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Original Article

AUTOMATED DENTAL FILLING DISPENSING AND POST INSERTION MULTIFOCAL STRESS DISTRIBUTION ANALYSIS FOR IMPROVED TREATMENT OUTCOMES: A PROOF OF CONCEPT

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ABSTRACT

Objectives: *The objective of this manuscript was to integrate COMSOL-generated data and use a dental filling robot to fill a wax model of a molar tooth with the recommended filling material.*

Materials and Methods: *The study was exempt from the ethical review board. It was designed as a proof of concept. Von Mises stress distribution was calculated using COMSOL Multiphysics based on 4 different restorative materials: amalgam, composite, glass-ionomer and gold for a single wax tooth with a deep cavity. The Composite was chosen based on the size of the cavity and stress distribution as the most appropriate material. The restoration was completed using a custom-made robot that deposited composite into cavity incrementally. UV light was used to set the material.*

Results: *Composite was selected based on its superior properties in comparison to the other materials; Von Mises stresses 114.85 under a masticatory load of 100 MPa. A servo motor was used to control the composite increment deposition from the reservoir through a piston. Each increment was cured. This motion was repeated until the cavity was adequately filled as identified through the camera.*

Conclusion: *Light cured composite was the most appropriate filling material selected following simulations generated through COMSOL Multiphysics. Simulations on COMSOL using DICOM images from prepared teeth can be coupled with a filling dispension robot to automate the filling process.*

Key words: *Dental caries, Automated dental filling, Von Mises stress, Simulations, Restorative materials*

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INTRODUCTION

Dental caries, commonly known as tooth decay, affect a significant proportion of the global population, leading to the formation of cavities that require dental fillings for restoration[1]. However, the success of these restorations depends on the appropriate selection of dental materials based on the cavity's shape and size. Currently, dentists rely on their clinical experience and judgment, which can be subjective and result in suboptimal treatment outcomes[2].

The most used restorative materials include amalgam, resin composites, and glass-ionomer cement. Amalgam was the material of choice for

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posterior restorations due to its excellent mechanical properties and long-term survival rates. Resin composites, on the other hand, have become widely used for anterior and posterior teeth owing to their aesthetic outcomes. Glass-ionomer cements (GIC) have gradually emerged as an "easy-to-use" restorative material, offering specific properties like fluoride release, biocompatibility, and reliable chemical bonding to enamel and dentine[3,4].

The conventional dental filling procedure involves manual cleaning, filling, and smoothening of the cavity, which places dentists in close proximity to the patient[2]. This became a significant challenge during the COVID-19 pandemic due to the risk of disease transmission[5,6]. To address these challenges and improve the efficiency of dental procedures, dental robots are slowly interested in the field of dentistry. Research studies have highlighted their potential in improving clinical outcomes and patient satisfaction, particularly in dental implant surgery and restorative procedures. Although there are still technical and clinical challenges to overcome, the use of robotics in dentistry shows promise[7].

In this context, COMSOL Multiphysics, a finite element analysis software, offers a valuable tool for modeling and simulating human tissue and biomaterials. By inputting desired characteristics, COMSOL can simulate the behavior of different materials, and assist in selecting the most appropriate material based on factors such as size, depth, and desired properties[8,9]. A few studies have utilized COMSOL in dental research to investigate the mechanical and thermal behavior of materials used in dentistry. These studies have demonstrated the significant impact of material choice on stress distribution within the surrounding tissues[10,11]. COMSOL can serve as a useful tool for predicting stress distribution and improving material performance[12]. To the best of our knowledge, this is the first case study employing COMSOL for investigation of restorative dental materials.

Integrating COMSOL-generated simulation data with a dental filling robot can optimize the filling process. The robot can utilize the data obtained from COMSOL, including cavity depth, size, and material properties, to select the appropriate filling material[13]. With precision motion control capabilities, the robot can accurately deposit the filling material, leading to improved clinical outcomes and reduced patient discomfort. The objective of this manuscript is to integrate COMSOL-generated data and use a dental filling robot to fill a wax model of a molar tooth with the recommended filling material.

MATERIALS AND METHODS

This study was exempt from the ethical review board at Riphah International Universty. A proof-of-concept study design was used for this investigation. Von Mises stresses generated within different restorative materials; Conventional GIC, composite resin, amalgam and gold under masticatory load of 100 MPa was analyzed using COMSOL Multiphysics software. The decayed tooth geometry was meticulously imported, and relevant tooth properties were assigned to the model. Parameters such as Poisson ratio, young modulus and density were given to the model from established literature. Figure 1 illustrates the visual representation of the imported tooth geometry in software interface.

Appropriate material properties of the restorative materials were assigned to the cavity which guaranteed an authentic simulation of stress distribution within commonly used filling materials (Table 1). Table 1 also summarizes the properties of the selected filing materials.

Masticatory load was applied on the restored tooth using solid mechanics physics in the software. Filling material was subjected to optimal masticatory load of magnitude 100 MPa. Boundary load was applied normally to the surface of filling material and loading angles were kept fixed for all materials under study. After application of load, tooth-filling material junction underwent meshing. This was one of the most crucial steps in the finite element analysis. High fidelity mesh was generated that integrated the minor details for accurate representation of stress distribution and mechanical behavior during masticatory load. Visual representation of the area of potential concern within the filled tooth structure is illustrated in Figure 2.

The hardware setup for the prototype as illustrated in Figure 3 is designed to integrate with the dental chair with the aim of automating the dental filling procedure. This setup was comprised of a glass fiber frame engineered to integrate with standard dental chair. Two holders were positioned on the frame to securely accommodate the syringe in an upright position which ensured stability and error free filling procedure. The glass fiber frame for prototype was designed by using advanced simulation environment of COMSOL Multiphysics. Software's Model builder feature facilitated the design process. It ensured that frame meets the required dimensions for prototype.

Transparent fiber was 0.5 cm thick and was strong enough to hold the other components. The overall size of the frame is 14 x 14cm. Both left and right holders were 6.25 cm wide each and of had the thickness of 0.5cm. Operator was provided with the precision control knob for fine-tuned control over the filling process. The knob enabled seamless adjustment of the reservoir considering the depth of cavity for delivery of the material. A micro camera integrated into the holders of the frame provided real-time visual feedback on the depth of cavity. Visual depth assessment enabled the operator to determine the amount of material required according to the depth of cavity. The prototype featured a tooth holder that replicated the positioning of the tooth in the patient's mouth and the stable surface to hold the decayed tooth. Wax model of a single the decayed tooth is mimicking the real tooth which is placed on tooth holder. The reservoir was in the form of a 10ml syringe that held the filling material and ensured the measured and controlled delivery of material in the decayed tooth. Filling procedure was automated in the prototype by integration of servomotor, which drove the piston of the reservoir and eliminated the need for manual delivery. The servomotor placed over the top of glass frame was controlled by potentiometer. This control mechanism facilitated the regulation of servomotor's speed and motion ensuring controlled operation during filling process. The potentiometer was interfaced with Arduino Uno board which served as a controller for automated system.14 Servomotor completed its 180-degree rotation clockwise for pulling the piston of syringe and stopping the composite flow. Conversely, the servomotor completed its 180-degree rotation anticlockwise for pushing the piston of syringe and allowing the composite flow.15 Potentiometer functioned as a controlling knob on dentist's control panel and prevented his direct exposure to the patient's oral cavity. The integration of distant control knob and the camera align with the idea of maintaining the distance from patient's mouth. The purposeful design for the proposed prototype is illustrated in Figure 4.

RESULT

Servo motor performed the function of pushing and pulling to precisely control the piston of reservoir. This manipulation allowed the efficient delivery of filling material into the cavity. The push and pull of the piston were obtained by the rotation of flap of servomotor[16]. If the depth of decayed tooth was higher, an increase in the degree of rotation of flap was required to accommodate stable and effective dental filling procedure. This increased rotation allowed larger amounts of filling material to be deposited into the cavity leading to the proper restoration. The filling volume increased as the flap rotated from 60 degrees to 90 degrees anticlockwise, triggering the pushing phenomena. This link between flap rotation and filling depth provided a control and adjustment mechanism for the quantity of filling material delivered.

The graphical analysis depicted in Figure 5 illustrates the relation between the angle of servo motor and depth of cavity being filled by material. There was a progressive increase noted in the depth being filled as the flap of servo motor shifted positively from the set point of 55 degrees. At 90-degree maximum depth was filled by the servo motor through pushing the filled restorative material into the cavity.

The potentiometer was the controlling knob for the release of filing material. As the knob was rotated, a specific volume of material came out of the reservoir. The graph indicating the relation between the volumes of material released with the rotation of potentiometer knob is depicted in Figure 6. The distant control knob facilitated the dentist in maintaining a safe distance from patient while comfortably adjusting filling parameters. The visual depth assessment lowered the risk of overfilling. The integration of the control knob and the visual feedback through video camera enhanced the interaction between the operator and the patient. The operator could opt for patient specific approach through visual feedback in real time.

For the simulation and analysis of the Von Mises stresses generated during mastication, the image of cavity including precise dimensions of cavity notably the depth of cavity was obtained. Geometry was extracted from the image to create accurate representation of cavity structure. The detailed geometry provided the basis for stress analysis. Rigorous selection of material properties was done based on scientific literature. The Young modulus, density and Poisson ratio of the filling material were considered prior to the analysis. In the initial phase, comparative analysis was carried out to access the behavior of restorative materials to the applied masticatory load. This comparison enabled the identification of material with the highest von Mises stress under given load conditions of 100MPa. Stress analysis was performed to determine the magnitude and direction of von Mises stress within each material. The computational analysis for different restoratives is illustrated in (Figure 7 A-D).

Table 1: Material properties of filling material

Type of filling material	Density (kg/m3)	Young modulus (GPa)	Poisson Ratio
Light Cured Composite	1600	5	0.3
Gold	19,300	79	0.415
Conventional GIC	2300	6	0.25
Amalgam	14000	50	0.3

Table 2: Von Misses Stress of Dental Filling Materials

Filling material	Von misses stress values
Amalgam	422.20
GIC	239.55
Light cured Composite	114.85
Gold	455.85

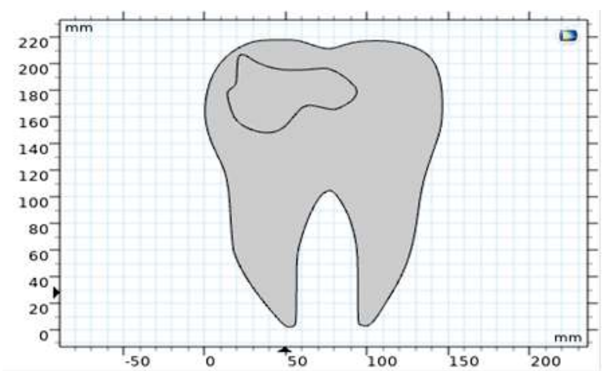

Fig 1: Decayed tooth geometry in geometry interface of COMSOL Multiphysics environment

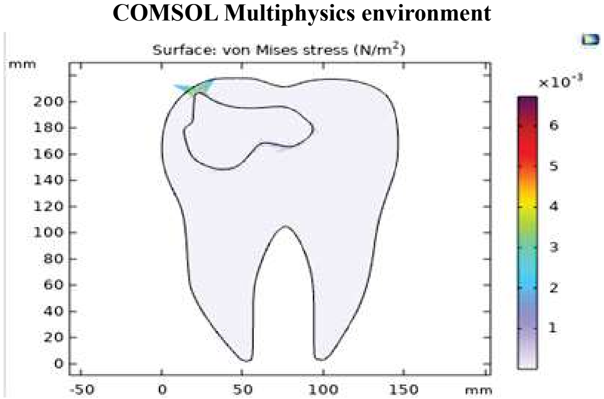

Fig 2: Comprehensive computational analysis to assess the mechanical behavior of filling materials

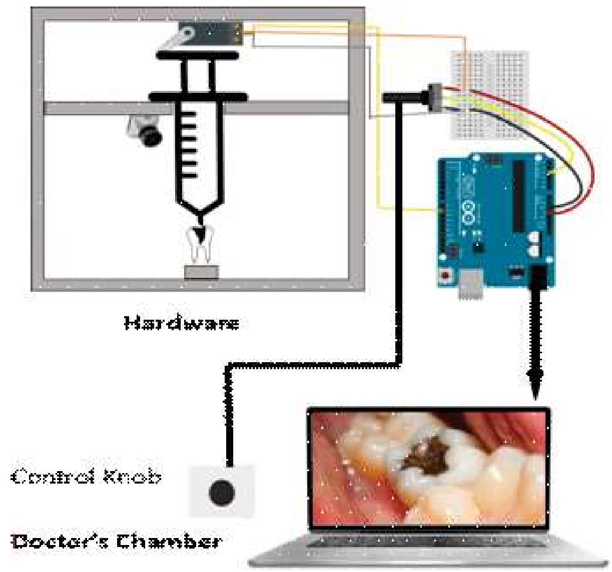

Fig 3: Block diagram for the proposed prototype to be integrated with dental chair for automatic filling procedure

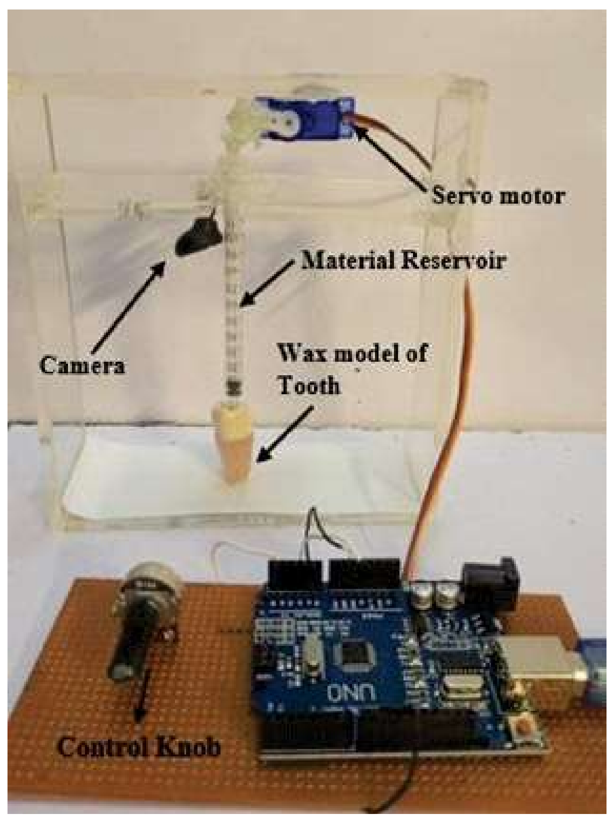

Fig 4: Prototype for Automatic dental filling procedure

Based on stress distribution, filling materials were ranked based on their mechanical performance under load condition. The material exhibiting the highest stress was susceptible to long-term failure risks. The tooth structure would also be at risk of deterioration if the stress values exceed the material's yield strength. The comparison of von Mises stress values served as an effective way of evaluating mechanical behavior of dental restoratives.

From the Von Mises stress values tabulated in Table 2, lower stress values observed in a Light Cured Composite indicate structural robustness and a lower risk of failure. It offered a bigger safety margin and the potential to optimize the materials'

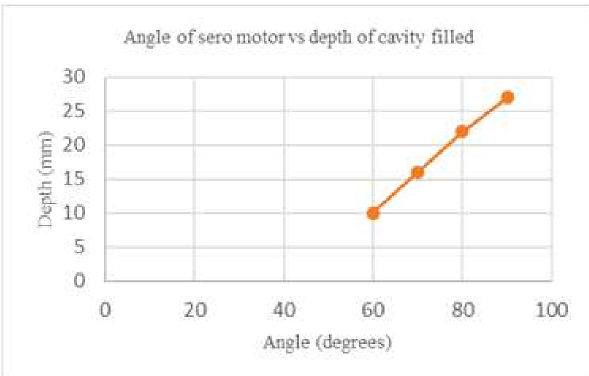

Fig 5: Graphical analyses of cavity being filled with the angle of flap of servo motor

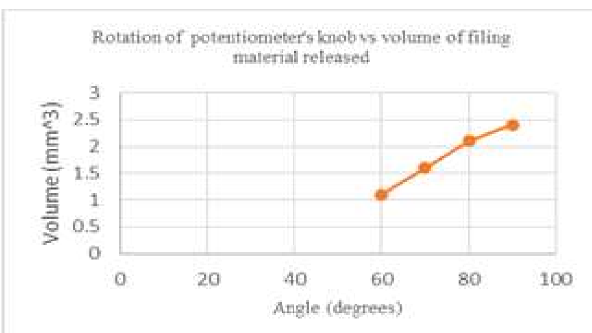

Fig 6: Relation between angle of rotation of potentiometer knob and volume of filing material released from reservoir

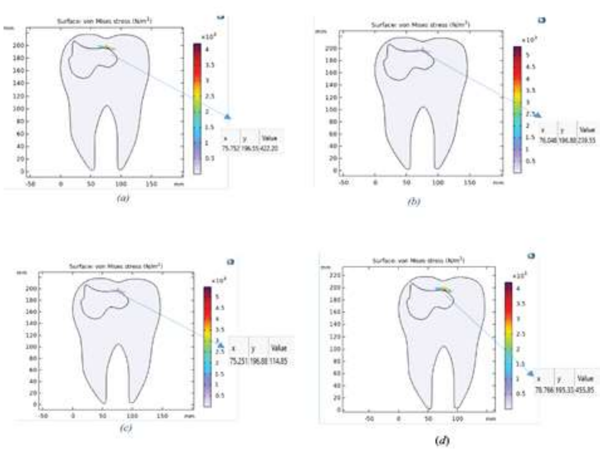

Fig 7: Von Mises Stresses generated within dental restoratives in the cavity after optimal Masticatory load application of 100MPa (a) Amalgam (b) Conventional GIC (c) Light cured Composite (d) Gold

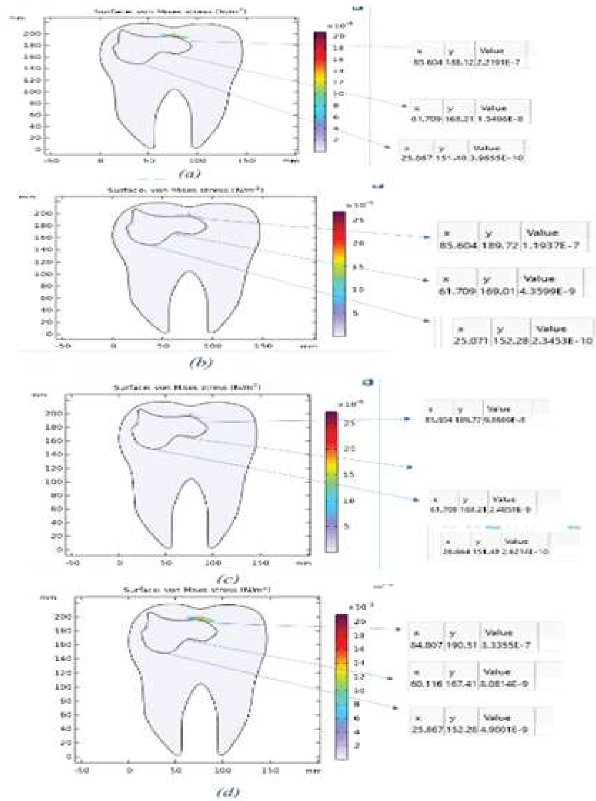

Fig 8: Relation of cavity depth with the stresses induced by masticatory load being applied on the filling material (a) Amalgam (b) Conventional GIC (c) Light cured composite (d) Gold

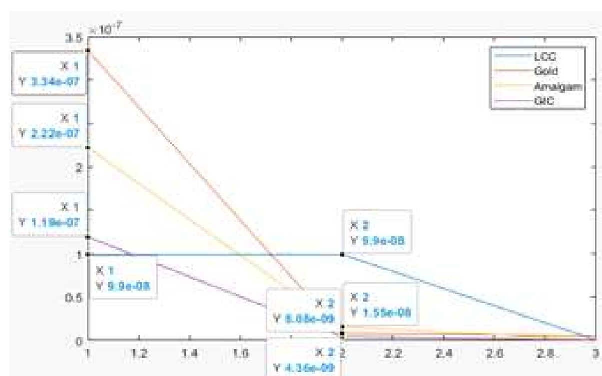

Fig 9: Response of Restorative materials under study at different depth points after application of optimal masticatory load [y-axis= von Mises Stress values, x-axis= Depths with 1 being the top, 2 the middle point and 3 the bottom, extreme depth of cavity]

usage. Conversely gold, with highest Von Mises stress values, was susceptible to deformation when subjected to strong mechanical forces. In addition to comparative analysis, we further performed the multifocal stress analysis to investigate the von Mises stress distribution at three distinct points within cavity. We examined the behavior at different depths to evaluate the overall performance of filling material in different regions of cavity. The depth points at which quantitative stress values were taken in the case of different filling materials and their responses were recorded, illustrated in (Figure 8 A-D). This analysis offered insights into the distribution of stress within the material, allowing the evaluation the identification of weak points, and potential optimization opportunities for improved structural integrity.

Multifocal stress analysis conducted at different depths revealed that the highest stress points lie particularly in the outermost layer of the filling material can be interpreted from the graph in Figure 9. The highest stress values were at the junction of filling material with enamel. Average stresses were noted in the middle of the restoration while minimal stresses were noted in depth. Throughout the cavity depths examined, gold consistently exhibited the highest von Mises stress values compared to other filling materials such as light cured composite, conventional GIC, and amalgam. This suggests that gold might be more vulnerable to areas of concentrated stress and potential dangers like localized deformation or failure. While comparing light cured composite to the other filling materials (conventional GIC, amalgam, and gold) at every depth point in the cavity, light cured composite consistently displayed the lowest von Mises stress values. This suggests that when compared to other materials, light cured composite may have better stress distribution and possibly higher structural robustness. To make a thorough assessment of material suitability, it's crucial to consider additional elements like material properties and clinical considerations etc .

DISCUSSION

Decayed teeth are commonly restored using dental materials. The choice of dental material primarily depends on the dentist's preference. Studies show that geometry, size and the depth of the cavity coupled with material properties are an effective way to reduce the stress on the tooth[17,18]. Our results from Table 2 conclude that stress distribution is not consistent throughout the cavity. The greatest stress is exerted at the enamel restoration junction; these results are consistent with a prior study[19]. Gold had the highest stress distribution when compared with other materials on all 3 points making our results consistent with a prior investigation[20]. While conventional GIC had the least stress distribution after filling compared to other dental filling materials shown in Table 2. This is also consistent with results from prior investigations[18].

Optimal material selected based on stress distribution was composite. It was also easier to dispense composite through our apparatus owing to its low density when compared to other materials. This created several advantages for us while designing the filling dispensing robot. Composite resin was easily transferred into the material reservoir, dispensing process was controlled using the clockwise and anticlockwise movement of the knob and each increment could be cured using a curing light[21]. Placement of amalgam would have required use of an amalgamator and a robot design with the ability to provide optimal condensation pressure[22]. GIC would have required mixing to produce an appropriate consistency of material before placement in the tooth[23]. While these challenges can be addressed in future studies, their absence made our robot design convenient.

Another avenue that we hope to explore in the future is an automated cavity preparation robot. We believe that such developments can ensure that patients have access to dental care without the risks of infection transmission.

CONCLUSION

Analyzing the post insertion stress distribution on the tooth, as discussed in this study, is essential for assessing the risk for restoration failure. Simulations on COMSOL using DICOM images from prepared teeth can be coupled with a filling dispensing robot to automate the filling process. By automating the dental filling technique, not only can improve the diagnosis and treatment but also ensure the operator's safety in case of splashes and avoid disease transmission.

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CONFLICT OF INTEREST
Authors declare no conflict of interest.
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None declared.

AUTHORS' CONTRIBUTION

The following authors have made substantial contributions to the manuscript as under:

Conception or Design:	KK, AZ, NMB, UH, AK, FA, ZR
Acquisition, Analysis or Interpretation of Data:	KK, AZ, NMB, UH, AK, FA, ZR
Manuscript Writing & Approval:	KK, AZ, NMB, UH, AK, FA, ZR

All the authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.