ACCURACY OF ORTHODONTIC DIGITAL STUDY MODELS

BY

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DECLARATION

I, **Earl Ari MacKriel** declare that "**Accuracy of Orthodontic Digital study models**" is my own work and that all the sources I have quoted have been indicated and acknowledged by means of references.

SIGNED: ....

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DEDICATION

I would like to dedicate this research project to my wife (Chrislynn), my daughter (Charissa) and son (Eoin). You make life worthwhile and without your constant encouragement and smiles I could not have done it. Thank you for your sacrifices so I could study further. I love you.

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Keywords

Orthodontics

Study models

Digital technology

ABSTRACT

Background :

Plaster study models are routinely used in an Orthodontic practice. With the recent introduction of digital models, an alternative is now available, whereby three dimensional images of models can be analyzed on a computer.

Aims and objectives:

The aim of this study was to compare the measurements taken on digital models created from scanning the impression, digital models created from scanning the plaster model, and measurements done on the plaster models.

The objectives were:

> Measurement differences between those taken directly on plaster models compared with measurements on digital models created from scanned impressions and digital models created from scanned plaster models.

Methods:

The study sample was selected from the patient records of one Orthodontist. They consisted of 26 pre-treatment records of patients that were coming for orthodontic treatment.

Alginate impressions were taken of the maxillary and the mandibular arches. Each impression was scanned using a 3Shape R700™ scanner. Ortho Analyzer software from 3Shape was used to take the measurements on the digital study models.

Within 24 hours plaster study models were cast from the impressions, and were scanned using a 3Shape R700™ scanner.

On the plaster models the measurements were done with a MAX-CAL electronic digital calliper. The mesiodistal width as well as intermolar and intercanine width for both the maxillary and mandibular models were recorded.

Results and discussion:

Box plots used to compare the variability in each of the three measurement methods, suggest that measurements are less variable for Plaster.

Plaster measurements for tooth widths were significantly higher (mean 7.79) compared to a mean of 7.74 for Digital Plaster and 7.69 for Digital impression.

A mixed model analysis showed no significant difference among methods for arch width.

Conclusions:

Digital models offer a highly accurate alternative to the plaster models with a high degree of accuracy. The differences between the measurements recorded from the plaster and digital models are likely to be clinically acceptable.

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1. Introduction

Diagnosis and treatment planning are essential components in everyday orthodontic practice. Different diagnostic records are taken which orthodontists analyse and use to determine a treatment plan. Usually comprising of photographs, panoramic and lateral cephalometric radiographs, study models, and a clinical examination, these records can also be used in the discussion of different treatment options with colleagues, without the need for the patient to be present.

When taking orthodontic records, plaster study models are a standard component. These study models are essential when doing the diagnosis and formulating a treatment plan. They are also used when treatment progress and results are evaluated, in case presentations, and for record keeping.

The orthodontist uses the study models to gather information. This includes identifying aberrations, classifying the malocclusions, and to formulate treatment objectives for a specific patient. The models are used to look at the morphology of individual teeth and also to visualize the position of the teeth in their individual dental arches. From the models the amount to which the certain teeth are malpositioned can be assessed. When a diagnostic set-up is done to evaluate treatment options, the plaster models are sectioned. Study models therefore appear to be one of the most important records for the planning of treatment (Peluso *et al*, 2004).

Crowding or spacing, overjet, overbite, tooth size, static occlusion, dental classification and Bolton analysis are usually calculated by hand on plaster study models. Model analysis plays a very important role in the diagnosis and consequent planning of treatment. A space analysis or an evaluation of crowding is an important factor to be considered for orthodontic diagnosis and treatment planning e.g., an evaluation of crowding is necessary when considering extraction therapy.

Sequential orthodontic study models document the progress of treatment from the initial status, through treatment progress, and to the final treatment result. When presenting their treatment results to patients and colleagues, orthodontists use these models as a presentation tool for the purposes of education, evaluation, and research (Peluso *et al*, 2004).

Peluso *et al*, (2004) states that a demanding orthodontic practice may commence upward of 300 new cases in one year, thus it may require an complete room for storing study models. The minimum amount of time that files should be kept is based on the appropriate statute of limitations period during which a malpractice suit may be filed. In the United States of America this period of time ranges from 5 to 15 years, varying from state to state. This statute may begin at the last day of treatment or might be delayed until the patient reaches the age of maturity. Whichever way this is looked at, there is a need for long-term storage. Over a period of ten years, if 300 new cases are started every year, this will amount to 6000 sets of models, pretreatment and posttreatment. Additional storage space might be necessary, possibly at a different site, with cost implications (Peluso *et al*, 2004).

With computer technology growing to incorporate more areas in a variety of scientific fields, we see it is also applicable in orthodontics. Orthodontists use computers for education of patients, keeping records of patients, managing their practices, to communicate with colleagues and a range of other tasks.

Digital technology has made significant changes in the way orthodontic records are taken and stored. Digital radiographs and photography are fast replacing traditional methods. With what is referred to as the progression to the “paperless office” there has been an increase in the use of digital records, consents, models and financial agreements.

With digital study models being introduced recently, the orthodontist now has an alternative to the traditional plaster study models. Digital technology enables computer analysis with software which can rotate the digital images of model to be rotated, examined from different views, and measured (Mullen *et al*. 2007).

2. Aims and Objectives

The aim of this study was to compare the measurements taken on digital models that were created from scanning the impression, digital models that were created from scanning the plaster model, and measurements done directlyon the plaster models.

The objectives were the following:

Measurement differences between plaster models compared to measurements on digital model created from scanned impressions and digital models created from scanned plaster models.

To assess whether measurements recorded from images of digital models were statistically significantly different from those taken directly on plaster study models.

3. Literature review

Different methods tested for storage other than conventional study casts

The performance of the "travelling microscope," was studied by Bhatia and Harrison (1987). This was a device which was customized to execute measurements on dental casts, and their study came to the conclusion that the method was more precise than some alternatives.

Champagne (1992) undertook a comparison between measurements made by hand on plaster models with those made on digitized models obtained from a photocopier. Their conclusion was that, manual measurements with a calibrated gauge produced the most "accurate, reliable and reproducible" data. They state that although photocopies are easy to handle, this method still requires a customary plaster model, and only provides a 2-dimensional picture of a 3-dimensional entity.

A holographic system for measurement on plaster models was studied by Martensson and Rydena (1992). The system was shown to be more accurate than earlier methods, and the authors believed it would alleviate storage problems.

The disadvantages of hologram use are that it can be difficult and expensive to create. The image captured by holography is three-dimensional; it is stored as a single image and cannot be manipulated as can a set of study models (Bell *et al*, 2003). The major problem that was discovered using this system is the poor quality of the details when the study models are evaluated. The incisor area was found to be of particularly reduced quality.

Malik *et al*. (2009) proposed an alternative method for study model storage. They evaluated whether the same orthodontic information can be obtained from study models and photographs of study models for the purpose of medico-legal reporting. They came to the conclusion that similar information can be obtained from plaster models and photographs of plaster models, for medico–legal purposes.

These methods never became popular, the major drawbacks being the practicality and the clinical implementation. With computer programs becoming available to do cephalometric analysis, incorporation of digital photos and radiographs into a patient's electronic file and the capability of producing digital models, towards 1999, the idea of a "paper-less" orthodontic practice also became popular.

Advantages and Disadvantages of Plaster and Digital models

With plaster models there are several advantages and disadvantages. The advantages include the possibility that direct and accurate measurements can be made on the models. Space problems, storing cost, reproduction, communication, risk of breakage and retrieval are potential disadvantages of plaster models compared with other methods of representing the dental arcades and their occlusion (Leifert 2009, Joffe 2004).

There are several advantages of digital images of dental casts over the plaster models themselves. These include the elimination of storage problems and of model breakage (Torassian *et al*. 2010). Digital models can be used with ease in communication with patients and colleagues and can be retrieved instantly. It is therefore a convenient presentation tool which also allows the orthodontist to electronically post images, to colleagues, third party funders or to journals (Santoro, 2003).

Disadvantages of digital images include the time required to study how to utilize the system and, notably, that there is a no tactile participation for the orthodontist. Other disadvantages are associated with the technology itself. There is a scarcity of companies that specialize in the technique, and there are also some questions surrounding the accuracy of the digital process (Alcan *et al*, 2009). This may be related to the additional time required when shipping impressions or models to the company. There is also the possibility of their being lost in the post.

If the Orthodontist decides to invest in a 3D model scanner, the capital outlay could be considerable and thus the choice of using digital technology for study models should be carefully weighed.

Table 1 Advantages and Disadvantages of Plaster models

Plaster models

Advantages	Disadvantages
direct and accurate measurements	model breakage
a routine dental technique	storage problems
ease of production	transferability
inexpensive	cost of storage
ease in measurement	retrieval
being able to be mounted on an articulator for study in three-dimensions	reproduction
	Communication beyond “face to face”

Table 2 Advantages and Disadvantages of Digital images

Digital images

Advantages	Disadvantages
eliminate breakage of models	lack of tactile input
elimination of storage problems	time required to learn how to utilize the system
models can be retrieved instantly	scarcity of digital model supplier companies
ease in communication with patients and colleagues	questions surrounding the accuracy of digital models
images can be e-mailed	Additional costs
handy presentation instrument	
possibly equal or better diagnostic capabilities	

History of Digital Models

Digital models were introduced in 1999 by OrthoCad™, followed by E-models in 2001. Several methods can be used to produce Digital models. The most direct system is an intra-oral laser scanner (Orametrix Inc., Richardson, TX, USA). Digital virtual models can also be created by a negative surface model technique generated by laser scanning the inner surface of an impression. The most commonly used system seems to be to pour a plaster model, which is then either non-destructively digitized using stereophotogrammetry, a surface laser scanner or industrial computer tomography or destructively, using the sequential slicing technique (Dalstra and Melsen 2009).

For commercial purposes, there are at present five companies globally which produce digital models. In the United States are three of these companies, there is one in Poland and another is in The Netherlands. These companies accept the use of disposable impression trays, and stipulate high-quality alginate impression material with a dimensional stability proven for a period over 100 hours (Alcan *et al*, 2009).

For most recent brands of digital virtual models, the expertise to produce the models is outsourced from the orthodontic practice by sending alginate impressions or plaster models to a company specializing in creating digital models (OrthoCad™, Cadent, Carlstadt, NJ, USA; E-models™, Geodigm Corp., Chanhassen, MN, USA; Digimodel™, Orthoprof, Nieuwegein, The Netherlands; O3DM™, Ortholab, Czestochowa, Poland). After a few of days the digital models can be retrieved from the website of the specific company. Individual practices do not then have to invest capital in the equipment and know-how of how to create virtual models (Dalstra and Melsen 2009). What has to be kept in mind is that there is a possibility that an error might be introduced because of the fact that the alginate impressions are mailed with attendant delays and handling problems (Dalstra and Melsen 2009). Figures 1-4 shows the digital models that different companies produce.

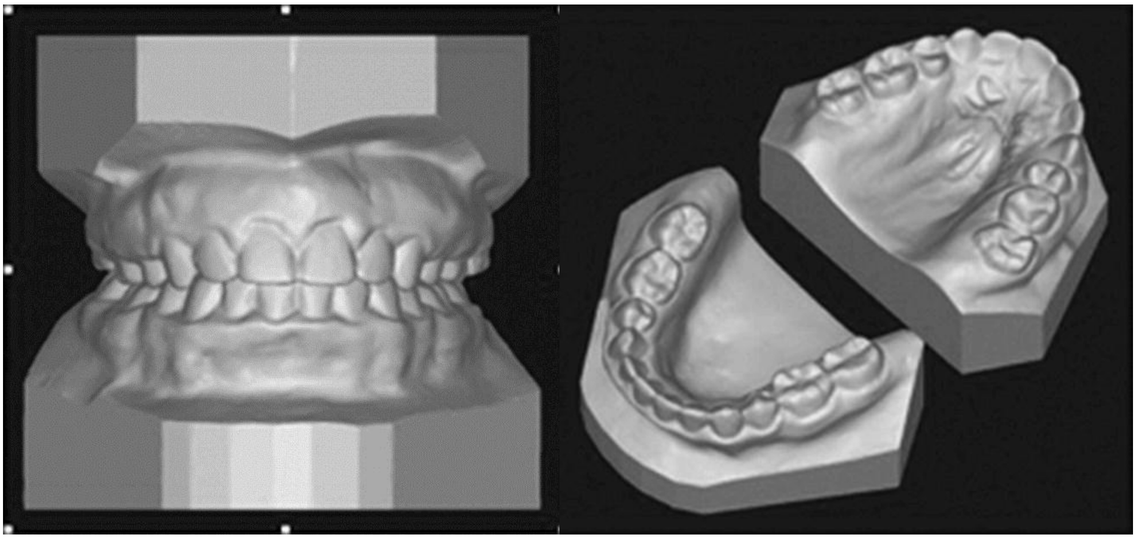

Fig 1.Example of E-models™, Geodigm Corp

Fig 2 Example of O3DM Pro Orthodontic 3D Digital Modeling and O3DM Basic Orthodontic 3D Digital Modeling from OrthoLab

Fig 3. Example of OrthoCAD iCast Orthodontic 3D Digital Modeling Study

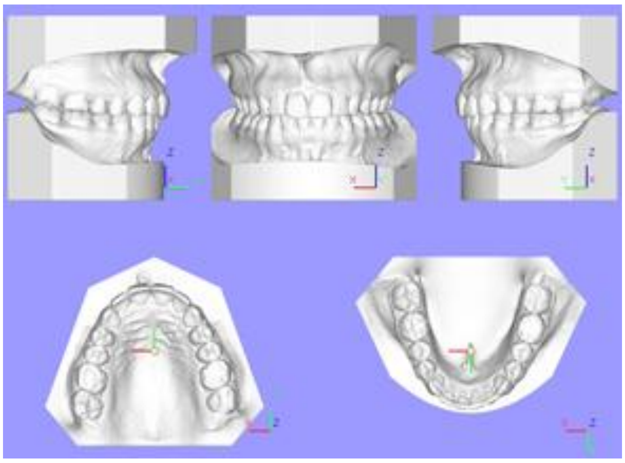

Fig 4. Example of 3D Models by OrthoProof

If the orthodontist decides to use OrthoCAD™, the company will send postage-paid next-day kits for shipping impressions and a bite registration. OrthoCAD™ recommends using specific alginate, disposable trays, and wax bites. After OrthoCAD™ has received the impressions and bite registration, the models are poured and then scanned through a proprietary procedure. Using the bite registration, the mandibular and maxillary digital models are articulated. The company strongly suggests the use of a fast setting polyvinylsiloxane be used for the bite registration since accuracy is essential when making measurements of interarch relationships. However a wax bite is also accepted. Digital images are generated from the digital models using stereo lithography. OrthoCAD™ puts the electronic file on their server five days after receiving the impressions, and the images can then be downloaded (Peluso *et al*, 2004).

OrthoCAD™ has additional features that can be used by the orthodontist at an additional charge. These include Virtual Set-Up, which allows the clinician to visualize and simulate any desired treatment option which includes expansion, levelling, virtual extractions, interproximal slenderizing**,** and to apply a variety of fixed appliances. Virtual Set-Up software can be used when one of the Orthocad tools is used, the Bracket Placement System. When using this, the clinician generates a digital model of the desired treatment objective.

Based on this digital model, virtual bracket placement can be made in the desired position (Peluso *et al*, 2004).

If the Orthodontist decides to use Geodigm postage-paid next-day shipping kits for impression and bite registration will be sent to the practitioner. Metal or disposable trays are accepted. When the impression is received by GeoDigm, a plaster model is fabricated. Using a nondestructive laser scanning process, the plaster model is scanned. While the plaster model is oriented on numerous axes to expose all areas for scanning, a laser strip is projected onto the cast. The distortion of the laser strip is captured using several cameras. Using the bite received, the mandibular and maxillary digital models are articulated. The geometry of the cast's anatomy is digitally mapped using this procedure to an accuracy of +/- 0.1 mm. The electronic information can be downloaded from the company server after 5 days (Peluso *et al*, 2004).

The messrs of OrthoCAD™ and E-model safeguard their secret proprietary methods to fabricate digital models. The laser surface-scanning techniques of these two manufacturers have essential differences, although their digital models appear similar on the computer screen (Stevens *et al*, 2006).

OrthoCAD™ relies on actual slicing through the plaster model when creating a digital image, and in contrast software to "slice through" the image to produce virtual slices is used by E-model. OrthoCAD™ therefore uses a "destructive scanning" method that takes several scans of a model reduced to thin slices. This method is repeated until the complete plaster model has been sliced and scanned, and because the interior aspects of the plaster are scanned and recorded a large file results. A characteristic OrthoCAD™ file is around 3000 kilobytes (3 megabytes). E-model uses their software to scan the exterior of a complete plaster model, and hence, because of surface scanning only, the file is quite small, about 800 kilobytes. From a transfer of information and storage perspective, the smaller size of E-model files is a benefit (Stevens *et al*, 2006).

Besides the companies that specialize in digital models, there are certain software companies, such as 3Shape™, Laserdenta™, and INUS Dental Scanning Solution ™, from whom the Orthodontist can purchase a 3D model scanner and software specifically developed for orthodontics. These are then used in their practices. 3Shape A/S is based in Copenhagen, Denmark and their scanner is used for plaster models only. Laserdenta AG is in Basel, Switzerland and with their scanner both the impression and plaster model can be scanned. INUS Technology, Inc is in Seoul, Korea (Alcan *et al*, 2009).

Accuracy and Reliability of digital models

Schirmer and Wiltshire (1997) evaluated the accuracy and reliability of computer-aided space analysis. They found the computer-aided measuring system to be reliable, but that mesiodistal measurements taken from photocopies of dental models are not accurate.

Bell *et al* (2003) did not find any statistical difference between measurements made on virtual and on stone casts. With their technique, the study models could be digitized to an accuracy of 0.2mm. A vernier calliper was used for measuring on the plaster models and a photostereometric technique was used to capture the plaster models three dimensionally and then storing the data digitally.

Zilberman *et al* (2003) repeating the comparisons found some statistically significant differences, but none that were clinically significant. They measured intermolar and intercanine widths as well as individual mesiodistal tooth measurement. They concluded that the measurements made using a digital calliper on plaster models created the most precise result. The accuracy of measurements done by the OrthoCad™ tool was high as well as the reproducibility thereof. These OrthoCad™ measurements were also inferior to measurements done on plaster models using a digital calliper. They nevertheless found the accuracy of OrthoCad™ to be clinically acceptable.

Mullen *et al* (2007) also found some statistically significant differences, but again none that were clinically significant. The accuracy and speed with which measurements could be done for the overall arch length and the Bolton ratio, and also the time needed to do a Bolton analysis for each patient was studied. With the E-model software they found that measuring the patients' teeth and to calculate the Bolton ratio was just as accurate and was faster than when digital callipers are used on plaster models. Using the two measurement methods, significant differences were found for mandibular arch length measurement between plaster models and E-models. The cast models compared with the e-models showed an average of 1.5 +/- 1.36 mm greater arch length. Significant differences between cast models and e-models were also found for measurement of the maxillary arch length. The cast model showed a larger arch length of an average of 1.47 +/- 1.55 mm compared with E-models.

Bell *et al* (2003) and Mullen *et al* (2007) also showed that measuring the mesiodistal tooth dimensions on digital models could be done faster when compared with the use of a digital calliper on stone casts.

When comparing plaster models and digital models, overall the measurements done on digital models were smaller compared with the measurements on plaster models. Differences between the measurements were greater than 0.5 mm; therefore a clinically significant difference is seen between data gathered from plaster and digital models (Torassian *et al*, 2010).

Horton *et al* (2010) did a study to establish the best method for measuring mesio-distal tooth width using a digital model. Using 32 plaster models and their corresponding digital models (E-models, GeoDigm) they measured the individual mesio-distal tooth widths (mandibular and maxillary arches from first molar to first molar,). Five different techniques were used for measurements on the digital models: occlusal aspect, occlusal aspect zooming in on each individual tooth, facial aspect rotating as needed, facial aspect from three standard positions (R buccal, facial, and L buccal), and qualitatively rotating the model in any position deemed necessary. According to their findings, the best combination of precision, speed of measurement, and repeatability, was with the Occlusal technique for measurements on digital models.

Impression material

Torassian *et al* (2010) showed that when alginate impression material was used it showed a clinically and statistically significant alteration in all proportions within 72 hours. According to these authors, if the impressions are not going to be poured right away, they should not be used. Over a longer period, Alginate substitutes (Alginot FS and Position PentaQuick) were found to have better dimensional stability. Digital models created by OraMetrix were found not to be acceptable for clinical use when they were compared with cast models (Torassian *et al*, 2010).

Impressions taken with dental alginate suffer a likelihood of distortion over time as they tend to lose (by syneresis and evaporation) or gain (by imbibition) water, thereby contracting or expanding. They state that alginate impressions will contract even when stored in an environment of 100% humidity. This shows that there are processes other than dehydration also involved, including syneresis and polymerization (Alcan *et al*, 2009).

To obtain the best results the dental alginate impression should ideally be poured within 10 minutes, to avoid deformation from initial expansion and elastic deformation. It should definitely be poured within 1 hour, to steer clear of distortion from alginate expansion or contraction as a result of syneresis and water movement (Alcan *et al*, 2009).

Previous studies incorporated the taking of two consecutive alginate impressions on the same day. One was poured and the other was shipped overnight to have digital models made (Dalstra and Melsen 2009, Leifert 2009).

Studies that measured Tooth size

Motohashi and Kuroda (1999) compared a 3D computer-aided design system with a digital calliper in measuring teeth and found no significant difference between these two methods at a level of 1%. A slit-ray laser beam was used to scan the dental study models. Their technique which involved scanning the plaster model with a laser and the use of a computer, was comparable to the technique used by the manufactures of E-model. The absolute value of maximum and minimum differences between the graphic and dental models was 0.2mm and 0.0mm, respectively.

In the study by Santoro *et al* (2003), two sets of alginate impressions were taken. One set of impressions was shipped without delay to OrthoCAD via overnight courier and from the second set plaster models were poured the same day. Tooth width measurements were done on the digital model and the cast model groups. Every tooth showed differences in the recorded measurements. The mean differences had a small range (0.16-0.38 mm), but were found to be statistically significant. Digitally measuring the teeth was found to produce smaller measurements compared with the manually measured data. Santoro *et al* stated that differences between alginate impressions cannot be the reason for this result. There was no significant difference between the comparisons of measurements made on cast models from two successive sets of alginate impressions. The two most likely explanations for the differences remain to be alginate shrinkage during transport to the OrthoCAD site and that the times that the impressions were poured differed (Santoro *et al,* 2003).

Quimby *et al* (2004) tested the accuracy, reproducibility, efficacy, and effectiveness of measurements made on 50 computer-based models. They found that the measurements on the computer-based models appeared to be generally as accurate and dependable as were the measurements from cast models. They found the mean difference between the same measurements (Digital versus Plaster) was 0.54 mm for the maxillary arch and 2.88 mm for the mandibular arch on models prepared from repeated impressions of 50 patients (Quimby *et al*, 2004).

Watanebe-Kanno *et al* (2009) used Bibliocast Company (Montreuil-France) in order to digitize plaster models through 3D CT Scanning. They used Cécile3, a digital modeling analysis software to measure the digitized models. A digital vernier calliper was used to measure the plaster models. Two examiners completed the measurements. The average mean difference of measurements made on the digital models was 0.23 ± 0.14 and 0.24 ± 0.11 for each examiner, respectively. Values obtained from the digital models were lower than those obtained from the plaster models, although the differences were not considered to be of clinical importance. The mean difference between plaster and the digital model data was 0.17 ± 0.06 mm for examiner 1. For examiner 2, the mean difference was 0.19 ± 0.06 mm (Watanebe-Kanno *et al*, 2009).

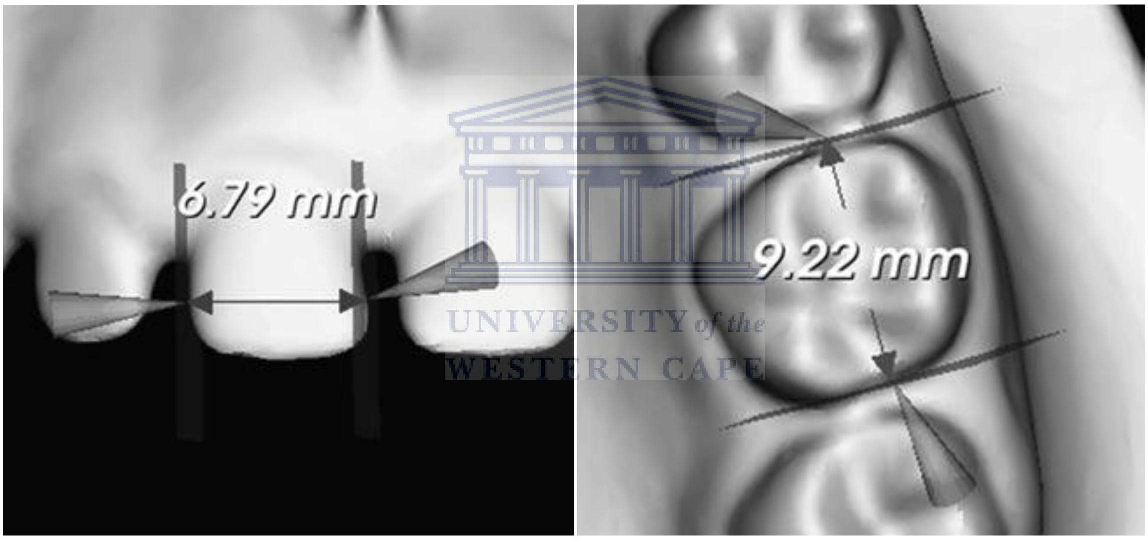

Figure 5 - Measurements of mesiodistal width of incisor, and molar using the Cécile3 tool, as shown from different views used by Watanebe-Kanno *et al* (2009).

Redlich *et al* (2008) looked at the accuracy of a new technique (cross-section planes on digital models) compared with digital linear measurements and also with the digital calliper as the gold standard. In their study, thirty orthodontic cast models were divided into three equal groups, according to severity of teeth crowding. The orthodontic plaster models were scanned using a holographic sensor ConoProbe (Optimet, Jerusalem, Israel). The data was imported to TELEDENT, a programme performing computer analyses. To mimic digital callipers, the TELEDENT software has interactive graphical tools such as cross-section planes. The 3D measurement of cross-section planes, were in general found to be comparable to manual measurement using callipers for measurement of tooth width and arch length. The computerized linear 3D measurements were shown to be statistically smaller.

The digital measurements of linear tooth width and segmental arch length were statistically smaller ($p < 0.05$) in the groups with mild to severe crowding than the calliper measurements. However, if one looks at how small is the difference (0.18–0.28 mm), clinical relevance is lacking (Redlich *et al*, 2008).

In the non-crowded to mildly-crowded dentition, the linear measurements were found to be statistically smaller but deemed to be clinical acceptable. A possible explanation for this could be the precision required in placing the line at the correct points to measure and also the 2-D line measurement deformation. The variation in space analysis between the callipers and the measurement by cross-section plane was very small (0.38–0.74 mm). This small difference can be considered clinically irrelevant. The difference of 1.19–3 mm found between the digital and the calliper measurements is high and this may have clinical implications particularly in the severely crowded dentition. According to this study, the measurements done by cross section planes and the manual calliper are of comparable accuracy and both could be used in a clinical setting, while there is sometimes doubt about the accuracy of linear measurements (Redlich *et al*, 2008).

Bell *et al* (2003), using a photostereometric technique involving stereo pairs of videocameras assessed and compared measurements of computer-generated 3D images and direct measurements of 22 study models. The same study models were used for the creation of the computer-generated 3D images. Results showed that there was no statistically significant difference between the measurements done on the plaster models and the 3D images. The cameras were linked to a personal computer and special coloured illumination to record the plaster models in digital format. Should a stereolithographic format be required, this data can be changed for the rebuilding of the study model. Six anatomical dental points were marked on each model. The average differences between the measurements were found to be 0.27 mm. Bell *et al* (2003) did not measure the accuracy of tooth structure (mesio-distal tooth width), but the distance between two points on the study models. These differences was within the range of operator errors (0.10-0.48 mm) and were not found to be statistically significant (P <.05).

Mullen *et al* (2007) in their study took alginate impressions of each patient in a sample of 30. This was done for both arches and the impressions were sent to GeoDigm. Geodigm cast a plaster model and produced an E-model by scanning the plaster model. For measurement purposes, the cast model was returned with the E-model. The Bolton analysis was undertaken, the amount of tooth structure being the sum of maxillary or mandibular teeth. Using E-model software Mullen *et al* (2007) found the amount of tooth structure in the mandibular arch to be an average of 1.5 +/- 1.36 mm smaller than the measurements on the cast model. The E-model software showed the amount of tooth structure in the maxillary arch to be an average of 1.48 +/- 1.55 mm smaller than the measurements on the cast model (Mullen *et al*, 2007).

With certain computer programs, prior training is necessary to make use of the software, and individuals who are more familiar with the computer resources are more skilled in achieving more accurate measurements. Watanebe-Kanno *et al* (2009) state that if the interproximal area between the teeth is not clearly defined when the points are marked, this may lead to altered reproducibility of the measurements.

Schirmer and Wiltshire (1997) did a study to determine whether there are differences between manual and computer-aided space analysis. The manual measurements were done using a Vernier calliper to determine the mesio-distal widths of teeth, and were found to be highly accurate between the two examiners. For the digital measurements, they made photocopies of the plaster models and these were digitized. The differences between manual measurements and the digital measurements were found to be significant. For arch length measurements in the maxilla the average discrepancy was 4.7 mm and for the mandible it was 3.1 mm.

Table 3. Different studies measurement of tooth size (mm)

Study	Measurement	Digital model Mean (SD)	Plaster model Mean (SD)	Mean difference
Santoro *et al*.(2003)	Overall mean			0.16-0.38
Redlich *et al*.(2008)	Maxillary mean Mandibular mean	7.73 (0.1) 7.1 (0.1)	7.7 (0.12) 7.11 (0.1)	0.03 0.03
Watanabe-Kanno *et al.(*2009)	21 26	8.76 (0.63) 9.9 (0.46)	8.94 (0.63) 10.1 (0.46)	-0.18 -0.2
Horton *et al*. (2010)	Overall difference			0.03

Studies that measured Arch Width

The accuracy, reproducibility, efficacy, and effectiveness of measurements was tested by Quimby *et al* (2004) on 50 computerbased models. It was found that the dimensions on the computer based models appeared to be generally as dependable and accurate as those made on cast models. The mean millimetre differences between measurements made on digital and plaster models were: maxillary intermolar: 0.29, maxillary intercanine: -0.4, mandibular intermolar: 0.04, mandibular intercanine: -0.34.

Keating *et al* (2008) evaluated the accuracy and reproducibility of a three-dimensional (3D) model and used an optical laser-scanning device to record the surface detail of cast study models. Each model was captured three-dimensionally by using a commercially available Minolta VIVID 900 non-contact 3D surface laser scanner (Konica Minolta Inc., Tokyo, Japan), a rotary stage and Easy3DScan integrating software (TowerGraphics, Lucca, Italy). Measurements made directly on the cast models and measurements made on the 3D digital surface models showed a mean difference of 0.14 mm, and this was found to be not statistically significant.

Watanebe-Kanno *et al* (2009) used Cécile3 software to measure digitized models. A digital vernier calliper was used for measurements on cast models. Fifteen pairs of cast models, the before treatment records of patients coming for orthodontic treatment were used. All patients had permanent dentition. The mean differences between measurements made on digital and plaster models were: maxillary intercanine width: -0.12mm, mandibular intercanine width: -0.14mm, maxillary intermolar width: -0.16mm and mandibular intermolar width: -0.12mm. The plaster measurements for inter arch measurements were slightly higher than the digital measurements.

Using a photostereometric technique to create 3D computer-generated images, Bell *et al* (2003) did a comparative assessment between manual measurements of cast study models and measurements of the same study models on computer generated 3D images. An Orthomax Vernier calliper was used for measuring the linear distances between the points on the plaster models. The mean differences between measurements made directly on the cast models and those measurements made with the computer on the 3D images ranged between 0.16 and 0.38 mm (mean 0.27 mm) with plaster measurements being slightly greater. The differences were found to be not statistically significant.

Table 4. Different studies measurement of Arch Width

Study	Measurement	Digital model Mean (SD)	Plaster model Mean (SD)	Mean Difference
Quimby *et al*.(2004)	Maxillary intermolar width (IMW)	54.72 (0.85)	54.43 (0.26)	0.29
	Maxillary intercanine width (ICW)	36.04 (0.51)	36.44 (0.26)	-0.4
	Mandibular intermolar width (IMW)	47.42 (0.52)	47.38 (0.33)	0.04
	Mandibular intercanine width (ICW)	26.31 (0.27)	26.65 (0.24)	-0.34
Watanabe-Kanno *et al*.(2009)	Maxillary intercanine width (ICW)	34.23 (1.78)	34.35 (1.78)	-0.12
	Maxillary intermolar width (IMW)	44.83 (2.54)	44.99 (2.54)	-0.16
	Mandibular intercanine width (ICW)	26.57 (1.57)	26.71 (1.58)	-0.14
	Mandibular intermolar width (IMW)	39.66 (2.25)	39.78 (2.25)	-0.12
Keating *et al*.(2008)	Between plaster models and those made on the 3D digital models			0.14
Bell *et al*.(2003)	Manual measurements			0.17
	3D measurements			0.06
	mean difference between various transverse and sagittal measurements			0.27

With the advent of digital scanning techniques, dentistry and orthodontics, currently has three dimensional digitization of study models or impressions available. With the accuracy of digital models being questioned, the current study wanted to look at the accuracy of the 3Shape R700™ scanner. The companies that specialize in digital models do not currently have a market here, but the 3Shape R700™ scanner is available in South Africa.

4. Research hypothesis

The aim of the study was to compare measurements taken on digital models created from impressions, on digital models created from plaster models and those taken directly on the plaster models.

The Null hypothesis states that the distributions of the SD's are the same across the three methods.

The research question was the following:

Are there any statistically significant differences between measurements on plaster models compared with measurements on digital models created from impressions and digital models created from plaster models?

5. Delimination of study area

The following selection criteria were used:

Patients

- No orthodontic appliances present
- Permanent dentition erupted from first molar to first molar
- Not more than two teeth per arch missing from first molar to first molar
- Stable centric occlusion with at least three occlusal contacts

Study Models

- Plaster and digital models made from the same alginate impressions
- No voids or blebs in the plaster or digital models
- No fractures on the teeth on the plaster models

6. Materials and methods

The sample of patients used in this study consisted of randomly selected subjects, each with not more than two permanent teeth per arch missing with all other permanent teeth from first molar to first molar erupted, and no orthodontic appliances present. The study sample to compare plaster models and digital models was randomly selected from the patient records of one Orthodontist, and consisted of pre-treatment records of twenty six patients that were presenting for orthodontic treatment.

Impressions were taken of both the maxillary arch and of the mandiblar arch. The alginate used was either Aroma fine Plus fast set (GC) or Smileginate (Orthoshop). The impression was scanned using a 3Shape R700™ scanner[1]. Ortho Analyzer software from 3Shape was used for the measurements on the digital study models.

A complete coverage of the entire geometry of the plaster or impression, which includes potential undercuts, is ensured with 3Shape´s unique 3-axis scanning technology. According to the manufacturers the 3Shape R700™ scanner has two cameras and one laser that are used to acquire the point cloud data to enable the production of fully surfaced 3D digital models. To comply with Medico-Legal requirements, the scanned 3D data may also be locked to prevent anyone from altering the digital models.

[1] 3Shape R700™ scanner from ESM

Fig 6. 3Shape R700™ scanner from ESM

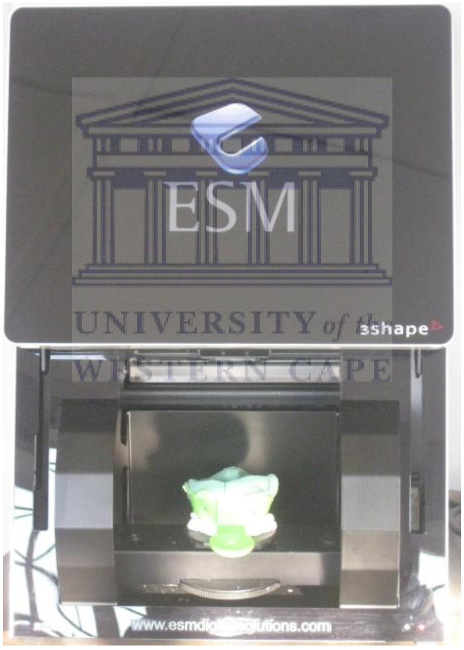

Fig 7. Impression in 3Shape R700™ scanner before being scanned.

The impression was placed in the scanner and the data saved. The same impression was then poured within 24 hours to produce a plaster study model. The plaster model was also scanned using a 3Shape R700™ scanner, also within 24 hours. The scanning of both the impression and the plaster model was done within 24 hours to minimize possible distortion of both the impression and the study model.

Fig 8. Plaster model in 3Shape R700™ scanner before being scanned.

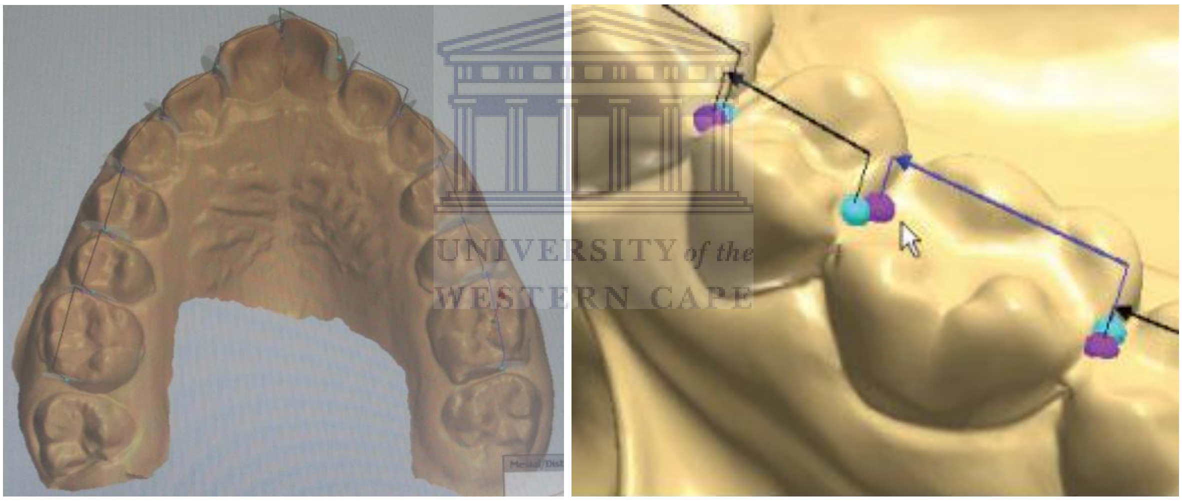

Fig 9. Digital model created by 3Shape R700™ scanner. Ortho Analyzer software was used for measurements.

After scanning patient cases using a 3Shape R700 3D scanner, 3Shape's OrthoAnalyzer™, which is a dedicated software package, can be used for analysis and orthodontic treatment planning. With 3Shape's software package, the orthodontists are able to analyze a patient's dentition to assess the effectiveness of a proposed orthodontic treatment. An intuitive interface, within the orthodontics software, allows the user to set references points on the scanned plaster models. It is easy to measure space available, paths and angles for orthodontic treatment. Different tools for measurement are available and the user is allowed to pick a point on 2D cross sections or on the plaster 3D model to calculate distances. Easy comparison among 2D cross sections is also allowed. Different predetermined analyses for treatment planning: tooth width, Ideal arch, Space (Tanaka & Johnston, Moyers), Bolton, etc, can be done.

Fig 10. Ortho Analyzer software data sheet.

Actual Tooth Widths (mm.)

Tooth	Width	Tooth	Width
11	9.16	21	8.98
12	7.67	22	7.44
13	8.04	23	7.72
14	7.36	24	7.38
15	7.01	25	6.36
16	10.13	26	10.40
17	0.00	27	0.00
18	0.00	28	0.00

Mandible

Actual Tooth Widths (mm.)

Tooth	Width	Tooth	Width
31	5.60	41	5.69
32	6.17	42	6.34
33	6.68	43	7.56
34	7.45	44	7.68
35	7.17	45	7.25
36	10.80	46	10.58
37	0.00	47	0.00
38	0.00	48	0.00

Fig 11. Individual tooth measurements given by Ortho Analyzer software after measuring teeth.

On the plaster models the measurements were done using a MAX-CAL digital electronic calliper[2]. At each tooth's greatest width, the mesiodistal width was measured, by holding the callipers perpendicular to the occlusal plane of the tooth (Mullen *et al*, 2007). This was done from first molar to first molar for both the maxillary and mandibular models. The intercanine and intermolar widths of both the maxillary and mandibular dentitions were also recorded. Intermolar width was measured as the distance between the mesiobuccal cusp tips of the permanent first molars. Intercanine width was measured as the distance between the crown tips of the permanent canines (Quimby *et al*, 2004). Measurements were written on a separate form for each patient (Addendum A).

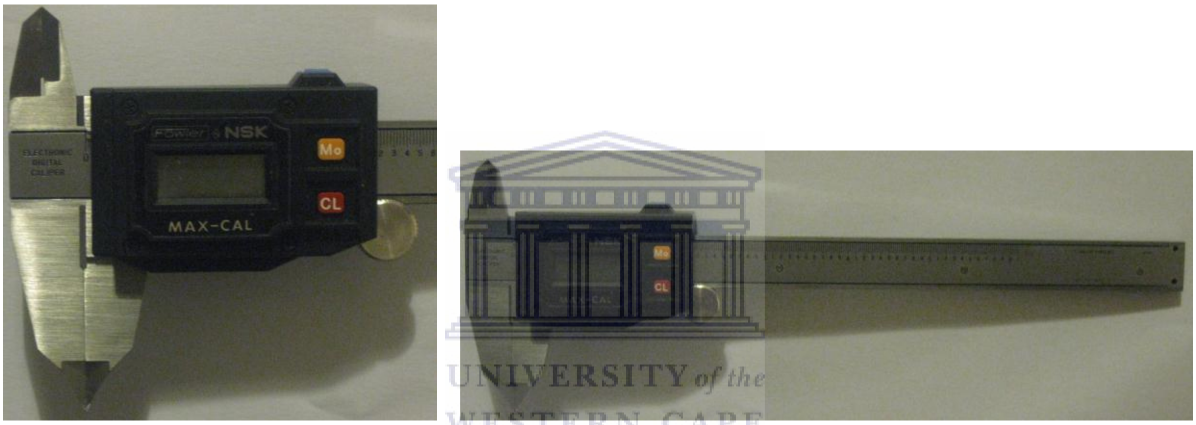

Fig 12. MAX-Series electronic digital calliper with which measurements on the plaster models were done.

A single examiner measured tooth and interdental widths on both the maxillary and mandibular casts (teeth 16-26 and 36-46). All measurements were repeated 3 times. The results were then statistically evaluated.

[2] MAX-Series electronic digital calliper with a resolution of 0,01mm, Fowler & NSK

Flow diagram of procedure:

Impression

(Scan impression→ **Digital model created from impression**)

↓

Pour plaster model of impression

(Scan plaster model→ **Digital model created from plaster model**)

↓

Plaster model

Measurements done on:

1. Digital model created from impression
2. Digital model created from plaster model
3. Plaster model

7. Ethics statement

This research protocol was presented to the Research Committee of the Faculty of Dentistry, UWC, for consideration for registration as an approved research project. It was then approved as a research project for a mini thesis as part of completion of the M.Ch.D (Ortho) degree.

Every patient was informed about the research project and asked for consent before records were taken. All patients in this study were patients who came for records for orthodontic treatment. No additional impressions or other records were done over and above those usually taken before starting orthodontic treatment. Included patients were not identifiable from the records that were used. (Addendum B).

8. Declaration

   No conflict of interest.

9. Statistical analysis

Maxillary and mandibular impressions of 26 patients were taken and measurements done. These measurements were repeated three times for each tooth. The intercanine and intermolar width of both the maxillary and mandibular models were also done, and repeated three times. The means and standard deviations for the tooth measurements and interdental measurements were then calculated. These repeat measurements were not done at the same visit, but were completed either on different days or weeks later.

Since each tooth was measured three times, a means was available for comparing the variability in each of the measurement methods. A simple way of doing this is to obtain the estimated standard deviation for each method and each tooth. The amount of variability observed in the three methods may then be compared. This was done graphically and by testing the null hypothesis that the standard deviations obtained are the same for each group. Examination of the box-plots suggests that the sets of three measurements are less variable for Plaster (fig 13). The descriptive statistics are consistent with this. The median value of the SD is about 0.10 for both Digital and Digital Plaster combination as compared with about a median of about 0.06 for the Plaster (table 5).

Table 5. Analysis of Variability in the three methods [3]

method	Number of observations	N	Mean	Median	Std Dev	Minimum	Maximum
Digital_Plaster	624	607	0.1215	0.1054	0.0944	0.0058	1.1435
Digital	624	607	0.1190	0.1039	0.0994	0.0058	1.7106

[3] Digital_Plaster (model created from scanning plaster model): Digital (model created from scanning impression)

Plaster	624	607	0.0757	0.0611	0.0531	0.0000	0.3313

Box plots of Standard deviations of sets of three measurements

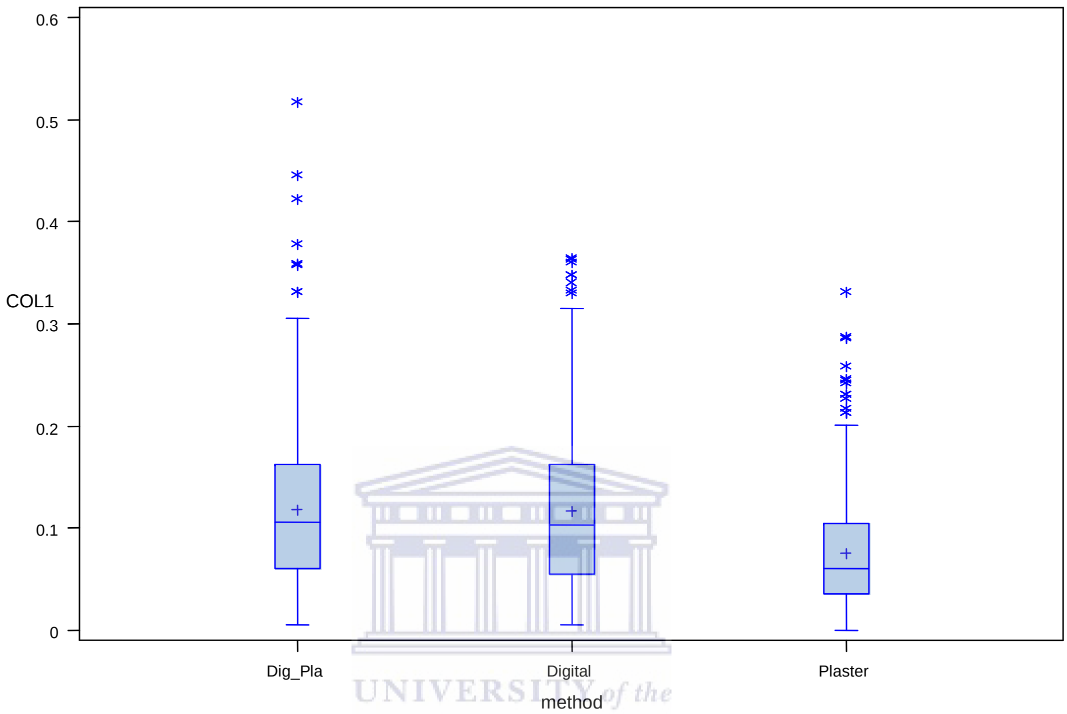

Fig 13. Box plots of standard deviations of sets of three measurements (excluding 3 extremes>1)

In doing a permutation test of the null hypothesis that the distributions of the SD's are the same across the three methods we find the estimated p-value to be less than 0.001 based on 1000 permutations. There was therefore a statistically significant difference between the three methods (table 6).

Table 6. Permutation test for the three methods

Effect	Pr > F
method	<.0001

The next factor to consider was how the methods compared with each other in terms of actual size recorded (as opposed to the variability of repeated measurements by the same method). (From this point on in the discussion, the 'size' of the tooth was taken to be the mean of the three measurements.) One possibility was that the means differed by a clinically significant amount. This was tested by using a mixed model analysis. There were repeated measures on the same model with measurements made at 24 locations. For this analysis the models were included as a random effect with the Tooth number being the factor on which the repeated measures were made. Examination of the results of the measurements indicated that the variability in sizes differed widely for different locations. For this reason we used a statistical model that allows for heterogeneous variances. This analysis was done using the MIXED procedure in SAS with both the RANDOM and REPEATED options. Since a preliminary analysis showed no significant interaction between Method and Location, a simpler main effects model was considered.

Table 7. Descriptive Statistics for Standard deviation of sets of three measurements on same tooth: The Mixed Procedure

Least Squares Means

Method	Estimate	Standard Error	Pr > |t|	Range Lower	Range Upper
Dig_Pla	7.7390	0.07153	<.0001	7.5923	7.8857
Digital	7.6947	0.07153	<.0001	7.5479	7.8414
Plaster	7.7940	0.07153	<.0001	7.6472	7.9407

Table 8. Differences of Least Squares Means

Method	_Method compared with	Estimate	Standard Error	Pr > |t|	Lower	Upper
Dig_Pla	Digital	0.04434	0.02092	0.0343	0.003288	0.08540
Dig_Pla	Plaster	-0.05498	0.02092	0.0087	-0.09604	-0.01393
Digital	Plaster	-0.09932	0.02092	<.0001	-0.1404	-0.05827

Results of Differences of Least Squares Means

The factor of Method was significant ($p<0.0001$) with the Plaster measurements being significantly higher (mean of 7.79) compared with a mean of 7.74 for Digital Plaster and 7.69 for Digital. Examination of 95% confidence interval estimates for the differences show that the upper limit is only about 0.14 (table 7).

One can certainly question whether the mean value is important or whether individual differences are important. For example, if the Plaster measurement is 7.8 on two teeth and the Digital measurements for those teeth are 7.2 and 8.4 respectively, then the mean values are the same but the difference in measurements away from the mean of 0.6 is clinically important. For this reason we can look at the difference in measurements and see how often they differ by a selected specific amount. This study used an amount of 0.5mm as a reference, but other values could be used as well. In this case it helps to think of one of the methods as the 'gold standard' and compare the others to it. The plaster was taken as the reference method.

According to Akyalcin (2011), a small range up to 0.5 mm may include operator error and may, therefore, be considered as clinically acceptable.

Table 9. The FREQ Procedure: Table of Digital and Digital plaster measurements where differed from Plaster by at least 0.50mm

		Number of instances	Percentage	
Digital		32	5.27	
Digital-Plaster		24	3.95	

Results of FREQ Procedure

Out of 607 teeth, the Digital method differed from the Plaster by at least 0.5mm (in either direction) in 32 cases or 5.3% of the time. The Digital-Plaster method differed from the Plaster by at least 0.5mm (in either direction) in 24 cases or 3.9% of the time. These frequencies and differences do not appear to be significant.

Arch Width measurements

Table 10. The MEANS Procedure for the Digital, Digital Plaster and Plaster measurements

method	Observations	Variable	Number of observations	Mean	Std Dev	Minimum	Maximum
Digital Plaster	26	Inter canine width(Maxilla)	22	33.317	2.232	29.300	37.233
		Inter molar width(Maxilla)	26	49.986	2.915	44.527	55.333
		Inter canine width(Mandible)	25	25.663	2.216	20.643	29.353
		Inter molar width(Mandible)	26	42.691	2.683	38.187	48.063
Digital	26	Inter canine width(Maxilla)	22	33.344	2.252	29.080	37.250
		Inter molar width(Maxilla)	26	49.893	2.829	44.853	55.047
		Inter canine width(Mandible)	25	25.720	2.308	20.280	29.353
		Inter molar width(Mandible)	26	42.607	2.670	37.780	47.657
Plaster	26	Inter canine width(Maxilla)	22	33.573	2.262	28.927	37.030
		Inter molar width(Maxilla)	26	49.945	2.908	45.327	55.323
		Inter canine width(Mandible)	25	25.559	2.238	20.443	28.663
		Inter molar width(Mandible)	26	43.263	2.479	38.963	48.217

The observations in the intercanine area are less than the number of cases which were used for measurements, as some of the patients had impacted canines and in others the canines were still erupting.

Table 11. Difference between MEANS Procedure for the Digital, Digital Plaster and Plaster measurements

Variable	Plaster- Digital	Plaster-Digital Plaster
Inter canine width(Maxilla)	0.229	0.256
Inter molar width(Maxilla)	0.052	0.041
Inter canine width(Mandible)	-0.161	-0.104
Inter molar width(Mandible)	0.656	0.572

Were there significant differences among methods for the arch width measurements? A mixed model analysis showed no significant differences between the mean data for the methods (p=0.64) at a level of p<0.01.

Table 12. Type three tests of fixed effects

Effect	Pr > F
method	0.6399

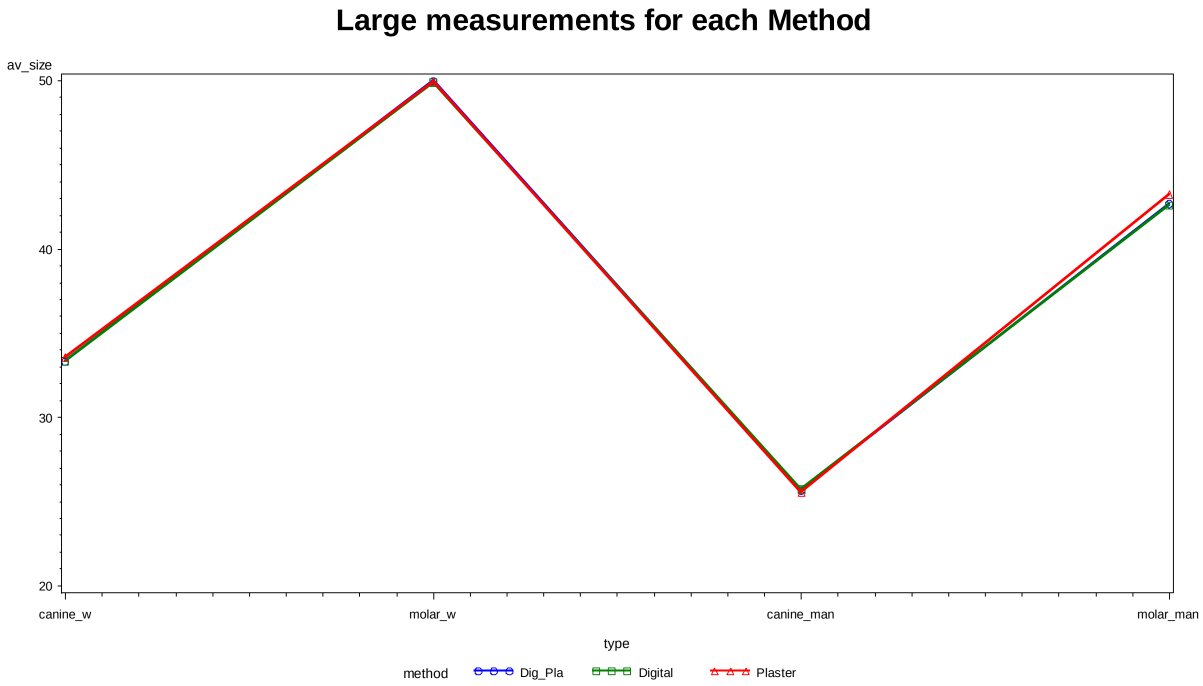

Fig 14. Means of different methods (digital-plaster, digital and plaster) for intercanine and intermolar width.

The mean for the maxillary intercanine width for the plaster measurement (33.573) was slightly higher than the same measurement for the digital and digital plaster, with the latter two measurements almost similar at 33.344 and 33.317 respectively.

For the maxillary intermolar width, the digital measurement (49.893) was slightly lower than the same measurement for the plaster and digital plaster, with the latter two measurements almost similar at 49.945 and 49.986 respectively.

The mean for the mandibular intercanine width for the digital measurement (25.720) was slightly higher than the same measurement for the plaster and digital plaster, with the latter two measurements almost similar at 25.559 and 25.663 respectively.

For the mandibular intermolar width, the plaster measurement (43.263) was higher by ±0.6mm than the same measurement for the digital and digital plaster. The latter two measurements were almost similar, at 42.607 and 42.691 respectively.

Table 13. Means for each tooth, by method: Digital Plaster

method	Number of observations	Variable	N	Mean	Median	Std Dev	Minimum	Maximum
Digital _Plaster	26	t11	26	8.6156	8.6667	0.6260	7.2500	9.6267
		t12	26	6.8899	6.9300	0.6515	5.7567	8.0867
		t13	24	7.7143	7.6717	0.6358	6.5400	9.2833
		t14	24	7.4004	7.4117	0.4302	6.6100	8.1700
		t15	26	7.3550	7.1983	0.7496	6.0167	9.6867
		t16	26	10.5412	10.6767	0.6143	9.3067	11.9867
		t21	26	8.6359	8.6767	0.6586	7.0300	9.6700
		t22	26	6.7640	6.7950	0.5863	5.8267	8.2200
		t23	23	7.4471	7.5400	0.6352	6.3867	8.9233
		t24	23	7.2806	7.2800	0.4618	6.4200	8.2100
		t25	26	7.1469	7.0100	0.8907	6.0733	9.6300
		t26	26	10.3531	10.3883	0.5530	9.4233	11.7000
		t41	26	5.3819	5.3683	0.3688	4.7233	6.2667
		t42	26	5.9187	5.9017	0.3763	5.3300	6.7200
		t43	25	6.9721	6.7733	0.5573	5.8933	7.9767
		t44	25	7.4075	7.3567	0.4274	6.5667	8.1433
		t45	26	7.8344	7.7200	0.9686	6.5933	10.6933
		t46	26	11.2669	11.3117	0.7820	9.5767	13.3900
		t31	26	5.3073	5.3317	0.3522	4.7767	6.0067
		t32	26	5.9379	5.9067	0.3857	5.2867	6.6500
		t33	25	6.9307	6.8533	0.5439	5.7433	8.4100
		t34	24	7.3606	7.3933	0.5661	6.1867	8.5500
		t35	24	8.1243	7.9767	1.1660	6.6333	10.7800
		t36	26	11.2569	11.1650	0.8216	9.4700	13.4867

Table 14. Means for each tooth, by method: Digital

method	Number of observations	Variable	N	Mean	Median	Std Dev	Minimum	Maximum
Digital	26	t11	26	8.6590	8.7250	0.6153	7.1967	9.8567
		t12	26	6.8846	6.9950	0.6189	5.7600	8.1200
		t13	24	7.6506	7.7367	0.5932	6.5733	9.1733
		t14	24	7.3222	7.4100	0.3946	6.6450	8.0067
		t15	26	7.1978	7.1467	0.7631	6.1767	9.4267
		t16	26	10.4746	10.4100	0.6362	9.4967	12.2500
		t21	26	8.6113	8.6550	0.5770	7.2300	9.8700
		t22	26	6.7840	6.6883	0.6242	5.9133	8.5633
		t23	23	7.4597	7.4433	0.6376	6.3600	8.8400
		t24	23	7.2439	7.2900	0.4834	6.4133	8.0700
		t25	26	7.0808	7.0333	0.8776	6.1167	9.6000
		t26	26	10.3674	10.3100	0.5909	9.4767	11.7067
		t41	26	5.2615	5.2600	0.3834	4.2800	5.9733
		t42	26	5.8671	5.8800	0.3672	5.2900	6.6200
		t43	25	7.0137	6.8900	0.5078	6.0933	7.7767
		t44	25	7.3691	7.4267	0.4906	6.4267	8.4433
		t45	26	7.7990	7.6633	0.9873	6.5800	10.7533
		t46	26	11.2710	11.2683	0.7460	9.6000	13.1433
		t31	26	5.1986	5.2317	0.3495	4.3767	5.8633
		t32	26	5.9296	5.9667	0.3052	5.4100	6.4767
		t33	25	6.9727	6.8467	0.5472	5.9467	8.1700
		t34	24	7.3332	7.4367	0.5626	6.0333	8.4633
		t35	24	8.0254	7.8767	1.2188	6.4067	10.7200
		t36	26	11.1792	10.9800	0.8559	9.6833	13.7433

Table 15. Means for each tooth, by method: Plaster

method	Number of observations	Variable	N	Mean	Median	Std Dev	Minimum	Maximum
Plaster	26	t11	26	8.8808	8.9150	0.5907	7.3167	9.8633
		t12	26	6.9035	6.8633	0.6234	5.7667	8.2167
		t13	24	7.6457	7.7183	0.6047	6.6367	9.2033
		t14	24	7.2667	7.3150	0.4444	6.4733	7.9733
		t15	26	7.1917	7.1083	0.7800	6.0767	9.3767
		t16	26	10.2931	10.2300	0.6435	9.0367	11.7800
		t21	26	8.9176	9.0017	0.6243	7.5133	10.0533
		t22	26	7.0232	7.0733	0.5959	6.1833	8.6033
		t23	23	7.5975	7.7433	0.6594	6.5267	9.0967
		t24	23	7.3113	7.3633	0.4372	6.4733	7.9467
		t25	26	7.0628	6.8967	0.9125	5.9400	9.5700
		t26	26	10.4369	10.4667	0.5787	9.2733	11.8600
		t41	26	5.5014	5.4617	0.3703	4.8067	6.3967
		t42	26	5.9994	6.0600	0.3741	5.3833	6.7800
		t43	25	6.9404	6.8567	0.5186	6.1167	8.0467
		t44	25	7.4076	7.4133	0.5271	6.3633	8.4467
		t45	26	7.7537	7.6350	1.0463	6.5667	11.0450
		t46	26	11.1842	11.2650	0.8672	9.2200	13.3300
		t31	26	5.4910	5.4717	0.3642	4.9100	6.3500
		t32	26	6.0549	6.0667	0.3739	5.5233	6.8433
		t33	25	6.8955	6.7500	0.5804	5.8767	8.3067
		t34	24	7.3101	7.4350	0.5628	6.1133	8.4500
		t35	24	7.9986	7.9667	1.1092	6.5000	10.3000
		t36	26	11.1408	11.0750	0.8627	9.3467	13.6633

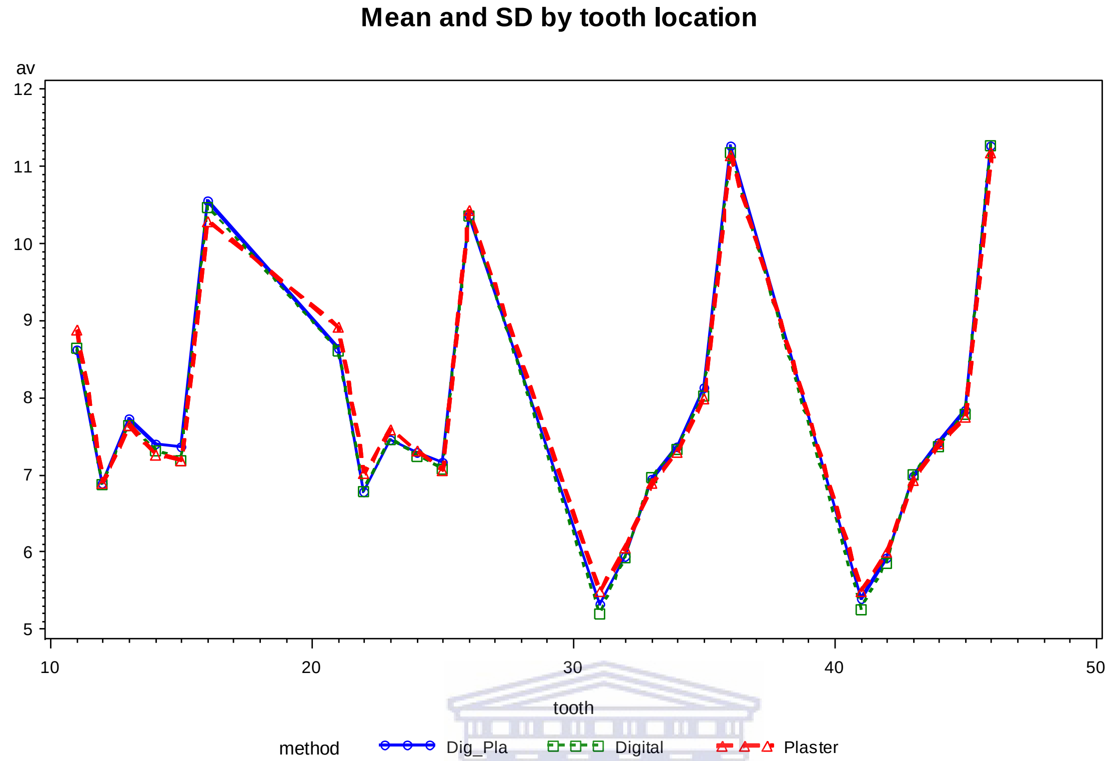

Fig 15. Means of different methods (digital-plaster, digital and plaster) for tooth widths.

From the graph it is evident that the means for the three methods (plaster, digital and digital plaster) by tooth location do not differ to any extent, as they cannot be distinguished in certain parts of the graph.

10.Discussion

Tooth size

When deciding whether it is necessary to remove teeth in a crowded dentition, an accurate space analysis is an important step before a diagnostic decision is made in orthodontics. This step in diagnosis requires comparing the space available in that arch to the overall mesiodistal (MD) widths of all the teeth to be accommodated. In addition, to achieve functional occlusion with proper overbite and overjet, the mandibular and maxillary dentition must be well proportioned in size (Mullen *et al*, 2007).

The regular measurements done on plaster models include arch length and tooth width, both needed for analyzing space. Space estimation is done using these measurements which is often required when deciding on the appropriate treatment plan (Redlich *et al,* 2008). Today's 3D sensor technology provides the clinician with new possible alternatives to replace manual measurements. This technology includes 3D digital images of scanned objects and the relevant computerized measuring software. Akyalcin (2011) states that with measurements, a small range up to 0.5 mm may include operator error and may, therefore, be considered as clinically acceptable.

For the tooth width measurements from this study the means of the Plaster measurements were found to be being significantly higher (mean of 7.79) compared with a mean of 7.74 for Digital Plaster and 7.69 for Digital. Thus the mean of the digital plaster was 0.05mm smaller than the mean of the plaster measurements with the Digital-Plaster data 0.1mm smaller than the mean of the plaster measurements. The results of this study compare favourably with those obtained from studies by Motohashi and Kuroda (1999), Santoro *et al* (2003), Quimby *et al* (2004) (their maxillary arch measurements), Watanebe-Kanno *et al* (2009), Redlich *et al* (2008) and Bell *et al* (2003).

Mullen *et al* (2007) also mounted 0.25-mm ball bearings on the casts to be measured before they were digitized and then subsequently measured the diameter of the ball bearings in addition to the mesial tooth widths. They found that the ball bearings were digitally measured slightly greater than their actual diameter, but when digitally measuring the mesio-distal tooth widths on the same casts, the values were found to be measured statistically smaller than the measurements made on the plaster models.

Quimby *et al* (2004) found the differences between the cast and computer models to be statistically significant, although they were generally small. When one looks at these small measurements, it is questionable whether such small measurements are clinically significant. The computer models are reasonably reliable and accurate. These models can provide the clinician with sufficient information to develop a treatment plan and thus eliminate the requirement for storing plaster casts (Quimby *et al*, 2004).

Watanebe-Kanno *et al* (2009), Santoro *et al* (2003) and Mullen *et al* (2007) stated that the digital measurements were smaller than the manual measurements. Quimby *et al* (2004) differed from these studies, for they found manual measurements to be smaller than the digital measurements.

Watanebe-Kanno *et al* (2009) explain that a possibility for the differences can be the difficulty in locating the points, particularly at the site of the interproximal contacts. This is also affected by the operator's familiarity in using a digital model. According to the authors one disadvantage of digital models is that in order to mark or locate the points necessary to obtain a measurement, the models need to be stationary. In the computer screen the digital model can be enlarged, which gives a significant benefit to locating landmarks because a 3-dimensional structure is viewed as a 2-dimensional image (Watanebe-Kanno *et al,* 2009).

Watanebe-Kanno *et al* (2009) also state that they observed difficulty with the occurrence of shadows (especially in crowded areas), as a result of the digitalization process with Cécile3 digital models. With their method they also noted that wear facets and occlusal anatomy in

Cécile3 digital models did not present a high clarity (Watanebe-Kanno *et al,* 2009). In the present study, using the 3Shape R700™ scanner, these difficulties were not found to affect the location of points. It might be that in the current study the sample there amount of crowding was not as severe as in the study by Watanebe-Kanno *et al* (2009).

Redlich *et al* (2008) found the accuracy of digital linear measurements to be smaller than those of the manual calliper and those measurements that were done using cross section planes were as accurate as the measurements done by manual calipers.

Zilberman *et al* (2003) concluded that the measurements made with digital callipers on cast models produced the most accurate results.

In the study by Quimby *et al* (2004) in the mandibular arch, the mean difference between the same measurements (Digital minus Plaster) was 2.88mm, which is much higher than the mean measurements from the present study.

According to Mullen *et al* (2007) several factors may be attributed to explain measurement differences between the emodel software and the digital calipers. One was that with the emodel software it is difficult to find the greatest mesio-distal width of the teeth. To precisely calculate the points chosen as the greatest diameter, the model can be rotated on the screen, but there is still difficulty doing this. Although E-models have a high resolution, it is difficult to select the correct contact point between any two teeth. In certain cases, the interproximal area may not be clear enough for certainty that the greatest mesio-distal width is being measured. In some cases, the interproximal area may be well defined and simple to see, but there might still be some difficulty in getting a measurement at the tangent at right angles to the maximum width.

The intrinsic differences between the two methods might also be a likely cause of different tooth size measurements. With OrthoCAD, because of their 3-dimensional visual pointing to interproximal contacts, the user gets an enlarged image and digital tools to calculate diameters and distances along certain planes. Depending on the orthodontist's preferences, abilities and training, measurements can be done more (or less) accurately on a computer screen than with the conventional calliper on plaster method (Santoro *et al*, 2003).

Watanebe-Kanno *et al* (2009) states that as the interproximal area between teeth may not be well defined, this can have the effect that the reproducibility of the measurements can be altered when the points are marked.

Schirmer and Wiltshire (1997) also found the digitized dimensions to be smaller than the manual dimensions. This was attributed to the complexity of measuring a 3D model in 2 dimensions, because of the curve of Spee, the convex structure of the teeth, and in inclination differences of the teeth.

Arch Width

Few studies in the literature have measured arch width, with only the those of Quimby *et al* (2004) and Watanebe-Kanno *et al* (2009) giving the individual arch width measurements.

In the current study the mean for the maxillary intercanine width for the plaster measurement was very slightly higher than that recorded for the digital and digital plaster, with the difference between plaster and digital and plaster and digital plaster being 0.229mm and 0.256mm respectively. This compared favourably with the study of Quimby *et al* (2004) and Watanebe-Kanno *et al* (2009) the comparable differences being 0.4mm and 0.16mm respectively, and their plaster measurements also being slightly higher.

For the maxillary intermolar width the plaster measurements and digital plaster measurements were very close with the digital measurement being slightly lower. For the maxillary intermolar width, the differences between the means for plaster and digital plaster models were 0.041mm and between plaster and digital models, 0.052mm (table 11). This compared favourably with Watanebe-Kanno *et al* (2009) and Keating *et al* (2008), their difference for this parameter between plaster and 3D models being 0.12mm and 0.14mm respectively. They found the plaster measurement to be slightly higher. Quimby *et al* (2004) differ in that they found the digital measurement of maxillary intermolar width to be higher by 0.4mm.

The mean for the mandibular intercanine width for the plaster measurement was slightly lower than the mean widths for the digital and digital plaster. The differences in the means between plaster and digital and plaster and digital plaster were 0.161mm and 0.104mm respectively (table 11). Watanebe-Kanno *et al* (2009) and Keating *et al* (2008) found the plaster measurement to be slightly higher, both recording 0.14mm difference. Quimby *et al* (2004) also found their mandibular intercanine width to be higher by a mean of 0.34mm for plaster measurements.

The plaster measurement of mandibular intermolar width was higher than that recorded for the digital and digital plaster. The differences in the means between plaster and digital and plaster and digital plaster were 0.656mm and 0.572mm respectively. Watanebe-Kanno *et al* (2009) found the plaster measurement for the mandibular intermolar width to be slightly higher by 0.12mm. Quimby *et al* (2004) found their mandibular intermolar width to be almost similar for plaster and digital measurements, with the digital measurement being slightly higher by 0.04mm.

The measurements for arch width in this study compared favourably with other reports, except for the mandibular intermolar arch width, which recorded a plaster measurement higher by ±0.6mm compared with the digital and digital plaster measurements (table 11). For the current study, the reason for such a high difference may be that quite a few patients who were included in the study had fillings and attrition on their lower molar teeth, making it difficult to consistently identify a cusp tip.

In the current study, the measurements of the plaster models were found to be higher, except for the mandibular intercanine arch width where the plaster measurements were actually the smallest. For the mean maxillary intermolar widths the plaster measurements were almost similar to the digital plaster measurement, being slightly lower at only 0.041mm. Both parameters recorded measurements higher than that taken on the digital version.

Accuracy of measurements

When using measuring callipers, such as the Vernier calliper, the method relies on the operator placing the tips of the calliper on definite landmarks and the distance must be read from the ruler on the calliper. Using a measuring calliper is for that reason subject to inter- and intraoperator variation (Bell *et al*, 2003), who state that even slight differences in the manual positioning of measuring callipers, and even when the points to be measured are visibly marked, there will always be variations in manual measurements. This applied equally to their study, as the operator was required to place the measuring tool on the landmarks on the 3D computer images.

Operator variation also plays a role when the measurements are done on 3D computer images. The operator has to use a mouse to click on the relevant points. Since the computer calculates the distance between points, there is no need for the operator to read a measuring scale (Bell *et al*, 2003).

In comparing the two systems, measurements done on computer-based models were larger than those done on plaster casts (Quimby *et al*, 2004). They hypothesized that the larger values for measurements done on the computer-based models may have several possible sources: (1) the process involved in producing the plaster models by the manufacturer, (2) the procedure when the cast model is scanned and data points recorded, (3) the increased time that gone before the irreversible hydrocolloid impressions were poured in plaster, (4) the display and measurement algorithms of the manufacturer's proprietary software, and (5) the examiners' lack of familiarity with the computer-based measurement of computer-based models.

All of these possibilities mentioned by Quimby *et al*, (2004) could also lead to smaller values.

According to Watanebe-Kanno *et al* (2009) the interproximal area between teeth may not be well defined, and this can have the effect that the reproducibility of the measurements can be altered when the points are marked.

The acceptance of computer-based models will depend primarily on their utility, and this in turn will depend on the cost-benefit ratio to the individual practitioner (Quimby *et al*, 2004).

Models can be viewed chair-side at the click of a button, and thousands can be stored on an external hard drive which can be the size of a book. The model can be shared over a network within an office or offices of a practice or with another party without it ever leaving the practice or without the danger of the models being damaged by handling. For minimal or no cost, a copy of the model can be secured at a second site. All these benefits are based on networked chair-side computers with their associated capabilities (and costs). When looking at the negative side, manufacturer insolvency, software failure or computer failure could possibly mean that the models may become unattainable for a time or lost forever (Quimby *et al*, 2004).

Digitizing of models would reduce the problems of space and cost concerned with the long-term mass storage of plaster study models. Since it is possible to make accurate measurements on 3D models, these models may still be used when reviewing treatment and for research purposes if the real plaster models have been discarded (Bell *et al*, 2003).

Malik *et al* (2009) in their study, states that for medico-legal purposes in the United Kingdom the Consumer Protection Act (1987) stipulates that retention of all patient records should be for no less than 11 years or, alternatively, until the patient reaches the age of 26 years (Machen 1991 cited in Malik *et al* 2009). However, if the equivalent information can be obtained from digital models, then problems such as model breakage, storage cost and storage space are removed, while medico-legal requirements are still fulfilled (Malik *et al*, 2009).

Rheude *et al* (2005) looked at the treatment planning and diagnostic value of digital study models when compared with plaster study casts. They evaluated whether the diagnosis or treatment plan (or both) would be altered if digital study models were used for orthodontic patients. They found that as the evaluators proceeded with their study and looked at more digital models, they recorded fewer variations between the plaster and electronic models. They suggested that for those who wish to use digital models, it may be advantageous to use both digital and plaster casts for an initial few patients. In addition, clinically recording the overbite, overjet, and the dental classification would be useful. For proposed surgical patients or unusual extraction patterns, plaster casts, for the present, may be more accurate. Rheude *et al* (2005) state that the results of their study indicate that digital study models can be used with success for orthodontic records in the vast majority of situations (Rheude *et al*, 2005).

Most studies concluded that digital models are clinically acceptable in initial diagnosis and treatment planning despite the occurrence of some statistically significant differences in the variables between the analog and the digital formats.

Akyalcin (2011) speculated that the causes of these results and the variability between different studies could be related to impression materials, handling techniques/operator errors, and the inevitable differences between the proprietary software used.

Considering the differences in the generation of digital study models, one can understand that scanning directly from the impression material, scanning through slices or surface scanning leading to the creation of the final digital model with proprietary algorithms may slightly alter the 3D volume and any spatial relation on it (Akyalcin, 2011).

Quimby *et al* (2004) found the computer models to be reasonably accurate and reliable. They found the differences between the plaster and computer models to be statistically significant. However these differences are generally small and leaves the clinician with the question as to whether such small differences are clinically significant. Digital models can furnish the clinician with enough information to develop a treatment plan. With this information available it might eliminate the need for storing plaster casts. According to these authors, the true test of clinical significance would be to establish whether treatment plans produced with plaster models differed significantly from treatment plans formed with computer-based models (Quimby *et al*, 2004).

Horton *et al* (2010) found that digital measurements tended to be slightly higher than actual plaster measurements. According to the authors this bias is small and they also found a strong correlation between the plaster and digital measurements. As a result they state that this should not restrict clinical use.

11.Conclusion

Digital models offer an alternative to plaster study models that is accurate, easy-to-use and efficient. Digital models have the potential to advance the practice of orthodontics and can also be seen to add value to the practice. When a practice is sold for instance, with digital models, the new practitioner can have all records available electronically and does not have to worry about broken or lost models. Digital models allow accurate measurements and the technique enables the visualization of planned treatment outcomes.

In a consultation, a patient's digital model has the potential to make possible improved communication between patient and clinician and also to have positive impacts on treatment.

When we compare digital study models to manual measurement on plaster study models, the digital study models offer a high degree of validity; any differences in measurement between the methods are likely to be clinically acceptable.

Many clinical Orthodontists prefer to have the plaster model available at chair side when treating patients. They use this as reference to arch form, intercanine width, intermolar width, etc. To save space after treating patients, these models can then be digitized after treatment has been completed.

Quimby *et al* (2004) state that the acceptance of computer-based models will depend primarily on their utility and this in turn will depend on the cost-benefit ratio to the individual practitioner.

12. Recommendations

From the results of the study, digital models for orthodontic purposes using the 3Shape R700™ scanner can be recommended as an alternative to plaster models.

For further studies looking into the accuracy of the 3Shape R700™ scanner, it is recommended that the inclusion criteria be extended. With the current study it is believed that the variability found for the intermolar width is partly due to the fact that a quite a few subjects had fillings on their molar teeth, or the cusps were worn down. This made it difficult to assess the intermolar width with the method that was chosen. This was only discovered after records were taken and near the end of collection of data. It is recommended that patients without fillings on the molar teeth be included in future studies.

The effect of measurement discrepancy on diagnosis and treatment plan could also be looked at in further studies.

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ADDENDUM A

MODEL NR ___________

DIGITAL MODELS

Max right	11	12	13	14	15	16
1st						
2nd						
3rd						

Max left	21	22	23	24	25	26
1st						
2nd						
3rd						

Man right	41	42	43	44	45	46
1st						
2nd						
3rd						

Man left	31	32	33	34	35	36
1st						
2nd						
3rd						

MAXILLA	INTERCANINE	INTERMOL1ST
1st measurem		
2nd measurem		
3rd measurem		
MEAN		

MANDIBLE	INTERCANINE	INTERMOL1ST
1st measurem		
2nd measurem		
3rd measurem		
MEAN		

PLASTER MODELS

Max right	11	12	13	14	15	16
1st						
2nd						
3rd						

Max left	21	22	23	24	25	26
1st						
2nd						
3rd						

Man right	41	42	43	44	45	46
1st						
2nd						
3rd						

Man left	31	32	33	34	35	36
1st						
2nd						
3rd						

MAXILLA	INTERCANINE	INTERMOL1ST
1st measurem		
2nd measurem		
3rd measurem		
MEAN		

MANDIBLE	INTERCANINE	INTERMOL1ST
1st measurem		
2nd measurem		
3rd measurem		
MEAN		

DIGITAL MODELS CREATED FROM SCANNED PLASTER MODELS

Max right	11	12	13	14	15	16
1st						
2nd						
3rd						

Max left	21	22	23	24	25	26
1st						
2nd						
3rd						

Man right	41	42	43	44	45	46
1st						
2nd						
3rd						

Man left	31	32	33	34	35	36
1st						
2nd						
3rd						

MAXILLA	INTERCANINE	INTERMOL1ST
1st measurem		
2nd measurem		
3rd measurem		
MEAN		

MANDIBLE	INTERCANINE	INTERMOL1ST
1st measurem		
2nd measurem		
3rd measurem		
MEAN		

Addendum B

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September 2011

Informed consent

Dear Patient,

Dr E MacKriel is a postgraduate student at the Faculty of Dentistry, University of the Western Cape. He will be using the impressions that will be taken as part of your normal orthodontic records to scan into a computer, and then poured into a plaster model. This is all part of the normal procedures during record taking in the course of your orthodontic treatment.

The impressions and the plaster models will then be used by Dr MacKriel for the purpose of a research project investigating the accuracy of orthodontic digital study models. There will be no cost implications to you, the patient other than what is set out by Dr Johannes for record taking. There will be no extra cost as a result of the research project.

The information that we receive from the impressions will be treated in strict confidentiality. Participation in the project is completely voluntary. No patient will be identifiable from the records and no patient related information will be used if research project is published.

Participation is voluntary and if you decide for your records not to be used, it will not affect whether you receive treatment or not. Please do not hesitate to contact me should you require any further information: Dr Earl MacKriel Tel: 0826571973 e-mail: earl.chrislynn@telkomsa.net

Thanking you in advance for your participation.

I understand the information that has been provided to me and I hereby give consent for my records to be used for the research project.

Patient Name & Signature:

Witness Name & Signature:

Date: