Application of Modular Design Methodology for Endodontic Instrument Fatigue Test Bench

Aplicación de Metodología de Diseño Modular en Banco de Pruebas de Fatiga de Instrumentos Endodónticos

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***Abstract*— In endodontic procedures, nickel-titanium (NiTi) instruments, which conform to the geometry of root canals, are employed to enhance the mechanical properties of files. However, the high cost of these instruments necessitates repeated use, increasing the risk of fatigue fractures during treatment. With various brands and types of endodontic instruments available in the market, characterizing the mechanical properties of files and their behavior under fatigue loads is essential. Currently, no standardized tests exist for assessing fatigue resistance, and each research study adopts its own equipment and methodology. This project aims to develop a test bench for fatigue testing of endodontic instruments without restrictions on material, cross-section, or external design, enabling both static and dynamic tests. The test bench employs a modular design strategy to identify components suited for modularization, utilizing readily available elements and manufacturing techniques such as 3D printing. The device operates on two axes, X and Y, and allows regulation of the instrument's depth of entry into the channel. Furthermore, it features an electronic system for automating dynamic and static tests, an LCD screen for menu navigation, and the ability to record the number of cycles until file fracture.**

***Index Terms*— Dynamic test; Fatigue; Modular design; NiTi alloy; Static test; Test bench.**

***Resumen*— En los procedimientos endodónticos se utilizan instrumentos de Níquel-Titanio (NiTi), que se adaptan a la geometría de conductos radiculares. Estas aleaciones han favorecido las propiedades mecánicas de las limas, sin embargo, el alto costo que presentan estos instrumentos conlleva a un uso repetido, aumentado el riesgo de fractura por fatiga durante el tratamiento. En el mercado existen distintas marcas y referencias de instrumentos endodónticos por lo que es de gran importancia caracterizar las propiedades mecánicas de las limas y su comportamiento cuando se someten a cargas de fatiga. Hasta el momento no se tiene una estandarización para las pruebas empleadas para comprobar su resistencia a fatiga y por ende en cada investigación se proponen equipos y metodología de análisis. En este proyecto, se desarrolla un banco de pruebas para fatiga de instrumentos endodónticos, sin restricciones de material, sección transversal o diseño exterior, permitiendo realizar pruebas estáticas y dinámicas. Para el banco de pruebas se aplica la estrategia de diseño modular con el propósito de identificar componentes susceptibles de adquirir dicha característica, emplear elementos de fácil adquisición y técnicas de manufactura como la impresión 3D, propiciando la modularización del diseño. El dispositivo se desplaza en dos ejes X, Y, y es posible regular la profundidad de ingreso del instrumento en el canal. También posee un sistema electrónico que permite automatizar la prueba dinámica y estática, una pantalla LCD para acceso al menú y registro del número de ciclos a la ruptura de la lima.**

***Palabras claves*— Aleación NiTi; Banco de pruebas; Diseño modular; Fatiga; Pruebas dinámicas; Pruebas estáticas.**

I. Introduction

Endodontics is a specialty of dentistry responsible for studying the structure, morphology, and physiology of coronal and root canal cavities [1]. This science has shown significant progress in aseptic techniques, principles of preparation, and obturation of root canals, which has increased the number of successful cases of endodontic treatment. However, problems such as sudden instrument breakage during procedures are still faced [2]. File fracture is caused by the fatigue stress that the instrument undergoes in the root canal [3]; this added to the lack of knowledge of the specific mechanical properties of each NiTi alloy file and the absence of standardized tests to check the fatigue resistance of this type of instruments [1].

Cyclic fatigue testing of endodontic instruments is crucial for assessing their durability; however, it lacks standardization [4]. Various devices have been developed, including two-dimensional and three-dimensional anatomical models [5], which can significantly affect test outcomes. Static and dynamic tests yield inconsistent results, with factors such as environmental temperature influencing instrument lifespan by up to 500% [6]. This variability raises questions regarding the clinical relevance of such tests. Nondestructive testing methods, such as stiffness monitoring utilizing strain gauges to assess instrument integrity [7], have been proposed. Nevertheless, the scientific and clinical benefits of fatigue resistance tests remain limited. Consequently, further research is necessary to develop standardized testing protocols and enhance the clinical applicability of cyclic fatigue evaluations for endodontic instruments.

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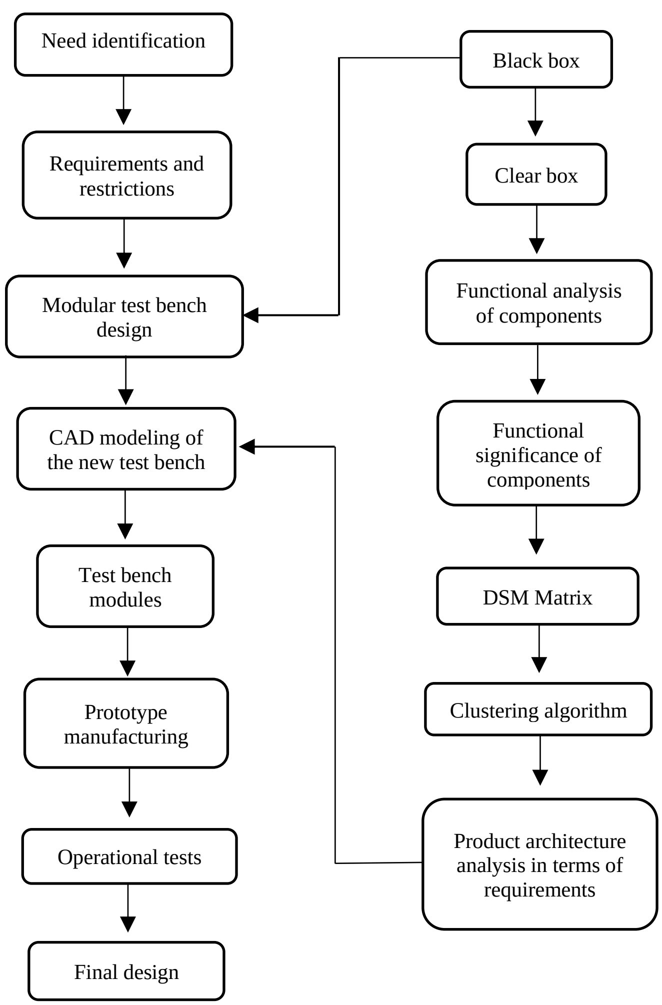
Due to this necessity, certain researchers construct custom test benches tailored to specific requirements for evaluating the service life of endodontic files. Consequently, this study presents the design of a fatigue test bench with modular characteristics, capable of performing automated tests. This design facilitates the standardization of fatigue tests for endodontic files and incorporates a control system for the displacement of the endodontic motor and the cubes that simulate artificial canals.

II. MATERIALS AND METHODS

This investigation employs two design methodologies; the first comprises the design process proposed by Norton, followed by identifying the necessity to develop the prototype with the respective functional tests [8]. The second methodology is predicated on a modular design, encompassing design parameters such as geometry, functional relationships, assembly, and spacing between components [9]. Figure 1 delineates the implemented process.



a) b)

Fig. 1 a) Schematic design methodology proposed by Norton b) Modular design methodology schematic

A. *Identification of the need*

A literature review of the various fatigue test benches for endodontic instruments revealed that certain equipment performs static and dynamic tests either manually or automatically. The apparatus described in the literature necessitates the use of a video camera and a stopwatch to determine the precise moment of file fracture, thereby enabling manual calculation of the number of cycles to fracture (NFC) [10]. Consequently, there is a need to develop a test bench for endodontic files capable of conducting dynamic and static tests while simultaneously recording and storing in removable memory, in real-time, the number of cycles at which the file fractures.

B. *Requirements and Restrictions*

In accordance with the methodology proposed by Norton, once the objective of the equipment to be designed has been identified, it is appropriate to formulate a set of performance or task specifications [8]. Consequently, a list of requirements that the system or test bench must fulfill is compiled, as presented in Table I.

TABLE I
FUNCTIONAL REQUIREMENTS FOR THE TEST BENCH

REQUIREMENT	INCORPORATED	
	YES	NO
Perform dynamic and static test	X	
Move on two axes of symmetry	X	
Modular equipment	X	
Coupling endodontic micro-motors	X	
Coupling several artificial canals	X	
Use of batteries		X
Connection to the electrical grid	X	
Electric motors	X	
Automated test bench	X	
Display and control buttons	X	
Fracture detection sensor	X	
Connection to a computer	X	

To delineate the functional limitations of the test bench, a comprehensive list of equipment restrictions is generated, as certain functions or tasks cannot be performed by the bench [8]. One such limitation is the return to zero point, which involves aligning the file with the artificial channel to initiate the fatigue test, as illustrated in Table II.

TABLE II
FUNCTIONAL RESTRICTIONS FOR THE TEST BENCH

RESTRICTION	DESCRIPTION
Zero point	The equipment will not be able to locate the zero point automatically. This process will be done manually.
Automatic micromotor ignition	The micromotor will not have automatic ignition. It will be started manually.
Electric batteries	The equipment will not have electric batteries. The electric grid will power it.

C. Modular design.

The modular methodology is implemented as a baseline termed "Automatic Electronic Device (AED)" [11] to fulfill the functional requirements, including horizontal displacement, compatibility with various endodontic motors, and the capacity to incorporate one or more artificial canals into the test apparatus, as illustrated in Figure 2.

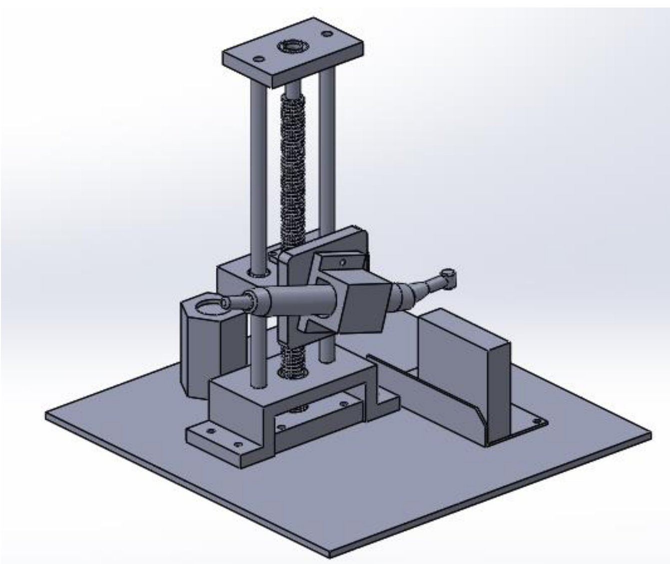


Fig. 2 Automatic electronic device

For the analysis of the AED automatic electronic device [11], an exploded view diagram is utilized to identify the components of the apparatus, as illustrated in Figure 3. Table III delineates the nomenclature of each component of the device.

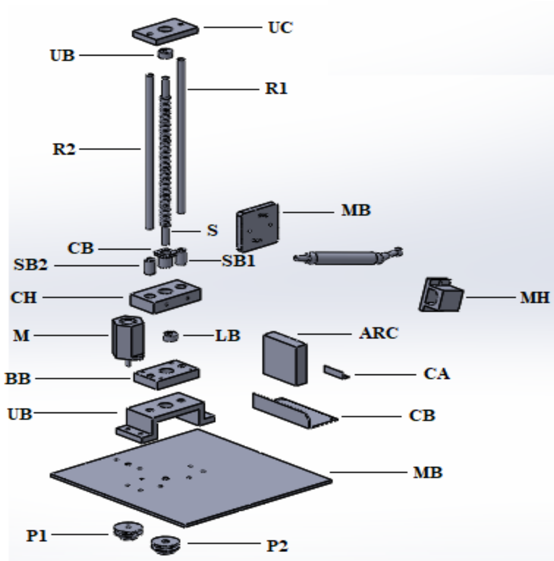


Fig. 3 Explosion view of the electronic device

TABLE III
COMPONENTS OF THE AED DEVICE

NOMENCLATURE	TEST BENCH COMPONENTS
P1	Pulley 1
P2	Pulley 2
MB	Main base
UB	U-base
BB	Bearing Base
LB	Lower Bearing
M	Motor
CH	Central Hub
MB	Micromotor Base
MH	Micromotor Holder
SB2	Spherical Bearing 2
SB1	Spherical Bearing 1
CB	Central Bearing
R1	Rod 1
R2	Rod 2
S	Screw
UB	Upper Bearing
UC	Upper Cover
CB	Canal Base
ARC	Artificial Root Canal
CA	Canal Adjuster

D. Black box and clear box

The black box diagram in Figure 4 illustrates the input data, which encompasses the essential information required for system operation: the test type, angular velocity of the endodontic motor, the file, and the electrical power supply [12]. The outputs comprise the results generated by the bench, including fatigue test outcomes and energy loss. Figure 4 provides a summary of the process.

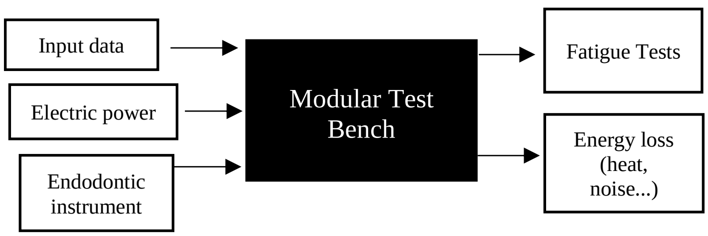


Fig. 4 Test bench black box

The clear box diagram illustrates the general functions of the bench components in a simplified manner and demonstrates the relationships between the elements [12], as depicted in Figure 5.

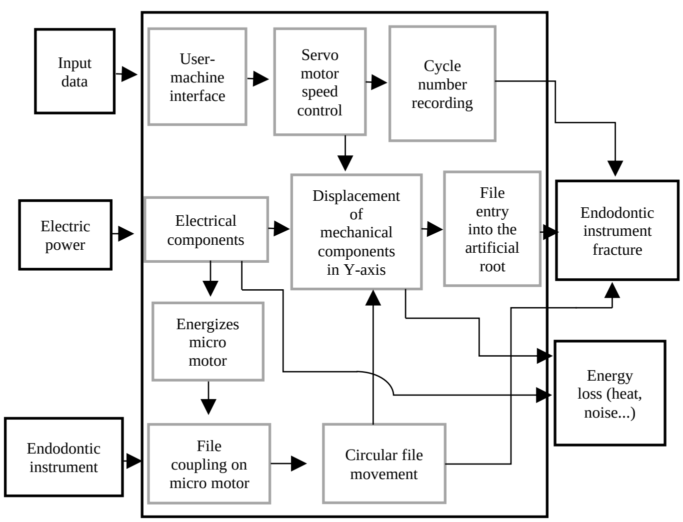


Fig. 5 Clear box for the test bench

Upon identifying the relationships between components through the clear box analysis, the mechanical, electrical, and electronic elements utilized by the AED device become evident [11].

E. Functional Analysis, Connection Diagram, and Functional Significance of Components

Upon identification of each component of the AED [4], the functions of individual elements are delineated in Table IV, with a determination of which components possess multiple functions.

TABLE IV
FUNCTIONS OF EACH COMPONENT OF THE TEST BENCH

COMPONENT	FUNCTION
Pulley 1	1. Transmits the movement to the pulley 2.
Pulley 2	1. Transmits motion to the helical screw.
Main base	1. Supports all test stand components.
U-base	1. Supports bars B1 y B2.
Bearing Base	1. Supports bars B1 y B2. 2. Holds the bearing
Lower Bearing	1. Facilitates screw movement.
Motor	1.Generates the movement for vertical displacement.
Central hub	1. Generates the movement for vertical displacement.
Micromotor base	1. Holds the micromotor fastener.
Micromotor holder	1. Holds the micromotor.
Spherical bearing 2	1.Facilitates linear displacement of the central cube.
Spherical bearing 1	1. Facilitates linear displacement of the central cube.
Central bearing	1. Facilitates linear displacement of the central cube.
Rod 1	1. Guides the central cube 2. Support the top cover.
Rod 2	1. Guides the central cube 2. Support the top cover.
Screw	1. Facilitates linear displacement of the central cube.
Upper bearing	1. Facilitates screw movement.
Upper cover	1. Holds rods 1 and 2. 2. Holds the upper bearing.
Canal base	1. Holds the artificial radicular canal.
Artificial root canal	1. Allows the entry of the endodontic instrument.
Canal adjuster	1. Positioning the artificial radicular canal.

Upon analysis of Table 4, it is evident that several bank components possess multiple functions: the Bearing Base BR with two functions, Rod 1 with two functions, Rod 2 with two functions, and the Upper Cover UC with two functions. These components exhibit increased complexity in terms of modularization due to the multiplicity of functions they perform within the system [9]. A diagram illustrating the connections between components has been constructed, as depicted in

Figure 6, which facilitates the identification of parts with a higher number of connected elements, thus indicating greater complexity in modularization.

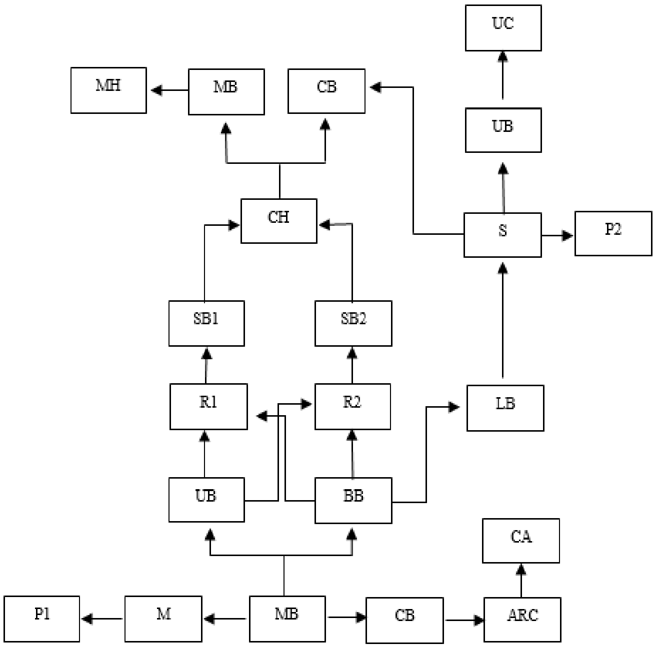


Fig. 6 Diagram of component connections

Analysis reveals that the components exhibiting the highest number of connections are MB, S, BB, and CH, each with four connections, followed by UB, R1, and R2, each with three connections. These highly connected components present a significant challenge to modularization efforts due to their numerous interconnections with other elements of the bench.

The relative functional significance of each bench component is quantified, considering the number of functions, the number of components in contact within the assembly, and the number of components identified in the aforementioned diagrams, as presented in Table V.

TABLE V
FUNCTIONAL RELEVANCE OF COMPONENTS

Component	Number of functions (F)	Number of components in contact with assembly (N)	Number of components (n)	(F*N)/n	Relative functional significance %
Pulley 1	1	1	1	1	1.5
Pulley 2	1	1	1	1	1.5
Main base	1	4	1	4	6.2
U-base	1	3	1	3	4.6
Bearing Base	1	4	1	4	6.2
Lower Bearing	1	2	1	2	3.1
Motor	1	2	1	2	3.1
Central hub	2	4	1	8	12.3
Micromotor base	1	2	1	2	3.1
Micromotor holder	1	1	1	1	1.5
Spherical bearing 2	1	2	1	2	3.1
Spherical bearing 1	1	2	1	2	3.1
Central bearing	1	2	1	2	3.1
Rod 1	2	3	1	6	9.2
Rod 2	2	3	1	6	9.2
Screw	1	4	1	4	6.2
Upper bearing	1	2	1	2	3.1
Upper cover	2	3	1	6	9.2
Canal base	1	3	1	3	4.6
Artificial root canal	1	2	1	2	3.1
Canal adjuster	1	2	1	2	3.1
			TOTAL	65	100

Subsequently, the components exhibiting the highest relative functional importance and presenting significant complexity in modularization are:

- Central cube CH with 12,3 %
- Rod 1 R1 with 9,2%
- Rod 2 R2 with 9,2%
- Upper cover UC with 9,2%

The other components in Table V, due to their low relative functional importance, can be modularized without significant adverse effects [9].

F. Relations Matrix, Clustering Algorithm, and Product Architecture Analysis

The FAS (Functionality, Assembly, Space) methodology evaluates selected components for modularization by assigning values to the functional, assembly, and spatial relationships between testbed components [13]. The values are assigned as follows:

Function = 1 / Assembly = 2 / Space = 3

The values are entered into the DSM matrix in a non-specific order, as illustrated in Table VI, considering the relationships between components of the test bench to utilize these values and generate the clustering algorithm that determines which complex components to modularize [13].

TABLE VI
DSM MATRIX

Component			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Upper cover	UC	1	1	2	1	2	2												1		1		
Upper bearing	UB	2	2	2	2					1	1			1									
Screw	S	3	3	2	3					1					2	3							
Rod 1	R1	4	3			4	1	2	1	1						3			2				
Rod 2	R2	5	3			1	5	1	2	1	1					3			2				
Spherical bearing 1	SB1	6			1	2	1	6	1	1	2												
Spherical Bearing 2	SB2	7			1	1	2	1	7	1	2												
Central Bearing	CB	8		1	2	1	1	1	1	8	2			1									
Central Hub	CH	9			2	1	1	2	2	2	9	2						1					
Micromotor base	MB	10				1	1	1	1	1	2	10						2					
Motor	M	11		1	1	1	1	1	1	1			11	1							2	2	1
Lower Bearing	LB	12		1	2					1			1	12		2						1	1
Artificial Root Canal	ARC	13													13		1			2			
Bearing Base	BB	14			1	2	2							2		14					2		
Root canal	RC	15													1		15			1			
Micromotor Holder	MH	16									2							16					
U Base	UB	17				2	2												17		2		
Canal base	CB	18													2		1			18	2		
Main base	MB	19											2			2			2	2	19		
Pulley 1	P1	20		1	1								2	1								20	1
Pulley 2	P2	21		1	2								1	1								1	21

Figure 7 illustrates the distances of the DSM matrix plotted in the UCINET software [13]. The more substantial and thicker lines and arrows represent the most significant elements with respect to spatial relationships. The magenta lines denote functional relationships, while the blue lines indicate assembly relationships.

The components that encompass the three relationships of function, assembly, and space, as illustrated in Figure 7, are the UC, BB, S, R1, and R2. The components exhibiting only two relationships, namely function and assembly, as depicted in Figure 7, are UB, CH, MB, SB1, M, CB, SB2, UB, P1, LB, CB, CA, MB, P2, and MH. According to the figure, the component that solely demonstrates the function relationship is the ARC.

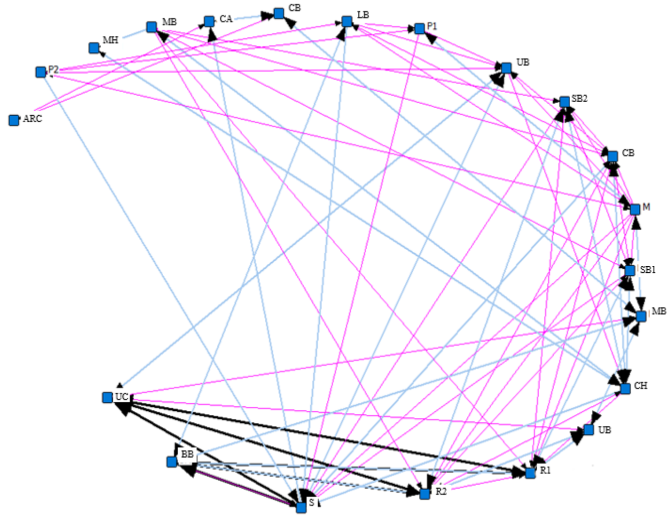


Fig. 7 Network diagram of component relations

Based on the network diagram analysis, it is determined that utilizing the FAS methodology reveals elements with a higher number of relationships relative to other components are challenging to modularize.

Upon examination of the relative functional importance values for each component presented in Table 5 and the relationship network values illustrated in Figure 7, components exhibiting low percentage values of functional relationships are selected. Furthermore, an analysis of functional variability and variable capacity is conducted, informing the design and fabrication requirements for the new test bench architecture, as delineated in Table VII.

TABLE VII
PRODUCT ARCHITECTURE ANALYSES IN TERMS OF REQUIREMENTS

Name	Compone nt	Functional variability	FV	Variable capacity	CV
P1	Pulley 1		NO		Yes
P2	Pulley 2		NO		Yes
MB	Main base		NO	Horizontal displacement of the bench	Yes
UB	U-base		NO		Yes
BB	Bearing base		NO		Yes
LB	Lower bearing		NO		Yes
M	Motor		NO		Yes
CH	Central Hub		NO		Yes
MB	Micromot or base		NO		Yes
MH	Micromot or holder	Any geometry of endodontic micromotor	SI		Yes
SB2	Spherical bearing 2		NO		Yes

SB1	Spherical bearing 1	NO		Yes
CB	Central Bearing	NO		Yes
R1	Rod 1	NO		Yes
R2	Rod 2	NO		Yes
S	Screw	NO		Yes
UB	Upper bearing	NO		Yes
UC	Upper Cover	NO		Yes
CB	Canal Base	NO		Yes
ARC	Artificial Root Canal	NO		Yes
CA	Canal adjuster	NO	Varying artificial root canal cube thicknesses	Yes

Components such as MB (main base), MH (micromotor holder), and CA (Canal adjuster) exhibited low values in relative functional importance and, in the clustering algorithm, demonstrated only two function and assembly ratios, indicating.

Their suitability for manufacture using the modular design strategy [9]. An analysis of the architecture of the new test bench in terms of requirements, as presented in Table 7, reveals that the BP component necessitates an electromechanical system for movement along the X-axis, thus obtaining variable spatial capacity. The MH component requires a specific geometry to accommodate various instruments, while the CA component necessitates different thicknesses of artificial root canals for adjustment, as evidenced in the table.

III. RESULTS.

The test bench is modeled utilizing SolidWorks® 2018, taking into account the modular design methodology [9], the requirements, and the functional constraints previously established [8]. Figure 8 illustrates the assembly of the bench components.

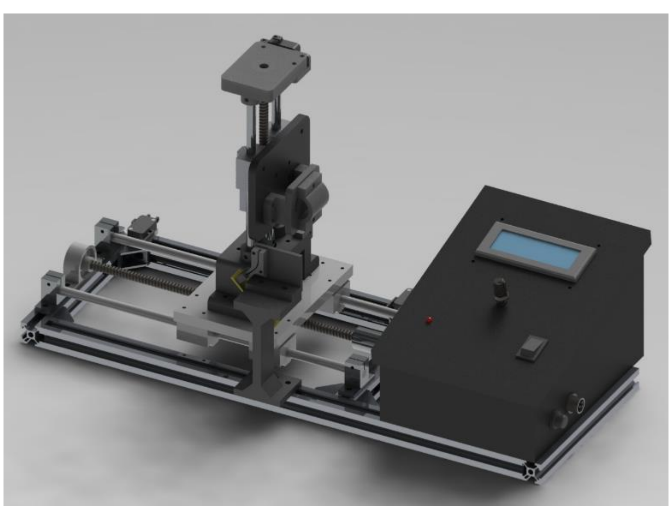


Fig. 8 SolidWorks rendering of the test bench

Utilizing the modular design methodology [9] and the clustering algorithm [13], three potential modularization components were identified, taking into account the requirements and constraints established at the project's inception [8]. The primary base module satisfies the displacement requirement along the symmetry axis X and is interconnected with the vertical column of the bench, as illustrated in Figure 9.

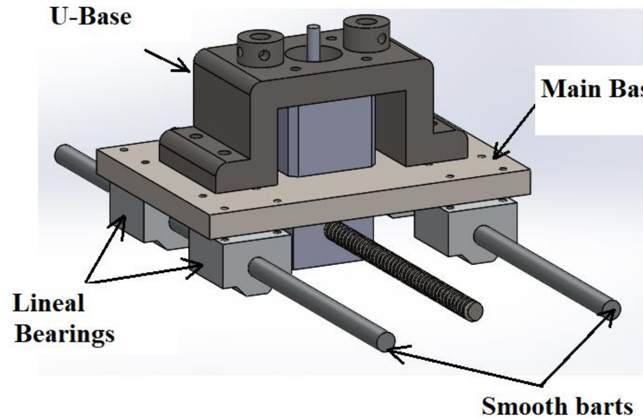


Fig. 9 Design of the main base module

The modularized component described herein serves the purpose of coupling various geometries of endodontic motors. Additionally, it provides the requisite angle of inclination to ensure proper alignment of the file with the artificial canal, as illustrated in Figure 10a. The support structure for the artificial canal is similarly modularized, comprising two sections: the first in the form of a column, and the second as a base accommodating two linear artificial canals. The resultant design is presented in Figure 10b.

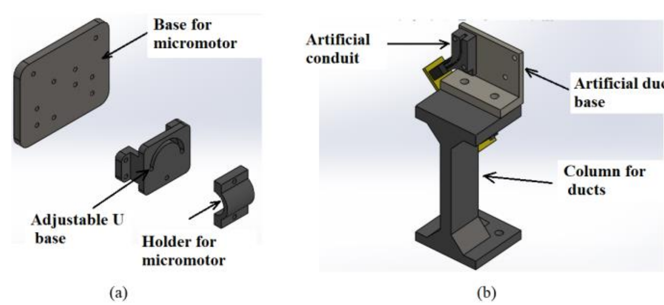


Fig. 10 (a) Design of the endodontic motor base (b) Design of the artificial root canal base

For the fabrication of the test bench prototype, three-dimensional printing materials (PLA - polylactic acid filament) and electronic components readily available in the country's central region are utilized. Several of these components are illustrated in Figure 11.

The fatigue test bench underwent evaluation in a dental clinic with the assistance of an endodontics expert. The specialist was responsible for programming the endodontic motor to the appropriate revolutions per minute (r/min) required for the specific file type utilized in the fatigue test. The micromotor was subsequently assembled with the endodontic instrument in the modular device.

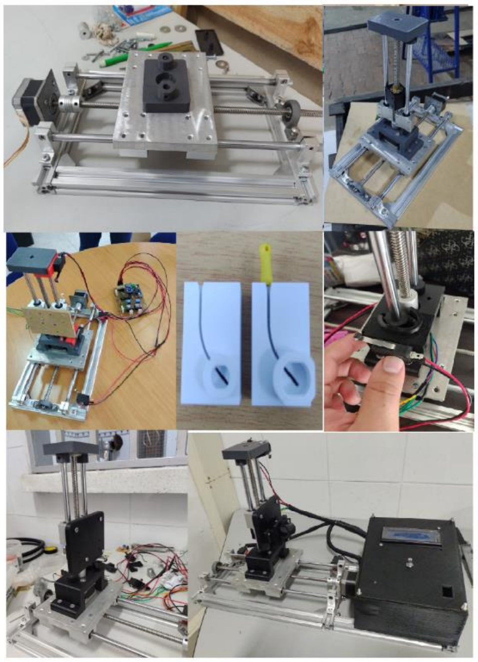


Fig. 11 Test bench components

Prior to conducting the dynamic test, the endodontic motor was configured at 280 r/min in accordance with the specifications of the file, which was a 25 mm Azdent® brand F1 type. Upon completion of the equipment programming, the dynamic test was initiated by reciprocally moving the file in an up and down motion at a predetermined linear speed of 0.08 mm/s, as illustrated in Figure 12.

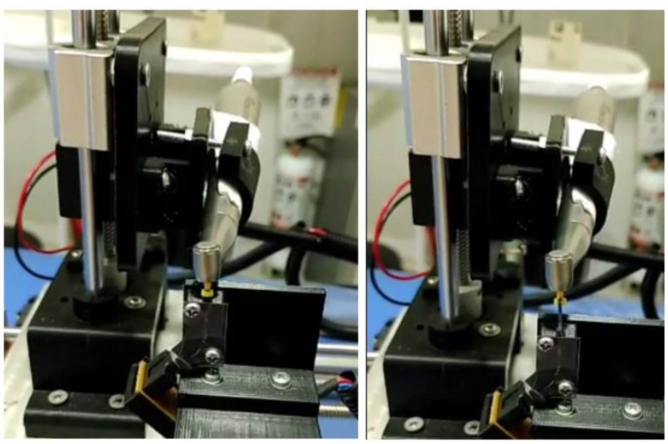


Fig. 12 Dynamic test on Azdent® F1 brand file

The Azdent® brand Ni-Ti file experienced fracture, prompting the horseshoe-type sensor to immediately transmit a signal to the main board, thereby halting the test equipment. The apparatus recorded on the display screen the following parameters: final time TF= 5 minutes, 30 seconds, and 35 tenths of a second, number of cycles CI= 1634, and repetitions RE= 131.

The static test was performed on the bench to the Westcode® brand Ni-Ti file, using the same values as in the dynamic test, 280 r/min in the endodontic motor. During the static test, the bench enters the file in a single vertical displacement at 22 mm, and then the file rotates inside the artificial canal.

The westcode® brand Ni-Ti file experienced fracture, prompting the horseshoe-type sensor to immediately transmit a signal to the main board, resulting in the cessation of the test equipment. The apparatus recorded on the display screen various parameters, including the final time TF = 16 minutes, 37 minutes and two-tenths of a second, number of cycles CI = 7639, and repetitions RE = 1.

IV. DISCUSSION

The dynamic and static fatigue tests were conducted utilizing Azdent® and Westcode® files, both of type F1. A "VDW SILVER" endodontic motor and the Azdent® file were employed in the dynamic test. The motor was configured at 280 r/min, and the file stroke (depth of entry into the artificial canal) was set at approximately 17 mm. The file experienced fracture at a time (TF) of 5'50"35"' (five minutes, fifty seconds, and 35 tenths of a second) and achieved a cycles to fracture (CI) value of 1634.9.

In the static test, the Westcode® file was utilized with the same 280 r/min, recording a time to fracture (TF) of 16'37"2"' (sixteen minutes, thirty-seven seconds, and two-tenths of a second) and yielding a value of cycles to fracture (CI) of 7639. The results obtained during the dynamic and static tests are comparable to the values reported by Pereira et al. [7], who conducted static tests on Alfa Aesar® brand files at 500 r/min, one with a diameter of 0.58 mm and the other with 0.25 mm. These researchers observed that when subjected to stress levels in the transformation phase condition, both files exhibited a reduced fatigue life, which remained nearly constant during this phase: between 145 cycles and approximately 1000 cycles for the thicker files with 0.58 mm; and between 1989 cycles and approximately 15000 cycles for the thinner file with 0.25 mm. Pereira et al. concluded that the fatigue life of the thinner file consistently exceeds that of the thicker one [1]..

Regarding modularity, the resultant design facilitates the interchangeability of certain components to enhance the functionality of the equipment. Consequently, it would be feasible to adapt a device that enables the utilization of the modular bench in tests of various types of elements, such as wires or components obtained through drawing processes, irrespective of their medical applications. Furthermore, the modularity of the test bench and the additive manufacturing of the majority of components via 3D printing technology simplify the maintenance of this type of device and render the scalability of the prototype feasible, contingent upon the element under analysis.

V. CONCLUSIONS

It is concluded that the majority of the requirements proposed at the outset of this document were successfully fulfilled. The designed and constructed apparatus facilitates the performance of dynamic and static tests on various endodontic instruments. The modular design methodology was implemented, which, through the analysis of functional relationships, assembly processes, and spatial configurations, facilitated the identification and selection of three components suitable for modularization: the main base module, the base module for micro-motor, and the base module for artificial channels.

One of the requirements that was not implemented was the utilization of batteries in the equipment due to the specifications of the endodontic motor and the variability in test duration. Furthermore, the bench is designed for use in environments such as laboratories, dental offices, or classrooms, which are equipped with a 110-volt electrical network. Consequently, a 110-volt to 12-volt adapter with a type B plug was selected. Although this aspect was initially stated as a requirement, during the detailed design stage, it was designated as a future improvement option. This decision was made considering the characteristics of the fatigue test and the variability in test duration depending on the type of test, material, and prior conditions of the element. Thus, it is necessary to ensure a constant and regulated power supply.

The second requirement that was eliminated is the connection cable to the computer, as the configuration of the bench facilitates the generation of an Excel table containing information on final time (TF), cycles performed (CI), and file repetitions (RE) at the conclusion of each test. A microSD memory port was implemented for data extraction to eliminate the need for additional cables.

A modular test bench was developed for fatigue testing of endodontic instruments, capable of conducting dynamic and static tests through an automated process. The apparatus accommodates multiple artificial canals arranged linearly, which can be designed and fabricated using 3D printing materials. The device records real-time data on Time to Fracture (TF), number of cycles (CI), and repetitions (RE) performed by the file.

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