0.67	0.19	0.37	0.00	1.33	**-0.14**	0.057
Posterior x-bite severity	0.06	0.19	0.00	0.67	0.08	0.23	0.00	0.67	**-0.03**	0.575
Anterior x-bite severity	0.08	0.23	0.00	0.67	0.33	0.71	0.00	2.67	**-0.25**	0.083
1.6 size mm	0.16	0.09	0.05	0.37	0.23	0.09	0.02	0.42	**-0.07**	0.017
1.5 size mm	0.11	0.07	0.03	0.29	0.19	0.11	0.00	0.40	**-0.08**	0.026
1.4 size mm	0.07	0.04	0.01	0.15	0.18	0.12	0.03	0.52	**-0.11**	0.000
1.3 size mm	0.13	0.12	0.03	0.50	0.21	0.12	0.00	0.49	**-0.07**	0.044
1.2 size mm	0.10	0.06	0.01	0.23	0.19	0.12	0.04	0.46	**-0.09**	0.003
1.1 size mm	0.08	0.06	0.01	0.31	0.18	0.09	0.04	0.39	**-0.10**	0.000
2.6 size mm	0.18	0.09	0.03	0.33	0.22	0.13	0.03	0.46	**-0.04**	0.141
2.5 size mm	0.10	0.06	0.02	0.26	0.17	0.08	0.02	0.32	**-0.07**	0.004
2.4 size mm	0.08	0.07	0.01	0.32	0.14	0.08	0.02	0.33	**-0.06**	0.034
2.3 size mm	0.11	0.08	0.00	0.35	0.18	0.11	0.00	0.43	**-0.07**	0.008
2.2 size mm	0.09	0.04	0.01	0.15	0.24	0.12	0.07	0.55	**-0.15**	0.000
2.1 size mm	0.09	0.06	0.01	0.31	0.17	0.14	0.01	0.47	**-0.09**	0.008
3.6 size mm	0.16	0.11	0.02	0.41	0.17	0.10	0.03	0.46	**-0.01**	0.749
3.5 size mm	0.10	0.06	0.02	0.21	0.19	0.08	0.07	0.41	**-0.09**	0.000

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3.4 size mm	0.12	0.07	0.02	0.29	0.20	0.10	0.01	0.40	**-0.08**	0.004
3.3 size mm	0.10	0.07	0.01	0.25	0.18	0.13	0.05	0.51	**-0.08**	0.012
3.2 size mm	0.06	0.04	0.01	0.18	0.17	0.16	0.02	0.83	**-0.11**	0.003
3.1 size mm	0.08	0.12	0.01	0.61	0.14	0.07	0.04	0.29	**-0.06**	0.015
4.6 size mm	0.13	0.09	0.01	0.35	0.15	0.07	0.03	0.28	**-0.02**	0.343
4.5 size mm	0.10	0.07	0.01	0.32	0.18	0.12	0.03	0.49	**-0.09**	0.002
4.4 size mm	0.07	0.04	0.01	0.22	0.20	0.09	0.08	0.42	**-0.13**	0.000
4.3 size mm	0.10	0.06	0.03	0.25	0.18	0.12	0.01	0.62	**-0.09**	0.010
4.2 size mm	0.07	0.05	0.01	0.26	0.22	0.14	0.05	0.66	**-0.16**	0.000
4.1 size mm	0.05	0.03	0.01	0.10	0.16	0.10	0.00	0.41	**-0.11**	0.000
Average Tooth Difference	**0.10**				**0.19**				**-0.08**	
						# Negative ALL			42	
						# Positive ALL			8	
						# = 0 ALL			0	
						# Neg. tooth size			24	
						# Pos. tooth size			0	
						# = 0 tooth size			0	

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Table 2.3 (Comparing Reliability Between Plaster and Emodels)

Inter* **Examiner: Average Mean of Absolute Difference of Repeated Measurements**

	Descriptives				**Descriptives**				**Paired Samples T-Test**	
Measurement	**Plaster** Ave [Diff]				**Emodel** Ave [Diff]				**Diff** (+/-) Plaster (-) Emodel	
	Mean	S.D.	Range (Min/Max)		Mean	S.D.	Range (Min/Max)		Diff (+ value = plaster is larger)	P value
Bolton 6	0.49	0.27	0.14	1.21	0.86	0.42	0.29	1.67	**-0.36**	0.001
Bolton 12	0.85	0.48	0.15	1.95	1.06	0.59	0.30	2.49	**-0.22**	0.185
6 Max Length mm	0.64	0.33	0.09	1.41	0.68	0.40	0.12	1.67	**-0.04**	0.700
6 Man Length mm	0.60	0.21	0.23	1.13	0.80	0.39	0.13	1.60	**-0.21**	0.047
12 Max Length mm	1.38	0.63	0.53	3.08	1.41	0.64	0.33	2.79	**-0.03**	0.872
12 Man Length mm	1.25	0.61	0.35	3.57	1.37	0.56	0.25	2.31	**-0.12**	0.477
PAR (raw score)	2.92	1.80	0.67	7.33	2.97	2.05	0.00	8.00	**-0.06**	0.917
PAR US	4.14	2.17	0.67	8.00	5.64	4.51	0.67	14.67	**-1.50**	0.082
PAR UK	4.33	2.73	0.67	10.67	6.36	5.37	0.67	17.33	**-2.03**	0.045
OJ mm	0.85	0.82	0.15	3.13	0.93	0.98	0.03	4.01	**-0.08**	0.676
OB mm	0.78	0.71	0.03	3.35	0.38	0.27	0.05	1.12	**0.40**	0.014
OB quantitative	0.25	0.33	0.00	0.67	0.25	0.33	0.00	0.67	**0.00**	1.000
Total contact displacement mm	4.05	2.34	0.37	9.61	4.30	3.22	0.69	14.87	**-0.25**	0.764
Post. contact displacement mm	2.76	1.24	0.51	4.87	2.59	1.49	0.59	6.74	**0.17**	0.682
Ant. contact displacement mm	2.28	1.63	0.39	7.21	2.37	2.13	0.52	8.13	**-0.10**	0.865
Total contact displacement #	1.53	0.77	0.00	3.33	1.89	1.12	0.67	5.33	**-0.36**	0.158
Post. contact displacement #	1.33	0.59	0.67	2.67	1.36	0.77	0.00	2.67	**-0.03**	0.892
Ant. contact displacement #	0.78	0.70	0.00	2.67	0.81	0.81	0.00	3.33	**-0.03**	0.896
Right interdig. quantitative	0.39	0.44	0.00	1.33	0.31	0.34	0.00	0.67	**0.08**	0.450
Left interdig. quantitative	0.42	0.33	0.00	0.67	0.25	0.33	0.00	0.67	**0.17**	0.083
Right interdig mm from "good"	0.85	1.03	0.00	3.63	0.60	0.41	0.00	1.33	**0.26**	0.180
Left interdig mm from "good"	0.77	0.95	0.00	3.65	0.53	0.52	0.00	1.67	**0.25**	0.224
Centerline mm	0.51	0.71	0.00	3.23	0.44	0.55	0.00	2.67	**0.07**	0.645
Centerline quantitative	0.19	0.31	0.00	0.67	0.25	0.38	0.00	1.33	**-0.06**	0.539
Posterior x-bite severity	0.14	0.34	0.00	1.33	0.11	0.32	0.00	1.33	**0.03**	0.328
Anterior x-bite severity	0.11	0.25	0.00	0.67	0.44	0.73	0.00	2.67	**-0.33**	0.020
1.6 size mm	0.21	0.13	0.05	0.54	0.29	0.14	0.05	0.74	**-0.08**	0.061
1.5 size mm	0.19	0.16	0.03	0.74	0.24	0.15	0.01	0.66	**-0.05**	0.293
1.4 size mm	0.17	0.15	0.04	0.72	0.21	0.12	0.04	0.42	**-0.04**	0.189
1.3 size mm	0.19	0.08	0.06	0.37	0.22	0.13	0.03	0.64	**-0.03**	0.259
1.2 size mm	0.22	0.15	0.05	0.71	0.22	0.13	0.05	0.47	**-0.01**	0.883

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1.1 size mm	0.14	0.07	0.05	0.29	0.20	0.13	0.02	0.63	**-0.06**	0.066
2.6 size mm	0.24	0.14	0.03	0.61	0.33	0.14	0.05	0.61	**-0.09**	0.023
2.5 size mm	0.20	0.18	0.05	0.88	0.23	0.08	0.04	0.37	**-0.02**	0.552
2.4 size mm	0.17	0.14	0.03	0.62	0.17	0.09	0.02	0.41	**0.00**	0.905
2.3 size mm	0.16	0.09	0.00	0.34	0.21	0.15	0.00	0.51	**-0.05**	0.196
2.2 size mm	0.16	0.13	0.01	0.56	0.23	0.15	0.07	0.68	**-0.07**	0.071
2.1 size mm	0.12	0.06	0.04	0.25	0.21	0.13	0.05	0.53	**-0.08**	0.004
3.6 size mm	0.13	0.11	0.01	0.53	0.22	0.15	0.03	0.63	**-0.08**	0.040
3.5 size mm	0.19	0.17	0.03	0.90	0.24	0.14	0.05	0.69	**-0.05**	0.100
3.4 size mm	0.14	0.10	0.03	0.42	0.22	0.09	0.07	0.44	**-0.08**	0.013
3.3 size mm	0.15	0.11	0.02	0.57	0.20	0.12	0.02	0.57	**-0.05**	0.199
3.2 size mm	0.16	0.11	0.03	0.52	0.25	0.11	0.08	0.43	**-0.09**	0.008
3.1 size mm	0.14	0.07	0.03	0.29	0.18	0.08	0.06	0.33	**-0.04**	0.049
4.6 size mm	0.17	0.10	0.02	0.43	0.20	0.08	0.07	0.33	**-0.03**	0.344
4.5 size mm	0.18	0.14	0.09	0.75	0.19	0.12	0.03	0.47	**-0.01**	0.741
4.4 size mm	0.20	0.11	0.03	0.52	0.21	0.13	0.03	0.45	**-0.01**	0.679
4.3 size mm	0.17	0.09	0.03	0.37	0.18	0.09	0.05	0.45	**-0.02**	0.582
4.2 size mm	0.17	0.13	0.03	0.67	0.21	0.12	0.06	0.50	**-0.05**	0.232
4.1 size mm	0.16	0.11	0.01	0.53	0.19	0.09	0.04	0.38	**-0.03**	0.404
Average Tooth Differences	**0.17**				**0.22**				**-0.05**	
						# Negative ALL			41	
						# Positive ALL			8	
						# = 0 ALL			1	
						# Neg. tooth size			24	
						# Pos. tooth size			0	
						# = 0 tooth size			0	

**Time trial #2 of Primary examiner randomly selected for comparison*

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Table 2.4 (Validity of Plaster vs. Emodel Measurements)

Measurement Means for all 5 Time Trials Per Category

	Descriptives				**Descriptives**				**Paired Samples T-Test**			
Measurement	**Plaster** Mean Value of 5 Trials				**Emodel** Mean Value of 5 Trials				**Diff** (+/-) Plaster (-) Emodel		**Average of Absolute Differences (Pl-Em)**	
	Mean	S.D.	Range Min/Max		Mean	S.D.	Range Min/Max		Diff (+ value = plaster is larger)	P value	**Mean**	**S.D.**
Bolton 6	-0.51	1.80	-6.41	2.79	-0.55	2.00	-7.39	2.55	**0.04**	0.790	0.60	0.38
Bolton 12	-0.37	2.20	-6.22	2.92	-0.75	2.64	-7.99	3.34	**0.38**	0.084	0.92	0.58
6 Max Length mm	46.15	3.22	39.01	51.73	45.56	3.19	38.39	50.26	**0.59**	0.000	0.69	0.52
6 Man Length mm	36.23	2.32	27.96	39.28	35.84	2.34	28.16	38.77	**0.40**	0.004	0.61	0.40
12 Max Length mm	94.78	5.33	79.95	105.11	94.58	5.25	80.89	105.00	**0.20**	0.226	0.69	0.43
12 Man Length mm	86.96	5.17	70.80	94.24	87.16	5.44	70.92	95.34	**-0.20**	0.256	0.65	0.55
PAR (raw score)	25.08	9.30	10.80	52.20	25.91	8.79	10.20	48.00	**-0.83**	0.128	2.11	1.62
PAR US	27.03	10.39	12.00	56.20	26.98	9.77	10.40	54.20	**0.04**	0.941	2.14	1.66
PAR UK	30.84	13.52	13.60	70.80	30.77	12.60	14.20	69.20	**0.08**	0.906	2.43	1.82
OJ mm	4.90	2.97	1.82	13.33	4.91	2.98	2.06	13.70	**-0.01**	0.884	0.33	0.21
OB mm	3.96	1.75	0.40	6.54	3.67	1.82	0.13	6.68	**0.30**	0.001	0.38	0.27
OB quantitative	1.23	0.92	0.00	3.00	1.31	1.00	0.00	3.00	**-0.08**	0.144	0.18	0.21
Total contact displacement mm	20.99	7.47	6.20	34.97	23.70	7.81	5.89	40.28	**-2.71**	0.003	3.70	3.05
Post. contact displacement mm	10.21	4.21	3.33	19.14	11.10	4.59	2.84	21.17	**-0.89**	0.108	2.11	1.70
Ant. contact displacement mm	10.78	4.53	2.87	19.72	12.61	4.84	3.05	24.09	**-1.83**	0.000	1.98	1.85
Total contact displacement #	10.71	2.67	4.80	16.80	11.57	2.86	3.80	15.60	**-0.86**	0.006	1.31	0.95
Post. contact displacement #	5.29	1.78	2.00	9.20	5.61	1.70	1.60	8.80	**-0.32**	0.189	1.00	0.61
Ant. contact displacement #	5.42	1.84	2.40	9.80	5.96	2.02	2.20	9.80	**-0.54**	0.000	0.68	0.42
Right interdig. quantitative	0.98	0.59	0.00	2.00	1.01	0.58	0.00	2.00	**-0.03**	0.682	0.28	0.27
Left interdig. quantitative	0.78	0.58	0.00	1.80	0.84	0.57	0.00	2.00	**-0.06**	0.475	0.29	0.26
Right interdig mm from "good"	1.64	1.05	0.00	3.35	1.61	1.09	0.00	3.30	**0.03**	0.782	0.34	0.31
Left interdig mm from "good"	1.28	1.12	0.00	3.29	1.38	1.11	0.00	3.30	**-0.10**	0.411	0.45	0.38
Centerline mm	1.32	1.10	0.00	3.45	1.23	1.04	0.00	3.90	**0.10**	0.300	0.34	0.28
Centerline quantitative	0.61	0.63	0.00	2.00	0.45	0.46	0.00	1.40	**0.16**	0.007	0.21	0.22
Posterior x-bite severity	0.74	1.84	0.00	6.00	0.75	1.86	0.00	6.00	**-0.01**	0.747	0.04	0.12
Anterior x-bite severity	0.67	1.09	0.00	3.20	0.63	0.98	0.00	3.00	**0.03**	0.590	0.15	0.26

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1.6 size mm	10.36	0.59	8.72	11.35	10.50	0.62	9.00	11.59	**-0.14**	0.001	0.19	0.11
1.5 size mm	6.83	0.51	5.83	8.05	6.94	0.55	5.67	7.98	**-0.11**	0.005	0.16	0.12
1.4 size mm	7.12	0.46	5.99	7.86	7.12	0.46	6.29	8.00	**0.01**	0.872	0.16	0.13
1.3 size mm	7.69	0.46	6.46	8.53	7.55	0.50	6.32	8.46	**0.13**	0.005	0.19	0.16
1.2 size mm	6.97	0.64	5.67	8.34	6.96	0.65	5.58	8.08	**0.01**	0.822	0.21	0.12
1.1 size mm	8.63	0.56	7.22	9.56	8.47	0.50	7.22	9.21	**0.16**	0.009	0.25	0.18
2.6 size mm	10.37	0.57	8.74	11.36	10.52	0.58	8.94	11.72	**-0.15**	0.000	0.18	0.13
2.5 size mm	6.81	0.54	5.68	8.25	6.85	0.56	5.84	8.35	**-0.03**	0.406	0.16	0.11
2.4 size mm	7.13	0.44	5.98	7.81	7.09	0.51	5.94	8.22	**0.04**	0.244	0.13	0.09
2.3 size mm	7.24	1.64	5.88	8.24	7.21	1.64	5.27	8.27	**0.03**	0.478	0.16	0.14
2.2 size mm	6.95	0.61	5.64	8.24	6.91	0.62	5.53	8.14	**0.04**	0.459	0.19	0.15
2.1 size mm	8.67	0.62	7.39	9.79	8.46	0.68	7.19	9.75	**0.21**	0.001	0.28	0.22
3.6 size mm	11.00	0.72	9.26	12.01	11.08	0.72	9.25	12.14	**-0.08**	0.174	0.22	0.16
3.5 size mm	7.23	0.54	6.44	8.46	7.42	0.55	6.66	8.69	**-0.19**	0.000	0.20	0.14
3.4 size mm	7.20	0.49	5.89	7.85	7.31	0.50	5.93	8.16	**-0.11**	0.003	0.17	0.12
3.3 size mm	6.75	0.45	5.43	7.60	6.68	0.59	4.86	7.56	**0.07**	0.198	0.20	0.15
3.2 size mm	5.97	0.43	4.42	6.67	5.92	0.46	4.33	6.52	**0.05**	0.156	0.15	0.11
3.1 size mm	5.40	0.42	3.96	6.04	5.32	0.45	4.12	5.92	**0.08**	0.085	0.17	0.14
4.6 size mm	10.90	0.61	9.42	11.97	10.98	0.70	9.32	12.45	**-0.08**	0.108	0.22	0.12
4.5 size mm	7.24	0.57	6.13	8.43	7.34	0.61	6.00	8.69	**-0.10**	0.013	0.16	0.12
4.4 size mm	7.16	0.54	5.69	8.05	7.20	0.61	5.50	8.02	**-0.04**	0.385	0.18	0.12
4.3 size mm	6.71	0.43	5.64	7.57	6.69	0.48	5.67	7.53	**0.02**	0.718	0.20	0.17
4.2 size mm	6.00	0.37	4.70	6.55	5.93	0.42	4.69	6.46	**0.07**	0.112	0.16	0.13
4.1 size mm	5.40	0.44	3.81	6.04	5.29	0.36	4.49	5.82	**0.12**	0.053	0.22	0.21
					# Negative ALL				24.00			
					# Positive ALL				26.00			
					# = 0 ALL				0.00			
					# Neg. tooth size				10.00			
					# Pos. tooth size				14.00			
					# = 0 tooth size				0.00			

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Table 2.5

Non-Parametric Kruskal-Wallis Test *P*-values to Detect Differences Amongst 8 Groups (using Differences of Repeated Measurement Means for all 5 Time Trials Per Category)

Measurement	Mean	Range		*P* values
		Minimum	Maximum	
Bolton 6	0.04	-1.15	1.42	0.725
Bolton 12	0.38	-1.77	2.38	0.210
6 Max Length mm	0.59	-0.40	2.00	0.504
6 Man Length mm	0.40	-0.90	1.49	0.217
12 Max Length mm	0.20	-1.05	1.72	0.191
12 Man Length mm	-0.20	-2.11	1.47	0.049
PAR (raw score)	-0.83	-5.20	4.20	0.448
PAR US	0.04	-3.60	8.00	0.126
PAR UK	0.08	-5.60	6.00	0.275
OJ mm	-0.01	-0.84	0.53	0.521
OB mm	0.30	-0.44	1.02	0.797
OB quantitative	-0.08	-0.80	0.40	0.591
Total contact displacement mm	-2.71	-11.62	5.00	0.678
Post. contact displacement mm	-0.89	-5.89	5.17	0.755
Ant. contact displacement mm	-1.83	-5.72	1.04	0.517
Total contact displacement #	-0.86	-3.60	2.20	0.690
Post. contact displacement #	-0.32	-2.40	2.20	0.535
Ant. contact displacement #	-0.54	-1.40	0.80	0.694
Right interdig. quantitative	-0.03	-0.60	1.00	0.265
Left interdig. quantitative	-0.06	-1.00	0.60	0.142
Right interdig mm from "good"	0.03	-0.85	1.01	0.075
Left interdig mm from "good"	-0.10	-1.20	1.24	0.174
Centerline mm	0.10	-0.80	0.94	0.900
Centerline quantitative	0.16	-0.20	0.80	0.456
Posterior x-bite severity	-0.01	-0.40	0.40	0.386
Anterior x-bite severity	0.03	-0.80	0.80	0.066
1.6 size mm	-0.14	-0.50	0.17	0.377
1.5 size mm	-0.11	-0.41	0.17	0.056
1.4 size mm	0.01	-0.42	0.39	0.414
1.3 size mm	0.13	-0.16	0.53	0.232
1.2 size mm	0.01	-0.34	0.45	0.282
1.1 size mm	0.16	-0.74	0.59	0.658
2.6 size mm	-0.15	-0.53	0.12	0.517
2.5 size mm	-0.03	-0.34	0.36	0.875
2.4 size mm	0.04	-0.41	0.25	0.641
2.3 size mm	0.03	-0.47	0.42	0.609
2.2 size mm	0.04	-0.43	0.56	0.880
2.1 size mm	0.21	-0.23	0.80	0.295
3.6 size mm	-0.08	-0.67	0.37	0.089
3.5 size mm	-0.19	-0.47	0.08	0.883
3.4 size mm	-0.11	-0.37	0.32	0.792
3.3 size mm	0.07	-0.33	0.57	0.287
3.2 size mm	0.05	-0.36	0.39	0.092
3.1 size mm	0.08	-0.35	0.54	0.257
4.6 size mm	-0.08	-0.48	0.50	0.029
4.5 size mm	-0.10	-0.42	0.20	0.657
4.4 size mm	-0.04	-0.51	0.38	0.159
4.3 size mm	0.02	-0.49	0.51	0.273
4.2 size mm	0.07	-0.27	0.59	0.049
4.1 size mm	0.12	-0.68	0.70	0.944

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Chapter Three

General Discussion

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3.1 Discussion:

Orthodontics and the medical profession in general are increasingly utilizing computer technology with each passing day. This study focuses on the replication of a patient's dentition in digital format. The transformation from today's gold standard of plaster orthodontic study models to a digital counterpart will greatly affect the profession in many ways.

One of the most obvious benefits of digital study models is storage. Thousands of Emodels are compactly stored on a single DVD or other disk-like format. As time goes on and technologies improve, the storage method will undoubtedly change, but will most likely only decrease in physical size. In contrast, today's plaster study models require a significant amount of storage space for orthodontic practitioners that must be kept almost indefinitely for legal reasons[1]. As well, another benefit to digital storage is that the data can be backed up in different locations offsite to avoid loss of information—not to mention that it is impossible to chip or break the digital model as is a common problem with plaster[2].

Information exchange is crucial in today's society. Many patients want the best and most up-to-date treatment available. In orthodontics there are often multiple ways to treatment plan a patient's condition. Until now, if one wanted to share a patients study models they had to be physically transferred to another practitioner via mail or by self-transportation. This tedious and time consuming exercise usually encourages the orthodontist to seclude him or herself and make the decision with his/her own limited knowledge and background. However, with the ability to email a patient's digital study models along with their digital photographs and radiographs, virtual consultations amongst dental professionals are easier. This technology will allow for more information to be freely exchanged amongst professionals which will in turn increase knowledge of those involved and their profession as a whole should benefit[3].

In orthodontics, it is quite common for one practitioner to have multiple office locations. With digital models, one does not need to worry about physically transporting

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them back and forth between office locations. Also, occasionally a patient wants to take their plaster models home with them to show others. Until now this hassle requires a moderate duplication cost and valuable time. With digital models, if such a request is received, one simply asks for the patient's email address or burns a copy for them onto a disk[4-6].

Precision of certain measurement may improve with digital models. This is due to the lack of physical restraints when measuring on a computer. With plaster models one is limited visually when making certain measurements such as overbite. On a computer, one can effortlessly slice the model in any location on the screen and make an accurate recording of overbite, which is not a practical alternative for plaster.

Also, calipers on plaster models pose another physical barrier not present on computers. When measuring crowding or tooth sizes on plaster, often times even the most slender of calipers (which then flex and cause inaccuracies) is inhibited from reaching into the confined space necessary for an accurate measurement. Although plaster models are considered the gold standard, digital model measurements may in fact be more valid for specific items.

There is much debate on whether models need to be mounted on an articulator for the diagnosis and treatment planning of orthodontic problems[7-13]. One main problem with mounted models is the inherent inaccuracies introduced with a mounted model setup. No matter how painstakingly the operator tries to accurately transfer a patient's dentition orientation from the patient to the articulator, the transfer is flawed due to mobile soft tissue landmarks on or around the ear, nose, and face—not to mention the slight movements of the facebow itself.

With digital models, the technology exists (in relatively crude form) to superimpose the dentition directly on to a lateral ceph. This removes all inaccuracies of facebow transfers and articulators and will destine articulators a thing of the past[3]. No doubt this could improve our understanding of jaw movements relative to the cranial base and hopefully give us further knowledge into their relation to function as well as the pathology of the temporomandibular joint.

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Virtual diagnostic setups are also available with digital models. As with plaster models, this allows one to compare different treatment outcomes for various extraction patterns and/or surgical options. Plaster setups require a duplication process of the original model, a time-consuming, messy, and costly procedure to have the teeth separated, placed in wax, and moved into the newly desired position. This must be done for each separate outcome. With digital models, one simply moves the teeth with the computer mouse and saves each setup—no mess, no cost, and less time consuming. It also has the potential to be more esthetic on the computer and in the future will undoubtedly be linked to the patient's facial photograph so the soft tissue changes can be morphed on screen with each individual outcome.

There are several reasons as to why any given practitioner would not make the switch from plaster to digital study models. Both companies offering digital models (Emodels and OrthoCAD) have competitively priced their products. The cost of having a professional lab trim and finish an orthodontic study model is roughly equivalent to a digital model. Although the price of either type of service will fluctuate in the future, it may seem more likely that the digital model costs will rise in the future to pay for the technology. Some may not like the thought of being at another's mercy for the cost of their digital models. Also, many orthodontists do not currently pay the higher costs of a lab for model trimming and finishing and save a few dollars by doing it in office. This can keep their costs lower than a lab fee; however, the difficultly of tracking the exact savings of using plaster—if any—leaves the topic open for debate.

When chair side or in a conference with the patient, if the model needs to be seen a computer is necessary with Emodels. For an orthodontist who does not have a sufficient number of computers in his/her office, he/she would have to invest in the hardware for viewing availability. However, today's offices are starting to go more and more to a paperless environment and the computers are already in place making this a non-issue for those individuals. Furthermore, even though many orthodontists have computers, many have a phobia of them due to a lack of understanding them. This would obviously discourage a practitioner who is already familiar and comfortable with plaster models to learn the necessary technologic skills needed with Emodels.

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One common practice amongst orthodontists during treatment planning is to physically hold, caress, and hand 'wristulate' the model. It is similar to watching a small child with their favorite blanket, stuffed animal, or toy. The model becomes a diagnostic aid as well as a comfort object to allow the orthodontist to become acquainted with the patient's malocclusion. This inability to hold the digital model can be unsettling to those not comfortable with computerized images. That said, one of the biggest drawbacks to the digital model is indeed the inability to verify the interdigitation as with the plaster model.

What if these digital model companies go out of business? In today's dotcom society, software companies declare bankruptcy and disappear daily. However, it is the author's opinion that even though one or both of today's companies may indeed go bankrupt, the technology is here to stay and undoubtedly someone else would capitalize on the market and continue digital models in some fashion. As a precaution, one could keep a copy of the Emodel or OrthoCAD software stored with their digital models in the event the company went out of business. This would allow one to view their model even if the company had gone bankrupt.

Some practitioners do not trust that the alginate impression will produce an accurate study model due to the possible distortion that can occur in the shipping of the impression to the manufacturer. Not only is the impression subject to rough mail courier handling (delayed delivery, extreme temperatures, pressure distortion, etc), but typical alginate products suggest that the plaster pour up occur within 15 minutes for maximum accuracy. Although these digital model companies suggest "100 hour alginate" for maximum material stability during shipment, there is still cause for hesitation as to whether or not the digital model is routinely going to be of equal diagnostic quality as their plaster counterparts. Again, this study was not done with Emodels made from impressions, but rather from plaster models sent to Geodigm to decrease error. Also, aside from distortion, one might be concerned with temporary or permanent loss of the impression in the mailing process or at the manufacturer causing further delay in processing or the need for a new impression respectively.

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Finally, another reason one might not switch to digital models is the fear that the treatment planning process with digital models would be more difficult or of a lesser quality than the plaster method they are comfortable with. This is a study that must be done in the future to provide scientific evidence to the differences in treatment planning and/or outcome based on the format of the study model—digital vs. plaster. It is the author's opinion that a digital format will not lessen the quality of treatment planning skills, but may enhance it.

3.2 Conclusion

3.2.1 Main Conclusions

1. No measurement associated with a Bolton Analysis or PAR index made on plaster vs. digital models revealed any clinically significant differences.
2. Digital models are a clinically acceptable replacement of plaster casts for routine measurements made in orthodontic practice.
3. Preliminary results show no indication that digital models produce an altered visual appearance which would render an orthodontist to make a different diagnosis of malocclusion compared to plaster models.

3.2.2 Other General Conclusions

- Due to the PAR analysis and its constituent measurements being the same for both media, digital models are probably not a compromised choice for treatment planning or diagnosis
- Emodels provide a larger image on screen than plaster and thus accentuate model deficiencies
- Bolton analysis were found to be 26% faster with Emodels than plaster (2.3 vs. 3.1 minutes respectively) when measuring multiple casts in this study
- Emodels probably result in more accurate measuring of certain points due to the lack of physical hindrance of calipers
- PAR analysis is 46% slower with Emodels than plaster (6.5 vs. 3.5 minutes respectively) when measuring multiple casts in this study. This is most likely due to quicker initial judgment of 1mm increments with plaster resulting in more measurements made on Emodels that in reality were 1mm as well as time-consuming measurement of millimeter increments with the computer software. However, such PAR measurements are rarely if ever made by an orthodontist.

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3.2.3 Limitations of Emodels

Due to the 3D computer image being displayed on a one-dimensional screen, the biggest problem was observing crossbites. Especially in the posterior, teeth can falsely appear in crossbite on the screen. Or inversely, they will look to have positive overjet in the posterior when the reality is they do not. This phenomenon seems to be dependent on the amount of zoom and rotation; however the author found that it usually looks correct when in one of the 'Standard' preset views of the buccal or anterior segments. However, if there is any question on crossbites, it can easily be cross-checked with the 'vertical' or 'horizontal' cross section function (which can digitally slice a model from the buccal aspect of the occlusion in either a horizontal or vertical plane), but this is somewhat time consuming and a hassle.

Molar relationships are also more difficult to assess on the digital model because of this same 3D on a 2D screen situation. To avoid this phenomenon, one must take extreme care not to simply diagnose by the preset right and left buccal occlusion orientations of the digital model, but rather to rotate and view the casts perpendicular to the posterior quadrant as slight rotation of the model quickly changes the operator's perception. Also, detail for midlines, occlusal anatomy, wear facets, etc is not as clear on the digital Emodel due to the software and/or scanning process. However in the case of deep overbite, it is easier to check the midline and measure the overbite in most cases by using the software's cross-sectioning tool. This allows more accurate and easier overjet and overbite measurements in deep bite cases.

Finally, it is more difficult to quantify the precise interdigitation of a digital model than it is with plaster. Maybe this would improve with future software releases, but the picture on the screen seems to reveal more open bites than its plaster counterpart. This could be a function of zoom. More zoom exaggerates things that wouldn't normally be noticeable in plaster. This may be for good or bad—as long as this phenomena is recognized, one needs to calibrate themselves as to what is clinically significant when viewing the computer image as it may be magnifying an otherwise insignificant problem on the computer screen and make it appear like something that needs to be dealt with

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clinically when it clearly does not when viewed with plaster. It is quite possible that Emodels will allow clinicians to see imperfections better which in turn will raise the bar in clinical outcome of patient treatment.

The practitioner should be aware of the potential for image distortion in the shipment of alginate impressions. Further studies are necessary to determine this important factor. The average age of the examiners used in this study was 33.3 (range = 31-38). The learning curve for the use of the product was steep and short-lived. As with most computer-related activities, those more familiar with computers in general will probably experience very little learning curve with Emodels and be able to achieve accurate measurements without complication.

3.3 Limitations

One of the limitations of this study was the relatively low number of cases (24) per category used. At roughly $50.00US per case, higher numbers of subjects quickly becomes cost prohibitive. However, because a wide range of malocclusions was used without clinically or statistically significant differences, there would be no reason to believe that more cases would produce a different result.

Another limitation of this study is the use of only one of the two digital companies (Emodels by Geodigm). Although the only difference in result that is foreseeable lies in the accuracy of the digital model scanning process, this research can only state that the company studied (Emodels by Geodigm) is indeed a viable replacement for plaster study models. Future studies will need to be done for other companies to prove model accuracy.

Another limitation to the study is the amount of time it requires to make the measurements. The use of more orthodontists in this study would have been ideal, but for this study, one set of measurements of digital and plaster for 24 cases took roughly 12 hours.

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Emodel measurements for PAR index scoring took almost twice as long as plaster. The average time associated with assessing PAR measurements was 6.5 minutes on Emodels and 3.5 minutes on plaster. However, the digital tooth width measurements took on average 29% less time than on plaster at 2.5 vs. 3.5 minutes respectively. However most of this extra time is attributed to displaced contacts appearing more severe on the larger image on the computer screen compared to a plaster model in hand. This is a time disadvantage until one becomes familiar with the computer image. However this does not equate to a lesser diagnostic quality of the digital model, but rather shows that one is more likely to see the severity of a malocclusion on the larger computer screen image.

Limitations of measurement methods also existed. Digital measurements for overbite and tooth widths appear to be more precise due to the lack of physical hindrance of the caliper. Although a tapered finishing bur was attached to each caliper prong for a fine and sturdy measuring point, there were still many times that it was physically impossible to obtain a measurement at the ideal location due to hindrance of the caliper's ability to fit into the tight space.

Due to the 3D computer image being displayed on a 2D screen, the biggest problem was observing crossbites. Especially in the posterior, teeth can falsely appear in crossbite on the screen. Or inversely, they will look to have positive overjet in the posterior when the reality is they do not. This phenomenon seems to be dependent on the amount of zoom and rotation; however the author found that it usually looks correct when in one of the 'Standard' preset views of the buccal or anterior segments. However, if there is any question on crossbites, it can easily be cross-checked with the 'vertical' or 'horizontal' cross-section function, but this is somewhat time consuming and a hassle. (which can digitally slice a model from the buccal aspect of the occlusion in either a horizontal or vertical plane). However in the case of deep overbite, it is easier to check the midline and measure the overbite in most cases by using the software's cross-sectioning tool. This allows more accurate and easier overjet and overbite measurements in deep bite cases.

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Molar relationships are also more difficult to assess on the digital model because of this same 3D on a 2D screen situation. To avoid this phenomenon, one must take extreme care not to simply diagnose by the preset right and left buccal occlusion orientations of the digital model, but rather to rotate and view the casts perpendicular to the posterior quadrant as slight rotation of the model quickly changes the operator's perception. Also, detail for midlines, occlusal anatomy, wear facets, etc is not as clear on the digital Emodel due to the software and/or scanning process.

Finally, it is more difficult to quantify the precise interdigitation of a digital model than it is with plaster. Maybe this would improve with future software releases, but the picture on the screen seems to reveal more open bites than its plaster counterpart. This could be a function of zoom. More zoom exaggerates things that wouldn't normally be noticeable in plaster. This may be for good or bad—as long as this phenomena is recognized, one needs to calibrate themselves as to what is clinically significant when viewing the computer image as it may be magnifying an otherwise insignificant problem on the computer screen and make it appear like something that needs to be dealt with clinically when it clearly does not when viewed with plaster. It is quite possible that Emodels will allow clinicians to see imperfections better which in turn will raise the bar in clinical outcome of patient treatment.

3.4 Future Studies (Recommendations)

The orthodontic study models used for this research are traditional bench top articulated models. This means they are trimmed using a wax wafer bite recorded from the patient's occlusion so that when the models are placed on a flat surface, the model's occlusion replicates the patient's biting into a wax wafer bite. As some orthodontists' personal preferences do not find this adequate for diagnosis of some or all malocclusions, a future study might include replication of the PAR index portion of the present research. However, because the measurements taken in this study did not involve any articulation of the models, arguably a mounted model would make no difference except possibly the orientation of the occlusal plane.

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Although this study would not necessarily change with the use of mounted models, the aim of this study was to establish a foundation for a future study involving treatment planning with digital vs. plaster models. This would allow us to see if the same treatment plan and diagnosis results in either media. Because some orthodontists do not use mounted study models at all while others use them exclusively, the use of both mounted and non-mounted study models amongst a wide range of orthodontists with varying preferences to using mounted models would be valued research. The average age of the examiners used in this study was 33.3 (range 31-38) years of age. The learning curve for the use of the product was steep and short lived. As with most computer-related activities, those more familiar with computers in general will probably experience very little learning curve with Emodels and be able to achieve accurate measurements without complications.

The practitioner should be aware of the potential for image distortion in the shipment of alginate impressions. Further studies are necessary to determine this important factor. The measurements in the current study show no clinically significant difference for accuracy between digital and plaster study models. However, it would be helpful for a future study to use 3D imaging to compare distortion of both plaster and digital models. Through the use of a type of intraoral measuring device or, less desirably, a polyvinyl siloxane (PVS) impression (one of the most accurate impression mediums)[14,15] as the gold standard, one could compare distortion of plaster study models with digital study models. Digital models should be compared to those made from separate impressions (of both alginate and PVS) as well as those made directly from the plaster model used for comparison. This would reveal the distortion index of models shipped and poured up several days later vs. digital models scanned from plaster casts.

There is no question that storing a thousand digital study models on one disk requires less storage space and requires less effort to retrieve a given model amongst thousands put in storage over the lifetime of a practice. One study could critically evaluate the actual cost savings of digital models. This study would look at such costs as materials used, fabrication of the model, staff time for model fabrication and routine retrieval, storage costs, etc.

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As a clinical follow up study to this one, it would be interesting to evaluate the actual vs. predicted Bolton discrepancies found on a patient's digital and plaster model. Although a Bolton discrepancy is dependant on many variables such as tooth angulations[16 17], it might be worth seeing if plaster or digital Bolton scores were closer to the final outcome. Also, this study could include virtual setups vs. plaster setups to compare if either one was more beneficial to evaluate the actual final outcome.

Due to the increasing percentage of North American orthodontists becoming ABO (Amercian Board of Orthodontics) certified, it would also behoove us to compare ABO scoring methods on both digital and plaster study models. If digital models are soon widely accepted by practicing orthodontist, this would force the ABO to use either plaster or digital study models and keep up with the latter as the future gold standard.

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Appendices

3.1 For the malocclusion to satisfy the Class II category requirement, the mesiobuccal cusp of the maxillary permanent first molar must occlude, at least on one side, in the embrasure between the mandibular second premolar and the mandibular permanent molar, or farther to the mesial. If the maxillary or mandibular permanent first molar is missing, the buccal cusp of the maxillary second premolar must occlude in the embrasure between the mandibular first and second premolars, or farther to the mesial.

3.2 For the malocclusion to satisfy the Class III category requirement, the mesiobuccal cusp of the maxillary permanent first molar must occlude, at least on one side, in the distobuccal groove of the mandibular permanent first molar, or farther to the distal. If the maxillary permanent first molar is missing, the buccal cusp of the maxillary second premolar must occlude in the mesiobuccal groove of the mandibular permanent first molar, or farther to the distal. (Appendix 3.1, 3.2, and the following figure taken from the Case Report Category Specifications of The American Board of Orthodontics Information for Candidates Phase III clinical examination publication 6th Edition)

ILLUSTRATION OF CLASS II MALOCCLUSION

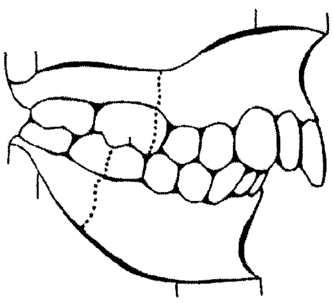


ILLUSTRATION OF CLASS III MALOCCLUSION

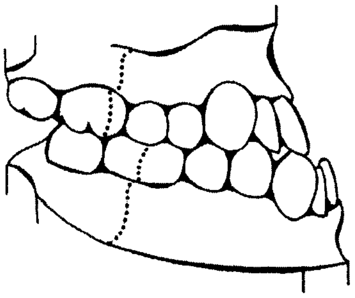
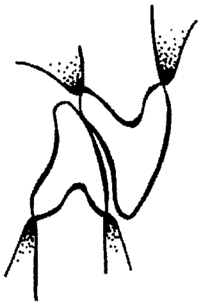


ILLUSTRATION OF 100% OVERBITE



3.3 As the PAR scoring technique can be somewhat unclear for specific situations, the following self-imposed regulations were applied:

- Buccal occlusion A-P relationship is based on the canine to molar region with heavier emphasis on the molar
- Vertical open bite >2mm only applies to non-erupting teeth
- Open bite taken at closest tooth-tooth vertical measurement

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- If a posterior tooth is blocked out due to inadequate space but is erupted, then both contact points are measured and scored
- Canines are considered impacted if <4mm space exists from tooth 4 to tooth 2. Only canines are assessed for 'impacted' status due to the fact that most mandibular incisors are around 5mm and a 0.5mm contact slip on both sides would qualify a mandibular incisor as impacted.
- All teeth were scored without a prosthetic replacement option

Bolton measurement guidelines were as follows:

- Widest measurement of each tooth is from mesial to distal parallel to the central groove or incisal edge where the clinician foresees future tooth contact in ideal alignment
- All measurements taken from occlusal view pressing "Upper" or "Lower" regardless of tooth orientation unless tooth is severely malpositioned
- Measurements taken from molar to central in quadrants 1, 2, 3, 4 in that order
- Before each quadrant is measured, "Upper" or "Lower" is pressed on the Emodel software to reset the model in a standard and reproducible view
- After each measurement, the tooth to be measured is automatically centered using the Emodel 'Auto Center' feature, thus allowing almost exact reproducibility of subsequent measurements taken of each tooth
- If a tooth border is not clear due to the angulation of a model, then rotation of the model is allowed; however, the model must then be rotated back to the originating position in order to make the measurement.
- If a definite border to a tooth is not obvious due to alignment, impression quality, or Emodel software, then the clinician's best guess was made
- If a tooth is partially erupted, the interface of the erupting tooth and gingiva is measured

Plaster specific Bolton measurement self-imposed rules:

- Try and keep calipers parallel to occlusal plane in order to simulate Emodel measurement which will allow apples to apples comparison
- Zero out Boley gauge after each subject's set of measurements
- View each tooth perpendicular to model base

3.4 Raw Data Set: Please refer to Microsoft Excel 2000 spreadsheet CD enclosed in the back cover of this book or kept with the Graduate Orthodontic Department Research Coordinator.

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