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Load–deflection characteristics of superelastic and thermal nickel–titanium wires

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SUMMARY The aim of this study was to investigate the mechanical properties of superelastic and thermal nickel–titanium (NiTi) archwires for correct selection of orthodontic wires. Seven different NiTi wires of two different sizes (0.014 and 0.016 inches), commonly used during the alignment phase, were tested. A three-point bending test was carried out to evaluate the load–deflection characteristics. The archwires were subjected to bending at a constant temperature of 37°C and deflections of 2 and 4 mm.

Analysis of variance showed that thermal NiTi wires exerted significantly lower working forces than superelastic wires of the same size in all experimental tests ($P < 0.05$). Wire size had a significant effect on the forces produced: with an increase in archwire dimension, the released strength increased for both thermal and superelastic wires. Superelastic wires showed, at a deflection of 2 mm, narrow and steep hysteresis curves in comparison with the corresponding thermal wires, which presented a wide interval between loading and unloading forces. During unloading at 4 mm of deflection, all wires showed curves with a wider plateau when compared with 2 mm deflection. Such a difference for the superelastic wires was caused by the martensite stress induced at higher deformation levels.

A comprehensive understanding of mechanical characteristics of orthodontic wires is essential and selection should be undertaken in accordance with the behaviour of the different wires. It is also necessary to take into account the biomechanics used. In low-friction mechanics, thermal NiTi wires are to be preferred to superelastic wires, during the alignment phase due to their lower working forces. In conventional straightwire mechanics, a low force archwire would be unable to overcome the resistance to sliding.

Introduction

The introduction of innovative systems became possible as a result of friction studies that demonstrated how the presence of ligature binding delays orthodontic tooth movement (Frank and Nikolai, 1980; Sims *et al.*, 1993; Pizzoni *et al.*, 1998; Kusy and Whitley, 2000; Hain *et al.*, 2003; Harradine, 2008; Matarese *et al.*, 2008). To overcome these limitations, self-ligating brackets were introduced that allow the archwire to slide into the slot with a reduction in the amount of friction. (Rinchuse and Miles, 2007). Nevertheless, the real mechanics of the system is the orthodontic archwire through its engagement in the brackets, which generates the biomechanical forces necessary to move the teeth (Mallory *et al.*, 2004). An ideal archwire should exert light and constant forces capable of producing an adequate biological response in the periodontal ligament to achieve physiological bone remodelling (Profitt and Fields, 1993).

Nickel–titanium (NiTi) archwires are widely used for initial alignment due to their properties of shape memory and superelasticity (Miura *et al.*, 1986; Khier *et al.*, 1991; Oltjen *et al.*, 1997). Both these effects are related to thermoelastic transformation (austenitic to martensitic phase), which can either be induced by cooling or be produced by stress (Gurgel *et al.*, 2001; Meling and Odegaard, 2001; Wilkinson *et al.*, 2002).

NiTi wires can be classified into two types: superelastic and thermal. Superelastic wires, in the austenitic active alloy state, undergo martensitic transformation by mechanical deformation. Thermal NiTi wires are a martensitic active alloy and exhibit a thermally induced shape memory effect (Kusy, 1997). For these latter wires, transition temperatures from martensite to austenite occur in the region of the ambient oral temperature (Parvizi and Rock, 2003).

The aims of the present study were to determine the mechanical properties of thermally activated and superelastic NiTi wires in a three-point bending test and to compare the data for the different types of archwire.

Materials and methods

The samples included seven different upper archwires with dimensions of 0.014 and 0.016 inches, commonly used during the alignment phase (Table 1).

Table 1 Orthodontic wires tested.

Manufacturers	Code	Superelastic NiTi	Thermal NiTi
American Orthodontics, Sheboygan, Wisconsin, USA	AO	NiTi Force One 0.014 and 0.016 inches	NiTi heat activated 0.014 and 0.016 inches
3M Unitek, Monrovia, California, USA	3M	Nitinol Superelastic 0.014 and 0.016 inches	Nitinol heat activated 0.016 inches
GAC, Bohemia, New York, USA	GAC	Sentalloy 0.014 and 0.016 inches	Not available*
Rocky Mountain Orthodontics, Denver, Colorado, USA	RMO	Orthonol 0.014 and 0.016 inches	Thermalloy 0.014 and 0.016 inches

*Not tested because not available in round section.

Table 2 Chemical composition of superelastic and thermal nickel titanium wires (in wt per cent).

	Ni (%)	Ti (%)
Superelastic wires		
Sentalloy (GAC)	54.30	45.70
NiTi Force One (AO)	54.58	45.42
Nitinol Superelastic (3M)	54.52	45.48
Orthonol (RMO)	55.13	44.87
Thermal wires		
NiTi heat activated (AO)	54.40	45.60
Nitinol heat activated (3M)	54.86	45.14
Thermalloy (RMO)	54.35	45.65

The chemical compositions in weight percentage of the superelastic and thermal NiTi wires were determined through energy-dispersive X-ray spectroscopy by scanning electron microscopy (SEM, Model 5600 LV, equipped with an Oxford probe for microanalysis; Jeol Ltd, Tokyo, Japan).

A three-point bending test was carried out to investigate the load–deflection mechanical characteristics of the wires. The loading and unloading phases were performed under the same conditions with a span of 12 mm using a universal testing machine (model Tenso Test TT2,5-GU, Lonos, Italy) with a 10 N load–cell and sensitivity of 0.001 N. The crosshead speed was 0.05 mm/seconds. The archwires were subjected to orthodontic bending at a constant temperature of 37°C. During testing, the temperature was monitored using a thermocouple. From each archwire, the two straight end sections were cut and tested. The mid-portion of the wire segment (22 mm in length) was deflected to 2 and 4 mm.

In the three-point bending test, during the unloading phase, two force values for each test were selected. With a deflection of 2 mm, the load values were measured at 1 and 2 mm and at 4 mm at 1 and 4 mm, to represent a standardized portion of the unloading phase plateau in the load–deflection curve. Such values include the ranges of forces that the tooth undergoes after the engagement phase. Each bending test was carried out five times, with a new piece of wire.

Statistical analysis

A design of experiments (DOEs) was performed employing commercial software (Minitab® Statistical Software; Minitab Inc., State College, Pennsylvania, USA) to evaluate the effect of the variables (i.e. type, size, deflection, and wire manufacturer) on the mechanical properties of the wires.

Two different analyses of variance (ANOVAs) were performed according to the number of variables and their levels. Regression analysis was also undertaken to obtain a prediction of the forces.

Results

The chemical composition of the superelastic and thermal wires, evaluated by X-ray spectroscopy, is shown in Table 2. There was no significant difference in composition between the wires as they were fabricated in equiatomic alloy (Fischer-Brandies *et al.*, 2003). Only Orthonol (RMO) showed a small increase in nickel content (55.13 per cent).

During bending, a loading/unloading cycle was used with fixed deflections of 2 and 4 mm. The load–deflection curves showed the typical 'hysteresis' trend with higher loads during loading and lower ones during unloading.

A comparison of the curves was undertaken for all samples. Moreover, for each brand, the superelastic and thermal wires of the same size were compared at the same deflection level. From these curves, the mean load values during the unloading phase (working forces) were recorded. The superelastic wires and thermal wires of all manufacturers at a maximum deflection of 2 mm for the 0.014 and 0.016 inches are shown in Figure 1a and 1b and Figure 2a and 2b, respectively. The curves of the superelastic wires, at the same deflection and of the same size, demonstrated a smaller and narrower hysteresis than the thermal wires, i.e. the thermal wires exhibited a wider range of forces during the loading and unloading phases. In particular, the thermal wires had lower working forces than the superelastic wires. This was evident when comparing the curves of the superelastic and thermal wires of the same manufacturer, size, and deflection (2 mm; Figure 3).

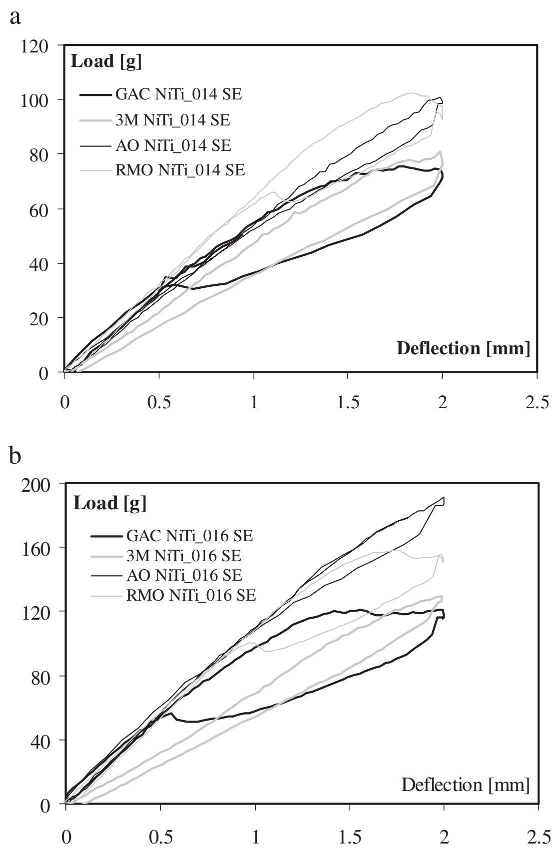


Figure 1 Load–deflection curves of superelastic wires at 2 mm deflection for all manufacturers (GAC, 3M, AO, and RMO) with dimensions of (a) 0.014 and (b) 0.016 inches.

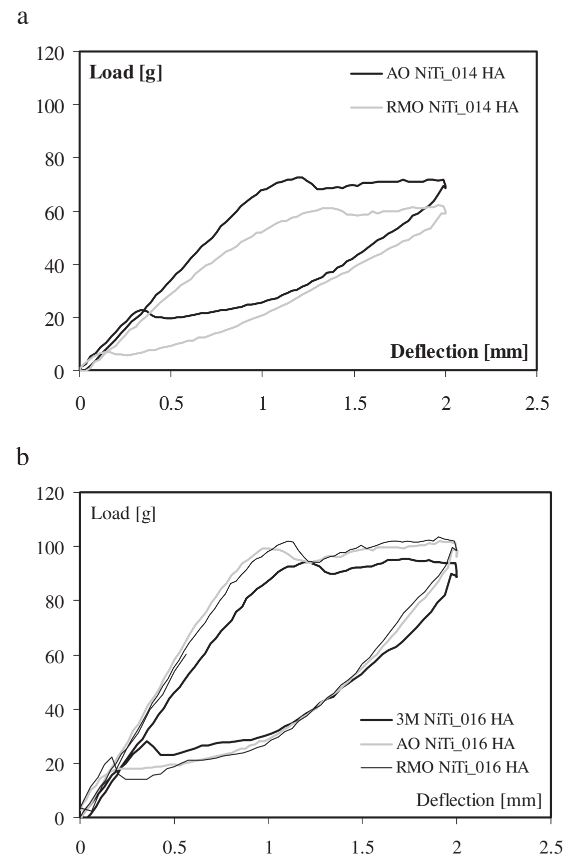


Figure 2 Load–deflection curves of thermal wires at 2 mm deflection with (a) dimension of 0.014 inch, producers: AO and RMO; (b) dimension of 0.016 inch, producers: 3M, AO, and RMO.

The load–deflection curves of all superelastic and thermal wires at a maximum deflection of 4 mm and with dimensions of 0.014 and 0.016 inches are shown in Figure 4a and 4b and Figure 5a and 5b, respectively. From these curves, the superelastic and thermal wires of the same size had similar behavioural characteristics (wide hysteresis curves). The difference for the superelastic samples was caused by the martensite stress induced at higher deformation levels (Garrec and Jordan, 2004). The working forces recorded for the superelastic samples were still higher than those of the thermal wires. This was also the case at higher deformation.

Comparisons among the different samples were carried out by evaluating the mean load (working force) obtained from the above described curves. A complete DOE was not possible since the various manufacturers do not all produce thermal wires in all the considered sizes. Two different analyses were performed: in the first analysis, only two manufacturers were compared (AO and RMO) who produce both superelastic and thermal wires of the same sizes (0.014 and 0.016 inches). The second analysis was carried out on the data for the four manufacturers but only for the superelastic wires.

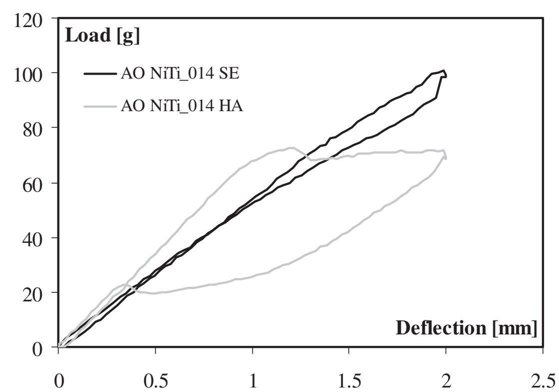


Figure 3 Comparison between a 0.014 inch superelastic and thermal wire for the same manufacturer (AO) at a deflection of 2 mm.

Statistical analysis

Analysis 1. To evaluate the effect of the variables on the working forces, ANOVA included the following factors: manufacturer (AO and RMO), wire type (superelastic and thermal), size (0.014 and 0.016 inches), and maximum deflection (2 and 4 mm).

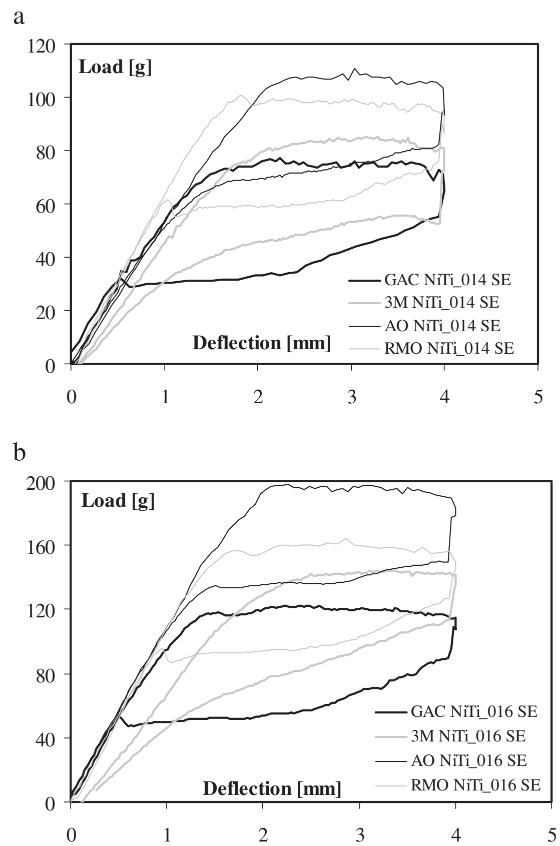


Figure 4 Load–deflection curves of superelastic wires at 4 mm deflection for all producers (GAC, 3M, AO, and RMO) (a) 0.014 and (b) 0.016 inches.

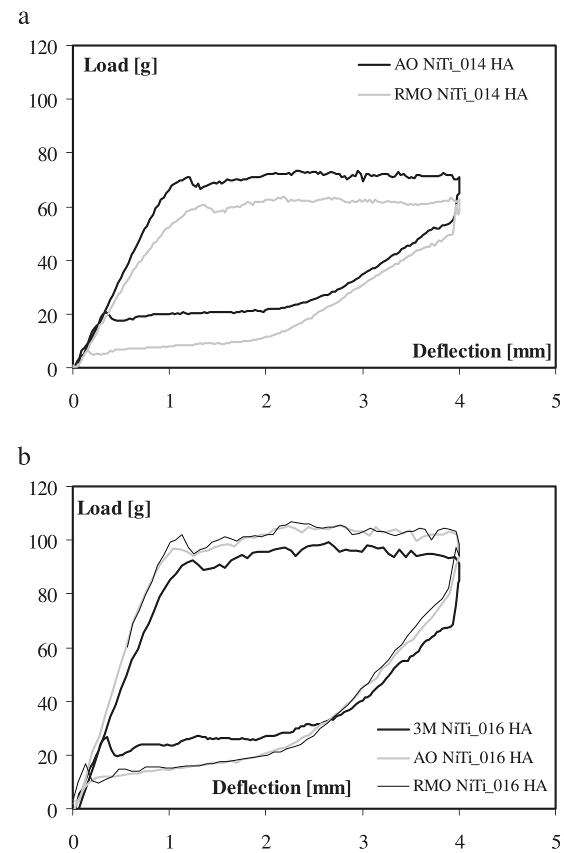


Figure 5 Load–deflection curves of thermal wires at 4 mm deflection (a) 0.014 inch, producers: AO and RMO; (b) 0.016 inch, producers: 3M, AO, and RMO.

The residual plots for the working forces F [g] allowed acceptance of the normality hypothesis for the F data distribution. ANOVA and Pareto analyses for the single or coupled factors are shown in Table 3 and Figure 6, respectively. All single factors were statistically significant ($P < 0.05$) but for the Pareto analysis, only the factors, type, size, and deflection had a relevant level of significance.

Type showed a higher level of significance in comparison with the other variables, indicating that there was a greater statistically significant difference between the thermal and superelastic wires; the working forces were significantly different for the two sizes of wire and for the two deflections. Such observations on the single effect of the factors were confirmed by a main effects plot (Figure 7). Here, the slope of the segments that links the mean values was directly correlated with the significance of the effect.

Thermal wires showed working forces much lower than superelastic wires; with increasing wire size, the forces significantly increased for both types of wire, while a decrease of strength was observed with increasing wire deflection. The effect of manufacturer was statistically significant but the mean values of the working forces exerted by the wires of the two manufacturers (AO and

Table 3 Analysis of variance for F[g] for superelastic and thermal wires (AO and RMO). SE, standard error.

Term	Effect	Coefficient	SE coefficient	F	P
Constant		71.19	0.4139	171.99	0.000
Producer	1.89	0.95	0.4139	2.28	0.026
Type	−51.40	−25.70	0.4139	−62.08	0.000
Size	−34.83	−17.41	0.4139	−42.07	0.000
Deflection	11.39	5.69	0.4139	13.76	0.000
Producer × type	0.75	0.37	0.4139	0.90	0.372
Producer × size	−3.52	−1.76	0.4139	−4.25	0.000
Producer × deflection	−0.91	−0.46	0.4139	−1.10	0.276
Type × size	15.65	7.82	0.4139	18.90	0.000
Type × deflection	0.43	0.21	0.4139	0.51	0.609
Size × deflection	−1.87	−0.94	0.4139	−2.26	0.027
Producer × type × size	5.25	2.62	0.4139	6.34	0.000
Producer × type × deflection	1.25	0.63	0.4139	1.52	0.134
Producer × size × deflection	−0.87	−0.44	0.4139	−1.06	0.294
Type × size × deflection	0.09	0.05	0.4139	0.11	0.914
Producer × type × size × deflection	−1.04	−0.52	0.4139	−1.26	0.214

$P < 0.05$.

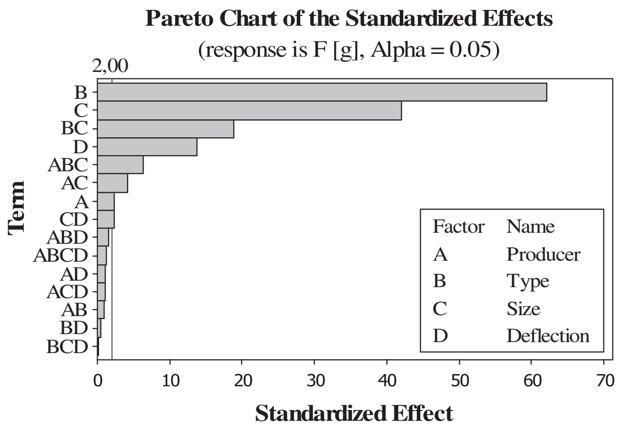


Figure 6 Pareto chart of the standardized effects for superelastic and thermal wires (AO and RMO).

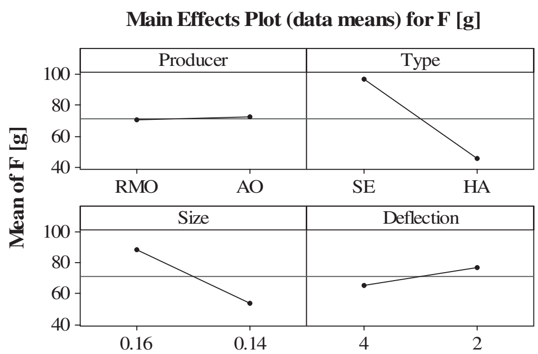
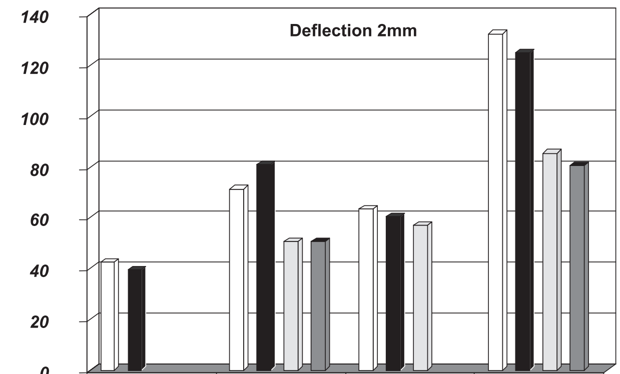


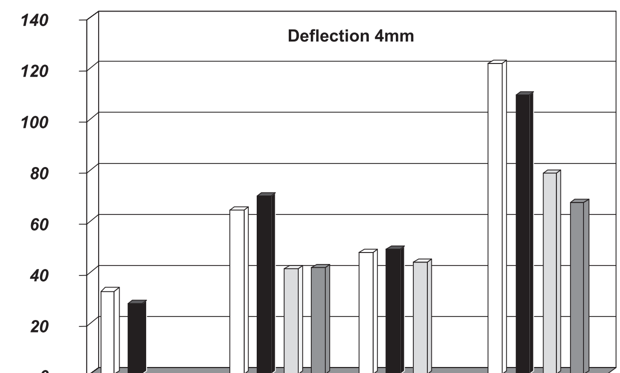
Figure 7 Main effects plot for F [g] for superelastic (SE) and thermal (HA) wires (AO and RMO).

a



	HA 0.014	SE 0.014	HA 0.016	SE 0.016
□ AO	42.31	71.32	63.44	132.36
SD	3.492	5.283	1.080	8.403
■ RMO	39.50	80.94	60.28	124.78
SD	0.894	3.350	2.300	3.095
□ 3M		50.47	56.93	85.38
SD		1.542	3.041	0.617
■ GAC		50.58		80.32
SD		1.571		2.422

b



	HA 0.014	SE 0.014	HA 0.016	SE 0.016
□ AO	32.59	64.32	47.61	121.76
SD	2.957	1.827	3.326	6.712
■ RMO	27.76	69.95	48.94	109.53
SD	0.883	2.946	0.651	1.578
□ 3M		41.16	43.82	78.83
SD		1.044	2.566	1.049
■ GAC		41.65		67.13
SD		2.259		1.855

Figure 8 Mean values of the working forces [g] and standard deviation (SD) for the superelastic (SE) and thermal (HA) wires tested of all the manufacturers at deflection of (a) 2 mm and (b) 4 mm.

RMO) were quite similar when considering the wires of both manufacturers together without distinction of type, dimension, and deflection. Figure 8 shows that the slope is near to zero for this factor. Concerning the interactions between two factor ANOVA analysis (Table 3), the couples, manufacturer–size, type–size, and size–deflection were statistically significant, while manufacturer–type, manufacturer–deflection, and type–deflection were not significant ($P > 0.05$). With the Pareto analysis (Ishikawa, 1982; Montgomery, 1996), only the interaction of type–size was significantly higher. This means that the working forces of the superelastic wires had a greater increase than the thermal wires with increasing wire size. The observed interactions among two terms slightly affect the relevance of the single-term effects.

For the interactions at three and four factors (Table 3), only manufacturer–type–size was significant.

The mean values of the forces and their variance for all the investigated combinations and for all manufacturers are shown in Figure 8a and 8b.

Regression analysis performed on the above data allowed the attainment of a force function dependent on both size and deflection of the wires. The manufacturer factor was intentionally not included, resulting in no statistically significant difference. The data set was divided into two main groups: superelastic and thermal wires. The results are summarized in the following equations:

$$F_{SE}[g] = -80.6 + 9587 \times \text{size} - 5.91 \times \text{deflection}, \quad (1)$$

$$F_{HA}[g] = -265 + 25237 \times \text{size} - 5.48 \times \text{deflection}, \quad (2)$$

Where F_{SE} is the mean value of the working forces (g) for the superelastic wires, as a function of the wire size (inch) and level of deflection (mm); such regression has a very high coefficient of determination (R^2 = 94.4 per cent) that suggests a good data fit.

F_{HA} is the mean value of the working forces (g) for the thermal wires, as a function of the same variables of the previous function. The coefficient of determination is R^2 = 93.5 per cent.

Analysis 2. ANOVA was undertaken only for the superelastic wires; the following factors were taken into consideration: manufacturer (AO, RMO, 3M, and GAC), wire type (superelastic), size (0.014 and 0.016 inches), and maximum deflection (2 and 4 mm). The residual plots for F [g] allowed acceptance of the normality hypothesis.

For the single factors, the effects of manufacturer, size, and deflection were all significant ($P < 0.05$; Table 4). As a consequence, the difference in working forces of the wires produced by the different manufacturers was statistically significant, as well as the difference in the two sizes and two deflections (Figure 9). In this last instance, the slope of the segments was different for manufacturer, size, and deflection. In particular, with increasing wire size the working forces significantly increased, while with increasing deflection, the forces decreased. The GAC superelastic wires (Sentalloy) exerted forces significantly lower than the others. This finding is not contrary to the data from Analysis 1; the main difference was due to the introduction in the data set of two other producers (3M and GAC) that both manufacture wires with lower mean forces.

Table 4 Analysis of variance for F[g] for superelastic wires (AO, RMO, 3M, and GAC). Seq SS, sequential sum of squares; Adj SS, adjusted sum of squares; Adj MS, adjusted means.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Producer	3	24574.9	24574.9	8191.6	653.69	0.000
Size	1	33961.2	33961.2	33961.2	2710.09	0.000
Deflection	1	2094.1	2094.1	2094.1	167.11	0.000
Producer × size	3	2674.3	2674.3	891.4	71.14	0.000
Producer × deflection	3	81.9	81.9	27.3	2.18	0.099
Size × deflection	1	27.5	27.5	27.5	2.19	0.143
Producer × size × deflection	3	43.8	43.8	14.6	1.17	0.330
Error	64	802.0	802.0	12.5		
Total	79	64259.8				

$P < 0.05$.

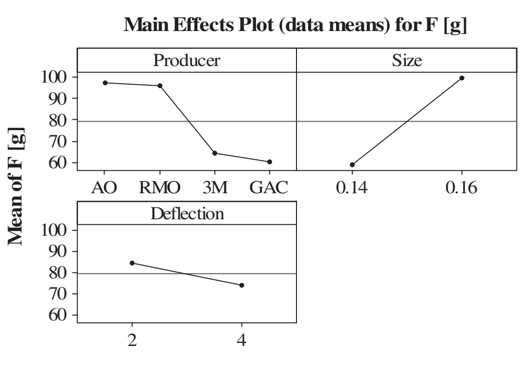


Figure 9 Main effects plot for F [g] for superelastic wires of all producers (GAC, 3M, AO, and RMO).

With regard to the interaction among factors, ANOVA showed that only producer–size were significant. This means that by increasing the wire size from 0.014 to 0.016 inches, the working forces increased but by different amounts.

ANOVA for the regression analysis performed on the data set confirmed that the factor, manufacturer, was also statistically significant ($P < 0.05$) as the others factors (in such cases, it is necessary to include this last factor in the regression procedure).

The result is the following function:

$$F_{SE}[\text{g}] = -178 - 14.5 \times \text{producer} + 20604 \times \text{size} - 5.12 \times \text{deflection}, \quad (3)$$

Where F_{SE} is the mean value of the working forces (g) for the superelastic wires, as a function of the manufacturer (following the code: A0 = 1, RMO = 2, 3M = 3, and GAC = 4), wire size (inch), and level of deflection (mm); this function has a coefficient of determination, R^2 = 88.3 per cent, that is lower than the coefficient of function 1 obtained for the superelastic wires of AO and RMO. The predicted values of forces from function 3 are in good agreement with the values of function 1 relative to the above two manufacturers.

Discussion

In this study, only data from the unloading portion of the load–deflection curve are reported because these are the forces actually distributed to the teeth by orthodontic wires during treatment (working forces). The unloading curve is in fact the curve of interest for orthodontic tooth movement (Segner and Ibe, 1995). The tests were performed under the same conditions at 37°C which represents the intraoral temperature (Nakano *et al.*, 1999; Iijima *et al.*, 2002; Wilkinson *et al.*, 2002; Mallory *et al.*, 2004; Bartzela *et al.*, 2007). Temperature is important when examining the performance of heat-activated NiTi archwires.

Several researchers have used the three-point bending test to evaluate the mechanical properties of orthodontic wires (Nakano *et al.*, 1999; Gurgel *et al.*, 2001; Iijima *et al.*, 2002; Wilkinson *et al.*, 2002; Parvizi and Rock, 2003; Kusy and Whitley, 2007; Kasuya *et al.*, 2007). This test offers a high level of reproducibility and allows comparison with other studies (Bartzela *et al.*, 2007).

Wire deflections of 2 and 4 mm were selected in this study. The same deflection values have been used by other authors (Wilkinson *et al.*, 2002; Parvizi and Rock, 2003; Sakima *et al.*, 2006) although the principles of physics recommend a deflection of no greater than 5 per cent of span length to ensure that a wire is tested within the range of its metallurgical properties, but in the oral environment, wire deflections of 2 and 4 mm are the norm (Parvizi and Rock, 2003). For strain higher than 8 per cent, the wire cannot return to its initial shape (Graber *et al.*, 2005).

The analysis performed on thermal wires was limited to two manufacturers (AO and RMO) because the other manufacturers considered did not produce thermal wires of the two examined sizes (0.014 and 0.016 inches). ANOVA showed the effect of the factors; in particular, manufacturer, even if statistically significant, showed a negligible level of significance in comparison with other factors (type, size, and deflection). Therefore, the forces expressed by thermal wires tested were not dependent on manufacturer.

In the present study, a statistically significant increase of working forces exerted by thermal wires with increasing wire dimension was observed. This is in agreement with the results of Parvizi and Rock (2003) who found that an increase in wire cross-section from 0.4 mm round to 0.4×0.7 mm rectangular approximately doubled each mean force value in the beam test at both 2 and 4 mm of deflection. Comparison between thermal wires of the same size at two different deflections showed a statistically significant reduction of forces with increasing deflection level.

Parvizi and Rock (2003) found no statistically significant force changes for three thermally activated wires when deflection was increased from 2 to 4 mm in the three-point bending test.

Nakano *et al.* (1999) showed that NiTi wires exerted, in the unloading phase, constant continuous forces as the amount of deflection increased.

When considering the results related to the superelastic wires (AO and RMO), the manufacturer factor was not significant (Pareto analysis). When all companies were considered, the effect of manufacturer was statistically significant; this was due to the fact that 3M and GAC produce superelastic wires, which released significantly lower forces compared with the others. Therefore, the forces exerted by superelastic wires of the same size and different manufacturers, at the same deflection level, were significantly different.

Nakano *et al.* (1999) also showed that different brands of NiTi alloy wires of the same size varied widely in the force levels they exerted.

Taking into account the factor 'deflection', superelastic wires of both dimensions (0.014 and 0.016 inches), at 2 mm presented narrow and steep load–deflection curves, while the same wires at 4 mm of deflection showed wider curves with larger plateaus. This means that at 2 mm these wires did not express their superelasticity. Greater deformations generated the martensitic transformation induced by this stress (SIM). Such differences were more evident for superelastic wires compared with thermal wires both for the shape of the curve, which showed a wider range between the loading and the unloading phases, for any force level. Meling and Odegaard (2009) found that with a small deflection (0.5 mm), there was no significant plateau in the deactivation phase of superelastic and thermal wires. They reported that this deformation was insufficient to induce SIM. In contrast, when the wires were deactivated from larger deformations, plateaus were readily observable.

Garrec and Jordan (2004) showed that the load–deflection curves of NiTi wires presented, at small deformation, a linear elasticity, similar to conventional alloy, and exhibited superelastic behaviour at large deformation. Therefore, in a malocclusion with a low dental irregularity index, the superelasticity of these wires could not be fully expressed thus reducing the benefits of NiTi wires.

The working forces of superelastic archwires were significantly higher with increasing wire dimension for both the considered deflections, as for the thermal wires.

The main difference between superelastic and thermal wires was in the force levels. Thermally active wires produced significantly lower working forces than superelastic wires of the same size. The same results were found by other authors who analysed the load–deflection characteristics of NiTi wires using a three-point bending test (Wilkinson *et al.*, 2002; Fischer-Brandies *et al.*, 2003; Parvizi and Rock, 2003; Sakima *et al.*, 2006).

Having determined the force levels of the wires tested, the appropriate force level should be known. The amount of force capable of producing tooth movement during orthodontic treatment is at present not known.

Ren *et al.* (2003), in a meta-analysis of the literature concerning the optimal force or range of forces for orthodontic tooth movement, concluded that there is no evidence concerning optimal force levels in orthodontics. In particular, they mention the findings of Oppenheim (1942) and Reitan (1967) that advocated the use of the 'lightest forces capable to bring about tooth movement'.

In particular, in the initial phase of the orthodontic treatment (alignment), the use of thermal archwires is in accordance with this principle.

The experimental data of the present research allowed determination of the force function capable of predicting the values of force in the range of the parameters considered (i.e. level of deflection, wire dimension, wire type, manufacturer). Based on these considerations, thermal and superelastic wires should have different uses according to biomechanical need. In low-friction mechanics, thermal wires are to be preferred to superelastic wires, during the alignment phase, for their lower working forces and ability to express the particular characteristic of superelasticity, also at lower deflection levels. Moreover, these wires permit the so-called 'full-bracket engagement' at the start of treatment and in subjects with severe dental crowding decrease the risk of generating excessive forces. The feature of thermal wires to produce low forces over long ranges of activation at high deflections, confirmed by the results, allows the archwire to work longer thus making frequent reactivation unnecessary. In conventional straightwire mechanics, the use of superelastic wires is recommended. A thermal archwire would be unable to overcome the frictional forces due to ligatures and thus produce tooth movement.

Conclusions

The following results were obtained:

1. Thermal archwires exerted significantly lower working forces than superelastic wires of the same size in all the experimental tests at both 2 and 4 mm of deflection.
2. Wire size had a significant effect on the forces produced: with increasing archwire dimensions a statistically significant increase in working forces for both superelastic and thermal wires was observed.
3. In the unloading phase, a statistically significant decrease of forces with increasing wire deflection for all wire types was observed.
4. Superelastic wires at 2 mm of deflection showed curves with a smaller hysteresis than thermal wires of the same size. At 4 mm deflection, the superelastic and thermal wires of the same size demonstrated similar behaviour, characterized by wide hysteresis curves but with different force levels.
5. A 'prediction function' of the forces for each archwire (thermal or superelastic) at varying wire size and deflection levels was determined.

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