ORIGINAL ARTICLE

Mechanical behavior and clinical application of nickel-titanium closed-coil springs under different stress levels and mechanical loading cycles

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Introduction: The main advantage of superelastic nickel-titanium (NiTi) products is their unique characteristic of force plateaus, which allow for clinically precise control of the force. The aims of this study were to define the mechanical characteristics of several currently available closed-coil retraction springs and to compare these products. **Methods:** A universal test frame was used to acquire force-deflection diagrams of 24 NiTi closed-coil springs at body temperature. Data analysis was performed with the superelastic algorithm. Also, the influence of temperature cycles and mechanical microcycles simulating ingestion of different foods and mastication, respectively, were considered. **Results:** Mechanical testing showed significant differences between the various spring types (ANOVA, ≤0.05), but constant intrabatch behavior (*t* test). Four groups were formed according to the mechanical properties of the springs: strong superelasticity without bias stress, weak superelasticity without bias stress, strong superelasticity with bias stress, and weak superelasticity with bias stress. **Conclusions:** In sliding mechanics, the strongly superelastic closed-coil springs with preactivation are recommended. In addition, we found that the oral environment seems to have only a minor influence on their mechanical properties. (Am J Orthod Dentofacial Orthop 2010;137:671-8)

Nickel-titanium (NiTi) materials have become more popular in the last decade. Their main advantage is their nonlinear force deflection behavior, resulting in the expression of force plateaus. Within these plateaus, NiTi products are relatively insensitive to imprecise activation. Their clinical applications are therefore much easier than with conventional alloys. However, plateau force levels vary widely, and product information from manufacturers is not always reliable. Clinicians must have accurate, unbiased information on the properties of the springs.

The superelastic (SE) coil springs we studied are mainly used for canine retraction. There is no consensus about the optimal force for canine distalization and probably never will be because of individual variations. Forces between 1 and 2 N are most commonly accepted for canine retraction.[1-3] These quoted variations in applied forces are closely related to the bracket and wire system used, because they have different frictional forces to overcome.[4-8] To apply forces in this range with conventional alloys, the mechanics dictate that they must be reactivated several times. In contrast, NiTi retraction coil springs allow for treatment with 1 activation, with the force maintained even over the distance of a whole extraction site. This has the following advantages: reduced chair time, optimal rates of distalization, and conservation of anchorage.

However, NiTi products are temperature sensitive, and small differences in alloy composition can lead to considerable differences in the mechanical characteristics of individual SE coil springs. It is important to consider oral temperature changes from ingestion of different types of food. Meeling and Odegaard[9] investigated the torsional behavior of several SE archwires. They found that the influence of temperature changes on the activation curve is opposite to the deactivation curve and that temperature changes lead to clinically significant changes in force level.

In addition to oral temperature changes, repetitive mechanical microdeflections caused by tongue play or

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Submitted, May 2006; revised and accepted, June 2008.
0889-5406/$36.00

doi:10.1016/j.ajodo.2008.06.029

mastication might also cause changes in the force level of NiTi springs. However, we found no data reporting the influence of mechanical microcycles on SE materials in the literature. Theoretically, it might be expected that an increase of stress-induced martensite (SIM) would lead to a decrease of plateau force level. The amount by which the force could decrease, however, is unknown.

Because of the nonlinear force-deflection relationship of SE alloys, the prediction of mechanical properties becomes challenging. Several attempts have been made to characterize the plateaus of NiTi products such as archwires or coil springs. Melsen and Terp[10] proposed a regression line connecting maximum force and force at 0.5-mm activation to compare SE products. However, this procedure allows only a rough approximation of the plateau. Another proposal is the SE ratio by Segner and Ibe,[11] relating the maximum and minimum slopes on the deactivation curves. This procedure allows for classification into products with SE tendency (ratio, ≥2), superelasticity (ratio, ≥8), or no SE behavior. But this approach does not tell the orthodontic practitioner the typical force level of the plateau. A more sophisticated approach is described by the SE algorithm (Fig 1). Based on a modification of the SE ratio, it allows for identification of the extension and the force level of the clinically relevant plateau by means of a mathematical calculation and is especially valuable for unbiased comparisons of different products. The aims of this study were to define and compare the mechanical characteristics of several currently available closed-coil retraction springs. Furthermore, the influence of temperature and mastication was investigated.

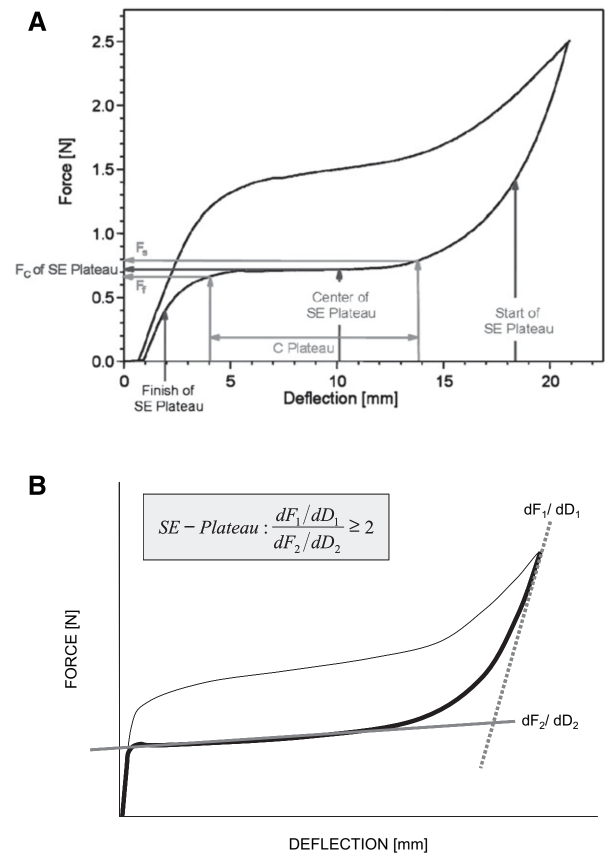

Fig 1. A, Calculation of the clinical plateau: the clinical plateau is based on the midforce of the SE plateau (F_C). It is defined as the force range ($F_s - F_f$) of 20% of the SE plateau midforce, which represents the widest span (mm) on the deactivation curve. **B**, Definition of the modified SE ratio from the ratio of the slopes at the start of the unloading curve (*grey dotted line*) and the slope at the center of the plateau (*grey line*). This modification allows also for the evaluation of preactivated NiTi materials.

MATERIAL AND METHODS

Table I lists all closed-coil springs included in this study. The mechanical properties were examined in a tensile test at a displacement rate of 1 mm per second^{-1} with a universal test frame (model 4444, Instron Corp, Wilmington, Del). The load frame was equipped with a ±100-N static load cell (serial number, UK480), and the temperature was kept constant at 37.0°C (±0.1°C) by submersing the samples and fixtures in a water bath. Temperature control and agitation of the water bath was achieved by a thermostat (FS 18 HP, Julabo, Seelbach, Germany). Closed-loop temperature control was achieved with an external resistive precision temperature sensor (PT100, Haraeus Sonsore-Nite GmbH, Kleinostheim, Germany) in the water bath. The sensor was calibrated at 0°C in a water-ice mixture (Fig 2).

In the tensile procedure, the specimens were prestressed to a force level of 0.1 N to eliminate experimental error from mechanical play in the fixtures. Starting from the 0.1-N prestress displacement, the specimens were consecutively strained to displacements of 4, 8, 15, 20, 25, and 30 mm. Straining was done twice, and only the second data set was used for evaluation to prevent further experimental error from mechanical setting in the fixtures and the crimping connections between the NiTi coil components and the stainless steel attachments of the retraction coils. Five coil springs were measured for each group.

Time, force, and displacement data were acquired electronically with data-acquisition and machine-control software based on Origin7pro (RockWare, Golden, Colo) through the machine's IEEE488 interface. The data acquisition rate was more than 10 samples per

Table I. NiTi closed-coil springs in this investigation

Number	Manufacturer	Product	Size (mm)	Force (N)	Catalog number	Lot
1a	Dentaurum	Rematitan Lite	9	—	758-160-00	26649
1b	Dentaurum	Rematitan Lite	12	—	758-161-00	27490
2a	Forestadent	Titanol Instant Zugfeder extra light	—	—	311-1026	231
2b	Forestadent	Titanol Instant Zugfeder light	—	—	311-1027	20218439
2c	Forestadent	Titanol Instant Zugfeder medium	—	—	311-1028	061 tc
3a	GAC	Coil springs ultra light	—	0.25	10-000-26	A5Z9
3b	GAC	Coil springs extra light	—	0.50	10-000-25	A322
3c	GAC	Coil springs light	—	0.98	10-000-03	A462
3d	GAC	Coil springs medium	—	1.47	10-000-02	A522
3e	GAC	Coil springs heavy	—	1.96	10-000-01	A222
3f	GAC	Coil springs extra heavy	—	2.45	10-000-18	A332
4a	Masel	Elastinol coil spring constant closed	9	0.50	4107-319	87665
4b	Masel	Elastinol coil spring constant closed	9	0.98	4107-320	78770
4c	Masel	Elastinol coil spring constant closed	9	1.47	4107-321	76589
4d	Masel	Elastinol closed	9	1.96	4107-322	5697
4e	Masel	Elastinol coil spring variable closed	9	—	4107-309	86093
4f	Masel	Elastinol coil spring variable closed	12	—	4107-312	5697
5a	Ormco	NiTi extension spring light force	—	—	222-5610	02C114
5b	Ormco	NiTi extension spring medium force	—	—	222-5612	02D74
5c	Ormco	NiTi extension spring heavy force	—	—	222-5620	01L6
6a	Ortho Org.	Nitanium closing spring	9	—	100-622	510873A02
6b	Ortho Org.	Nitanium closing spring	12	—	100-623	332206
7a	RMO	Nitinol coil spring medium force	9	—	F0207	41916
7b	RMO	Nitinol coil spring medium force	12	—	F0208	45650

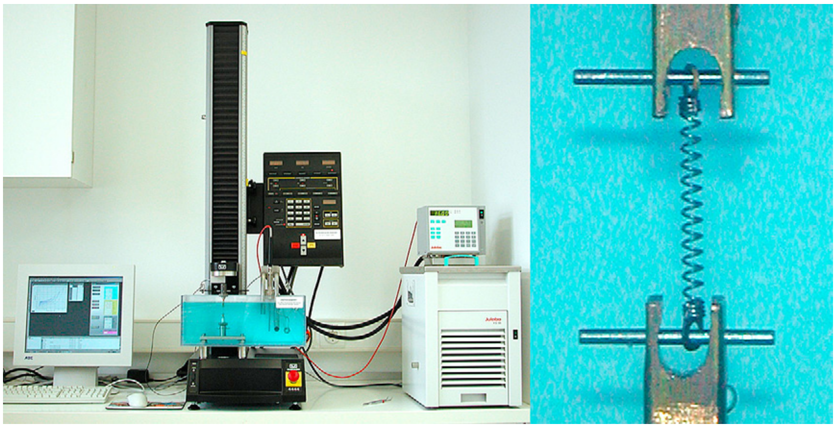

Fig 2. Testing equipment consisting of a tensile test frame and a thermostat, with a detailed view of the stretching mechanism for the coil springs. Testing was done in a water bath.

second^{-1}, corresponding to a displacement resolution of better than 0.1 mm at the chosen speed.

The same setup was used for further evaluation of certain NiTi springs. Two specimens from each coil type were tested for their behavior under repetitive mechanical microcycles of 2 mm expansion and environmental temperature changes. For the evaluation of mechanical microcycles, the coil springs were activated to 15 mm and deactivated to the plateau midpoint evaluated by the data analysis of the above-described mechanical testing. The springs were expanded 20 times. For the thermal evaluation, the handling of the specimens was identical to the setup for the mechanical microcycles. Instead of mechanical influences, 2 thermocycles between 4°C and 60°C were applied to the specimens, starting with the heating side.

The acquired data were analyzed for the clinically important plateau phase by using the SE algorithm (Fig 1, *A*). Unlike previous methods, this algorithm allows for a mathematical definition of the orthodontically

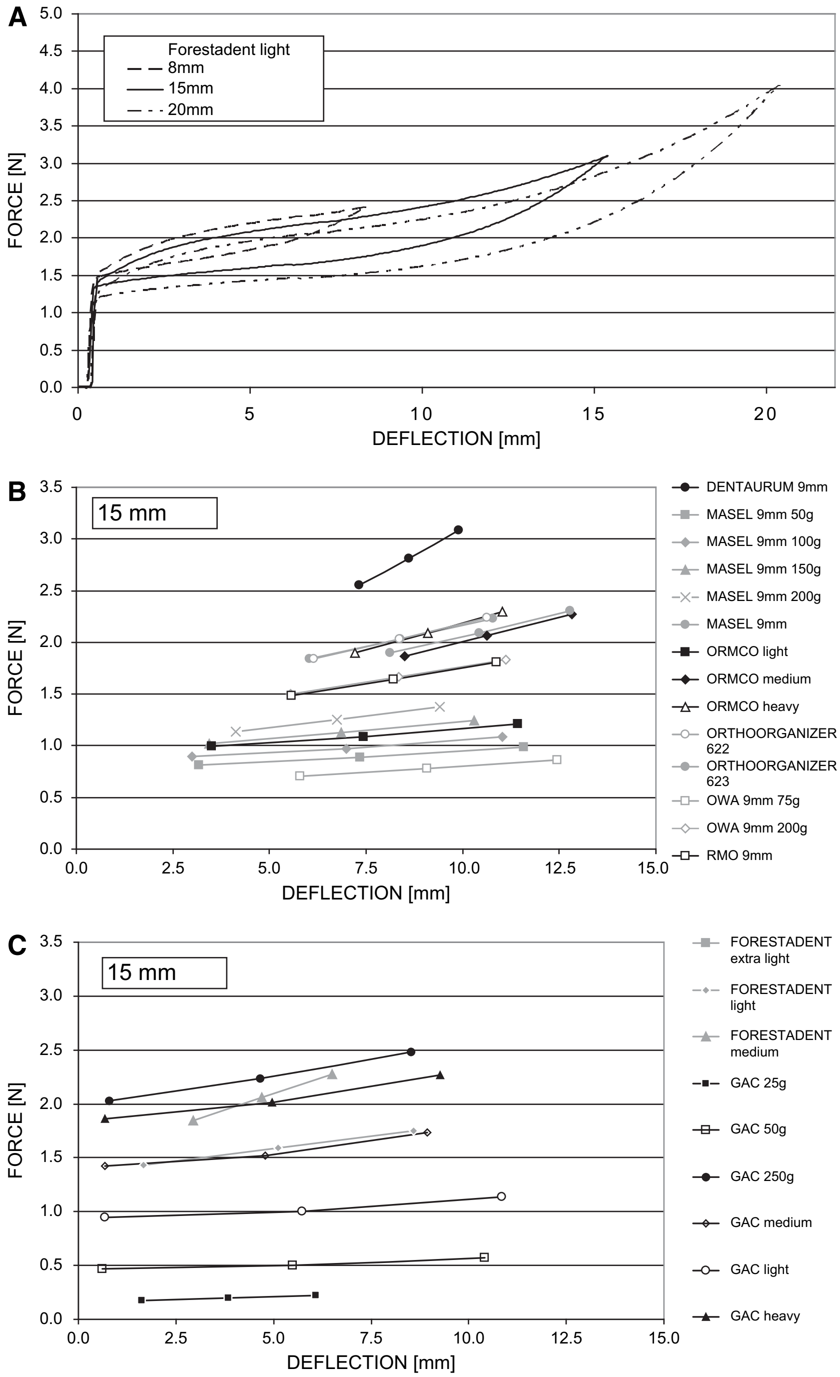

Fig 3. Clinical plateaus varied with different preactivations: **A,** with increasing preactivation, force levels and plateau slopes decrease, whereas plateau length is increased. Activation of 15 mm results in noticeable differences between **B,** not preactivated, and **C,** preactivated coil springs.

relevant force plateau and is therefore suitable for product comparisons. It is based on the SE ratio defined by Segner and Ibe.[11] This ratio describes the relationship between the maximum slope in the terminal region of the deactivation curve and the minimal slope in the plateau region. A ratio ≥2 is defined as "SE tendency."

Because of integrated preactivation in some products, the SE ratio is not suitable for the evaluation of

Table II. Classification of NiTi closed coil springs into the following groups

Strong superelasticity without preactivation	
Masel	Elastinol coil spring constant 0.5 N
	Elastinol coil spring constant 1 N
	Elastinol coil spring constant 1.5 N
	Elastinol coil spring constant 2 N
Ormco	NiTi extension spring light
Ortho Organizer	Nitanium closing spring 9 mm
RMO	Nitinol coil spring medium 9 mm
	Nitinol coil spring medium 12 mm
Weak superelasticity without preactivation	
Dentaurum	Rematitan Lite 9mm
	Rematitan Lite 12 mm
Masel	Elastinol variable 9 mm
	Elastinol variable 12 mm
Ormco	NiTi extension spring medium
	NiTi extension spring heavy
Ortho Organizer	Nitanium closing spring 12 mm
Strong superelasticity with preactivation	
Forestadent	Titanol Instant Zugfeder light
	Titanol Instant Zugfeder medium
GAC	Coil spring ultra light
	Coil spring extra light
	Coil spring light
	Coil spring medium
	Coil spring heavy
	Coil spring extra heavy
Weak superelasticity without preactivation	
Forestadent	Titanol Instant Zugfeder extra light

all products and had to be modified. A reliable relationship can be achieved by comparing the maximum slope of the initial parts of the deactivation curve with the plateau slope instead of the final slope of the deactivation curve (Fig 1, *B*). By displaying all data points with a modified SE ratio ≥2 on the graph, a plateau-like region can be generated. The clinically relevant "C plateau" is then defined by evaluating the deactivation curve for the range with the largest span on the deflection axis and a force range of 20% of the SE plateau midpoint force.

Statistical analysis

Statistical evaluation was performed by evaluating means and standard deviations for plateau extension, slope, force level, and plateau midpoint. In addition, analysis of variance (ANOVA) (the Student-Newman-Keuls test) was calculated for the deflection of 15 mm, classifying the springs at a probability level of 0.05 for the 2 criteria of plateau length and plateau slope.

RESULTS

Figure 3 displays the clinical plateaus for an activation of 15 mm, evaluated by the SE algorithm. According to the SE algorithm, only products achieving an SE ratio of at least 2 (SE tendency) were evaluated. The results show that plateau height and localization varied considerably with different activation levels. Four groups were formed according to the mechanical properties of the springs (Table II): (1) strong superelasticity without preactivation, (2) weak superelasticity without preactivation, (3) strong superelasticity with preactivation, and (4) weak superelasticity with preactivation.

Table III shows the results for springs with 15 mm without activation. The strongly SE spring can be differentiated from the weakly SE spring by the difference in the gradient of the clinical plateau. The difference in applied force is clearly greater for the weakly SE springs (Fig 3, *B*). The difference between groups 1 and 2 compared with 3 and 4 was the location of the plateau on the x-axis. Preactivated springs show a clinical plateau that extends until the spring is almost fully deactivated (Figs 3, *C*, and 4, *B*). This is in contrast to the unpreactivated springs, for which the plateaus end 3 to 5 mm before being fully deactivated (Figs 3, *B*, and 4, *A*).

At the 4-mm activation, only the springs from GAC and 2 from Masel had SE properties resulting in small force plateaus.

At 8 mm, the GAC springs still predominated, but also most springs from Forestadent and Masel began to show clinical plateaus. The force levels of the clinical plateaus varied strongly between different products. Although the GAC light produced a force of 0.5 to 0.75 N, that of the Forestadent spring was 1.5 to 1.8 N. For sagittal movement of teeth along the wire, a force of 1.5 to 2 N is needed, and this is possible with an 8 mm activation of these springs: RMO, 9 mm; Masel, 9 mm and 150 g; Forestadent light; and GAC medium. No other springs gave a relevant force level for this type of tooth movement. GAC heavy und Forestadent medium when activated by 8 mm produced forces in excess of 2.5 N.

For a 15 mm extension, most springs had clinical plateaus (Fig 3, *B* and *C*). As well as the GAC springs, Forestadent light; Masel, 9 mm and 50, 100, and 150 g; and Ormco light also exhibited well-pronounced plateaus with large extensions. Springs with force levels from 25 to 250 g are available with these plateau distributions. An activation of 8 to 15 mm clearly increases the size of the relevant clinical plateau. This allows application of defined forces to the teeth. However, force levels tend to decrease with the amount of activation. Thus, Forestadent light showed force levels of 15 to 1.8 N at 8-mm activation and 1.4 to 1.7 N at 15 mm activation

Table III. Comparison of coil springs (15 mm activation) with ANOVA and Student-Newman-Keuls tests at a significance level of ≤0.05 (lowest group indicates the best results and the highest the worst)

Number	Manufacturer	Plateau length (mm) and corresponding group		Plateau slope (N/mm) and corresponding group	
1a	Dentaurum	2.58	9	0.21	7
2b	Forestadent	6.91	3	0.05	3,4
2c		3.55	8	0.12	6
3a	GAC	4.46	5,6,7,8	0.01	1
3b		9.79	1	0.01	1
3c		10.17	1	0.02	1
3d		8.25	2	0.04	2,3,4
3e		8.59	2	0.05	3,4
3f		7.72	2	0.06	4
4a	Masel	8.42	2	0.02	1
4b		8.02	2	0.02	1,2
4c		6.87	3	0.03	1,2,3
4d		5.29	4,5,6	0.05	3,4
4e		4.75	4,5,6,7	0.09	5
5a	Ormco	7.91	2	0.03	1,2,3
5b		4.33	6,7,8	0.09	5
5c		3.82	7,8	0.11	5,6
6a	Ortho Organizer	4.47	4,5,6,7,8	0.09	5
6b		4.65	4,5,6,7	0.09	5
7a	RMO	5.31	5	0.06	4

(Fig 3, *A*). The main clinical advantage of a 15 mm activation is the long clinical plateau that extends to around 10 mm. Figure 3, *B* and *C*, clearly shows the large variance in force levels for individual springs between 0.25 and 3.2 N. At the moment, the labels of springs by different manufacturers do not give absolute force levels. Thus, the Forestadent light spring applies a similar force as the GAC medium spring (Figs 3, *C*, and 4, *B*).

Fifteen plateaus were seen at the 20-mm deflection. GAC 50 g and GAC light both exhibited plateau lengths of 12 mm. Forestadent light and Masel 9 mm, 50 g, also had broad plateaus of 10 mm in length. At the 25 mm deflection, most springs produced SE plateaus. However, many already had permanent deformation and therefore were not further evaluated. Only Forestadent light, GAC light, and GAC extra light displayed plateaus ending within 5 mm of the unstretched values for the spring.

At 30 mm, most springs showed either considerable permanent deformation or even breakage. With an extension of slightly more than 15 mm, GAC 50 g had the largest plateau in this study.

Regarding plateau extension, slope, plateau force level, and plateau midpoint, only 48 of 576 measurements showed a standard deviation exceeding 10% of the mean. By comparing group assignments for plateau length and plateau slope, most springs were in different but fairly close groups. Only GAC extra light and light were in group 1 for both criteria.

Results for mechanical microcycles and thermocycles are shown in Figures 5and 6. Mechanical microcycles result in a force reduction of about 10% within the first 5 cycles. Thereafter, the force remains relatively stable.

The thermal evaluation showed a force increase by heating and a decrease by cooling. Overall, thermocycles resulted in a permanent force increase of 15% to 20%.

DISCUSSION

SE materials have become increasingly important in orthodontic treatment. However, there are few basic data to provide unbiased information about the mechanical properties of these alloys. We evaluated 24 SE retraction coil springs for their mechanical behavior at oral temperature. Different activation levels and the influence of temperature cycles and mechanical microcycles from tongue play or mastication were evaluated.

To compare the different coil springs, a new algorithm had to be developed. Earlier attempts were made to characterize the plateaus of NiTi products. Melsen and Terp[10] proposed a regression line connecting maximum force and the force at 0.5 mm activation to compare SE products. However, this procedure gives only a rough approximation of the plateau. Another proposal is the SE ratio by Segner and Ibe,[11] relating the maximum and minimum slopes on the deactivation curves. This procedure allows for classification of the

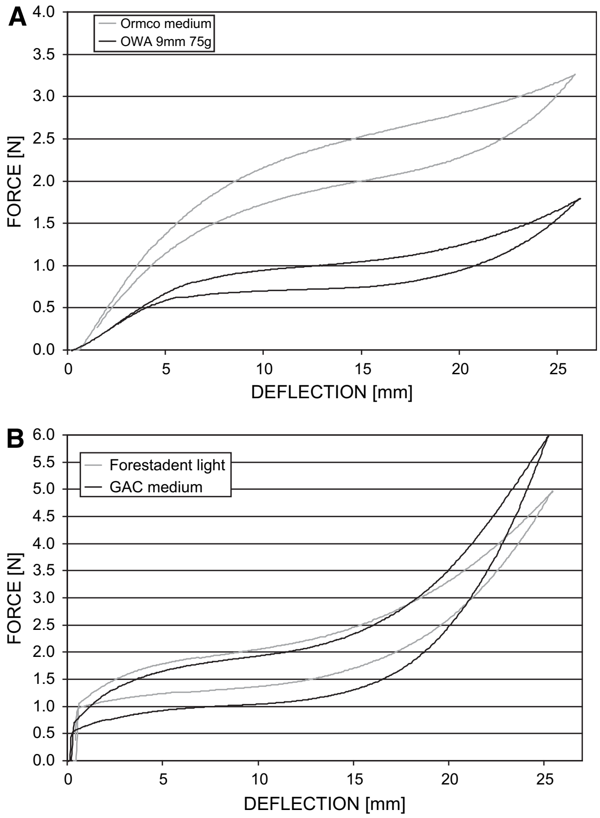

Fig 4. Strong SE closed-coil springs. **A,** Without preactivation. **B,** With preactivation, the force remains until the end of the tooth movement compared with coil springs without preactivation.

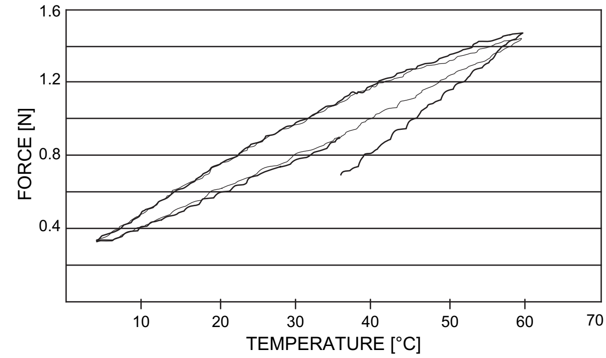

Fig 5. Multiple deflection cycles cause force drop of approximately 15% over the first 3 cycles. Thereafter, the forces remained reasonably stable.

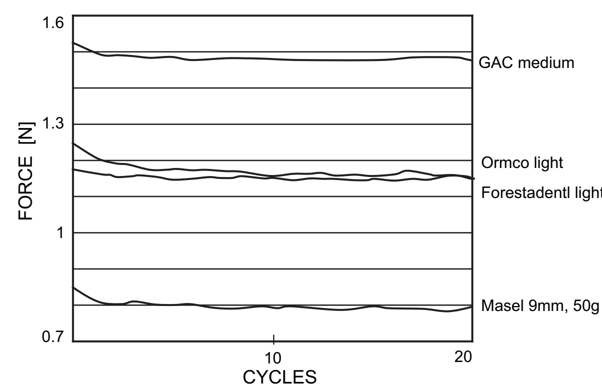

Fig 6. Typical influence of temperature cycles on SE coil springs as shown by this example of a Masel 9-mm, 50-g closed-coil spring. Cycles begin with heating. Note the force increase at mouth temperature induced by the first temperature cycle (*wide line*). The second cycle (*thin line*) did not change the alloy properties any more.

products with SE tendency (ratio ≥2), superelasticity (ratio ≥8), or no SE behavior. But this approach does not tell the orthodontic practitioner the typical force level of the plateau. A more sophisticated approach is described by the SE algorithm. Based on a modification of the SE ratio, it allows for identification of the extension and the force level of the clinically relevant plateau by means of a mathematical calculation and is especially valuable for an unbiased comparison of different products. Therefore, the force-deflection data in this study were evaluated with the SE algorithm.

The results of this evaluation of the data suggest that the expression of a clinical plateau in SE retraction coils highly depends on the initial activation. A considerable deflection is necessary to form enough SIM. Only the expression of SIM leads to the characteristic development of force plateaus in the deactivation curve. To obtain good plateau regions, it is important to activate all springs by at least 15 mm when attaching them to the appliance. Activations of more than 25 mm cause a higher failure rate because of permanent deformation and even breakage of the coil springs.

As shown in the literature, different amounts of activation also lead to variable force levels at a predetermined deflection.[12] This is unlike stainless steel, when, unless the spring is permanently deformed, a predetermined deflection can be related to a defined force, independent of the previous deflection history. In NiTi alloys, deflection memory (not to be confounded with shape memory) can be observed. This means that, at a certain defined deflection, a closed-coil spring might deliver highly variable forces depending on whether the extension is small or large. In extreme cases, this can lead to force variations up to 100% as seen in the GAC heavy spring. At an initial activation of 30 mm, the plateau force level is 1 N, whereas, at an activation of only 8 mm, the plateau force exceeds 2 N. Thus, it is important to consider the selection of not only the appropriate spring type, but also the right initial activation. It seems important to us that initial activation should be considered a criterion in further force-deflection studies with SE materials regardless of the product design.

The influences of oral temperature changes and mechanical microcycles on SE coil springs have not been investigated so far. Interestingly, it seems that mechanical and thermal influences compensate for each other. Thermocycles resulted in an increase of 15% to 20% of force levels, whereas mechanical microcycles led to a decrease of approximately 10%. Completing this calculation by adding the force decrease from deactivation of the spring by tooth movement, the forces balance.

Some manufacturers preactivate their coil springs. This preactivation results in a steep force increase at the beginning of the activation curve and a steep drop at the end of the deactivation curve. The manufacturers probably applied a torsional component to the wire while manufacturing the coil spring. As a result, the whole clinical plateau is shifted toward a smaller deflection on the y-axis. From the clinical aspect, this means that a tooth can be moved to its desired position without reactivation of the spring. The preactivation might partially explain the performance of the GAC springs, especially in the 4-mm activation group, where the springs without preactivation could not build up enough SIM for an SE plateau. The clinical advantage of preactivation is less need for intraoral extension of the coil springs.

CONCLUSIONS

SE closed-coil springs display highly constant force plateaus unrivalled by conventional materials. However, attention must be paid not only to the selection of the proper product, but also to the right amount of activation. Preactivated NiTi springs have a distinct advantage over springs without preactivation.

The influences of intraoral temperature changes and mechanical microdeflections cancelled each another and need not be considered when calculating the applied force needed.

The SE algorithm proved to be a useful tool for the unbiased evaluation of the retraction springs.

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