Influence of bracket-slot design on the forces released by superelastic nickel-titanium alignment wires in different deflection configurations

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ABSTRACT

Objective: To evaluate how different bracket-slot design characteristics affect the forces released by superelastic nickel-titanium (NiTi) alignment wires at different amounts of wire deflection.

Materials and Methods: A three-bracket bending and a classic-three point bending testing apparatus were used to investigate the load-deflection properties of one superelastic 0.014-inch NiTi alignment wire in different experimental conditions. The selected NiTi archwire was tested in association with three bracket systems: (1) conventional twin brackets with a 0.018-inch slot, (2) a self-ligating bracket with a 0.018-inch slot, and (3) a self-ligating bracket with a 0.022-inch slot. Wire specimens were deflected at 2 mm and 4 mm.

Results: Use of a 0.018-inch slot bracket system, in comparison with use of a 0.022-inch system, increases the force exerted by the superelastic NiTi wires at a 2-mm deflection. Use of a self-ligating bracket system increases the force released by NiTi wires in comparison with the conventional ligated bracket system. NiTi wires deflected to a different maximum deflection (2 mm and 4 mm) release different forces at the same unloading data point (1.5 mm).

Conclusion: Bracket design, type of experimental test, and amount of wire deflection significantly affected the amount of forces released by superelastic NiTi wires ($P < .05$). This phenomenon offers clinicians the possibility to manipulate the wire's load during alignment. (*Angle Orthod.* 2014;84:541–547.)

KEY WORDS: Archwire loads; Slot design; Nickel-titanium; Alignment wires; Superelastic NiTi

INTRODUCTION

Nickel titanium (NiTi) archwires are widely used during the alignment phase of orthodontic straight-wire mechanics. These archwires have unique properties of superelasticity and shape memory,[1–5] which are responsible for their growing use among clinicians.

One important goal during the alignment phase of orthodontic treatment is to use suitable and predictable force levels.[6,7] To achieve this goal, an adequate knowledge of load-deflection characteristics of NiTi archwires is necessary.

The three-point bending test is considered a suitable method to investigate the load-deflection characteristics of NiTi archwires.[8] Load-deflection plots of NiTi archwires, obtained by use of classic three-point bending tests, are characterized by a horizontal unloading plateau,[1,4,8–10] which shows that NiTi archwires are able to exert constant forces during teeth alignment in a certain range of tooth movement.[1,4,8–10]

More recently, new experimental settings were developed to more realistically simulate the clinical environment. Some authors modified classic three-point

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bending tests by introducing the brackets at the wire-testing machine interface (three-bracket bending test).[1,2,11,12] Other authors evaluated unloading forces of NiTi archwires in an experimental setting by incorporating more than three brackets on the same spatial plane[13–16] or positioning them to simulate a dental typodont.[15,17–21]

These experimental settings[13–21] are able to simultaneously measure the force released by NiTi wires and resistance to sliding (RS) at the wire-bracket interface. Both factors are fundamental contributors to determining the amount of force delivered to the teeth during alignment by NiTi archwires. Indeed, during alignment, part of the force exerted by the wires is used to overcome RS.[6,7] Consequently, during the experimental test, the sensor will measure the net force resulting from archwire unloading force minus RS. RS is the result of two factors: classic friction (Fr) and binding (BI).[6,7,22] Fr is the frictional force generated by conventional ligation methods (stainless steel ligatures, elastomeric modules).[22] BI is the force that opposes the wire sliding when the archwire is in contact with the lateral edges of the bracket-slot.[22] Several studies have shown that bracket-slot design affects RS.[23–25] Consequently, bracket design can potentially affect the force delivered to the teeth by NiTi alignment wires. Studies that evaluated the role of bracket design on the unloading forces of alignment NiTi wires confirmed that bracket design influences wire load.[11–13,15,17,18]

Nevertheless, none of the aforementioned studies were specifically designed to assess how different variables of bracket design affect the unloading forces. In this regard, some characteristics of the bracket design, such as vertical bracket dimensions, have not yet been evaluated. The aim of this experimental research was to evaluate how different bracket-slot design characteristics affect the forces released by superelastic NiTi alignment wires at different amounts of wire deflection.

MATERIALS AND METHODS

A universal testing machine (Tenso Test TT2, 5-GU, Lonos Test, Monza, Italy) was used to investigate the load-deflection properties of one superelastic 0.014-inch NiTi alignment wire (Superelastic Titanium Memory Wire, American Orthodontics, Sheboygan, Wis) under different experimental conditions. Two straight-end sections, 27 mm in length, of each archwire were used for testing. The universal testing machine presented a 10 N load–cell with 0.001 N sensitivity. The crosshead speed was set at 0.01 mm/sec. The machine was assembled with two different experimental models: a three-bracket bending apparatus (performed with different bracket systems) and a three-point bending apparatus (Figure 1).

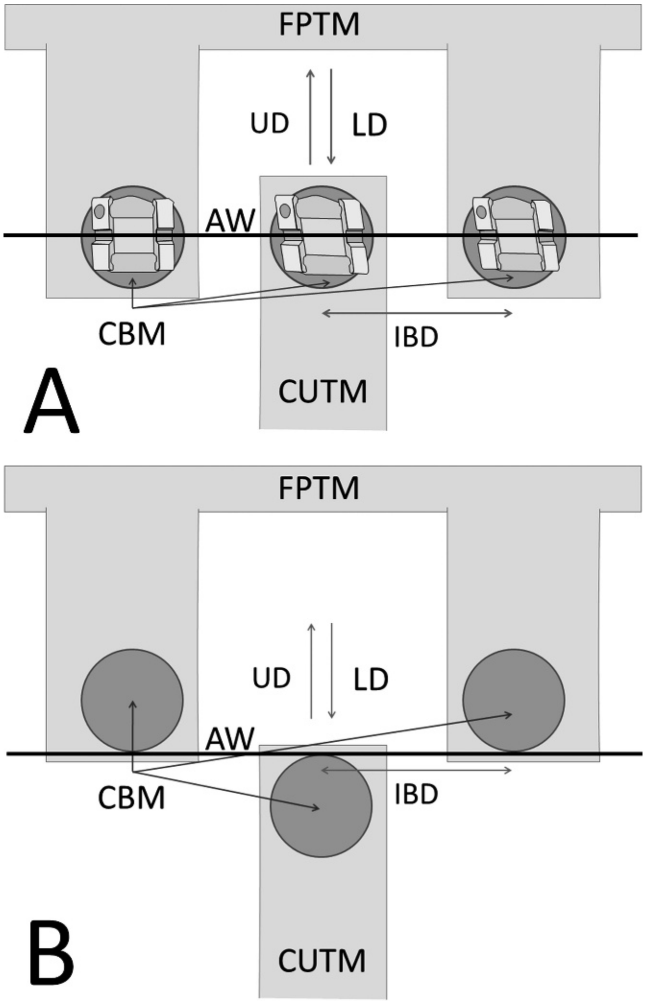

Figure 1. Testing machine at zero wire deflection. Three-bracket bending apparatus (A) and three-point bending apparatus (B). FPTM indicates fixed-part testing machine; UD, unload direction; LD, load direction; AW, archwire; CBM, cylindrical brass mount; IBD, interbracket distance; CUTM, crosshead of the universal testing machine.

The three-bracket experimental model was set up aligning three brackets corresponding to the lateral incisor, canine, and first premolar to simulate a portion of the upper right maxillary arch. Three different types of bracket systems were evaluated: (1) conventional twin-ligated brackets with a 0.018-inch slot (Mini Master Series, American Orthodontics) coupled with elastomeric modules (Clear ligatures, American Orthodontics, Sheboygan, WI, USA); (2) a self-ligating bracket with a 0.018-inch slot (Time 3, American Orthodontics); and (3) a self-ligating bracket with a 0.022-inch slot (Time 3, American Orthodontics). The characteristics of the tested bracket are reported in Table 1.

The central bracket (corresponding to the canine bracket) was mounted onto the crosshead of the universal testing machine. The lateral brackets (lateral incisor and first premolar) were mounted onto the fixed

Table 1. Bracket-Slot Characteristics of Tested Brackets

Commercial Bracket Name	Corresponding Tooth	Bracket Prescription Torque	Angle	Rotation	Nominal Slot Dimensions Slot Height (inches)	Mesiodistal Width (inches)	Ligation Method
Mini Master Series	12	+10	+8	0	0.018	0.115	Elastomeric module
Mini Master Series	13	−7	+8	0	0.018	0.122	Elastomeric module
Mini Master Series	14	−7	0	0	0.018	0.120	Elastomeric module
Time 3	12	+12	+9	0	0.018	0.093	Self-ligation
Time 3	13	−7	+9	0	0.018	0.098	Self-ligation
Time 3	14	−7	0	0	0.018	0.106	Self-ligation
Time 3	12	+12	+9	0	0.022	0.093	Self-ligation
Time 3	13	−7	+9	0	0.022	0.098	Self-ligation
Time 3	14	−7	0	0	0.022	0.106	Self-ligation

part of the three-bracket apparatus. The interbracket distance, considered from the midpoint of every mounted bracket, was set at 7.5 mm. Before being mounted in the three-bracket bending test apparatus, the brackets were individually bonded to a cylindrical brass mount with a diameter of 4 mm. The bonding procedure was performed by positioning the brass mounts on a stainless steel stay and aligning the three brackets using a full bracket-slot stainless steel jig (0.018 inch or 0.022 inch according to the vertical dimension of the tested bracket-slot). Once the brackets were assembled to the three-bracket bending test apparatus, the jig was used to align the bracket-slot to ensure that the bracket orientation was correct before performing each individual test. The three-point test was performed by using three cylindrical brass mounts at the wire-testing machine interface according to Figure 1. Tests were performed at two different maximum deflection (MD) values: 2 mm and 4 mm. Loading and unloading phases were carried out under the same conditions at a constant temperature of 36°C. During testing, temperature was monitored by a thermocouple connected to the bending apparatus. For every test, a new segment wire and new brackets were used.

Sample Size Calculation and Statistical Analysis

To evaluate the proper number of repetitions for each test, a preliminary session of tests was performed. The data obtained from this session were used to perform the power analysis for analysis of variance (ANOVA) sample size calculation setting: β at 0.99, α at 0.05, and number of sample groups at four. Based on the results of the power analysis, each experimental condition was tested four times.

To perform descriptive and inferential statistics, specific data points of the load-deflection curves were set as performed previously by several authors.[8,11,15,18,20] For loading and unloading curves, the following data points were selected: at 4 mm, MD test 1.5 mm and 3.5 mm; and at 2 mm, MD test 1.0 mm and 1.5 mm. Two-way ANOVA was used to evaluate the effect of two independent variables (ie, slot design and wire deflection) and their possible interaction with the wire loads. The multiple post hoc comparison Tukey test was used to evaluate the single effect of the tested variables. All data were preliminarily tested by the Shapiro-Wilk normality test and by the Levene test to evaluate data distribution and equality of variance, respectively. The unpaired *t*-test and Mann-Whitney test were used to compare the forces registered at the same data point (1.5 mm) of the tests performed at 2-mm and 4-mm MD. For all of the tests, the significance level was set at $P < .05$. All statistical analyses were executed using software (SigmaStat 3.5, Systat Software, Point Richmond, Calif).

RESULTS

Figures 2 and 3 report the representative load-deflection curves obtained by plotting the data registered

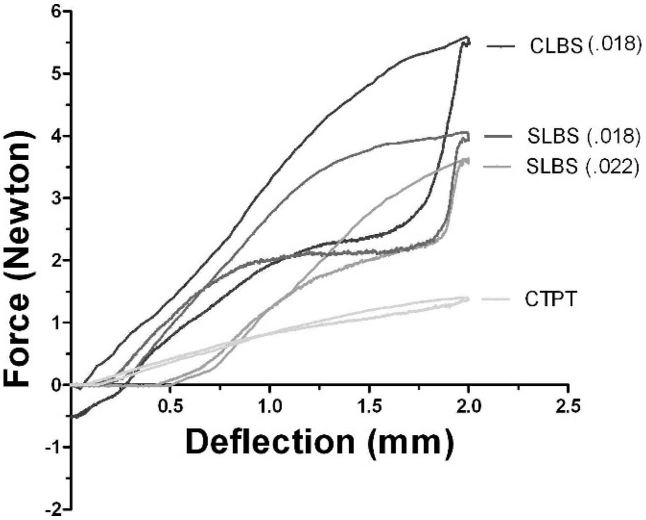

Figure 2. Load-deflection hysteresis curves registered by testing the superelastic wire in all of the considered experimental conditions at 2-mm maximum deflection. CLBS (.018) in indicates 0.018-inch conventional ligated bracket system; SLBS (.018) in, self-ligating bracket system with a 0.018-inch slot; SLBS (.022) in, self-ligating bracket system with a 0.022-inch slot; CTPT, classic three-point test with no brackets.

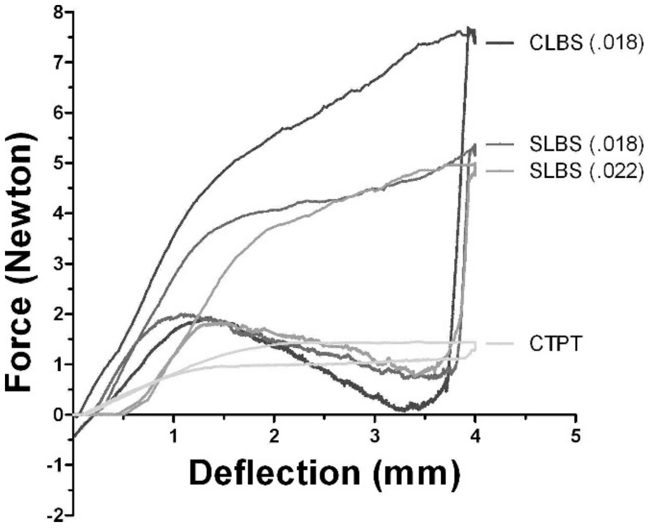

Figure 3. Load-deflection hysteresis curves registered by testing the superelastic wire in all of the considered experimental conditions at 4 mm maximum deflection. CLBS (.018) in indicates 0.018-inch conventional ligated bracket system; SLBS (.018) in, self-ligating bracket system with a 0.018-inch slot; SLBS (.022) in, self-ligating bracket system with a 0.022-inch slot; CTPT, classic three-point test with no brackets.

for all of the evaluated experimental conditions. Descriptive statistics of registered forces at selected data points for both the 2-mm and 4-mm MD curves are reported in Tables 2 and 3. During the unloading phase at 2-mm MD, the average forces registered at 1.5 mm were higher than those registered at 1.0 mm for all of the experimental conditions. The bracket system with the 0.022-inch slot exhibited lower force than the bracket system with a 0.018-inch slot. During the unloading phase at 4-mm MD, in all of the experiments with the exception of the CTPT (Classic Three-point test), the average forces registered at 3.5 mm were lower than those registered at 1.5 mm. Inferential statistics are reported in Tables 4 and 5.

DISCUSSION

To the best of our knowledge, this is the first study that evaluates the impact of vertical bracket-slot dimension on the force released by NiTi alignment wires. It was evaluated by comparing two self-ligating bracket systems that differing only in vertical bracket-slot dimension (0.018 inch vs 0.022 inch). During unloading, the two bracket systems showed significant differences ($P < .05$) at 2-mm MD and no differences at 4-mm MD.

The .018-inch bracket system decreases the free play of the wire compared with the 0.022-inch bracket. With the 0.018-inch bracket system, this aspect causes an earlier deflection of the wire and greater wire deflection at both 2-mm and 4-mm MD. At 2-mm MD the stress-induced martensitic (SIM) transformation of the wire is not complete; consequently, the greater deflection of the wire, caused by the use of the 0.018-inch bracket system, induces the release of significantly higher forces during unloading. At 4-mm MD, the SIM transformation of the wire is complete; consequently, a greater deflection of the wire does not cause the release of higher forces. Clinically, this could cause higher forces to be delivered to the teeth during alignment in cases of 2 mm of wire deflection when 0.018-inch bracket systems are used; comparable forces are exerted by the 0.018-inch and 0.022-inch bracket systems in the case of 4-mm MD.

To evaluate whether the ligation bracket-wire method affects the mechanical properties of NiTi wires, two different bracket systems were compared: a 0.018-inch self-ligating bracket system and a 0.018-inch

Table 2. Descriptive Statistics of the Registered Forces (Newtons) During Tests Performed at 2-mm Maximum Deflection

Variables							
Tested Brackets	Hysteresis Phase	Data Point	Observations	Mean	SD	Minimum	Maximum
Conventional ligated bracket system (slot 0.018 inch)	Loading	1.0 mm	4	3.33	0.11	3.18	3.42
		1.5 mm	4	4.91	0.15	4.73	5.07
	Unloading	1.5 mm	4	2.35	0.10	2.20	2.44
		1.0 mm	4	2.04	0.16	1.93	2.28
Self-ligating bracket system (slot 0.018 inch)	Loading	1.0 mm	4	2.59	0.17	2.36	2.74
		1.5 mm	4	3.71	0.15	3.52	3.87
	Unloading	1.5 mm	4	2.29	0.13	2.14	2.43
		1.0 mm	4	2.01	0.13	1.89	2.19
Self-ligating bracket system (slot 0.022 inch)	Loading	1.0 mm	4	1.20	0.09	1.11	1.31
		1.5 mm	4	2.83	0.12	2.70	2.95
	Unloading	1.5 mm	4	2.03	0.09	1.92	2.12
		1.0 mm	4	1.22	0.08	1.12	1.30
Classic three-point test (no brackets)	Loading	1.0 mm	4	0.86	0.09	0.76	0.97
		1.5 mm	4	1.19	0.07	1.10	1.28
	Unloading	1.5 mm	4	1.04	0.08	0.93	1.12
		1.0 mm	4	0.83	0.08	0.74	0.94

Table 3. Descriptive Statistics of the Registered Forces (Newtons) During Tests Performed at 4-mm Maximum Deflection

Variables							
Tested Brackets	Hysteresis Phase	Data Point	Observations	Mean	SD	Minimum	Maximum
Conventional ligated bracket system (slot 0.018 inch)	Loading	1.5 mm	4	4.94	0.17	4.78	5.17
		3.5 mm	4	8.00	0.44	7.35	8.34
	Unloading	3.5 mm	4	−0.11	0.27	−0.35	0.20
		1.5 mm	4	1.53	0.26	1.23	1.84
Self-ligating bracket system (slot 0.018 inch)	Loading	1.5 mm	4	3.55	0.18	3.37	3.78
		3.5 mm	4	4.88	0.11	4.74	5.00
	Unloading	3.5 mm	4	0.69	0.16	0.49	0.86
		1.5 mm	4	1.64	0.16	1.50	1.85
Self-ligating bracket system (slot 0.022 inch)	Loading	1.5 mm	4	2.84	0.09	2.75	2.96
		3.5 mm	4	4.85	0.09	4.72	4.93
	Unloading	3.5 mm	4	0.77	0.11	0.62	0.89
		1.5 mm	4	1.84	0.09	1.73	1.94
Classic three-point test (no bracket)	Loading	1.5 mm	4	1.11	0.08	1.00	1.19
		3.5 mm	4	1.42	0.08	1.31	1.50
	Unloading	3.5 mm	4	1.07	0.05	1.01	1.12
		1.5 mm	4	0.96	0.08	0.84	1.04

conventional ligated bracket system. At the 3.5-mm unloading data point and 4-mm MD, the comparison showed that NiTi wires release significantly lower forces when coupled with a 0.018-inch conventional ligated bracket system compared with the 0.018-inch self-ligating bracket system. This result could be explained assuming that part of the archwire force is used to overcome the greater RS generated testing the 0.018-inch conventional ligated bracket system during the unloading phase.[23–25] These findings are supported by previous studies[13–15,17,18] and confirm that NiTi wires coupled with self-ligating bracket systems generate significantly higher forces if compared with conventional ligated bracket systems. Clinically, these findings suggest that clinicians should couple self-ligating bracket systems with an alignment wire that exerts lighter forces.

The two data points selected to analyze the obtained load-deflection curves were chosen to properly represent a standardized portion of the unloading plateau. Consequently, the evaluation of the force differences registered at the two data points of each load-deflection curve provides some information about the archwire capability to exhibit its superelasticity properties.[10]

Comparing the forces registered at the two plateau data points, significant differences were detected for every tested bracket system with the exception of the forces registered at the unloading data points at 4-mm MD of the classic three-point test. These findings confirmed that the design of the experimental test qualitatively and quantitatively affected the release of unloading forces of superelastic NiTi alignment wires,[15,21] and showed that when the forces released by alignment wire are evaluated in an experimental setting incorporating bracket systems, they tend to lose their superelasticity properties, thus showing characteristics of force variation. These findings corroborate the work of previous authors.[12,15,16,20]

However, none of the previous studies mentioned that unloading force variations for superelastic NiTi wires are qualitatively and quantitatively different at 4-mm and 2-mm MD. At 4-mm MD, all bracket systems showed significantly lower unloading forces at 3.5 mm compared with 1.5 mm, exhibiting a gradual increase of forces in the first portion of the unloading curve while decreasing the wire deflection (Figure 3). The increase of the force levels could be explained assuming that the reduction of wire deflection (from 3.5 mm to

Table 4. Comparison of Forces Registered by Different Bracket Systems (Inferential Statistics)[a]

	Loading 2 mm		Unloading 2 mm		Loading 4 mm		Unloading 4 mm	
	1.0 mm	1.5 mm	1.5 mm	1.0 mm	1.5 mm	3.5 mm	3.5 mm	1.5 mm
CLBS (0.018 inch) vs CTPT	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)
CLBS (0.018 inch) vs SLBS (0.022 inch)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	NS
CLBS (0.018 inch) vs SLBS (0.018 inch)	*(A;B)	*(A;B)	NS	NS	*(A;B)	*(A;B)	*(A;B)	NS
SLBS (0.018 inch) vs CTPT	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)
SLBS (0.018 inch) vs SLBS (0.022 inch)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	NS	NS	NS
SLBS (0.022 inch) vs CTPT	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	*(A;B)	NS	*(A;B)

[a] CLBS indicates conventional ligated nracket system; SLBS, self-ligating bracket system; CTPT, classic three-point test with no brackets; NS, not significant.

* $P < .05$; [A] two-way ANOVA; [B] Tukey post hoc test.

Table 5. Comparison of Measured Forces at Different Amounts of Deflection (Inferential Statistics)

	2 mm		4 mm		2 mm vs 4 mm
	Loading	Unloading	Loading	Unloading	Unloading
	1.5 mm vs 1.0 mm	1.5 mm vs 1.0 mm	3.5 mm vs 1.5 mm	3.5 mm vs 1.5 mm	1.5 mm
CLBS (0.018 inch)	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(C)}$
SLBS (0.018 inch)	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(C)}$
SLBS (0.022 inch)	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(C)}$
CTPT	*$^{(A;B)}$	*$^{(A;B)}$	*$^{(A;B)}$	NS	*$^{(C)}$

[a] CLBS indicates conventional ligated bracket system; SLBS, self-ligating bracket system; CTPT, classic three-point test with no brackets; NS, not significant.

* $P < .05$; ^{A} two-way ANOVA; ^{B} Tukey post hoc test; ^{C} *t*-test; ^{D} Mann-Whitney test.

1.5 mm) changes the wire-bracket interaction geometry, reducing binding and RS,[6,22] and consequently increasing the archwire load registered by the load cell.

This force variation of NiTi archwires at 4-mm MD was previously registered by other authors,[16,17,20] although no author commented on the trend of load-deflection curve reporting this explanation. Clinically, this finding could be responsible for a gradual force augmentation during the first phase of teeth alignment when the wire presents a 4-mm deflection.

Conversely, after 2-mm MD, when comparing the unloading forces registered at the two selected data points (1.5 mm and 1.0 mm), a significant reduction in all evaluated bracket systems was noted (Table 5). Clinically, this phenomenon could be responsible for a force reduction during teeth alignment when the wire presents a 2-mm deflection. The different force variations at 2-mm and 4-mm MD could be explained considering that 2 mm of deflection is not sufficient to fully promote the SIM transformation of superelastic NiTi wire.

This study is the first in the orthodontic literature that offers a direct comparison of the forces exerted by the same wire at the same deflection after a different MD (2 mm and 4 mm).

In particular, unloading forces registered at the 1.5-mm data point after 4-mm MD are significantly lower than the forces registered after 2-mm MD. The different SIM transformation of NiTi wires at 2 mm and 4 mm could be responsible for this phenomenon.

This finding could be clinically relevant in those situations where the engagement of the alignment wire causes a bracket displacement of 4 mm. In such conditions, during the periodic clinical check, the clinicians could have the ability to influence the force exerted by NiTi wires. In particular, when part of the alignment of teeth is realized and the displacement of the wire is consequently reduced, two possibilities are available: if the clinician's goal is to increase the forces exerted by the NiTi wire, he or she should remove the wire from the bracket system, allowing the wire to return to its original shape; the clinician should then subsequently reinsert the wire in the bracket system.

This procedure could result in modifications of the NiTi load-deflection properties to make them similar to a 2-mm MD test, thus increasing the force released by the superelastic NiTi wire. If the clinician's goal is to maintain the forces exerted by the NiTi wire at the lowest possible level, he or she should leave the wire in the bracket system for as long as possible.

CONCLUSIONS

- The design of the bracket significantly affects the amount of force released by superelastic NiTi alignment wires. The use of a 0.018-inch slot bracket system, compared with a 0.022-inch system, increases the force exerted by the superelastic NiTi wires after 2 mm of maximum deflection. After 4 mm of maximum wire deflection, the vertical slot dimension does not affect the forces released by superelastic NiTi wires. The use of a self-ligating bracket system increases the force released by superelastic wire in comparison with that of the conventional ligated bracket system.
- The type of experimental test qualitatively and quantitatively affects the wire force release. Superelastic NiTi alignment wires show their horizontal unloading plateau only with the classic three-point test. When superelastic NiTi wires are tested in experimental conditions that present brackets at the wire-testing machine interface, they release forces that show high qualitative and quantitative variability that depends on the maximum wire deflection.
- NiTi wires deflected to a different maximum deflection (2 mm and 4 mm) release significantly different forces at the same unloading data point (1.5 mm). This phenomenon gives clinicians the potential to manipulate the forced released by the NiTi wire during alignment.

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