COMPUTER-AIDED DESIGN & APPLICATIONS, 2016
VOL. 13, NO. 1, 32–38
http://dx.doi.org/10.1080/16864360.2015.1059186

Comparison of 3-D Printing and 5-axis Milling for the Production of Dental e-models from Intra-oral Scanning

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ABSTRACT
Recently, chairside production in dentistry has garnered attention because of the time-saving, low-cost and high level of predictability of outcomes. Compared to traditional manufacturing using computer numerical control (CNC) milling machines, 3D printing plays a new and perhaps more important role in dental chairside production. The aim of this paper is to compare the dental e-models manufactured by 3D printer with those fabricated by CNC milling machines. In this paper, a patient with mal-positioned mandible was initially selected. Through an intra-oral scanner, the 3D STL model of the patient's denture was created. After that, a computer-aided virtual orthodontic treatment was planned. After planning, 8 steps were respectively fabricated by CNC milling machine and 3D printer. These models were digitized via a scanner and then compared with the original data from the virtual planning of orthodontic treatment. In the experiment, it is found that the smoothness and repeatability for CNC machining is better than for 3D printing, especially for inclined and curved surfaces such as occlusal surfaces. However, the 3D printer could produce concave and intricate geometry that is often not achievable by milling.

KEYWORDS
Intra-oral scanner; 5-axis milling; 3-D printing; dental e-model

1. Introduction

The global dental industry is now in a rapidly changing and developing era. Dentures, implants and orthodontic products are faced with the changes in their manufacturing processes, from the traditional handmade to fully digital production process. The key technology which makes it happen is the highly automated dental CAD/CAM system, including friendly planning and design software, as well as the easy operation of production equipment. In the traditional handmade process, the dentist uses impression material to copy the denture geometry. But for design purposes, the impression model needs to be transferred to a plaster model. Finally, the dental technician designs and plans based on this model according to the treatment needs. Generally, what the traditional dental technician can mostly involves artificial denture, easy implant guide and hand-made transfer jig for orthodontic treatment. However, the traditional process needs to copy and turn over the models several times. Accumulated multiple conversion errors lead to inaccurate design and production of the final prosthesis or product, and cannot fit precisely in the mouth. Therefore, clinically, the dentist often has to spend a lot of time trimming or grinding the prosthesis or teeth to ensure that the fit is proper or the occlusion is right. Moreover, the traditional manual production is often limited to low-end denture-related products. For more high-end products, such as implant bar, custom implant abutments, or orthodontic clear aligners, most manual processes are labor intensive, inaccurate and very costly. Hence the best choice to overcome these bottlenecks is digital dental technology. Since 2000, there has been an explosive growth in the customized dental CAD/CAM system which arose from the continuous advancement of 3D scanning and computer graphics technology. In the early stage, those dental CAD/CAM systems were composed of large 3D scanners and industrial multi-axis machines, integrated with traditional CAD/CAM software. Up to now, more and more dental equipment manufacturers are providing automated optical scanner, lightweight table-top milling machine and customized CAD/CAM software to increase the efficiency and productivity of dental laboratories. In addition, 3D printing technology which is enjoying rapid regrowth in recent years is also being applied to the field of digital dentistry. Differing from the traditional material removal process, 3D printing produces a workpiece based on the additive manufacturing method. It is suitable for mass customization, which is

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characteristic of the dental production of individualized prosthesis. In this paper, dental applications are obtained by integrating dental intra-oral scanner and customized design software for dentures, implants and orthodontic products. Finally, we manufacture dental e-models by 5-axis machining and 3D printing respectively, and analyze the difference on the accuracy of the manufactured products.

2. Overview of CAD/CAM technologies for dentistry

Dr. Francois Duret was the pioneer who brought the CAD/CAM concepts into dental applications in 1973 [6,7]. He developed and patented a CAD/CAM device in 1984. Since then, digital dental CAD/CAM technology has undergone several years of technological development period, and began to experience explosive growth from 2000. In this paper, two important components of dental CAD/CAM technology are classified and described as follows.

2.1. Dental 3D scanner

2.1.1. Desktop scanner

A scanner is a data collection tool that measures 3D jaw and tooth structures and transforms them into digital data sets. Currently, laser and structure light are the two main methods for optical scanners in dental application. In a laser-based scanner, triangulation is the core algorithm. The laser emitter and the camera are positioned in a definite triangular pose. Through this angle, a 3D data set from the image on the camera can be calculated by a computer. Either white light projections or a laser beam can serve as a source of illumination. In general, the scanning time of the optical scanner is faster than the mechanical scanner. However, the color, curvature and roughness of the measured surface can affect the results. In addition, the environmental light and the camera focus are also important factors affecting the results during scanning. Therefore, the accuracy in the optical scanner is less than that of the mechanical scanner.

2.1.2. Intraoral scanner

Traditional desktop scanners digitalize oral geometry by scanning plaster models. However, dental features such as margins may disappear due to frequent model conversions. In 1987, CEREC® was the first commercial CAD/CAM system for producing chair side dental restorations [11]. They employ blue light-emitting diodes (LEDs) as the light source to project patterns on the object. The blue LEDs allow for greater precision of the virtual dental model, and the resulting images are free of distortions, even at the periphery [4,9]. In clinical settings, the desktop scanner cannot accurately obtain the characteristics of teeth gap because of institutional constraints. However, with an intra-oral scanner, those characteristics can be clearly digitized. In practice, the biggest problem of intra-oral scanners is multi patch registration mistakes. In the traditional procedures, coarse positioning can be achieved by mechanism parameters, and get better results. Digital models acquired by intra-oral scanners will be less accurate due to the accumulated discrepancy, especially in the posterior teeth during the full arch reconstruction process.

2.2. Production manufacturing

2.2.1. Milling machining

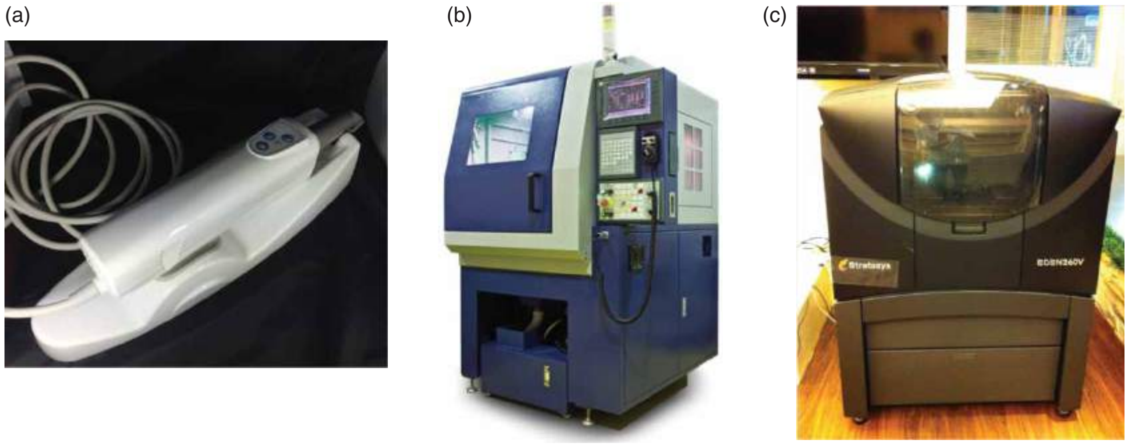
The construction data produced with the CAD software are converted into milling strips for the CAM-processing and finally loaded into the milling device [1]. Milling devices, depending on their number of axes include 3-axis devices [3,12], 4-axis devices and 5-axis devices [8].

A 3-axis device has degrees of movement in the three spatial directions. Thus, the mill path points are uniquely defined by the X –, Y – and Z – values. The calculation effort is therefore minimal. All 3-axis devices used in the dental area can rotate the milled component by 180° in the course of processing the inside and the outside of, say, a capping or a crown. The advantages of these milling devices are short milling time and simplified control via the three axes. As a result, such milling devices are usually less costly than those with 4 or 5 axes. Examples of 3-axis devices are inLab (Sirona), Lava (3M ESPE) and Cercon brain (DeguDent).

With a 5-axis milling device, in addition to the three spatial dimensions and the rotatable tension bridge (4th axis), there is also the possibility of rotating the milling spindle (5th axis). This enables the milling of complex geometries with subsections. An example used for the Laboratory Area is the Everest Engine (KaVo); an example used for the Production Center is the HSC Milling Device (etkon).

2.2.2. 3D printing

3D printing is a technology that allows the fast and automated fabrication of physical objects directly from virtual 3D computer-aided design data without significant process planning related to part features and geometry. 3D printing was initially set up to increase the speed of prototype manufacturing in the manufacturing industry, but it can also be used for different applications such as medicine [16] and dentistry [5,15].



(a) Intra-oral scanner (b) 5-axis machining (c) 3D printing

Figure 1. Intra-oral scanner for data digitization and dental models are fabricated by 5-axis machining and 3D printing.

Clinically, 3D models are reconstructed from computer-tomography (CT) images and produced by a 3D printer [10]. These models, such as bone structures, foreign bodies, vascular structures, implants and so on, are used for diagnosis and planning of complex surgical cases.

3. Material and method

In this paper, a compact intra-oral scanner (3D Progress Digital Impression, Medical High Technologies) was adopted to capture geometry information from the patient's mouth. Then, the 3D virtual data of tooth surface can be generated by mesh reconstruction algorithm. During the clinical scanning, a dentist must move the intra-oral scanner slowly for successful data acquisition because during the data capturing process, the camera must be in constant focus and the registration process needs to be ongoing in real time. After that, a 3D STL model can be created.

Once the 3D STL model is constructed, in-house orthodontic software is used for the virtual planning of orthodontic treatment. After the virtual planning of orthodontic treatment, a CNC 5-axis milling machine (TME-300, TDS Biotech) and a 3D printer (Eden260V, Stratasys) are used to manufacture physical models. In this paper, the CNC 5-axis milling machine includes a milling spindle with three spatial degrees of freedom, and a table with two rotation degrees of freedom. In addition, dry milling was used to reduce equipment cost for the milling machine and to prevent moisture absorption by the material. On the other hand, the 3D printer jets 16 micron thickness of photopolymer material for each layer. The micro jet head moves back and forth along the X-Y axis depositing onto the build tray a single layer of photopolymer, which is immediately cured and hardened by UV light. The result is that fully cured models can be created immediately without additional post-curing and are ready for product testing. Figure 1 shows those devices mentioned above.

4. Case study

In this paper, one orthodontic case with an internal premolar rotation was selected. First, 3D oral geometry was digitized by an intra-oral scanner. Here, a non-contact structured-light 3D scanner developed by Medical High Technologies (MHT) was used to capture the oral geometry. Then, the acquired data was processed by real-time registration and surface reconstruction algorithms to create an orthodontic setup model. The mesh post-processing included topology checking, curvature-based hole-filling, and so on. After the water-tight STL model was created, we used in-house developed orthodontic planning software to generate the 8 continuous variation steps of the correction process, which can be directly translated to the making of 8 different sets of clear aligners for the patient to wear. Table 1 summarizes the overall teeth movement for every individual tooth that will be affected.

In this case, the diagnosis result is that there is a slight rotation problem in the left second premolar of the

Table 1. Tooth movement overview of the selected example case.

Teeth	**31**	**32**	**33**	**34**	**35**	**36**	**37**
Translation (mm)	0	0	0.02	0.78	2.95	1.13	0.6
Rotation (deg)	0	0	0.08	2.86	23.93	3.67	0
Teeth	**41**	**42**	**43**	**44**	**45**	**46**	**37**
Translation (mm)	0	0.32	0.5	0.4	1.0	0.2	0
Rotation (deg)	0	3.67	2.45	0	9.31	0	0

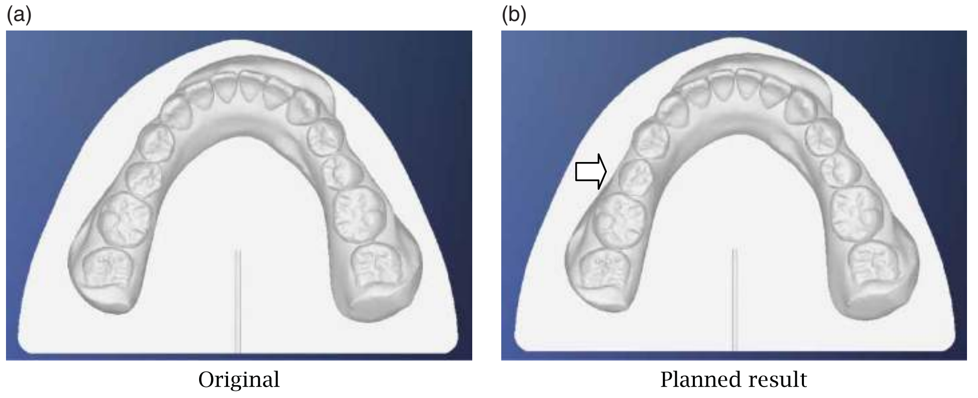


Figure 2. The setup difference between the original and planned result.

Figure 3. The working models fabricated by 5-axis machining and 3D printing, respectively.

mandible. After clinical dentist treatment, eight steps are planned, and Figure 2 shows the variation of teeth positions from the original to the final condition. After being smoothly divided into 8 different steps, each step of the planned model can be output as a 3D STL model and imported to 3D printing and 5-axis machining, respectively. This model is mainly designed for the treatment of invisible braces or the so-called clear aligners. In recent years, this kind of orthodontic treatment method has become more and more popular. However, for clear aligner application, the continuous tooth path needs to be broken down into several steps and exported for the manufacturing of the working models. Then, the clear aligner can be obtained by thermoforming using the working models. Clinically, when the patient wears it, the force caused by the aligner exerted on the tooth surface will achieve the desired tooth movement. For this purpose, the key point is determining how to plan the tooth moving path precisely and efficiently. Generally, it is impossible for the traditional manual planning process to complete this delicate process. Therefore, the manufacturing of clear aligners can best rely on the digital dental technology. So, in addition to the friendly planning software, suitable manufacturing equipment is also a major key point. The most common manufacturing technologies suitable are 5-axis machining and 3D printing. The objective of this paper is to take the orthodontic treatment application as an example to assess the applicability between 5-axis machining and 3D printing. Figure 3 shows the physical working model produced by 5-axis machining and 3D printing.

5. Comparison and discussion

First of all, this paper obtained 3D virtual data via an intra-oral scanner. Then, 8 setup models were exported from treatment-planned software and fabricated through 5-axis machining and 3D printing, respectively. The finished products shown in Figure 4 need to be digitized again through a digital desktop scanner for further comparison and analysis. In this research, a 5-axis milling machine developed by Pou-Yu technology (TDS) was selected. This machine was designed specifically for dental processing and can machine full series of dental products, including dentures, precision milled implant abutments and bars. The machining system is also equipped with automated machining path generation software. The 3D printer this paper chose to use is Stratasys' Objet 260v.

Figure 4. The 8 working models fabricated by 5-axis machining and 3D printing, respectively.

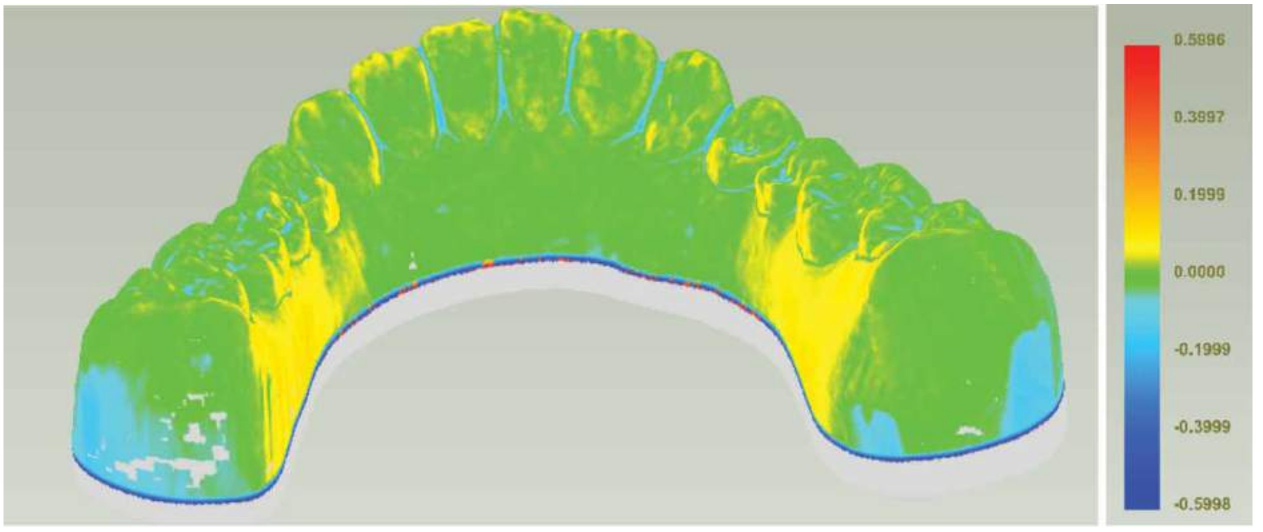


Figure 5. Error analysis between planned model and working model fabricated by 5-axis machining.

Stratasys Object has been used extensively for making medical models and surgical stents. The purpose of this paper is to compare the differences between the products of 5-axis machining and 3D printing.

In order to verify the applicability of 5-axis machining and 3D printing in the dental field, this paper obtained 3D virtual data on physical working models, and compared them with the digitally planned results. Figures 5 and 6 show the difference analysis between planned result and fabricated working model' respectively. Figure 5 indicates that the model fabricated by 5-axis machining has smoother surface quality, especially in the crown portion. However, part of the crowns has over-cut problems, and the inside vertical wall of the gums also has greater error. This problem exists among every working model fabricated through 5-axis machining. That means there must be some error that occurred in a particular direction of 5-axis machining, but which does not affect the repeatability of the machine. On the contrary, Figure 6 shows the comparison between planned result and working model made by 3D printing. The result show that the working model fabricated by 3D printing has poorer surface quality due to its fabrication method, and most of the offset regions located on the ridges of crowns, especially in the horizontal directions, change severely. This error obviously has great relevance with 3D printing direction.

According to the above results, the several differences between CNC machining and 3D printing can be discussed, including manufacturing efficiency, model quality, cost and processing. Generally, the largest difference between CNC and 3D printing is the fabricating method. CNC machining is known as a subtractive manufacturing process which meets the purpose by removing materials from the workpiece. In contrast, 3D printing fabricates models in a layer-by-layer method which is known as an additive manufacturing process. In the manufacturing

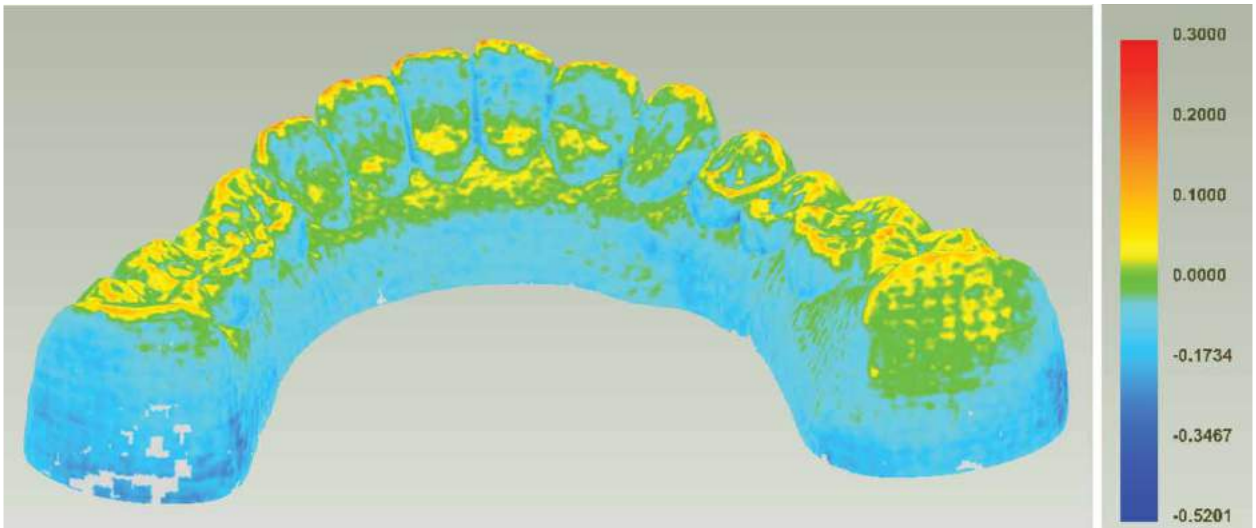


Figure 6. Error analysis between planned model and working model fabricated by 3D printing.

efficiency, CNC machining can only create one model at one time while 3D printing has the advantage of mass production. Furthermore, CNC machining needs to calculate tool cutting path during fabrication. This operation is very difficult when taking the complexity of dental product geometry into consideration. The machining calculation of 3D printing is relatively easy, by slicing the model in a specific axis. In the model quality, CNC machining has better model accuracy and surface quality since 3D printing may form a stepped surface and model deformation because of its fabricating mode. About cost, 3D printing will be more expensive compared to CNC manufacturing if taking biomedical application into consideration. Summarily, the dental products industry is highly customized, and only 3D printing fits the requirements of customization and mass production. Although, parts of denture products still need CNC machining for the needs of accuracy and surface quality, 3D printing can replace CNC manufacturing in the future if 3D printing equipment and materials can be improved continuously.

6. Conclusion

This paper used an intra-oral scanner to capture a patient's oral information and then built a 3D virtual oral model. Then, the treatment step models were calculated by our orthodontic planning software. The working models were fabricated by 5-axis machining and 3D printing and the accuracy and advantages were analyzed for both solutions. 5-axis machining has been one of the most indispensable equipment for the manufacturing industry. Many highly precise dental products can be fabricated by the milling process, such as crown, abutment, implant bar, orthodontic working molds, etc. The comparison shows that 5-axis machining can achieve the 0.01–0.02 mm accuracy level that is normally required by the dental industry standard. However, for a 5-axis milling machine, only one model can be fabricated at one time. On the other hand, 3D printing suffers from less accuracy (about 0.03–0.05 mm) but has the advantage of multiple simultaneous production. Cost-wise, precision 3D printers are still quite expensive and comparable to precision 5-axis milling machines. However, the current explosion of 3D printer development and commercialization will soon lead to significant price reduction of 3D printers in the near future. For orthodontic and even prosthodontic applications that require as much as 20 micron accuracy, we expect to see the increasing use and acceptance of 3D printers over the 5-axis milling machines in both dental labs and clinical offices.

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