Fatigue failure of NiTi endodontic files: scoping review

Falla por fatiga de limas NiTi para endodoncia: revisión exploratoria de cobertura temática

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Abstract

Introduction: Nickel-Titanium (NiTi) endodontic files are made of hyperelastic material with shape memory. However, these files suffer a sudden fracture during the endodontic treatment, which is considered an unfavorable prognosis. Many studies have been conducted to establish fatigue resistance focused on file brands and determine which is better. Although the most common failure mechanisms have been established for motorized endodontic files, the information is scattered, making it difficult to develop clear research trends. ***Methods:*** a scoping review was carried out using Scopus, Dimensions.ai, Web of Science, and Science Direct databases to answer screening questions related to the predominant fracture mechanism in NiTi files, test types, and equipment used for experimentation and to identify the most active authors. ***Results:*** using the general search terms, 432 research papers were found, of which 75 were finally selected after eliminating duplicates and applying exclusion criteria. ***Conclusions***: typical failure mechanisms for rotatory and reciprocating files were identified based on the panoramic review and bibliometric indicators. Also, the standard mechanical tests for endodontic files and the characteristics of their assemblies were summarized. The most active authors in the area and their nationality were tagged. Finally, gaps for future research are proposed to generate a comprehensive knowledge of NiTi file failure.

Keywords: nickel-titanium, endodontics, fatigue, scoping review

Resumen

Introducción: las limas de Níquel-Titanio (NiTi) utilizadas en endodoncia están hechas de un material hiperelástico con memoria de forma. Sin embargo, estas limas sufren fractura repentina durante el tratamiento, lo cual se considera un pronóstico desfavorable. Se han realizado diversos estudios para establecer la resistencia a la fatiga de limas, y determinar cuál marca es mejor. Aunque se han establecido los mecanismos de falla más comunes para las limas de endodoncia motorizadas, la información se encuentra dispersa, dificultando la definición de tendencias claras de investigación. ***Métodos:*** se realizó una revisión de cobertura temática utilizando las bases de datos Scopus, Dimensions.ai, Web of Science y Science Direct, para responder a preguntas orientadoras relacionadas con el mecanismo de fractura predominante en las limas NiTi, tipos de pruebas y equipos utilizados para la experimentación e identificar los autores más activos en el área. ***Resultados:*** utilizando términos generales de búsqueda, se encontraron 435 trabajos de investigación. Finalmente se seleccionaron 75, tras eliminar duplicados y aplicar criterios de exclusión. ***Conclusiones:*** a partir de la revisión panorámica de literatura y empleando algunos indicadores bibliométricos, se identificaron los mecanismos de falla más comunes para las limas rotatorias y reciprocantes. Se obtuvo información sobre ensayos mecánicos y los montajes más utilizados para las limas de endodoncia. Se identificaron los autores más activos en el área y su nacionalidad. Por último, se sugieren oportunidades de investigación para generar un conocimiento exhaustivo sobre la falla de las limas NiTi.

Palabras clave: níquel-titanio, endodoncia, fatiga, revisión de literatura

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INTRODUCTION

Fracture forms an integral part of fatigue cracking mechanisms in NiTi endodontic files. Due to the hyperelastic material behavior of NiTi, this alloy enables elastic deformations that are useful to follow the random geometry of the root canal[1]. However, these instruments are susceptible to fracture by fatigue[2], which is considered harmful for the prognosis and treatment.[3] A failure during the procedure implies a significant reduction in its effectiveness since the separated fragment can become an element that stands in the way of the successful eradication of the infection. In addition, this failure generates subsequent medical inconveniences if it is not possible its immediate removal.[4]

NiTi instruments are driven by an electric motor initially used with a continuous rotary motion. About ten years ago, the reciprocating motion (rotation changes direction at some point of the revolution) was introduced. From the beginning, studies have been conducted to minimize or eliminate the intrinsic defects of the material, increasing its hardness and flexibility, improving resistance to fatigue life, and prolonging its cutting efficiency.[5] Fatigue failure resistance of NiTi files has been widely studied, mainly by comparing brands. However, few studies are related to completely understanding the fatigue failure mechanism[1,6–9]. Others are focused on the use of Finite Element Analysis[10]. Some experimental approaches have been developed to identify that the failure mechanism for rotatory files is flexural fatigue caused by the bending of the file when it is placed in the root canal. In this case, one of the file surfaces acts in tension, and the other works in compression.[11]

Figure 1 shows the primary failure process of the file when it is used inside the root canal. Tension and compression stresses occur when the file rotates inside the canals, causing fatigue failure (Figure 1A). Another mechanism is the torsional failure caused when a part of the NiTi instrument becomes trapped in the root canal (by friction and/or adhesion). At the same time, the driven motor continues rotating; this mechanism is illustrated in Figure 1B. A third failure mechanism known as the torsional fatigue can be identified for reciprocating instruments. In this case, the file is not trapped, but in the reciprocating motion, the friction between the root canal walls generates torsional opposition loads to the file, as shown in Figure 1C. The alternating direction of these friction forces causes fatigue failure. Stress vs. time behaviors is illustrated in Figure 1D.

There is a wide variety of cross-sectional geometries. NCF (number of cycles for fracture) values for NiTi rotary files have been recorded depending on this design[12], demonstrating variability and randomness in fatigue failures due to the limited information collected during their operation. The biggest drawback is that the shape memory and superelasticity properties of the NiTi alloy imply that the files do not exhibit deformation or signs of the proximity of failure detectable with the human eye during endodontic treatment[13,14]. The operator does not perceive any deterioration until the file is fractured.

This scoping review focuses on identifying the different endodontic files studies related to fatigue behavior as well as gathering relevant information about the tests, types of studies, authors, and gaps in the area.

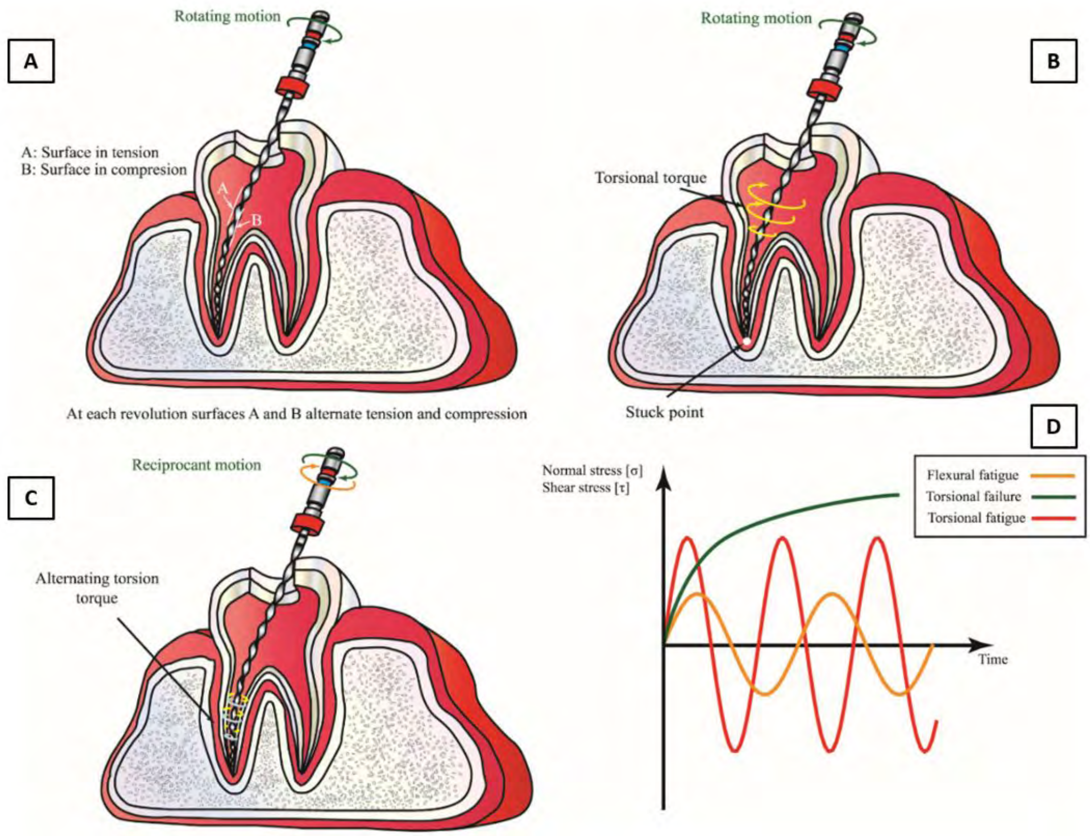

Figure 1. Failure mechanisms for NiTi endodontic files

Source: by authors

METHODS

Research type

This document presents a scoping review of the available research articles coupled with bibliometric indicators such as co-occurrence and co-authorship citations. Bibliographic matching maps were generated to help the data visualization.

Search Strategy

For the panoramic exploration of the available research articles, the methodology is summarized in the following steps[15,16]:

a) Search questions formulation

b) Search for publications (including search strings, databases selection, and inclusion and exclusion criteria)

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c) Data extraction and systematization

d) Information evaluation

e) Analysis and reports

The following questions were formulated to guide the information search: What are the failure mechanisms identified for NiTi files? What tests are performed to determine the mechanical behavior of NiTi files, and what type of equipment is used? Who are the most active authors? How has the study of the failure of NiTi files evolved?

The following databases Scopus, Web of Science (WOS), Science Direct, and Dimensions.ai were reviewed to define which one provides more information and establish a general overview of the topics of interest. It was found that the answer to the question about the failure mechanism is summarized in the phenomenon of fatigue, which involves failure considerations related to torsional and bending loads. Therefore, the words "fatigue" (involving the most complex failure phenomenon) and "endodontic file" (object of study) were used to construct the search equation applied for filtering titles, abstracts, and keywords. Table 1 summarizes the search strings, databases, and the number of articles found in the review process. In this step of the review were found 412 research papers.

Table 1. Databases, search strings, and documents found for the initial stage of database review

Database	Initial search equation	# Docs
Scopus	(TITLE-ABS-KEY ("endodontic file") AND TITLE-ABS-KEY(fatigue))	208
Dimensions.ai	"endodontic file" AND "fatigue"	183
WOS	TEMA: ("endodontic file") AND TEMA: (fatigue)	25
Science Direct	"endodontic file" AND "fatigue"	19

Source: by authors

The search was refined using language inclusion criteria (documents in English, Spanish, Portuguese, and Italian), and as exclusion criteria, the areas of knowledge aerospace, chemistry, and earth unrelated to the subject of interest. This screening procedure results in 302 documents. The documents found in each database were compared to define duplications. A total of 154 documents were selected in this stage. Abstracts were reviewed to classify them according to the topic of interest and facilitate the filtering of documents. Finally, 75 papers were selected after discarding some that only discuss manufacturing techniques, thermal treatments, mechanical properties analysis (not including fatigue and torsion), and the alloy's morphological characterization.

Since most of the documents were found in Scopus, it was established as the primary database for bibliometric indicators analysis. The documents obtained were exported using VOSviewer[17]. A thesaurus was built to unify terms. Co-occurrence, co-authorship, and bibliographic coupling maps were generated to identify the networks and answer the questions about the type of tests performed on NiTi endodontic files, authors associated with the area, and nationality, respectively.

RESULTS

For the co-occurrence map, the unit of analysis was the keywords. Figure 2 shows a density visualization graph of the network.

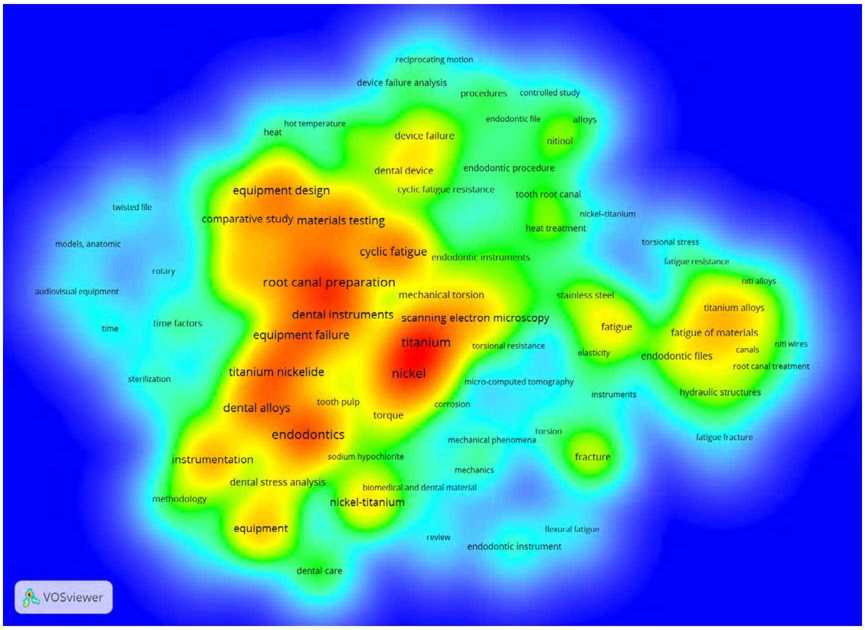

Figure 2. Density visualization. Co-occurrence analysis of the keywords in documents for review

Source: by authors

The colors in the figure are related to the number of times that a keyword appears in the article set; the most repeated words are shown in red, in orange and yellow colors appear other less repeated terms related to the research topic. The graph confirmed that endodontic files made of NiTi are commonly subjected to fatigue, and torsion tests are generally made through the preparation of artificial canals.

For the construction of co-authorship networks, authors' names were used as the unit of analysis—the graph obtained with the software's graphical tool shows seven clusters. However, only three of them were related, which means the presence of collaborative work. Authors such as Gambarini, Plotino, Testarelli, Grande, and Pedullá appeared with the highest number of published documents. Other clusters of authors were also identified, but the publications were not interrelated. The most active authors belong to the bigger cluster. However, in one of the smaller clusters, widely cited authors such as Freitas, Carvalho, and Lopes appeared. In another cluster appeared the author Shen, who was identified as relevant in early analyses of the entire databases.

To know about the evolution of the NiTi file fracture studies, the selected unit of analysis was authors and countries. The map established that in 2016 increased in United States, Brazil, and Italy the publication of papers related to fatigue failure tests for NiTi endodontic files. However, these days the tests are usually performed to establish resistance values (maximum values for failure) and used for brands comparison and sometimes to compare files from the same manufacturer.

Relevant information was extracted and allowed to establish the variables recorded in the tests such as time, the number of cycles to fracture-NCF, torque values, and the most common statistical analysis used for the experiments. Moreover, it gave a baseline for research parameters on endodontic file fatigue. This information is summarized in Figure 3.

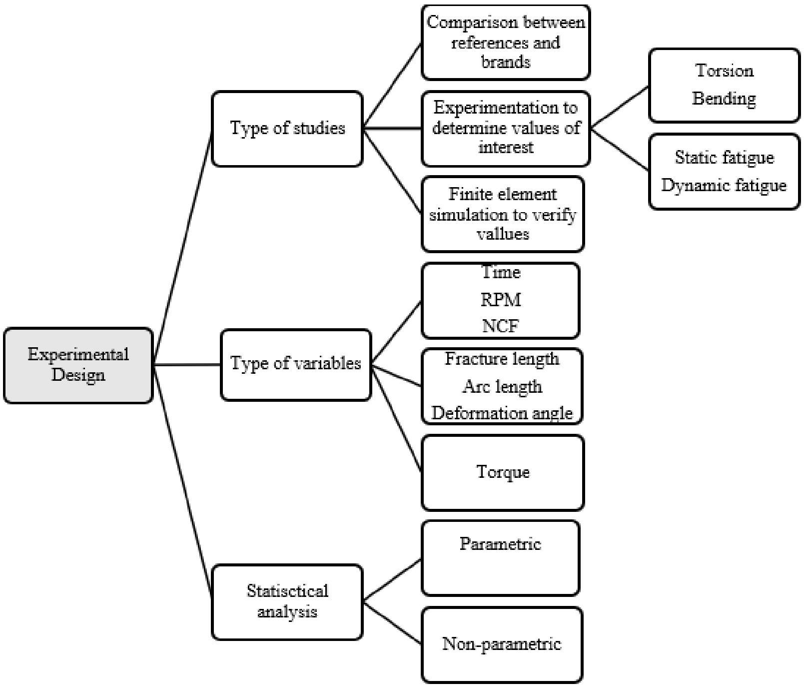

Figure 3. Experimental design abstracted from the review

Source: by authors

Similarly, from the documents that report experimental tests, it was possible to compile information regarding the experimental setups implemented and to characterize the endodontic files fatigue tests as follows:

- Instrument operation can be with devices or with human operators
- The type of applied loads can be bending fatigue, torsional fatigue, or combined loads
- The materials used for artificial canals are steel, stainless steel, polymethyl methacrylate-PMMA, Polyester resin, 3D printing materials such as polylactic-acid-PLA, or acrylonitrile-butadiene-styrene-ABS, also glass.
- Temperatures for the tests are room temperature or oral cavity temperature simulation
- For lubrication, researchers used deionized water, Hypochlorite solution, Glycerin or No-lubrication

- Most common inspection techniques: Optical microscopy, Scanning Electron Microscope-SEM, X-ray Diffraction-XRD, Transmission Electron Microscopy-TEM, Focused Ion Bema-FIB, Differential Scanning Calorimetry-DSC, and Micro Computed Tomography-MicroCT-scanning

Table 2 summarizes the studies found in the scoping review. The scheme used to present data allows appreciating research evolution, associated authors, relevant findings, and observed variables.

Table 2 Summary of the fatigue failure on endodontic file research studies

Study findings	Analyzed Variable(s)	Authors	Year
E: Cyclic axial motion significantly extends fatigue life.	Fracture Time	Dederich et al. [18]	1986
C: Life cycle depends on the radius of curvature	Fracture Time	Haïkel et al. [19]	1999
E: Analyze the type of defects after clinical use	Fracture type	Sattapan et al. [20]	2000
C: Cutting edge design does not affect fatigue life, but the file size does.	Fracture Time	Chaves-Craveiro et al. [21]	2002
I: Fatigue is the failure mechanism of Hedstrom files.	Cracks	Zinelis et al. [22]	2002
E: The shape of root canals affects the life of the file.	Flexibility	Kuhn et al. [23]	2002
E: Curved canals adversely affects torsional strength for Profile files.	Angular speed and Torque	Azevedo-Bahía et al. [24]	2006
E: Evaluate the influence of curvature on fatigue life	Arc length	Pereira-Lopes et al. [25]	2007
E: Heat treatment temperature influences fatigue strength	Temperature and rotations	Zinelis et al. [6]	2007
E: Exposure to sodium hypochlorite does not affect fracture toughness.	Torque, angle and NCF	Ormiga et al. [26]	2007
E: As angular deformation increases, fatigue cycles decrease.	Torque, angle and NCF	Ormiga et al. [27]	2007
C: Material alloys ratio affects the fatigue life	Angle of twist	Johnson et al. [28]	2008
E: Electropolishing does not affect the fatigue life of the files.	Torque, angle and NCF	Ormiga et al. [29]	2008
E: Fracture patterns obtained by SEM can explain the fracture process.	Torque, angle and NCF	Ormiga et al. [7]	2008
C: Files manufactured by twisting showed increased fatigue strength.	Fracture Time	Gambarini et al. [30]	2008
L: Normative is required to standardize fatigue testing	None	Plotino et al. [11]	2009
E: Fatigue is the main cause of file fracture over a static torsion	Fracture type and rate	Inan et al. [8]	2009
E: Argon implantation improves performance of S1 files moderately.	Number of cycles and crack	Brilhante-Wolle et al. [31]	2009
C: The process of manufacturing affects the fatigue strength of the file	Angle of twist	Park et al. [32]	2010
E: Standard operation does not affect the self-adjusting file.	Fracture Time	Hof et al. [33]	2010
C: M-wire exhibits higher fatigue strength than SE-Wire files	Number of cycles	Gao et al. [34]	2010
C: Fracture is related to austenitic size grain	Size and type of alloy grain	Pirani et al. [9]	2011
C: Twisting files show higher strength. Ductile fracture is observed.	Fracture type and NCF	Rodrigues et al. [35]	2011
C: Reciprocating motion and twisting manufacturing improve strength.	Fracture time	Castelló-Escrivá et al. [36]	2012
C: TF files have a higher fatigue resistance than GTX files.	Number of cycles	Miglio et al. [37]	2012
S: Constitutive relationship for flexural fatigue	Bending stresses	Leroy et al. [38]	2012
C: Manufacturing affects the fatigue life	Number of cycles	Bhagabati et al. [39]	2012
E: Preflaring helps to increase fatigue life	Number of cycles	Ehrhardt et al. [40]	2012
E: Geometry of canal affects fatigue life and fracture size	Fracture length	Al-Sudani et al. [41]	2012
C: Manufacturing affects the fatigue life	Number of cycles	Bouska et al. [42]	2012
C: NiTi files have better mechanical fatigue behavior than steel	Strength failure	Pereira-Lopes et al. [43]	2012
C: Compare brands to find the one with higher fatigue life	Number of cycles	Capar et al. [44]	2013
C: Fracture length is an invariant	Fracture length	Plotino et al. [45]	2014

Study findings	Analyzed Variable(s)	Authors	Year
E: Reciprocate motion affects the fatigue life	Angular speed and torque	Testarelli et al. [46]	2014
E: Immersion in different irrigation solutions affects the fatigue life	Time of immersion	Pedullá et al. [47]	2014
C: 15% torsional preload reduces the fatigue strength of EDM files	Preload, torque, and angle	Campbell et al. [48]	2014
C: Mwire and CM treatments increase fatigue resistance of rotary files.	Fracture time	Braga et al. [49]	2014
C: Compare brands to find the one with higher fatigue life	Number of cycles	Sousaa et al. [50]	2015
C: Compare brands to find the one with higher fatigue life	Number of cycles	Capar et al. [51]	2015
E: Preloads of torsion and fatigue are inversely proportional	Number of cycles	Shen et al. [52]	2015
C: Preloads reduce the fatigue strength of files	Preload, torque and angle	Pedullá et al. [53]	2015
E: Austenitic phase shows long fatigue life but reduced in R phase	NCF, % elongation	Freitas et al. [54]	2015
C: Compare brands to find the one with higher fatigue life	Number of cycles	Özyürek et al. [55]	2016
S: Stress intensity factors allow understanding the fatigue failure	Stress intensity factor	Isidoro et al. [56]	2016
C: Compare brands to find the one with higher fatigue life	Number of cycles	Uslu et al. [57]	2016
E: Large strains affect the fatigue life	Number of cycles	Chih-Wen et al. [58]	2016
C: Compare new and used files to find the one with higher fatigue life	Number of cycles	Taha et al. [55]	2016
E: Martensitic grain decreases the fatigue life	Size and type of alloy grain	Carvalho et al. [1]	2016
E: The depth of the machining groove affects the NCF	Fracture time	Lopes et al. [59]	2016
C: EDM, CMwire support lower torque but higher angle than Mwire	Torque and angle	Lo Savio et al. [60]	2016
E: Back-forward motion extends fatigue life	Fracture time	Loios et al. [61]	2016
C: Cyclic bending load reduces the torsional strength of CM files	Torque and NCF	Peláez-Acosta et al. [62]	2016
E: The temperature of the environment influences the NCF	Water temperature, NCF	Dosanjh et al. [63]	2017
C: Low environment temperature increases fatigue resistance	Temperature, NCF	Grande et al. [64]	2017
E: Ti-Zr-B coating can improve fatigue resistance	Fracture time	Chih-Wen et al. [65]	2017
E: Reduced apical depth generates less stress on the file	Screw-in force	Jung-Hong et al. [66]	2017
E: Heat treatment increases fatigue resistance and cutting efficiency.	Fracture time	Chih-Wen et al. [67]	2017
C: Compare brands to find the one with higher fatigue life	Number of cycles	Gundogar et al. [68]	2017
C: Compare brands to find the one with higher fatigue life	Number of cycles	Azim et al. [69]	2018
E: Relationship between the kinematics of file motor and fatigue life	Number of cycles	Iacono et al. [70]	2018
E: Torsional preloads reduce fatigue strength of EDM files	Preload, torque and angle	Shen et al. [71]	2018
E: Hypochlorite concentrations and temperature influence resistance	Number of cycles	Alfawaz et al. [72]	2018
E: Fatigue life is affected by torque and curvature of the canal	Torque and curvature	Bhatta et al. [73]	2019
C: Compare brands to find the one with higher fatigue life	Number of cycles	Jamleh et al. [74]	2019
E: Microtomography allows non-destructive analysis of files	Number of cycles	Bastos et al. [75]	2019
C: Compare new and used files to find the one with higher fatigue life	Number of cycles	Alvez et al. [3]	2020
E: 2D-3D representations of canals show differences in stresses	Number of cycles	Piasecki et al. [76]	2020
C: S-One files with higher resistance than M-Two, used in natural canals.	Fracture time	Miccoli et al. [77]	2020
C: Fatigue resistance decreases at body temperature	Fracture time	Generali et al. [78]	2020
C: All files are efficient in the preparation of the canal.	Fracture time	Drukteinis et al. [79]	2020
C: ReFlex Smart file reciprocating motion increases fatigue resistance	Fracture time	Zubizarreta et al. [80]	2021
C: Gold and Blue treatment improves resistance (bending and fatigue)	Fracture time and load	Xiao-Mei et al. [81]	2021
E: Increasing apical and taper diameter reduces the dynamic fatigue strength	Fracture time and pecks	Faus-Llácer et al. [82]	2021

C: Comparison between brands; E: Experimental study on particular factors; L: Literature review; S: Simulations; I: Inspection

Source: by authors

Regarding the information presented in Table 2, it can be established that most of the literature reviewed (47.9%) was focused on conducting comparative experiments (C) to determine which brand is more resistant to cyclic fatigue. Regarding the variables analyzed, the time for file fracture in continuous operation is generally measured (23.3%)[65,77], and the number of cycles to fracture or NCF was determined (53.4%)[21,62]. Those results provide information about the research trends in endodontic files failure and show possibilities for future studies not centered on comparison only.

DISCUSSION

From the information presented in Table 2, it is established that most of the literature reviewed (47.9%) is focused on conducting comparative experiments (C) to determine which brand is more resistant to cyclic fatigue. Regarding the variables analyzed, the time for file fracture in continuous operation is generally measured (23.3%)[65,77], and the number of cycles to fracture or NCF was determined (53.4%)[21,62]. Those results provide information about the research trends in endodontic files failure and show possibilities for future studies not centered on comparison only.

DISCUSSION

Flexural fatigue tests are generally performed by allowing free rotation of the file within the canals. However, some documents discuss other types of tests applied to files, one of them is related with torsional loads in which the file´s tip is fixed with resin or bronze jaws[64,73]. It should be noted that most of the studies were in-vitro, and only two were previously in human patients. After the endodontic treatment, the files were subjected to fatigue tests in artificial canals[40,79]. Most of the experiments were performed with artificial canals made of metal plates, resin, and other materials (30.1%)[20,68], which severely affected the file's fatigue life. Also, two studies were developed simulating body temperature[72,78]. These studies allowed the establishment of the actual methods used for experimentation and show the need to approach the research to simulate oral cavity conditions.

Experimental tests for NiTi files can be classified as static in the case of keeping a constant file's length inside the artificial canal; and dynamic in the case of operating with axial motions inside and outside the canal, which is known as pecking motion. This movement contributes to extended fatigue life, which is reduced by the complex geometry of the root canals[32,80]. Fracture occurs in the middle of the bending radius in experimental tests that involve static fatigue loads[38,41]. These results contribute to determining the fracture's length and can be considered a basis for future studies that focus on understanding failure.

Immersion in substances such as sodium hypochlorite does not affect fatigue resistance. However, immersion in ethylenediaminetetraacetic-acid-EDTA for more than three minutes considerably affects fatigue resistance. In addition, the effect of different percentages of sodium hypochlorite concentrations have been studied and are defined to be used between 2.5% - 5.0%[47].

Some files show differences in fatigue resistance depending on the motor with which they are operated. However, Wave One® files do not significantly differ when working with X-Smart or EVO motors[46]. Inherent file factors such as cross-sectional geometry, number of spirals in the working section, coating, and manufacturing method influence fatigue, torsional, and bending strength. Finally, the files manufactured by twisting have higher resistance values than those manufactured by grinding[35].

In all the experimental tests, a preliminary inspection was made to verify that the file's surface was free of imperfections that may affect the results. When the file is broken, SEM analysis is the most common technique to inspect the fractured sections[19,57,82]. Small austenitic grains are observed near the tip after the operation and fracture of the file[9].

Many tools are used for the experiment's statistical analysis as shown by Bonferroni[45], Weibull and Levene[69]. However, those methods related to the comparison of the population tend to prevail[25,83], according to the trend to make comparative studies between files references and brands.

Regarding publications, the diffusion of knowledge about the failure of endodontic files manufactured with NiTi alloy started in 1986. Publications increased around 2012, and 2019 was one of the most productive years, reinforcing the relevance of this topic and the need to continue researching NiTi endodontic file failure comprehension.

Due to the operating conditions of the NiTi files (most like dynamic fatigue test) and values identified for fracture failure, the fatigue can be classified as low cycling. So, it is necessary to develop the strain-life curves and crack propagation models. Because most tests are performed in artificial canals made of different materials, which differ from dentin behavior, it is necessary to generate knowledge related to the friction and adhesion generated between the file and the canal material. Additionally, it is required to establish the differences in performance of the same NiTi file in canals made of different materials.

Concerning the operation of the files, it is required to use equipment and assemblies that ensure the repeatability of the experiment and eliminate errors introduced by a human operator. Finally, very few studies attempt to understand the instrument's fracture mechanics and therefore do not delve into the phenomenology of the failure process. And, there are no proposals for failure proximity detection methodologies.

CONCLUSIONS

Scopus contains the most significant number of documents and includes the majority of the articles present in other databases. Also, it was verified that the Dimensions.ai open-access database contains more than 80% of Scopus articles, positioning this database as a relevant information source.

It was found that most studies have focused on comparative experimentation between references and brands but do not delve into the understanding of the failure phenomenon that would allow predicting it.

The predominant failure mechanism for NiTi endodontic files was identified as cyclic fatigue caused by bending or torsion. Besides, most tests are static and are conducted for rotational motion of the files more than for reciprocanting movement. It is relevant to quote that reciprocanting motion of files involves a more severe regime of cyclic fatigue.

It was noted that there are no standardized tests for the development of cyclic fatigue experimentation. Each author conducts tests using different measurement parameters and methods. Therefore, it is necessary to work on the standardization of the tests to unify the failure criteria.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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