Torsional superelasticity of NiTi archwires

Myth or reality?

Yves Bolender[a]; Anne Vernière[b]; Christophe Rapin[c]; Marie-Pierryle Filleul[d]

ABSTRACT

Objective: To reproduce and compare the intraoral torsional behavior of 10 commonly used preformed upper NiTi 0.017 × 0.025 archwires in 0.018-slot brackets at 20°C, 35°C, and 55°C.

Materials and Methods: Ten upper preformed NiTi archwires were compared to a multibraided stainless steel wire. An original testing bench was used to reproduce palatal root torque applied onto an upper central incisor with a maximum value of 1540 g × mm. Ten samples of each wire type were tested at 20°C, 35°C, and 55°C each.

Results: Loading and unloading at 20°C revealed three categories of wires: a group of four NiTi wires of relative stiffness bereft of any superelasticity, a group of six NiTi wires displaying some horizontal plateau, and finally the stainless steel wire of lesser stiffness. Testing at the average oral temperature of 35°C produced the same three categories of wires, with only 2 of 10 NiTi wires displaying a superelastic effect (Copper NiTi 35°C and 40°C). None of the NiTi wires was superelastic at 55°C. Moments increased with temperature as the martensite was replaced by the more rigid austenite.

Conclusion: This study showed that most NiTi wires did not exhibit in torsion the superelastic effect traditionally described in bending. The combination of straight-wire prescriptions and rectangular superelastic NiTi archwires did not provide optimal constant moments necessary to gain third-order control of tooth movement early in treatment. A braided stainless steel rectangular archwire displayed better torsional behavior at 35°C than most NiTi archwires of the same dimensions. (*Angle Orthod.* 2010;80:1100–1109.)

KEY WORDS: Nickel; Titanium; Orthodontic wires; Temperature; Torsion; Elasticity

INTRODUCTION

Since the initial works of Buehler and colleagues[1–3] at the Naval Ordnance Laboratory in the 1960s and the

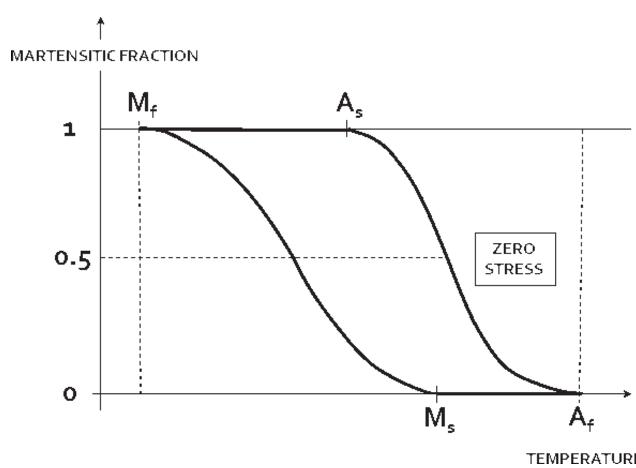

Figure 1. Transition temperatures during martensitic transformation.[12] Martensite start (Ms) is the initial temperature at which the first crystals of martensite appear within the alloy structure, whereas martensite finish (Mf) corresponds to the final temperature at which the alloy is fully martensitic. Austenite start (As) and austenite finish (Af) are the initial and final temperatures at which the austenite is formed.

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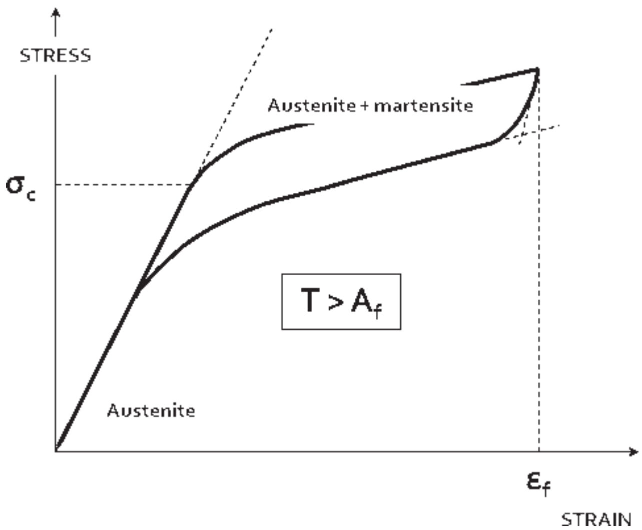

Figure 2. Superelastic plateaus on a stress-strain diagram.[12]

publications of Andreasen and colleagues[4–7] in the early 1970s, NiTi archwires have gained wide popularity among orthodontists during the initial aligning stage of treatment. These alloys have at least two distinct crystallographic phases: a crystalline form present at high temperature and low stress, called the austenitic phase; and a low-temperature and high-stress variant, called the martensitic phase. The initial Nitinol marketed by Unitek (Monrovia, CA, USA) was preferred over stainless steel because of its low stiffness and high springback. This alloy, which undergoes a severe hardening during its manufacturing process, presents a stable martensitic phase under clinical conditions.

The 1980s[8–11] saw the introduction of NiTi archwires that could undergo a reversible solid-state transformation, called the martensitic transformation, from one phase to the other and vice versa. Hence, they opened the way to two interesting additional properties: superelasticity and the shape memory effect. This

Table 1. Distributors, Types of Products, and Archforms of the Different 0.017 × 0.025 Archwires Tested

Product	Distributor	Type of Product	Archform
Nitinol	3M-Unitek	NiTi	Orthoform II
Nitinol SE	3M-Unitek	NiTi	Orthoform II
Nitinol HA	3M-Unitek	NiTi	Orthoform II
Copper NiTi 27°C	Ormco	NiTi	Broad (L)
Copper NiTi 35°C	Ormco	NiTi	Broad (L)
Copper NiTi 40°C	Ormco	NiTi	Broad (L)
Neosentalloy 100 g	GAC	NiTi	Ideal
Neosentalloy 200 g	GAC	NiTi	Ideal
Rematitan Lite	Dentaurum	NiTi	Standard
Rematitan Lite White	Dentaurum	Coated NiTi	Standard
D-Rect	Ormco	Multibraided stainless steel	Standard

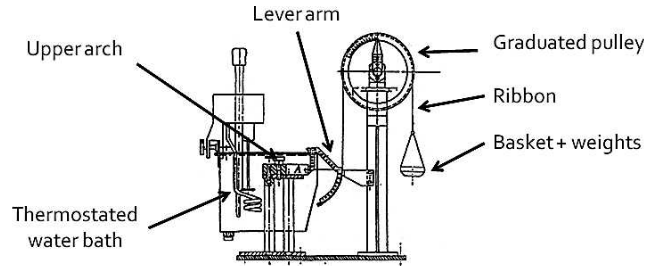

Figure 3. Testing bench.

martensitic transformation leads to the definition of transition temperatures (Figure 1). The superelastic effect is a remarkable orthodontic feature that is characterized by the presence on a stress-strain diagram of a horizontal plateau upon unloading (Figure 2). This property is because an initial austenitic structure incorporates stress-induced martensite at a temperature greater than austenite finish. Superelasticity allows the archwires to exert a constant force or moment on a large range of deactivation. The superelastic effect was initially described in bending[8] and has been largely documented in this mode since.[9,10,13–27] The literature, however, is less abundant when torsion is considered.[28–33] Some authors[28–31] were able to identify some degree of superelasticity at certain temperatures and above a certain value of twist, whereas Meling and Ødegaard[32,33] were not able to obtain a superelastic effect when wires were subjected to up to 25° of torsion at different temperatures.

In the 1990s, new copper NiTi alloys[34,35] with austenite finishes were introduced to the market on the assumption that adding copper would stabilize the transformation temperatures and result in horizontal plateaus of reduced slope.[36]

The purpose of this study is to test torsion in representative NiTi 0.017 × 0.025 inch archwires in conditions reproducing a palatal root torque being applied on an upper central incisor and to compare the

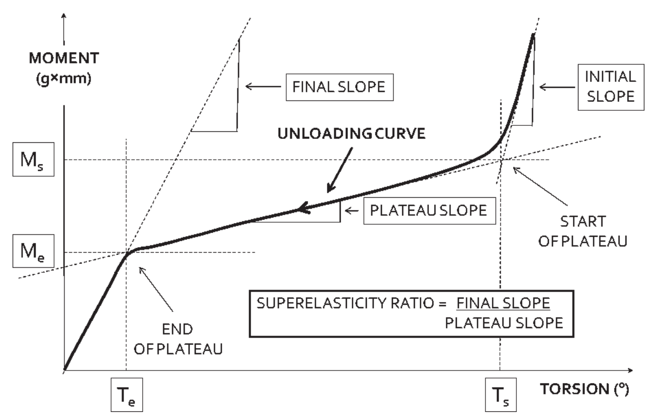

Figure 4. Unloading parameters.

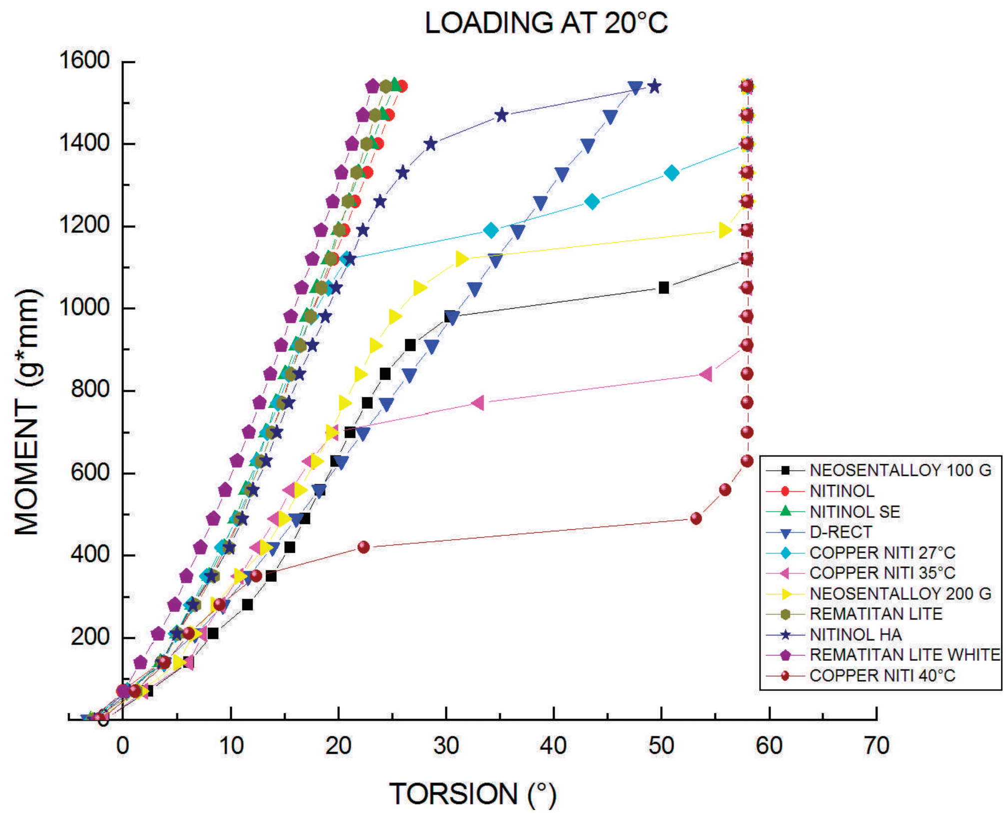

Figure 5. Loading at 20°C.
Color figures are available online.

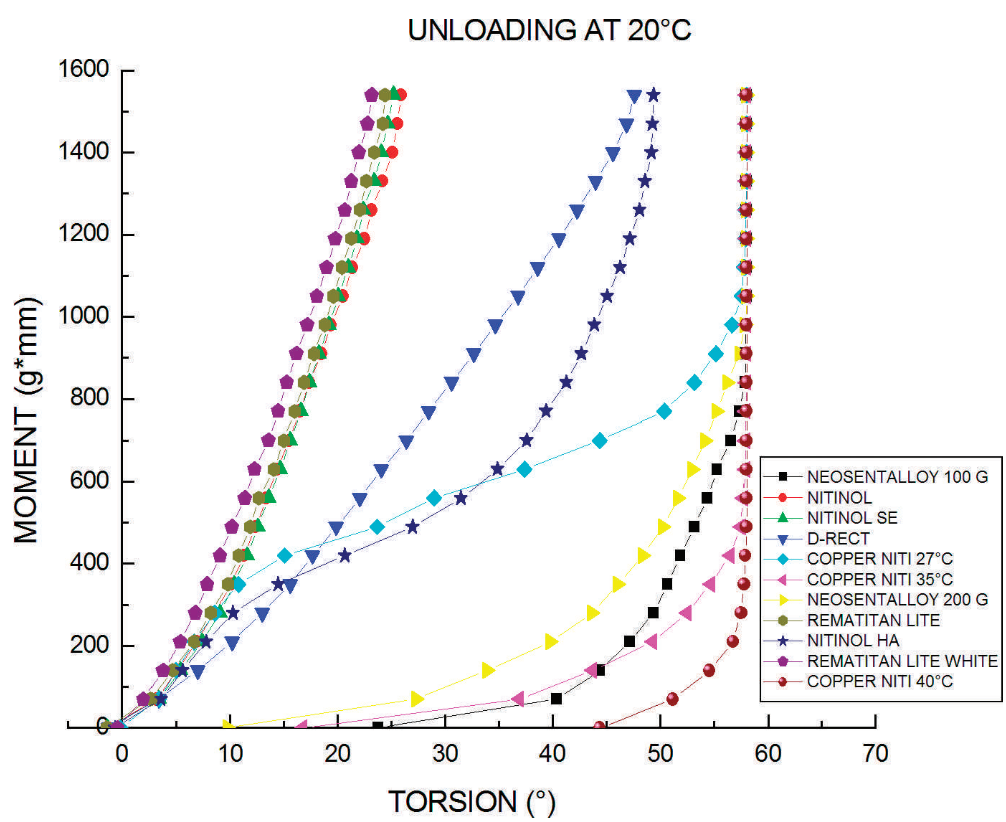

Figure 6. Unloading at 20°C.

Table 2. Unloading Parameters at 20°C (According to Segner and Ibe[43])

Product Tested at 20°C	Superelasticity	Final Slope (g × mm/°)	End of Plateau (°)	Level of Plateau (g × mm)	Plateau Slope (g × mm/°)	Superelasticity Ratio
Nitinol	No	60.8				
Nitinol SE	No	63.7				
Nitinol HA	Yes	26.5	11	297	13.4	1.98
Copper NiTi 27°C	Yes	33.7	12	370	10.6	3.18
Copper NiTi 35°C	Residual plastic deformation					
Copper NiTi 40°C	Residual plastic deformation					
Neosentalloy 100 g	Residual plastic deformation					
Neosentalloy 200 g	Residual plastic deformation					
Rematitan Lite	No	63.8				
Rematitan Lite White	No	67.2				
D-Rect	No	32.1				

influence of the variation of temperature by testing the samples at 20°C, 35°C, and 55°C.

MATERIALS AND METHODS

Ten upper preformed NiTi 0.017 × 0.025 archwires were selected among the most commonly mentioned material in the literature and compared to a multi-braided stainless steel wire of same cross-section (Table 1). Thus, 30 specimens of each of the 11 different wire types were included in the study.

A novel testing bench was used to test the wires under controlled clinical conditions of torque and temperature.[28–30,37] This system attempted to reproduce the intraoral conditions of palatal root torque applied on an upper right central incisor (Figure 3). The bench was composed of a thermostated water bath in which a stainless steel duplication of an upper arch was immersed. This upper arch simulator was bonded with 0° torque 0° angulation 0.018-slot brackets and was cut out at the level of the upper right central incisor. The archwire was tied in the

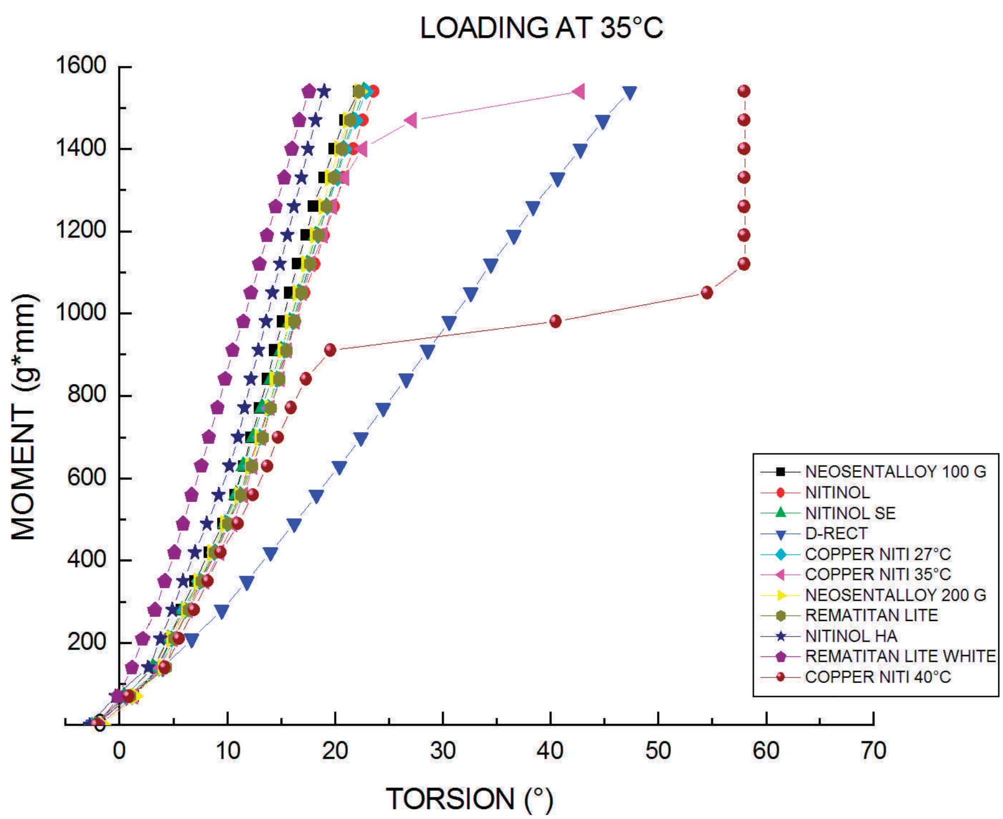

Figure 7. Loading at 35°C.

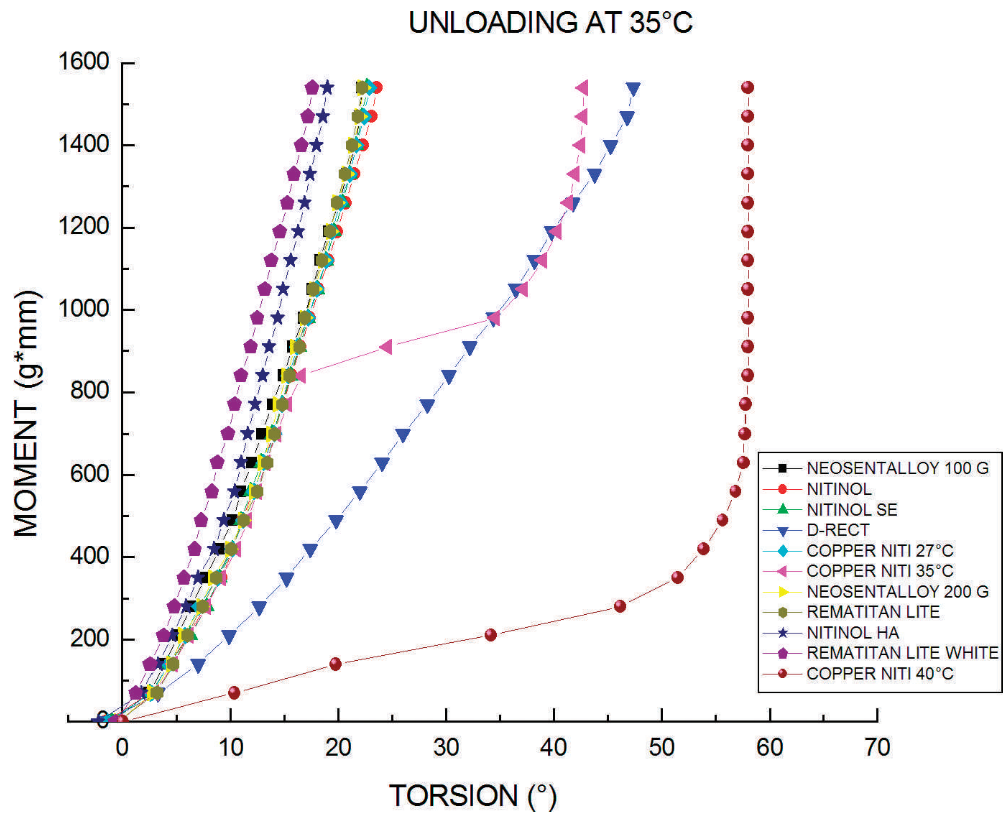

Figure 8. Unloading at 35°C.

brackets with elastomeric ties. Torsion was applied onto the archwire at the level of the upper right central incisor via a bracket attached to one extremity of a light aluminum lever. This lever was connected to a scale pan with a stainless steel ribbon passing over a graduated pulley.

The geometry of the system allowed calculations (g × mm) of the moment being applied at the level of the central incisor, with a maximum exerted value of 1540 g × mm. On the other hand, the graduated pulley allowed the resulting torsion to be determined. The wire sample was divided into three subsamples; thus, 10 specimens of each wire type were tested, respectively, at 20°C, 35°C, and 55°C. A temperature of 35°C is supposed to represent the average intraoral temperature,[38,39] whereas 55°C corresponds to an intake of a hot beverage.[40–42]

Unloading parameters were defined on the deactivation curves according to the methodology described by Segner and Ibne[43] and Meling and Ødegaard (Figure 4).[32] The ratio between the slope of the final part of the unloading curve and the plateau slope was

Table 3. Unloading Parameters at 35°C (According to Segner and Ibe[43])

Product Tested at 35°C	Superelasticity	Final Slope (g × mm/°)	End of Plateau (°)	Level of Plateau (g × mm)	Plateau Slope (g × mm/°)	Superelasticity Ratio
Nitinol	No	67.3				
Nitinol SE	No	72.6				
Nitinol HA	No	79.8				
Copper NiTi 27°C	No	68.8				
Copper NiTi 35°C	Yes	51.5	18	855	7.8	6.63
Copper NiTi 40°C	Yes	[a]	[a]	[a]	7.0	NA[b]
Neosentalloy 100 g	No	69.2				
Neosentalloy 200 g	No	71.6				
Rematitan Lite	No	72.6				
Rematitan Lite White	No	88.7				
D-Rect	No	32.3				

[a] Not identifiable.
[b] NA indicates not applicable.

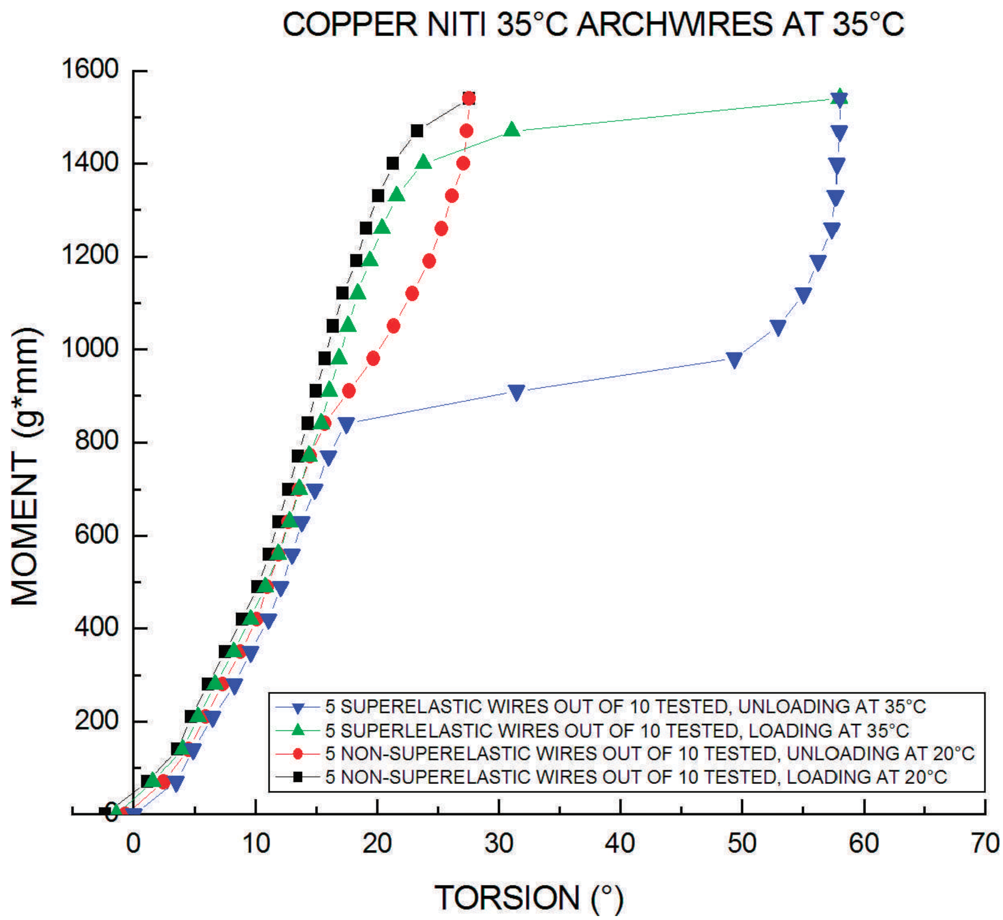

Figure 9. Loading and unloading curves at 35°C of the Copper NiTi 35°C wires.

defined as the superelastic ratio.[43] A wire with a ratio between 2 and 8 was considered as displaying a superelastic tendency whereas a ratio greater than 8 characterizes a definite superelasticity.

RESULTS

Tests at 20°C

Loading (Figure 5) revealed three distinct categories of wires: a group of four NiTi wires of relative stiffness completely lacking any superelasticity Rematitan Lite White, Rematitan Lite, Dentaurum (Pforzheim, Germany); Nitinol SE, Nitinol, (3M-Unitek, Monrovia, CA), a group of six NiTi wires displaying a distinct horizontal plateau Nitinol HA, (3M-Unitek, Monrovia, CA); Copper NiTi 27°C, (Ormco, Glendora, CA); Neosentalloy 200 g, Neosentalloy 100 g, (GAC, Central Islip, NY); Copper NiTi 35°C, Copper NiTi 40°C, (Ormco, Glendora, CA), and a non-superelastic wire of lesser stiffness crossing the diagram in diagonal (the braided stainless steel D-Rect Ormco, Glendora, CA). Deactivation curves (Figure 6) of more interest to orthodontists were plotted. Unloading displayed the same three classes of wire performance. The second category of wires, however, did not show clearly identifiable horizontal plateaus upon deactivation. Moments delivered by this second category of wires were below the 800 g × mm value. The Nitinol HA and Copper NiTi 27°C were the only wires to display a superelastic tendency according to Segner and Ibe[43] (Table 2), and the Neosentalloy 100 g and 200 g and the Copper NiTi 35°C and 40°C were characterized by some residual plastic deformation at the end of the cycle.

Tests at 35°C

Loading (Figure 7) at the average oral temperature of 35°C again showed three different categories of wires. Eight types of wires were in the first category of non-superelastic NiTi wires of relative stiffness: Rematitan Lite White, Nitinol HA, Neosentalloy 100 g, Neosentalloy 200 g, Rematitan Lite, Nitinol SE, Copper NiTi 27°C, and Nitinol. Two types of wires were in the second category of superelastic wires: Copper NiTi 35°C and Copper NiTi 40°C. Finally, the stainless steel D-Rect did not display any superelasticity but had a stiffness that was less than the rigidity of the first group of eight NiTi wires. Unloading (Figure 8) showed the

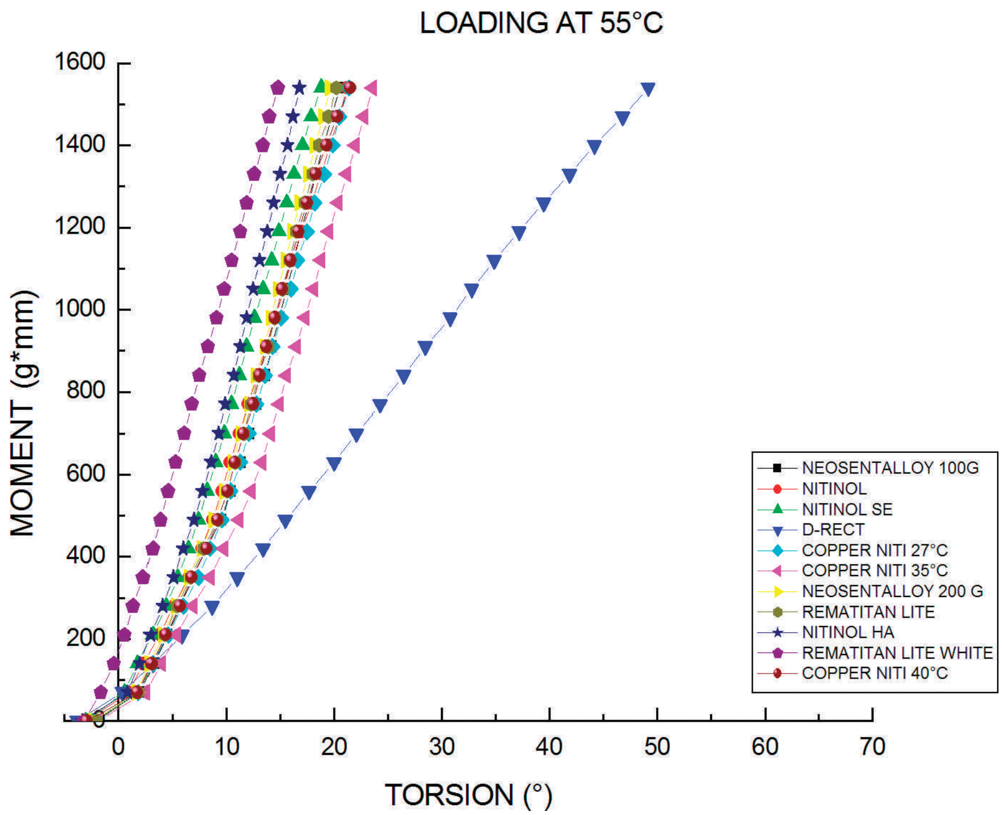

Figure 10. Loading at 55°C.

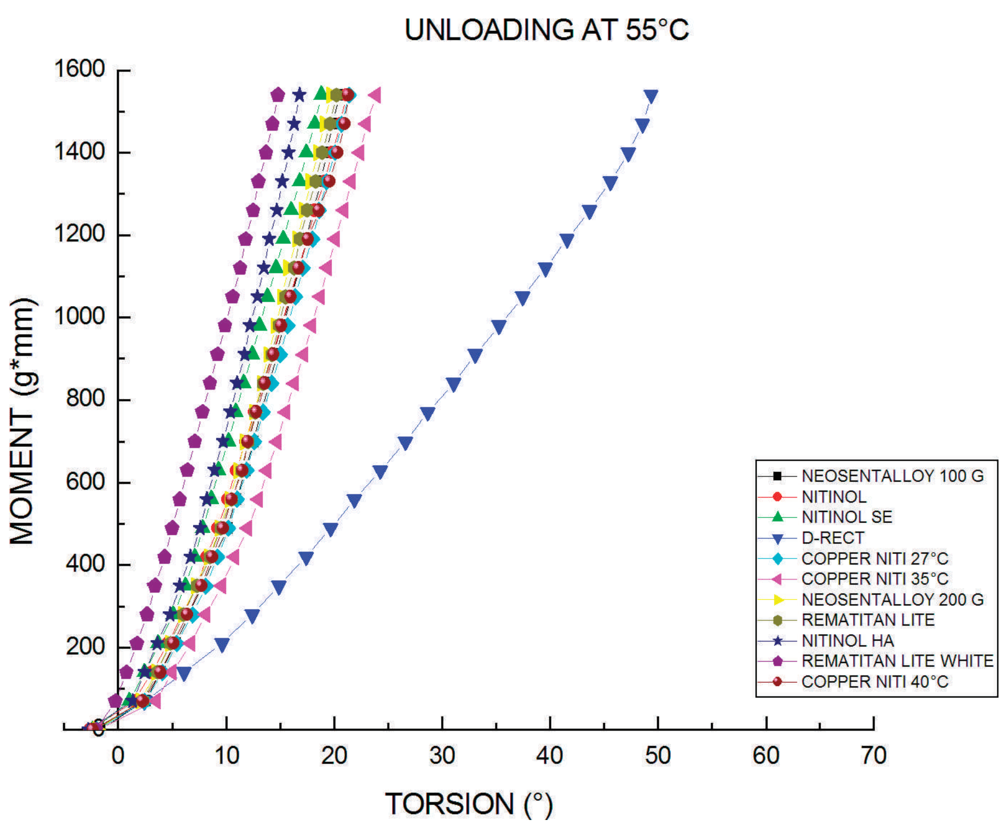

Figure 11. Unloading at 55°C.

Table 4. Unloading Parameters at 55°C (According to Segner and Ibe[43])

Product Tested at 55°C	Superelasticity	Final Slope (g × mm/°)
Nitinol	No	71.8
Nitinol SE	No	81.0
Nitinol HA	No	88.4
Copper NiTi 27°C	No	74.0
Copper NiTi 35°C	No	67.5
Copper NiTi 40°C	No	72.8
Neosentalloy 100 g	No	76.9
Neosentalloy 200 g	No	79.0
Rematitan Lite	No	76.8
Rematitan Lite White	No	96.1
D-Rect	No	30.3

same groups of wires (Table 3). At this temperature, Copper NiTi 35°C did not display homogenous behavior as only 5 of 10 wires showed a superelastic plateau (Figure 9). Upon deactivation, the superelastic Copper NiTi 35°C delivered moments of the order of 900 to 1000 g × mm, whereas the Copper NiTi 40°C was characterized by values less than 400 g × mm.

Tests at 55°C

Loading (Figure 10) showed only two categories of wires at this temperature. The first group included all NiTi wires that did not display any superelastic plateau and were characterized by a relative stiffness. The second group included the unique stainless steel D-Rect, which was defined by a lower rigidity. Unloading (Figure 11) led to the same findings; the D-Rect wire displayed a torsional stiffness less than half the value of all other NiTi's rigidity (Table 4).

Final slopes of the NiTi wires increased naturally with temperature as the martensite was progressively replaced by the more rigid austenite (Table 5).

DISCUSSION

Methodology

Most studies have examined torsion utilizing straight posterior portions of preformed wires.[31–33] Our system more closely resembled the intraoral conditions of a torque being applied onto the anterior part of a preformed archwire. Although we were trying to reproduce exclusively third-order activation at an upper central incisor level, we believe the light weight of the aluminum lever arm most probably generated some additional second-order stress onto the wire.

Moment values used in this experiment were comparable to those mentioned in the literature. Nikolai[44] recommended a value of 1020 g × mm and 3000 to 3500 g × mm torque, respectively, on a maxillary canine and four maxillary incisors. Feldner et al.[45] identified a lower value of 1000 to 2000 g × mm for the upper incisor segment. According to Burstone,[46] a force of 1000 g × mm was necessary to torque one upper central incisor, whereas a force of 1500 g × mm was optimal to torque two upper incisors per side. Meling and Ødegaard[47,48] recommended an ideal moment of 15N × mm (1530 g × mm) to torque a single tooth with a maximum value of 20N × mm (2040 g × mm). Finally, Casa et al[49] applied low moments of 3N × mm (306 g × mm) and 6N × mm (612 g × mm) on upper first premolars during a 1- to 4-week period before extracting them for orthodontic purposes. Scanning electron microscopy of these premolars revealed significant root resorption lacunae, which increased with moment magnitude and duration despite the low values of torque tested. Hence, the maximum moment of 1540 g × mm that had been used to torque one upper central incisor in this experiment corresponds to the physiological torquing values published anteriorly. The optimal conditions of a torque being applied to an upper central incisor should therefore be well within the limits represented on our diagrams.

Table 5. Comparison of Unloading Parameters at 20°C, 35°C, and 55°C (According to Segner and Ibe[43])

Product Tested	Final Slope at 20°C (g × mm/°)	Final Slope at 35°C (g × mm/°)	Final Slope at 55°C (g × mm/°)
Nitinol	60.8	67.3	71.8
Nitinol SE	63.7	72.6	81.0
Nitinol HA	26.5	79.8	88.4
Copper NiTi 27°C	33.7	68.8	74.0
Copper NiTi 35°C	Residual plastic deformation	51.5	67.5
Copper NiTi 40°C	Residual plastic deformation	[a]	72.8
Neosentalloy 100 g	Residual plastic deformation	69.2	76.9
Neosentalloy 200 g	Residual plastic deformation	71.6	79.0
Rematitan Lite	63.8	72.6	76.8
Rematitan Lite White	67.2	88.7	96.1
D-Rect	32.1	32.3	30.3

[a] Not identifiable.

Experimental temperatures were chosen to simulate the variation of temperature in the oral environment. Hot beverage intakes induce transient temperatures in the range of 52°C to 68°C,[39–42] whereas average oral temperature is around 34°C[41] to 35°C.[38,39] On the other hand, cold drinks can induce oral temperatures as low as 5°C to 9°C.[39,40,42] As a consequence of hot or cold liquid intake, the oral cavity suddenly reaches these extreme values, and then recovers its average temperature in an exponential way after 10 to 15 minutes.[42] Moreover, such factors as mouth breathing[38] or lip incompetency[39] have been shown to decrease intraoral temperature. Over a 24-hour period, the labial surface of an upper central incisor can be expected to be in the temperature range of 33°C to 37°C for 79% of the time, below it for 20%, and above it for only 1% of the time.[39]

Most of the tested NiTi wires did not display any superelasticity at average oral temperature (Figure 8). These results might be due to four distinct factors. First, severe work-hardening, such as in the original Nitinol wire, prevents its stable martensitic structure to transform into an austenite structure. The second factor might be the difficulty of manufacturing an alloy with an exact transformation temperature illustrated in this study by the inconsistent behavior at 35°C of the Copper NiTi 35°C. Third, the maximum moment used in this experiment might not be high enough to reach the superelastic plateau of certain wires, and thus we might only be observing the final proportional part of the unloading curves (Figure 4). Increasing these moments, however, would result in nonphysiological conditions with probable resorptive sequelae. Fourth, the angle of torsion might not be high enough for certain wires to get to the superelastic plateau. Because the maximum palatal root torque of 22° is to be found in the Ricketts prescription, most clinicians would consider a maximum value of 25° of torque as clinically relevant for an upper incisor. Therefore, to go beyond the values used in this experiment would probably be clinically irrelevant. Our results corroborate the lack of superelasticity shown by Meling and Ødegaard,[32–33] who used a maximum angle of torsion of 25°.

CONCLUSIONS

- Torsional moments increased with temperature.
- Most NiTi archwires did not display any superelasticity in torsion at average oral temperature.
- Copper NiTi 35°C and 40°C were the only superelastic wires at 35°C.
- Of the 10 Copper NiTi 35°C wires tested, only five displayed a superelastic effect at 35°C.
- The tested braided stainless steel D-Rect rectangular archwire displayed better torsional properties at 35°C than most NiTi archwires of the same dimensions.

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