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ORIGINAL RESEARCH

Cyclic fatigue resistance of different nickel-titanium instruments in single and double curvature at room and body temperatures: A laboratory study

Giusy Rita Maria La Rosa DDS, PhD[1] | **Maria Laura Leotta DDS**[1] | **Francesco Saverio Canova DDS**[1] | **Virginia Rosy Romeo DDS**[1] | **Gabriele Cervino DDS, PhD**[2] | **Luigi Generali DDS**[3] | **Eugenio Pedullà DDS, MSc, PhD**[1]

[1]Department of General Surgery and Medical-Surgical Specialties, University of Catania, Catania, Italy

[2]Department of Biomedical and Dental Sciences and Morphological and Functional Imaging, Messina University, Messina, Italy

[3]Department of Surgery, Medicine, Dentistry and Morphological Sciences with Transplant Surgery, Oncology and Regenerative Medicine Relevance (CHIMOMO), University of Modena and Reggio Emilia, Modena, Italy

Correspondence
Giusy Rita Maria La Rosa, Department of General Surgery and Medical-Surgical Specialties, University of Catania, Catania, Italy.
Email: g_larosa92@live.it

Abstract

The aim of this study was to compare the cyclic fatigue resistance of nickel-titanium instruments inside single and double-curved canals at different temperatures. 160 HyFlex EDM #20.05 (HEDM), VDW.ROTATE #20.05 and #25.06, Mtwo #25.06 were randomised ($n=10$) for the dynamic cyclic fatigue tests according to the curvature (i.e. single and double) at $20° \pm 1°C$ and $35° \pm 1°C$. The number of cycles to fracture (NCF) was analysed by two-way ANOVA with $p<0.05$. Fatigue resistance of all instruments significantly decreased at body temperature in single and double curvatures, except for HEDM in double curvature. The NCF was significantly lower in double curvature than single at both temperatures for all files, except for VDW.ROTATE #20.05 at $35° \pm 1°C$. Within the study limitations, temperature significantly impaired cyclic fatigue resistance of all files except HEDM #20.05 in double curvature. Similarly, double curvature had a detrimental effect on cyclic fatigue resistance of all files except for VDW.ROTATE #20.05 at body temperature.

KEYWORDS

body temperature, cyclic fatigue, double curvature, dynamic model, HyFlex EDM, Mtwo, VDW.ROTATE

INTRODUCTION

Since their introduction in 1988, nickel-titanium (NiTi) files have drastically improved endodontic treatment [1]. However, to minimise the risks of file separation, knowledge of the NiTi instruments' characteristics is crucial [2]. NiTi files can suddenly separate during root canal preparation due to torsional and cyclic fatigue [3]. Cyclic fatigue occurs as the consequence of repeated cycles of tensile-compression stress to which the instruments are subjected when it rotates inside curved canals [4]. Many variables are involved in the fracture of rotary files, some of which depend on the instrument properties [4]. Other parameters implicated in the file separation are related to the canal configuration, including root canal curvature, angle and radius, length of the curve and its location [5]. In particular, the degree of curvature represents a critical factor mainly in S-shaped canals [6]. Furthermore, environmental temperature affects cyclic fatigue resistance of NiTi instruments [7–9].

Luigi Generali and Eugenio Pedullà equally contributed.

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During last years, manufacturers have proposed several heat treatments with the aim to improve mechanical properties of NiTi alloy [10]. The HyFlex EDM (HEDM; Coltene/Whaledent, Altstätten, Switzerland) is a rotary file system made from controlled memory alloy and using the 'Electrical Discharge Machining' (EDM) to enhance its mechanical performance. These files have a tip size and taper of #25 and 0.08, respectively, with a variable cross-section [11]. In accordance with the concept of conservative root canal preparation, reduced-taper NiTi files should preserve dental structure. Exploiting this approach, VDW.ROTATE (VDW GmbH) is a file system recently introduced, consisting of three file basic sequence (#15.04, #20.05, #25.04, or #25.06 for wide canals) with a S-shaped cross-section, off-centre design and constant taper. Files are made with a heat treatment developed by the manufacturer to increase their flexibility [12]. Mtwo (VDW) instrument is a traditional NiTi rotary system. The S-shaped cross-section with two blade-cutting surfaces confers the instrument extreme flexibility [13, 14].

To date, no studies evaluated the effect of temperature on cyclic fatigue resistance of HEDM, VDW.ROTATE and Mtwo instruments inside single and double-curved canals by using a dynamic cyclic fatigue model.

Thus, the aim of this study was to compare the cyclic fatigue resistance of EDM #20.05, VDW.ROTATE #20.05, Mtwo #25.06 and VDW.ROTATE #25.06 inside single and double-curved canals at room and body temperature using a dynamic model. The null hypothesis is that (i) there is no difference between the different curvatures and temperatures for the same instrument and (ii) there is no difference between the different instruments in the same laboratory conditions.

MATERIALS AND METHODS

The files were examined using a stereomicroscope at ×20 magnification (Imaging Systems; Leica Ltd.) to detect any deformation, before the cyclic fatigue test. No file was discarded.

A total of 160 NiTi instruments (HEDM #20.05, VDW.ROTATE #20.05, Mtwo #25.06 and VDW.ROTATE #25.06) were randomly allocated in four groups (for each file) according to single and double curvature and 20°±1°C and 35°±1°C temperatures (Available at: www.random.org). Cyclic fatigue resistance was evaluated through a dynamic model in a customised device specifically created for this purpose [4]. Each instrument was located inside the artificial canals in a reproducible way. The canal with a single curve was manufactured with a 5-mm radius of curvature and 60° curvature angle. The double-curved artificial canal had the first coronal curve with 5-mm radius and 60° curvature and the apical with 2-mm and 70° [2]. All the files were operated using a torque-controlled motor following the manufacturers' instructions: HEDM #20.05 was rotated at 400 rpm, VDW.ROTATE #20.05 and #25.06 at 350 rpm, Mtwo #25.06 at 300 rpm. A continuous back-and-forth axial oscillation motion inside the artificial canal was performed with an amplitude of 3 mm/s to simulate clinical usage [15, 16]. A 6:1 reduction electrical handpiece (Sirona Dental Systems GmbH), has been maintained in a standardised tridimensional position through the fixing block with which the device was equipped. A high-flow synthetic oil was applied to the artificial canal as lubricant to reduce the friction [4, 8, 9]. The two temperatures were reached, maintained constant (±1°C) and electrically monitored by the thermostat and thermocouples connected to the device [8, 9]. Instruments were rotated until fracture occurred. A digital camera (Nikon D90) was used during the tests to confirm the exact fracture time. The time to fracture recorded with a digital chronometer was multiplied by the number of rotations per minute (number of rotations per second) to obtain the number of cycles to fracture (NCF). The length of broken files was measured using a digital calliper and fractured fragments were analysed using a field-emission scanning electron microscope (ZEISS Supra 35VP; GmBH) under different magnifications to examine the fractured surfaces. A single expert operator performed all the experiments. A second blinded examiner was responsible for the surface examination.

Statistical analysis

Data were subjected to the Shapiro–Wilk test to verify their normality and statistically analysed using two-way analysis of variance and the Bonferroni multiple comparison post hoc test (Prism 8.0; GraphPad Software, Inc) with $p < 0.05$. A sensitivity power analysis was performed to determine the minimum effect size that can be reliably detected from the two-way ANOVA. The analysis was performed with G*Power 3.1 (Heinrich Heine, Universität Düsseldorf, Dusseldorf, Germany). The present manuscript was written according to Preferred Reporting Items for Laboratory Studies in Endodontology (PRILE) 2021 guidelines (Figure 1) [17].

RESULTS

With a sample size of 160 instrument, a power of 0.90, 16 groups and $\alpha = 0.05$, the present sample size was adequate to detect a minimum effect size of 0.36, which is considered a medium effect [18].

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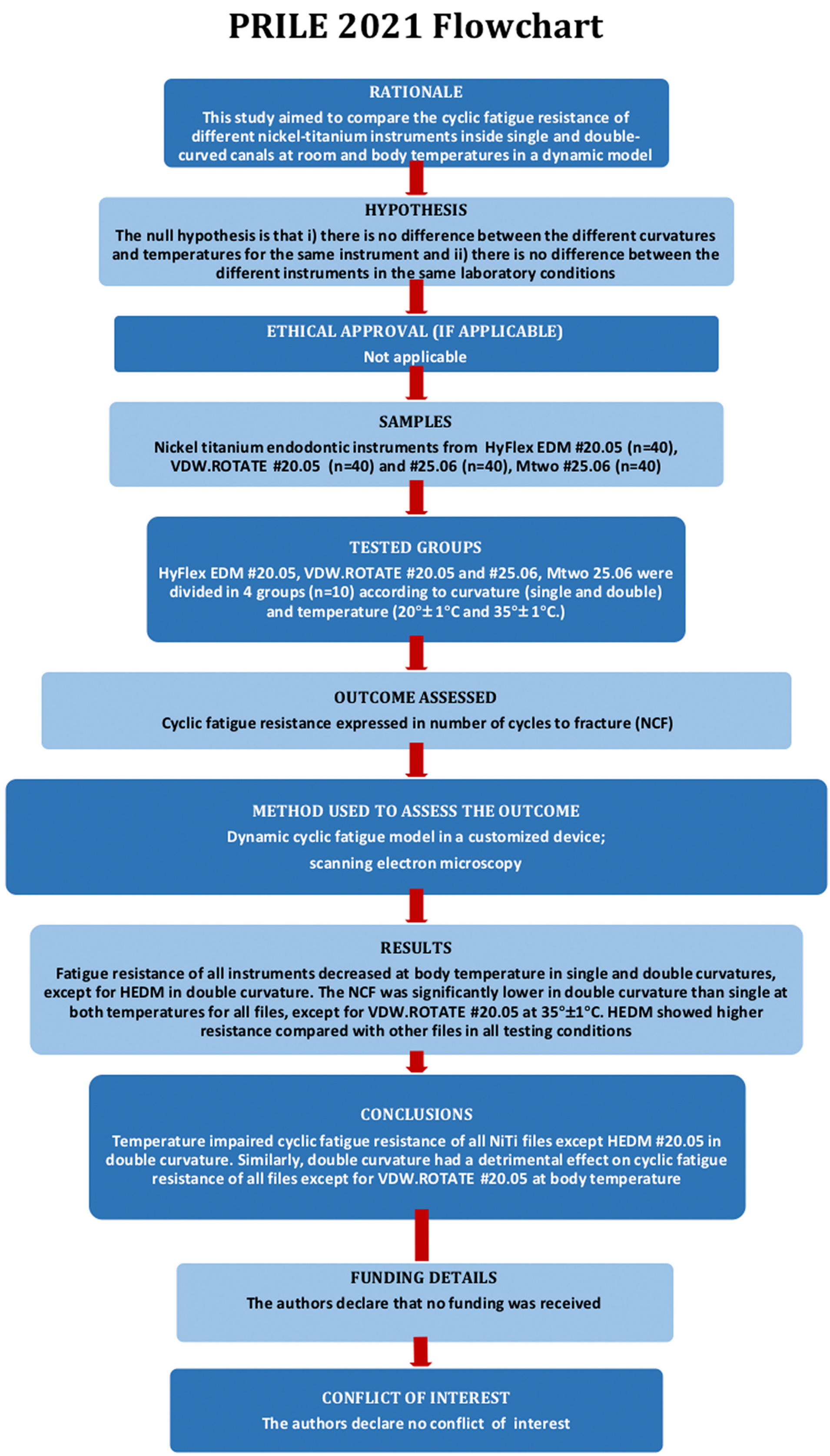

FIGURE 1 PRILE (2021) flowchart [17].

Table 1 shows mean and standard deviation of NCF values for all the files tested in all laboratory conditions. Cyclic fatigue resistance of all instruments significantly decreased at body temperature, both in single and double curvatures ($p < 0.05$), except for HEDM #20.05 for which no significant differences were observed between room

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TABLE 1 Mean ± standard deviation of number of cycles to fracture (NCF) of the tested instruments at room and body temperatures, in single and double curvatures.

	Number of cycles to fracture (NCF)			
	Temperature			
	20°C ± 1°C		35°C ± 1°C	
Instrument	Single curvature	Double curvature	Single curvature	Double curvature
HEDM #20.05	$4892^{a1} \pm 344$	$1508^{b1} \pm 242$	$4136^{c1} \pm 566$	$1285^{b1} \pm 302$
VDW ROTATE #20.05	$2078^{a2} \pm 262$	$881^{b2} \pm 121$	$821^{bc2} \pm 224$	$651^{cd2} \pm 41$
Mtwo #25.06	$962^{a3} \pm 129$	$430^{b3} \pm 79$	$709^{c2} \pm 57$	$308^{d3} \pm 64$
VDW ROTATE #25.06	$1256^{a3} \pm 174$	$607^{b3} \pm 58$	$847^{c2} \pm 121$	$446^{d3} \pm 71$

Note: Different superscript letters indicant significant differences between instruments in the same row ($p < 0.05$). Different superscript numbers indicant significant differences between instruments in the same column ($p < 0.05$).

and body temperatures in double curvature ($p > 0.05$). All instruments exhibited lower NCF in double curvature compared with single at both temperatures ($p < 0.05$), except for VDW.ROTATE #20.05 at 35°C (±1°C) ($p > 0.05$).

Comparing instruments with the same size, overall, HEDM showed the highest cyclic fatigue resistance among the all-tested files ($p < 0.05$). No statistical differences were observed between Mtwo #25.06 and VDW.ROTATE #25.06, both in single and double curvatures, regardless of the temperature ($p > 0.05$). Among the other files, VDW.ROTATE #20.05 reported significantly higher NCF compared with the other files except at 35 ± 1°C, in single curvature, for which no significant difference emerged with the Mtwo #25.06 and VDW.ROTATE #25.06 ($p > 0.05$).

The mean length of fractured fragments showed no significant differences between all-tested files (5 ± 0.1 mm) in single curvature. In the double curvature, the all-tested files fractured first in the second apical curvature and with fractured fragments long 2 ± 0.1 mm.

The fractographic analysis of the instruments' surface exhibited fatigue crack initiation at one or more points. The fracture surface showed areas with fatigue striations and regions with dimpled surface (Figure 2).

DISCUSSION

Hyflex EDM and Mtwo are some of the most used files in clinical practice. VDW.ROTATE files are new instruments, and some studies evaluated their behaviour in static condition [11, 19], but no previous studies have examined their cyclic fatigue resistance in a dynamic model. Dynamic cyclic fatigue test was chosen to better simulate clinical situations [1, 20]. The back-and-forth movement that the instruments perform inside the artificial canal mimics the pecking motion. This permits the distribution of the stresses along the entire surface of the files increasing their fatigue life [21]. Conversely, in the static model, compression and tensile stresses affect a small area of the file reducing the number of cycles to fracture [16]. The dynamic cyclic fatigue tests were conducted using a customised device projected to guarantee standardised and reproducible conditions for the mechanical tests [4, 8, 9]. The correct placement of each file was confirmed by the absence of significant differences in the mean lengths of fractured fragments. Natural extracted teeth were not used because it is challenging to achieve the standardisation and adequate clinical conditions [22]. Several factors are involved in NiTi instrument fracture, some of which are related to file design and other to root canal anatomy, especially double curvature [6, 23]. No studies compared cyclic fatigue resistance of HEDM, VDW.ROTATE and Mtwo at two different temperatures in single and double-curved canals, and few studies evaluated the resistance of NiTi files in S-shaped canals under dynamic conditions [1, 24].

According to the current results, the body temperature had a negative impact on cyclic fatigue resistance of NiTi files both in single and double curvature, as previously reported [7, 25, 26], except for HEDM file #20.05 in double curvature. Topcuoglu et al. [24] compared cyclic fatigue resistance of different NiTi rotary files at room and body temperatures in a S-shaped canal observing that the intracanal temperature caused a significant decrease in fatigue life for all files tested. The HEDM #20.05 exhibited lower NCF at 35 ± 1°C compared with 20° ± 1°C in double curvature without reaching a significant value. This result is probably due to the fact that the HEDM file is more affected by root canal configuration and rotates for a significant lower time in double curvature such that there is no significant difference in NCF between room and body temperatures.

Cyclic fatigue resistance of all instruments tested was significantly lower in double curvature compared with

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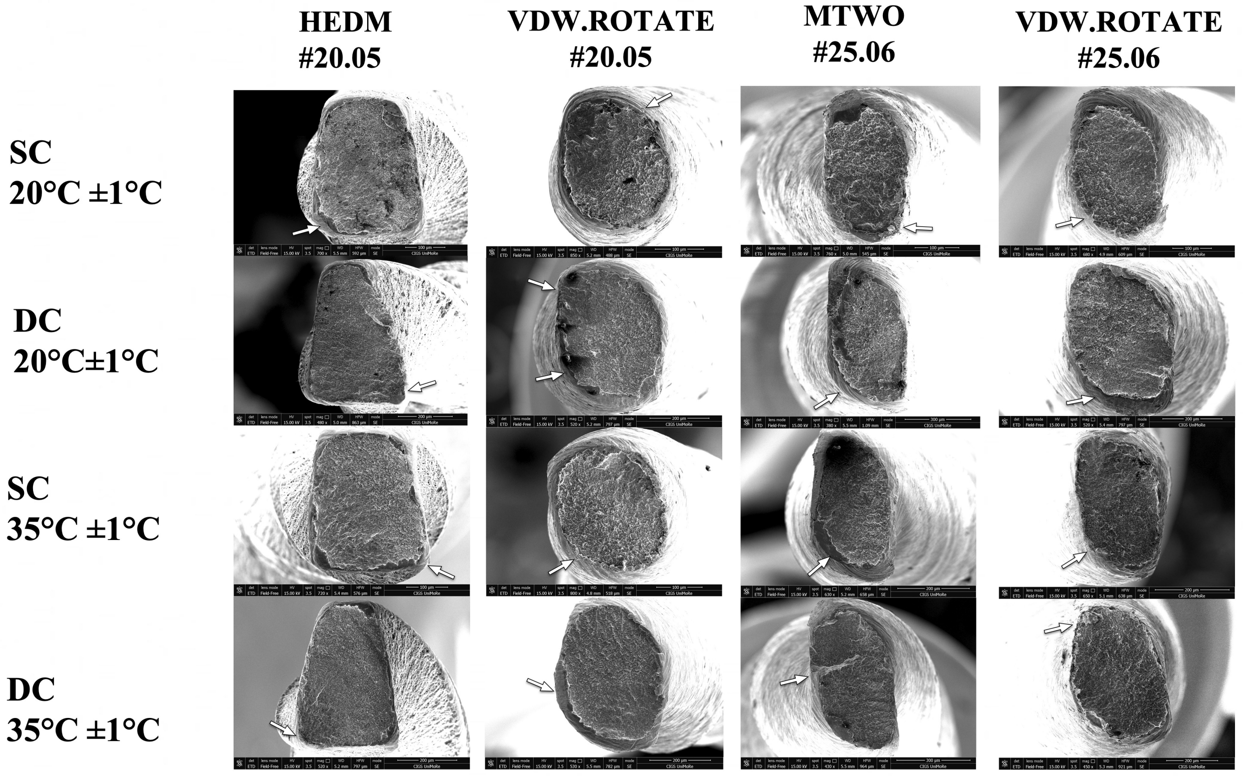

FIGURE 2 Scanning electron micrographs of the fracture surface of HyFlex EDM #20.05, VDW.ROTATE #20.05, Mtwo #25.06 and VDW.ROTATE #25.06 fragments in the axial view (380×−850× magnification) after the cyclic fatigue tests in the single and double curvatures at room (20°C ± 1°C) and body (35° ± 1°C) temperatures. The white arrows identify the origins of the crack. All the fracture surfaces displayed characteristic signs of the fibrous fatigue zone. DC, double curvature; SC, single curvature.

single one, at both temperatures except for VDW.ROTATE #20.05 at body temperature. NiTi files last longer before breaking within simpler root canal anatomies like single curved canals [23] while number of cycles to fracture decreases as the complexity of the intracanal anatomy increases [15, 27, 28]. The different behaviour of VDW. ROTATE #20.05 at body temperature could be explained by it suffering more of an increase in temperature and thus the lower NCFs at body temperature are not sufficient to reach a significant value between single and double curvature. On the basis of these results, the first null hypothesis can be rejected.

The alloy and metallurgical proprieties of NiTi instruments are significantly involved in their cyclic fatigue life; for this reason, new production treatments have been developed to improve their mechanical properties and clinical performance [29, 30]. Among instruments with same size, Hyflex EDM files exhibited higher cyclic fatigue resistance compared with VDW.ROTATE #20.05, inside single and double-curved canals at both temperatures. These findings might be attributed to the benefits of electrical discharge machining procedure applied for the production of Hyflex EDM files [29]. In addition, the higher martensite phase of HEDM probably makes them more flexible and resistant than VDW.ROTATE #20.05 [31] for which no clear information is available about the alloy composition.

No differences were observed between Mtwo and VDW. ROTATE #25.06 in single and double curvature, at both temperatures. Previous studies evaluated cyclic fatigue resistance of VDW.ROTATE #25.06 and Mtwo #25.06 demonstrating that cyclic fatigue resistance of VDW. ROTATE was higher than that of Mtwo under static conditions [14, 32]. The different results of our study are probably due to testing conditions. Indeed, the dynamic model could compensate for the differences in terms of cyclic fatigue resistance between these instruments, allowing a stress distribution along the all-instrument surface [20].

Comparing instruments with different dimensions, #20.05 files showed higher cyclic fatigue resistance than #25.06, in agreement with previous studies reporting that smaller instruments had high flexibility and fatigue resistance [33, 34]. In particular, the HEDM #20.05 reported the highest values of cyclic fatigue resistance. These results are probably due to the advantages of alloy treatment combined with the reduced dimensions of the instrument. Of note, no significant difference emerged between VDW. ROTATE #20.05, Mtwo #25.06 and VDW.ROTATE #25.06 only at body temperature in single curvature probably due to the detrimental effect of increased temperature

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which impacts more VDW.ROTATE #20.05 than #25.06 instruments. Yet, the bigger files suffered more of the temperature increase in double curvature where the stress is major and thus VDW.ROTATE #20.05 maintained significantly higher NCF compared with #25.06 files in double curvature.

No previous studies evaluated cyclic fatigue resistance of VDW.ROTATE and Mtwo under dynamic conditions; therefore, the results of the current study cannot be compared with previous findings. On the basis of the above findings, also the second null hypothesis can be rejected.

All fractures occurred at the apical curve in the double curvature model. This is probably due to the apical curvature being more abrupt, with a radius of 2 mm, while the coronal had a 5-mm radius [23]. The SEM analysis of fractured fragments demonstrated that the crack originated at the edge and propagated until the fatigue striations with the typical dimple pattern (Figure 2).

The study has some limitations. Cyclic fatigue is a complex phenomenon to which several factors contribute simultaneously. These factors include but are not limited to operator experience, anatomical complexities and NiTi instruments tested [35].

Under these laboratory limitations, the findings are clinically relevant because they confirm as different NiTi files can respond differently to anatomical and environmental variations. The clinician should be aware of this and select the best instrument for each clinical condition. Further investigations are needed to confirm these results and investigate the metallurgical characterisation of VDV. ROTATE and other mechanical properties including torsional resistance and cutting efficiency.

CONCLUSIONS

Under the limitations of a laboratory study, temperature affected cyclic fatigue resistance of all NiTi files except for HEDM #20.05 for which no significant difference emerged between room and body temperature in double curvature. Double curvature impaired the cyclic fatigue resistance of all instruments except VDW.ROTATE #20.05 at 35°C for which no significant difference was detected between the two curvatures. The HEDM instrument exhibited the highest cyclic fatigue resistance among the all-tested files.

AUTHOR CONTRIBUTIONS

All authors have contributed significantly and are in agreement with the manuscript. EP and GRMLR contributed to the conceptualisation. GRMLR, MLL, FSC and LG contributed to the data curation. VRR, GRMLR and GC contributed to the formal analysis. GRMLR, MLL and FSC contributed to the investigation. EP, GRMLR and LG contributed to the methodology. EP and LG contributed to the project administration. EP and LG contributed to the resources. GRMLR contributed to the software EP and LG contributed to the supervision. VRR, MLL, FSC and GC contributed to the validation. GRMLR, LG and VRR contributed to the visualisation. GRMLR, MLL and FSC contributed to the roles/writing—original draft. GRMLR, VRR, GC, LG and EP contributed to the writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors deny any conflicts of interest.

ORCID

Giusy Rita Maria La Rosa https://orcid.org/0000-0001-5127-5299

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