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A FUZZY LOGIC CONTROL SYSTEM FOR THE ROTARY DENTAL INSTRUMENTS*

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Abstract– Nickel-titanium alloy (Ni-Ti) rotary dental instrument files are devices which are commonly used in the field of endodontics for root canal preparation. However, Ni-Ti file breakage is common and is often caused by excessive hand pressure by the endodontist during a root canal preparation. The present solution is to automate the control of file failure (caused by pressure) through the development of a fuzzy logic controller to maintain the file breakage. Both in vitro and in vivo experiments were conducted to gather enough data to observe the system behavior and to modify the control system. In vivo results showed that a fuzzy logic control system was able to improve the file life up to 22% compared to existing rotary instrument control systems. Thus the fuzzy logic system presented in this paper not only improves the filing process performance, but reduced the time and costs spent by the endodontist as well through maximizing the use of file life and preventing file failures with the use of an applied intelligent control system.

Keywords– Fuzzy Logic, Ni-Ti, endodontics, file, control

1. INTRODUCTION

The restoration of an endodontically treated tooth is a challenging task in the field of Endodontics. Yet, root canal preparation remains one of the most problematic operations in endodontics due to the file failure. A more recent innovation in this regard has been the replacement of stainless steel files with Ni-Ti (Nickel Titanium alloy) files. Ni-Ti files have shown a greater degree of elastic flexibility in bending and torsion, as well as superior resistance against torsion fracture compared to stainless steel files made with the same process [1, 2].

This gives Ni-Ti files a greater ability to negotiate curved canals, to reduce the tendency of iatrogenic errors and to allow larger apical preparations of curved canals, while maintaining the original path [3]. It is difficult to identify and anticipate different types of mechanical stress that may occur when an endodontic instrument is rotated inside a curved, irregular root canal. However, many studies have already been conducted to clearly define which parameter affects file fatigue life. The tests carried out on the low-cycle fatigue of pseudo elastic Ni-Ti have been reported in both materials engineering and endodontics fields [4, 5]. Several studies on the fatigue properties of Ni-Ti files have focused on either stress or strain under controlled conditions [6, 7]. Several parameters such as RPM, torque, apical force, specific heat, strain value, canal shape, and file specification that affect file fatigue have been investigated [8-11]. The intensity of each parameter has non-linear effects on the endurance limit of the file instruments. This

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would result in the frequent occurrence of file fractures. When the instruments come near to reaching their endurance limits, failure may occur. When using Ni-Ti rotary instruments for canal preparation, the continuous tensile and compressive stress cycles in the canal region of the maximum curve leads to mechanical fatigue. Thus, Ni-Ti fatigue resistance is the parameter that in most cases determines the applicability of the device [12]. In order to prevent the file failure in endodontics, a Ni-Ti rotary instrument is usually rotated under low-cycle, at a frequency of 150rpm; and retired from use (or has failed) in less than 1000 cycles [13] to enlarge the root canal space. To reduce the risk of breakage during the root canal preparation, files are often placed well before the end of their actual fatigue life and this is not cost effective.

Many attempts have already been made to control the rotary instrument speed and torque of the unit to improve canal preparation performance and to maximize file life as well as preventing file fracture [14]. Ordinary control systems based on the torque limit auto reverse (motor reversed when it reached a fixed current) and the speed adjustment have been used in the market to solve the breakage problem. However, the problem still exists due to off-line and constant consideration of this system without investigating the on-line control of the file condition to achieve the maximum use of the tool life. It is necessary that the model of the controlled system be known [15] in order to implement conventional control, however, the implementation of the conventional control is difficult in an endodontics setting due to the non-linear effects of mechanical variables during the root canal preparation. The usual computation method of the mathematical model in a system is not an easy task. When there are variations in the system parameter or in the case of environmental disturbances, the behavior of the system would not be satisfactory. On the other hand, fuzzy logic control is a non-mathematical decision algorithm which is based on an operator's experience. This type of control strategy is well-suited for nonlinear systems. In many cases, FLC (Fuzzy Logic Controller) performs better than a conventional controller and it can be feasibly controlled by conventional control techniques [16, 17].

A new specification was therefore needed to control the quality, dimensions and mechanical properties of the Ni-Ti variable taper for rotary instruments, and to establish the precise minimum strength requirements [18]. These modifications included design changes, which had a significant effect on the instrument's physical and mechanical characteristics [19, 20]. The fuzzy logic control algorithms can be used to solve problems that are difficult to address by traditional control techniques. The use of fuzzy control for motor speed control systems has been demonstrated in several studies [21, 22]. Researchers have developed the use of Fuzzy sets and theory applications in the field of medicine as well [23], and FLC is increasingly being used in medical devices. Some of them also use FLC for biomedical device control purposes as well as in some surgical devices [24, 25]. Fuzzy logic is a technique to embody human-like thinking into a control system. A fuzzy controller can be designed to emulate human deductive thinking, that is, the process people use to infer conclusions from what they know. Fuzzy control has been primarily applied for controlling processes through fuzzy linguistic descriptions. Based on a real-time diagnosis of file wear conditions, the FLC is able to adaptively control the rotary instrument speed and torque control limit of the unit to improve canal preparation performance by maximizing file life and preventing file fracture.

The purpose of the present study was to design and test a novel fuzzy control system and compare it to the ordinary rotary instruments (Endo IT professional). The current study is therefore conducted to determine the Ni-Ti instrument lifetime as a function of several inputs that can be controlled and quantified by a fuzzy logic control system in a clinical setting. The method developed in this paper provides a feasible means for controlling the canal preparation filling process in endodontics applications.

2. METHODS

A novel automated system using FLC for an engine-driven rotary endodontic instrument was designed to control file wear condition, which consequently improves the durability of rotary instruments. As illustrated in Fig. 1, the design process of the controlled rotary instrument encompasses two stages. In the first stage a hardware apparatus was designed and consequently a FLC system which was synchronized with a novel-designed software called Intelligent Control for Endodontics (ICE) was developed. Finally, the file failure of a rotary instrument that had been generated/modified by FLC was compared with that of the ordinary rotary control system for root canal preparation.

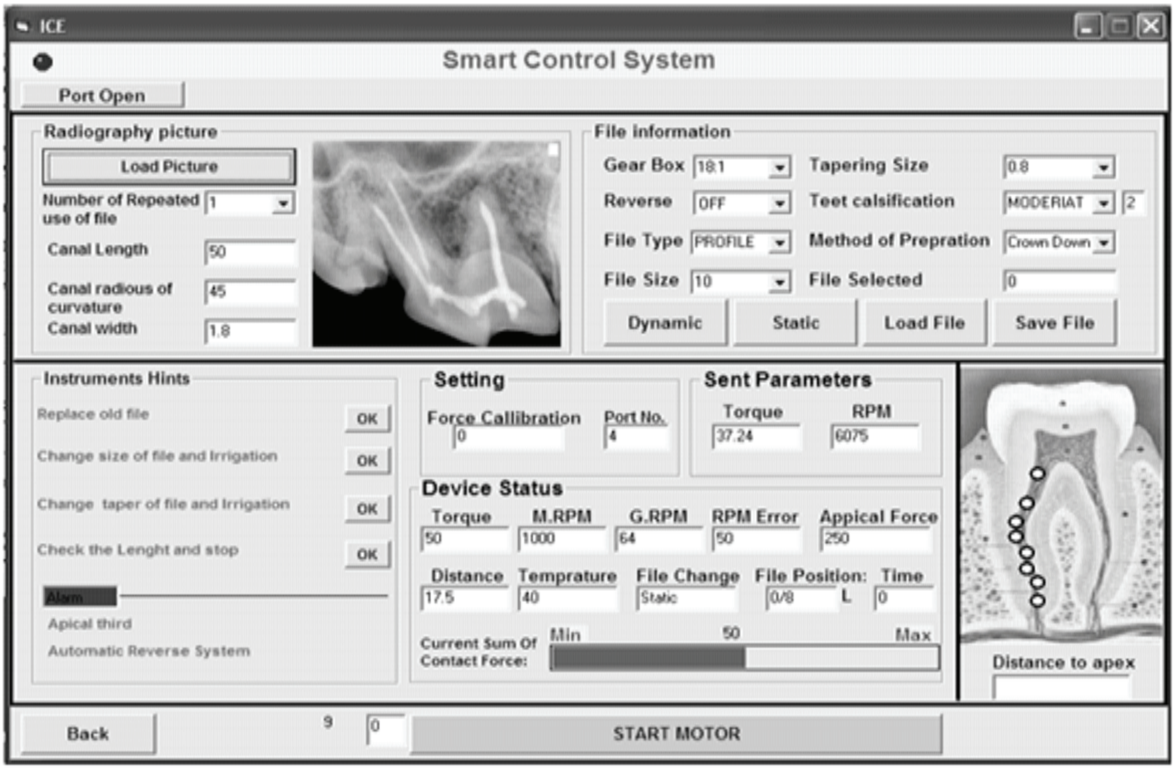

Fig. 1. ICE software control box

3. SOFTWARE AND HARDWARE DESIGN

As shown in Fig. 2, the major components of the system are: Fuzzy Expert System (FES), database, hardware/software interface, and ICE. ICE is a software developed for integration and implementation of the designed system which is a user-friendly graphical interface (GUI). It was designed to integrate all components together which allow the endodontist to interact with the system. FES is processed by FuzzyTech software functioning as an expert system that uses fuzzy logic to reason the received data through collecting the membership function and rules as part of the controlling system. The database analyst uses Microsoft Access database software for storing the data collected by the sensors via micro controller (MIC). The Hardware/Software interface is a part of the software which controls the hardware components through both the computer and the MIC by using software codes developed for this special purpose.

To synchronize the rotary instrument with the FLC system, micro-electronic devices were designed that were capable of working with ICE. Figure 3 illustrates the experimental set-up used in this work. The MIC monitors all the inputs from sensors such as the RPM encoder (GEL 2443-LENORD) and temperature sensor (PT100-Pico). Meanwhile, the load cell (MLC 902-MANYYER), RPM, torque, temperature and apical force were recorded in various stages of file wear according to the file position that was received by the apex locator (Rayapex 5). The apex locator plays an important role since it acts as a position sensor inside the root canal and all the input parameters are defined as real time monitoring according to the file position inside the root canal. The outputs from the sensors were connected to a microcontroller board composed of the Atemega 16 microcontroller sending signals to the computer via serial ports. Three separate microcontrollers (Atemega 16 type) were synchronized in a designed board to process input and output signals. Thus, it was important to set the system in a way that it can record pressure, temperature, RPM, angle and specification of the root canal, torque, file specifications, and RPM error, which can cause file fatigue fracture accurately. It is important to note that all these input and output variables were used by FLC with the supervision of ICE software.

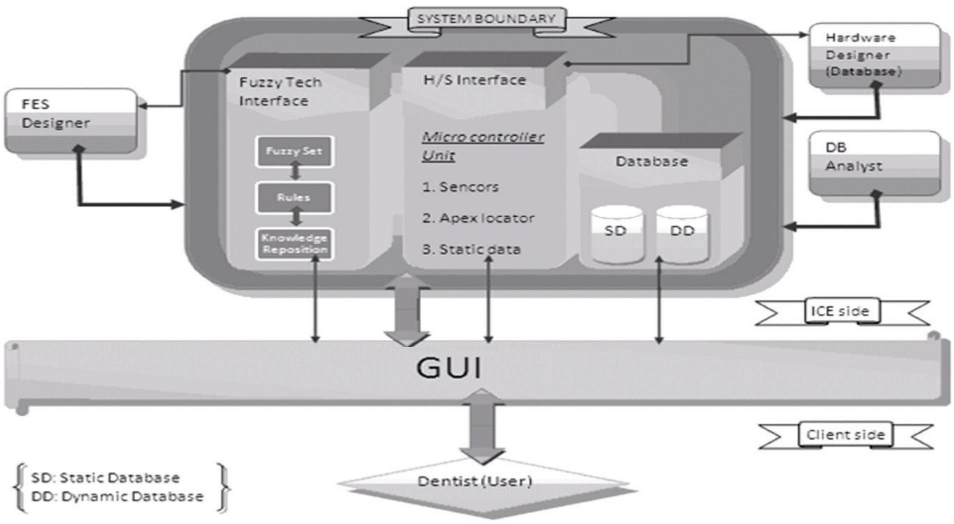

Fig. 2. Schematic diagram of real-time Fuzzy logic control system

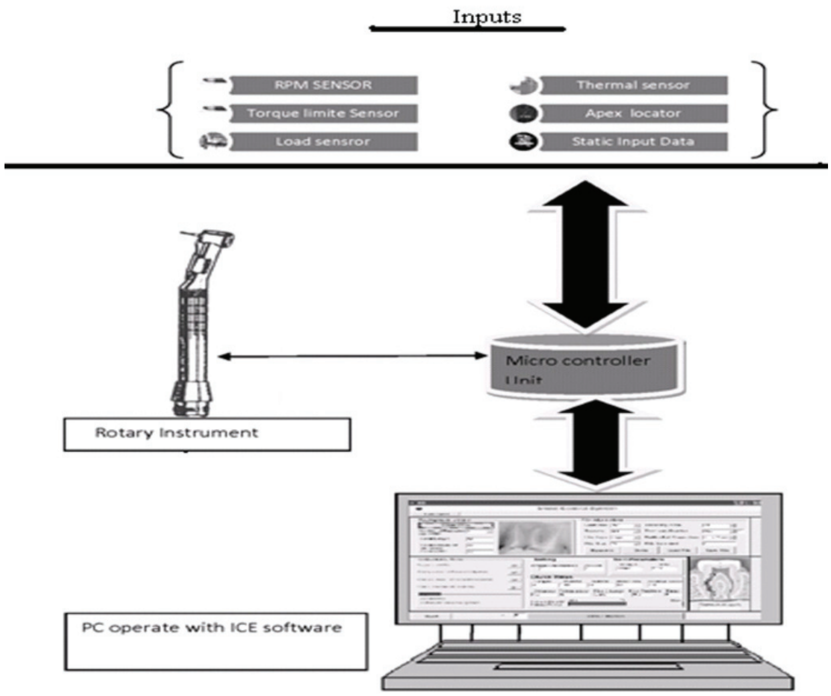

Fig. 3. Experimental apparatus

4. FLC DESIGN

The first step in establishing the algorithm for diagnosis of the rotary file wear and the strategy for speed and torque limit control was the selection of appropriate shapes of Fuzzy membership functions (or fuzzy sets) for the process variables. An analytical approach was required to determine the fuzzy controller describing function and it was generated by experiments. However, the obtained describing function was very complicated. Therefore, a symmetrical fuzzy controller with triangular membership functions was applied for the procedure [27]. The procedure was developed based the experimental data and behaviors of the final control system were designed accordingly. The interrelationships between signal features and filling process states were developed based on engineering knowledge, experimental results and the level of the endodontist's experience. The initial FLC and its components were created in vitro by performing experiments in an artificial environment.

The endodontist can modify the fuzzy rules based on his/her own practical experiences before and during root canal preparation. According to the Mamdani method, the interval variable shapes were applied in the FLC design [28]. A total number of 150 rules were applied in the FLC system. Their values were estimated by the results of the experiments and simulations according to the input and output parameters. In a closed-loop control system, as illustrated in Fig. 4, the process output (controlled variable) is constantly monitored by a MIC, which receives signals from sensors and dentist initial data system. There are several physical input variables that affect the file fatigue, leading to file failure. The fatigue of metals is influenced by a number of factors and has been described by the Coffin–Manson equation [29, 30] which is as follows:

$$N_f = \left(\frac{\alpha}{\varepsilon_a} \right)^{-b} \tag{1}$$

Where N_f is number of rotation to failure, and α and b are constant coefficients.

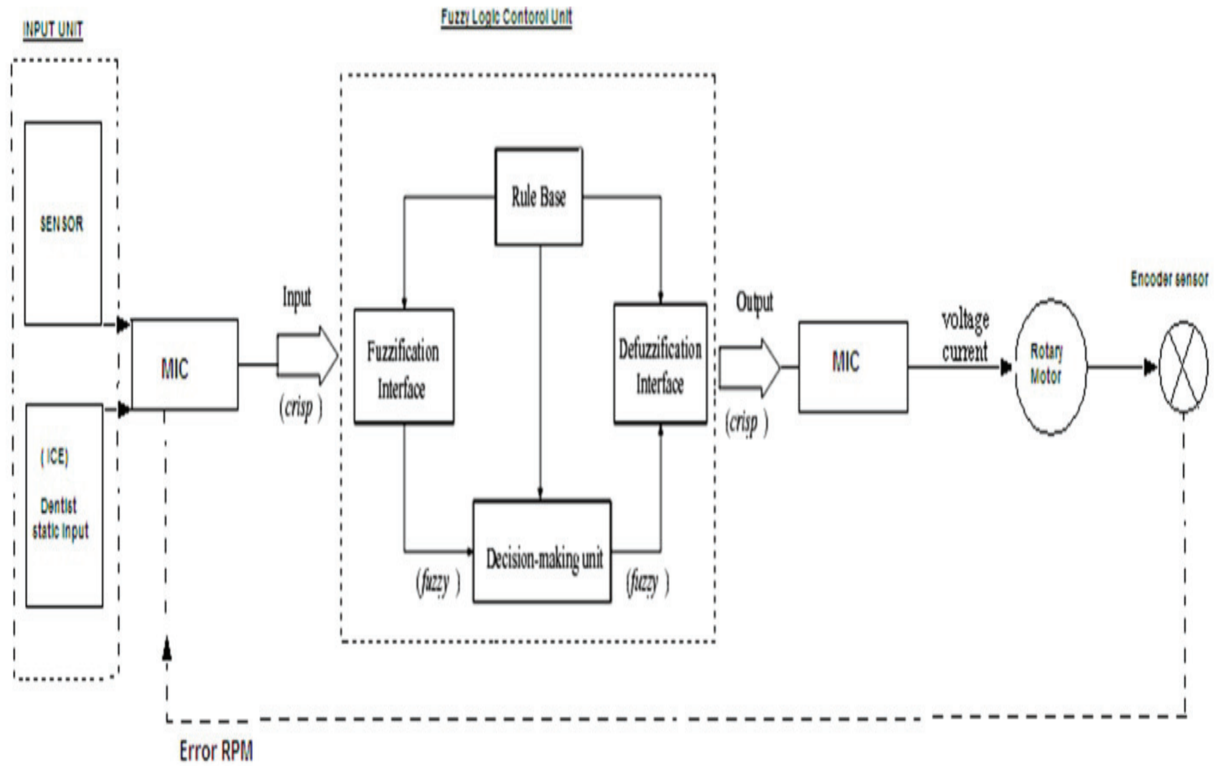

Fig. 4. Experiment control loop

In an in vivo root canal preparation study, the mechanical parameters that affect the fatigue of the file were defined. The file was reflected by α and b and the equation was modified as follows:

$$N_f = \frac{\left(\dfrac{1.57\ln[RPM]*Ca}{\varepsilon_a}\right)^{\frac{1}{[0.1C.\ln[RPM]-0.75]}}}{V} \tag{2}$$

Where specific heat (Ca), strain value (V), and Ɛa (strain amplitude), the input parameters shown in the above equation, affect the file fatigue life. Meanwhile, the final FLC components of the system were designed by determining the interaction between the input and output parameters. The transfer function was obtained by dividing the output by the input. In the present study this amount was determined and optimized automatically by FuzzyTech software.

In vitro measurement can be performed under the identified and controlled operational conditions. The rotary instrument canal preparation model should also include the file and root canal condition. The system was changed into a model with the normal rotary instrumentation based on the whole range of input parameters. The faults and errors were detected according to the analysis of the behavior of the diagnosed system parameters. The number of rules in this fuzzy system were defined based on the accuracy of the work, data collection possibilities and determining the type of membership function. The firing of the rules could be observed by selecting different input values of fuzzy outputs and it could be compared with the actual values obtained from the in vivo experiment. Therefore, by selecting appropriate rules, one can ensure system accuracy. The hardware control algorithm is shown in Fig. 5. All the steps shown in this figure were considered in the process. The fuzzy control unit has several sets of Fuzzy membership functions for inputs (online torque, temperature, error, temperature, file specification, canal specification and apical force) and outputs (RPM and torque limit).

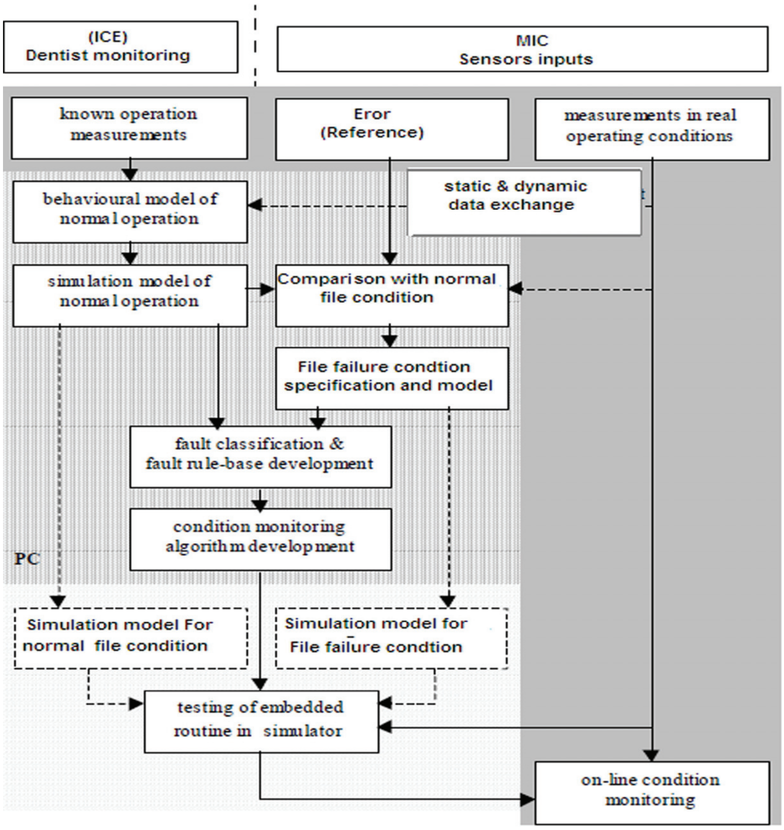

Fig. 5. Simulation algorithm method

A trapezoid shape has been chosen to establish the fuzzy membership functions of the inputs. General fuzzy membership functions for all levels of inputs are defined as follows:

(I_1)= a I_1+b , 0<I_1<100 □(I_5)= g I_5 +h, 0< I_4<90

(I_2)= c I_2+d , 0< I_2<100 □(I_5)= j I_5+k , 0< I_5<500 (3)

(I_3)= e I_3+f , 0< I_3<70 □(I_6)= l I_6+m, 0< I_{56}<10

The fuzzy membership value for the file inputs and a, b, c, d, e, f, g, h, j, s, k, l and m are constant for different fuzzy sets and could be obtained as it has been indicated in Fig. 6. Through the use of fuzzy min-max algorithm, the following equation will be generated to calculate the fuzzy membership values for inputs:

$$\mu(Input) = \bigcup_{1}^{n} (\mu(I_1) \cap \mu(I_2) \cap \mu(I_3) \cap \mu(I_4) \cap \mu(I_5) \cap \mu(I_6)) \quad (4)$$

Given below are the key points of this study:

(a) Choosing the shapes for the input variables (Fig. 6),

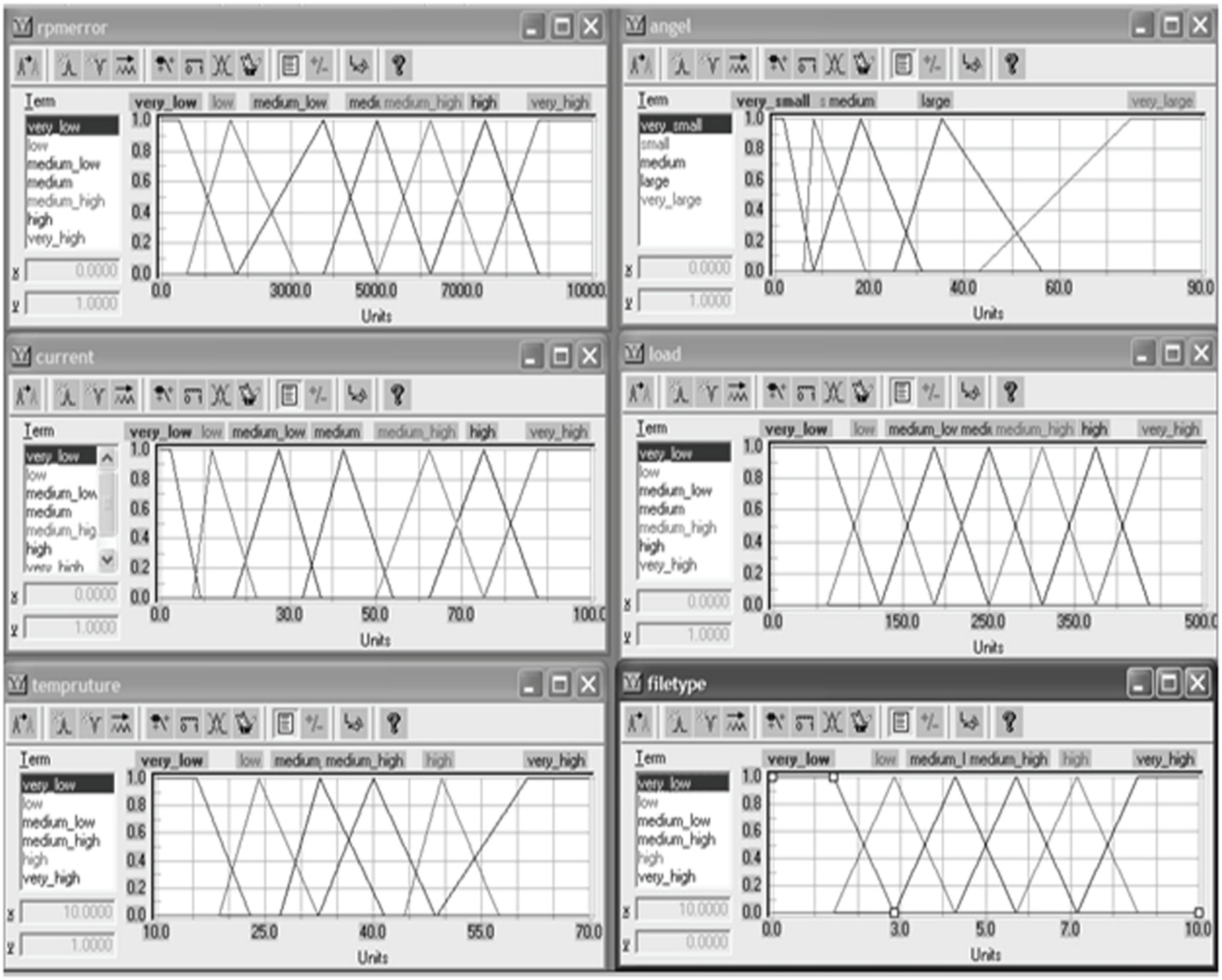

Fig. 6. Fuzzy sets for inputs

(b) Determination of the fuzzy intervals for the input and output variables was based on a comparative study of several of the most popular forms of membership functions by using the same set of experimental data,

(c) Figure 7 illustrates the RPM output membership function and its intervals. This figure also illustrates the torque limit variables used in the fuzzy set control system, which was divided into four intervals. The number of linguistic levels for each variable should be large enough to provide an adequate approximation, and yet be small enough to increase the system response and save memory storage. For any variable, such as the output (Torque Limit, RPM) with five linguistic levels (very slow, slow, moderate, fast and very fast), an overlap between any two adjacent levels (such as slow and moderate) was accepted. An overlap between any two separate levels (such as very slow and medium) was not accepted. Table 1 consists of the Fuzzy membership functions for the baseline input variables including RPM, torque, apical force and temperature. Fuzzy sets were designed to "fuzzify" the input variables such as the RPM, temperature, and apical force, etc.

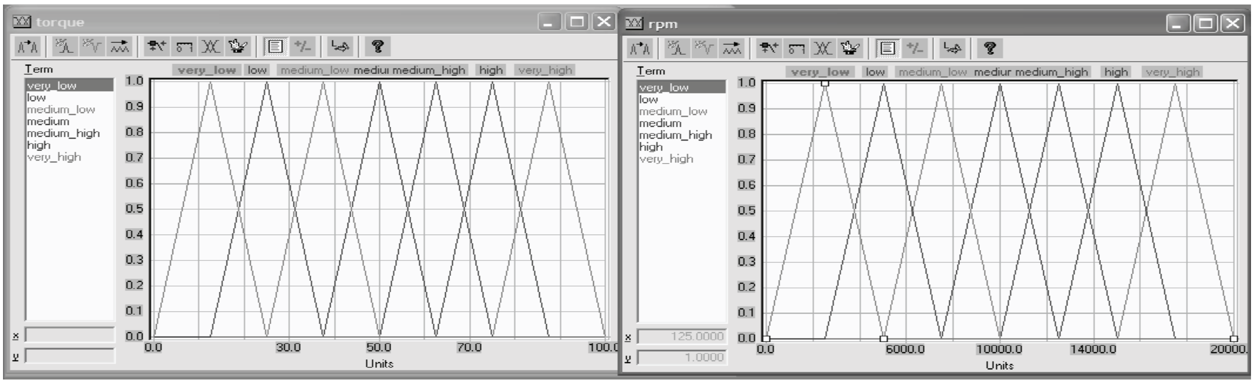

Fig. 7. Fuzzy sets for outputs

Table 1.Baseline variables

File condition	RPM	Torque limit (%)	Temperature	Applied force	Applied Torque (%)	File specification	Error
Initial status	100-300	10-30	10-27	0-1.5	0-30	6-10	0-10
Acceptable status	300-400	30-60	27-35	1.5-5	30-60	2-6	10-50
File failure	400-900	60-100	35-75	5-10	60-100	0-2	50-100

A trapezoid shape was chosen to establish fuzzy membership functions of the output. A general fuzzy membership function for all three levels of the initial file condition, the acceptable file condition, and the file failure was defined. The relationship between inputs and outputs in a fuzzy system was characterized by a set of linguistic statements called fuzzy rules. Their definitions were based on the experimental work, and endodontist and engineering knowledge. The number of fuzzy rules in a fuzzy system is related to the number of fuzzy sets for each input variable. In this study, there were six input variables, each classified into different fuzzy sets, and three file states were determined. Therefore, the maximum number of rules after modification was one hundred and fifty. In many cases, it was reasonable and more efficient to use fewer rules after posing some limitations on the combinations of input variables, which were impossible to calculate due to the physical properties of the rotary instrumentation process. Based on the experimental work, some rules were developed for file condition diagnosis. These rules were classified into two groups of RPM and Torque limit that corresponded to three file condition states. The outputs of the inference process are still fuzzy values that need to be defuzzified. The defuzzified file outputs can then be obtained using the following centroid formula, as indicated in the following equation:

$$\text{Outputs values} = \frac{\int y[\mu(I)I]dt}{\int y[\mu(I)]dt} \tag{5}$$

Following the investigation and calculation of the FLC results and rules, the effect of incorporating the new system on the file failure was analyzed with sixty ProFile in 6 groups of 10 new rotary instruments each. In vivo, experiments were conducted to modify the FLC rule baseline and intervals. Experiments were repeated under constant and controlled conditions to determine the greatest file life.

5. EXPERIMENTAL WORK

Several tests were carried out on a computer-controlled rotary instrument, using sixty new ProFile files with different tapers and sizes for a total of 180 root canal preparations. The experiments were conducted in different stages.

The specimens were divided into 6 groups and the root canals were prepared using the following Nickel-Titanium instruments: Group 1 Pro-File T. 0.2-25 (Dentsply Tulsa, Switzerland); Group 2 ProFile T. 0.4-25 (Dentsply Tulsa, Switzerland); Group 3 Pro-File T. 0.2-40 (Dentsply Tulsa, Switzerland); Group 4 ProFile T. 0.4-40 (Dentsply Tulsa, Switzerland); Group 5 ProFile T. 0.6-40 (Dentsply Tulsa, Switzerland); Group 6 ProFile T. 0.6-40 (Dentsply Tulsa, Switzerland). Each test group contained ten ProFile files which were tested with both the FLC system and an ordinary control system for different canal depths under a wide range of cutting conditions. The in vitro experiments tested each group of files under irrigated water conditions on virtual canals. Sixty different sizes of Profiles were tested in one hundred and eighty virtual plastic canals. After repeating the experiment in constant conditions, and considering the parameters' influence on the file failure, the initial fuzzy rules were modified to improve file life. In the in vivo experiments, a new group of ProFile files were tested with one hundred and eighty human second premolars with single roots. Canals with mature roots were used for root canal perpetration after temporary storage in 2% formal-saline. All teeth were crack-free when examined under a microscope. Prior to canal preparation some 3.5 mm of the crowns were removed from the end of the tooth crown. An oval access preparation was made and the canals were prepared to a standard flare. The testing time for each canal preparation was approximately five minutes. The experiments were conducted under three different file conditions: initial, acceptable wear, and file failure. A set of experiments were performed to determine file failure and the results were compared with the outcomes derived from the use of an ordinary rotary instrument. Microscopic evidence showed that the files were worn out after three root canal preparations, which is typically one of the main causes of the file failure.

6. RESULTS

The parameters that influence the file failure were used to modify the fuzzy rules for file life improvement. Following in vitro and in vivo analysis, the optimal intervals and the rule bases of the fuzzy controller were determined to prevent file failure and to increase the file life time. The output variables in fuzzy sets were classified in two threshold categories related to wear status or feeding rate. The outputs were considered as the RPM and torque limit control for the rotary instrument. The output values are dependent on the input values. For example, in vivo conditions, primary values such as the angel of curvature of the root canal (30 deg), error of RPM (164), torque (T = 30Nm), apical force (1.47N), temperature (30deg C) and file specification (4), were obtained from sensors and ICE software and the torque (10 Nm) and the RPM (950) were generated via FLC. These were converted to FuzzyTech software for the fuzzy control process [31]. The data was fuzzified by the input and output fuzzy sets. Diagnosis was performed based on the file condition state and fuzzified by the fuzzy sets of system outputs. It was defined from the defuzzified outputs obtained from the software. These output values were defined as non-fuzzy values such as RPM=705 and torque limit =46, which could be sent to the rotary instrument motor for real time speed and torque adjustment as shown in Fig. 8. Based on the initial simulation data, the experiment was continued until the maximum file life time was determined. In vivo, the final control system was developed according to the experimental conditions, and the fuzzy rule baseline was generated. Finally, after modification of the fuzzy control rules, the new control system was compared with the ordinary rotary controller in accordance with each performance over the files life time. *Q* square test was used in this study to identify and reject the outliers. This test was used for validity of the experiments. The number of rotations for each treatment stage and for each tested tooth, which finally resulted in instrument failure and consequently file fracture, were determined by the use of designed novel fuzzy control system. The total number of rotations causing file failure has been illustrated in Fig. 9. The mean values of number of rotations to failure received from the hardware in different environments were analyzed using a single-factor analysis of variance (ANOVA).

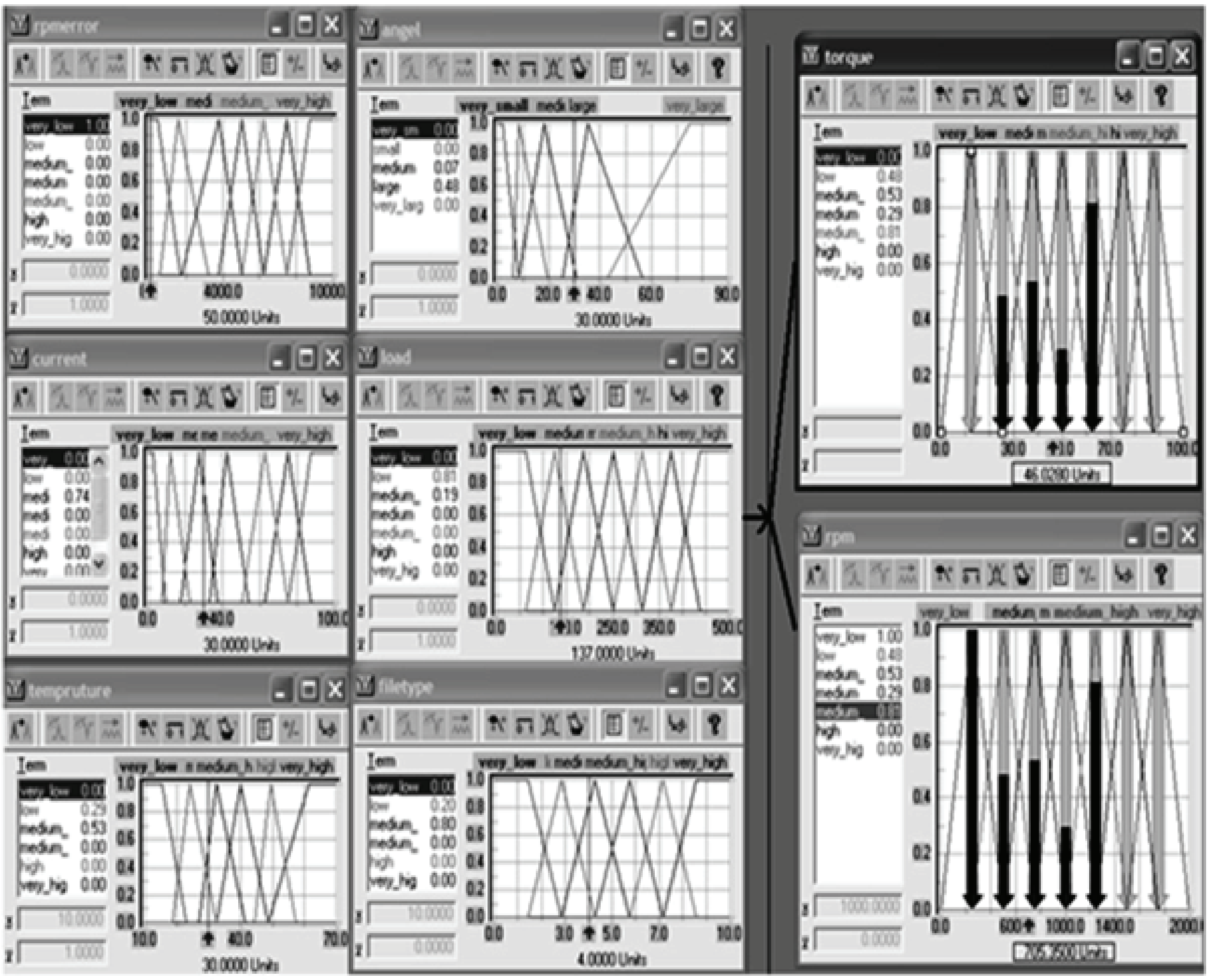

Fig. 8. Difuzzification and online results

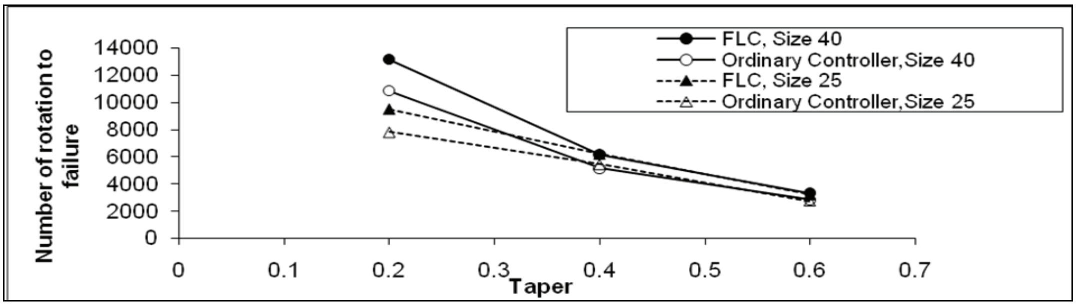

Fig. 9. Mean values for file rotation to failure in a fuzzy control system VS ordinary control system in size 25 and 40 in different tapers

As it is observed from Fig. 9, the number of rotations to failure under fuzzy controller monitoring was significantly greater than those of the ordinary controller ($P < 0.001$). There was a significant difference between the fuzzy logic control system and the ordinary control system in the ProFile T.0.2 group. Q-square showed a significant difference between the Fuzzy control system and the ordinary control system in their ability to increase the file life time. As shown in Fig. 9, for ProFile files of 40 mm in diameter with tapering of T.0.2, T.0.04, T.0.06 the mean rotation values increased by 21.9%, 20.5%, and 17.48 %, respectively, in the Fuzzy logic control system compared to the ordinary system. Similarly, for ProFile files of 25 mm in diameter with tapering of T.0.2, T.0.04, T.0.06, the mean rotation values increased by 12.9%, 11.42%, and 10.08 % in the FLC system as compared with the ordinary system.

7. DISCUSSION

Ni-Ti Rotary instrument files are widely used in endodontics for canal preparation. This paper presents a novel fuzzy control system for improving the filing process performance and reducing production costs by maximizing the file life time and preventing file failures. It is essential in endodontics to have an effective device which can monitor the files wear status and determine the appropriate rotary speed and torque actions to reduce the risk of breaking the Ni-Ti files during the root canal preparation. To minimize the risk of inter canal breakage, the instruments should operate at an appropriate speed and with efficient torque. The ordinary endodontic motor controllers are not able to allow precise, low-torque settings and RPM for many reasons [32, 33].

This study has brought a deeper understanding into the effectiveness of the Fuzzy control system operating on the designed rotary instrument. The method described in this paper provides a feasible means for real time monitoring of the file wear and control of the instrument speed and torque limit to improve the root canal preparation process performance and to increase durability of the file. Based on the designed system in this study, file replacement time can also be predicted before file fracture. Control software ICE would help the dentist by sending various alarms when the files are exposed to harmful conditions.

There are some advantages in using FLC in the control of Ni-Ti rotary instruments operations including focusing on problem solution rather than on problem analysis and working well on conventional embedded microcontroller (MIC) and, finally, the ease of combination with conventional software. However, there is no way to prove analytically that the FLC system will behave as intended. [26] In addition, an analytical description of dynamic behavior could not be easily defined with the FLC system. To overcome this problem, real experiment and modification of the system could be performed. In the present study, by in vivo experiments the final FLC were designed with all modifications in rule bases.

The Fuzzy logic control method presented in this study is very flexible in the data experimental intervals. More research is needed to elicit the knowledge of the effect of this particular file before adopting any effective control strategy. In this study, the fuzzy set theory has been successfully used to control the root canal preparation with Ni-Ti rotary instruments for achieving the maximum use of tool life based on the file wear conditions. The Fuzzy controller developed in this project is capable of simulating human experience, intelligence and reasoning while controlling the root canal preparation processes. On the other hand, this study does have some limitations due to the different non-linear parameters inside the root canal which affect the failure of the files. The ProFile rotary instrument has a significantly higher number of rotations to failure with the Fuzzy control system on all the groups as compared to the ordinary controller. This was achieved by intelligent control of the RPM and torque limit in this study. Therefore, it can be concluded that by using the new control system for a rotary instrument, the lifetime of Ni-Ti files were shown to be significantly longer than the file life time that used the ordinary rotary instrument. This new system was tested both in vivo and in vitro in different conditions and more comprehensive results were obtained. This system could be used by endodontists and dentists. It helps them cause less file failure. One of the other advantages of this system is that by adjusting the device precisely, it will help endodontists reduce the cost of replacing files by 22% and also prevent root canal preparation failure. Further studies are necessary to explore the use of other artificial intelligent control systems, such as artificial neural networks controllers in this process.

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