Original Article

Load deflection characteristics and force level of nickel titanium initial archwires

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ABSTRACT

Objectives: To investigate and compare the characteristics of commonly used types of traditional and heat-activated initial archwire by plotting their load/deflection graphs and quantifying three suitable parameters describing the discharge plateau phase.

Materials and Methods: Forty-eight archwires (22 nickel titanium [NiTi] and 26 heat-activated) of cross-sectional diameter ranging from 0.010 to 0.016 inch were obtained from seven different manufacturers. A modified three-point wire-bending test was performed on three analogous samples of each type of archwire at a constant temperature (37.0°C). For each resulting load/deflection curve, the plateau section was isolated, along with the mean value of the average plateau force, the plateau length, and the plateau slope for each type of wire obtained.

Results: Statistically significant differences were found between almost all wires for the three parameters considered. Statistically significant differences were also found between traditional and heat-activated archwires, the latter of which generated longer plateaus and lighter average forces. The increase in average force seen with increasing diameter tended to be rather stable, although some differences were noted between traditional and heat-activated wires.

Conclusions: Although great variation was seen in the plateau behavior, heat-activated versions appear to generate lighter forces over greater deflection plateaus. On average, the increase in plateau force was roughly 50% when the diameter was increased by 0.002 inch (from 0.012 to 0.014 and from 0.014 to 0.016 inch) and about 150% when the diameter was increased by 0.004 inch (from 0.012 to 0.016), with differences between traditional and heat-activated wires noted in this case. (*Angle Orthod.* 2012;82:507–521.)

KEY WORDS: Arch wire; Light force; Nickel titanium

INTRODUCTION

Because of their superelasticity and shape memory effect, nickel titanium (NiTi) archwires have become increasingly popular in orthodontics over the past decade. Their superelasticity is reflected in a load/deflection graph characterized by a flattish slope upon discharge, known as the *plateau,* which indicates that the force exerted is relatively constant in the range of tooth movement.[1] This feature is linked to reversible transformation from the austenitic to the martensitic phase beyond a certain stress threshold, which is reached during activation and deactivation.[2]

Some alloys, if deformed in the martensitic phase and heated up to a certain transition temperature range (TTR), are able to recover their original form as they return to the austenitic phase, and therefore are said to possess shape memory. Although the first nickel titanium archwires featured this characteristic, their TTRs did not permit this property to be exploited for orthodontic purposes.[3] However, thanks to the recent development of temperature-dependent (heat-activated) alloys, this shape memory characteristic can now be used to clinical effect.

Although many authors have investigated the properties of NiTi archwires,[4–7] most published studies have tended to concentrate on evaluating the force

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Table 1. Orthodontic Wires Tested

Manufacturer	Type	T°[a]	Diameter				
			.010	.012	.013	.014	.016
Dentaurum							
Rematitan Lite	Traditional			•		•	•
Tensic	Heat-activated	30		•		•	•
Forestadent							
Titanol-Superelastic	Traditional			•		•	•
Biostarter	Heat-activated	37	•	•		•	•
Ormco							
NiTi	Traditional			•			
Copper NiTi	Heat-activated	27			•	•	•
Copper NiTi	Heat-activated	35					•
Ortho Technology							
TruFlex	Traditional			•		•	•
TruFlex Thermal	Heat-activated	32				•	•
G&H							
Orthoforce G4	Traditional			•	•	•	•
Orthoforce M5	Heat-activated	37		•		•	•
3M							
NiTi Classic	Traditional			•		•	•
NiTi Super Elastic	Traditional					•	•
NiTi Heat Activated	Heat-activated	27					•
American Orthodontics							
Titanium memory wire	Traditional			•		•	•
Therma-Ti D	Heat-activated	25			•	•	•
Therma-Ti	Heat-activated	28			•	•	•
Therma-Ti Lite	Heat-activated	35		•		•	•

[a] T° indicates transition temperature range (TTR).

exerted by various wires at specific deflections and have considered their complete behavior during the discharge phase in just a few cases.[8] The aim of the present study, therefore, was to investigate the characteristics of the aforementioned plateau phase occurring during discharge, described using three parameters: the average plateau force, the plateau length, and the plateau slope. That is to say, we set out to evaluate the average force exerted by each type of archwire during tooth displacement, to discover the entity of displacement at which the average force is approximately constant, and to determine the effective degree of constancy of the plateau phase.

Furthermore, analysis was focused on the types of archwires typically employed during the first stages of orthodontic treatment by practitioners of a wide range of orthodontic techniques and philosophies.

MATERIALS AND METHODS

To make our study as clinically relevant as possible, numerous types of nickel titanium archwires tested were grouped into two macro-categories: traditional and heat-activated; all wires with TTRs were placed above room temperature, but close to body temperature in the latter. Of 48 archwires tested, 22 were classed as traditional NiTi wires and 26 as heat-activated, but all were circular in cross-section and had a diameter between 0.010 and 0.016 inch. The seven different manufacturers who provided the archwires in question were G&H (Franklin, Ind), Ortho Technology (Tampa, Fla), 3M Unitek (St Paul, Minn), Ormco (Orange, Calif), American Orthodontics (Sheboygan, Wis), Dentaurum (Ispringen, Germany), and Forestadent (St Louis, Mo) (Table 1). Samples of each archwire were obtained by cutting the straightest distal portion of an archwire; thus an approximate length of 5.5 cm was recovered.

Means of Deflection

Tests were performed on three samples. For each sample, different wires (material and size) were tested using a three-point bending test, which commonly has been used to compare the load/deflection characteristics of NiTi archwires.[9–11] However, in our experiment, so as to evaluate the samples in a condition similar to the final operating one, samples were mounted in four passive self-ligating brackets (Damon 3Mx, Ormco).[12] These brackets were glued to an acrylic resin base[13] in such a way as to create a 14 mm span between the

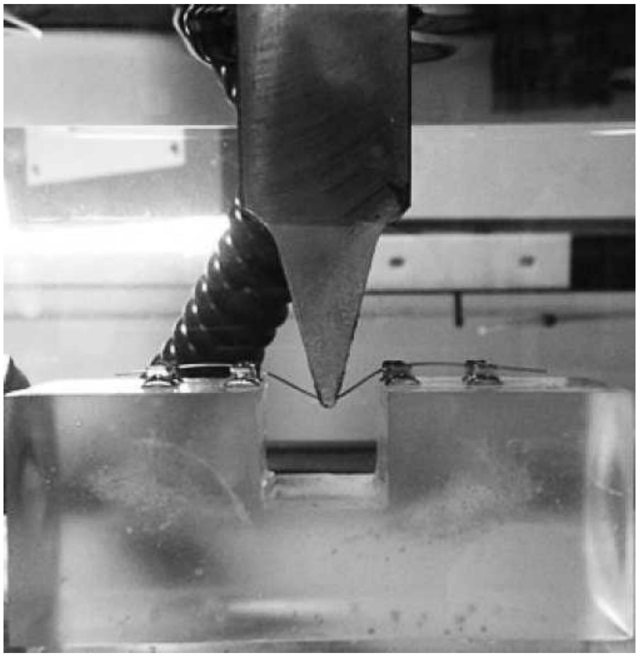

Figure 1. Deflection, with 1 mm blade, of mounted archwire kept in a water bath at a constant temperature of 37.0°C.

internal sides of two adjacent brackets. The resin base was, in turn, placed in a Plexiglas bath filled with water kept at a constant temperature of 37.0°C. This temperature was maintained thanks to a heating pump (Julabo, Julabo Labortechnik Gmbh, Seelbach, Germany), which, to avoid potential interference caused by its vibration, was placed in a separate water bath connected to the first by a hydraulic circuit. Each archwire section was immersed in the heated water for a minimum of 60 seconds before being subjected to the testing procedure to reach thermal equilibrium. Water temperature was controlled by means of a thermocouple (Tekkal T8303, Tekkal, Milano, Italy) submerged in the test bath and monitored continuously by the same operator responsible for performing the mechanical tests.

The force applied was regulated by means of an Instron 4467 dynamometer (Instron, Norwood, MA) connected to a 100 N load cell. A metal blade, with a curvature range of 1 mm at its extremity, was fixed to the load cell to deflect the archwires (Figure 1). Each wire was deflected 4 mm, at a deflection speed of 1 mm/min, and then was returned to its horizontal starting point ''0'' at the same speed. This degree of deflection was chosen because of its possible occurrence under clinical conditions, although some authors maintain that far smaller deflections are more authentic.[14]

Measurements

Data were gathered by means of a personal computer connected to the measuring device and were processed using Labview 8.5 (National Instruments Corporation, Austin, Tex). Data thereby collected were presented in spreadsheet form using Microsoft Excel (Microsoft Corporation, Redmond, Wash). These spreadsheets in turn were used to plot a graph for each test, showing deflection of the test strip on the x-axis, reported in mm, and the force exerted on the y-axis, reported in gram force and indicated by ''g'' on the plots. Each curve thereby obtained represented the initial loading phase, of no particular clinical relevance, and the discharge phase, which indicates the entity of the force exerted on the teeth during orthodontic treatment. Our intention was not so much to evaluate the forces expressed by certain points of deflection on the archwires, but to characterize their behavior in the plateau phase by measuring three parameters: average plateau force, plateau length, and plateau slope (Figure 2).

The length of the plateau was used to indicate extension of the displacement range in which the force may be considered approximately constant. The

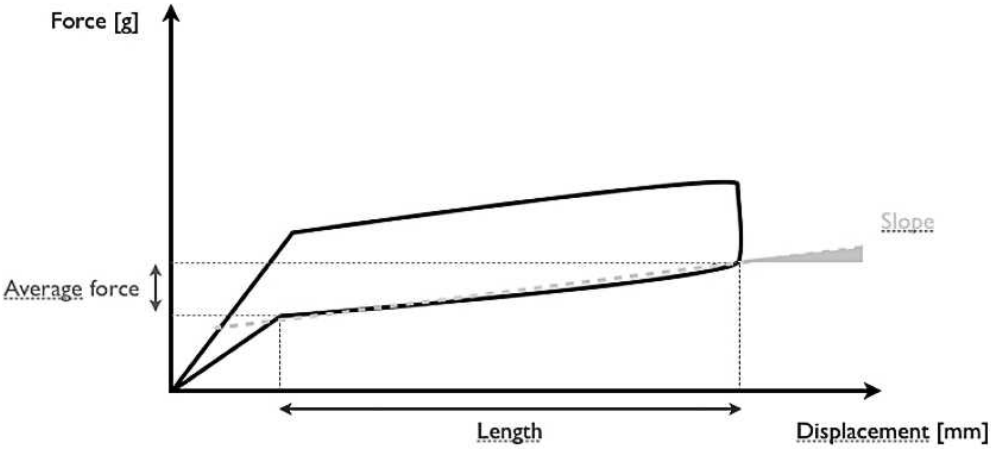

Figure 2. Isolation of the discharge plateau for each graph and calculation of the three parameters chosen to characterize it: average plateau force, plateau length, and plateau slope.

Table 2. Orthodontic Wires Grouped According to Type and Cross-Sectional Diameter (Test at 37.0°C)[a]

	Plateau Slope, g_f/mm	Plateau Length, mm	Average Plateau Force, g_f
.012 NiTi			
Dentaurum	5.0	2.77	68.8
Forestadent	8.6	2.87	69.4
Ormco	8.8	3.03	54
Ortho Technology	6.1	2.97	45.1
G&H	9.1	2.91	71
3M Classic	−2.8	1.96	63.3
American Orthod	3.6	2.54	68.8
.013 NiTi			
G&H	9.6	3.02	74.8
.014 NiTi			
Dentaurum	11.4	2.84	109.6
Forestadent	8.9	2.91	107.6
Ortho Technology	9.9	2.99	85.4
G&H	14	3.21	78.4
3M Classic	−0.7	2.36	108.3
3M SE	6.1	2.57	85.3
American Orthod	5.6	2.77	109.5
.016 NiTi			
Dentaurum	10.8	2.79	180.2
Forestadent	26.5	3.04	174.9
Ortho Technology	16	3.08	137
G&H	19.6	3.05	144.4
3M Classic	−28.4	2.32	172.1
3M SE	13	2.63	132.9
American Orthod	10.2	2.79	186
.010 NiTi T°			
Forestadent	6.0	3.06	30.42
.012 NiTi T°			
Dentaurum	13.9	3.41	40.9
Forestadent	11.4	3.17	47.4
G&H	9.5	3.23	41.3
American Orthod Ti L	9.7	3.33	39.3
.013 NiTi T°			
Ormco CuNiTi	9.8	3.04	67.9
American Orthod Ti	8.5	3.25	56
American Orthod Ti D	5.7	2.86	88.2
.014 NiTi T°			
Dentaurum	19.2	3.48	61.3
Forestadent	15.9	3.23	77.1
Ormco CuNiTi	4.3	2.8	86.1
Ortho Technology	12.7	3.45	48.7
G&H	14.2	3.31	61.6
American Orthod Ti	9.3	3.15	80.2
American Orthod Ti D	10.3	2.96	108.2
American Orthod Ti L	15.8	3.42	50.2
.016 NiTi T°			
Dentaurum	32.8	3.5	99.1
Forestadent	20.0	3.06	135.7
Ormco CuNiTi 27°	8.3	3.05	143.4
Ormco CuNiTi 35°	13.9	3.26	122.5
Ortho Technology	17.8	3.35	91.3
G&H	20.0	3.36	85.9
3M	20.9	3.07	122.3
American Orthod Ti	22.6	3.26	81
American Orthod Ti D	13.3	3.09	141.4
American Orthod Ti L	22	3.31	77.8

[a] In the first part are traditional wires (NiTi), and in the second part, heat-activated wires (NiTi T°).

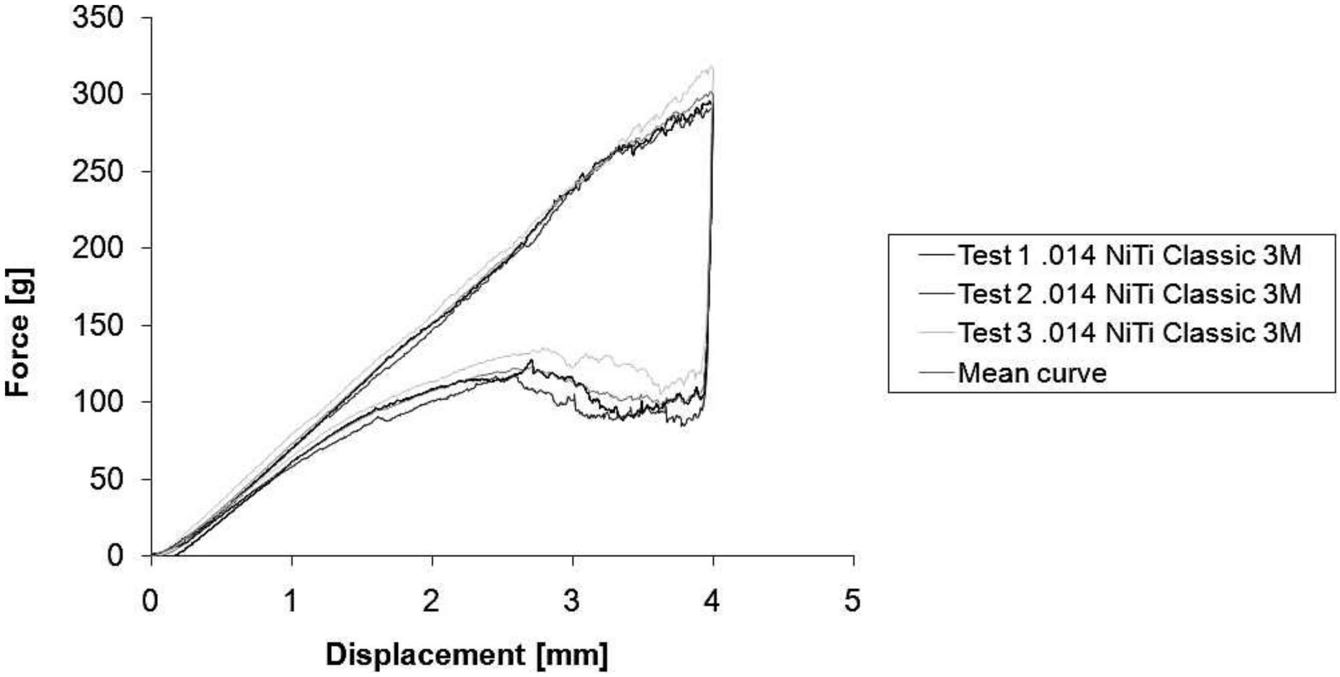

Figure 3. Load/deflection curve of 0.014 NiTi Classic (3M).

average force was given by the arithmetic average of the values of force pertaining to this phase identified on the curve. The effective slope is a measure of the degree of plateau flatness; therefore, the closer the slope was to zero, the more constant was the force.

A load/deflection curve was obtained for each of the three samples of each type of wire tested. A sole operator subjectively identified and isolated the discharge plateau. This was identifiable clearly on each graph. The same operator calculated the values yielded by the three samples for each of the parameters considered (average plateau force, plateau length, and plateau slope) and for each type of wire tested. Data pertaining to each type of wire,

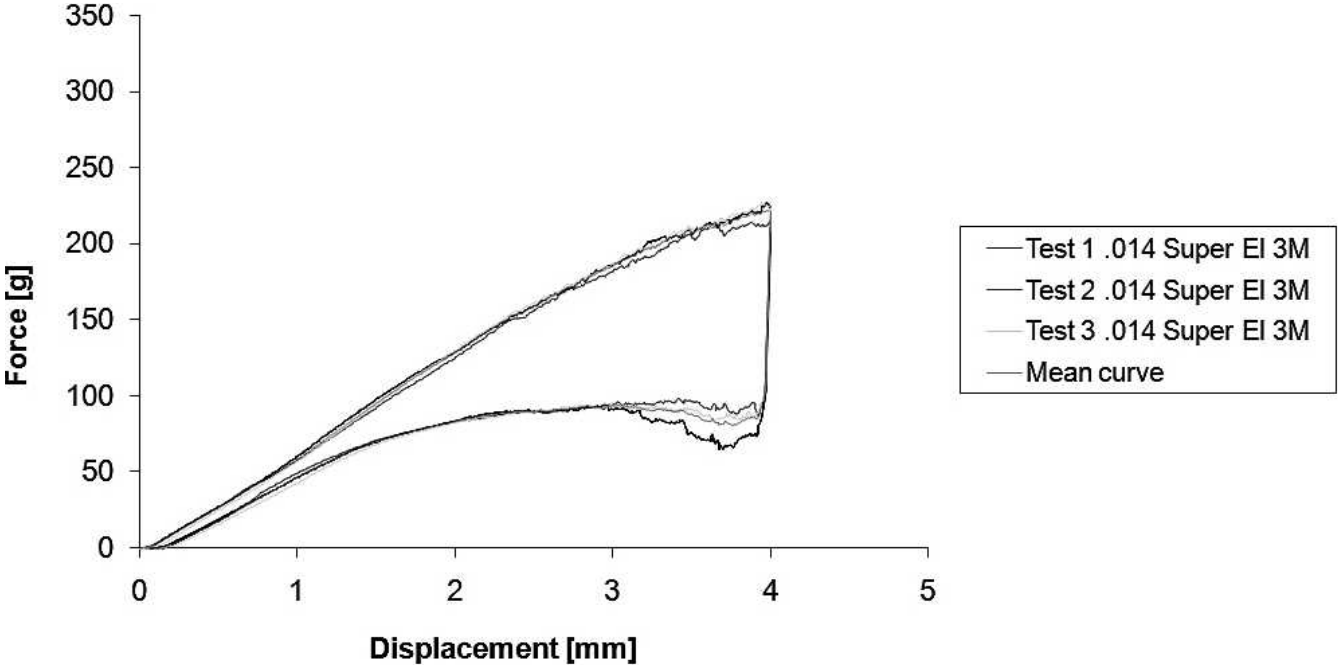

Figure 4. Load/deflection curve of 0.014 NiTi Super Elastic (3M).

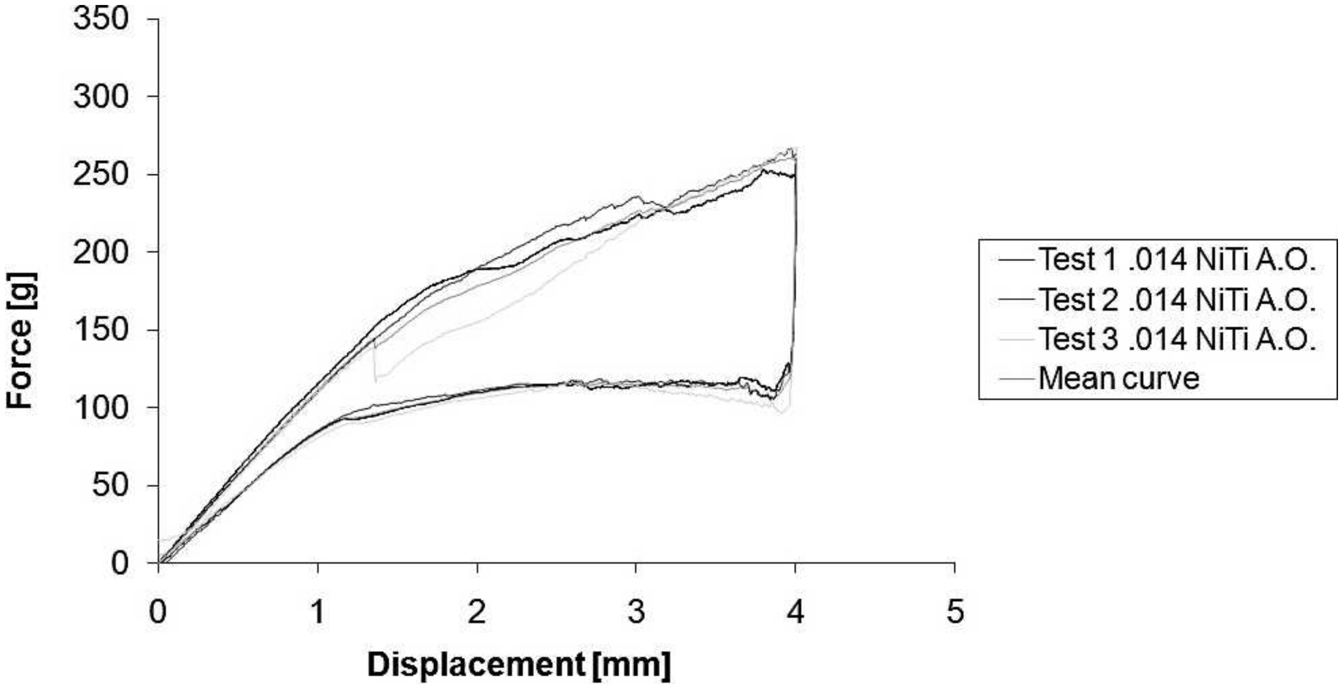

Figure 5. Load/deflection curve of 0.014 NiTi Titanium memory wire (American Orthodontics).

grouped according to cross-sectional diameters, are summarized in Table 2.

Statistical Analysis

Statistical analysis of the data was performed with the aid of analysis of variance (ANOVA), with *P* values $< .05$ considered significant. For each of the parameters considered, an internal comparison of each group of wires of the same type and diameter was made, as was a comparison of wires of different types and diameters.

RESULTS

Most of the graphs plotted displayed readily identifiable plateau areas in which the force was relatively

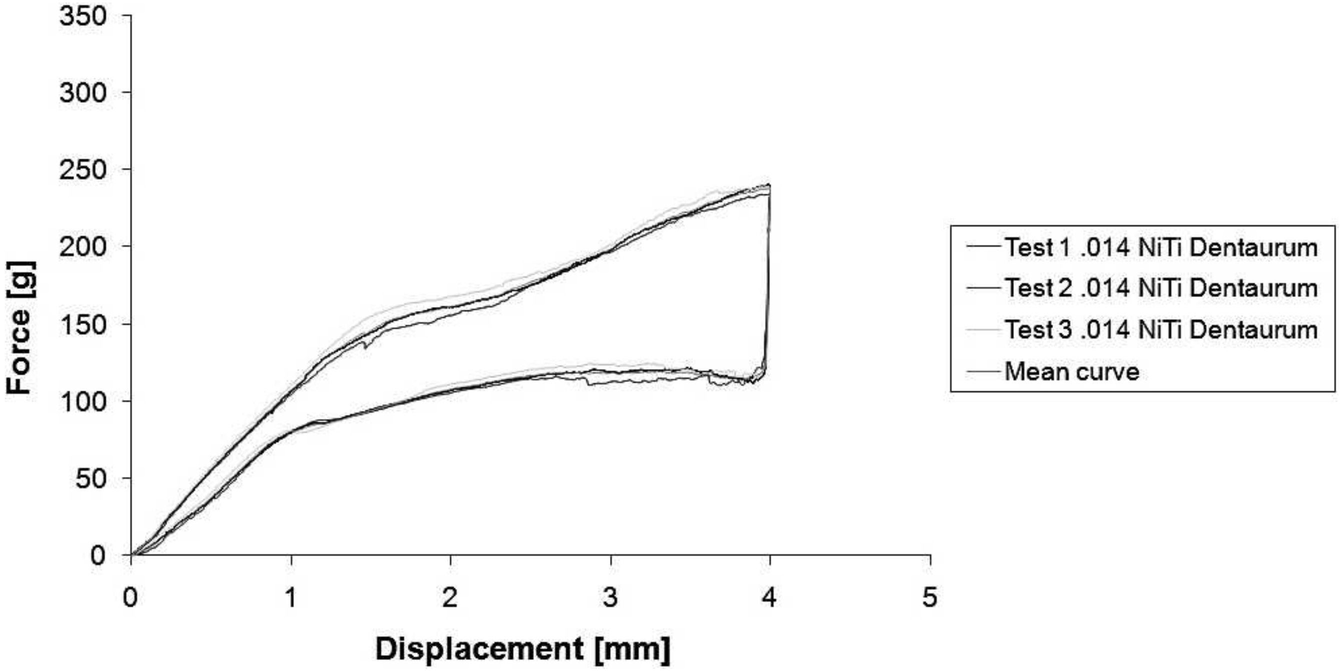

Figure 6. Load/deflection curve of 0.014 NiTi Rematitan Lite (Dentaurum).

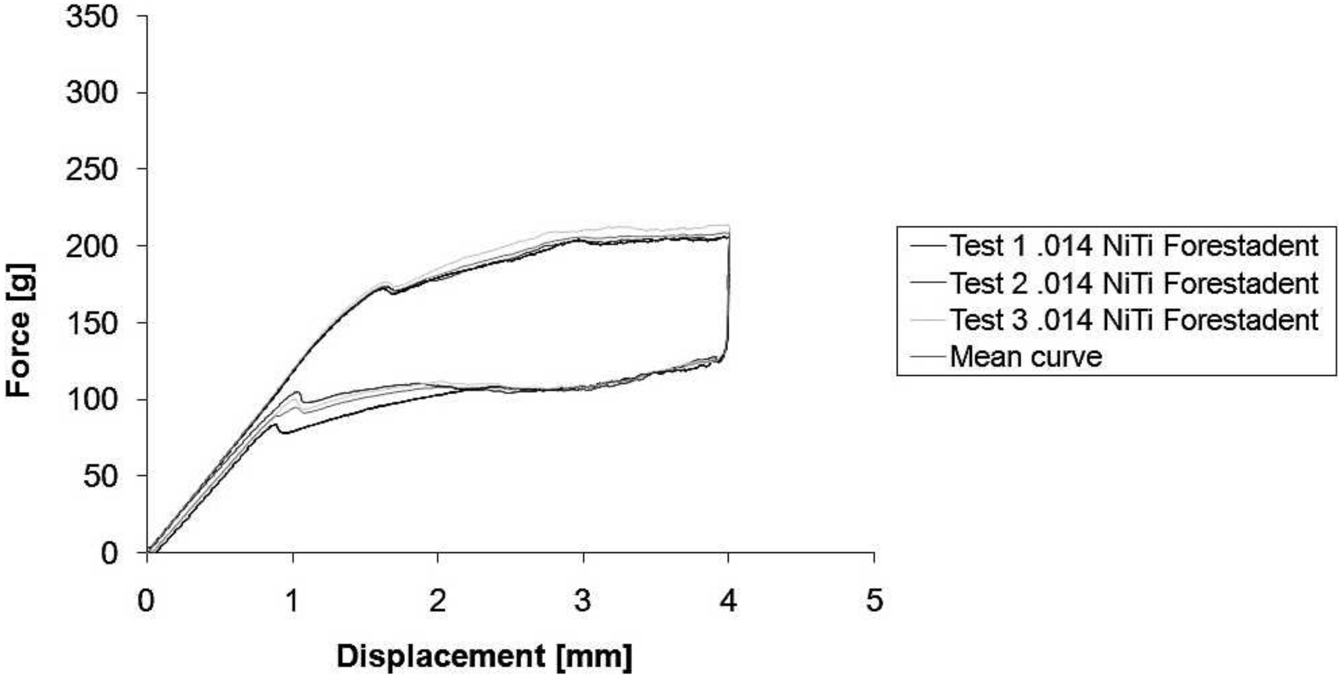

Figure 7. Load/deflection curve of 0.014 NiTi Titanol-Superelastic (Forestadent).

constant with a slight tendency to decrease. However, in several cases, an increase in force was seen in initial stages of the discharge phase, probably caused by a different friction coefficient between the wires and the brackets,[6] resulting in negative values for slope parameters (Table 2, Figures 3 through 17).

Given the sample of archwires as a whole, the average plateau force exerted ranged from roughly 30 g_f to 186 g_f. It is interesting to note that the minimum force measured was less than that obtained by other authors,[15] who measured a minimum force of 37 g_f, albeit with a 0.016 inch coaxial wire deflected by 1 mm.

Statistical analysis of these data, performed using ANOVA, revealed statistically significant differences between manufacturers regarding archwires of the same type and diameter, except for slope values yielded for

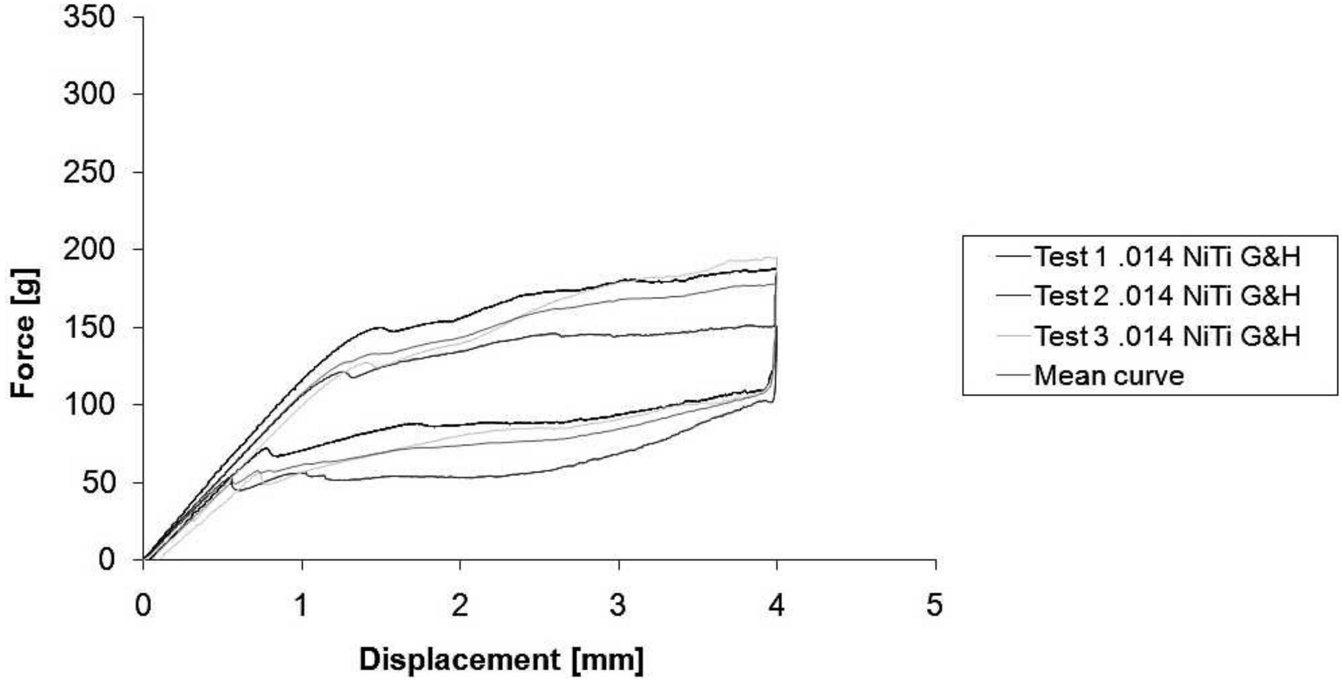

Figure 8. Load/deflection curve of 0.014 NiTi Orthoforce G4 (G&H).

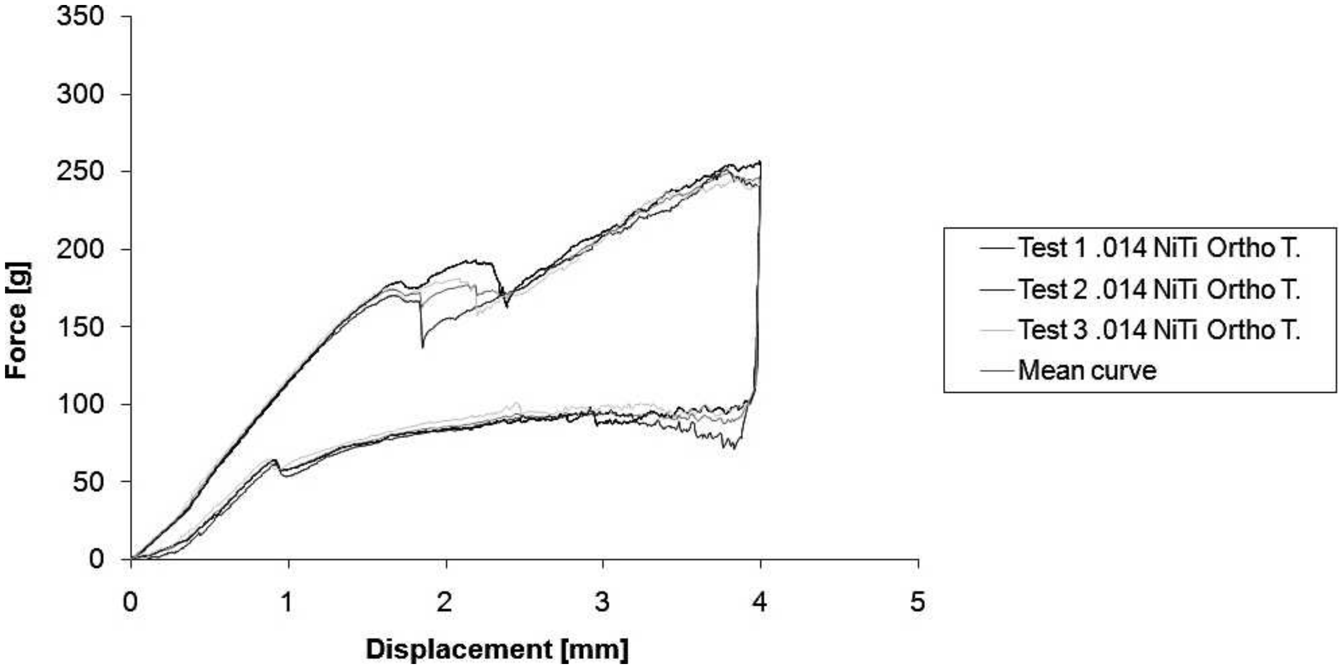

Figure 9. Load/deflection curve of 0.014 NiTi TruFlex (Ortho Technology).

0.013 and 0.016 inch heat-activated wires. Hence, with these values excluded, the manufacturer variable has a great influence on the parameters considered.

Effect of Type of Archwire

Our analysis was focused on differences in the parameters examined between traditional and heat-activated nickel titanium archwires. Table 3 shows the mean values yielded by traditional and heat-activated NiTi wires of the same cross-sectional diameter.

The decrease in average plateau force and the increase in plateau length were consistent differences between the two types of wire. In fact, ANOVA (performed on 0.012, 0.014, and 0.016 inch wires because data pertaining to 0.010 and 0.013 inch wires were insufficient for statistical purposes) showed a

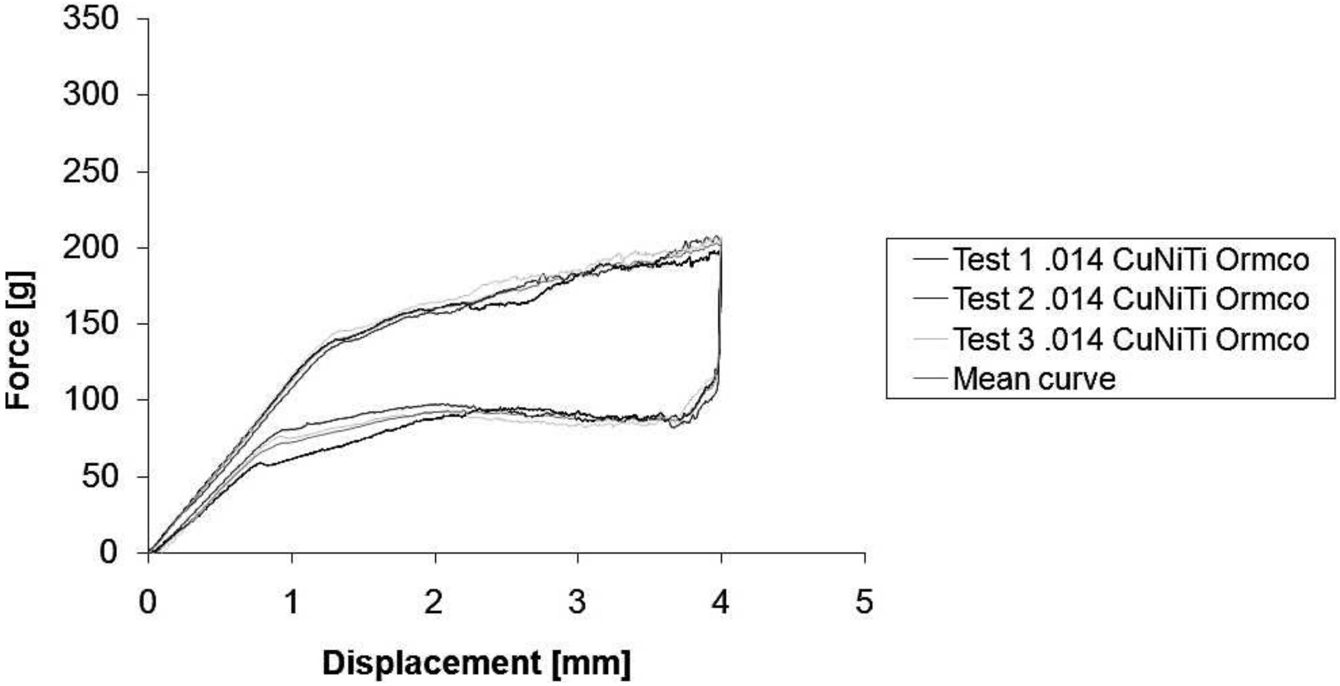

Figure 10. Load/deflection curve of 0.014 CuNiTi (Ormco).

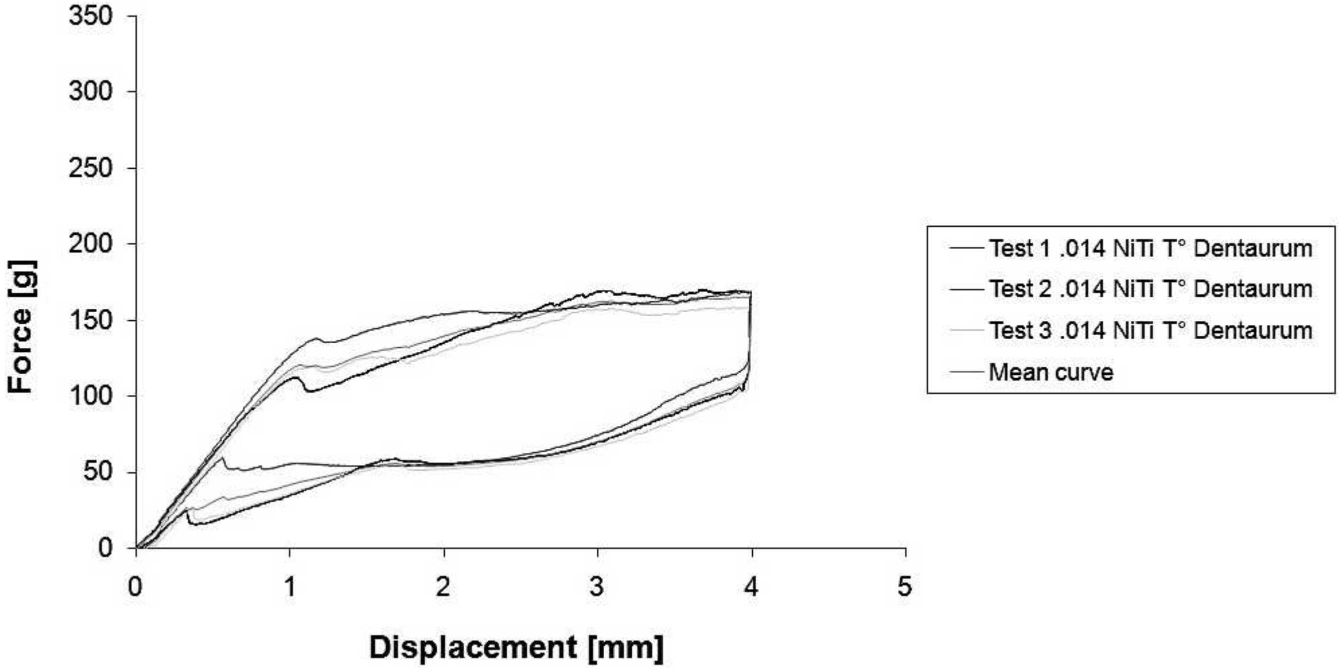

Figure 11. Load/deflection curve of 0.014 Tensic (Dentaurum).

significant difference between the two groups regarding values for these two parameters, whereas differences in slope values were not statistically significant, except in the case of 0.012 inch wires. Table 4 shows the difference in values for each of the three parameters in a comparison of traditional and heat-activated wires of the same diameter and manufacturer.

Effect of Archwire Diameter

Table 5 shows the percentage increase in average plateau force seen with increasing diameter of archwires of the same type and manufacturer (eg, Ortho Technology, from 0.012 to 0.014 NiTi, and from 0.012 to 0.016 NiTi). The trend was not constant for all wires, and differences ranging between 1% and 89% were

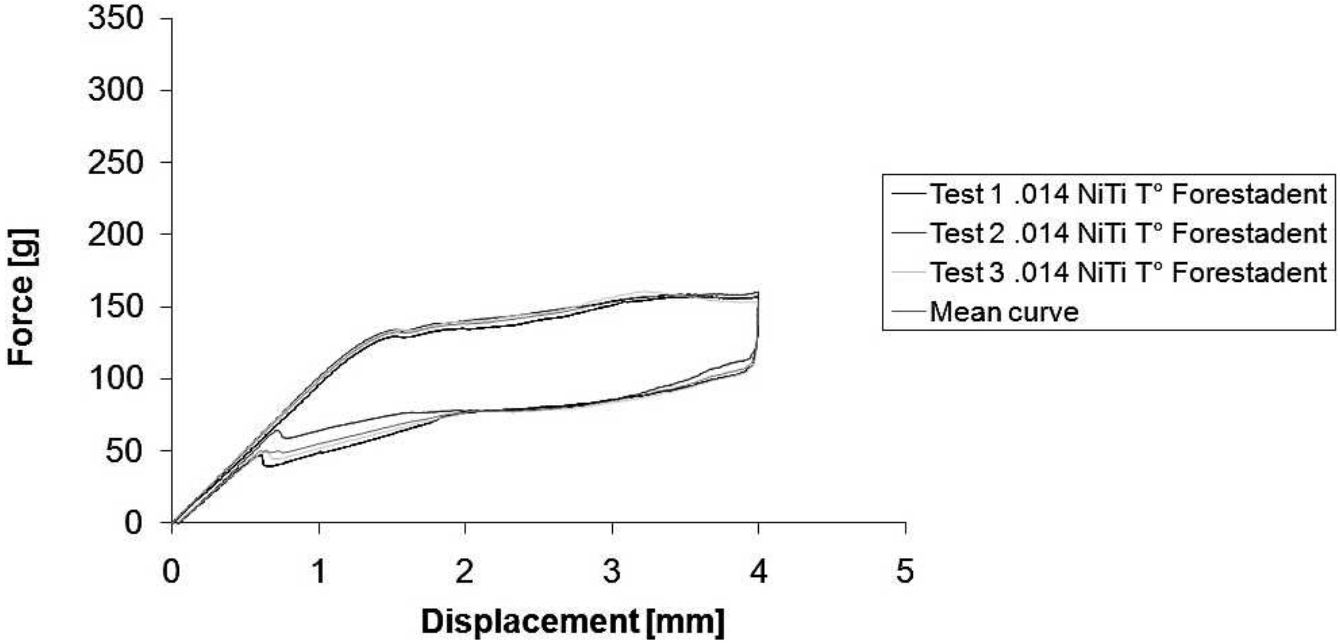

Figure 12. Load/deflection curve of 0.014 Biostarter (Forestadent).

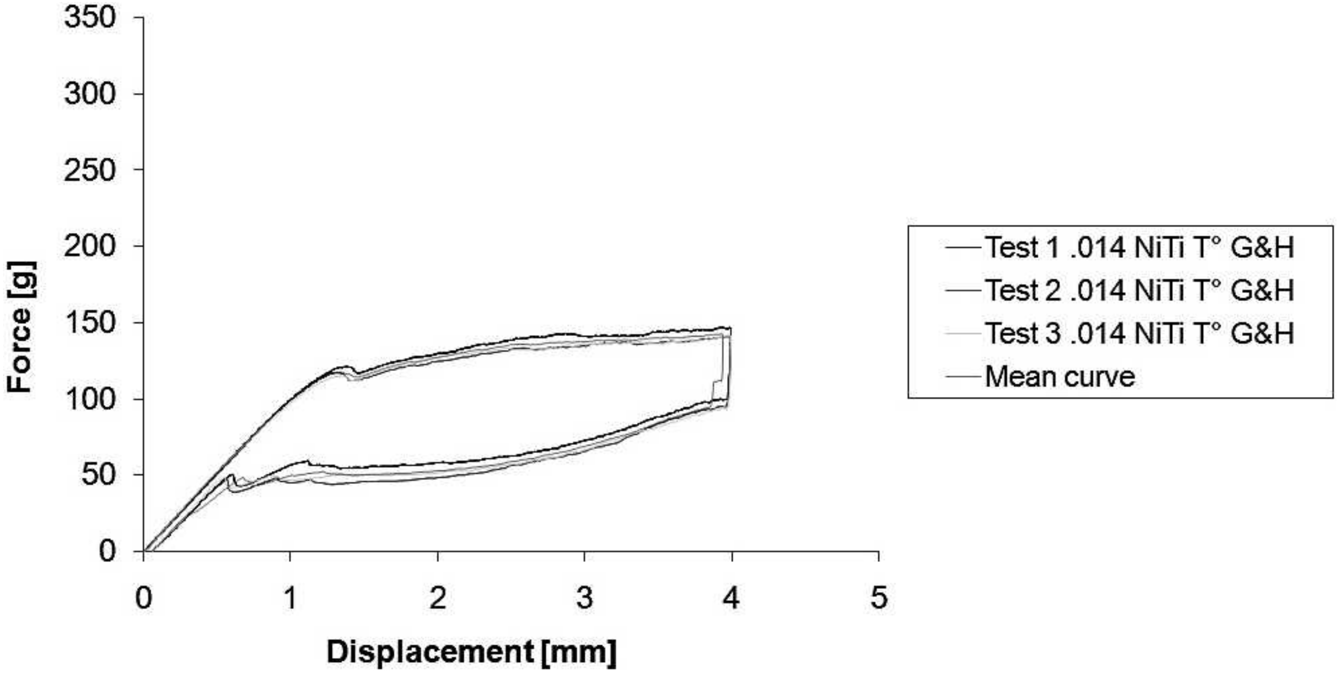

Figure 13. Load/deflection curve of 0.014 Orthoforce M5 (G&H).

reported. However, the average increase in plateau force observed in traditional wires was as follows:

- 57% from 0.012 to 0.014
- 161% from 0.012 to 0.016
- 65% from 0.014 to 0.016

For heat-activated wires, the average increase was as follows:

- 47% from 0.012 to 0.014
- 134% from 0.012 to 0.016
- 50% from 0.014 to 0.016

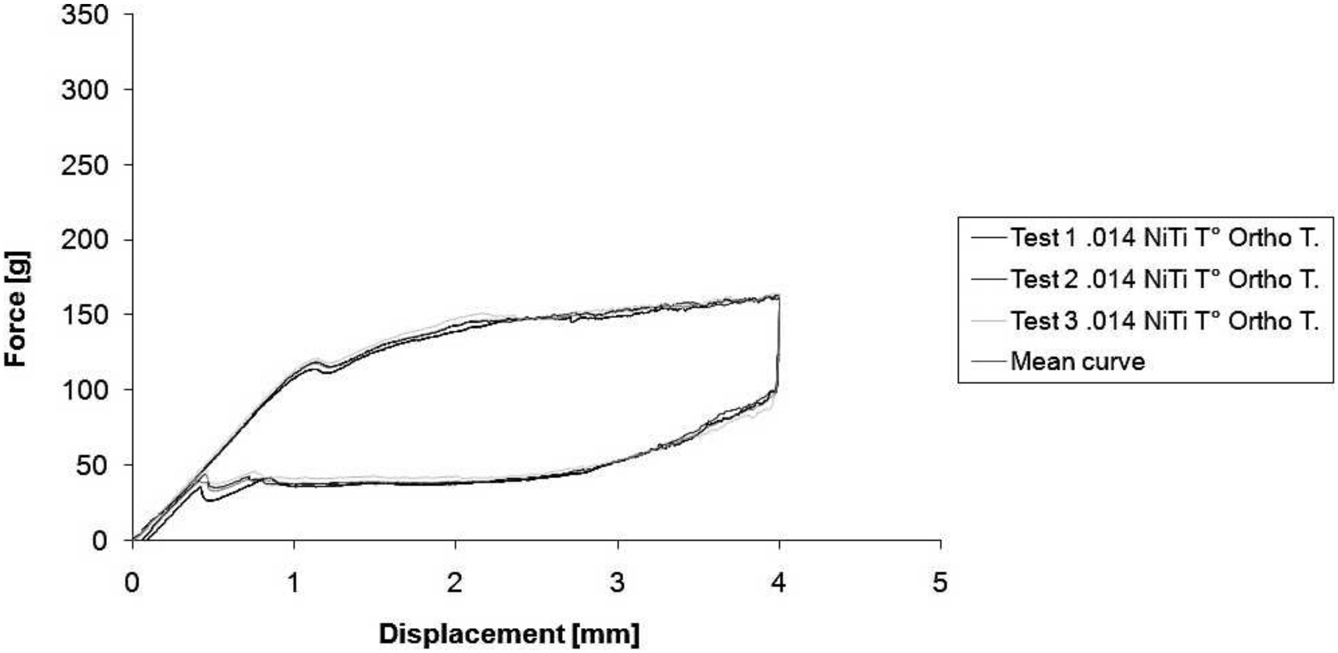

Figure 14. Load/deflection curve of 0.014 TruFlex Thermal (Ortho Technology).

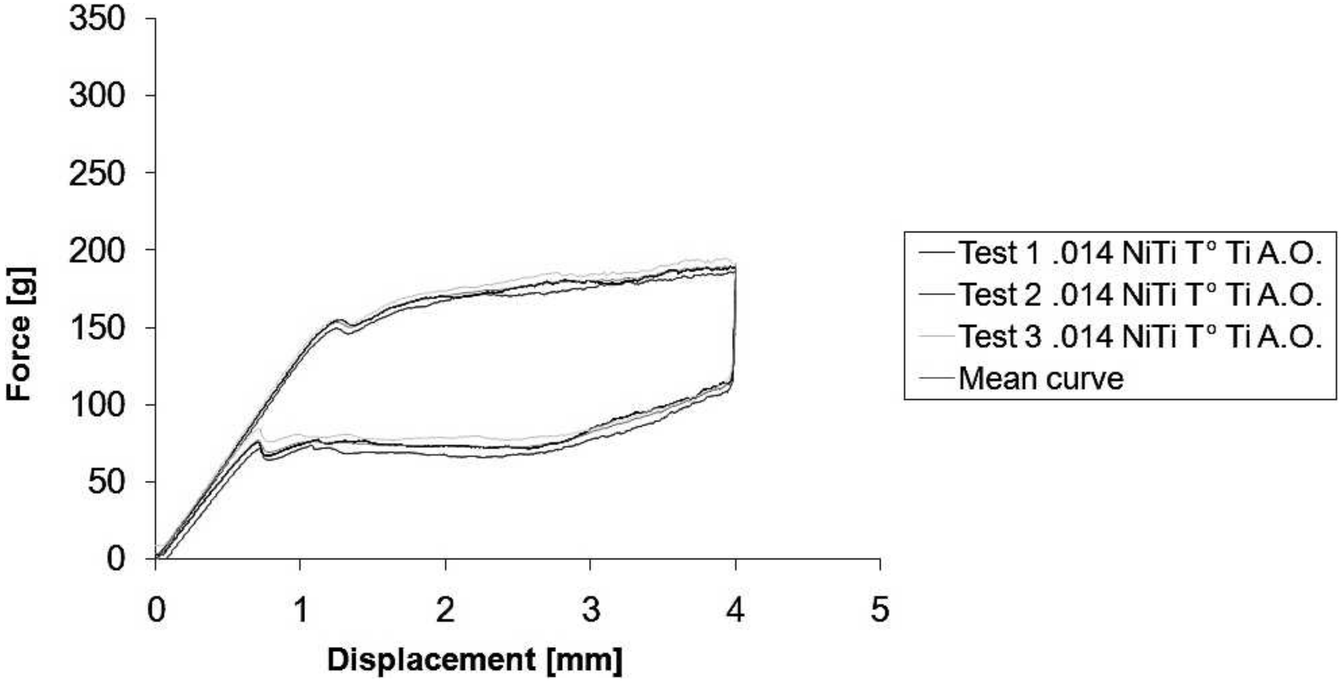

Figure 15. Load/deflection curve of 0.014 Therma-Ti (American Orthodontics).

It is interesting to note that the force expressed by traditional archwires shows a slightly greater tendency to increase with increasing diameter with respect to heat-activated wires, amounting to roughly 50% with a 0.002 inch increase in diameter, and 150% with a 0.004 inch increase in diameter.

DISCUSSION

The concept of optimal orthodontic forces has been discussed since the early 20th century. In particular, Schwarz defined *optimal force* as that which determines a change in pressure similar to capillary

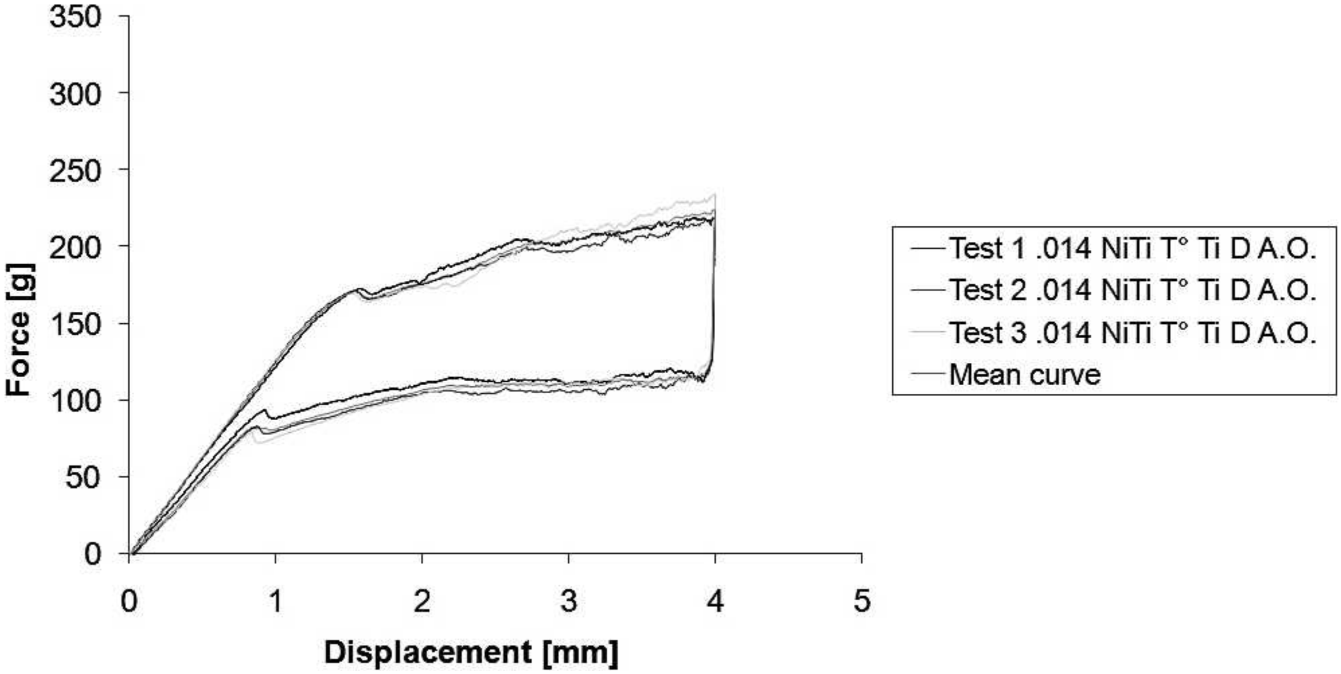

Figure 16. Load/deflection curve of 0.014 Therma-Ti D (American Orthodontics).

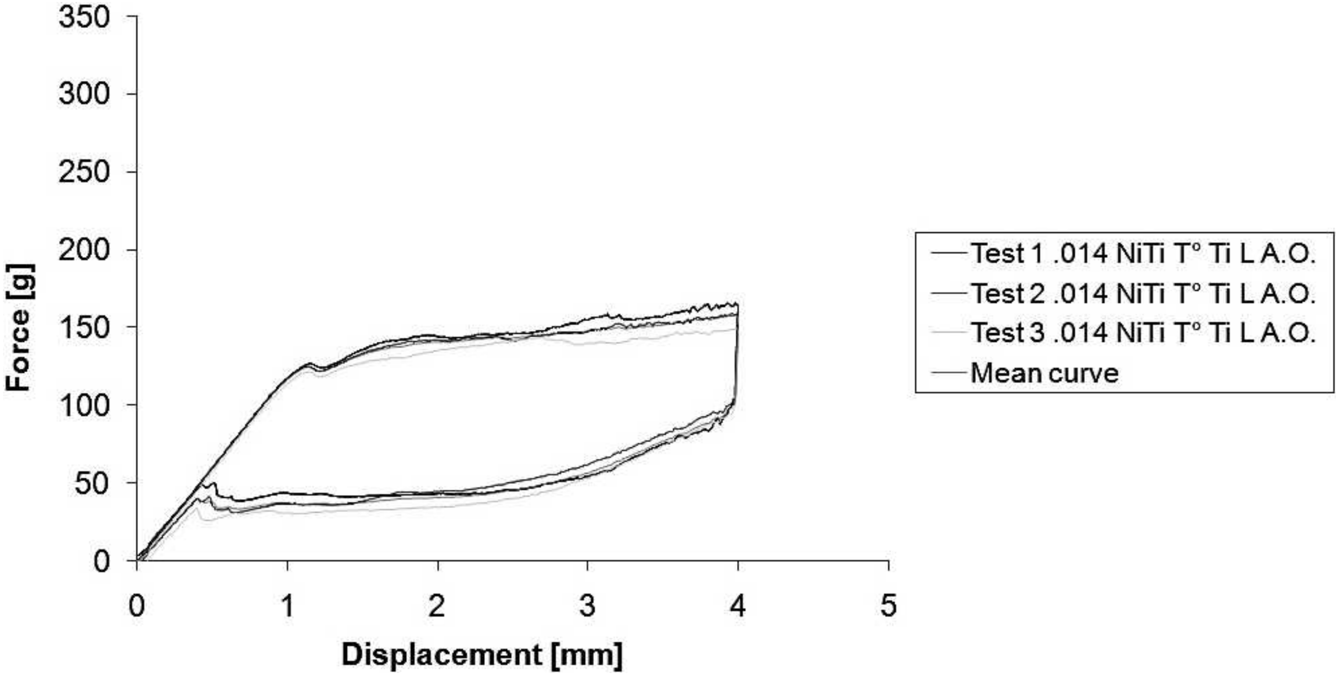

Figure 17. Load/deflection curve of 0.014 Therma-Ti Lite (American Orthodontics).

pressure, so that occlusion of these vessels in the compressed area of the periodontal ligament is prevented.[16] This idea has been reiterated by authors such as Reitan,[17] Righ et al.,[18] and Proffit,[19] but thus far no research has managed to quantify this ideal force applied with continuity.

Nowadays, "light continuous forces" are thought of as physiologically suitable and efficacious, but in this case, the term is used somewhat arbitrarily. In fact, no consensus whatsoever has been reached among the scientific community about what constitutes a "light" force and what does not. Thus, no concrete scientific evidence is available to quantify the optimal force for orthodontic movement,[20] and clinicians must judge for themselves the most suitable force for each particular clinical situation. In this context, nickel titanium archwires have become increasingly popular in recent years because of their ability to release constant, light forces, which are considered to improve the efficiency and efficacy of treatment, especially during initial alignment and leveling phases.

In this context, the aim of our study was to evaluate and compare the behaviors of traditional and heat-activated nickel titanium archwires, with a view toward providing indications, rather than absolute values, regarding the force exerted by each, bearing in mind both the practical impossibility of defining this value in vivo[21] and the fact that force values, using self-ligating brackets, are lower than those of conventional archwires.[22]

The method we chose for this comparison not only considered the force expressed by each wire at specific points of deflection, but aimed to characterize the behavior of each type of archwire in the discharge phase, represented as a plateau on the force/deflection graph. Characteristics of this plateau phase (average force, length, and slope) were evaluated for each wire, so each could be described from a clinical perspective. In fact, the greater the capacity of an archwire to exert more constant forces with increasing displacement, the better its performance in terms of dental movement. Particular attention was paid during our study to wires of round cross-section and small diameter (from 0.010 to 0.016 inch) to investigate the behavior of so-called light wires.

The first information emerging from this study was, according to ANOVA, the significant differences

Table 3. Mean Values Yielded by Traditional (NiTi) and Heat-Activated (NiTi T°) NiTi Wires of the Same Cross-Sectional Diameter

	Plateau Slope, g_f/mm	Plateau Length, mm	Average Plateau Force, g_f
.012 NiTi	5.5	2.72	62.9
.013 NiTi	9.6	3.02	74.8
.014 NiTi	7.9	2.81	97.7
.016 NiTi	9.7	2.82	161.1
.010 NiTi T°	6.0	3.06	30.4
.012 NiTi T°	11.1	3.28	42.2
.013 NiTi T°	8	3.05	70.7
.014 NiTi T°	12.7	3.23	71.7
.016 NiTi T°	19.2	3.23	110

Table 4. Comparison of Traditional (NiTi) and Heat-Activated (NiTi T°) Wires of the Same Diameter and Manufacturer for the Three Parameters Considered: Plateau Slope, Plateau Length, and Average Plateau Force[a,b]

	Plateau Slope, %	Plateau Length, %	Average Plateau Force, %
Dentaurum			
From .012 NiTi to T°	180	23	−41
From .014 NiTi to T°	69	23	−44
From .016 NiTi to T°	204	26	−45
Forestadent			
From .012 NiTi to T°	32	11	−32
From .014 NiTi to T°	79	11	−28
From .016 NiTi to T°	−24	1	−22
Ortho Technology			
From .014 NiTi to T°	28	16	−43
From .016 NiTi to T°	11	9	−33
G&H			
From .012 NiTi to T°	5	11	−42
From .014 NiTi to T°	1	3	−21
From .016 NiTi to T°	2	10	−41
3M			
From .016 NiTi classic to T°	173	33	−29
From .016 NiTi SE to T°	60	17	−8
American Orthodontics			
From .014 NiTi to T° Ti	65	14	−27
From .016 NiTi to T° Ti	121	17	−56
From .014 NiTi to T° Ti D	84	7	−1
From .016 NiTi to T° Ti D	30	11	−24
From .012 NiTi to T° Ti L	173	31	−43
From .014 NiTi to T° Ti L	182	23	−54
From .016 NiTi to T° Ti L	115	19	−58

[a] The symbol (-) before the value indicates a decrease, while absence of this symbol indicates an increase.

[b] Comparisons for each manufacturer were made while excluding the diameters that, in our study, were not present in both traditional and heat-activated typology; this is why Ormco is not present.

($P < .05$) between archwires of the same diameter and type (traditional and heat-activated) for all parameters considered. This was true except for the slope of 0.013 and 0.016 inch heat-activated wires, depending on the manufacturer. This fact agrees with the study of Nakano et al.,[6] who observed great variation in force values with different NiTi wires of the same diameter, indicating that the wires are intrinsically different and therefore can be differentiated according to their characteristics. In fact, it is important to underline that mechanical properties of NiTi alloy wires are greatly influenced by different technological parameters, such as chemical composition, heat treatment, and degree of working, which are beyond the discussion of this study but can be included in the manufacturer classification here exposed.

Moreover, a significant reduction in force and a concomitant increase in plateau length ($P < .05$) were noted between heat-activated and traditional wires, indicating that heat-activated archwires exert lighter, more constant forces at a greater deflection with respect to those exerted by traditional NiTi wires. In fact, our tests showed that, on average, heat-activated archwires exert a 24% lighter force and generate a 13% longer plateau than their traditional counterparts. This confirms results reported by Parvizi and Rock,[23] who also recorded a greater force exerted by traditional with respect to heat-activated archwires, as well as an increase in force exerted at an increased measurement temperature.

CONCLUSIONS

- Significant differences in behavior between almost all wires of equal section and type produced by different manufacturers were seen for the parameters considered (mean force, plateau length, and slope).
- Comparison of traditional and heat-activated archwires of the same diameter showed that the latter exerted a significantly lighter force (~24%) and generated a significantly longer plateau (~13%) than the former.
- On average, a 0.002 inch increase in cross-sectional diameter generated a 50% increase in plateau force (0.012 × 0.014 and 0.014 × 0.016 inch), and a

Table 5. Percentage increase in average plateau force seen with increasing diameter of archwires of the same type (traditional NiTi and heat-activated NiTi T°) and manufacturer

	Increase in average plateau force [%]
Dentaurum	
da .012 a .014 NiTi	59
da .012 a .016 NiTi	162
da .014 a .016 NiTi	64
da .012 a .014 NiTi T°	50
da .012 a .016 NiTi T°	142
da .014 a .016 NiTi T°	62
Forestadent	
da .012 a .014 NiTi	55
da .012 a .016 NiTi	152
da .014 a .016 NiTi	63
da .010 a .012 NiTi T°	56
da .010 a .014 NiTi T°	153
da .010 a .016 NiTi T°	346
da .012 a .014 NiTi T°	63
da .012 a .016 NiTi T°	186
da .014 a .016 NiTi T°	76
Ortho Technology	
da .012 a .014 NiTi	89
da .014 a .016 NiTi	60
da .012 a .016 NiTi	204
da .014 a .016 NiTi T°	87
G&H	
da .012 a .013 NiTi	5
da .012 a .014 NiTi	10
da .012 a .016 NiTi	103
da .013 a .014 NiTi	5
da .013 a .016 NiTi	93
da .014 a .016 NiTi	84
da .012 a .014 NiTi T°	49
da .012 a .016 NiTi T°	108
da .014 a .016 NiTi T°	39
3M	
da .012 a .014 NiTi classico	71
da .012 a .016 NiTi classico	172
da .014 a .016 NiTi classico	59
da .014 a .016 NiTi super el.	56
American Orthodontics	
da .012 a .014 NiTi	59
da .012 a .016 NiTi	170
da .014 a .016 NiTi	70
da .013 a .014 NiTi T° Ti	43
da .013 a .016 NiTi T° Ti	45
da .014 a .016 NiTi T° Ti	1
da .013 a .014 NiTi T° Ti D	23
da .013 a .016 NiTi T° Ti D	60
da .014 a .016 NiTi T° Ti D	31
da .012 a .014 NiTi T° Ti L	28
da .012 a .016 NiTi T° Ti L	98
da .014 a .016 NiTi T° Ti L	55

0.004 inch (0.012 × 0.016) increase in diameter resulted in an increase in plateau force of roughly 150% (differences were also noted between traditional and heat-activated wires in this case).

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