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WIP: A Study on Development of Endodontic Micro Robot*

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Abstract

Endodontic therapy, also called root canal treatment, is a procedure performed to remove damaged tissue from the inner canal of a tooth and seal the canal to prevent the tooth from being a source of infection. A typical procedure includes access preparation, root canal preparation and root canal filling. The treatment process is time-consuming and prone to human error. The outcome relies on the clinician's master skills that can be gained only through years of training and practice. The treatment successful rate is 60 - 65% by general dentists and 90% by specialists. In order to improve the quality and reliability of endodontic therapy, an endodontic micro robot is proposed to be built. This computer controlled micro machine will be mounted on the teeth within patient's mouth. With on-line monitoring and positioning control, the multi-purpose micro robot performs automatic treatment procedures, including probing, drilling, filing, cleaning and filling.

This paper will discuss the preliminary results on mechanical design and manufacture of micro robot, choosing of embedded sensors and actuators, and design of the electrical control system with NC controller. The paper will also discuss the innovations involved from the traditional way endodonticsts treat root canal to science and technology based automation.

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1. Introduction

Endodontic (root canal) treatment is common. Approximately 24 million root canal therapies are performed annually in the United States [1]. Endodontic treatment is performed to prevent the tooth from being a source of infection. Typically, endodontic treatment involves root canal preparation and root filling. The root canal preparation, preparing the root canal for root filling, can be divided into three phases: (1) access preparation, (2) coronal canal preparation, and (3) apical canal preparation. Figure 1 shows canal characteristics and the three phases in

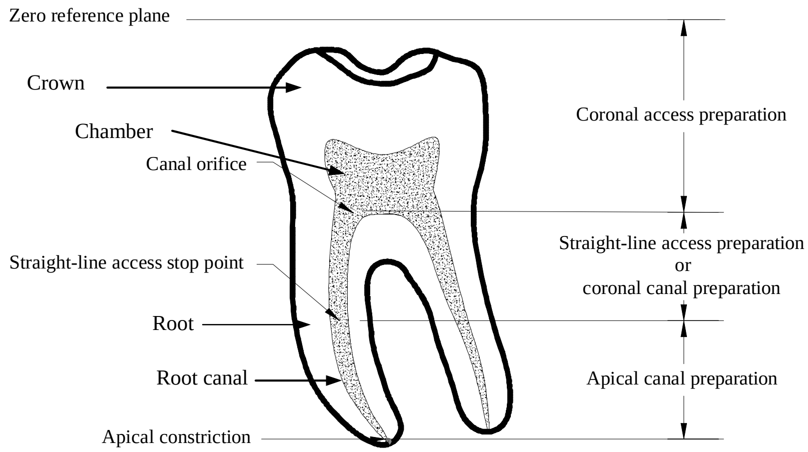

Figure 1. Canal characteristics and three phases in root canal treatment preparation

canal preparation for a posterior tooth.

An endodontic access preparation is to create an unimpeded passageway to the pulpal space and the apical portion of the root canal [2]. By using an access bur attached to a high-speed turbine hand-piece, the chamber is unroofed, and canal orifices are exposed. In order to obtain instrument control, the straight-line access to the apical portion of the root canal should be created during access and coronal canal preparation [3]. Coronal and apical canal preparation is also called root canal cleaning and shaping. Successful cleaning entails the use of instruments to physically remove substances, irrigating systems to flush loosened materials away, and chemicals to dissolve contents from inaccessible regions. Root canal shaping is a mechanical process accomplished with instruments, to establish a continuously shaped conical form from apical to coronal to facilitate filling of the root canals with gutta-percha cones and sealer that are today's most commonly used filling materials [4].

Successful outcome of the preparation depends largely on the clinician's expertise, such as tactile sense and judgement. To expose canal orifices and establish a straight-line access to the canal, a relatively large amount of the tooth structure has to be removed during access preparation. This excessive removal may weaken the teeth.

There are also problems that can occur in current endodontic techniques for the canal preparation [5] [6]. Perforation and Furcal perforation causes periodontal (surrounding tissues) destruction, weakens tooth structure, and often-subsequent loss of tooth. Canal ledging is an artificially created irregularity in the surface of the root canal wall that prevents the placement of instruments to the proper length in the original canal path. Transportation of the apical portion of the canal is characterized by a normal curved canal that has been straightened, especially in the apical third. Stripping, or lateral wall perforation, is primarily caused by overzealous instrumentation in the mid-root areas. Excessive instrumentation beyond the apical construction causes damage to the periodontal ligament and alveolar bone. Inadequate canal preparation refers to the failure to remove pulp tissue, dentinal debris, and microorganisms from the root canal system. In addition, the root canal may be improperly shaped, thus preventing adequate filling.

The problems identified cannot be resolved solely by training of clinicians. Endodontics is a clinical specialty, but the great need for endodontic therapy makes it impossible for specialists to handle all cases. There is a need for advanced endodontic technology innovation by applying advanced engineering and computer aided technology to reduce the potential for human error and improve the quality of care during endodontic therapy.

The need for advanced endodontic technology innovation has prompted the research plan of "Advacned Endodontic Technology Development". The Advanced Endodontic Technology Development project consists of four sub-subjects:

(1) development of a technique to thoroughly assess the teeth's condition using 2-dimensional x-ray images to build a computer 3-D tooth model, displayed with state-of-the-art computer graphics;
(2) develop an automatic prescription system from the 3-D root canal model, using computer-aided treatment procedure planning;
(3) design and build a smart multi-purpose precision micro machine to perform automated root canal treatment;
(4) develop a new ultrasonic cleaning tool with pressure assisted jetting/vacuum waste removal.

The development of an endodontic micro machine is the center piece of Advanced Endodontic Technology Development project, as the final implementation of advanced endodontic technology will come down to the micro machine with a precision beyond what the human hand can achieve. This computer-controlled machine will be mounted on the teeth within the patient's mouth. With on-line monitoring and intelligent control, the micro machine or robot will perform the automated probing, drilling, cleaning, and filling of root canal. All other sub-project results will be incorporated into this robotic operation.

This paper will focus on the preliminary study on mechanical design of endodontic robot, design and choosing of embedded sensors, and design of the electrical control system with NC controller.

2. Essences in Endodontic Process Automation

Root canal shaping is a mechanical process that is currently done with hand files and reamers, along with drills of various designs and tools that attach to rotary engines of different speeds. In principle, though not in scale, it does not differ from the drilling/reaming process in the machining industry. The machining industry has moved from manual operation to Numerical Control (NC) and Computer Numerical Control (CNC). The quality and accuracy of a produced part is controlled by a computer program on an automatic precision machine. The master skill, so critical in the past, is no longer needed. Currently in endodontics, the success of the root canal shaping technique principally depends on the skill and thoroughness of the clinician. This is because endodontic therapy relies almost entirely on "feel" - the tactile sense of clinicians [7].

The quality and accuracy of clinical care could be greatly enhanced by applying technological advancements, such as process automation with CNC controlled micro robot, to this therapy.

The tasks to develop the micro robot include:
(1) define the specification and requirements for the robot;
(2) mechanical design, manufacture, and positioning of the robot;
(3) design, select or fabricate the sensors and actuators;
(4) design and build the electrical control system.

3. Endodontic Micro Robot Specification and Requirements

Specific objectives for micro robot design include: (1) reducing the reliance on the skills of the dentist, (2) minimizing human error, and (3) offering a method for precise diagnosis and treatment. This machine should have the following features:

- A micro-position and orientation adjustment to ensure that the tools start at a precise point;
- An automatic feed rate and travel distance control to ensure that the tools can reach the required canal depth and stop at a designated point;
- Built-in micro sensors to monitor the probing and drilling/reaming process;
- Apex sensing and control to prevent root perforations or the potential to over shoot (exceeding the apex of the canal);
- Flexible drills or files to allow for cleaning and shaping curved canals;
- Vacuum attachments capable of sucking the debris or loose tissue from the root canal and/or pressurized solution jets to flush the chips away.

A preliminary quantitative study has given the design requirements. In order to provide accurate positioning of the tool with correct angular orientation, an ideal basic machine must have five degrees of freedom to control the following axes:

- X-axis, along the teeth row, with travel range of 5 mm;
- Y-axis, across the teeth row, with travel range of 4 mm;
- Z-axis, the tool advancement direction, perpendicular to the tooth occlusal surface, with a travel range of 15 mm minimum. When using a longer tool, the endodontic tool should be able to reach 28 mm from the tooth crown, covering the required range of treatment;
- The angular adjustment of the tool entrance angle of ± 12° in the X-Z plane;
- The angular adjustment of the tool entrance angle of ± 12º in the Y-Z plane.

In addition, the design must meet the following requirements:

- The size of the machine must be compact enough to fit into the patient’s mouth and sit on the teeth between his/her two jaws. The dimension should be within 20 mm x 20 mm x 28 mm;
- The spindle must have the rotational power to drive the tool at speeds and torque used in endodontic treatment tools;
- The machine should be able to provide a thrust force not less than 500g (4.9 Newtons) for tool penetration into the crown and dentin.

4. Endodontic Micro Robot Mechanical Design

There are different potential machine configurations. Here is introduced the design of a multi-purpose micro machine for root canal preparation, which is illustrated in Figures 2 and 3. As indicated in the figure, this machine has five axes of motion: linear motion in the *X*, *Y*, *Z* directions, and rotational motion in θ_x, θ_y directions. The tilt angles θ_x, θ_y are controlled by additional linear actuators *X'* and *Y'*. There is another rotational motion provided for the spindle ω_z.

The machine has a saddle-shaped base. It will ride on a pair of reference brackets and the teeth row. Before taking X-rays and mounting this machine, the pair of brackets, in assorted sizes to fit the patients' teeth, must be pre-clamped firmly on the tooth to be treated. Neighboring teeth may be used as support.

The bracket pair provides three radiopaque reference points for machine registration, thus establishing a coordination system for the machine. Once the machine is seated on the reference bracket, the machine base will have no motion relative to the patient's teeth, regardless of the patient's head or jaw movements. The machine is designed compact and rigid so that the patient can bite on it. There is no need for the patient to actively keep his/her mouth wide open, nor is there a need for the patient to keep his/her head absolutely still. There is no sharp corner to hurt the patient, and a protecting case (shown in the photo only, not in the drawings) further enhances the safety.

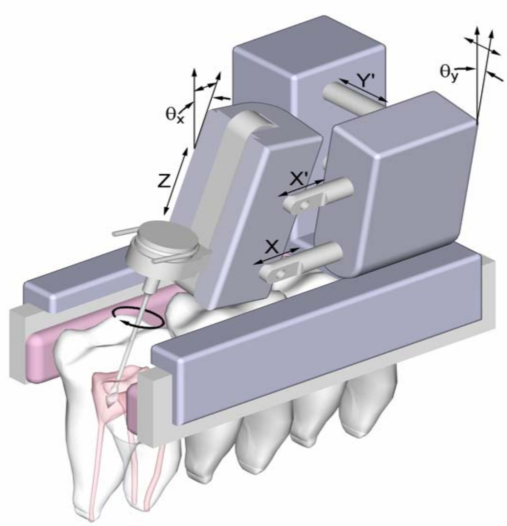

Figure 2. Multi-purpose micro-machine for automatic endodontic treatment

Designed for multi-purpose use, this machine can hold various endodontic tools and auxiliary devices. With a quick tool change concept, utilizing a cartridge design, different tools can be pre-mounted on a small modular unit, which can be inserted into a sliding adaptor on the Z axis.

Figure 3. Machine model showing how it fits in the patient's mouth: to the left is the machine placed together with a rubber dam. The machine is protected by a stainless steel cover. To the right is the machine without cover or rubber dam, showing the relationship in size to the teeth.

5. Micro Sensors, Actuators, and Controllers

This machine design also incorporates sensors for intelligent monitoring of the treatment process. Because the compact feature of the sensors, it can be fabricated using surface micromachine method into silicon-on-insulator (SOI) wafers and embedded in the micro robot. Six micro actuators will be used to control the five axes (five degrees of freedom) and turn on/off the spindle of the tool. Each actuator is independently controlled by a digital NC controller. The controller should react the sensor input quickly, such as in a few millisecond. Choosing embedded microcontrollers or cord connected controller is to be determined by further research.

Auxiliary functions will be also provided such as: irrigation nozzle for cleaning, vacuum suction cup for chip and waste fluid removal, and/or optical fibers for lighting, imaging and observation. A manual remote control will be provided for the clinician, but a fully automatic operation with computer-aided treatment procedure planning and control is the ultimate goal for zero-defect operation. An interface system is provided for the clinician to interact with the machine control.

6. Computer Aided Treatment Process Planning

Computer-aided treatment process planning system functions like CAD/CAM programs in the machinery industry. The output of the program is standard NC codes from computer aided design file and this codes control the movements of the robot through NC digital controller. The computer-aided method for root canal treatment deals with tool positioning and movement control for automated endodontic therapy [8]. This computer program is developed to automatically select the appropriate tool and to determine: (1) the tool's starting point, position, and direction, (2) the tool's path, (3) the tool's stopping point, (4) the cutting parameters, such as speed and feed, and (5) the geometry of the 3-D tooth model after treatment. The computer program plans the sequence of the operations using a variety of tools and motion control parameters to complete the preparation of the root canal. An optimization program is integrated into this auto-prescription program to minimize the removal of tooth structure and to eliminate unnecessary tool change.

7. Conclusion

The development of an endodontic micro robot is the center piece of Advanced Endodontic Technology Development. Compared to conventional access methods for root canal treatment, this research presents a less invasive method for automated access and canal preparation during endodontic therapy. The automated treatment using micro endodontic robot prevents problems identified with conventional techniques (e.g., inadequate opening, overzealous tooth removal), and provide safe, accurate, and reliable root canal treatment for patients. With on-line monitoring and intelligent control, this machine will perform the automatic probing, drilling, cleaning, and filling of root canal. The success of the fabrication of the robot and integration into the Advanced Endodontic Technology Development plan will change the traditional way of root canal treatment to science and technology based automation, and lead the micro electronic mechanical technology to a new application area in endodontics.

The paper described preliminary development of endodontic micro robot for root canal treatment, including specification and requirements, mechanical design, and controller systems. Further study is still needed, especially in micro sensor and actuator design and fabrication. It is expected that the new model with embedded sensors and actuators will be fabricated in the near future.

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