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RESEARCH

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Effect of repetitive up-and-down movements on torque/force generation, surface defects and shaping ability of nickel-titanium rotary instruments: an ex vivo study

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Abstract

Background The screw-in effect is a tendency of a nickel-titanium (NiTi) rotary endodontic file to be pulled into the canal, which can result in a sudden increase in stress leading to instrument fracture, and over-instrumentation beyond the apex. To reduce screw-in force, repeated up-and-down movements are recommended to distribute flexural stress during instrumentation, especially in curved and constricted canals. However, there is no consensus on the optimal number of repetitions. Therefore, this study aimed to examine how repeated up-and-down movements at the working length affect torque/force generation, surface defects, and canal shaping ability of JIZAI and TruNatomy instruments.

Methods An original automated root canal instrumentation device was used to prepare canals and to record torque/force changes. The mesial roots of human mandibular molars with approximately 30° of canal curvature were selected through geometric matching using micro-computed tomography. The samples were divided into three groups according to the number of up-and-down movements at the working length (1, 3, and 6 times; $n = 24$ each) and subdivided according to the instruments: JIZAI (#13/0.04 taper, #25/0.04 taper, and #35/0.04 taper) or TruNatomy (#17/0.02 taper, #26/0.04 taper, and #36/0.03 tape) ($n = 12$ each). The design, surface defects, phase transformation temperatures, nickel-titanium ratios, torque, force, shaping ability, and surface deformation were evaluated. Data were analyzed with the Kruskal-Wallis and Dunn's tests ($\alpha = 0.05$).

Results The instruments had different designs and phase transformation temperatures. The 3 and 6 up-and-down movements resulted in a smaller upward force compared to 1 movement ($p < 0.05$). TruNatomy generated significantly less maximum torque, force, and surface wear than JIZAI ($p < 0.05$). However, TruNatomy exhibited a larger canal deviation ($p < 0.05$). No statistical differences in shaping ability were detected between different up-and-down movements.

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Conclusions Under laboratory conditions with JIZAI and TruNatomy, a single up-and-down movement at the working length increased the screw-in force of subsequent instruments in severely curved canals in the single-length instrumentation technique. A single up-and-down movement generated more surface defects on the file when using JIZAI. TruNatomy resulted in less stress generation during instrumentation, while JIZAI better maintained the curvature of root canals.

Keywords Canal centering ability, Microcomputed tomography, Nickel-titanium rotary instrumentation, Screw-in force, Torque, Up-and-down movement

Background

Efficient instrumentation is a crucial step in endodontic procedure as it facilitates thorough disinfection and hermetic sealing of the root canal [1]. Nickel-titanium (NiTi) rotary instruments have been used increasingly for instrumentation due to increased flexibility and reduction of preparation errors than stainless steel hand instruments but they also pose a greater risk of fracture [2]. The screw-in effect is one of the most significant causes of NiTi rotary instrument fracture in clinical practice. It is a tendency of an instrument to be pulled into the canal, leading to a sudden increase in stress, resulting in torsional fracture and over-instrumentation beyond the apical foramen [3]. Therefore, instrumentation techniques and mechanical characteristics of NiTi rotary instruments have also been continuously improved to reduce screw-in force and fracture [4].

In recent years, the single-length instrumentation technique has been recommended for several NiTi instruments. Single-length instrumentation refers to a technique where a sequence of files is used to prepare the canal to the full working length from the beginning [5, 6]. This approach simplifies the procedure by reducing the need to change the working length of the instruments during the different stages of cleaning and shaping. In this technique, NiTi files are designed to progressively enlarge the canal at the same working length, preventing coronal over-flaring and reducing the risk of procedural errors [5]. However, it can exert more stress on the instrument and root canal dentin during shaping compared to the traditional crown-down technique [7, 8]. Therefore, every instrumentation in each sequence in the single-length technique should sufficiently create a smooth radicular canal to minimize screw-in force and the risk of instrument fracture during subsequent instrumentation [9].

The JIZAI rotary system (MANI, Utsunomiya, Japan) is a recently introduced single-length NiTi rotary system, which has a cross-sectional shape of quasi-rectangular with a radial land and consists of a mixture of martensite or R-phase and austenite at room temperature [5, 10]. The JIZAI instrument has similar superelasticity and number of cycles to fracture as the HyFlex EDM instrument [5]. A comparison between JIZAI instruments with a radial land and those without a radial land also showed that the instrument with the radial land significantly reduced the screw-in forces [11].

The TruNatomy rotary system (Dentsply Sirona, Ballaigues, Switzerland) is another contemporary single-length NiTi rotary system made of a 0.8 mm diameter wire with a unique heat treatment [12]. It has an eccentric parallelogram cross-section with a variable regressive taper that can preserve radicular dentin during root canal instrumentation [13]. Due to its unique characteristics and heat treatment, the TruNatomy rotary instrument has been reported to exhibit high flexibility and efficient shaping, while increasing the fatigue resistance of the instrument [14].

When these single-length instruments are used in severely curved and constricted canals, the presence of apical sclerotic dentin causes an abrupt increase in stress accumulation and increases the risk of file fracture in the apical region [15]. Repeated up-and-down movements may help to distribute stress concentration and to smoothly advance the file into the apex. [9]. A sufficiently sized canal preparation allows subsequent larger files to encounter less torsional stress and move easily to the working length with minimal resistance in severely curved canals. On the contrary, undersized preparation of the canal could result in an increased risk of stress accumulation and fracture on the subsequent file or a master cone that does not reach the full working length, whereas overpreparation could compromise the hermetic seal of the obturation [16, 17]. Therefore, it is essential to determine the most suitable number of up-and-down movements at the working length with minimum frequency.

A previous study reported that increasing the number of up-and-down movements increases the canal volume and minor diameters of long oval-shape canals [18]. In another study, the number of up-and-down movements of glide path preparation did not result in a remarkable increase in the apical preparation diameter [9]. Although the number of up-and-down movements on apical preparation size has been studied, knowledge of its effect on screw-in force generation of subsequent instruments is still lacking.

The purpose of this analysis was to study the impact of different numbers of up-and-down movements from various aspects such as stress generation during rotary instrumentation, shaping ability of root canal, the incidence of postoperative defects on the surface of files by using JIZAI and TruNatomy instruments. To the best of our understanding, this is the very first study to analyze the impact of repetitive up-and-down movements on screw-in force generation using an automatic instrumentation device. The null hypotheses for this analysis were as follows: (1) there are no differences in design and metallurgy between the tested instruments; and (2) the frequency of up-and-down movements at the working length does not have any impact on the torque/force generation, surface defects and shaping ability of the tested NiTi rotary systems.

Methods

A total of 432 new 25-mm NiTi instruments ($n=12$ per group) from JIZAI [Glider (size 13, 0.04 taper), JIZAI I (size 25, 0.04 taper), and JIZAI III (size 35, 0.04 taper)] and TruNatomy [Glider (size 17, 0.02 variable(v) taper), Prime (size 26, 0.04v taper), and Medium (size 36, 0.03v taper)] were tested for their torque/force generation and canal preparation ability (changes in volume, surface area, canal centering ratios, apical canal deviation and percentages of untouched area) in canals of extracted molar teeth. A further 42 instruments ($n=7$, each) were used to compare the geometric designs and metallurgical characteristics. The overview of the experiment is outlined in Fig. 1.

Design of the instrument

The files were inspected with a digital microscope (VH-8000; Keyence, Osaka, Japan) at a magnification of ×20, and analysis was performed using ImageJ v1.50e software (Laboratory for Optical and Computational Instrumentation, Madison, WI, USA). The assessment included measuring the number of blades in the active part of the instrument and measuring the helix angle (the blades near the shaft in triplicate). Subsequently, the same instrument was examined under a scanning electron microscope (SEM) (JSM-7900 F; JEOL, Akishima, Japan)

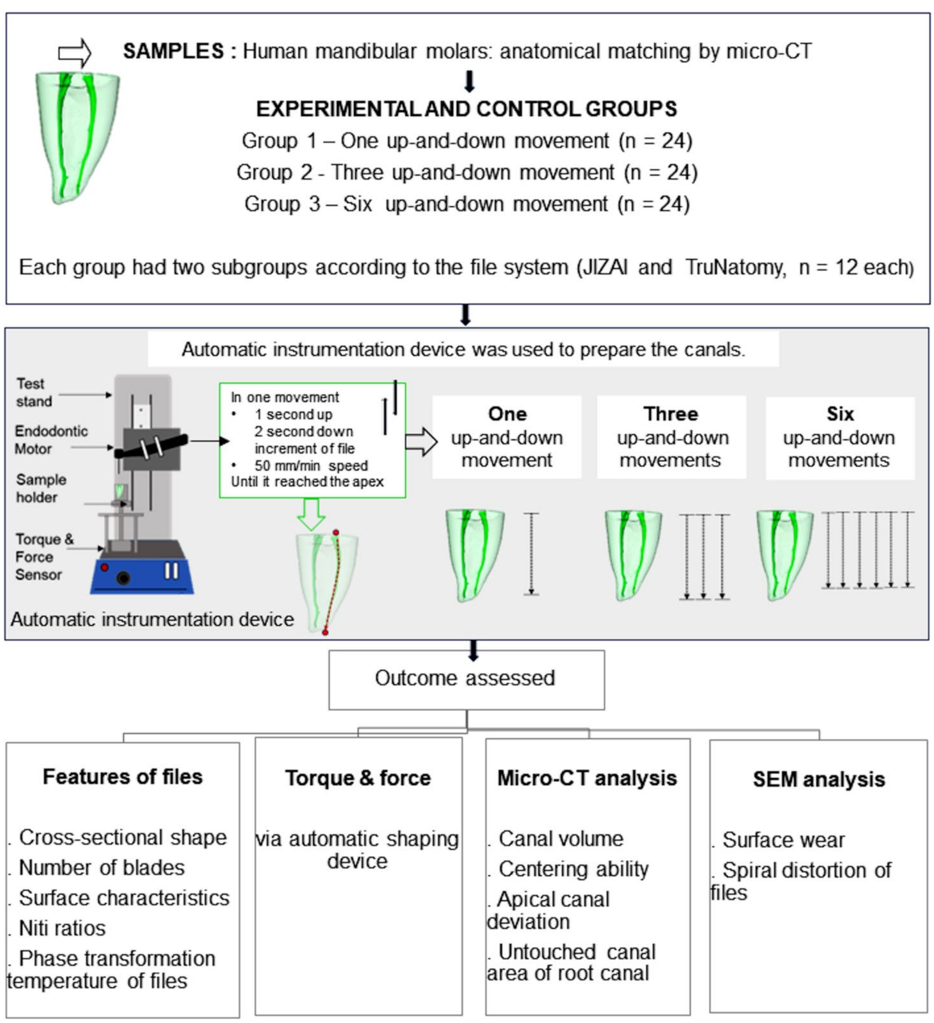

Fig. 1 Flow of the procedure

at 15 kV. Images were taken at ×100, ×150, and ×500 magnification to assess the blade geometry, cross-section, tip (active or non-active), surface finishing, and surface wear.

Metallurgical characterization

The EDS/SEM analysis (JSM-7900 F; JEOL) was performed on the surface of six instruments of each type at a working distance of 10 mm and a beam voltage of 15.0 kV.

The differential scanning calorimetry (DSC) analysis was conducted with three instruments of each brand. The working part of the instrument was cut into portions of 3 mm length and placed in an aluminum case, with a total weight of 20 mg. These cases were then placed in a DSC device (DSCe60; Shimadzu, Kyoto, Japan) together with a vacant aluminum case, which served as a reference. The experimental setup involved filling the chamber with argon gas and using liquid nitrogen as a coolant, with a cooling/heating rate of 0.33 °C/s. The thermal cycles were conducted by initially raising the temperature from 20 to 100 °C, then lowering it to −100 °C to record the cooling chart, and then raising it to 100 °C to record the heating chart. The start and finish temperature of martensitic transformation (M*s* and M*f*, respectively), the R-phase transformation (R*s* and R*f*, respectively), and the reverse transformation (A*s* and A*f*, respectively) were analyzed by determining the points of intersection between the maximum lambda gradient line and the baseline data.

Torque, force and shaping ability

This study was approved by the Dental Research Ethics Committee of Tokyo Medical and Dental University (number D2014-033-03). A total of 120 human mandibular molars, extracted for reasons unrelated to this study, were collected with informed consent from the donors. The teeth were stored in 100% relative humidity at 5 °C. After the distal root and crown were removed, the mesial root was measured and cut to a length of 12±1 mm. It was then firmly fixed on a specially made-mold.

The teeth were scanned prior to preparation using a micro-CT device (inspeXio SMX-100CTPlus; Shimadzu) with specifications of 70 kV, 100 mA, a rotational pace of 0.5° through 360°, 1.0 mm thick aluminum filter, and a volumetric resolution of 0.03 mm. The images were visualized using three-dimensional imaging software (Amira 5.4.4; Visage Imaging, Berlin, Germany) with consistent parameters which resulted in 400–500 greyscale transaxial slices per sample. The buccolingual and mesiodistal diameters of the root canal at 5 mm prior to the apical foramen were measured. The cross-sectional configuration was determined by comparing the buccolingual and mesiodistal measurement ratios. The canals were classified as oval, long oval, or flattened, based on their aspect ratio of ≤2, 2 to 4, and ≥4, respectively [19].

The quantity of sample was identified using G*Power 3.1.7 software (Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany) with an alpha level of 0.05, a beta power of 85%, and an effect size of 0.6, as guided by the outcomes of prior investigation [20]. This study utilized twelve samples for each group since a minimal sample size of 10 per group was specified. To ensure anatomical homogeneity, the samples were standardized according to criteria such as volume, surface area, degree of curvature (approximately 30°), cross-sectional diameter (buccolingual and mesiodistal diameter of the root canal), internal morphology (oval canal), and canal length [21]. From this initial sampling, 72 mesial canals were sorted out and assigned to one of the six test groups ($n=12$ each). There were no statistical differences in canal geometric criteria between the test groups (Table 1). The canals were subjected to random categorization (http://www.random.org/), resulting in three groups in accordance with the frequency of up-and-down movements at working length (1, 3, or 6 times) and further subdivided into two groups in accordance with the instrument system (JIZAI or TruNatomy).

An original automated canal instrumentation device [8, 22–24] was used (Fig. 1), which consisted of an endodontic motor (J Morita), a speed adjustable bench (MX2-500 N, Imada, Toyohashi, Japan) enabling up-and-down movement, and sensing apparatus for torque/force measurement. The device was structured to deliver

Table 1 Morphometric values of root canals before root canal instrumentation

	One up-and-down movement		Three up-and-down movements		Six up-and-down movements	
	JIZAI	TruNatomy	JIZAI	TruNatomy	JIZAI	TruNatomy
Volume (mm^3)	0.8 (0.4-1)	0.81 (0.57–1.2)	0.69 (0.5–1.4)	0.78 (0.3–1.2)	0.69 (0.42–1.6)	0.65 (0.4–1.7)
Surface area changes (mm^2)	35.9 (21.9–47.6)	36.6 (29.7–55.8)	33.5 (26.9–49.9)	35.9 (31.2–44.7)	32.7 (20.3–50.4)	29.2 (26.2–57.9)
Angle of curvature (degrees)	32.5 (25.7–35.3)	32.2 (24.9–33.5)	33.5 (25.8–33.4)	30.1 (24.3–35)	28.9 (27.7–32.3)	30.1 (28.6–34.3)
Buccolingual cross-sectional diameter (mm)	0.45 (0.2–0.9)	0.48 (0.3–0.9)	0.55 (0.4–0.9)	0.55 (0.35–1)	0.39 (0.3–0.8)	0.41 (0.3–0.8)
Mesiodistal cross-sectional diameter (mm)	0.36 (0.2–0.6)	0.38 (0.3–0.5)	0.39 (0.29–0.6)	0.45 (0.3–0.5)	0.37 (0.2–0.7)	0.39 (0.2–0.6)
Aspect ratio	1.2 (0.9–2)	1.5 (1–2.02)	1.1 (0.91–1.9)	1.24 (1.1–1.9)	1.29 (1.07–1–2)	1.3 (0.95–1.8)

Values are median (minimum–maximum). No significant differences were observed among the groups according to the Kruskal–Wallis test ($p>0.05$)

an artificial up-and-down movement to simulate a manual shaping procedure (2-second descent followed by a 1-second ascent at 50 mm/min, regardless of the stress applied).

The same instrumentation protocol was used for each group. This included verifying the patency of the root canal and establishing the working length of 1 mm from the apical foramen with a 10 K file (Ready Steel; Dentsply Sirona). The canals were then instrumented using a single-length technique, with the JIZAI and TruNatomy instruments. The glide path preparation was performed with the JIZAI Glider (size 13, 0.04 taper) and the TruNatomy Glider (size 17, 0.02v taper). The first shaping was conducted with the JIZAI I (size 25, 0.04 taper) and the TruNatomy Prime (size 26, 0.04v taper), followed by the second shaping with the JIZAI III (size 35, 0.04 taper) and the TruNatomy Medium (size 36, 0.03v taper). The instruments were operated at 500 rpm and 1.5 N·cm. Each specimen was instrumented according to repeated up-and-down movements of 1, 3, or 6 times at the working length. The upward/downward force and torque values during the root canal preparation procedure were registered. The canal was disregarded from additional examination if an instrument fractured.

A total of 10 mL of 2.5% sodium hypochlorite (Takasugi Pharmaceutical, Fukuoka, Japan) was applied by gently moving a 30-G needle (Ultradent, South Jordan, Utah, USA). Additionally, a lubricant (RC-Prep: Premier Dental Products, Norristown, PA, USA) was utilized in the process. Three mL of 17% ethylenediaminetetraacetic acid (BSA Sakurai, Nagoya, Japan), 3.0 mL of 3% sodium hypochlorite, and 2.0 mL of saline solution (Otsuka Pharmaceutical, Tokushima, Japan) were applied following completion of the instrumentation. After the moisture in the canal was absorbed with paper points (Dentsply Sirona), the samples were rescanned, and micro-CT analysis was carried out as detailed previously.

The alteration in canal volume and surface area was determined by calculating the difference between the values measured before and after instrumentation (Fig. 2). The datasets prior to the instrumentation were overlayed onto datasets taken after instrumentation using the Affine Registration algorithm in the Amira 5.4.4 software (Visage Imaging). Four transaxial slides at one, three, five, and seven millimeters from the apical foramen were used to calculate the centering ratio: (the width of removed dentin in mesial direction − the width of removed dentin in distal direction)/ post-treatment canal width [20].

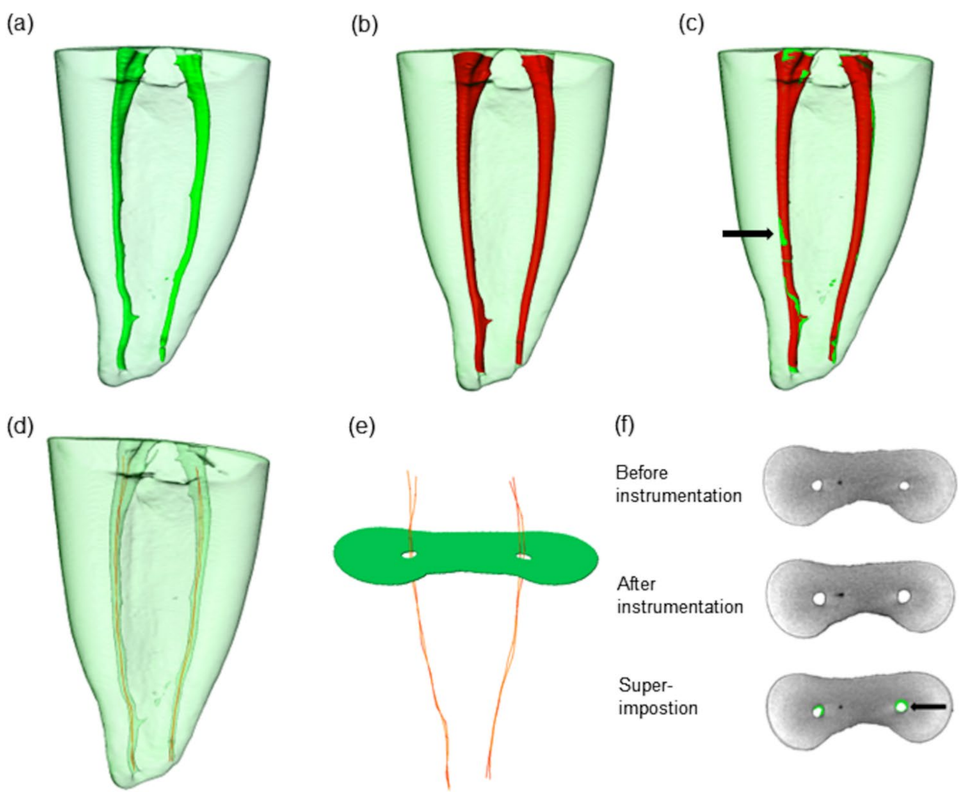

Fig. 2 (**a–c**) Three-dimensional images of the mesiobuccal and mesiolingual canals before instrumentation (**a**), after instrumentation (**b**) and after superimposition (**c**) in a mandibular molar. **(c)** The black arrow indicates the uninstrumented canal area (in green), and the red area indicates the instrumented canal area. (**d**) The centroid line inside the root canal. (**e**) Illustrative image showing the shift of the central canal axis of both the mesiobuccal and mesiolingual canals of the mandibular molar. (**f**) Two-dimensional cross-sectional axial images before instrumentation, after instrumentation, and after superimposition. The black arrow indicates the canal before instrumentation (white) and canal after instrumentation (green) (**f**)

A better centering ability is indicated by scales that are close to 0. The untouched area was computed by: (number of static voxels × 100) / number of surface voxels [21]. Static voxels refer to the voxels that stayed in the same spot on the canal surface prior to as well as following the shaping procedure.

The apical canal deviation was calculated using the multi-dimensional coordinates of the x, y, and z axes. The geometric center of the apical canal axis was determined at 0.3 mm intervals, both pre- and post-canal preparation, over a 3 mm distance from the apex. The centroid line (Fig. 2e) was created by connecting the coordinates along the vertical axis and apical canal deviation (D) was calculated by the equation [25]:

$$D^2 = (x1 - x2)^2 + (y1 - y2)^2 + (z1 - z2)^2$$

SEM analysis of surface defects

Following fifteen minutes of ultrasonic rinsing, SEM photographs of the utilized files were taken at ×500 and ×1500 magnification to assess surface wear such as microcracks, blunt cutting edges, and disruption of the cutting edges. The evaluation was determined as described in a previous article [26] with adjustments as follows: Score 1, no wear on the active portion of the blade; Score 2, one to five areas of wear on the active portion of the blade; and Score 3, more than five areas of wear on the active portion of the blade [23].

The analysis was performed by two evaluators, with Cohen's kappa intra-rater reliability of 0.8 and 0.79 and an inter-rater reliability of 0.79. The investigators were concealed from the instrumentation methodology.

Statistical analysis

All the statistical analysis was performed using SPSS software (v26.0; IBM, Armonk, NY, USA). Kolmogorov-Smirnov and Shapiro-Wilk tests were used to assess whether the data had a normally distributed population. The Kruskal-Wallis test with post-hoc Dunn's test was conducted for statistical analysis of the morphometric values of the root canals before instrumentation, torque/force values, canal volume changes, and canal centering ratios. A significant value of 0.05 was set.

Results

Table 1 shows the morphometric values (minimum-maximum) of the root canals before root canal instrumentation. No statistical differences were noted between the frequencies of up-and-down movements at working length (1, 3, or 6 times) or between the subgroups of the instrument systems (JIZAI or TruNatomy), as indicated by the Kruskal-Wallis test ($p > 0.05$).

Design

Figure 3 illustrates the SEM images of the evaluated instruments while Table 2 presents a summary of the design analyses. The JIZAI glider has a triangular outline with a radial land, JIZAI I and III feature quasi-rectangular cross-section with a radial land (Fig. 3a), while TruNatomy has an off-centered parallelogram cross-sectional shape (Fig. 3a). The blade count and helical pitch angle were different between the two instruments, with the TruNatomy instrument having fewer blade numbers and angles (Table 2). The SEM analysis of the surface showed that the JIZAI instrument had porous parallel marks (Fig. 3b), while the TruNatomy instrument had milling horizontal strokes on the surface of the blade (Fig. 3g). The tips of the JIZAI instrument had bullet-like shape while the tips of the TruNatomy instrument were flat (Fig. 3a). The tip cannot be described as active, and their transition angles were also varied. Upon microscopic and optical examination, neither instrument showed any significant flaws or deformations.

Metallurgy

Energy-dispersive X-ray spectroscopy (EDS) tests showed a similar ratio of nickel/titanium composition in instruments with no additional metallic element (Table 2).

JIZAI and TruNatomy instruments exhibited two exothermic peaks at cooling, indicating R-phase transformation followed by martensitic transformation. The R*s* and R*f* of the JIZAI instrument (25–28 °C and 13–15.6 °C, respectively) were higher than those of the TruNatomy instrument (15.9–19 °C and 8.1–10.5 °C, respectively) (Fig. 4). At heating, both instruments exhibited a single peak corresponding to the reverse transformation. The A*f* of the JIZAI instrument (35.4–42 °C) was higher than that of the TruNatomy instrument (23.8–26.5 °C).

Torque and force

The TruNatomy instrument generated significantly lower downward force than the JIZAI instrument during the first and second shaping (Fig. 5a, b), as well as lesser upward force (Fig. 5d) and torque (Fig. 5f) during the second shaping ($p < 0.05$). However, the upward force of the TruNatomy instrument was greater than that of the JIZAI instrument during the first shaping procedure (Fig. 5c; $p < 0.05$).

Increasing the frequency of up-and-down movements at the working length resulted in a significant reduction in upward force ($p < 0.05$), using both JIZAI and TruNatomy instruments (Fig. 5c and d). Specifically, 6 up-and-down movements resulted in a smaller upward force, followed by 3 and 1 up-and-down movements when using the JIZAI I instrument (Fig. 5c). Additionally, 6 up-and-down movements generated significantly smaller

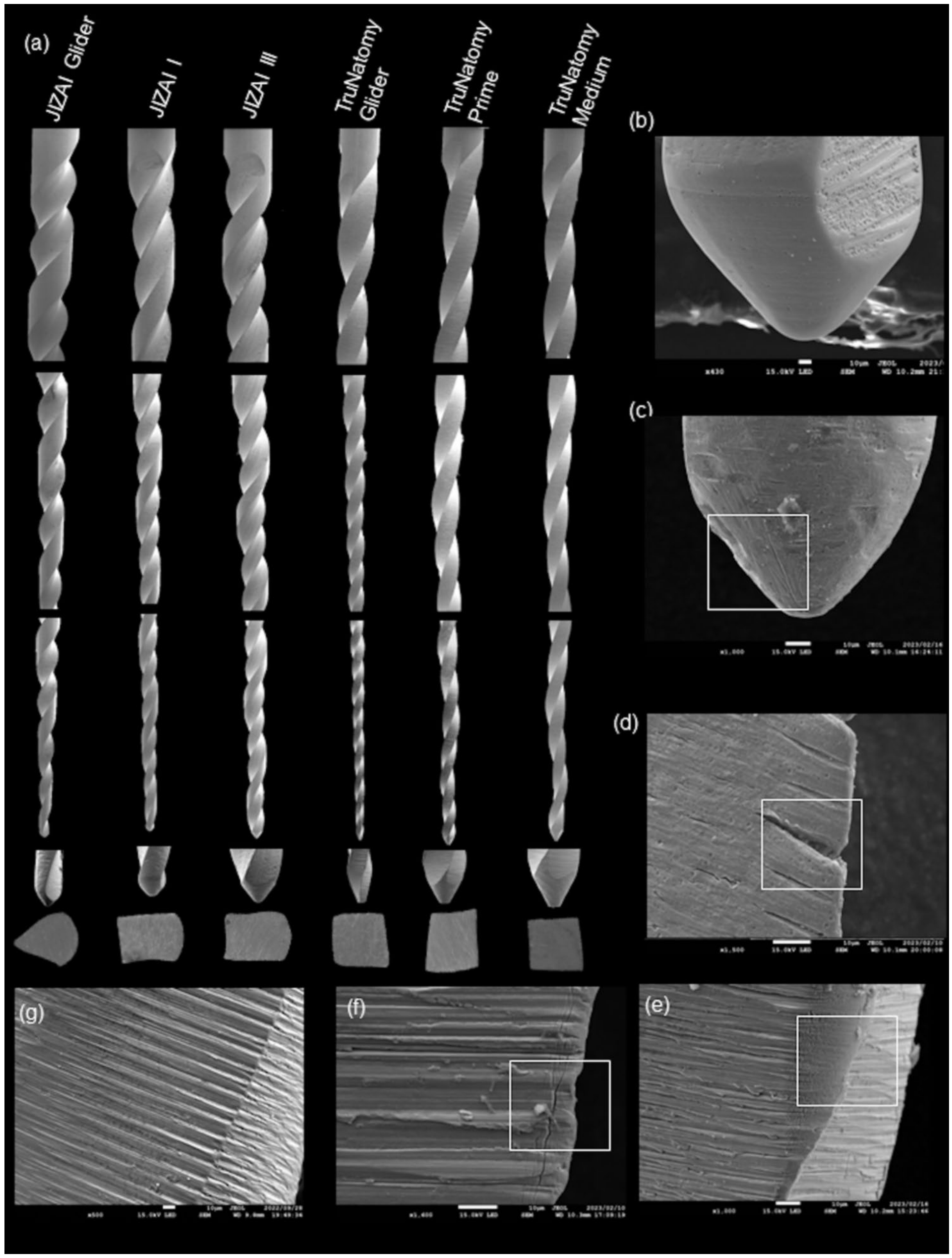

Fig. 3 Scanning electron microscopy images of the tested instruments showing (**a**) the active portions of the blade (×20) and various tip configuration (×100), their cross-sectional design (×150). The JIZAI glider has a triangular cross-section with radial land, JIZAI I and III feature quasi-rectangular cross-sections with radial land. TruNatomy has an off-centered parallelogram cross-sectional shape. The tips of the instruments have various configurations and transition angles (**a**). The unused JIZAI instrument with porous parallel marks (**b**), the used JIZAI with grooves (white box) (**c**), the used JIZAI with horizontal microcracks on the cutting edge (white box) (**d**), the used TruNatomy with blunt cutting edge (white box) (**e**), the used TruNatomy with vertical microcracks on the cutting edge (white box) (**f**) and the unused TruNatomy with horizontal marks from the grinding manufacturing process (**g**), Scale bars = 10 μm (**b**, **g**)

upward force than 1 up-and-down movement with JIZAI III and TruNatomy Medium instrument (Fig. 5d).

Figure 6 shows the typical torque and force patterns during the sequential order of the first, second, and third up-and-down movements of the same instrument: the JIZAI I (size 25, 0.04 taper) instrument (Fig. 6a) and the TruNatomy Prime (size 26, 0.04 taper) (Fig. 6b). The apical force in the negative domain increased intermittently, while the torque values simultaneously increased in the positive region. This pattern of torque and force changes is defined as screw-in forces. The screw-in forces and torque/force values decreased significantly in the second and third sequences of up-and-down movements.

Table 2 Design analysis (minimum–maximum) and Ni/Ti composition of the instruments

System	n	Number of blades	Helix angle (degrees)	Ni%	Ti%	Defects or deformation
JIZAI Glider	6	25	40 (36.9–41.8)	56.0	43.9	0
JIZAI I	6	27	36 (34.4–37.6)	56.3	43.7	0
JIZAI III	6	26	38.7 (36.3–39.6)	56.3	43.7	0
TruNatomy Glider	6	24	24.3 (23.5–25.5)	53.9	46.1	0
TruNatomy Prime	6	18	21.8 (20.7–24)	53.6	46.4	0
TruNatomy Medium	6	16	21.4 (20.5–23.3)	52.9	47.0	0

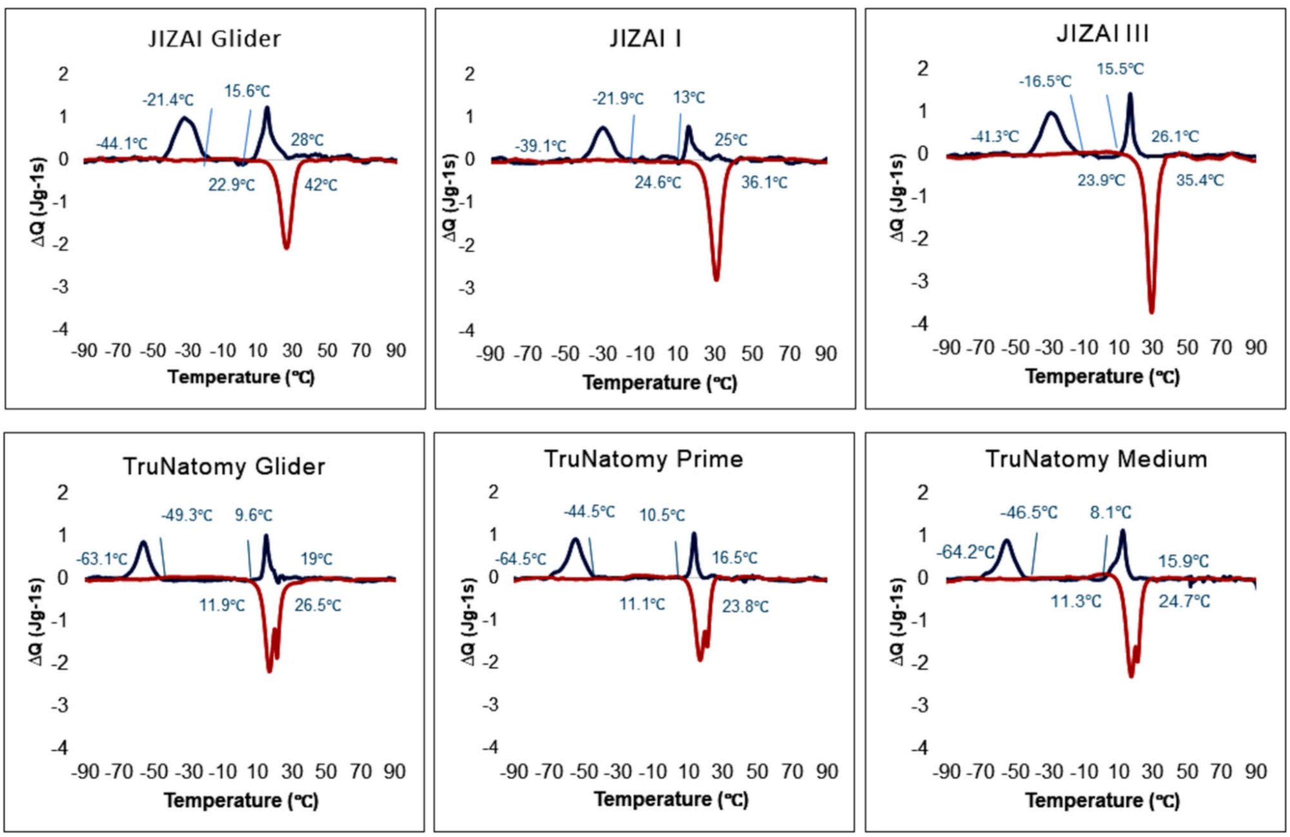

Fig. 4 Typical differential scanning calorimetry curves for each instrument (JIZAI Glider, JIZAI I, JIZAI III, TruNatomy Glider, TruNatomy Prime, and TruNatomy Medium). The blue line on the top is reading from right to left and corresponds to the cooling curve and highlights the R-phase start (R*s*) and finish (R*f*) and martensitic start (M*s*) and finish (M*f*) temperatures. The red line on the bottom is reading from left to right and corresponds to the heating curves showing the austenitic start (A*s*) and finish (A*f*) temperatures

Surface defects

As shown in Fig. 7a-c, TruNatomy produced significantly fewer surface defects than JIZAI after glide path preparation and first shaping. A single up-and-down movement also resulted in more surface wear on the file when using JIZAI instrument (Fig. 7b). The SEM evaluation of the JIZAI and TruNatomy instruments after instrumentation revealed surface wears such as grooves (Fig. 3c), horizontal microcracks on the cutting edge (Fig. 3d), blunt cutting edge (Fig. 3e) and vertical microcracks on the cutting edge (Fig. 3f).

Shaping ability

There were no statistical differences in the changes in volume, surface area, unprepared canal areas, centering ratios (Table 3), and apical canal deviation (Fig. 7d), between the different up-and-down movements. However, the TruNatomy instrument resulted in more apical canal deviation than the JIZAI instrument (Fig. 7d). TruNatomy also generated significantly higher centering ratios (i.e., more deviation) at 5 and 7 mm compared to the JIZAI instrument after 3 and 6 up-and-down movements ($p<0.05$) (Table 3).

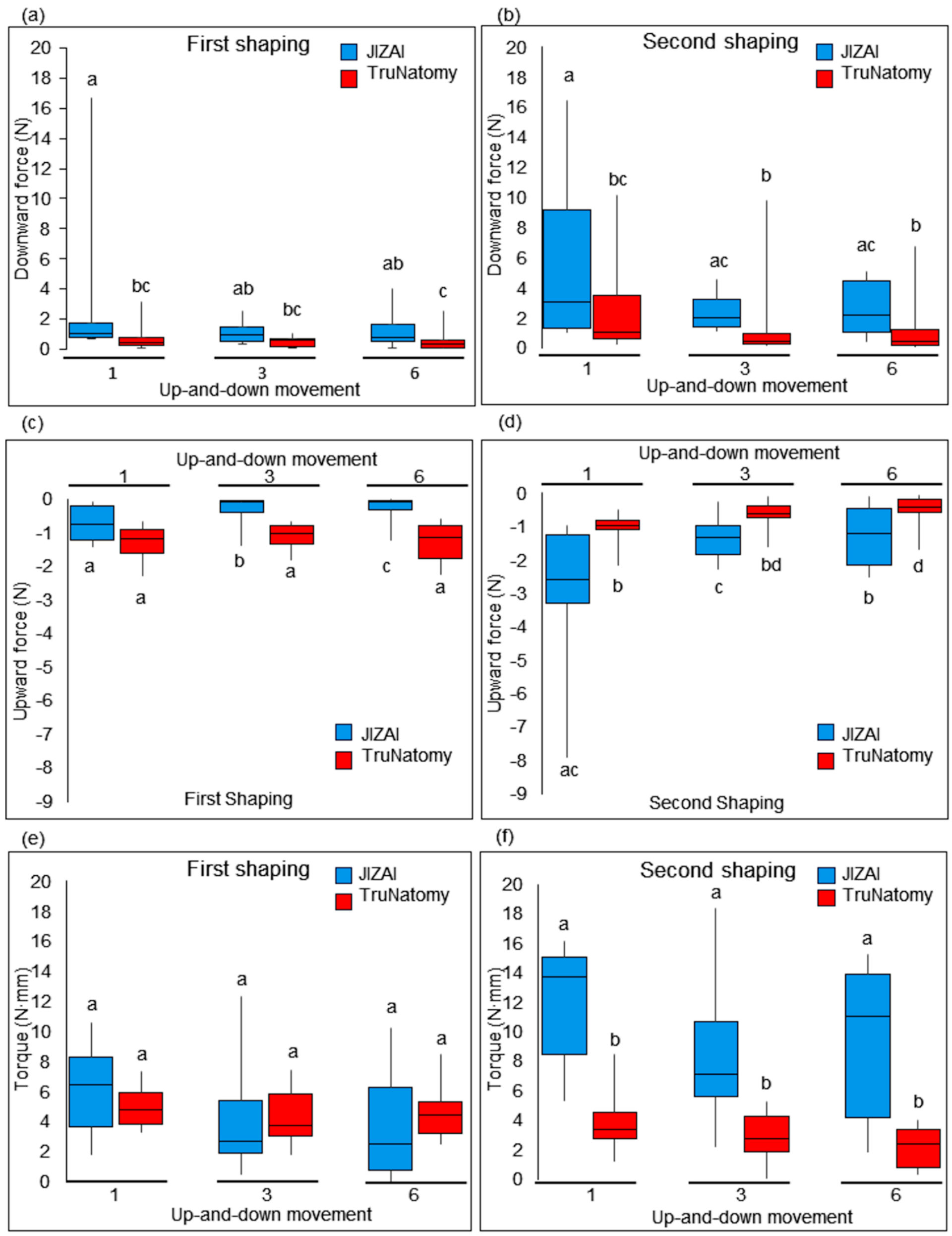

Fig. 5 Maximum, the 75% percentile, median, 25% percentile, and minimum values of (**a**, **b**) downward force, (**c**, **d**) upward force, and **(e**, **f)** torque of first shaping (**a**, **c**, **e**) and second shaping (**b**, **d**, **f**). Different small letters in a panel represent a statistical significance between the tested groups as determined by the Kruskal-Wallis test ($p < 0.05$)

Discussion

The results of the present study showed differences in design, metallurgy, torque/force generation, apical canal deviation, and surface defects between the JIZAI and TruNatomy instruments. Moreover, a single up-and-down movement increases the stress generation and surface wear on the file compared to the 3 or 6 up-and-down movements in severely curved canals in the single-length instrumentation technique. Therefore, the null hypotheses were rejected.

To better understand the performance of JIZAI and TruNatomy, we compared both their geometric and metallurgical features. The geometric configuration (numbers of blades, helical pitch, surface deformity, cross-section, and tip structure) was examined using stereomicroscope and SEM, and the composition was examined using EDS/SEM. DSC measured their phase transformation temperatures, and their canal preparation ability in extracted teeth was analyzed by micro-computed tomography. All the tests were undertaken as specified by universal specifications (ASTM International

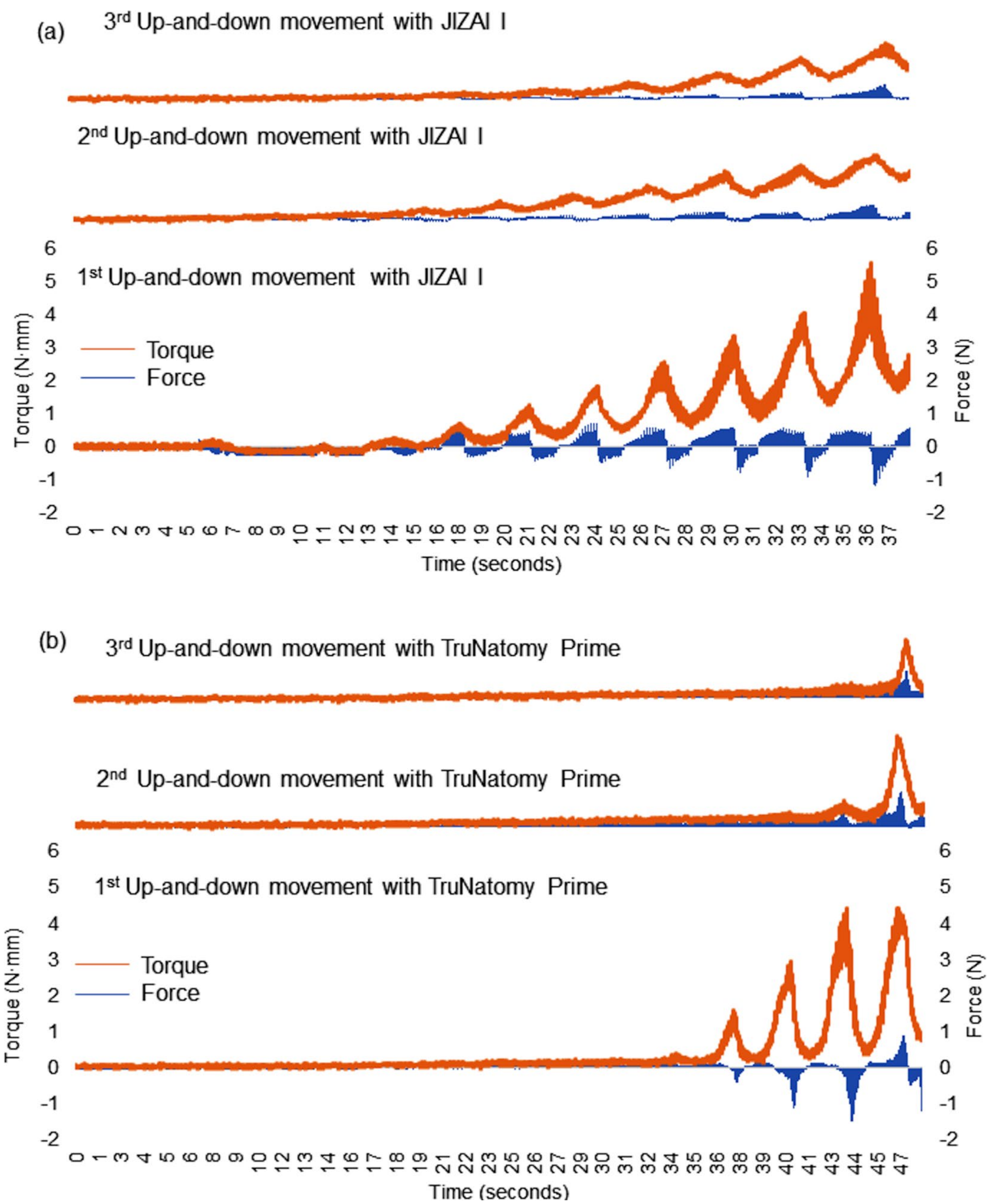

Fig. 6 Representative images illustrating the torque and force patterns during the sequential order of first, second, and third up-and-down movements of the first shaping instrument at the same working length. (**a**) JIZAI I (size 25, 0.04 taper) instrument and (**b**) TruNatomy Prime (size 26, 0.04v taper) instrument

2004, ISO 3630–3631:2008) or reliable and recognized procedures [27, 28].

Additionally, we demonstrated the stress generation on the file from various perspectives by strictly controlling the standardization of the tested parameters. An advanced automated root canal instrumentation device was employed in the current study to achieve a reproducible analysis of torque and force changes without the need for manual preparation. Axial forces can be influenced not only by the operating person [29] but also by the mass of the handpiece [20]. Therefore, handpiece, motor, and instrumentation settings were standardized. As canal structure can significantly affect the outcome of root canal preparation [30], the root canal configuration parameters were determined through preoperative scans to ensure the homogeneity of the samples [31]. Severely curved and oval-shaped canals were selected in this study to achieve the research objective of determining the minimal optimal number of up-and-down movements for severely curved canals [21].

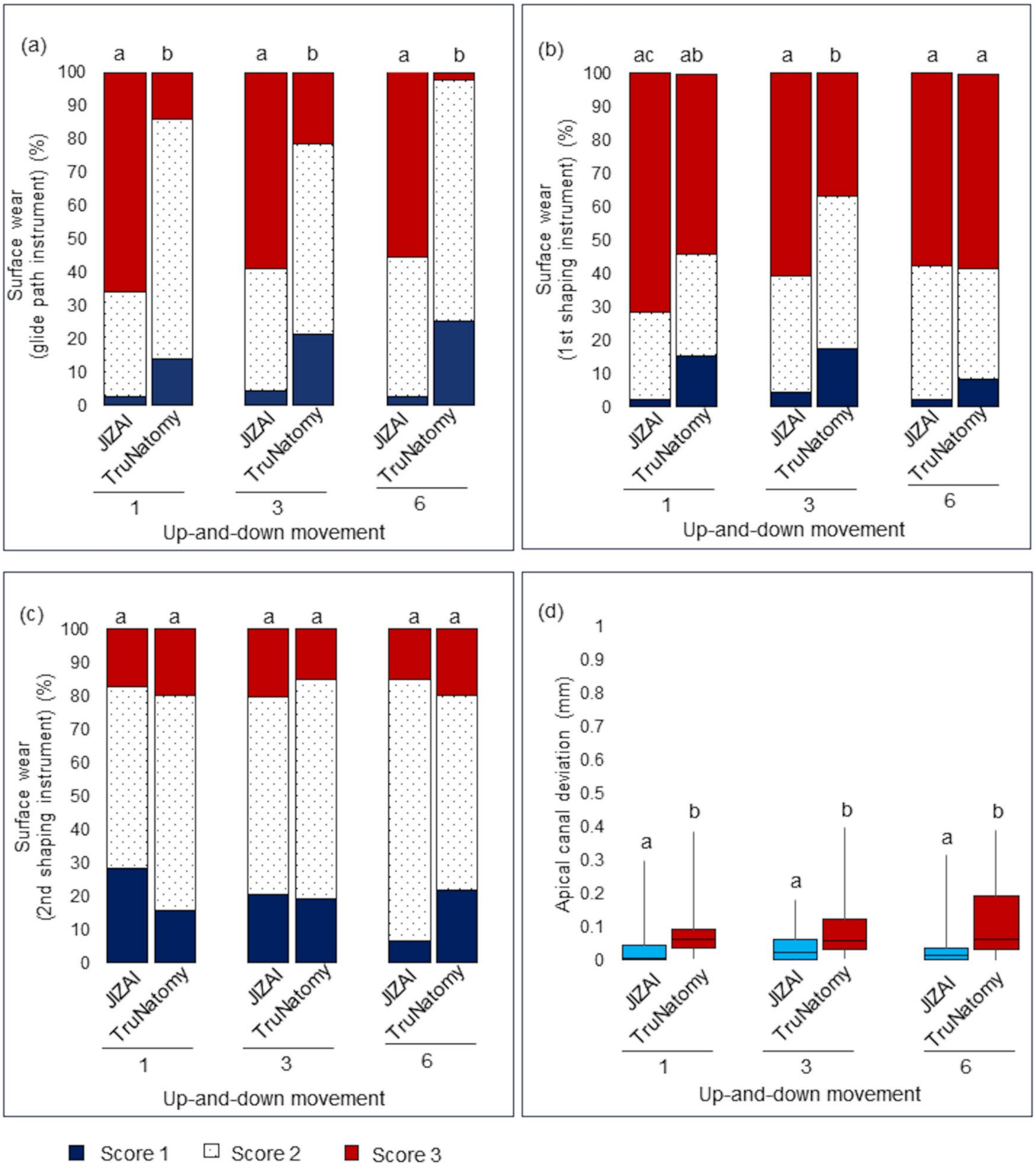

Fig. 7 (**a**–**c**) Percent distribution of surface wear scores after glide path preparation (**a**), first shaping (**b**), and second shaping (**c**). (**d**) Maximum, 75% percentile, median, 25% percentile, and minimum values of apical canal deviation. Different small letters in a panel represent a statistical significance between the tested groups as determined by the Kruskal-Wallis test ($p < 0.05$)

According to the findings, the TruNatomy instrument exhibited significantly smaller values for force, torque, and fewer surface defects than the JIZAI instrument. The features of the TruNatomy instrument – such as regressive taper, the off-center parallelogram cross-section, and the smaller cored diameter wire – could be responsible for the results [28, 32]. Moreover, the envelope of motion of the TruNatomy instrument can help to reduce the point of contact or engagement of the cutting edge with dentin and create more space to reduce debris accumulation along the instrument [28, 33].

Increased engagement between the cutting edge of the instrument and the root dentin wall generates larger torque values. This phenomenon is observable in representative images of torque and force patterns of JIZAI and TruNatomy (Fig. 6). When the torque values of JIZAI increased in the positive region (i.e., the moment when the cutting edge of the file touches the canal wall), the force values also increased in both the positive and

Table 3 Canal volume, surface area changes, untouched areas, and centering ratios after instrumentation

	One up-and-down movement		Three up-and-down movements		Six up-and-down movements	
	JIZAI	TruNatomy	JIZAI	TruNatomy	JIZAI	TruNatomy
Volume changes (%)	46.1 (28.1–127.7) [a]	48.7 (22.9–102) [a]	39.5 (8.6–96.8) [a]	49.9 (32.5–95) [a]	57.3 (22.8–104) [a]	88.1 (2.7–271) [a]
Surface area changes (%)	11.7 (2.5–33.6) [a]	17.32 (4.9–33.8) [a]	12.9 (0.85–33.76) [a]	10.1 (0.33–24.5) [a]	19.62 (5–33) [a]	20 (1.3–33.4) [a]
Untouched area (%)	17.4 (4.1–51.8) [a]	20.5 (13.1–35.9) [a]	21.3 (3.7–51.5) [a]	26.4 (12.2–55.5) [a]	17.8 (7.7–44.7) [a]	19 (9.6–70.4) [a]
Centering ratio 1 mm	0.06 (0.02–0.29) [a]	0.14 (0.02–0.35) [a]	0.1 (0.002–0.28) [a]	0.13 (0.003–0.21) [a]	0.12 (0.01–0.39) [a]	0.14 (0.03–0.47) [a]
Centering ratio 3 mm	0.11 (0.03–0.33) [a]	0.15 (0.01–0.3) [a]	0.09 (0.02–0.18) [a]	0.12 (0.05–0.36) [a]	0.14 (0.04–0.37) [a]	0.11 (0.02–0.29) [a]
Centering ratio 5 mm	0.13 (0.03–0.29) [a]	0.13 (0.02–0.31) [ab]	0.08 (0.02–0.15) [a]	0.21 (0.1–0.25) [b]	0.08 (0.01–0.31) [a]	0.29 (0.06–0.41) [b]
Centering ratio 7 mm	0.18 (0.04–0.31) [a]	0.28 (0.04–0.49) [ab]	0.19 (0.02–0.37) [a]	0.31 (0.13–0.48) [b]	0.16 (0.03–0.46) [a]	0.35 (0.2–0.51) [b]

Values are median (minimum–maximum). Different letters in a row are significantly different between JIZAI and TruNatomy according to the Kruskal–Wallis test ($p < 0.05$). There were no significant differences between different up-and-down movements ($p > 0.05$)

negative regions (Fig. 6a). Particularly, the force in the negative region representing the screw-in force lasted for 1.5 s and then decreased slowly (Fig. 6a). Meanwhile, the torque and force values in the TruNatomy increased and decreased rapidly within 1 s (Fig. 6b). This implies that the cutting edge of the TruNatomy engaged the dentin and released quickly due to the envelop of motion, subsequently reducing screw-in forces.

However, the TruNatomy Prime exhibited a higher level of upward force than JIZAI I, and this could be attributed to the larger size of the TruNatomy Prime instrument as well as the smaller taper of the glide path instrument compared to the corresponding JIZAI glider.

Regarding the untouched canal area, there was no statistical significance between JIZAI and TruNatomy instruments. This revealed that both systems were unable to comprehensively shape the oval, curved root canals of the mandibular molars. A multidimensional analysis of the canal deviation was conducted to obtain a more precise calibration of the root canal transportation ability [25]. The results indicated that the JIZAI instrument performed better in maintaining the original curvature of the canal (Fig. 7d), possibly because of the cross-sectional shape of the JIZAI, which features radial lands. The passive cutting nature of the radial land may keep a rotating instrument in the center and prevent any canal transportation [11, 34]. The phase transformation temperature of the instruments can also partly explain the better performance of JIZAI. JIZAI instrument had an A*s* that was close to room temperature and an A*f* that was similar to or higher than body temperature, suggesting that this instrument fundamentally includes martensite/R-phase and austenite phase at room temperature. TruNatomy instrument exhibited an A*f* of 23.8–26.5 °C around the room temperature, indicating a higher austenite-rich composition than JIZAI at room temperature. Martensitic/R-phase instruments are more flexible [35] and result in a more centered canal preparation and reduced transportation, compared to austenitic instruments [4, 36].

A single up-and-down movement at the working length led to a significantly larger screw-in force compared to the 3 or 6 up-and-down movements. Moreover, a single up-and-down movement resulted in more surface deformation or wear on the file, thus increasing the probability of file fracture. It is likely because additional up-and-down movements increase the number of contact points between the blade and the root canal walls, leading to the effective removal of dentin [9]. This subsequently reduces the likelihood of blade engagement and enables subsequent instruments to progress more smoothly toward the end of the canal with less stress generation, particularly in severely curved canals [15, 18]. The reduced stress generation on the file can be clearly seen in the SEM findings of the JIZAI instrument (Fig. 7b), which displays less surface wear in 3 or 6 up-and-down movement groups.

An interesting finding in this study is that the different up-and-down movements do not significantly change the original canal anatomy (as shown by criteria such as changes in volume, surface area, unprepared canal area, apical canal deviation, or centering ratios) which contradicts previous studies [16, 18]. It may be attributed to the evolution and enhancement of physical properties of the instrument such as the smaller core diameter of the TruNatomy instrument with enhanced geometry [12] and the passive cutting radial-land and R-phase of the JIZAI instrument that allows for dentin preservation [5].

Supporting the above finding is the lack of a significant difference in torque values across various up-and-down movements (Fig. 5d, e). As previously discussed, torque measures the contact between the blade and the dentin. The consistent torque generation between the different up-and-down movement groups implies that the contact area between the file and the dentin in various groups is similar. This indicates that the file did not remove too much dentin during the additional movements in the 3 or 6 up-and-down movement groups. This can be verified in the representative images in Fig. 6, which show the torque and force patterns of the consecutive first, second, and third movements at the same working length. The torque and force values decreased drastically compared to the first time, indicating less dentin removal due to reduced contact with the blade of the instrument and dentin during the additional second and third preparations.

One of the strengths of our study lies in the fact that we demonstrated stress generation on the file through a multidisciplinary approach, incorporating torque and force data, representative images of real-time screw-in force patterns, and SEM observations of surface deformation of files. Another strong point is the use of an original automatic instrumentation device to simulate up-and-down movement without human intervention and to record screw-in forces. Moreover, the samples were standardized by geometric matching via micro-CT.

According to the DSC analysis, JIZAI is primarily composed of martensite/R-phase and austenite phase, while TruNatomy is mainly composed of austenite at room temperature. As the current experiments were conducted at room temperature, the results may correspond to the austenite state of the instruments. NiTi instruments exhibit prominent phase compositional differences between room temperature and body temperature, the temperature change might affect the performance of heat-treated instruments [10]. Therefore, if we conduct the experiments at body temperature, the JIZAI and TruNatomy instruments may function differently, particularly in their shaping ability.

Another limitation of this study may be the age variation of the teeth specimens, which was not adjusted but could cause variations in mechanical properties among groups. Moreover, only one type of rotary motion, continuous rotation, was used in the study. To address this limitation, it would be beneficial to conduct further research that compares different rotary movements with repeated up-and-down movements.

Generally, once an instrument reaches the working length, the procedure proceeds to a subsequent file. However, the present findings indicate that in severely curved canals, only a single up-and-down movement of the instrument can increase the screw-in tendency and stress generation of subsequent instruments in the single-length instrumentation technique. Additionally, increasing the number of up-and-down movements may not drastically alter the original root canal morphology; rather, it simply increases the instrument's cutting efficiency to the point where the dentin and working blade of the file have less surface area in touch. Therefore, from a clinical perspective, additional up-and-down movements may create a sufficiently sized canal in curved and constricted canals. Subsequently, this allows for the smooth insertion of subsequent instruments and helps avoid unexpected torsional fractures, particularly in single-length instrumentation techniques. However, clinicians must find a balance between improving the efficiency of canal shaping and the potential for increased post-operative complications such as over-enlargement of canals, which could result in apical canal transportation and compromise the apical seal.

Conclusions

Under laboratory conditions, using JIZAI and TruNatomy instruments, only a single up-and-down movement at the working length increased the screw-in force generation of subsequent files in severely curved canals, especially in single-length instrumentation technique. A single up-and-down movement also resulted in more surface defects on the file when using JIZAI instrument. Increasing the number of up-and-down movements using the JIZAI and TruNatomy instruments did not significantly alter the apical anatomy of curved canals. The TruNatomy instrument caused less stress during instrumentation, while the JIZAI instrument better maintained the original curvature of the curved root canals.

Abbreviations

A*s*	Reverse transformation starting temperature
A*f*	Reverse transformation finishing temperature
ANOVA	Analysis of variance
DSC	Differential scanning calorimetry
EDS	Energy Dispersive Spectroscopy
Micro-CT	Micro-computed tomography
M*s*	Martensitic transformation starting temperature
M*f*	Martensitic transformation finishing temperature
NiTi	Nickel-titanium
R*s*	R-phase transformation starting temperature
R*f*	R-phase transformation finishing temperature
SEM	Scanning electron microscope

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Author contributions

MSK was primarily responsible for conceptualization, study design, formal analysis, and investigation, as well as the original draft manuscript preparation. TO contributed to the study design, majorly reviewed and edited the manuscript. AE and YI were involved in funding acquisition and supervision. PHH, MT, KM, and SK contributed to resources and data collection. All authors reviewed and approved the final manuscript.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study has been reviewed and approved by the Dental Research Ethics Committee of Tokyo Medical and Dental University (no. D2014-033-03). The teeth samples used in this study were originally extracted for reasons unrelated to this research, and informed consent was obtained from all donors prior to sample collection.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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