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ORIGINAL RESEARCH

Methodology for Stress Measurement by Transparent Dental Aligners using Strain Gauge

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ABSTRACT

Aim: Orthodontic tooth movement is a pressing issue nowadays. An increased esthetic demand during orthodontic treatment has resulted in several alternative treatments. However, the need to avoid conventional fixed orthodontic prosthesis has led to the usage of computer-aided scanning, imaging, and printing technology along with the emergence of transparent dental aligners. The motive of this study is to present methodology of measurement of the stress applied by transparent dental aligners on human teeth using a strain gauge-based measurement device.

Materials and methods: Three dimensional (3D) scanner, 3D printer, thermoforming machine, strain gauge, data acquisition device, 3Shape Ortho Analyzer software were used.

Results: For a full-bridge Wheatstone bridge data acquisition system (DAQ), a standard aligner can strain a constantan-based strain gauge by nearly 2.5×10^{-4}. This is based on the strain gauge factor of 2, input voltage 5 V for which a change in voltage of 2.5 mV was detected. Young's modulus for constantan strain gauge is given as 17.5 MPa; hence, this produced a stress of nearly 4.38×10^{-3} MPa.

Conclusion: This article describes an effective and convenient methodology for orthodontic treatment design for patients with crowding problem using computer-aided design (CAD) and computer-aided manufacturing (CAM) software and, thereafter, printing different stages of maxilla and mandible using fused deposition modeling (FDM) rapid prototyping technique. A transparent aligner is fabricated using thermoforming process, and the applied stresses on manipulated teeth by aligner can be evaluated using a strain gauge-based DAQ.

Clinical significance: This approach is expected to understand the efficacy of the thermoformed aligners for teeth movements by calculating applied forces and stresses.

Keywords: Fused deposition modeling, Mandible, Maxilla, Rapid prototyping, Strain gauge, Thermoforming, Three-dimensional printing, Transparent aligners.

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INTRODUCTION

The increasing use of dental models has made a significant contribution in orthodontics. These models are currently used in clinical practice as useful diagnostic aids and efficient tools to visualize the details of anatomic structures in practical situations. Orthodontic models document the initial conditions, treatment progress, and the final result. Various CAD/CAM software are available through which modifications on the scans of dental models in the standard template library (STL) format are performed virtually to design the replicas of dental models.[1] Initially, the scanner is used to collect the digital data (.stl files) after which the recordings of the topographical characteristics of teeth are performed with the help of CAD/CAM software.[2,3] Virtual planning of orthodontic treatment is, thereafter, carried out, which is further converted into the 3D model by rapid prototyping. Cuperus et al[4] presented a study for validation and reproducibility for dental models using intraoral scanners. They initially scanned the dentition using chairside oral scanner. These scanned files were then corrected for missing data by computer programs and were converted into digital models using software, such as Orthoproof. Finally, these files were converted into stereolithographic (SLA) models using the 3D printer with 3M ESPE algorithm. The measurements of dentition and SLA models were performed using a digital caliper, and that of the digital models were performed using Digimodel software. Measures used for the analysis were the width of the tooth, transversal distances, skull segments, and dimensions of SLA and digital models. According to the analysis, differences were clinically insignificant. The standard values used for analysis were mean measurements of the skulls with cutoffs for segments of 0.2 mm, widths of mesiodistal of 0.1 mm, arch discrepancies and transversal distances of 1.0 mm, and discrepancies in tooth size of 1.5 mm.

Ender and Mehl[5] evaluated the accuracy of new reference scanner. From the reference model, conventional impressions were made and exported as digital models. In addition, digital models were exported from the digital impressions of the reference model. By superimposing the digital model within each group, precision was measured. Reference scanner delivered high accuracy with a precision of 1.6 ± 0.6 µm and a trueness of 5.3 ± 1.1 µm.

Conventional impressions showed significantly higher precision 12.5 ± 2.5 μm and trueness values 20.4 ± 2.2 μm. Digital impressions were significantly less accurate with a precision of 32.4 ± 9.6 μm and a trueness of 58.6 ± 15.8 μm.

Wiranto et al[6] assessed the validity, reliability, and reproducibility of digital models obtained from the oral scanner and computed tomography (CT) scans of impressions. The intraoral scanner was used for scanning the maxilla and mandible. Totally, 22 sets of study models were taken for digital and manual measurements. On the plaster model, tooth widths were measured with a digital caliper. DigiModel software was used for measuring tooth widths on Digimodels. The differences of tooth width measurements of the digital models and the intraoral scans never exceeded 1.5 mm, and this difference was regarded as clinically insignificant.

Rapid prototyping is an immoderate developing 3D printing technique that plays a significant role in the eventual replacement of plaster dental models. Hazeveld et al[7] developed a rapid prototyping approach focusing on how to create replicas of plaster models. In this study, authors initially scanned the plaster models to form 3D surface models in STL format using dual-sensor laser scanner. They then transformed these STL files to physical models using 3D rapid prototyping methods, such as a jetted photopolymer, digital light processing, and 3D printing. Height and width measurements of models were carried out using a digital caliper. On analyzing the performance of the proposed approach, mean differences for measurements of clinical crowns were recorded as 0.04 mm for digital light processing models, –0.02 mm for jetted photopolymer models, and 0.25 mm for 3D printed models. Similarly, for the width of teeth, the systematic mean difference was –0.05 for digital light processing model, –0.08 mm for jetted photopolymer models, and –0.05 mm for 3D printed models. However, this study lacked accuracy in some cases due to distortions in STL files after conversion and manipulation.

Ayoub gave the accuracy of composite models as compared with the original mandible. A CT scanner was used to scan mandibles. Digital Imaging and Communications in Medicine (DICOM) files were processed and converted into STL files. Through rapid prototyping techniques, 3D composite models were printed. To calculate accuracy, both the composite and original mandibles were scanned and, thereafter, imported into STL format into Virtual Grid software. Totally, 12 landmarks were chosen, six dental and six skeletal, to assess the accuracy. After superimposition of the images, the mean distance between the landmarks was recorded. The mean distance for six paired landmarks between dental landmarks was 0.35 mm, with a standard deviation (SD) of 0.03 mm. The mean distance between the skeletal landmarks on the mandible was 0.72 mm, with the SD being 0.1 mm. Superimposition of the entire 3D image of the human mandible and the 3D reconstructed mandible based on the 12 landmarks showed larger mean distance than for the six-point superposition. It showed the mean value of 0.93 mm and SD of 0.46 mm.[8]

Wan Hassan et al[9] gave an analysis of the accuracy of measurements made with stone models and rapid prototyping. The stone models were scanned using a structured light scanner and exported as binary SLA files. Totally, 10 sets of models for each category of crowding (mild, moderate, and severe) were printed using Zprinter 450. Digital calipers were used for measuring Stone and RP models. Bland–Altman analysis showed the mean bias of measurements between the models to be within 60.15 mm (SD, 60.40 mm), but the 95% limits of agreement exceeded the cutoff point of 60.50 mm (lower range: –0.81 to –0.41 mm; upper range: 0.34–0.76 mm). The rapid prototyping models were not clinically comparable with conventional stone models regardless of the degree of crowding.

Fused deposition modeling begins with a software process that processes an STL file by mathematically slicing and orienting the model for the build process.[10] The FDM method forms 3D objects from computer-generated solid or surface models like in a typical rapid prototyping process. Models can also be derived from CT scans, magnetic resonance imaging scans, or model data created from 3D object digitizing systems. The FDM uses a small temperature-controlled extruder to force out a thermoplastic filament material and deposit the semimolten polymer onto a platform in a layer–by-layer process. The designed object is fabricated as a 3D part based solely on the precise deposition of thin layers of the extrudate. Lee et al[11] evaluated the accuracy of fabrication of teeth using FDM and Polyjet rapid prototyping technology. They used extracted molar teeth as samples and these were scanned to generate .stl files. These 3D surface models were printed using FDM and Polyjet techniques. Scans of these models were again taken. Geomagic software was used to perform mean deviation, linear, and volumetric measurements. Geomagic was also used to measure the volume for each tooth. The original crown width (in mm) was 11.441 and the same through FDM and Polyjet was 11.325 and 11.505 respectively. The original tooth height (in mm) was 17.226 and the same through FDM and Polyjet was 17.083 and 17.219 respectively. One observer made all measurements; therefore, only intraobserver variation was relevant. The intraclass correlation coefficient of 0.927 (95% confidence interval, 0.859–0.974) showed that the intraoperator reproducibility was high. Budzik et al[12] presented the accuracy of FDM and 3DP rapid prototyping techniques. Cone beam CT methods along with subsequent segmenting was used to make a 3D model of two teeth. These models were printed; measurements were carried out using FV microscope. The mean deviation for tooth 1 for side surface, top surface, and assembly for FDM is –25, –59, –43 respectively, and that for 3DP was found to be 41, 145, 98 respectively, in the micrometer. The mean deviation for tooth 2 for side surface, top surface, roots, and assembly for FDM in micrometer were –30, –8, –10, –11 respectively, and that for 3DP was 137, 77, 11, 71 respectively. He stated that FDM models are manufactured with the accuracy specified by the printer's manufacturer.

Stereolithography is a rapid prototyping technique. It uses a laser to polymerize photosensitive resin, producing higher-resolution printed objects of more complex geometry. Ibrahim et al[13] presented an analysis study of capacities of selective laser sintering (SLS), 3DP, and Polyjet model to reproduce the anatomy of the mandible and find their dimensional errors. They started with the acquisition of CT images from dry mandible and then performed manipulations on it using Invesalius software and converted them to .stl format. These files were then converted into SLS, 3DP, and Polyjet model. Thereafter, linear measurements were performed on these rapid prototyped models and statistical analyses were performed using descriptive statistics, such as mean and variance with student t-test for comparing paired samples. Results gave a dimensional error of 1.79% for SLS model, 2.14% for Polyjet, and 3.14% for 3DP. Hence, it was analyzed that SLS prototype had the greatest dimensional accuracy among the three. However, cost analyses showed that 3DP technique had the lowest final cost. Furthermore, Silva et al[14] gave a capacity analysis of SLS and 3DT models for reproduction of craniomaxillary anatomy with a dimensional error. They used Invesalius software to segment CT images using thresholding and converted them to .stl format. Thereafter, these .stl files were converted into 3D printing and SLS using rapid prototyping. Finally, linear measurements were made using electronic caliper and data were analyzed for performance using descriptive statistics to compare the samples using statistical t-test. Analysis showed the 0.89 mm (2.10%) of dimensional error for SLS model and 1.07 mm (2.67%) of dimensional error for the 3DT model. These techniques are found to have incurred least cost and time of manufacturing among all the existing SLA approaches. Among these, the 3DP model has a lesser final cost than SLS model, which costs further less than SLS techniques. However, prototypes of SLS have higher precision in dimensions as well as the accuracy of reproduction than the 3DP model.[15] Khalil et al[15] gave an analysis of the accuracy of four different 3D printers of 3D reconstructed models of teeth compared with natural teeth. They used 3D planning software SIMPLANT for segmentation of DICOM images. 3-matic software was used to make 3D models from the segmented tooth. These STL files were sent to four 3-D printers: SLA, Objet Eden 250, Objet Connex 350, and UP Plus 2. To assess accuracy, volume differences between the natural teeth and the printed models were evaluated using the Archimedes principle. The accuracy of the SLA-fabricated replicas in the present study showed a mean error of 4.6 mm^3 (1.1%) to 4.4 mm^3 (2.1%). For FDM technology UP2 plus, accuracy was 0.6 and 0.7%, with a mean difference of 1.3 and 3.1 mm^3. Objet Eden 250 and Objet Connex 350 revealed an accuracy of 4.4 mm^3 (1%) and 8.5 mm^3 (1.9%) respectively.[16]

After printing of 3D models using FDM and SLS, the rapid prototyping technique, aligners from these molds are created using the process called thermoforming. Thermoforming is a generic term of the art and science of forming commercial products by heating plastic sheet to a pliable state, pressing the sheet against a cool mold, holding the formed sheet against the mold until cool, and trimming the formed part from the web or skeleton surrounding it. Thermoforming is characterized as capable of forming many polymers, of forming large surface area-to-wall thickness parts, of forming parts against single-surface molds that can be made of many materials, and of using moderate forming temperatures and pressures.[17] Clear transparent aligner is constructed by first forming an impression of a patient's upper or lower dentition and constructing a cast from the impression. The retainer is vacuum thermoformed over the cast using a sheet, plate, or disk of thermoformable plastic and a vacuum or pressure thermoforming machine.[18]

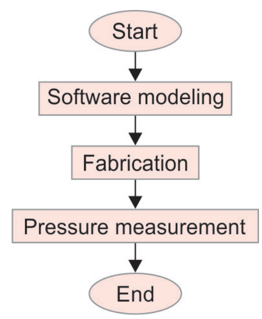
MATERIALS AND METHODS

In this section, a detailed procedure for designing of Clear Aligner has been presented, which uses a series of steps as mentioned in Flow Chart 1 and discussed in steps 1 to 3.

Software Modeling

The maxilla and mandible data of the patients were obtained either by taking the impression of the teeth and

Flow Chart 1: Methodology used



making a model of Plaster of Paris or using an intraoral scanner that directly scans the teeth of the patients. The scanned file of the patient's teeth was in STL format, which we analyzed through any orthoanalyzer software, for example, 3Shape Ortho Analyzer software. In this software, a series of steps were involved, which include marking the missing teeth of the patient, measuring the width of each tooth as well as deciding on an ideal arch length. According to the measured width of the tooth and ideal arch, the spacing or cutting of tooth was decided. Then, manipulations were performed on the teeth so that they were perfectly aligned. These manipulations can be in the form of linear movements, such as forward/backward, left/right, extrusion/intrusion, and angular movements, such as rotation and inclination. These manipulations were performed in multiple stages based on the biological limits of teeth movements. In general, the linear movement of one stage can be at the maximum of 0.5 mm, and the angular movement of a tooth can be at the maximum of 3°. Therefore, based on specific patient requirements and conditions, the total numbers of stages were generated keeping in mind the constraints of linear and angular movements for each stage. The substages generated were obtained in STL format, which was further converted into G-Code files.

Figure 1 shows the initial molds which were the output of 3D scanner on which manipulations were performed using CAD software.

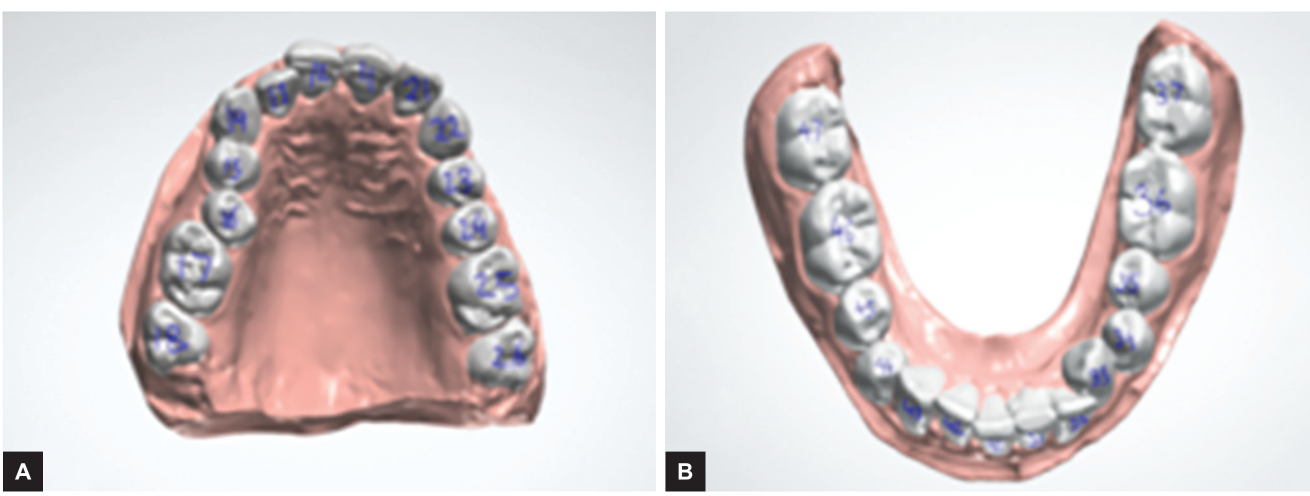
Fabrication

These stages in G-code format can be printed using various printing techniques, such as Polyjet, SLA, and FDM and also using various materials, such as acrylonitrile, butadiene and styrene, and polylactic acid.[9] After obtaining the 3D prints of the models, the process of thermoforming was performed for each stage. Every patient, therefore, obtained a set of clear transparent aligner equivalent to a number of planned stages. In this process, Duran Sheet was used to manufacture the aligner on the printed model. This was done through thermoforming. Duran sheet is a biomedically approved material for preparation of aligners. This sheet can be used in various thicknesses, such as 0.5, 0.625, 0.75, 1, or 1.5 mm. The selection of sheet thickness depends on biological limits and treatment direction in general, thicker the sheet, higher the stress on teeth.

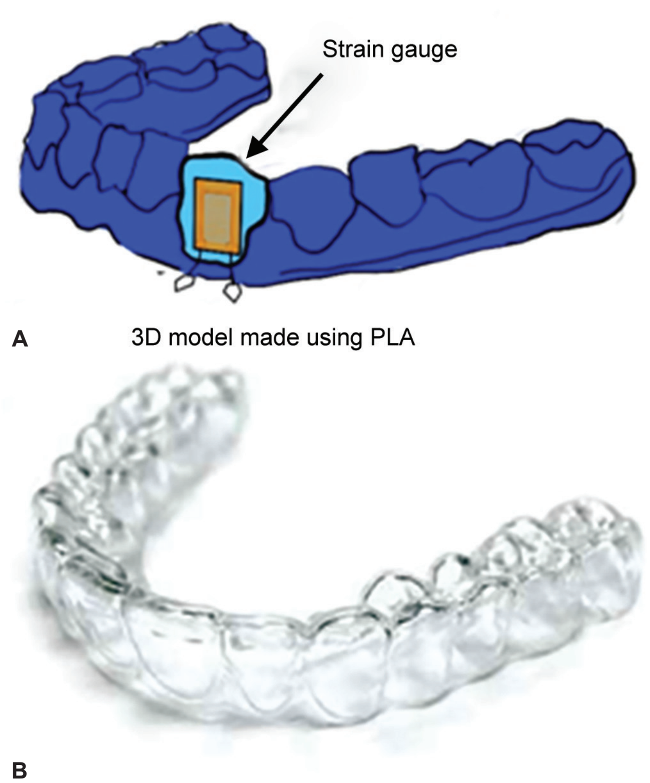
Pressure Measurement

To evaluate the efficacy of a thermoformed clear aligner, a separate pressure measurement system needs to be developed. Since the aligner applies a certain requisite pressure on the specific tooth for manipulation, a strain gauge-based measuring device can be used for pressure measurement.[19] Once the aligner and the 3D printed model of the patient's teeth were ready, stress can be calculated on each manipulated tooth using a strain gauge. Before calculating the stress, the 3D printed model has to be cleaned using dilute acetone.[20] Then, the strain gauge was mounted on each manipulated tooth. Each stage of aligner needs to be worn for 20 hours a day for 2 to 3 weeks.[21] The time needed for this treatment depends on the manipulations required to achieve an ideal arch. On an average, treatment using clear aligners takes about 13.5 months (Figs 2 and 3).[22]

To attach the strain gauge, it is suggested to use polymer-based adhesive that is nonporous and thermoplastic in nature, e.g., cyanoacrylate.[20,23] To obtain stresses using gauges, they need to be electrically connected to a DAQ. Based on the material properties of the gauge, a mechanical strain is recorded by DAQ in the form of change in voltage. Based on the sensitivity, quarter half, and full bridge circuit can be selected.



Figs 1A and B: (A) Maxilla; and (B) mandible



Figs 2A and B: (A) Strain gauge mounted on the specific tooth of 3D printed model; and (B) transparent aligner obtained after thermoforming

Equation below indicates the measurement of stress using change in voltage

$$dV_0 = Vs \times F\epsilon \quad (1)$$

where

dV_0 = Change in voltage

Vs = Voltage supplied

F = Gauge factor

ϵ = Strain

σ = Stress

$$\text{Young's modulus} = \frac{\frac{F}{A}}{\frac{\Delta L}{L}} = \sigma/\epsilon = (\text{stress})/(\text{strain}) \quad (2)$$

Here known factors are:

- Young's modulus $= 17{\cdot}5 \times 10^6$ Pa
- Gauge factor (F) = 2 (max 2.2)[24]
- R(resistance of sensor) = 350 Ω[24]
- Vs (voltage supplied) = 5 V

These values of stresses applied by aligners must be within biological limits that human teeth can tolerate which is approximately 0.0050 MPa. These stress values can also assist in selecting sheet thickness for aligners. Ultimately, for characterizing any new aligner for patient apart from comfort, the efficiency needs to be determined by evaluating applied stress.[25]

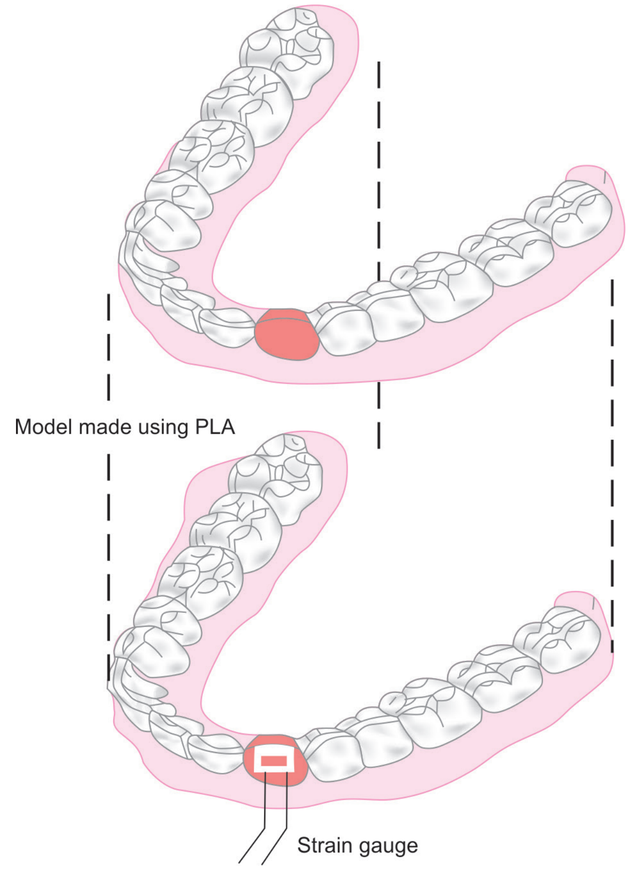


Fig. 3: Line diagram of 3D printed model with strain gauge applied to the manipulated tooth along with the clear teeth aligner prepared after thermoforming

CONCLUSION

In this article, we have presented a methodology for designing and fabrication of various stages of misaligned teeth using Autodesk. The FDM-based 3D printer was used to fabricate the stages that ultimately were used to generate transparent dental aligners for all the stages using thermoforming. In order to evaluate the stress applied by aligners on the misaligned teeth, a strain gauge-based measurement and DAQ were devised to measure and define the safety limits of aligner.

Future Scope

The methodology presented in this article can be used to produce real-time clear transparent aligners.

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