Load-deflection rate measurements of activated open and closed coil springs

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Coil springs[1] were introduced for orthodontic tooth movement in 1931. Coil springs can be divided into two groups — those with open coils and those with closed coils. Many variables affect the force levels produced by coil springs. These include the alloy, wire size, lumen size, pitch angle of the coils, and the length of the spring. As wire size increases, the load-deflection rate increases.[2-7] As the angle between the coils and a perpendicular to the long axis of the spring, referred to as the pitch angle, increases, the load-deflection rate increases.[7-9] Conversely, as lumen size[6] and spring length[2-4] increase, the load-deflection rate decreases.

Previous studies show that coil springs made from Cobalt-Chromium-Nickel (Co-Cr-Ni) alloy are stiffer than stainless steel coil springs of the same dimensions.[6,7,9] However, the differences reported are variable among recent studies. Webb[6] reported closed coil 0.009 x 0.030 inch Co-Cr-Ni alloy springs to be approximately 50 percent stiffer than stainless steel. Kiura[9] reported Co-Cr-Ni of the same wire and lumen size to be only 10 percent stiffer than stainless steel. Chaconas[7] reported 0.010 x 0.030 inch open coil springs of Co-Cr-Ni alloy to be approximately 30 percent less stiff than stainless steel. Miura[9] found 0.009 x 0.030 inch Co-Cr-Ni open coil springs 12 percent less stiff than stainless steel. Not only do these studies lack agreement, but only one size of Co-Cr-Ni coil spring was reported in each study.

Since several different wire and lumen sizes are currently in use for springs made from stainless steel and Co-Cr-Ni alloys, it will be clinically important to have more complete data on the coil springs being utilized in orthodontic mechan-

Abstract

The purpose of this investigation was to provide load-deflection rate data for a variety of open and closed coil springs. Ten millimeter lengths of open and closed coil stainless steel and Cobalt-Chromium-Nickel (Co-Cr-Ni) alloys in combinations of 0.008, 0.009 and 0.010 inch wire sizes, and 0.030 and 0.032 inch lumen sizes were tested. Other groups included heat treated Co-Cr-Ni springs and springs of 15 and 20 millimeter lengths. Forces and activations were measured by a tension load cell with an Instron universal testing instrument.

Stiffness increased dramatically with wire size and pitch angle of the coils. Stiffness decreased slightly with increased lumen size. Co-Cr-Ni closed coil springs were slightly stiffer than stainless steel, whereas stainless steel open coil springs were much stiffer than Co-Cr-Ni. Heat treatment increased the stiffness of Co-Cr-Ni coil springs. The length of the spring had a great effect on the load-deflection rate. A shorter spring is stiffer than a longer spring by an amount directly proportional to the ratio of the length of the longer spring to that of the shorter spring.

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Key Words

Coil springs • Cobalt-Chromium-Nickel alloy • Stainless steel • Heat treatment • Load-deflection rate • Spring rate

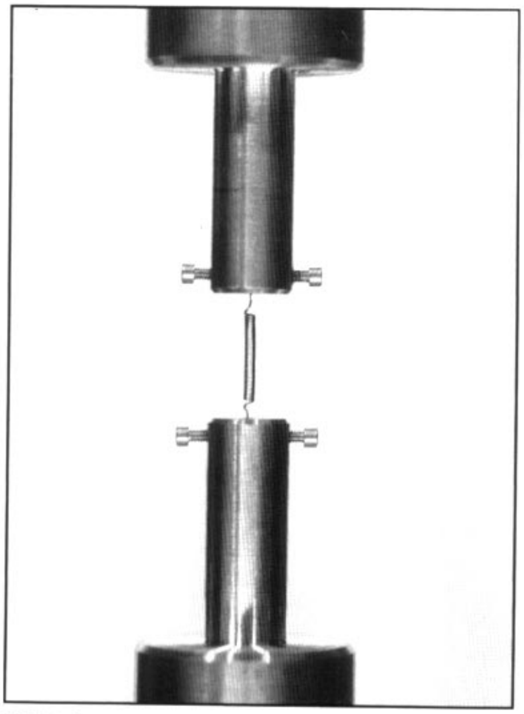

Figure 1

Figure 1
The modified ends of the springs are fixed in the holding device attached to the crosshead of the Instron machine for the extension tests.

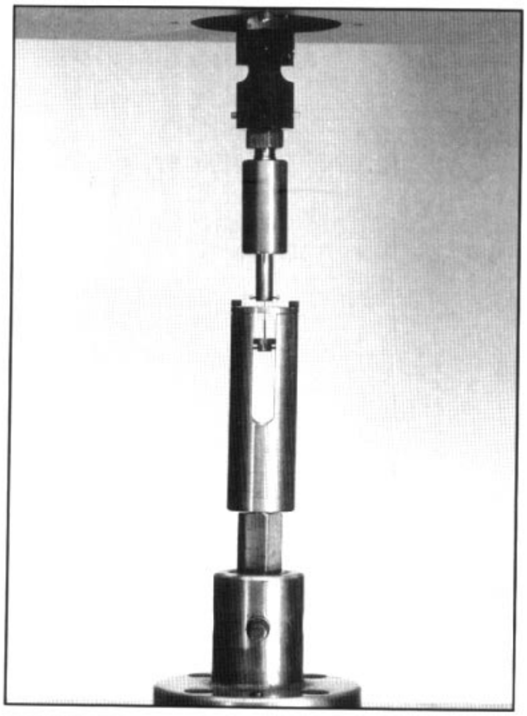

Figure 2

Figure 2
A mounted open coil spring is placed in the apparatus for compression testing.

ics. Also, a method of comparison of various lengths of the same spring would be beneficial since spring length will vary according to the clinical situation. Therefore, this study was undertaken to add to the body of knowledge relating to activation of coil springs.

Materials and methods

Open and closed coil springs of stainless steel* and Co-Cr-Ni** were used in this study to evaluate the spring rates and to provide potential comparisons with the findings of previous investigations. Ten millimeter lengths of six clinically applicable coil springs were tested: 0.008 x 0.030, 0.008 x 0.032, 0.009 x 0.030, 0.009 x 0.032, 0.010 x 0.030, and 0.010 x 0.032 inch. For each coil spring size and alloy combination, compression tests were made on 30 open coil springs and extension tests were made on 30 closed coil springs in accordance with usual clinical application.

In addition, 10 Co-Cr-Ni open and closed coil springs each of 0.008, 0.009, and 0.010 x 0.030 inch sizes were heat treated before being tested. The manufacturer does not recommend heat treating Co-Cr-Ni coil springs. However, Co-Cr-Ni archwires can be heat treated to increase stiffness and resilience. Hence, it was decided to heat treat the springs under controlled conditions to determine the effect on the springs' properties. The coil springs were placed in an oven at 900 degrees Fahrenheit for five minutes. To test the effect of spring length upon the load-deflection rate, a group of five 15 millimeter lengths and a group of five 20 millimeter lengths of 0.008 x 0.032 stainless steel closed coil springs were also tested.

An Instron*** universal testing instrument was used for both extension and compression tests. See Figures 1 and 2. For the extension tests, the ends of the springs were modified to provide a method for pulling along the long axis of the spring. The total initial length of each specimen was 10 millimeters for reasons of comparison. The extension, ΔL, was determined by the product of the speed or rate of crosshead movement and the time interval of movement ($\Delta L = r \times t$). One to two coils were straightened out at both ends of each specimen. The specimen was secured into a holding device attached to the Instron with a 10 pound load cell.

For the compression tests, the 10 millimeter lengths of open coil springs were not modified. The specimen was slid over a 0.017 x 0.022 inch rectangular archwire which allowed one one-thousandth of an inch clearance on each corner between the archwire and an 0.030 inch lumen coil spring. This tolerance was large enough to prevent undue friction, yet small enough to permit only minimal buckling of the spring. The archwire was attached to a plate at one end and slid through an aperture of a second plate at the other end. This procedure resulted in the specimen being held on the archwire between two plates. The archwire was free to slide through the upper plate, thereby allowing the upper plate

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* *Unitek Hi T II, Unitek Corp./3M, Monrovia, CA*

** *Blue Elgiloy, Rocky Mountain Orthodontics, Denver, CO*

****Instrom model 1135, Instrom Corp., Canton, MA*

Table 1

Alloy	Wire and lumen sizes inches	Load deflection rates gm/mm			Linear range mm	
		mean ± SD	min.	max.	Lower limit mean ± SD	Upper limit mean ± SD
Elgiloy	0.008 x 0.030	48.1 ± 2.9	41.3	51.4	0.5 ± 0.3	2.6 ± 0.7
	0.008 x 0.032	48.3 ± 3.1	42.0	57.8	0.7 ± 0.3	2.5 ± 0.6
	0.009 x 0.030	82.8 ± 3.6	73.0	88.2	0.7 ± 0.3	2.4 ± 0.4
	0.009 x 0.032	81.6 ± 3.3	73.0	88.7	0.8 ± 0.3	2.7 ± 0.6
	0.010 x 0.030	138.4 ± 5.1	125.0	147.0	0.6 ± 0.2	2.0 ± 0.3
	0.010 x 0.032	110.6 ± 6.6	100.0	122.0	0.5 ± 0.3	2.2 ± 0.5
Stainless steel	0.008 x 0.030	68.1 ± 2.9	60.9	73.6	0.8 ± 0.3	3.0 ± 0.3
	0.008 x 0.032	70.6 ± 4.0	63.6	79.6	1.0 ± 0.4	3.0 ± 0.4
	0.009 x 0.030	122.3 ± 5.4	111.0	135.0	0.9 ± 0.4	2.4 ± 0.2
	0.009 x 0.032	114.9 ± 10.0	101.0	136.0	1.0 ± 0.4	2.7 ± 0.3
	0.010 x 0.030	167.4 ± 11.2	146.0	203.0	0.8 ± 0.3	2.4 ± 0.2
	0.010 x 0.032	169.8 ± 6.9	155.0	183.0	0.8 ± 0.3	2.5 ± 0.2

Table 1
Load-deflection rates and linear ranges for all open coil springs: their means, standard deviations, and maximum and minimum values.

to be pulled toward the lower when the crosshead was lowered.

Continuous curves of force versus time were obtained on an X-Y recorder. The time axis values were converted to distances of activation by multiplying the crosshead rate by the one inch per minute chart speed.

Experimental results

The data obtained from the graphs were the load-deflection rates, upper or elastic limit, and lower end or initial activation of coils for the linear ranges of activation, as well as initial tensions. Table 1 depicts the means, standard deviations, and ranges of the spring rates for each of the 12 groups of open coil springs studied. Wire size had the greatest effect upon the spring rate, followed by pitch angle.

The data were analyzed using a multifactorial analysis of variance (SAS, Statistical Analysis System, SAS Institute, Cary, N.C.). The mean values for the spring rates were found to be significantly different at the $p < .0001$ level for all types of springs (all wire sizes and both alloys) in each group except the closed coil springs of 0.030 inch size. In this group, the alloys were also significantly different, at the $p < .009$ level.

The lumen size had a very small effect upon the spring rate, except in the 0.010 inch diameter wire Elgiloy springs. To see if this was a constant characteristic of this size, ten samples from three additional spools of Elgiloy 0.010 x 0.030 and 0.032 inch were tested.

The results were very consistent for the springs with 0.030 inch lumens, with all spring rates falling within a 2.2 gm/mm range. In contrast, the subsequent spring rate means for the 0.032 inch lumen size were found to be higher than that for the original spool. The original spring rate mean was 110.2 gm/mm, whereas the subsequent spring rate means were 130.5, 130.8, and 124.8 gm/mm. Although the exact cause for these differences is unknown, residual stresses from the manufacturer could be a factor. These latter figures are closer to those

Table 2

	Wire & lumen sizes inches	Initial tension gm	Load deflection rates gm/mm			Linear range mm	
						Lower limit	Upper limit
		mean ± SD	mean ± SD	min.	max.	mean ± SD	mean ± SD
Elgiloy	0.008 x 0.030	0.0 ± 0.0	25.0 ± 0.7	22.6	26.3	0 ± 0	5.4 ± 0.7
	0.008 x 0.032	0.0 ± 0.0	25.1 ± 1.0	23.4	27.8	0 ± 0	5.4 ± 0.8
	0.009 x 0.030	23.8 ± 3.7	44.1 ± 0.9	41.0	45.6	0.2 ± 0.1	4.5 ± 0.5
	0.009 x 0.032	0.0 ± 0.0	39.7 ± 0.9	37.4	42.1	0 ± 0	4.5 ± 0.7
	0.010 x 0.030	0.0 ± 0.0	70.6 ± 3.2	65.5	76.6	0 ± 0	3.7 ± 0.4
	0.010 x 0.032	5.5 ± 7.7	62.8 ± 2.6	57.2	68.6	0 ± 0	3.7 ± 0.4
Stainless steel	0.008 x 0.030	28.6 ± 5.1	24.5 ± 0.5	23.3	26.1	0.4 ± 0.2	5.7 ± 0.6
	0.008 x 0.032	32.0 ± 4.2	20.3 ± 0.4	19.3	21.3	0.3 ± 0.1	5.1 ± 0.7
	0.009 x 0.030	29.1 ± 5.6	42.4 ± 1.3	39.7	45.6	0.3 ± 0.1	4.9 ± 0.5
	0.009 x 0.032	36.6 ± 3.9	36.6 ± 0.6	35.8	39.2	0.2 ± 0.1	5.0 ± 0.4
	0.010 x 0.030	68.8 ± 7.3	70.8 ± 1.9	67.7	74.4	0.2 ± 0.1	4.4 ± 0.4
	0.010 x 0.032	35.4 ± 6.0	56.8 ± 1.2	54.3	60.0	0.2 ± 0.04	5.1 ± 0.6

Table 2
Load-deflection rates and linear ranges for all closed coils: their means, standard deviations, and maximum and minimum values as well as initial tensions where applicable.

of the 0.010 x 0.030 inch springs, which is consistent with the differences among other size springs. This spring size showed greater variability than any other of this alloy of Hi T II.

It was found that the pitch angle in open coil springs was 7.5 degrees higher in the Hi T II alloy springs as compared to the springs made from Elgiloy. The number of coils was correspondingly smaller in Hi T II. In a 10 millimeter length of spring there were 14 coils in Hi T II springs as compared to 20 to 25 coils for springs made from Elgiloy.

The difference between alloys in the number of coils per unit length also affects the maximum amount of activation available. With fewer number of coils per unit length, there is more space between the coils. Therefore, the Hi T II springs could be compressed to a greater extent than could the Elgiloy springs. The maximum amount of activation of Hi T II springs 10 millimeter lengths was 5.4 to 6.0 millimeters compared to 4.2 to 4.8 millimeters for Elgiloy springs.

The effect of alloy upon the load-deflection rate is better illustrated in closed coil springs, which have similar configurations in both alloys. The Elgiloy load-deflection rates averaged five percent greater than Hi T II for springs of similar wire size, lumen size, and spring length. Table 2 gives force-extension data for closed coil springs.

Certain groups of closed coil springs exhibited a phenomenon termed initial tension.[10] This means that a certain threshold of force must be reached before the spring will stretch. The spring would actually be shorter at its natural length were it not for the coils contacting each other. This characteristic is imparted to the spring during manufacture. All of the samples of Unitek Hi T II closed coil springs and 0.009 x 0.030 inch Rocky Mountain Elgiloy exhibited initial tension, while only 11 of the 30 0.010 x 0.032 Elgiloy closed coil springs exhibited initial tension (Table 2). A second group of the latter size was tested and exhibited no initial tension. Data for

Table 3

Springs inches	Load deflection rates gm/mm		Linear range mm			
	Mean ± SD		Lower limit		Upper limit	
	stock	heat treated	stock	heat treated	stock	heat treated
Open						
0.008 x 0.030	48.1 ± 2.9	53.4 ± 1.5	0.5	0.6	2.6	2.3
0.009 x 0.030	82.8 ± 3.6	96.8 ± 2.3	0.7	0.8	2.4	2.4
0.010 x 0.030	138.4 ± 5.1	150.2 ± 7.4	0.6	0.7	2.0	1.9
Closed						
0.008 x 0.030	25.0 ± 0.7	30.3 ± 1.1	0.0	0.0	5.4	7.2
0.009 x 0.030	44.1 ± 0.9	47.0 ± 0.9	0.2	0.0	4.5	6.6
0.010 x 0.030	70.6 ± 3.2	79.7 ± 3.8	0.0	0.0	3.7	5.9

Table 3
The effect of heat treatment of Elgiloy springs on load-deflection rates and linear ranges. All differences in spring rates were significant at $p<0.0001$. Differences for the upper limits of the linear range for the closed coil springs were significant at $p<0.0001$. The lower limits of the linear ranges were not statistically significant.

heat treated Elgiloy versus stock Elgiloy appear in Table 3. Heat treated springs averaged 13 percent stiffer than those which were not heat treated. Although there was no change in the linear ranges of the open coil springs, the length of the linear ranges of the closed coil springs was extended by 46 percent.

The load-deflection rates for various lengths of 0.008 x 0.032 stainless steel closed coil springs indicate that longer springs are not as stiff as shorter ones. In this wire size, 10 millimeter lengths produced 20.3 gm/mm, whereas 15 and 20 millimeter lengths produced 13.6 gm/mm and 10.4 gm/mm, respectively, or would be predicted by force-deformation analysis.

Discussion

Many factors affect the load-deflection rates of coil springs. These include the alloy, wire size, lumen size, pitch angle of the coils, the total number of coils, and the length of the spring. The pitch angle and the number of coils are interrelated. As the pitch angle increases, the number of coils per unit length decreases. A decrease in the number of coils per unit length produces a decrease in the total length of the wire in the spring. Since load-deflection rates increase with decreasing length of wire,[12] an increase in pitch angle increases the load-deflection rate.

In order to compare the results of this study to those of others, a method of comparison of springs of different lengths is needed. It was shown experimentally that for springs which are identical, the ratio of the load-deflection rates is inversely proportional to the ratio of the lengths. Therefore, data from previous investigators was used to calculate load-deflection rates for a standardized length of 10 millimeters.

Miura[9] reported data on 0.009 x 0.030 inch Elgiloy and Hi T closed coil 10 millimeter specimens. From his data, spring rates of 55 gm/mm for Elgiloy and 50 gm/mm for Hi T can be calculated. Corresponding values in this research are 44 gm/mm and 42 gm/mm, respectively. The magnitude of the differences between springs of unlike alloys is consistent. In contrast, Webb[6] reported data with a larger difference between springs of unlike alloys. If his springs were 10 millimeters in length, the spring rates would have been 80 gm/mm for Elgiloy and 54 gm/mm for Hi T.

Previous investigators have found Elgiloy open coil springs less stiff than stainless steel open coil springs. This study showed similar differences, Elgiloy being 29 percent less stiff than Hi T II for 0.008 inch wire size. Miura[9] found 0.009 x 0.030 inch Co-Cr-Ni alloy 11 percent less stiff than stainless steel compared to 32 percent for this study. Chaconas[7] found 0.010 x 0.030 inch Co-Cr-Ni 30 percent less stiff than stainless steel. The number of coils in 10 millimeter lengths was 14 in Hi T II and 20 to 25 in Elgiloy springs. Correspondingly, the length of the wire in each of these springs will vary with the number of coils. It has been demonstrated that the length of wire affects the load-deflection rate; the longer the length of the wire, the less the load-deflection rate.[12]

It is possible to estimate the force produced by a given length of a coil spring using the following method.[11] Multiply the spring rate found in the table of spring rates by 10 and divide it by the length of the coil spring. This gives the spring rate for the coil spring in gm/mm. To obtain the force level, multiply the spring rate by the distance of activation and add the initial tension, if any.

Conclusions

The following conclusions can be drawn from this study:

1. The diameter of the wire has a strong effect on the spring rate of the coil springs. The average spring rates for coil springs made from 0.008, 0.009, and 0.010 inch wires were 41.2, 70.6, and 105.9 gm/mm respectively.
2. For 10 millimeter springs, the difference between 0.030 and 0.032 inch lumen sizes is very small. The average spring rate for all 0.030 inch lumen coils was eight percent greater than that for 0.032 inch lumen coils.
3. Elgiloy averages five percent stiffer than Hi T II for closed coil springs of similar dimensions and configurations. Open coil springs of these two products are not of similar configurations.
4. The number of coils and total length of wire in a coil spring has a profound effect upon the spring rate. For any given coil spring of specified wire size, lumen size, alloy and length, an open coil spring is stiffer than a closed coil spring. For Rocky Mountain Blue Elgiloy, 10 millimeter open coil springs ranged from 76 percent to 105 percent stiffer than closed coil springs. For Unitek Hi T II, 10 millimeter open coil springs ranged from 136 percent to 248 percent stiffer than closed coil springs.
5. The total length of wire in Elgiloy averaged 44 percent greater than those of open coil Hi T II springs. Accordingly, the Hi T II spring rates averaged 40 percent higher than Elgiloy.
6. Heat treated Elgiloy springs averaged 13 percent stiffer than those which were not heat treated. Although there were no changes in the linear ranges of open coil springs, there was a 46 percent increase in the linear range of closed coil springs prepared by heat treatment.
7. A shorter spring is stiffer than a larger spring of the same type by an amount directly proportional to the ratio of the length of the longer spring to that of the shorter spring.

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