Force characteristics of nickel-titanium open-coil springs

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Introduction: The objective of this study was to quantify the properties of commercially available nickel-titanium open-coil springs. **Methods:** Eleven springs from 3 manufacturers were tested 5 times over a 12-week period. A universal testing machine was used to measure the force generated when open-coil springs were compressed to half of their original length and then gradually allowed to decompress. **Results:** The average forces generated at the initial recording session for uniformly wound springs from GAC International (Bohemia, NY) and 3M Unitek (Monrovia, Calif) were 19.3% to 42.7% and 9.7% to 38.8% below the manufacturers' labeled force levels, respectively. GAC's 100-, 150-, and 200-g stop-wound coils demonstrated statistically and clinically significant stepwise force degradation over the 12-week experimental period ($P < 0.0001$). GAC's uniformly wound light (100 g) coils generated the lowest load-deflection ratios (23.7 g/mm). **Conclusions:** Open coils might need to be compressed by more than one-third of their original length to produce the labeled forces. Uniformly wound coils generally produce lower load-deflection ratios and maximum forces, which are generally more acceptable for tooth movement. (Am J Orthod Dentofacial Orthop 2010;138:142.e1-142.e7)

Nickel-titanium (NiTi) coil springs can produce continuous, light forces over a large range of activation. They have significantly limited the use of stainless steel coil springs as force-generating modules in orthodontics, since the latter can only produce initial forces of high magnitude that quickly dissipate even with small deactivations. Von Fraunhofer et al[1] compared the forces generated by open-coil springs fabricated from heat-activated superelastic NiTi (Sentalloy, GAC International, Bohemia, NY) and stainless steel (3M Unitek, Monrovia, Calif). The Sentalloy open-coil springs (0.010 × 0.035 in) produced forces of 55 to 70 g with 9 mm of activation, whereas the stainless steel springs (0.010 × 0.030 in) produced forces of 200 g when activated by just 1 mm.

The variables that determine the force produced by an open-coil spring are its lumen size, wire type, and wire size. All other things being equal, the larger the lumen size and the smaller the wire cross-section, the lighter the force produced, for the same activation. Another important physical parameter when considering biomechanical properties of open-coil springs is the winding pitch. Pitch is the distance between individual coils in the spring. As the pitch decreases, the amount of wire incorporated into the wire is increased. Therefore, tightly wound coils (small pitch) generally produce lower forces.[1]

Schneevoight et al[2] investigated 32 NiTi open-coil springs from 7 manufacturers, including GAC and 3M Unitek. Segments of coil springs 20 ± 2 mm long were tested at 27°C, 37°C, and 47°C with a universal testing machine. The springs were compressed maximally. Only GAC Sentalloy springs demonstrated constant forces on the unloading curve. Raising the temperature caused an increase of the magnitude at which the force plateaued by 0.4 to 0.9 N, and a shortening of the plateau width by 4% to 15%. The plateau magnitudes varied by as much as 18% between batches.

Manhartsberger and Seidenbusch[3] evaluated uniformly wound Sentalloy coil springs from GAC and found that the generated forces were actually greater than the labeled forces. According to the manufacturer, the coils should have produced the labeled forces when they were compressed up to 80% of their original length and maintained these forces during deactivation. The authors found that the Sentalloy open-coil springs with a suggested force delivery of 150 g actually produced 300 g of force when compressed to 80% of their original length. They concluded that a new activation

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Submitted, March 2009; revised and accepted, January 2010.
0889-5406/$36.00

doi:10.1016/j.ajodo.2010.01.026

range should be determined for Sentalloy springs, and they suggested activation ranges for each force level of open and closed coils.

Studies of closed-coil NiTi springs have shown similar results to the study of Manhartsberger and Seidenbusch.[3] Chow[4] found that closed coil springs manufactured by GAC and 3M Unitek produced lower generated forces than the labeled values (31% and 36% lower, respectively). In the same study, springs manufactured by TP Orthodontics (LaPorte, Ind) produced forces that were 24% higher than the manufacturer's labeled values. The 3M Unitek springs produced the most constant forces throughout an activation range of 13 mm and, therefore, were considered the most ideal for clinical tooth movement.

The objectives of this study were to quantify the biomechanical properties of commercially available NiTi open-coil springs from 3 manufacturers and compare them with their manufacturers' specifications.

MATERIAL AND METHODS

Eleven open-coil springs from 3 manufacturers (3M Unitek, TP Orthodontics, and GAC International) were selected. Springs of 3 force levels and 2 designs (uniformly wound and stop-wound) were tested (Fig 1, Tables I and II). The following parameters were measured for each spring: maximum force, average force during deactivation, load-deflection ratio, and force degradation over a 12-week period in a simulated oral environment. Based on the desired power of the study (approximately 80%, with an estimated magnitude of difference of 10% at a level of significance of $P < 0.05$), a sample size of 20 coil springs for each force level and each design was deemed adequate.

The uniformly wound coils from GAC came in lengths of 15 mm. According to GAC, the springs could be compressed by 12 mm (down to 3 mm) and still deliver the labeled forces. All other springs came in 7-in segments, with no manufacturer-recommended amount of compression.

All spring segments were cut to a length of 10 mm. This length was chosen for several reasons. First, 10 mm was considered an approximate length of coil used clinically to expand an interdental space to the full width of a tooth. Second, the uniformly wound coils could have been cut to any length, whereas the stop-wound coils had to be cut within the closed (tightly wound) regions of the coil. A 10-mm length was one that could apply to both stop-wound coil designs from the 2 manufacturers.

A universal testing machine (model 4301, Servo Hydraulic, Instron, Canton, Mass) was used for all measurements. The static load cell was set at a constant 50 N.

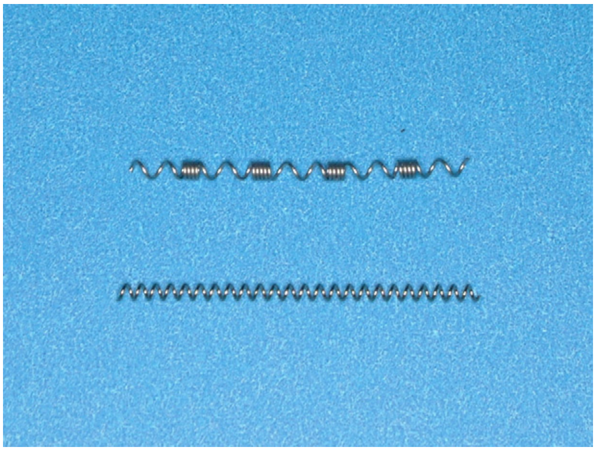

Fig 1. The 2 types of open-coil springs tested: stop-wound (*top*) and uniformly wound (*bottom*).

The speed with which the springs were compressed was set at 15 mm per minute. The springs were compressed to half of their original relaxed lengths (from 10 to 5 mm). This maximum amount of compression was chosen based on the methodology of Chaconas et al.[5] The testing machine was programmed to cycle once, by compressing the springs from 10 to 5 mm and then to return to the original length at the same speed.

The data were automatically recorded on a personal computer by using Lab View graphical programming for instrumentation software (version 5.0, National Instruments, Austin, Tex). The outputs were compiled as Excel files (Microsoft, Redmond, Wash). Values were recorded to .001 mm and .001 N (1 N = approximately 100 g).

The testing machine was fitted with a customized base that was bolted in place. The base was designed to allow the springs to be compressed along a length of wire. During the testing, springs were compressed on a 0.020-in diameter wire, which was attached to a custom-designed crosshead (Fig 2).

Between tests, the springs were kept compressed to 70% of their original length (7 mm) in custom-fabricated compression racks (Fig 3). Each compression rack could hold 40 springs. The racks were submerged in physiologic saline solution (0.9% sodium chloride) and stored in a sealed plastic container (Ziploc, S. C. Johnson & Son, Racine, Wis). The sealed containers were stored at 37°C in an incubator unit (Isotemp Incubator, senior model 205, Fisher Scientific, New York, NY).

The springs of various force groups were tested in the same order at every testing session. Testing sessions were performed at the beginning of the experiment (T0), at 24 hours (T1), 4 weeks (T2), 8 weeks (T3), and 12 weeks (T4). One investigator (A.B.) completed all testing sessions.

Table I. Details of uniformly wound coils

	Length	*Inner diameter*	*Labeled force level (catalog number)*
3M Unitek Nitinol	7 in	0.030 in	Light, 100 g (345-100) Medium, 200 g (345-200) Heavy, 275 g (345-275)
GAC International Sentalloy	0.59 in	0.035 in	Light, 100 g (10-000-09) Heavy, 200 g (10-000-07) Extra heavy, 300 g (10-00-17)

Table II. Details of stop-wound coils

	Length	*Inner diameter*	*Labeled force level (catalog number)*
TP Orthodontics	7 in	0.35 in (0.012-in wire)	(210-508)
Reflex		0.55 in (0.010-in wire)	(210-515)
GAC International Sentalloy	7 in	0.035 in	Light, 100 g (10-000-21) Medium, 150 g (10-000-22) Heavy, 200 g (10-000-23)

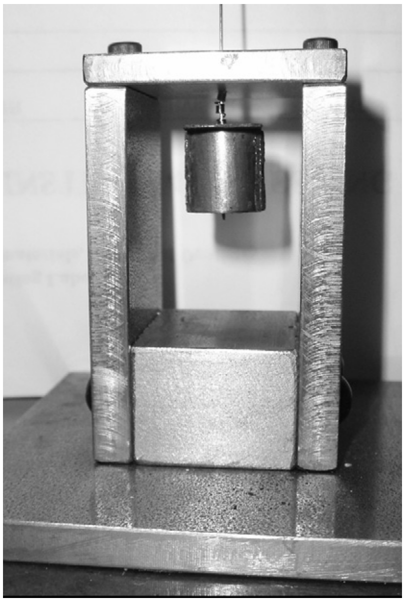

Fig 2. Jig attached to the testing machine.

The testing machine produced 2000 to 2500 data points per recording. The data sets were converted to Excel files. Only the data collected during the decompression (deactivation) of the springs were used to evaluate the force characteristics of the springs.

Statistical analysis

The mean forces and standard deviations were calculated for each group of springs. The mean maximum force, the mean average force, and the mean load-deflection ratio were also calculated. The average force was defined as the force magnitude produced between 20% and 80% compression during unloading (deactivation) of the springs.

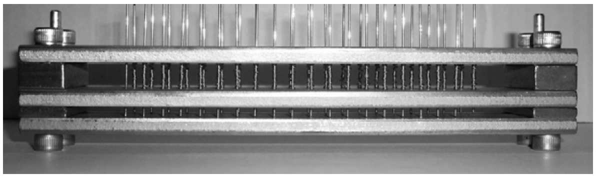

Fig 3. Compression rack with GAC International stop-wound coils.

The Student *t* test was used to determine whether the measured average force was significantly different from that labeled by the manufacturer. The significance level was set at $P < 0.05$. Repeated-measures analysis of variance (ANOVA) was used for intragroup comparisons between test sessions (T0, T1, T2, T3, and T4) and intergroup comparisons between manufacturers. This comparison only involved springs from GAC and 3M Unitek, since TP Orthodontics springs were not labeled with specific force values.

In each group of springs, comparisons were made of mean maximum force, mean average force (20%-80%), and load-deflection ratio (slope). The Prasad-Rao-Jeske-Kackar-Harville post-hoc test was then performed to determine differences between testing sessions and manufacturers. Repeated-measures ANOVA was also used to determine whether there were significant differences between GAC stop-wound and GAC uniformly wound coils at T0. The significance was set at $P < 0.05$.

Table III. Comparison of average force with manufacturers' labels for uniformly wound open-coils

Spring type	*Average force (g)*	*Difference from labeled value (%)*	*SD*	P
GAC International 100 g	71.203	28.8	32.141	0.0008
GAC International 200 g	114.64	42.7	35.559	0.0001
GAC International 300 g	241.99	19.3	86.84	0.0076
3M Unitek 100 g	90.245	9.7	11.725	0.0015
3M Unitek 200 g	122.48	38.8	23.015	0.0001
3M Unitek 275 g	191.19	30.5	18.205	0.0001

Table IV. Comparison of average force with manufacturers' labels for stop-wound open-coils

Spring type	*Average force (g)*	*Difference from labeled value (%)*	*SD*	P
GAC International 100 g	69.719	30.3	37.246	0.0018
GAC International 150 g	94.346	37.1	35.991	0.0001
GAC International 200 g	142.79	28.6	39.433	0.0001
TP Orthodontics 0.010 × 0.035	127.85	NA	34.483	NA
TP Orthodontics 0.055 × 0.055	162.82	NA	25.586	NA

NA, not applicable.

Force degradation was considered clinically significant if there was a total decline in measured force over the 3 months of 10% or more. The manufacturers' labels were described as clinically accurate if the measured mean force was within 10% of the labeled force.

RESULTS

All springs had average force values that were significantly lower than the manufacturers' values at T0 (Tables III and IV). The 3M Unitek 100-g springs produced average forces that were only 10 g lower than the labeled value. The GAC stop-wound 200-g springs produced average forces that were less than half of the labeled value.

The maximum force changed to a statistically significant degree over time for the 3M Unitek 100- and 200-g uniformly wound springs, and the GAC 100-, 200-, and 300-g springs, and for the TP Orthodontics stop-wound springs. The changes did not occur in a consistent stepwise pattern, with occasional increases in force between time periods.

The light (100 g), medium (150 g), and heavy (200 g) stop-wound open-coil springs from GAC all had similar changes in force characteristics over time. Statistically significant changes in force magnitude occurred for maximum force (P <0.0001). The changes followed a stepwise pattern with degradation between most time periods (Fig 4). No significant changes were found for average forces and load-deflection ratios.

To determine whether there were differences between springs from the different manufacturers, the uniformly wound springs from 3M Unitek and GAC were compared. Statistically significant differences were found between these springs for both the 100- and 200-g force levels. The differences in force characteristics between the springs from these manufacturers are summarized in Table V. GAC uniformly wound and stop-wound coils were then compared to determine whether spring design affects the force characteristics of open-coil springs. A significant difference between the GAC 100-g uniformly wound and stop-wound coils was found with regard to maximum force (P <0.0001) at T0. Significant differences were found between the

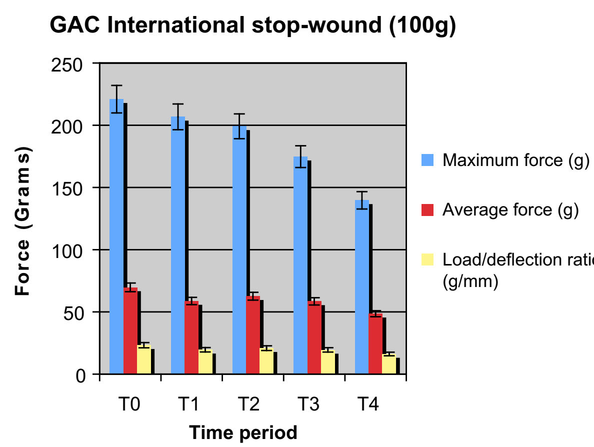

Fig 4. Change in force magnitude over time for GAC International stop-wound light springs. The GAC International medium and heavy stop-wound coil springs had similar changes in force magnitude over time.

Table V. Differences in force characteristics between uniformly wound open coils from 3M Unitek and GAC International

3M Unitek vs GAC International	*Average force*	*Maximum force*	*Load-deflection ratio*
100 g	Higher	Higher	No difference
200 g	No difference	Lower	No difference

GAC 200-g uniformly wound and stop-wound coils in average forces ($P < 0.004$), maximum forces ($P < 0.0001$), and load-deflection ratios ($P < 0.004$) at T0 (Fig 5, Table VI).

DISCUSSION

NiTi has a unique crystalline structure that can shift between 2 phases: austenitic and martensitic. For some of these alloys, conversion from the austenitic to the martensitic phase can occur by lowering the temperature, in others by submitting the wire to stress.

When using a NiTi coil spring to produce tooth movement (open space at a location in the arch), the part of the load-deflection diagram that is useful is the deactivation or unloading part of the diagram (ie, as the coil spring decompresses, part of the dynamic energy stored in it is used to produce the force for tooth movement). Therefore, the reverse transformation (from martensite to austenite), evident in the unloading curve of austenitic NiTi, is of interest when considering the force the teeth will feel. The more horizontal the deactivation curve, the more uniform and continuous the tooth-moving force will be. If we accept the widespread, yet somewhat arbitrary, notion that a force of low magnitude and continuous action is most advantageous for tooth movement, then a NiTi coil spring with a near-horizontal deactivation curve (ie, a low load-deflection ratio) would be preferable.[1,6]

In some clinical situations, springs are compressed more than the amount considered in this study to be average force. Therefore, the maximum force generated by springs was also an important characteristic examined in this study. Maximum force was defined as the force produced when the springs were compressed to 50% of their resting length. This definition was based on the investigator's ability to manipulate the heaviest springs in the study to the bottom-out point. Schneevoight et al[2] produced force-compression diagrams for 32 commercially available open-coil springs, including springs from GAC and 3M Unitek. The springs were compressed to what they termed "the maximum extent." This maximum compression was reported to be 76.37% of the original length of 20 mm. Therefore, it is possible that the 50% compression we used underestimates the maximum force for some springs that were evaluated. Despite this, the maximum force levels generated at the initial recording session by the coils from GAC and 3M Unitek springs were from 19.9% to 120.0% higher than the manufacturers' labeled forces. No manufacturers included any information with their products warning the clinician of the possible maximum force magnitudes produced by the springs. Based on the ability of the heavier springs to produce forces as high as 527 g, the clinician must use caution, especially when activating heavier springs.

No published studies have evaluated the force degradation of NiTi open-coil springs over a long period with the same testing machine. At the outset of the study, one objective was to measure force degradation. However, after evaluating the results, the term "force degradation" was deemed to be a misnomer. The force over time did not show a consistent stepwise decline for all uniformly wound coils and the TP Orthodontics stop-wound coils. On the contrary, in some instances, force magnitude increased over time (this was particularly true for maximum force). So, perhaps a more appropriate term for this part of the investigation should be "change in force magnitude over time." The maximum force values were evaluated by taking the highest force value at 50% compression from resting length. The introduction of error was possible because of the potential outlier effect. It was speculated that taking several force values at maximum compression and averaging the values could moderate the outlier effect. Reevaluating the data and using multiple values to calculate the maximum force tested this hypothesis. When the recalculated maximum forces were compared with the original maximum force, no significant differences were evident. Also, standard deviations calculated for maximum force were comparable with those for average force. The standard deviation for the maximum force would most likely be high if there was significant variation because of outliers in the maximum force values.

Only the GAC stop-wound coils demonstrated a statistically significant force degradation in a stepwise fashion. The degradation was also deemed clinically significant. The definition of "clinically significant force degradation," based on the previous study by Chow,[4] was arbitrarily set at a 10% reduction in force magnitude. All 3 GAC stop-wound coils showed statistically and clinically significant force degradation values over time for maximum force but not for average force or load-deflection ratio. There are 2 possibilities to explain this phenomenon. First, it might be due to measurement error. However, based on the recalculated maximum forces in which the maximum values were

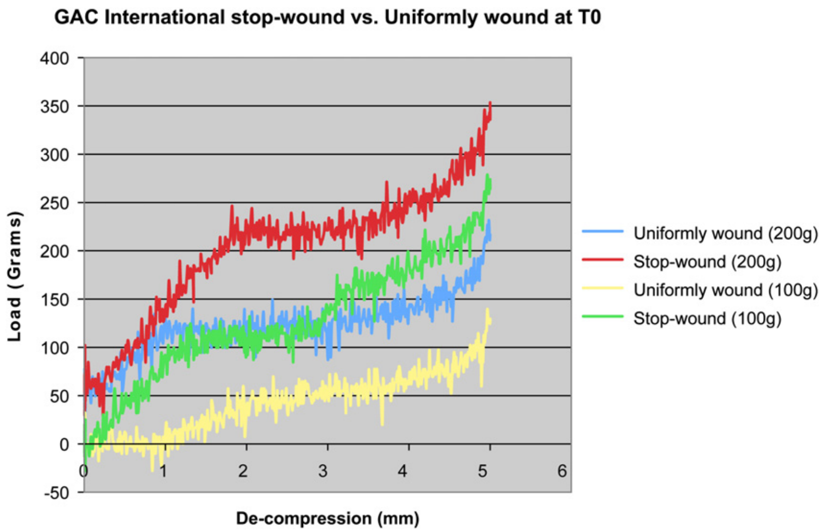

Fig 5. Load-deflection diagram for GAC stop-wound and uniformly wound coils (100 and 200 g).

averaged, this is unlikely. Second, force degradation might depend on the amount of activation.

In theory, if the springs exhibit the superelastic properties of NiTi, the force should be constant regardless of the compression within a certain activation range. However, some springs in this study did not demonstrate a high level of superelasticity. Therefore, differences in force levels existed at varying degrees of compression. We considered force degradation over time at a constant compression. This is not representative of tooth movement. Although several springs did not show force degradation over time, a decrease in force magnitude would occur clinically as the tooth moved, because of relaxation of the spring and lack of superelasticity. For the force to remain near constant despite tooth movement, the load-deflection ratio must be relatively low. The springs with the lowest load-deflection ratios were the GAC light (100 g) and the uniformly wound and stop-wound coils (23.7 and 23.2 g/mm, respectively).

GAC International suggests that Sentalloy products cannot be bench tested because small variations in the temperature of the product will affect their force characteristics. The transition temperature for the Sentalloy products ranges from 26.8°C to 31.6°C; for TP Orthodontics Reflex products, it is approximately 27°C; and for 3M Unitek Nitinol products, it is 48°C to 82°C.[7,8] It is possible that the Sentalloy and Reflex springs cooled to these temperatures during testing. However, Michailesco et al[9] suggested that mouth temperatures can range from 18.9°C to 48.8°C. The springs in our study were maintained within this temperature range at all times. Still, the reported force characteristics might not be completely representative of those in the oral environment. However, due to the reported great variations in mouth temperatures, springs should be able to maintain their superelastic properties over a relatively large temperature range in the oral environment.

Table VI. Differences in force characteristics between GAC International uniformly wound and stop-wound open coils (100 and 200 g)

GAC International stop-wound vs uniformly wound	*Average force*	*Maximum force*	*Load-deflection ratio*
100 g	No difference	Higher	No difference
200 g	Higher	Higher	Higher

Statistically significant differences were found between the 2 spring designs; yet it was difficult to determine whether these differences were clinically significant. The GAC 200-g stop-wound and uniformly wound springs demonstrated statistically significant differences for average force, maximum force, and load-deflection ratio. The stop-wound coils produced higher average forces, maximum forces, and load-deflection ratios. The lower load-deflection ratio of the uniformly wound coil could be considered more clinically appropriate. In explaining these differences, one should consider that the stop-wound coil has a mechanical disadvantage compared with a uniformly wound coil of the same length. The winding configuration of the stop-wound coil consists of areas of open and closed coil. Therefore, there is a smaller potential range of compression with increased stress created in the active portions of the coil during compression compared with the uniformly wound coil. The characteristics of the stop-wound coil would be comparable with those of a uniformly wound coil with a length equal to the sum of the uniformly wound (active) portions of the original stop-wound coil. This explains the higher average and maximum forces created during decompression.

CONCLUSIONS

1. The average force magnitudes produced by all NiTi coil springs in this study were significantly lower than their labeled values. In contrast, the maximum forces were significantly higher. Thus, the manufacturers' methods for determining the labeled values require clarification.
2. Statistically and clinically significant changes in maximum force magnitude occurred for GAC International 100-, 150-, and 200-g stop-wound open-coil springs over the 12-week period. Changes in maximum force magnitude for uniformly wound coils might be unpredictable.
3. All springs had relatively high load-deflection ratios, indicating nonsuperelastic behavior. Therefore, the magnitude of force delivered to a tooth being moved orthodontically decreases as the spring decompresses. This is in sharp contrast with the widely advertised notion of a near-constant force offered by these springs over a long activation.
4. There are significant differences between the open-coil springs from different manufacturers (3M Unitek and GAC International), as well as between uniformly wound and stop-wound springs.

REFERENCES

1. Von Fraunhofer JA, Bonds PW, Johnson BE. Force generation by orthodontic coil springs. Angle Orthod 1993;63:145-8.
2. Schneevoight R, Haase A, Eckardt VL, Harzer W, Bourauel C. Laboratory analysis of superelasic NiTi compression springs. Med Eng Phys 1999;21:119-25.
3. Manhartsberger C, Seiodenbusch W. Force delivery of Ni-Ti coil springs. Am J Orthod Dentofacial Orthop 1996;109:8-21.
4. Chow W. Force characteristics of closed coil nickel-titanium springs [thesis]. Toronto, Ontario, Canada: University of Toronto; 2006.
5. Chaconas SJ, Caputo AA, Harvey K. Orthodontic force characteristics of open-coil springs. Am J Orthod 1984;85:494-7.
6. Ren Y, Maltha JC, Van't Hof MA, Kuijpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a mathematic model. Am J Orthod Dentofacial Orthop 2004;125:71-7.
7. Hurst CL, Duncanson MG, Nanada RS, Angolkar PV. An evaluation of the shape-memory phenomenon of nickel-titanium orthodontic wires. Am J Orthod Dentofacial Orthop 1990;98:72-6.
8. Santoro M, Nicolay OF, Cangialosi TJ. Pseudoelasticity and thermoelasticity of nickel-titanium alloy: A clinically oriented review. Part I: Temperature transitional ranges. Am J Orthod Dentofacial Orthop 2001;119:587-93.
9. Michailesco PM, Marciano J, Griee AR, Abadie MJ. An in vivo recording of variations in oral temperature during meals: a pilot study. J Prosthet Dent 1995;73:214-8.