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Drilling force and speed for mandibular trabecular bone in oral implant surgery

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Abstract. Based on a survey done recently in Japan, 30 percent of the serious accidents occurred in oral implant surgery were concerned with the mandibular canal and 3/4 of them were related to drilling. One of the reasons lies in the lack of the education system. To overcome this problem, a new educational system focusing on drilling the mandibular trabecular bone has been developed mainly for dental college students in the form of an oral implant surgery training simulator that enables student to sense the reaction force during drilling. On the other hand, the conventional system uses polymeric model. Based on these systems, two approaches were proposed; the evaluation by experienced clinicians using the simulator, and experimental works on the polymeric model. Focusing on the combination of the drilling force sensed and drilling speed obtained through both approaches, the results were compared. It was found that the polymeric models were much softer especially near the mandibular canal. In addition, the study gave us an insight of the understanding in bone quality through tactile sensation of the drilling force and speed. Furthermore, the clinicians positively reviewed the simulator as a valid tool.

Keywords: oral implant; drilling force; drilling speed; trabecular bone; mandibular

1. Introduction

The oral implant surgery is one of the treatments of prosthesis for patient with tooth's deficiency that had been widely used for more than 30 years (Albrektsson *et al*. 2008). In particular, it mainly consists of the jawbone drilling process for implanting artificial teeth. The mandibular canal inside the jawbone contains nerve system and blood vessel running through the porous trabecular bone. Due to that, serious problems might happen if the drill penetrated through the canal. Based on a survey by Japan Academy of Maxillofacial Implants between 2009 and

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2011, it was estimated that 30 percent of the accidents occurred were concerned with the mandibular canal in trabecular bone region and 3/4 of those were related to drilling.

One of the reasons for oral implant failures is the dentist's lack of knowledge and surgical experience (Augustin *et al.* 2008, Chrcanovic *et al.* 2014, Kim *et al.* 2010, Limbert *et al.* 2010, Melo *et al.* 2006). The lack of experiences and knowledge of oral implant surgery gain during studies in dental colleges and universities causes them to work with various initiatives (De Bruyn *et al.* 2009, Donos *et al.* 2009, Kusumoto *et al.* 2006, Mattheos *et al.* 2009, 2014, Rhienmora *et al.* 2010, Ucer *et al.* 2014, Urbankova 2010, Wienrick *et al.* 2007). Particularly, technical practice using detailed models is adopted in order to teach surgical procedures. However, its properties are naturally different from a real jawbone and the models are expensive and not suitable for repeated practice. In addition, most of these models are made of resin and can only provide a single pattern of tactile sensation to the user during drilling (Van de Velde *et al.* 2008) although it is reported that there are 4 kinds of classification according to the size of the cortical and trabecular bone's microstructure (Lekholm 1985).

The tactile sensation can be considered as the sensation of the force at the tip of the doctor's finger or relatively considered as the drilling force. There are a few numbers of studies on the drilling force (Friberg *et al.* 1995, Sugaya 1990) but it is difficult to quantify the force sense felt by the clinician. As a result, it is nearly impossible to teach inexperienced clinicians the force sensed by a skilled clinician. The drilling force is closely related to the apparent mechanical properties, especially stiffness, which leads to the quality of the bone tissue. There are many studies in the biomechanics field related to oral implantology (Bonnet *et al.* 2009, Chang *et al.* 2011, Haïat *et al.* 2013, Mathieu *et al.* 2014, Matsunaga *et al.* 2010, 2011, Misch *et al.* 1999, Sui *et al.* 2014, Yeniyol *et al.* 2013) and it was found that the quality of the bone depends on various factors including its microstructure (Basler *et al.* 2013, Dempster 2000, Pothuaud *et al.* 2002) and bone mineralization (Sansalone *et al.* 2012). A way to predict the drilling properties is by using the image-based modeling technique and finite element analysis (FEA) that is widely used in bone stress analyses based allowing precise modeling of a three-dimensional trabecular bone structure (Ohashi *et al.* 2010).

In this study, the tactile sensation during drilling was quantified relatively to the drilling force and speed. Two approaches to study the drilling force and speed were considered. The first approach is from the clinicians' point-of-view based on their evaluation of the oral implant surgery training simulator's database calculated using FEA. The second approach of this study is based on the students' point-of-view while practicing on polymeric model conventionally used in dental colleges. Focusing on the combination of the drilling force and speed obtained, the results were compared.

2. Method

2.1 Development of oral implant surgery training simulator

The first approach for studying the drilling force and speed for the mandibular bone is from the viewpoint of the experts; the clinicians that have accumulated experiences of oral implant surgery cases. In order to get the clinicians' data and their view on the drilling force and speed, an oral implant surgery training simulator was used. The purpose of the simulator is actually to learn the correlation between the drilling force and the micro-architecture of trabecular bone for a variety of

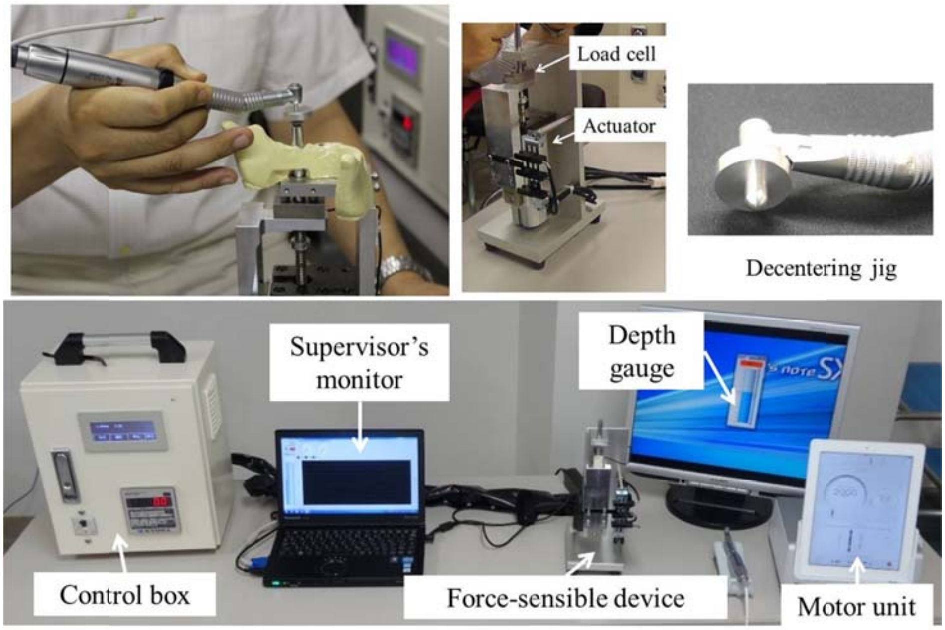

Fig. 1 Developed oral implant surgery simulator. The upper left figure shows a clinician handling the simulator using a decentering jig (upper right) made to be used with this simulator instead of normal drill

patients. The required drilling force for a patient may vary according to the drilling depth due to the distribution of bone density and micro-architecture of the trabecular bone region. Fig. 1 shows an overview of the oral implant surgery training simulator.

The training simulator has two parts, the hardware and the software. For the hardware, it has a force sensible device that consists of a load cell to monitor the input force given through a real handpiece by the user and an actuator to control the speed that refers to the database, that is, the software of the simulator. The database that contains the results of the drilling force is shown in Fig. 2 with their micro-CT images. Details of the calculation method will be described in the later chapter. With the training simulator, the user is able to sense the reaction force, as well as the sound and vibration of a real handpiece. This could make the user feel closer to a real surgery.

2.1.1 Micro-CT image based modeling

Firstly, the micro-CT images of the left part of the jawbone were extracted from a donor body by a micro-CT scanner (HMX-225 Actis4, Tesco Co., Tokyo, Japan) with a 100-kVp x-ray power voltage and a resolution of 0.066 mm and 0.05 mm slice. Three samples of jawbone from different individuals were taken. The jawbone was an edentulous jaw with no information of age or sex provided and its alveolar bone resorption had progressed. Using the CT images, a three-dimensional voxel FE model of the mandibular bone was reconstructed. The insertion position is hypothetically defined at the position of the first bicuspid tooth with reference to the position of the mental foramen. In order to reduce the computational cost, the analysis target was extracted from the jawbone area with a length of 30 mm in the mesiodistal direction from the insertion point of the implant. For accuracy, hexahedral voxel elements were used with the length set as the same resolution of the micro-CT images. The computational and numerical analysis and construction

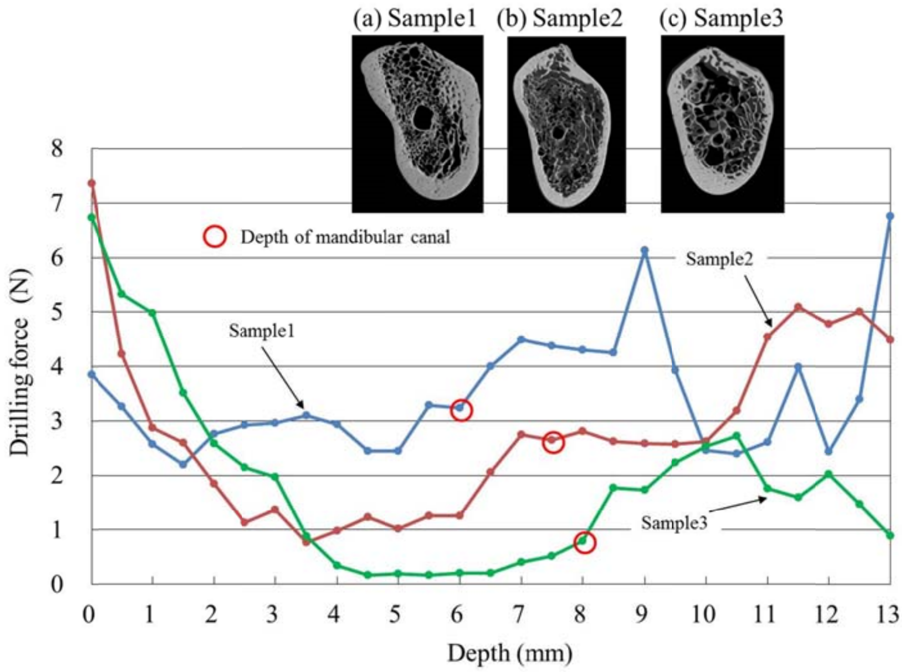

Fig. 2 Results of calculated drilling force with their micro-CT images

were done using VOXELCON (Quint, Tokyo, Japan).

2.1.2 Sequential linear static finite element analysis (FEA)

The calculations of the required force for drilling of jawbone were carried out by assuming the drilling stage in the implant surgery procedure. Considering the strict prediction for the drill behaviors, such as the dynamic motions of the drill, interaction of muscle and joints to the jawbone, effects of cutting the scraps of the jawbone, contact condition between the bone and the drill, and the destruction of the jawbone, a nonlinear analysis is required. However, with many unknown parameters, it was simplified into a sequential linear static analysis. The computational model consists of the jawbone constructed using micro-CT images, the drill which was simplified by a 2.0 mm cylinder and a rigid stand at the bottom part of the jawbone model. The drill or implant insertion position is set at the top of the model and the drilling direction is defined as the z-axis. Only the drilling force for the trabecular bone region was calculated. For the mechanical properties, assuming an isotropic material, the drill and bone Young's modulus and Poisson's ratio for all material were defined as 200 GPa, 15 GPa and 0.3 respectively. Elements which have low properties compared to the bone tissue were set surrounding the drilling area to indicate the contact condition between the drill and the bone tissue. The starting point was set at the position at which the drill enters the trabecular bone area. The analysis was carried out with intervals of 0.5 mm until the depth of 13 mm. For the boundary condition, we referred to the experiment done by drilling a fresh cadaver that will be described later. A prescribed displacement of 0.01 mm was applied to all the nodes of the front edge of the drill imitating the drill's movement inserted into the jawbone. The reaction force at the bottom side of the drill was then calculated.

Fig. 3 Experiment on fresh human cadaver (Tokyo Dental College Ethics Committee approval number: 00356)

2.1.3 Calibration of calculated procedure

To ensure the confidence of the numerical prediction, the numerical results were calibrated based on the experimental measurements of drilling force for fresh cadaver. Three cases were tested including normal drilling, perforation of mandibular canal and perforation of lingual cortical bone. Fig. 3 shows the fresh cadaver that was fixed completely to the stand. The cadaver was placed at the top of an electronic balance to measure the force impressed on the cadaver. Based on the experiment done, the drilling force ranges were between 10 N to 12 N for the cortical bone and between 5 N to 6 N for the trabecular bone. The results were used to calibrate the calculation of the drilling force using sequential linear static FEA.

2.1.4 Database's evaluation by experienced clinicians

The calculated drilling forces for all 3 samples were evaluated by eight clinicians from the Department of Implantology, Tokyo Dental College that have experienced implant surgical

Table 1 Clinicians' information with tested samples

Clinicians	Clinicians' information		Sample tested		
	Cases	Graduated (years)	Sample 1	Sample 2	Sample 3
A	Over 100	33	O	O	-
B	Over 100	14	O	O	O
C	30	5	O	O	O
D	20	6	O	O	-
E	15	3	O	O	-
F	5	6	O	O	-
G	3	5	O	O	-
H	1	2	O	O	-

procedures. Table 1 shows the information of the clinicians' that tested and evaluated the database. The clinicians were firstly given a detailed explanation of the system and the jawbone model by showing the micro-CT images of the samples (Fig. 2) and the targeted depth that had to be drilled located 1 mm above the depth of the mandibular canal. Then the drilling simulation was carried out using the oral implant surgery training simulator. During the simulation, the clinicians were not shown the required drilling force, and their input force and speed. After the simulation was done, they were shown the graph that contained their input drilling force and speed. They were also asked to give their overall impressions of the training simulator. In addition, based on their experiences of handling surgical procedure, they were asked to mark the stiffness felt while drilling the samples on a stiffness scale.

2.2 Experimental works on polymeric model

In order to obtain data from the second approach proposed which is the student's point-of-view, experimental work on polymeric models (Nissin Dental Products Inc, Kyoto, Japan) used during classes were done. The experiment was done on three types of models as shown in Fig. 4. The models imitate the mandibular part of the jawbone and made from polymeric foam material resembling the trabecular bone, surrounded by a thick dense polymer for the cortical bone. The model P9-IMP.6 is an exception, since it exclusively contains a wire surrounded by thick solid polymeric material that is used to show the mandibular canal inside the jawbone. This model was devised by the Japanese Oral of Implantology Society. According to its maker, based on the Lekholm and Zarb's bone classification (Lekholm 1985), all the models are of Type III with the exception of model P9-IMP.6 being in between Type II and III. By using two types of drill, the round bur and the twist drill with a 2 mm diameter (Drill kit 7-15 mm, Nobel Biocare, Zurich, Switzerland), the polymeric model was drilled until the desired depth. The model was drilled until the depth of 15 mm except for model P9-IMP.6, whose depth was set until the drill touches the mandibular canal. Using the same motor unit and handpiece used during the clinicians' evaluation, the rotation speed was set at 800 rpm.

The polymeric model was loaded on a precision balance (UW4200H, Shimadzu, Kyoto, Japan) connected to a computer. The precision balance was used to measure the input force given during

Fig. 4 Polymeric model of mandibular bone

the drilling and it was recorded in the computer. A scale was put parallel to the handpiece in order to measure the depth and calculate the drilling speed. 3 sets of model were used for each type and each of the model was drilled either 3 or 4 times. Each type and set of model was marked and drilled with a supposed constant input force of 1.5N, 2.2N and 3N. The polymeric models were divided into two regions based on the drilled depth. The shallow region for depth lower than 7.5 mm and the deep region for depth beyond 7.5 mm. The average drilling speed of each region was taken and recorded.

3. Results

The results of the calculated drilling force in the trabecular bone region from the micro-CT images are shown in Fig. 2. The drilling force is assumed under constant drilling speed. The force in the cortical bone region was fit with the calibration done on the fresh cadaver so that it best fit the force sensed during actual surgery. As it can be seen in the figure, the force appears to be higher when near the cortical bone region. In the trabecular bone region, the forces differentiate between each bone and it fluctuates reflecting the characteristics of the local microarchitecture.

Next, the evaluation of the calculated drilling force was done by 8 clinicians with different background and experiences of a real surgery based on the information shown in Table 1. During the evaluation, clinicians show different handpiece holding style as shown in Fig. 5, mirroring their personal drilling style. For the stiffness scale, each clinician was asked to evaluate the feeling of drilling the jawbone and some results are shown in Fig. 6. Based on the information given in Table 1 and Fig. 6, the bone stiffness felt by the clinicians differ and it gets softer as the clinicians had less and less experience of surgery cases. In comparison of each sample, all the clinicians felt the same difference of stiffness for each sample; Sample 1 is much stiffer than Sample 2. Overall, clinicians mostly gave positive comments about the training simulator and said it was very realistic.

Based on the evaluation done, the relation of drilling speed and force sensed by the clinicians became a point of interest, thus the approach from the students' point-of-view was proposed. The drilling speed for the polymeric model shown in Fig. 4 was recorded and compared with the drilling speed of the clinicians' evaluation. The results are as shown in Fig. 7. As it can be seen, there are unclear differences between each sample and each polymeric model, although they show

Fig. 5 Some of the clinicians' way of handling the handpiece (From right; Reverse hand handling, accompanying left hand handling, one hand handling)

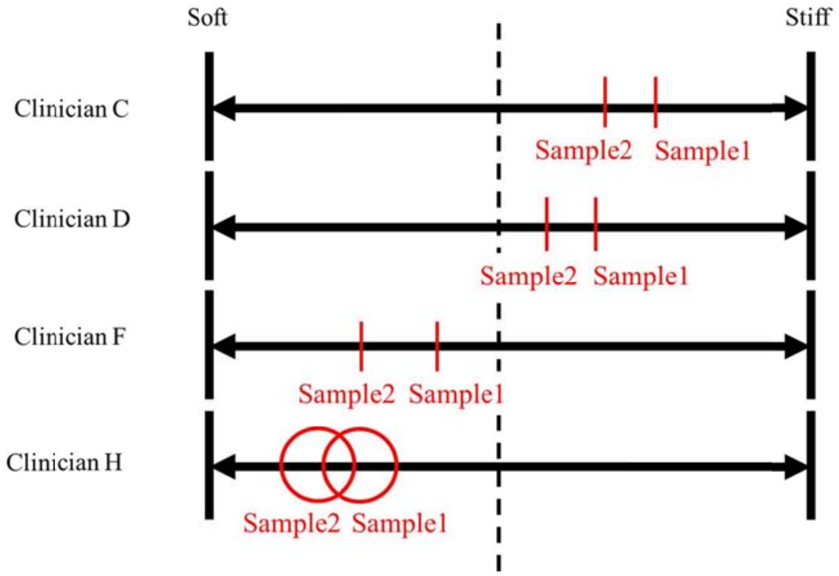

Fig. 6 Results of some of the clinicians' evaluation

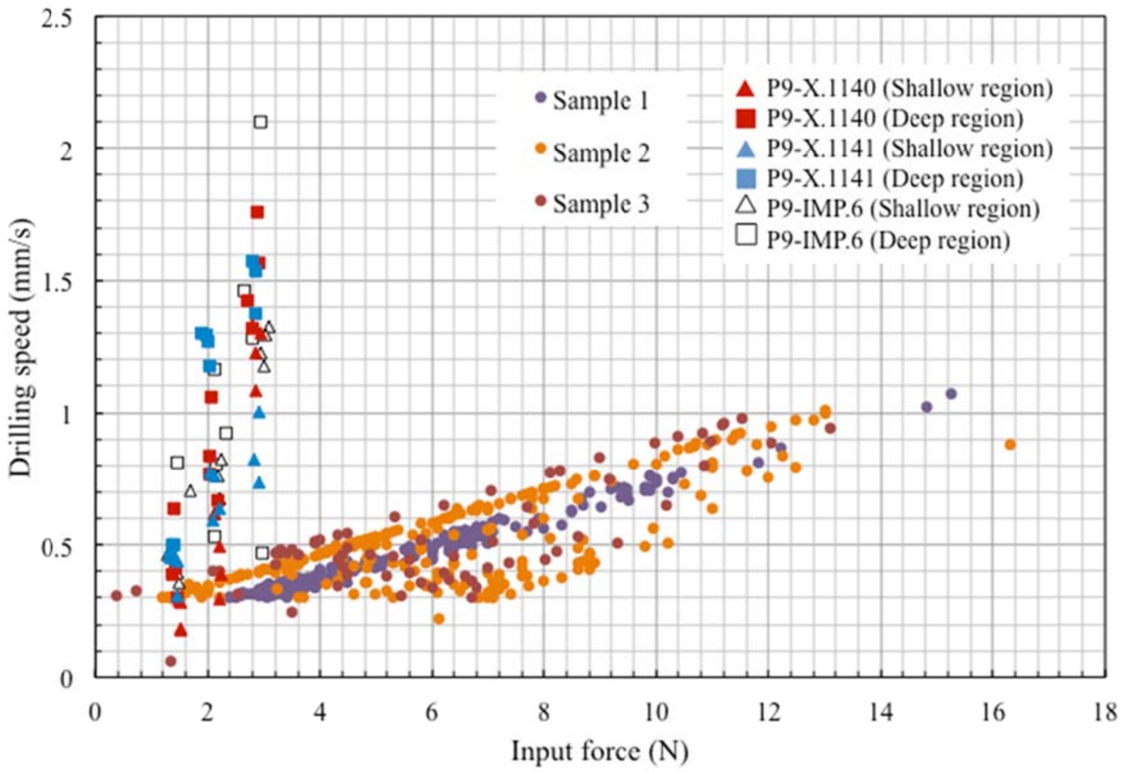

Fig. 7 Results of drilling force and speed on training simulator and polymeric model. The triangular and square markers indicate the results for the polymeric model experiment while the circle marker indicate the three samples evaluated by the clinicians

differences in terms of microstructure and bone type classification (Lekholm 1985). In general, the comparisons of the polymeric models show a much higher drilling speed in the deep region than in the shallow region. By comparing the drilling speed from both the proposed approach, the drilling speed of the clinicians' ranged from 0.3 mm/s to 0.9 mm/s but the drilling speed based on the experimental work on the polymeric model ranged as high as 1.5 mm/s. The higher drilling speed was obtained from drilling the polymeric model although it was done with an input force of 3 N, lower than the force used for clinicians' evaluation. Even with a higher input force of 9 N, the drilling speed is much lower than that of the polymeric models. Looking at the obtained data, the curve of the clinicians' evaluation seems to show a lower slope than the curves recorded using the polymeric model thus showing the polymeric model to be much softer than the calculated data from a real jawbone.

4. Discussion

Matsunaga *et al*. reviewed the biomechanical study on jawbone while considering the structural properties of the trabecular bone region and underlined the need to incorporate the bone quality in biomechanical analysis (Matsunaga *et al.* 2011). Although it only stated its need while analyzing three-dimensional FE models, the present study puts together two approaches including the FE analysis, as stated, in order to further expand the analysis. We proposed the approach of using the polymeric model and compared both of the analyses while incorporating the bone quality. As stated in the National Health Institutes of Health (NIH) Consensus Development Panel on Osteoporosis Prevention, Diagnosis, and Therapy, bone strength is also affected by bone quality hence comes the importance of incorporating the bone quality.

The comparison of drilling force and speed between the two approaches largely differs as shown in Fig. 7: the scattering of the clinicians' evaluation's data is denser than in the polymeric models. Regardless of the differences, Sugaya measured and recorded similar scattering while studying the relationship between the cutting force and bone mineral content (Sugaya 1990). The author's study aimed at finding out more about the bone quality for dental implant by taking into account mineralization parameter of the bone quality. The ranges of bone mineral content increases as the cutting force increase, thus showing the same similarity with the present study by changing the parameter of the bone mineral content with the drilling speed. This shows that the relation of the drilling force and speed could be one of the parameters in studying and quantifying the bone quality. It could also be a way to evaluate and quantify the tactile sensation while drilling the jawbone.

According to the evaluation done and the positive reviews obtained, the developed simulator can be considered as a valid tool. This shows that the polymeric model seems to be exaggerated based on the high drilling speed recorded even in low input force. Nevertheless, the structure of the polymeric model could potentially be helpful for students when they start learning the oral implant surgery since the high drilling speed could let the students be very careful while drilling, especially near the mandibular canal.

5. Conclusions

In order to carry on a deeper study about the drilling force and speed in oral implant surgery, a training simulator has been developed and evaluated by experienced clinicians. The tactile sensation of drilling the jawbone can be obtained through the simulator as it shows great potential while avoiding any risk in difficult procedures and enabling the user to increase their level of proficiency through repeated practice. The drilling speed and force obtained while doing the evaluation was further expanded and the experiment using polymeric model was done. All this enables us to study the biomechanics of oral implant surgery and learn more about the bone quality through the tactile sensation of the drilling process by studying the relation of the drilling force and speed. The two approaches gave different results thus providing us merits and demerits of both approaches in order to educate students in the field of oral implant surgery.

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