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Comparison of the accuracy between 3D printed and milled dental models by a digital inspection software

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THESIS

COMPARISON OF THE ACCURACY BETWEEN 3D PRINTED AND MILLED DENTAL MODELS BY A DIGITAL INSPECTION SOFTWARE.

by

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DEDICATION

There is a famous saying *"No man is an island".* With that in mind, I would like to dedicate my dissertation work to my family, friends and mentors. A special feeling of gratitude to my loving wife, Sana Banday, whose continuous support has led to this accomplishment. My parents Saeed and Lalarukh, whose words of encouragement and push for tenacity ring in my ears. My mentors Dr Ninette and Burhan Banday have never left my side and are very special.

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COMPARISON OF THE ACCURACY BETWEEN 3D PRINTED AND MILLED DENTAL MODELS BY A DIGITAL INSPECTION SOFTWARE

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ABSTRACT

Statement of Problem: The production of full arch dental models through Rapid Additive Prototyping (3D Printing) have been questioned for their accuracy in the past decade.

Purpose: To compare the accuracy of 3D printed and milled dental models, using a digital metrology software.

Materials and Method: A mandibular arch typodont was duplicated to produce a conventional Type IV dental stone model. This Model was scanned to create a digital model and an STL file was created which would be sent to Milling and 3D printing machines.15 models were printed using 3 different 3D printing companies and 10 models Milled with a CNC (Computerized Numeric Controlled) milling machine. Each model was scanned and a digital model was created. These scanned models were then super imposed to the scan of the master model through an inspection software (Geomagic Control X, 3D Systems) for accuracy of production.

Results: The mean difference in measurement in Absolute Gap, by either of the two methods of prototyping adopted, (0.075 mm for 3D Printed and 0.084 mm for milled) are well below the clinically acceptable values mentioned in previous literature.

The means in absolute tooth distance discrepancy for both prototyping methods (0.0361 mm for 3DPand 0.0353 mm for Milled) were not statistically significant.

Conclusion: 3D printed dental models were more accurate statistically than milled dental models. In general, the mean accuracy for both methods of rapid prototyping is within clinical tolerance and both are clinically acceptable.

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CHAPTER 1. INTRODUCTION

1.1 History

Conventional methods for fabrication of dental restorations have been practiced successfully and predictably in the past few decades. Advancements in material science have offered dentists a variety of impression materials which can allow them to reproduce patient's oral conditions[1]. Despite this, some inaccuracies are inevitable. These may be due to handling of material or properties of material themselves.

A study by *Nicholls* [2] showed that the accuracy and dimensional stability of different impression materials was affected by variables such as time taken to pour the impressions, conditions of storage and the elastic properties of the impression materials.

Murat Alkurt et al[3] conducted a study evaluating the effect of storage time on the accuracy of impression materials and concluded that different impression materials when stored under suitable conditions can produce accurate and clinically acceptable results as far as dimensional stability is concerned.

There is no single impression material of choice that can be used for all prosthetic procedures. This has been confirmed by *Hamalian et al*[4] who discussed the properties of different impression materials and reported that an ideal impression material has not yet been produced and each material is superior and inferior to the others in different aspects.

1.2 Conventional Methods

This inaccuracy of the impression materials in turn affects the casts obtained from them.

Pouring stone casts from impressions is an additional step which could induce error. All gypsum products undergo dimensional changes during setting[5,6,7]. Accuracy of casts is of vital importance to fabricate dental restorations**.** *Taylor and Lynch*[8] reported marginal adaptation is one of the most important factors in determining a restorations longevity. They concluded that inadequate margins can result in micro leakage which could cause a number of sequelae compromising the tooth's prognosis. *Christensen*[9], in one of the earliest studies on marginal integrity, reported that the least acceptable visually accessible margin is 39um. Despite its importance, a study by *Dedmon*[10] concludes that there is no agreement on the definition of what is a clinically acceptable margin among experts.

According to the ADA standards a cast restoration should not have a space between its abutment tooth of more than 40um which is the space for the cement thickness.[11]

According to, ADA dental gypsum products are classified into 5 types, depending on their physical properties and use[11]: Type I: impression plaster; Type II: model plaster; Type III: stone; Type IV: high strength, low expansion stone; and Type V: high strength, high expansion stone. To achieve accurate casts, Type IV and V dental stone have been the dental stone of choice as they are easy to use, have good dimensional stability, compatible with majority of impression materials, acceptable setting expansion and good resistance to abrasion.[12],[13]

However, *Schwedhelm and Lepe*[14] in their study reported that due to their hardness they have poor abrasion resistance and also result in fracture while removing them from impressions. This is why the authors recommend that casts should be removed 12-24 hours after they have been poured for optimal strength. This wait time creates delays in the process of fabrication of the restoration and prove to be costly for dental laboratories.

As gypsum products evolved, another problem to address was disinfection***.*** *Firtell et Al 1972*[15]*, Rowe and Forrest,1978*[16] *and Leung and Schonfield 198*[17*5*], all demonstrated that microorganisms have been recovered from gypsum casts. This resulted in studies that aimed to disinfect casts. A Study by *Ivanovski Et Al*[18]not only confirmed the results of the above authors but also concluded that not only do disinfectants effect the physical properties of stone casts but the effects vary with different disinfectants. Although glutaraldehyde is the disinfectant of choice due to its toxicity it cannot be used on a day to day basis in clinic or laboratory.

In addition, storage of dental models and accidental fractures during transportation could also occur. *Michalakis et al*[19] studied the delayed linear expansion of gypsum products and reported that the conditions in which gypsum models are stored, humidity and temperature, could have negative effects on the models expansion characteristics.

1.3 Digital Age

Digital impressions resulting in digital models have been studied for accuracy and reproducibility. Although digital models are slightly less accurate than their plaster counter parts the inaccuracies reported are clinically insignificant[20,21,22] A recent systematic review concluded that digital models obtained from different techniques offer a high degree of validity in linear measurements compared with those made on plaster models directly and are generally clinically acceptable. Therefore, digital models are recommended as an alternative to conventional plaster models[23].

After obtaining digital models, the two most common methods now being utilized for physical production of these models are subtractive prototyping and additive prototyping.

3D Printing is a manufacturing approach that builds objects, a layer at a time, either top – down or bottom – up which result in multiple layers forming an object. The process is more correctly described as Rapid Additive Prototyping[24,25]

Dentistry has had a long association with subtractive Prototyping, commonly known as “Milling” [26].CAD/CAM for the milling of crown and fixed partial denture frameworks is synonymous with modern dental technology.

CAM (Computer Aided Manufacture) has been present in dentistry since the 1980’s and since its introduction several advancements for efficient milling have been made. The 5 axis milling machines today are the most versatile as they are able to produce precise details which some complex restorations require. *Torabi et al* [25]in their study concluded that the CAD/CAM system could compete well with conventional systems for clinical fit and fracture resistance and can achieve acceptable results in vitro.

A recent study by *Jae Hong Kim* et al [27] was done in which milled polyurethane dental models were compared with conventional plaster models. The results showed that the mean difference between plaster models and PUT models ranged from 0.07 mm to 0.33 mm. These results were statistically different however clinically insignificant and they concluded that the accuracy of Subtractive rapid prototyping was acceptable.

Although Subtractive prototyping has dominated the dental industry in the past decade, in recent years Rapid additive prototyping has become the more appealing method in dentistry. This is because dental laboratories have realized that a lot of raw material is wasted due to unused portions of the milling blocks. In addition, the milling tools are exposed to abrasion and wear and replacing them is costly.

Contrary to Subtractive prototyping, *Andonovic et al and azari* et al[26] in separate studies discussed the most frequent rapid additive prototyping technologies that have been adopted in dentistry. They are:

1. Fused Deposition Modelling

2. Stereo lithography (SLA)

3. Inkjet-based system (3DP),

4. Selective laser sintering (SLS).

One of the early studies by *Keating et al* [28] compared the accuracy between plaster models and their 3D printed replicas concluded there was a significant difference in vertical dimension of the replicas possibly because of the thick layers (0.15 mm) which were used to build.

Since then there have been several studies comparing the accuracies of different methods of 3d printing technologies.

Hazeveld et al [29]compared plaster models with dental replica models. In this study, mean deviations of the replica teeth manufactured with FDM and PolyJet methods were 0.047 mm and 0.038 mm which meant that both printing technologies are reliable and accurate.

A similar study in which comparison of measurements were made on plaster and digital models to study overjet and overbite discrepancies. The conclusion was that although the models showed statistics that were significantly different, clinically they were insignificant and digital models could be a more efficient way of making routine orthodontic measurements and study discrepancies.

Since 3D printing involves additive layers being deposited on a platform, the angle at which the layers are being built could have an impact on the final product accuracy. A study by *Alharbi N et al* [30] concluded that the preferred build angle should be the one that minimizes the need for support of the built product and which requires the least time for finishing which reduce the chance of error.

This study is to compare the accuracy of 3D printed and milled dental models. It is evident from the above literatures that any material used in dentistry is expected to have some change in dimension due to material handling. The outcome of such a study could have an impact on the preferred method of model fabrication specially with respect to efficiency.

CHAPTER 2. MATERIALS AND METHOD

2.1 Master STL file preperation

In this study, a typodont (I21D-400G, Kilgore International, Coldwater, MI) of the mandibular arch was used to create a master stone model. This was done by creating a negative replica of the typodont by an Addition-vulcanizing duplication silicone Z-Dupe 15 Sh-A light blue (Henry Schein, Melville, N.Y.). The material was mixed according to the manufacturer's instructions in equal proportions and was allowed to set for the time recommended. After the negative replica was obtained it was poured with low expansion die stone Type IV (Silky-Rock WhipMix Louisville, KY, USA®) to create a positive replica which served as the master model for this study. (Fig 1)

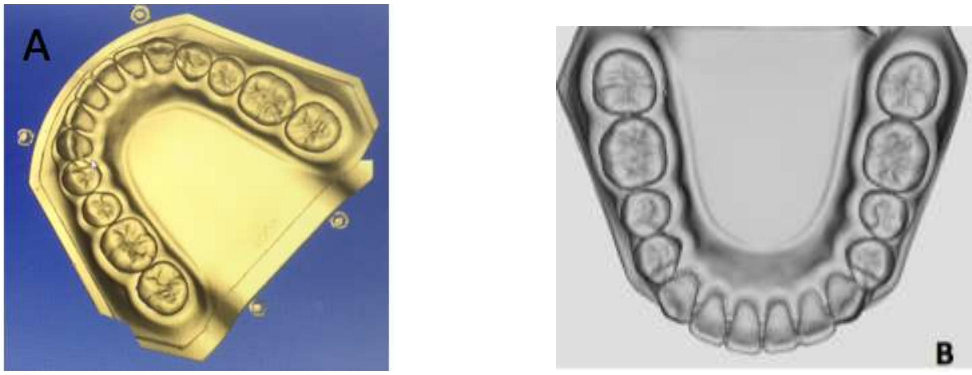
Figure 1. Master stone model mandibular arch

The CEREC- Optispray Sirona (Bensheim, Germany) was sprayed on master model for better image recognition by the scanner and the master model was scanned by an extra oral scanner inEos X5 (Sirona Version: 123523) (Fig 2) which is known for its high precision (<12um).

Figure 2.Sirona inEos X5 Scanner (Extra Oral)

Mandibular arch in type IV dental stone was mounted on the tripod after being sprayed by CEREC-Optispray.

The scanner was coupled with the Sirona(Version: 123523) inLab software. The model design “capture reduced” function of the software was utilized to scan the master model. This generated a virtual model through complete reconstruction of the mandibular arch. (Fig 3). The scanned image was stored as an StereoLithography (STL) file. (Fig 3).



A) Created by Sirona inLab software of the master model B) After the model was converted to an STL file format

Figure 3. Digital Images of master stone model

This STL file (Original) was then exported to a model builder which processed the model to create a base for the digital model which would later help in super imposition with the inspection software. (Geomagic, 3D systems) used in this study. The file obtained from model builder was designated as the master STL file which was then exported to 3D printers and Computerized-Numeric Controlled Milling machines.

A) File being processed in model builder B) Master STL file after processing

Figure 4.Model builder and master STL file

2.2 Rapid prototyping

A) FormLabs Form2. B) Stratasys Objet500. C) 3D Systems, Dreve ProJet 7000HD

Figure 5.Printers used in this study

In this study three different 3D companies namely, FormLabs Form2 (Somerville,MA) , Stratasys (Eden Prairie) and Dreve (3D systems Dentamid Unna, Germany) (Fig 4) were utilized to print models of the scanned mandibular arch. All printers utilize technology in which a photopolymer, resin, is cured upon exposure to UV light which builds high resolution physical models. The models from Formlabs and Dreve are built top-down and the models from Stratasys are built bottom up. A total of 15 models were printed, 5 from each company. Fig 5 shows an example of the printed models immediately after production and the steps required post production.

The models printed from Dreve required FotoDent Flash, a light curing unit, in which the models were exposed to 12 minutes of UV light.

The models from FormLabs require 20 mins of processing in a post curing oven. Stratasys required a water jet spray to remove the layer of uncured resin after production.

Fig.5 shows the printed models using the FormLabs Form2 printer with the supporting structures.

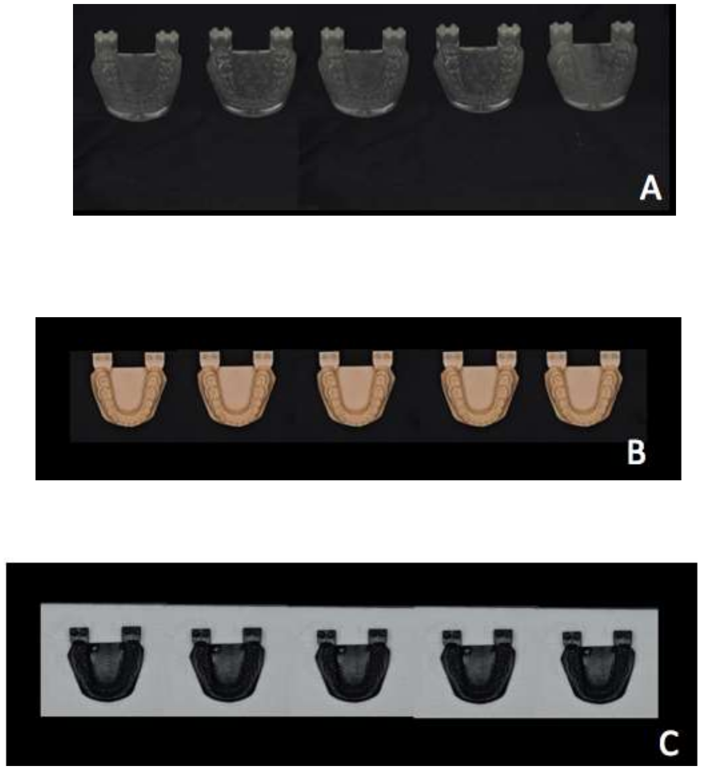
Figure 6.Printed models with support structures.

The resin used for each printer was the following:

FormLabs: Form2 Clear Standard V2 Resin - 0.025 mm layer height

Stratasys: VeroBlack Matte resin - 0.028 mm layer height

Dreve: FotoDent model opaque Beige Resin - 0.038 mm layer height



A) FormLabs. B) Dreve C.Stratasys

Figure 7.Printed models from different printers

10 models were milled using the CNC milling machine Weiland Dental ZENOTEC Select Hybrid (Pforzheim, Germany). The material that was used to mill was Polyurethane Puck 30 mm thickness Proto3000 (ON L4H 4G3, Canada) (Fig 7).

A)Weiland dental milling unit ZENOTEC select. B) Milled dental Models

Figure 8.Milling Unit

Depending upon the printing company the dental models then undergo different post production handling steps in order to obtain optimal product results. Similar post production steps are required for milled mandibular lower arch from a polyurethane puck. (Fig 8).

A) After post curing the support area was removed with pliers. B) The excess PUT was removed in the same way.

Figure 9.Printed and milled models post production

Following production, each of the printed and milled models were scanned with the same scanner (Sirona inEos X5). Virtual models were created using Sirona inLab software Version 15.0 and stored as STL files. (Fig 9)

2.3 Geomagic software

After all the specimens were scanned a 3D inspection software Geomagic Control X by 3D systems (Rock Hill, SC) was used to evaluate accuracy of the printed and milled models.

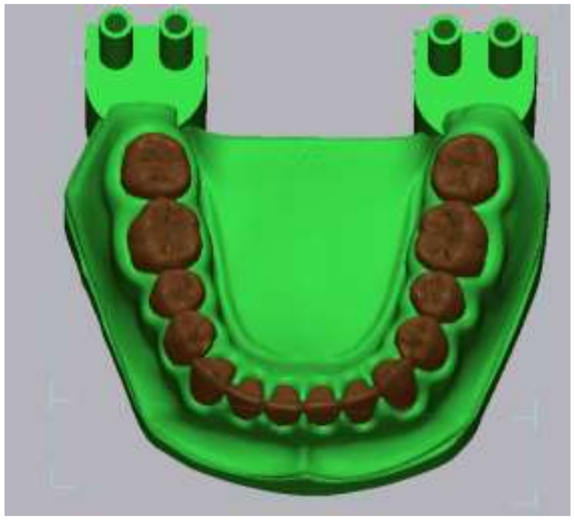
The master STL file created from the model builder (CARES® Sirona Software) was super imposed to the original STL file that was obtained after the mandibular arch was scanned. The super imposition was done by selection of several points on the master STL file. The Geomagic Control X software had a feature in which a particular region could be defined which is shown in below (Fig 11). A total of 568 comparison points were selected on the master STL file. For the purpose of this study the points of interest were located only on the teeth all other areas were excluded. The comparison points were grouped according their location of comparison points. (Fig 12)

1. Cervical – 380 points. These points were created on a curve by the software.

2. Buccal Cusp tips – 60. Manually selected and 3 points per cusp tip

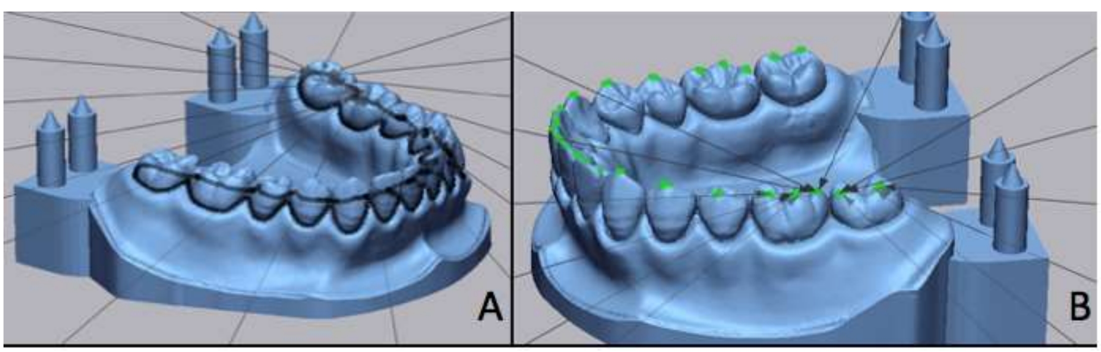
3. Lingual cusp Tips – 36. Manually selected and 3 points per cusp tip

4. Center of the Teeth – 92. Manually selected and 3 points per fossa.



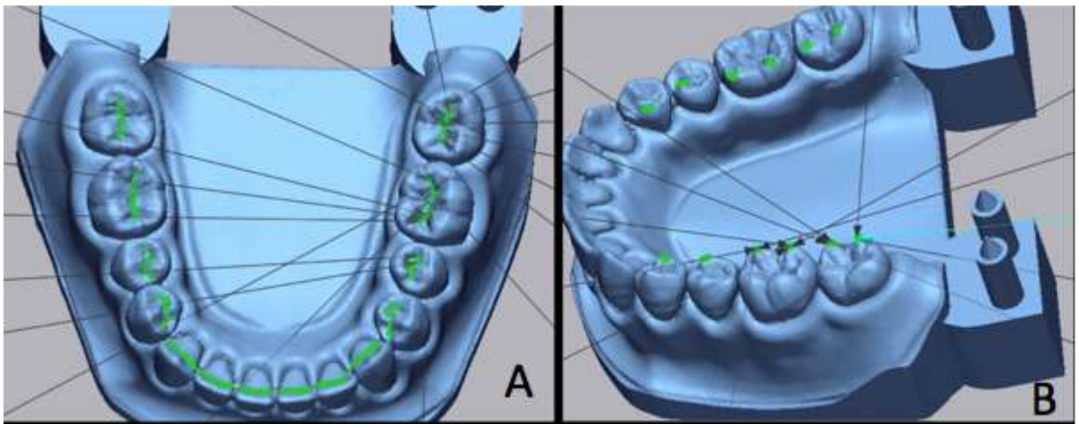
The master STL file was divided into two regions as depicted in the above image by difference in color.

Figure 10.Regional Division of master STL file



A) Cervical points were located on the buccal and lingual surfaces of the teeth from #18 to #31 B) On buccal cusp tips of #18 to #31

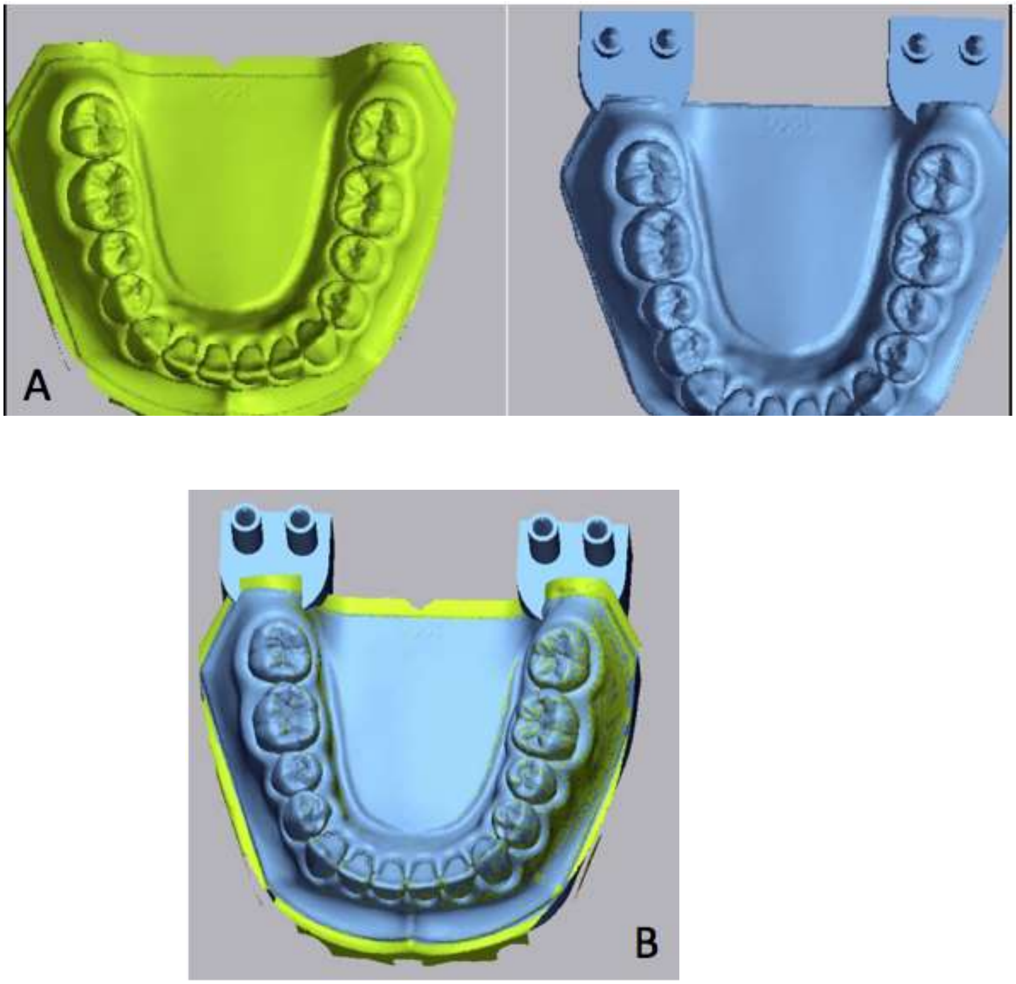
Figure 11. Location of comparison points



A) Occlusal comparison points from #18 to # 31. B) Lingual comparison points from #18 to #21 and #28 to #31

Figure 12. Location of comparison points

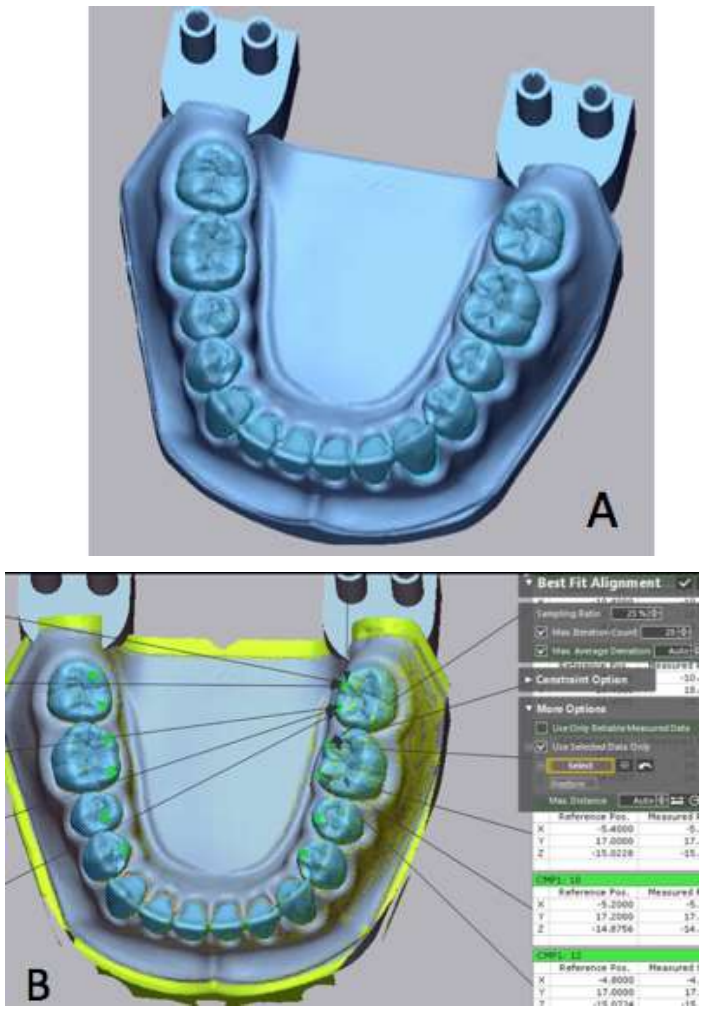
. Each point was defined by X, Y and Z coordinates. The software designates this file as the “reference model”. Following this, the “measured model”, which was the original file obtained, was imported to the software. Both the models were designated different colors in order to observe any differences to the naked eye on a macro level (Fig 14).



A) The measured model imported to the software before alignment B) After initial Alignment

Figure 13. Superimposition of images

The software “merges” the measured model on to the reference model with a function called “initial alignment” (Fig 14 B). This step is the most important step as it also reflects the quality of the scans for all specimens. If the scan quality is poor, the software doesn’t allow the user to proceed which means the scans have to be repeated. Following the initial alignment, a region is defined restricted to the teeth, as described previously in Fig 11 in order to command the software to use its “best fit alignment” function to further optimize the mapping.



A) Selecting a region prior to using the best fit alignment. B) After best fit alignment.

Figure 14. Best Fit alignment

The result is a set of data which is organized into X, Y and Z coordinates comparing both the reference and measured model. The method in which the software expresses any deviations is through “gap distances”. It is the analysis of these gap distances between the reference and measured model that help determine the accuracy of the measured model which in this case, was the control.

The measured data set obtained from the digital file (control) was then used to compare all the measured data that was obtained after mapping the previously scanned printed and milled dental models.

All specimens were imported to the Geomagic Control X software and sequentially mapped and each group (Cervical, buccal cusp tips, lingual cusp tips, center of the teeth) were done individually and stored as separate files.

The data from each was exported as an “Excel Data sheet “and was further organized into the following.

1. Company: Dreve, Formlabs, Stratasys

2. Method of fabrication: printed or milled

3. Material used: resin or polyurethane

4. Location of measurement points: cervical, buccal cusp tips, lingual cusp tips, center of teeth.

5. Orientation: buccal, lingual or occlusal

6. Point ID

7. Tooth number (American tooth numbering system).

In addition to comparing the gap distances mentioned above, the following distances were also obtained by selecting points of interest on the mandibular arch.

1) Inter - second molar: Tooth #18 and #31

2) Inter-first molar: Tooth #19 and #30

3) Inter - second premolar: #20 and #29

4) Inter - first premolar: #21 and #28

5) Inter canine: #22 and #27

These points of interest were selected on the buccal cusp tips of the premolars, molars and canine tooth. The first set of tooth distances was obtained for the reference file. Following this each sample of the printed and milled models were compared to the distance values of the reference files.

Clinically, the buccal cusp tips play an important role in holding the vertical dimension of occlusion and defining the curve of spee as they are the primary centric holding cusps. This is the reason why these were selected as our points of interest. 3 points were selected on each cusp tip.

2.4 Defination of accuracy

Since the purpose of this study is to evaluate the accuracy, ISO 5725 was referred to define the terminology about accuracy. ISO 5725 uses two terms "trueness" and "precision" to describe the accuracy of a measurement method. "Trueness" refers to the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value. "Precision" refers to the closeness of agreement between test results. In this study, the trueness of interested points for comparison is the mean gap distance of the comparison points. The precision of interested points, which can also be named ‘reproducibility’ in this study, is the standard deviation of the measured points. The trueness of interested tooth distance is the mean discrepancy of the tooth distances between measured and reference.

2.4 Statistical analysis

Statistical analysis was done using JMP Pro 13.0 software. One-way ANOVA was used to calculate the means and standard deviations for 1. absolute gap distance of the teeth, 2. absolute tooth – distance discrepancy, and compare the differences between groups with a significant level of a=0.05.

CHAPTER 3. RESULTS

3.1 Absolute gap distance of comparison points

3.1.1 Absolute gap distance of comparison points at buccal cusps

Absolute gap distance deviation from reference at buccal cusp is shown in Table 1 and Figure 16. The results show that the models printed with FormLabs, Weiland and Stratasys are significantly different.

Table 1.Means and standard deviations of absolute gap distance (mm) on buccal cusp.

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Digital	60	0.0037	0.0021	0.0027	A
FormLabs	300	0.0362	0.0270	0.0015	B
Stratasys	300	0.0474	0.0434	0.0025	C
Dreve	300	0.0533	0.0371	0.0021	C D
Weiland	600	0.0567	0.0413	0.0016	D

*Levels not connected by same letter are significantly different

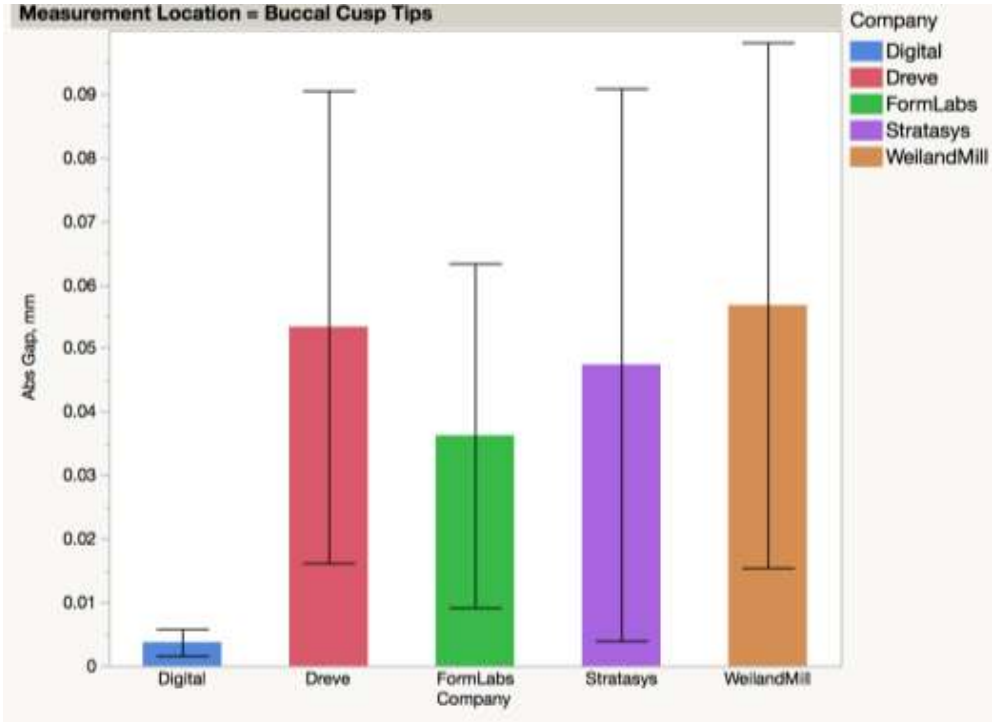


Figure 15.Mean of absolute gap distance at buccal cusp tips by company.

Each error bar is constructed using one standard deviation from the mean

3.1.2 Absolute gap distance of comparison points at centre of teeth.

Absolute gap distance deviation from reference at center of teeth is shown in Table 2 and Figure 17. The results show that no significant differences can be seen between the rapid prototyping methods.

Table 2. Means and standard deviations of absolute gap distance (mm) at center of teeth.

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Digital	92	0.0054	0.0030	0.0003	A
Weiland	920	0.0398	0.0316	0.0014	B
FormLabs	460	0.0415	0.0318	0.0014	B
Stratasys	460	0.0420	0.0307	0.0014	B
Dreve	460	0.0442	0.0344	0.0016	B

*Levels not connected by same letter are significantly different

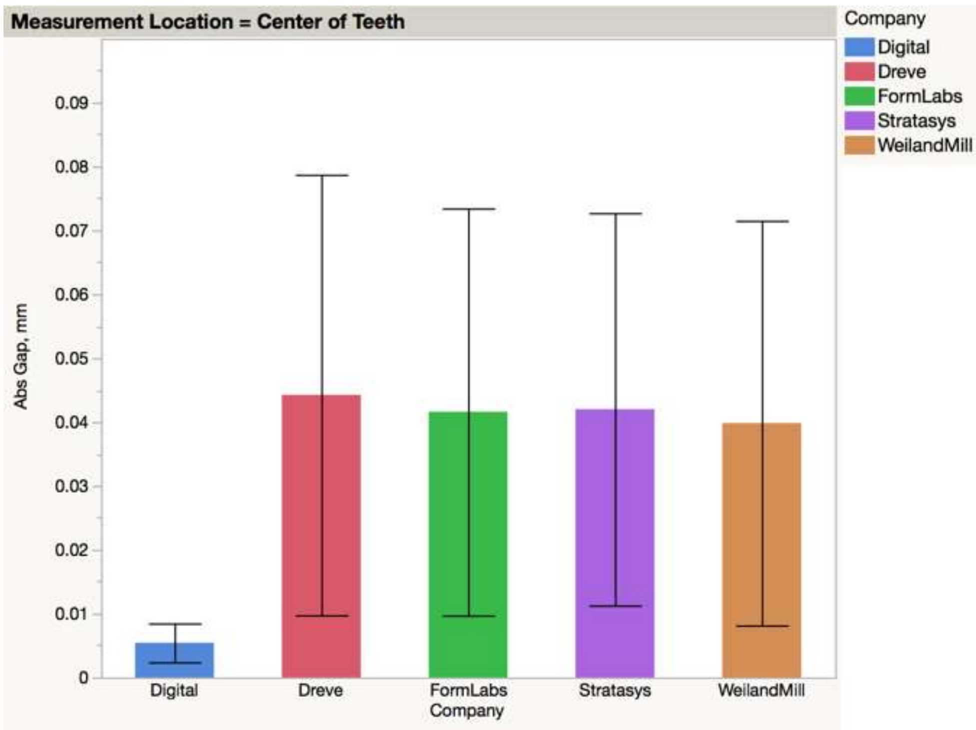


Figure 16. Mean absolute gap distance at center of teeth by company.

Each error bar is constructed using one standard deviation from the mean.

3.1.3 Absolute gap distance of comparison points at cervical

Absolute gap distance deviation from reference at cervical is shown in Table 3 and Figure 18. The results show that no significant difference can be observed between Dreve and Formlabs However, Weiland and Stratasys are significantly different.

Table 3.Means and standard deviations for absolute gap distance (mm) at Cervical

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Digital	380	0.0059	0.0070	0.0036	A
FormLabs	1899	0.0497	0.0604	0.0013	B
Dreve	1893	0.0558	0.0442	0.0010	B
Weiland	1887	0.1019	0.0944	0.0015	C
Stratasys	3736	0.1653	0.1501	0.0034	D

*Levels not connected by same letter are significantly different

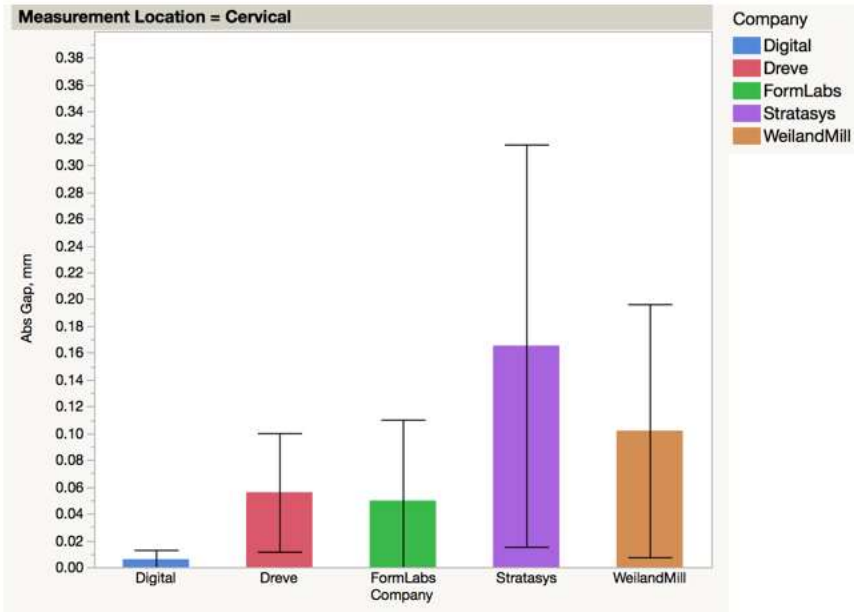


Figure 17.Mean absolute gap at cervical by company

Each error bar is constructed using one standard deviation from the mean

3.1.4 Absolute gap distance of comparison points at lingual cusp tips

Absolute gap distance deviation from reference at lingual cusp tips is shown in Table 4 and Figure 19. The results show that no significant difference exists between Formlabs and Stratasys. Weiland is significantly different to Formlabs.

Table 4.Means and standard deviations of absolute gap distance (mm) on lingual cusp tips.

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Digital	36	0.0034	0.0022	0.0038	A
FormLabs	180	0.0506	0.0367	0.0027	B
Stratasys	180	0.0509	0.0378	0.0028	B
Dreve	180	0.0600	0.0386	0.0028	B C
Weiland	360	0.0612	0.0413	0.0021	C

*Levels not connected by same letter are significantly different

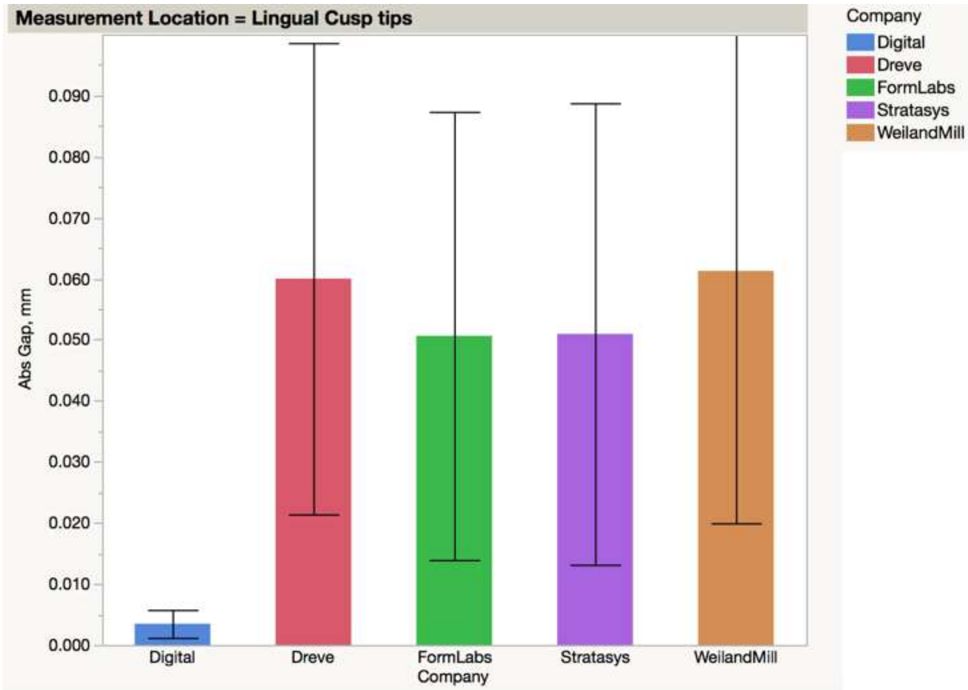


Figure 18**.** Mean absolute gap distance at lingual cusp tips by company.

Each error bar is constructed using one standard deviation from the mean.

Table 5.Summary of absolute gap and gap distances of tested models

			Abs Gap, mm			Gap Dist, mm		
Company	Material	Measurement Location	N	Mean	Std Dev	N	Mean	Std Dev
Digital	Digital	Buccal Cusp Tips	60	0.0037	0.0021	60	-0.0035	0.0024
		Center of Teeth	92	0.0054	0.0030	92	-0.0054	0.0031
		Cervical	380	0.0059	0.0070	380	-0.0046	0.0079
		Lingual Cusp tips	36	0.0035	0.0023	36	-0.0034	0.0024
Dreve	Resin	Buccal Cusp Tips	300	0.0534	0.0372	300	-0.0500	0.0416
		Center of Teeth	460	0.0442	0.0345	460	0.0235	0.0510
		Cervical	1899	0.0559	0.0442	1899	0.0517	0.0490
		Lingual Cusp tips	180	0.0600	0.0386	180	-0.0545	0.0461
FormLabs	Resin	Buccal Cusp Tips	300	0.0363	0.0271	300	-0.0302	0.0337
		Center of Teeth	460	0.0416	0.0319	460	0.0134	0.0507
		Cervical	1893	0.0497	0.0604	1893	0.0428	0.0655
		Lingual Cusp tips	180	0.0506	0.0367	180	-0.0442	0.0443
Stratasys	Resin	Buccal Cusp Tips	300	0.0474	0.0434	300	-0.0430	0.0478
		Center of Teeth	459	0.0420	0.0307	459	0.0176	0.0490
		Cervical	1877	0.1654	0.1501	1877	0.1353	0.1777
		Lingual Cusp tips	180	0.0510	0.0378	180	-0.0441	0.0456
WeilandMill	PUT	Buccal Cusp Tips	600	0.0568	0.0413	600	-0.0528	0.0463
		Center of Teeth	920	0.0398	0.0317	920	0.0213	0.0462
		Cervical	3736	0.1019	0.0944	3736	0.0906	0.1053
		Lingual Cusp tips	360	0.0613	0.0413	360	-0.0563	0.0479

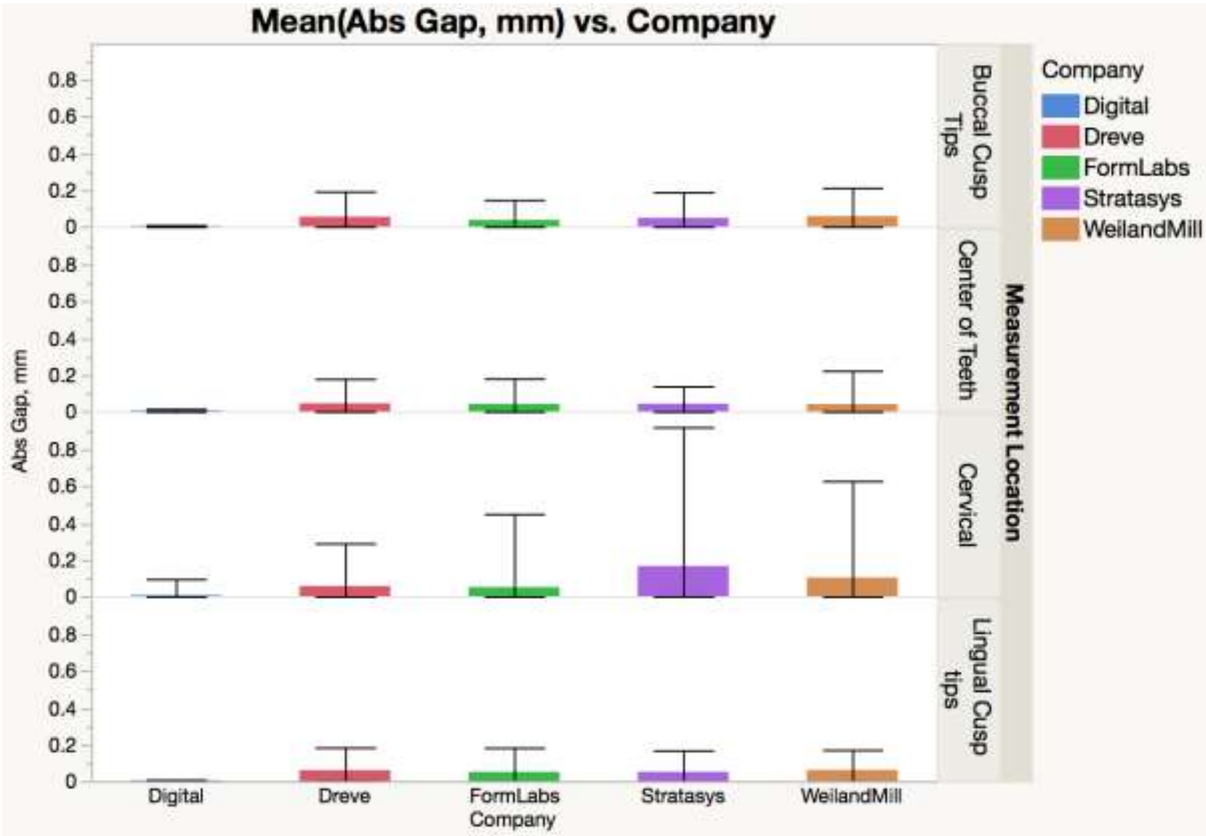


Figure 19.Means of absolute gap distances according to company and measurement location.

Each error bar is constructed using the maximum and minimum of the data.

3.1.5 Summary of absolute gap distance of comparison points by technique

Table 6 is a summary of results by 3D printing and milling. Statistically significant difference exists in absolute gap distance between the 3D printed and milled dental models.

Figure 21 depicts that the largest discrepancy is seen at cervical location for both printed and milled methods while the lowest is at the center of the teeth.

Table 6. Means for One Way ANOVA for absolute gap discrepancy by technique.

Levels	Number	Means	Std Err	*Sig
Control	568	0.0054	0.00372	A
Printed	8488	0.0753	0.00096	B
Milled	5616	0.0843	0.00118	C

*Levels not connected by same letter are significantly different

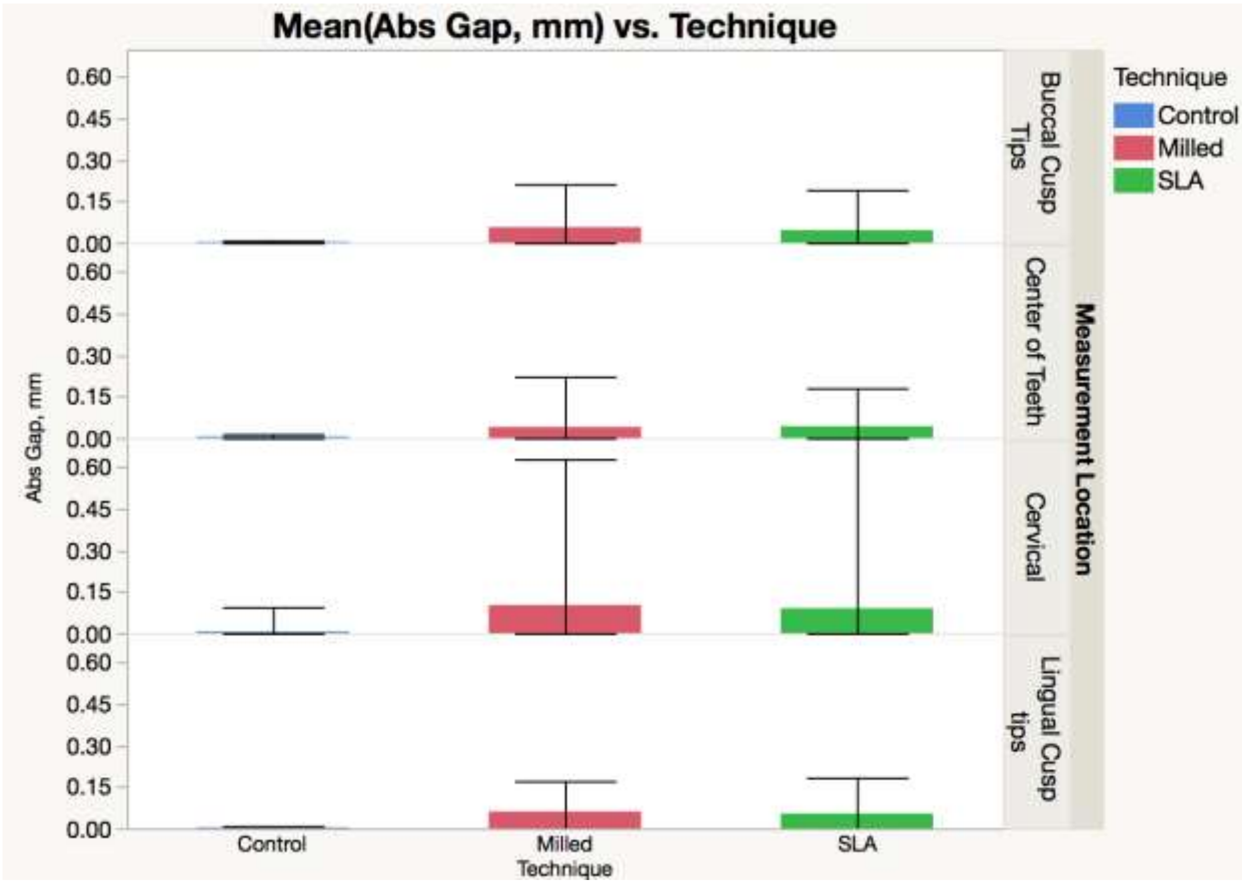


Figure 20.Means of absolute gap by technique where each error bar is constructed using maximum and minimum data

3.1.6 Measured X vs Measured Y on interested points

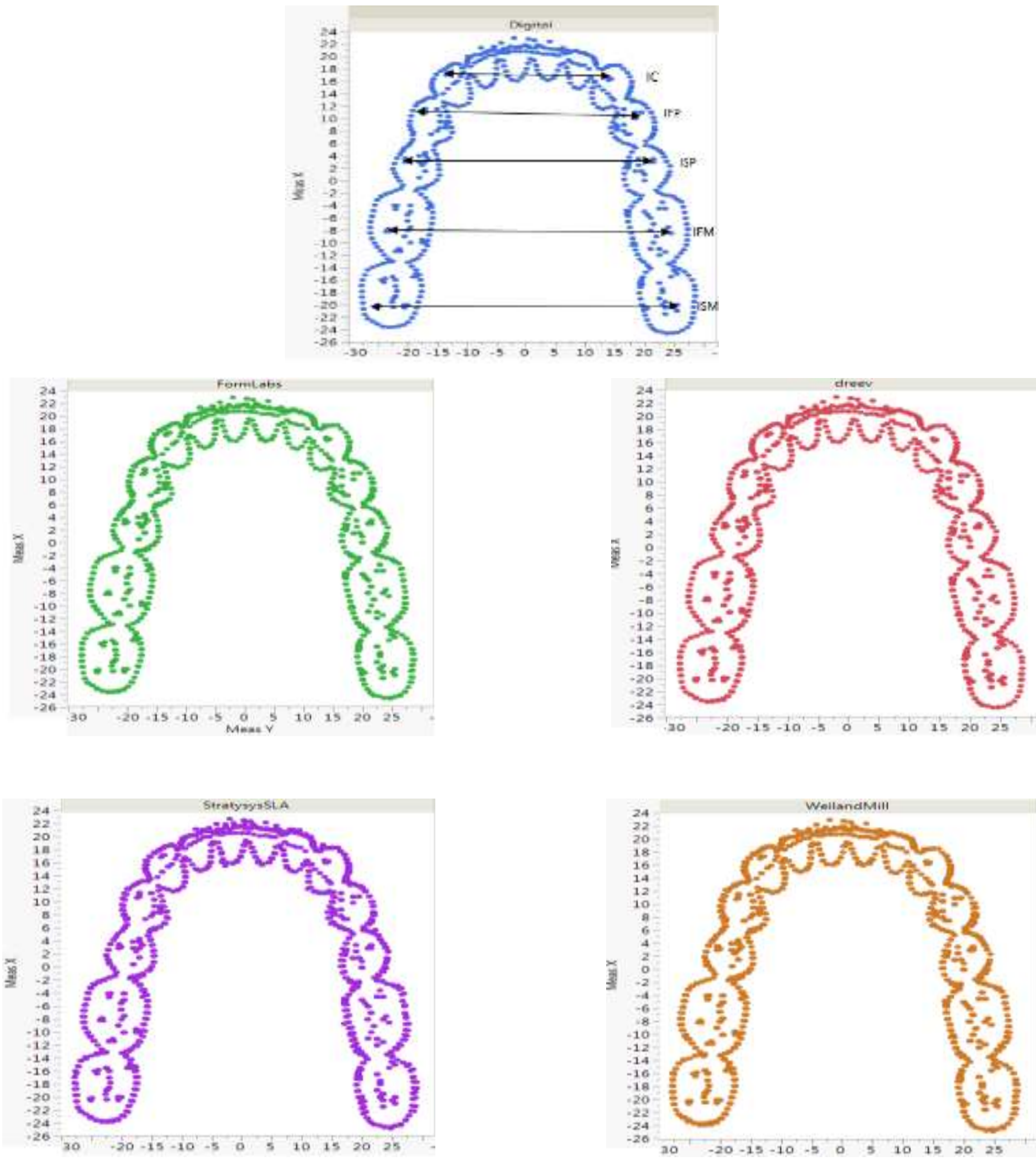


Figure 21.Plot of measurement X vs measurement Y on interested points.

3.2 Trueness and precision of interested points

Table 7. Trueness and precision of interested points.

	Trueness (mm)	Precision (mm)		
Company	**Mean ± SD**	**X**	**Y**	**Z**
Digital	0.0055 ± 0.0060 A	.	.	.
Dreve	0.0540 ± 0.0311 B	0.0137 ± 0.0114 A	0.0156 ± 0.0138 A	0.0213 ± 0.0174 A
FormLabs	0.0470 ± 0.0230 B	0.0224 ± 0.0255 B	0.0238 ± 0.0248 B	0.0242 ± 0.0178 A
Stratasys	0.1257 ± 0.937 D	0.0445 ± 0.0496 D	0.0518 ± 0.0538 D	0.0554 ± 0.0508 C
WeilandMill	0.0844 ± 0.0539 C	0.0310 ± 0.0331 C	0.0332± 0.0313 C	0.0363 ± 0.0270 B

In each column, levels not connected by same letter below numbers are significantly different.

Table 8.Trueness and precision of interested points by technique

	Trueness (mm)	Precision (mm)		
Company	**Mean ± SD**	**X**	**Y**	**Z**
Milling	0.0844± 0.0539 B	0.0310±0.0331 B	0.0332±0.0313 A	0.0363±0.0270 A.
Printing	0.0756 ± 0.0684 A	0.0268 ±0.0353 A	0.0304±0.0383 A	0.0336±0.0361 A

In each column, levels not connected by same letter below numbers are significantly different

Table 9.Trueness and precision of interested points by measurement location

	Trueness (mm)	Precision (mm)		
Measured Location	**Mean ± SD**	**X**	**Y**	**Z**
Buccal Cusp Tips	0.0395±0.0232 A	0.0094±0.0075 A.	0.0129±0.0113 A.	0.0375±0.0165 B.
Center of Teeth	0.0346±0.0240 A	0.0164±0.0099 A	0.0141± 0.0140 A	0.0238±0.0123 A
Cervical	0.0757±0.0747 B	0.0352±0.0400 B	0.0399±0.0413 B	0.0363±0.0400 B
Lingual Cusp tips	0.0453±0.0274 A	0.0105±0.0088 A	0.0121± 0.0104 A	0.0339±0.0159 B

In each column, levels not connected by same letter below numbers are significantly different.

3.3 **Trueness of tooth distance of models by company**

3.3.1 **Trueness of tooth distance by Dreve.**

Absolute deviations of tooth distance from reference by Dreve are shown in Table 10 and Figure 23. The results show that the trueness between inter first molar and intercanine distances was significantly different. No significant differences of trueness among inter first premolar, inter second premolar and inter - second molar distances were found.

Table 10.Means and standard deviations of absolute tooth distance discrepancy by Dreve

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Inter first molar	15	0.0205	0.0171	0.0044	A
Inter first premolar	15	0.0340	0.0190	0.0049	A B
Inter second molar	15	0.0448	0.0399	0.0103	A B
Inter second Premolar	15	0.0526	0.0495	0.0127	A B
Inter canine	15	0.0581	0.0403	0.0104	B

*Levels not connected by same letter are significantly different

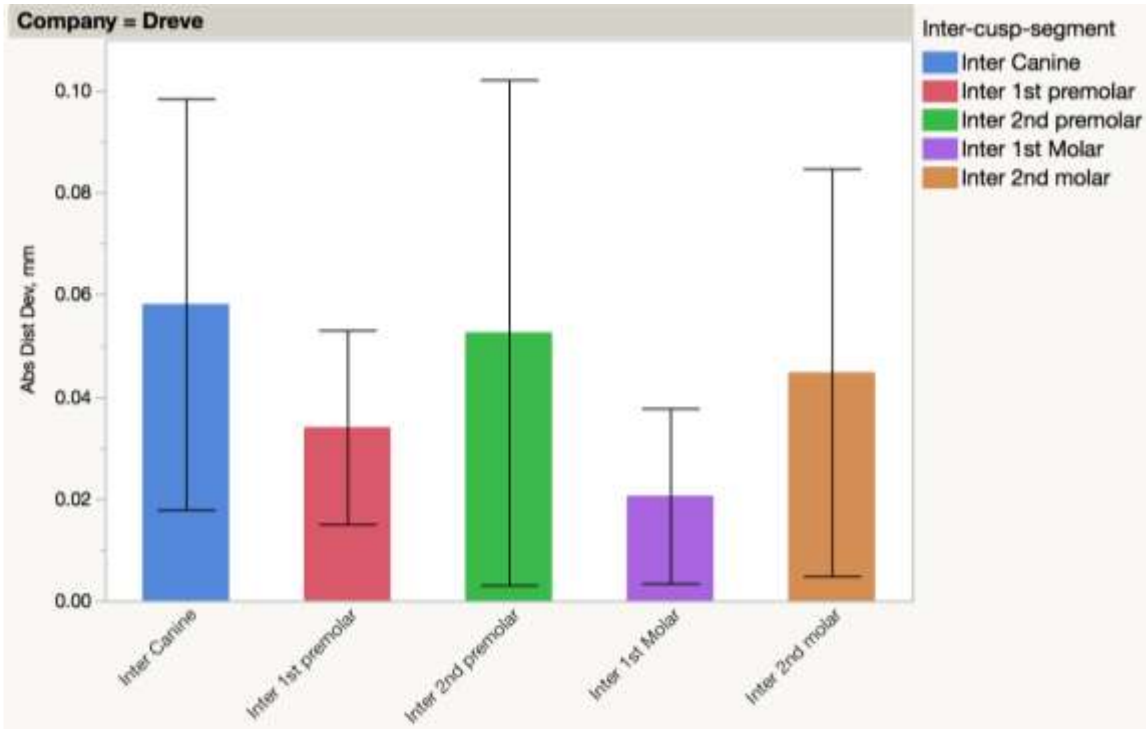


Figure 22. Mean of absolute distance deviation by inter - cusp segment for Dreve.

Each error bar is created by using one standard deviation from the mean.

3.3.2 Trueness of tooth distance by FormLabs

Absolute deviations of tooth distance from reference by FormLabs are shown in Table 11 and Figure 24. The results show that no significant differences of trueness were found between inter- first molar, inter- canine, inter first premolar and inter second premolar. Inter second molar was significantly different to other groups.

Table 11.Means and standard deviations of absolute tooth distance discrepancies by FormLabs.

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Inter first premolar	15	0.0121	0.0110	0.0028	A
Inter first molar	15	0.0257	0.0232	0.0059	A
Inter canine	15	0.0303	0.0238	0.0061	A
Inter second Premolar	15	0.0318	0.0267	0.0069	A
Inter second molar	15	0.0666	0.0331	0.0085	B

*Levels not connected by same letter are significantly different

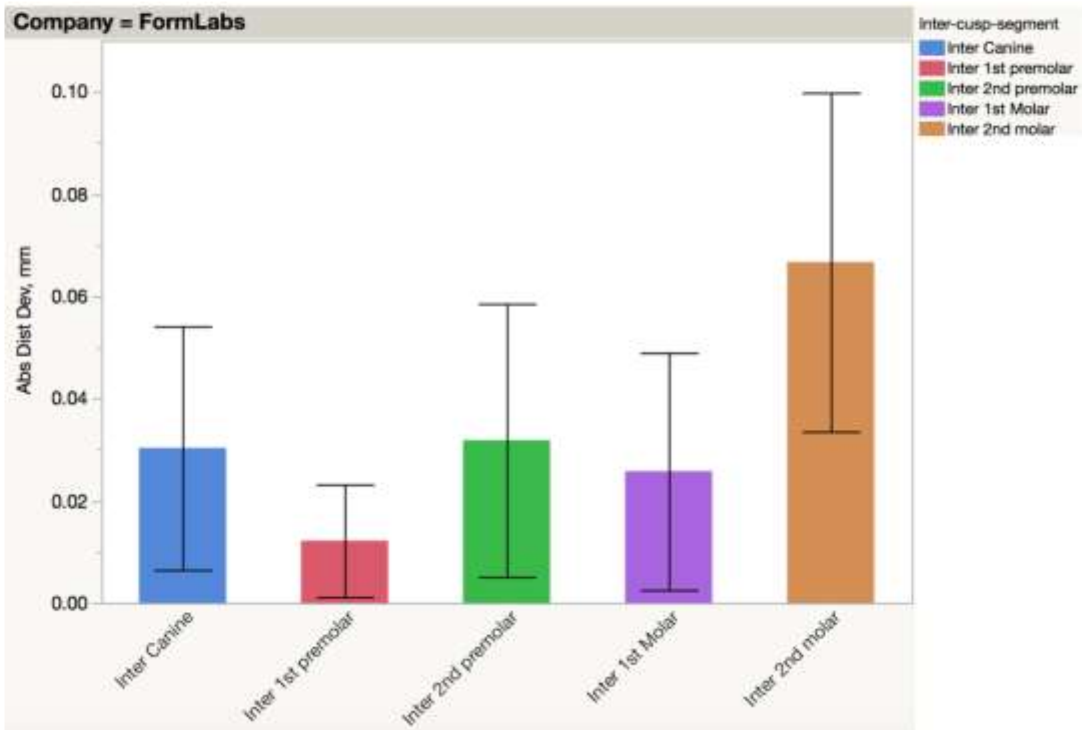


Figure 23. Mean of absolute distance deviation by inter-cusp segment for FormLabs.

Each error bar is constructed using one standard deviation from the mean

3.3.3 **Trueness of tooth distance by Stratasys**

Absolute deviations of tooth distance from reference by Stratasys are shown in Table 12 and Figure 25. The results show no significant difference in trueness between inter - first molar and inter - first premolar segments. No significant difference of trueness was observed between inter second premolar and intercanine. Inter second molar was significantly different to inter first molar .

Table 12.Means and standard deviations of absolute tooth distance discrepancies of Stratysys

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Inter first molar	15	0.0220	0.0188	0.0048	A
Inter first premolar	15	0.0238	0.0200	0.0051	A
Inter second premolar	15	0.0304	0.0345	0.0089	A B
Inter canine	15	0.0325	0.0350	0.0090	A B
Inter second molar	15	0.0557	0.0368	0.0095	B

*Levels not connected by same letter are significantly different

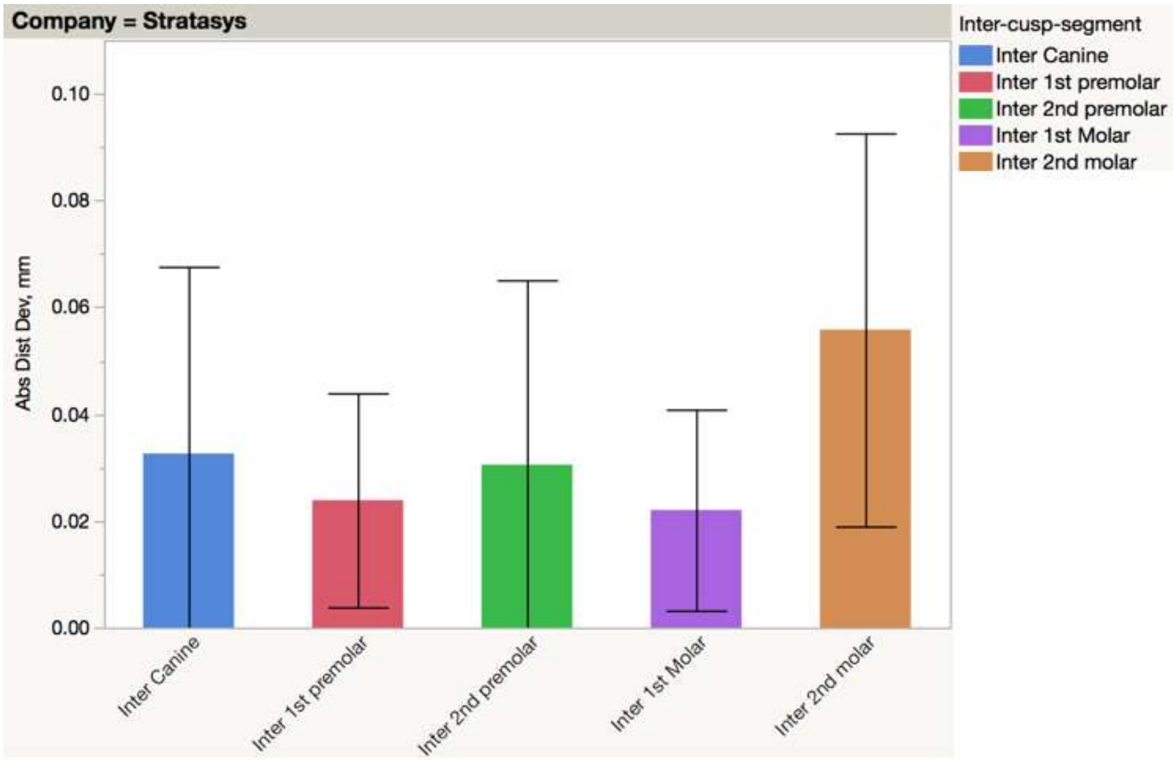


Figure 24. Mean of absolute distance deviation by inter-cusp segment for Stratasys

Each error bar is created by using one standard deviation from the mean

3.3.4 **Trueness of tooth distance by Weiland Mill**

Absolute deviations of tooth distance from reference by Weiland are shown in Table 13 and Figure 26. Significant difference in the trueness existed between inter first molar and intercanine distances, and between inter first molar and inter second-premolar distances.

Table 13.Mean and standard deviations of absolute tooth distance discrepancies in Weiland milled.

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Inter first molar	15	0.0204	0.0180	0.0033	A
Inter first premolar	15	0.0267	0.0267	0.0033	A B
Inter second molar	15	0.0380	0.0286	0.0052	A B
Inter canine	15	0.0447	0.0355	0.0064	B
Inter second premolar	15	0.0465	0.0355	0.0064	B

*Levels not connected by same letter are significantly different.

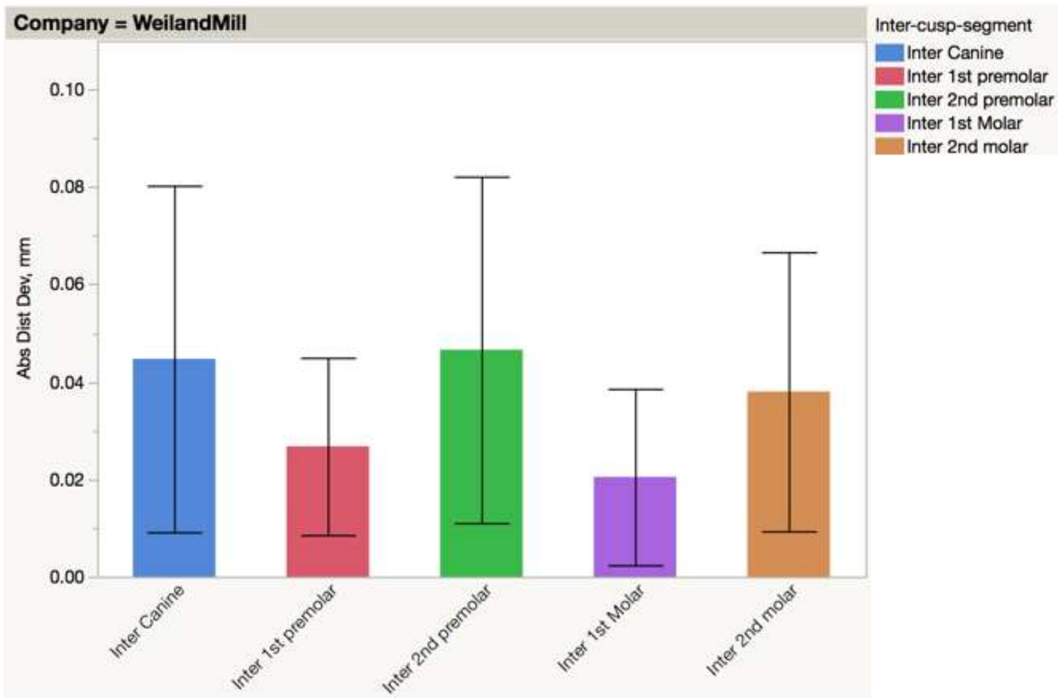


Figure 25. Mean of absolute distance deviation by inter- cusp segment for Weiland milled.

Each error bar is created by using one standard deviation from the mean

3.4 **Trueness of tooth distance by inter - cusp segment**

3.4.1 **Tooth distance trueness of intercanine segment by company**

Absolute deviations of intercanine distance from reference by tested companies are shown in Table 14 and Figure 27. The results show that no significant difference in trueness were found between the rapid prototyping methods for intercanine segment.

Table 14. Absolute deviation of intercanine distance (mm) from reference

Level	Number	Mean	Std Dev	Std Err Mean	Sig*
FormLabs	15	0.0303	0.0238	0.0061	A
Stratasys	15	0.0325	0.0350	0.0090	A
Weiland	30	0.0447	0.0355	0.0064	A
Dreve	15	0.0581	0.0403	0.0104	A

*Levels not connected by same letter are significantly different

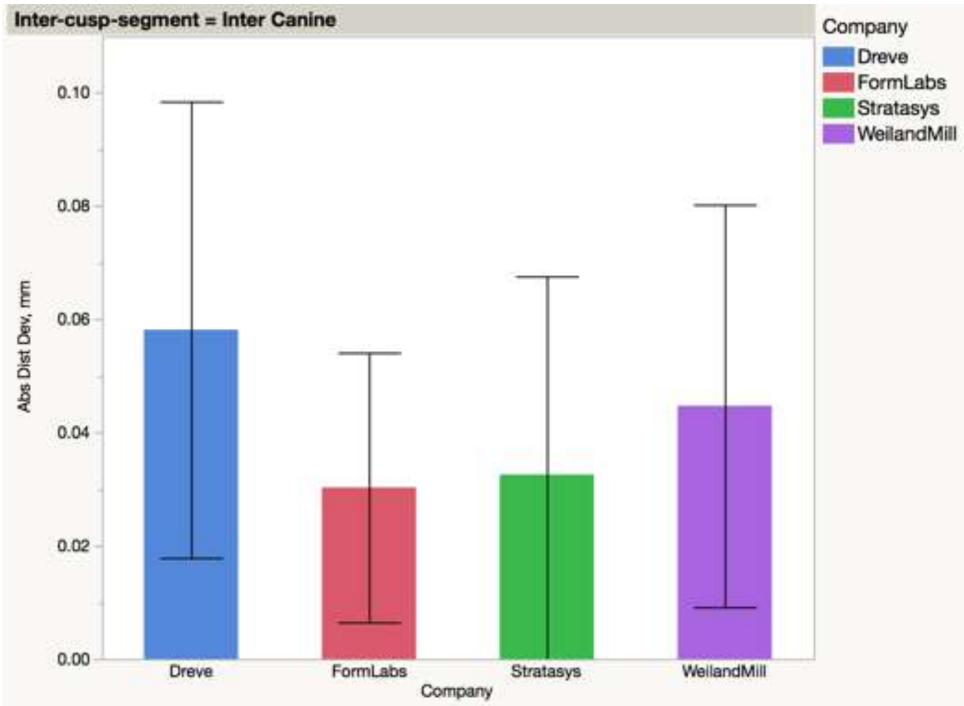


Figure 26.Means of absolute distance deviation of inter canine segment.

Each error bar is created by one standard deviation from the mean.

3.4.2 **Tooth distance trueness of Inter first Premolar Segment**

Absolute deviations of inter-first premolar distance from reference by tested companies are shown in Table 15 and Figure 28. The results show that Formlabs and Dreve are significantly different in trueness whereas Stratasys and Weiland showed no significant differences.

Table 15.Means and standard deviations of absolute distance deviation of inter first premolar segment

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
FormLabs	15	0.0121	0.0110	0.0028	A
Stratasys	15	0.0238	0.0200	0.0051	A B
Weiland	15	0.0267	0.0181	0.0033	A B
Dreve	15	0.0340	0.0190	0.0049	B

*Levels not connected by same letter are significantly different

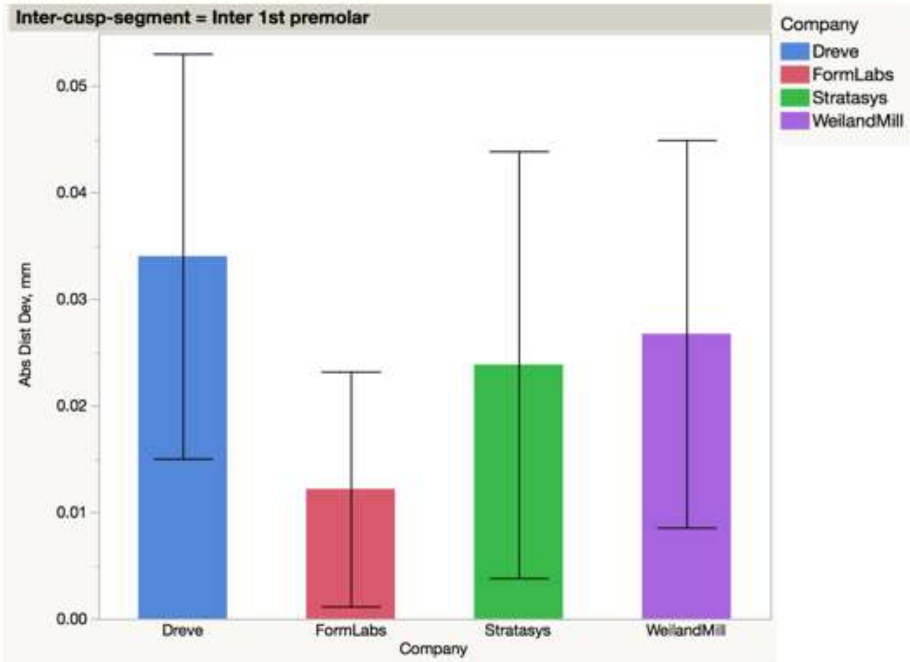


Figure 27.Means of absolute distance deviations of inter first premolar segment

Each error bar is constructed by using one standard deviation from the mean.

3.4.3 **Tooth distance trueness of inter second premolar segment**

Absolute deviations of inter-second premolar distance from reference by tested companies are shown in Table 16 and Figure 29. The results show showed no significant differences in trueness between the rapid prototyping methods.

Table 16.Means and standard deviations of absolute tooth distance discrepancy of inter second premolar segment

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Stratasys	15	0.0304	0.0345	0.0089	A
FormLabs	15	0.0318	0.0267	0.0069	A
Weiland	15	0.0465	0.0355	0.0064	A
Dreve	15	0.0526	0.0495	0.0127	A

*Levels not connected by the same letter are significantly different

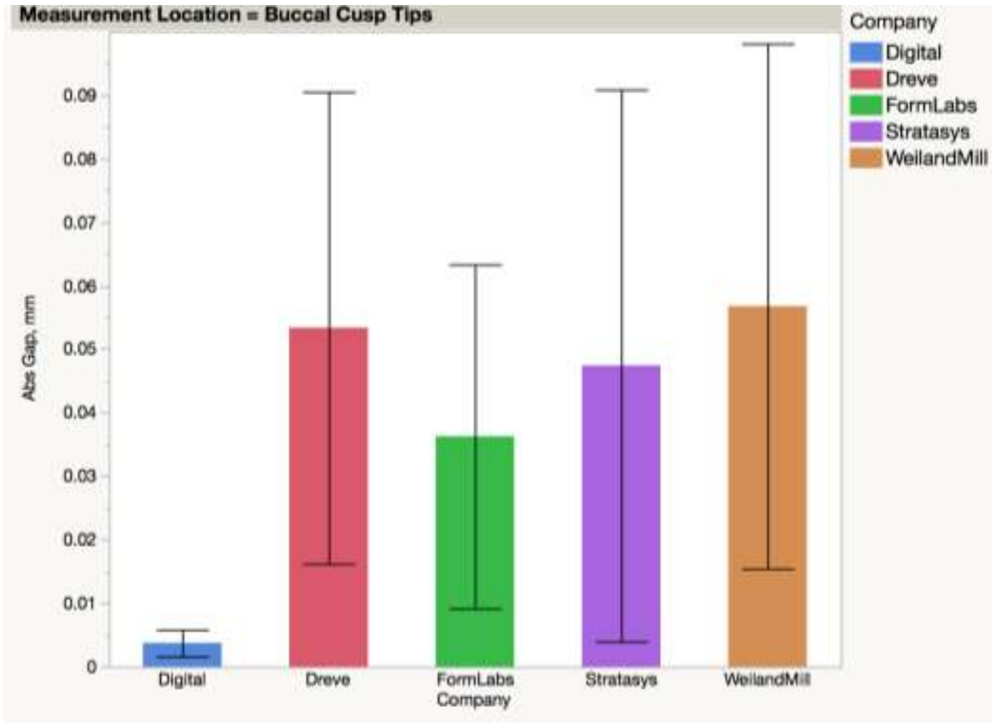


Figure 28.Means of absolute distance deviation of inter second premolar segment

Each error bar is constructed using one standard deviation from the mean

3.4.4 **Tooth distance trueness of inter first molar distance**

Absolute deviations of inter-first molar distance from reference by tested companies are shown in Table 17 and Figure 20. The results show no significant differences in trueness between the rapid prototyping methods.

Table 17.Means and standard deviations of absolute distance deviation of inter first molar segment

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Weiland	30	0.2048	0.0180	0.0033	A
Dreve	15	0.0205	0.0171	0.0044	A
Stratasys	15	0.0220	0.0188	0.0048	A
FormLab	15	0.0257	0.0232	0.0059	A

*Levels not connected by same letter are significantly different

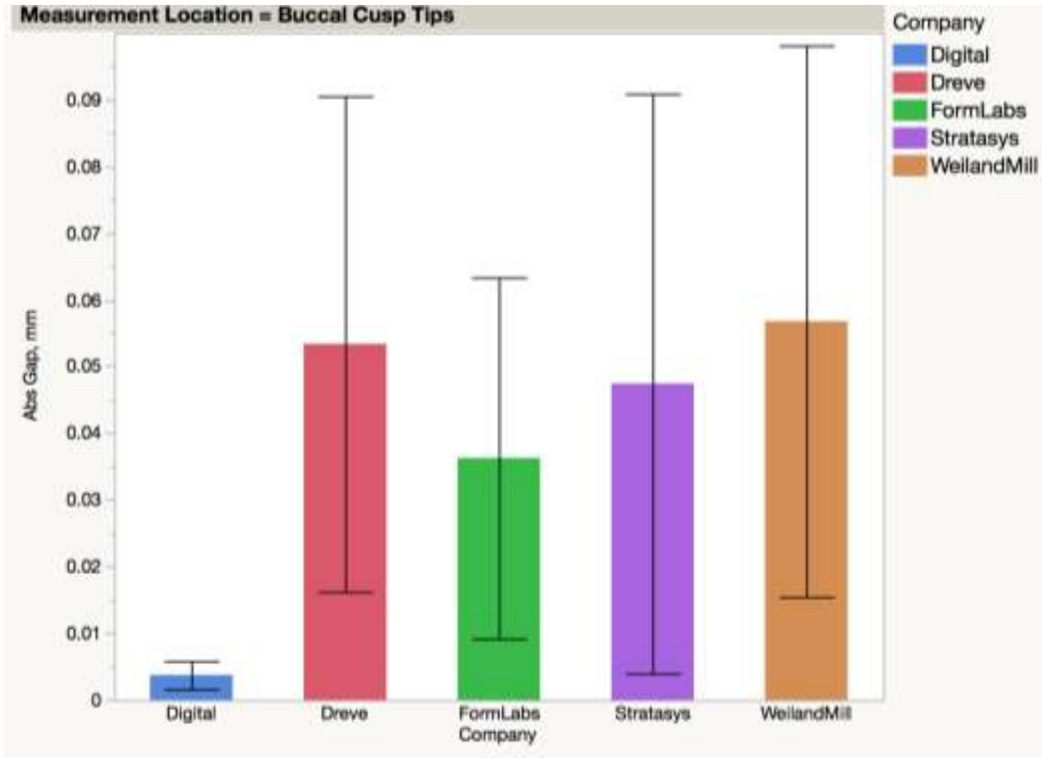


Figure 29.Means of absolute distance deviations of inter first molar segment.

Each error bar is constructed using one standard deviation from the mean.

3.4.5 **Tooth distance trueness of inter second molar segment**

Absolute deviations of inter-second molar distance from reference by tested companies are shown in Table 18 and Figure 31. The results show that significant difference in trueness exists between Weiland and FormLabs. whereas Dreve and Stratasys showed no significant difference.

Table 18.Means and Standard Deviations of Absolute Distance Deviations of inter second molar segment

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Weiland	30	0.0380	0.0286	0.0052	A
Dreve	15	0.0448	0.0399	0.0103	A B
Stratasys	15	0.0557	0.0368	0.0095	A B
FormLabs	15	0.0666	0.0331	0.0085	B

*Levels not connected by same letter are significantly different

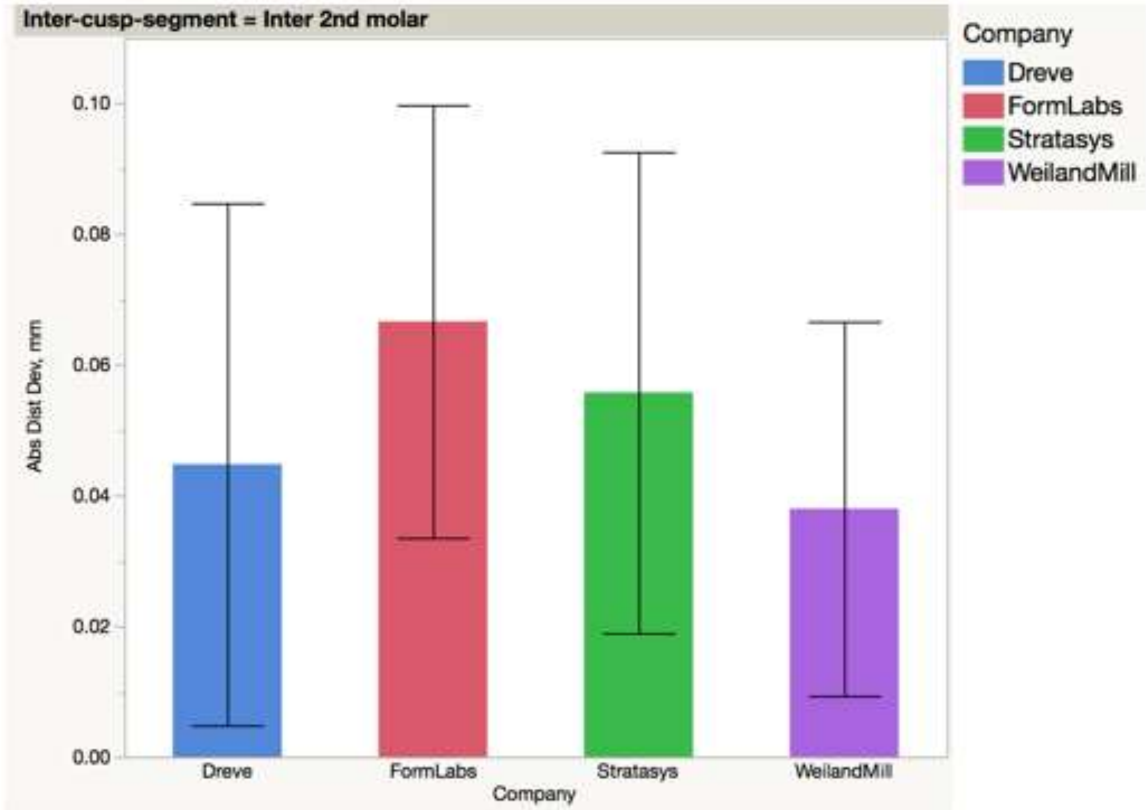


Figure 30. Means of absolute distance deviation of inter second molar segment.

Each error bar is constructed using one standard deviation from the mean.

3.4.6 Summary of tooth distance trueness

Table 19. Means and standard deviations of absolute distance deviation by technique

Levels	Number	Mean	Std Dev	Std Err Mean	Sig
Printed	225	0.0361	0.0332	0.0022	A
Milled	150	0.0353	0.0297	0.0024	A

Levels not connected by same letter are significantly different

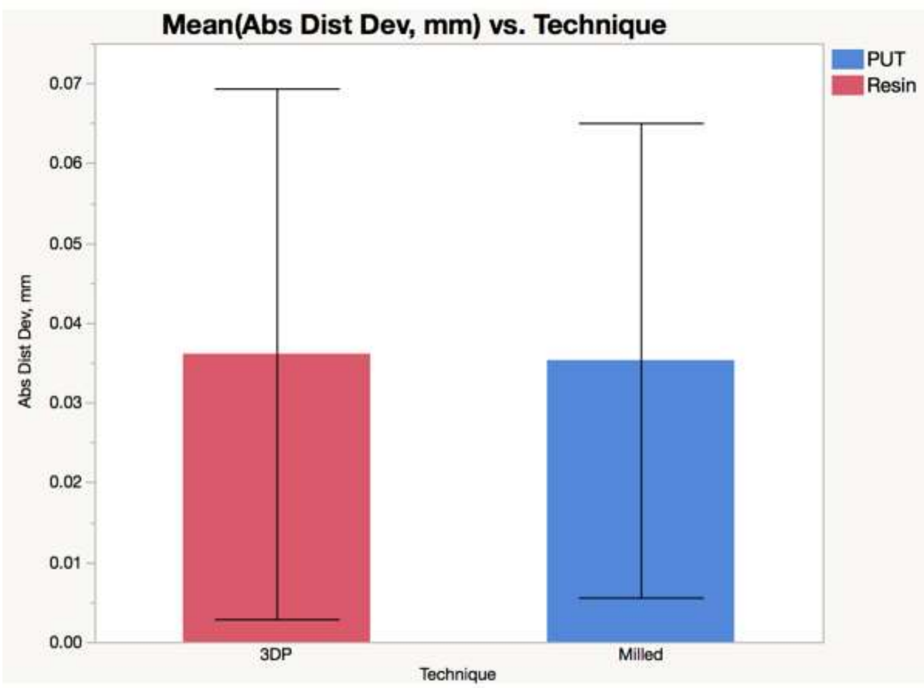


Figure 31.Means of absolute distance deviation by technique

Each error bar is constructed by using one standard deviation from the mean

Table 20.Means and standard deviations of absolute distance discrepancy of inter tooth segment by company

Levels	Number	Mean	Std Dev	Std Err Mean	Sig*
Stratasys	75	0.0329	0.0317	0.0036	A
FormLab	75	0.0333	0.0300	0.0034	A
Weiland	150	0.0353	0.0297	0.0024	A
Dreve	75	0.0420	0.0371	0.0042	A

Levels not connected by same letter are significantly different

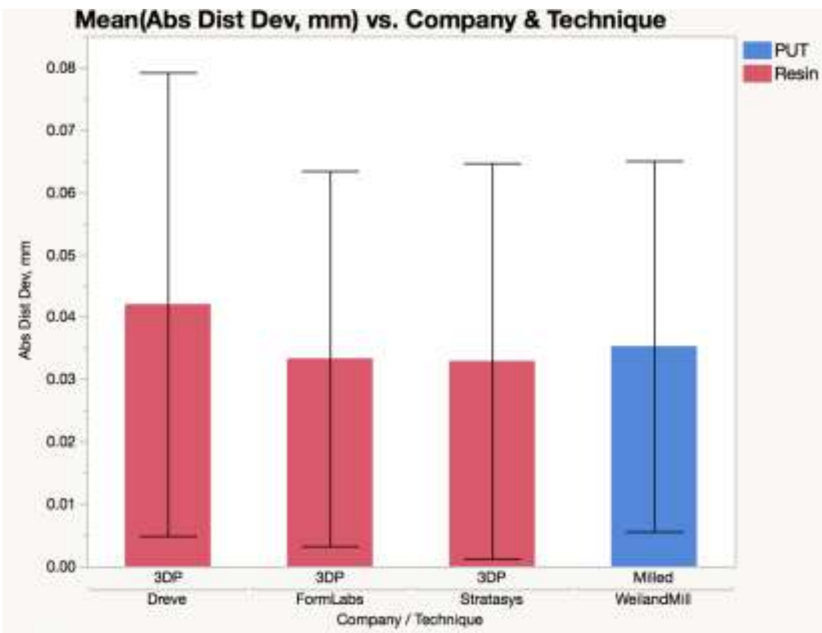


Figure 32.Means of absolute distance discrepancy of inter tooth segment by technique and company

Each error bar is constructed using one standard deviation from the mean

3.5 Trueness and precision of inter tooth distance

Trueness and precision of inter tooth distance in Table 21 shows no significant difference in trueness between companies.

Table 21.Trueness and precision of inter tooth distance

	Trueness (mm)		**Precision (mm)**	
Company	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Dreve	0.0420	0.0246	0.0281	0.0211
FormLabs	0.0333	0.0275	0.0151	0.0094
Stratasys	0.0330	0.0200	0.0251	0.0166
WeilandMill	0.0353	0.0196	0.0245	0.0147

Table 22.Inter segment tooth deviation.

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		Ref Dist, mm			Meas Dist, mm			Dist Deviation, mm			Abs Dist Dev, mm		
Company	Inter-cusp-segment	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
Dreve	Inter Canine	15	27.2212	0.3356	15	27.2630	0.2902	15	0.0419	0.0581	15	0.0582	0.0403
	Inter 1st premolar	15	39.2887	0.3365	15	39.2756	0.3074	15	-0.0132	0.0377	15	0.0341	0.0190
	Inter 2nd premolar	15	39.8333	0.6566	15	39.8286	0.6008	15	-0.0047	0.0735	15	0.0526	0.0495
	Inter 1st Molar	15	45.4421	0.5006	15	45.4626	0.4905	15	0.0206	0.0172	15	0.0206	0.0172
	Inter 2nd molar	15	49.6413	0.4801	15	49.6774	0.4825	15	0.0362	0.0484	15	0.0448	0.0400
FormLabs	Inter Canine	15	27.2212	0.3356	15	27.2461	0.3141	15	0.0250	0.0297	15	0.0303	0.0238
	Inter 1st premolar	15	39.2887	0.3365	15	39.2886	0.3292	15	-0.0001	0.0168	15	0.0122	0.0110
	Inter 2nd premolar	15	39.8333	0.6566	15	39.8490	0.6376	15	0.0157	0.0392	15	0.0318	0.0267
	Inter 1st Molar	15	45.4421	0.5006	15	45.4678	0.4888	15	0.0257	0.0233	15	0.0258	0.0232
	Inter 2nd molar	15	49.6413	0.4801	15	49.7079	0.4542	15	0.0667	0.0331	15	0.0667	0.0331
Stratasys	Inter Canine	15	27.2212	0.3356	15	27.2450	0.3116	15	0.0239	0.0419	15	0.0326	0.0350
	Inter 1st premolar	15	39.2887	0.3365	15	39.2869	0.3223	15	-0.0019	0.0317	15	0.0239	0.0200
	Inter 2nd premolar	15	39.8333	0.6566	15	39.8417	0.6304	15	0.0084	0.0460	15	0.0305	0.0346
	Inter 1st Molar	15	45.4421	0.5006	15	45.4637	0.4875	15	0.0217	0.0193	15	0.0220	0.0188
	Inter 2nd molar	15	49.6413	0.4801	15	49.6964	0.4652	15	0.0551	0.0379	15	0.0558	0.0368
WeilandMill	Inter Canine	30	27.2212	0.3298	30	27.2527	0.2965	30	0.0316	0.0480	30	0.0447	0.0356
	Inter 1st premolar	30	39.2887	0.3306	30	39.2800	0.3092	30	-0.0088	0.0315	30	0.0268	0.0182
	Inter 2nd premolar	30	39.8333	0.6452	30	39.8327	0.6037	30	-0.0006	0.0592	30	0.0466	0.0355
	Inter 1st Molar	30	45.4421	0.4919	30	45.4620	0.4819	30	0.0199	0.0187	30	0.0205	0.0181
	Inter 2nd molar	30	49.6413	0.4718	30	49.6734	0.4677	30	0.0321	0.0353	30	0.0380	0.0286

CHAPTER 4. DISCUSSION

In this study, the accuracy of both 3D printed and milled dental models were compared at specific points of clinical interest on the mandibular arch. These points were selected due to their clinical relevance and the effect they have on clinical situations. The results of the study reflect that both methods of prototyping differ statistically in accuracy at different sites when compared to the master digital file of the mandibular arch and 3D printed models showed more accurate than the milled models.

The area of interest is to determine whether the statistically significant data, between the two prototyping techniques in Table 6, is clinically significant or not. The clinical significance could vary depending upon the purpose these models are being used for.

Models developed by rapid prototyping techniques have been studied mostly in the field of orthodontics, as models are required to do a space analysis, an aspect critical to orthodontic diagnosis and treatment planning.

Previous studies have shown a range of clinically acceptable measurement differences in plaster and their replica models. *Bell and Ayoub*[31] suggested that measurement differences of 0.27 mm were clinically insignificant. *Santoro*[32] proposed a measurement difference ranging from 0.16 mm to 0.49 mm was within clinically acceptable limits.

A recent study *by Hazeveld*[29], in which he made linear measurements on plaster and its replica models, found the highest measurement difference of 0.25 mm was clinically acceptable.

Therefore, as we reflect on the results of our study, we see that the mean difference in measurement are 0.075 mm for 3D printed and 0.084 mm for milled, which are well below the clinically acceptable values mentioned in the above literatures. Therefore, those deviations are considered clinically accepted and the both methods are clinically accurate.

When using a statistical analysis, a typical error is expressed as a standard deviation. From Figure 20, when we compared the 3D printed models to the master digital model, the largest deviations observed were at “Cervical” comparison points as compared to the other three locations of interest. “Center of Teeth” was the most accurate. The only group in which the milling method is superior to the 3D printing methods is the ‘Center of Teeth’ (Fossa). However, the difference between milling and 3D printing (0.005 mm) in this group is statistically insignificant.

In the general model analysis of absolute gap discrepancy, we can see from Table 6 that the 3D printed models exhibited statistically significant lower mean values (0.0753 mm) as compared to milled models (0.0863 mm). However, from a clinical aspect these differences (0.009 mm) between the two methods in mean absolute gap discrepancies are insignificant.

In Table 19 a comparison of the distance deviation measurements between 3D printed and milled dental models, statistical difference was seen, The printed models had means in absolute distance deviation of 0.0361 mm whereas the milled models had mean value of 0.0353 mm. However, the difference of 0.008 mm was insignificant.

Since deviations, were observed in the digital sample which served as the control group, it was not surprising to find larger deviations in absolute gap distance between printed and milled models when compared to the digital file. Exactly which part of the digital work flow that these errors occurred is difficult to identify and predict. In this study we assume that the deviations are due to inaccuracies during data conversion into STL format, scanning, printing and milling.

The accuracy of the software can be appreciated as the software did not superimpose the files through “initial alignment” if the scans were not accurate. Therefore, when the scans were repeated, it was observed that the previous scans were insufficient in their completeness. A complete scan was not one that just captures the teeth but the entire boundaries of the model.

Since 3D printing is additive, it builds the product in layer by layer. The layer thickness and building angle is known to effect the accuracy of printed models.[28,30] In addition to this all SLA printed objects require a period of post curing as the materials do not fully cure while being printed. The process of printing and final cure in the oven could lead to shrinkage and affect the accuracy of the final product.

Errors in milling could occur due to size of milling burs and their efficiency to mill.[33] In clinical practice milling units are used to mill indirect restorations as they are quick and efficient. However, in our study milling units were milling entire models and whether the burs were changed in a timely manner is difficult to predict as changing the burs for every model could prove to be costly.

Large deviations in the cervical group could be due to the undercuts in teeth. As we move from occlusal to cervical, the height of contour increases. Stratysys and Weiland exhibited the highest deviation in cervical region of all rapid prototyping methods. Whether these deviations have any clinical significance at this point is difficult to determine. It could be clinically important if these models were being used to fabricate a prosthesis as it could affect margin adaptation of a restoration.

Digital inspection software's have been utilized to analyze a 3D comparison between scanned images assuring their reliability.[34,35] Not only are inspection software's appreciated for their accuracy, they also allow the user to obtain a larger set of data, which if done manually would be inefficient and not reliable. Recording measurements manually can have an additional problem in correct identification of the predefined landmarks.[36]

In the past decade, digital dentistry with in-office milling units have played a major role in creating an efficient work flow that has received tremendous appreciation from patients. With the recent commercialization of 3D printers, clinicians can now turn towards printing as a more economical and efficient means of achieving clinical and laboratory goals.

Since digital impressions can be stored in a “cloud” they can be retrieved at any time the clinician desires to study patient’s diagnostic information. This is beneficial as many clinics and dental laboratories have limited space to store physical patient’s models.

Despite the deviations exhibited by printed and milled models in this study, they are accurate enough to be used as diagnostic or study models which form the basis for treatment planning Dental models are also used for fabricating intra oral orthodontic and prosthetic appliances, dental restorations and surgical guides.

Appliances constructed on conventional stone models may need adjustment after fabrication. Hence it would not be uncommon if adjustments were needed on appliances made on printed or milled models.

Large deviations observed on the cervical region may affect the marginal fit of a restoration fabricated on these models.

Although there is enough evidence on the accuracy of digital models obtained by direct intra oral impressions[37,38,39], many dentists and specialists prefer to have physical models at the time of treatment planning and to better communicate the treatment modalities to their patients and professional counterparts. Therefore, the preference of clinicians of having a physical model that is accurate and reproducible emphasizes the relevance of this study.

CONCLUSION

Within the scope of this study the following conclusions are drawn:

1. 3D printed dental models showed statistically better trueness than milled dental models. However, accuracy for both methods of rapid prototyping is within the clinical tolerance and both methods are clinically acceptable.

2. The mean reproducibility (precision) between 3D printing and milling technique showed no significant difference.

3. No statistical difference were found in absolute distance discrepancies (trueness) of inter tooth distances between either of the prototyping methods.

4. No statistical difference were found in inter-tooth distance reproducibility (precision) of among all tested rapid prototyping methods.

5. In general, the cervical region had significant less trueness than cusp area.

6. In general, the cervical region had significant less precision in X and Y coordination than cusp tips and central of tooth, while had no significant different precision in Z coordination compared to cusp tips.

The location with the largest deviations was the Cervical region for both 3D printed and Milled Dental models.

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