Stiffness-deflection behavior of selected orthodontic wires

**Jay M. Oltjen, DDS, MS; Manville G. Duncanson Jr., DDS, PhD;
Joydeep Ghosh, DDS, MS; Ram S. Nanda, DDS, MS;
G. Frans Currier, DDS, MSD, M.Ed**

In order to optimize the biological environment for tooth movement and minimize patient discomfort, treatment of tooth discrepancies in the initial malocclusion requires wires of low stiffness to produce gentle forces as the teeth are leveled and aligned. Biomechanical considerations require that archwire stiffness be an important criterion, upon which rests the relationship between orthodontic force and deflection within the elastic working range.[1-3] Burstone[4] stated that the major reason the orthodontist should select a particular wire size is its stiffness or load-deflection rate. Stiffness is directly related to cross-sectional size and shape. However, with the introduction of titanium-based alloys and multistrand wires, stiffness can be reduced without reducing cross-sectional size or shape.[4-6]

O'Brien[7] defined stiffness as the slope of the straight line in a bending plot or the amount of force required per unit of activation. Some factors that affect wire stiffness include wire material, hardness, state of heat treatment, size, and cross-sectional shape. Wire stiffness is also affected by bracket width, interbracket distance, length of wire, and the incorporation of loops.[1,2,8]

Studies of nickel-titanium alloy wires have demonstrated a linear loading and unloading characteristic for some single-phase nickel-titanium alloys.[9,10] However, newer alloys have been shown to demonstrate nonlinear loading and unloading behaviors with relatively constant force levels throughout their midregions of deactivation.[9-11] Hence, it is impossible to obtain a single value for stiffness or slope of the bending plot for these nonlinear wires.[11] Quantifying the

Abstract
Treatment of horizontal and vertical tooth discrepancies requires wires of low stiffness to produce forces as the teeth are leveled and aligned. In this investigation, the stiffness characteristics of several solid and multistrand nickel-titanium and stainless steel orthodontic wires were determined at selected clinically relevant deflections. Twenty specimens of 24 different wires were tested in both three-point and three-bracket bending modes. The unloading force deflection plot of each wire was described by a polynomial regression from which wire stiffnesses were obtained by mathematical differentiation. Graphs of the functional relationship between stiffness and deflection are presented. The results of this investigation show that wire stiffness can be altered not only by changing the size, but also by varying the number of strands and the alloy composition. An equally important finding was the dependence of stiffness on deflection for most of the wires measured. Comparisons were also made between the stiffness values obtained in three-point bending and the three-bracket bending systems.

Key Words
Orthodontic wires • Stiffness

Submitted: July 1995 **Revised and accepted:** February 1996 Angle Orthod 1997; 67(3);209-218.

Table 1
All 24 wires from this study classified by alloy, number of strands, wire size, and commercial name

		Round		Square		Rectangular	
Alloy type	Strands	Size	Comm. name	Size	Comm. name	Size	Comm. name
Stainless steel	1 solid	0.016" 0.018"	Permachrome* Permachrome*	0.016"x0.016"	Permachrome*	0.017"x0.025" 0.021"x0.025"	Permachrome* Permachrome*
Stainless steel	3-stranded	0.0175" 0.0215"	Wildcat** Wildcat**	0.016"x0.016"	Quadcat**	0.017"x0.025" 0.021"x0.025"	Quadcat** Quadcat**
Stainless steel	6-stranded	0.0175" 0.0215"	Respond*** Respond***				
Stainless steel	8-stranded			0.016"x0.016"	8 Strand*	0.017"x0.025" 0.021"x0.025"	D-Rect** D-Rect**
Stainless steel	9-stranded					0.017"x0.025" 0.021"x0.025"	Force 9** Force 9**
Nickel-titanium	1 (solid)	0.016" 0.018"	Nitinol SE* Nitinol SE*	0.016"x0.016"	Nitinol SE*	0.017"x0.025" 0.021"x0.025"	Nitinol SE* Nitinol SE*
Nickel-titanium	9-stranded					0.017"x0.025" 0.021"x0.025"	Turbo*** Turbo***

* Unitek Corporation/3M, Monrovia, Calif ** GAC International, Inc, Central Islip, NY *** Ormco Corporation, Glendora, Calif

magnitude of orthodontic forces at varying deflections is not only necessary for these newer titanium alloys but for the recently introduced multistrand nickel-titanium wires as well.

In the past, researchers have evaluated the stiffness properties of wires in cantilever[4,10] and other bending modes.[3,4,8] This information cannot be directly applied to clinical situations because (1) the bracket slot constrains the longitudinal shape of the deflected wire, and (2) friction and binding at the bracket-wire interface affects force delivery characteristics of the wire.

The specific objectives of the current study were (1) to measure the unloading force-deflection behavior of selected single- and multistrand nickel-titanium and stainless steel orthodontic wires via conventional three-point free-end bending and via a simulated clinical bracket setup; (2) to plot the unloading data for each wire in a force-deflection diagram and use a polynomial regression procedure to fit the patterns of these data; (3) to compute and plot the derivatives of the polynomials to describe the stiffness-deflection character for each wire type; and (4) to compare stiffnesses with respect to mode of testing, wire size, alloy composition, and number of strands.

Materials and methods

Wires and their designations

The wires tested included single-strand and multistrand nickel-titanium and stainless steel orthodontic wires. They are listed in Table 1 according to alloy, number of strands, wire size, and commercial name. Wires composed of stainless steel alloy and single-strand cross-sections are denoted by size only. For example, the notation 016 refers to a single-strand 0.016 inch diameter stainless steel wire. Wires with multistrand cross-sections are denoted by the number of strands. The letter N is added to differentiate nickel-titanium wires from stainless steel ones. For example, a 0.0175 x 0.025 inch nine-strand stainless steel wire would have the abbreviation 17x25 9s; the same wire made of nickel-titanium alloy would be denoted as N 17x25 9s. Whenever possible, specimens were obtained from the manufacturer in straight lengths. If straight lengths were not available, preformed arches were obtained and the straight posterior segments were employed for testing. The specimen length for all tests was 30 mm. A sample consisted of 20 specimens. Twenty-four wire samples were tested in each of two modes of bending, resulting in 960 tests.

Three-point bending test

Two testing methods were employed in this investigation. The first method, a three-point bending test, was employed as a physical property test. The three-point bending apparatus used simple, free-end beam theory. A stylus was connected to the crosshead of an Instron Universal Testing Machine (Model # 1135, Instron Corporation, Canton, Mass) and centered at the midspan of each wire specimen. The span was 13 mm. Figure 1 shows the actual test area of the apparatus with a wire specimen in its deflected

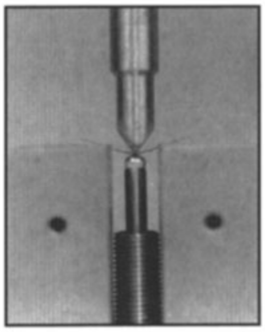


Figure 1

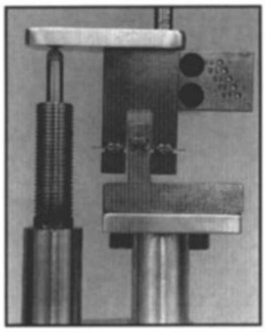


Figure 2

Figure 1
Three-point bending apparatus with the specimen deflected

Figure 2
Three-bracket bending apparatus with the specimen deflected

state. From top to bottom, the stylus, a deflected wire, and a linear variable displacement transducer (LVDT) are visible.

Three-bracket bending test

The second method of testing involved a three-bracket bending system. This apparatus employed a partially restrained bending mode. Figure 2 shows the actual test area and depicts a wire specimen in its partially restrained and deflected state within the three-bracket system. This apparatus consisted of a customized device to which the three-bracket system was affixed, as shown near the middle of Figure 2. A displacement plate affixed to this device contacted the tip of an LVDT, shown at the left of the figure. Deflection of the three-bracket system was measured by the LVDT and force was measured by the Instron load cell. The brackets employed were 0.022-inch slot maxillary premolar universal brackets with 0° angulation and torque with a bracket width of 3 mm (351-0506, Twin Mini, Ormco Corp, Glendora, Calif). The wire specimens were ligated into each bracket with elastic ligatures (0.110 grey, Power "O" modules, Ormco Corp, Glendora, Calif) using a ligature placing gun (Straight-Shooter, TP, Inc, LaPorte, Ind). For comparison of the stiffness characteristics, the three-bracket test system also employed 13-mm spans, measured as the shortest distance between each peripheral bracket. The interbracket distance in the three-bracket test system was 5 mm. It is important to note that the stiffness values reported are those from the three-bracket system and not specifically the physical properties of the wires themselves.

Data acquisition and analysis

An Instron Universal Testing Machine was used to deflect all wires. The crosshead rate was 0.05 inches/minute, or 1.27 mm/minute. The load cell registered the force placed on the wire specimen and transmitted this value to a computer as a DC analog voltage signal. In both bending modes, a linear displacement gauging transducer (Model #GCD-121-250, Lucas Schaevitz, Inc, Pennsauken, NJ) measured deflection and also transmitted values to a computer as a DC analog voltage signal. Specimens tested in both modes were loaded to either a deflection of 3 mm or to a load reaching the maximum capacity of the load cell (5 lbs for three-point, 10 lbs for three-bracket bending), whichever came first, and then unloaded. The load cell and transducer voltage signals were stored as ASCII files via a data acquisition system. This system comprised a multifunction data acquisition board (Model #CIO-DAS08-PGL, Omega Engineering, Inc, Stamford, Conn) and accompanying software (Lablog2, Omega Eng). Figure 3A shows the raw loading and unloading data plotted for the 20 N 016 wire specimens.

The unloading plots for each of the wire specimens were selected for analysis rather than the loading plots because the unloading behavior of a wire represents the force delivery characteristic of that wire during function in an orthodontic appliance. The stiffnesses were derived for all test wires from the slopes of the elastic unloading load-deflection plot. The raw unloading data from each trial were subjected to a polynomial regression procedure to generate an equation describing the force-deflection character of the unloading curve, seen as a solid line in Figure 3B. For each of the wire samples with the exception of solid stainless steel, a quartic (n=4) polynomial regression was used to describe the force-deflection character of the unloading. This equation can be expressed in terms of four coefficients and one intercept as described by Miller and Freund:[12]

$$y = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4$$

where b_1 to b_4 represent the coefficients of the polynomial and b_0 represents the intercept. A fourth power regression was used because it fit the force-deflection data noticeably better than the third power regression, and the fifth power did not show any appreciable improvement in fitting the distribution of data. For instance, the regression analysis (SAS Institute Inc, Cary, NC) of the 0.016 inch solid nickel-titanium force-deflection data in the three-bracket mode of bending showed R^2 (coefficient of determination) values of 0.72859 for n = 1, 0.80972 for n = 2, 0.91577 for n = 3, 0.95028 for n= 4, 0.95248 for n = 5, and 0.95665 for n = 6. The stiffness as a function of deflection, the derivative (slope) of this polynomial, was subsequently calculated using the equation:

$$y'(x) = (0)b_0 + (1)b_1 + (2)b_2x^1 + (3)b_3x^2 + (4)b_4x^3$$

This derivative was then plotted as the stiffness for each wire sample in order that the stiffness-

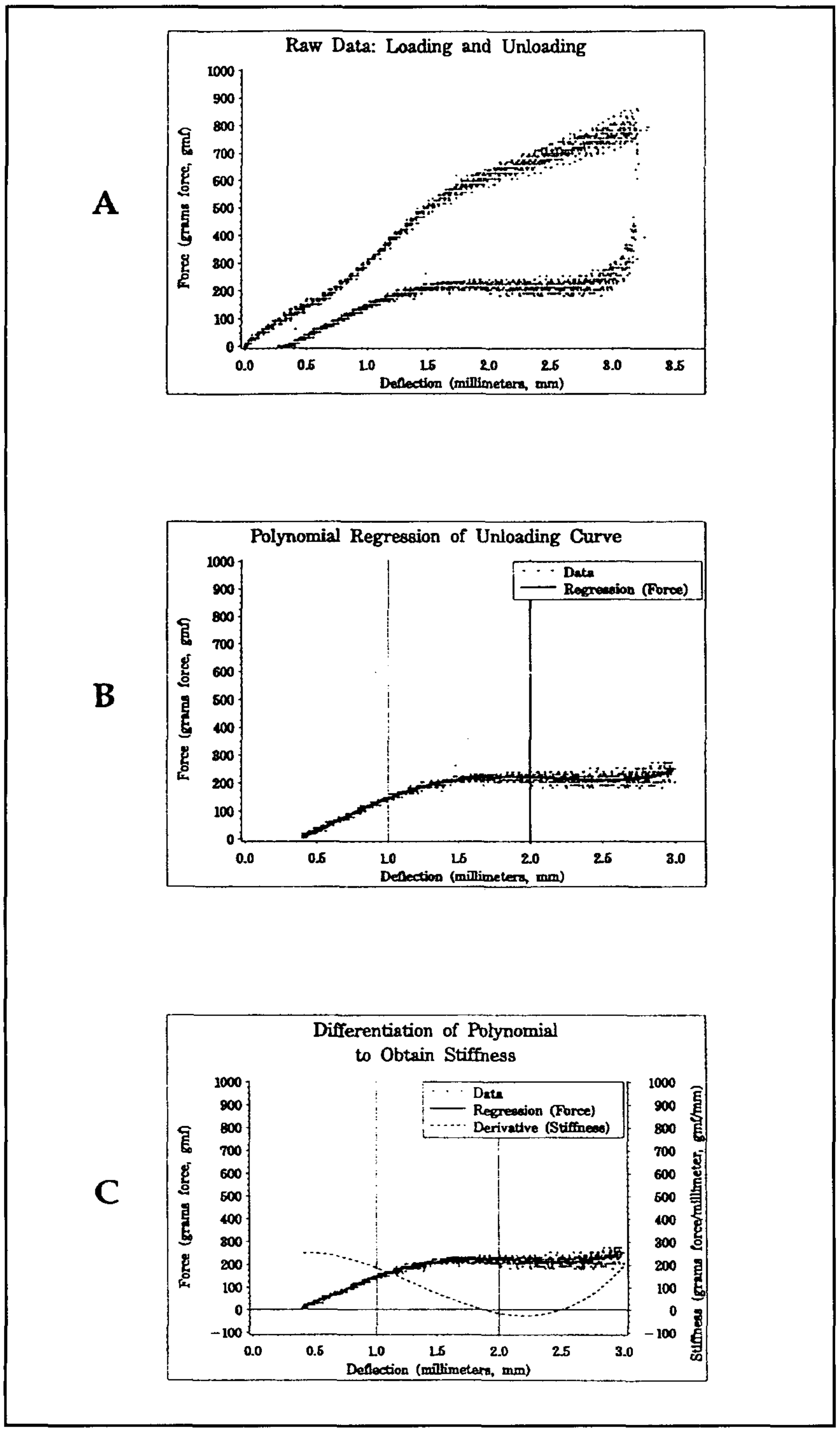


Figure 3A-C

Figure 3A-C

Force- and stiffness-deflection plots for 0.016-inch nickel-titanium wire.

A: Raw loading and unloading force deflection data for 20 trials in three-bracket bending mode.

B: Polynomial regression of unloading force-deflection data (solid line).

C: Derivative of polynomial (broken line) representing stiffness as a function of deflection.

deflection profiles could be graphically displayed. The stiffness of each wire sample can be viewed as the dashed line in the force-deflection/stiffness-deflection plot shown in Figure 3C.

The unloading curves for the solid stainless steel wires demonstrated nearly linear force-deflection characteristics. Therefore, a linear (n=1) regression was found to best describe these wires. Although the mean R^2 value for the first power polynomial (0.93594) was slightly lower than that of the fourth power (mean R^2 = 0.99001), it was still considered to be an accurate predictor of the force-deflection character of these wires.

Polynomial and derivative equations were calculated for each wire sample. The values for stiffnesses at specific deflections x were obtained by substitution into the derivative equation of x=3, x=2, and x=1, such that means and standard deviations for stiffnesses could be calculated at high (3 mm), medium (2 mm), and low (1 mm) deflections, respectively.

The means and standard deviations from the 20 trials for each of the 24 wire samples were analyzed statistically by a General Linear Model to test for statistically significant differences among the stiffnesses of the different wire samples at 1, 2, and 3 mm of deflection. Statistically significant differences ($P < 0.05$) were than analyzed by Bonferroni (Dunn) *t*-tests with respect to test mode, wire type, alloy, wire size, number of strands, and amount of deflection.

Results

Stiffness values for some of the test samples could not be derived directly from the unloading force-deflection data at certain deflections because either the maximum capacity of the load cell was reached prior to maximum deflection or plastic deformation occurred to such an extent that the test ended prior to 1 mm of deflection. Such samples included 016, 016x016, 017x025, and 018 at 1 mm, and 021x025 at 2 and 3 mm in the three-point bending mode and 016, 016x016, and 018 at 1 mm, 017x025 at 2 and 3 mm, and 021x025 at 1, 2, and 3 mm in the three-bracket bending mode. The stiffnesses of the single-strand stainless steel wires were determined to be constant, since the unloading curves for these wires were highly linear (R^2=94). Therefore, these wires were analyzed with a regression procedure where n = 1.

To enable the reader to determine the stiffness of each wire sample, the coefficients of the derivative of the polynomial are given in Table 2.

Table 2
Coefficients of the derivative of polynomial used to describe stiffness-deflection character of each wire in three-point and three-bracket bending
(N - nickel-titanium, s - number of strands)

Wire type	Three-point bending mode				Three-bracket bending mode			
	B1	B2	B3	B4	B1	B2	B3	B4
016	324.8	N/A	N/A	N/A	795.4	N/A	N/A	N/A
N 016	67.5	45.6	-56.3	13.5	188.6	300.7	-405.4	102.0
016x016	505.6	N/A	N/A	N/A	1284.7	N/A	N/A	N/A
N 016x016	230.3	-204.9	69.1	-5.0	527.5	-347.9	-30.6	37.5
016x016 3s	81.6	115.7	-65.4	8.3	-2035.3	4244.3	-2359.7	407.6
016x016 8s	39.3	47.6	-33.8	5.5	-97.7	651.8	-461.8	91.4
0175 3s	54.3	72.0	-56.2	9.3	-486.4	1589.8	-1054.3	198.6
0175 6s	28.0	58.0	-41.5	7.3	-327.6	995.5	-674.6	134.7
017x025	959.7	N/A	N/A	N/A	4429.8	N/A	N/A	N/A
N 017x025	389.3	-355.3	116.8	-8.3	1081.9	-982.9	184.6	20.5
017x025 3s	94.0	300.3	-176.5	27.0	-3625.9	7581.3	-4306.5	770.0
017x025 8s	79.2	87.7	-60.0	8.8	-372.9	1581.3	-1089.1	217.0
017x025 9s	55.7	87.3	-52.5	8.0	-250.3	1187.3	-821.6	167.7
N 017x025 9s	-43.0	101.3	-53.1	8.9	-85.2	310.9	-226.6	47.9
018	493.2	N/A	N/A	N/A	1263.9	N/A	N/A	N/A
N 018	168.2	-109.0	30.1	-1.6	856.9	-602.8	-18.3	49.9
0215 3s	34.4	364.4	-286.9	58.8	-947.6	2859.6	-2054.7	457.8
0215 6s	115.1	4.7	-6.3	-2.1	-317.8	1360.2	-1011.8	217.5
021x025	2510.6	N/A	N/A	N/A	8861.5	N/A	N/A	N/A
N 021x025	795.3	-985.9	469.9	-69.7	857.5	366.4	-1286.8	429.9
021x025 3s	269.5	246.3	-130.1	11.5	-411.1	2339.7	-833.6	14.2
021x025 8s	67.9	184.5	-117.3	18.4	-2708.4	5982.5	-3732.5	726.5
021x025 9s	56.5	203.7	-132.4	23.3	-2385.6	5623.0	-3613.8	717.9
N 021x025 9s	-37.6	138.7	-90.3	18.4	-128.3	773.4	-721.6	173.7

Using equation #2, the stiffness of each wire type can be determined at any deflection between 0 and 3 mm. The $y'(x)$ in the equation is the stiffness, x is the amount of deflection, and b_i is the coefficient. Table 2 shows that for single-strand stainless steel wire a single coefficient, b_1, is sufficient to describe the linear behavior. However, for all other wires, four b values are provided consistent with the $n = 4$ polynomial used to describe their nonlinear unloading curves. The stiffness data at 1, 2, and 3 mm of deflection for all wires tested are given in Table 3 for the three-point bending mode and Table 4 for the three-bracket bending mode.

Discussion

Stiffness comparisons

Mode of testing (three-point bending vs. three-bracket bending)

In general, the stiffness from the three-bracket bending system for a given wire was about 1.5 to 4 times the value for the same wire in the three-point bending test at 1 and 2 mm of deflection. An exception to this pattern was the nickel-titanium wire in three-bracket bending at 2 mm of deflection, where point-bending values exceeded the bracket-bending values. At 3 mm of deflection, the stiffness values in bracket-bending exceeded the stiffness values in point-bending by 7.5 to 40 times.

Figure 4 shows the stiffness-deflection plots for the single-strand 016 stainless steel wire in both the three-point and three-bracket bending tests. For the stainless steel wire, the stiffness in the bracket setup exceeded the stiffness in three-point bending by 2.4 times. The use of brackets created a more constrained mode of bending than that of the three-point bending mode, possibly due to friction and binding inherent at the bracket-wire interface.

Certain nickel-titanium wires exhibit behavior on unloading such that changes in deflection are not accompanied by significant changes in force

Table 3
Mean stiffness values (gm/mm) arranged from lowest to highest for all 24 wires at 1, 2, and 3 mm of deflection in three-point bending test (N - nickel-titanium, s - number of strands). Groupings are based on wire stiffnesses that are not significantly different. Means with the same letter are not significantly different at P<0.05

	1 mm				2 mm				3 mm		
Wire type	Mean	SD	Grp.	Wire type	Mean	SD	Grp.	Wire type	Mean	SD	Grp.
N 017x025 9s	16.2	9.7	A	N 017x025 9s	18.3	2.6	A	0215 6s	12.0	43.0	A
N 021x025 9s	30.1	4.2	B	N 021x025 9s	26.1	3.2	AB	0175 3s	21.0	75.2	A
0175 6s	51.9	3.6	C	0175 6s	36.9	4.0	BC	0175 6s	24.3	21.6	A
016x016 8s	58.5	1.8	CD	N 016	41.3	2.5	C	016x016 8s	24.9	13.4	A
N 016	70.0	3.1	DE	016x016 8s	43.0	2.0	C	N 017x025 9s	26.9	19.2	A
0175 3s	79.8	11.1	EF	0175 3s	47.8	18.2	CD	017x025 8s	39.8	15.9	AB
N 018	87.7	3.0	FG	N 016x016	56.8	4.3	D	017x025 9s	57.1	14.8	AB
N 016x016	89.4	3.6	FG	N 018	58.3	2.4	D	021x025 8s	58.6	23.9	ABC
017x025 9s	98.5	1.8	G	N 017x025	79.6	5.0	E	N 016	61.6	16.5	ABCD
0215 6s	111.2	6.0	H	0215 6s	82.5	8.2	E	016x016 3s	62.0	46.3	ABCD
017x025 8s	115.6	3.2	H	017x025 9s	84.3	2.0	E	N 021x025 9s	64.9	18.2	ABCDE
016x016 3s	141.6	4.8	I	017x025 8s	84.9	3.2	E	N 018	66.3	20.2	ABCDE
N 017x025	142.5	4.0	IJ	0215 3s	85.8	25.9	E	021x025 9s	99.5	32.6	BCDEF
021x025 9s	151.1	5.0	IJ	021x025 8s	115.8	2.9	F	N 016x016	103.4	22.3	BCDEF
021x025 8s	154.3	3.8	J	016x016 3s	117.5	8.3	F	017x025 3s	126.5	75.3	CDEFG
0215 3s	170.6	21.7	K	021x025 9s	120.7	5.2	F	021x025 3s	129.4	80.3	DEFG
N 021x025	209.6	8.3	L	N 021x025	146.2	6.2	G	0215 3s	131.9	226.1	EFG
017x025 3s	248.6	5.1	M	017x025 3s	204.1	11.9	H	N 017x025	149.5	20.6	FG
016	324.9	2.4	N	016	324.9	2.4	I	N 021x025	184.0	26.6	G
021x025 3s	400.8	7.5	O	021x025 3s	334.7	12.6	I	016	324.9	2.4	H
018	493.5	3.0	P	018	493.5	3.0	J	018	493.5	3.0	I
016x016	505.7	6.2	Q	016x016	505.7	6.2	J	016x016	505.7	6.2	I
017x025	960.9	20.5	R	017x025	960.9	20.5	K	017x025	960.9	20.5	J
021x025	2518.7	32.0	S	021x025	2518.7	32.0	L	021x025	2518.7	32.0	K

level. This phenomenon has been referred to as *superelasticity*. Behavior of this sort was observed in the three-bracket bending system for nickel-titanium wires (Figure 3B-C).

At 3 mm of deflection, the wires with larger cross-sections generally showed differences in stiffness between the two modes of bending. The differences in stiffness of the same wire types between the two test modes were generally 2 to 9 times greater at this deflection than at either 1 or 2 mm of deflection.

Wire type and size

Table 4 reveals four stiffness values at 2 mm deflection that are negative (N 021x025, N 021x025 9s, N 018, N 016). On the contrary, no negative values are seen in Table 3. The values in Table 3 reflect the stiffness properties of the wires, and one would not expect to measure negative values. However, in the three-bracket system, the "stiffness parameter" measured reflects the combined effects of friction, binding, deflection, constraint of the longitudinal shape of the wire especially from a facial perspective, and wire stiffness. Increasing force with decreasing deflection was observed, yielding a negative value for the slope.

In general, the lowest stiffnesses were delivered by the N 017x025 9s wire sample and the highest by the 021x025 sample. The lowest stiffnesses were generally delivered by the multistrand nickel-titanium wires regardless of the bending mode employed. This was not surprising, considering that the modulus of elasticity for nickel-titanium is roughly one-fourth that of stainless steel and that the introduction of multiple strands into nickel-titanium wire configuration further lowered stiffness. The three- and six-strand round stainless steel wires, as well as the 016x016 eight-strand stainless steel wire and the 016 and 018 nickel-titanium wires, were also very low in stiffness, regardless of the mode of bending employed. Due to the greater variability of

Table 4

Mean stiffness values (gm/mm) arranged from lowest to highest for all 24 wires at 1, 2, and 3 mm of deflection in three-bracket bending test (N - nickel-titanium, s - number of strands). Groupings are based on wire stiffnesses that are not significantly different. Means with the same letter are not significantly different at P<0.05

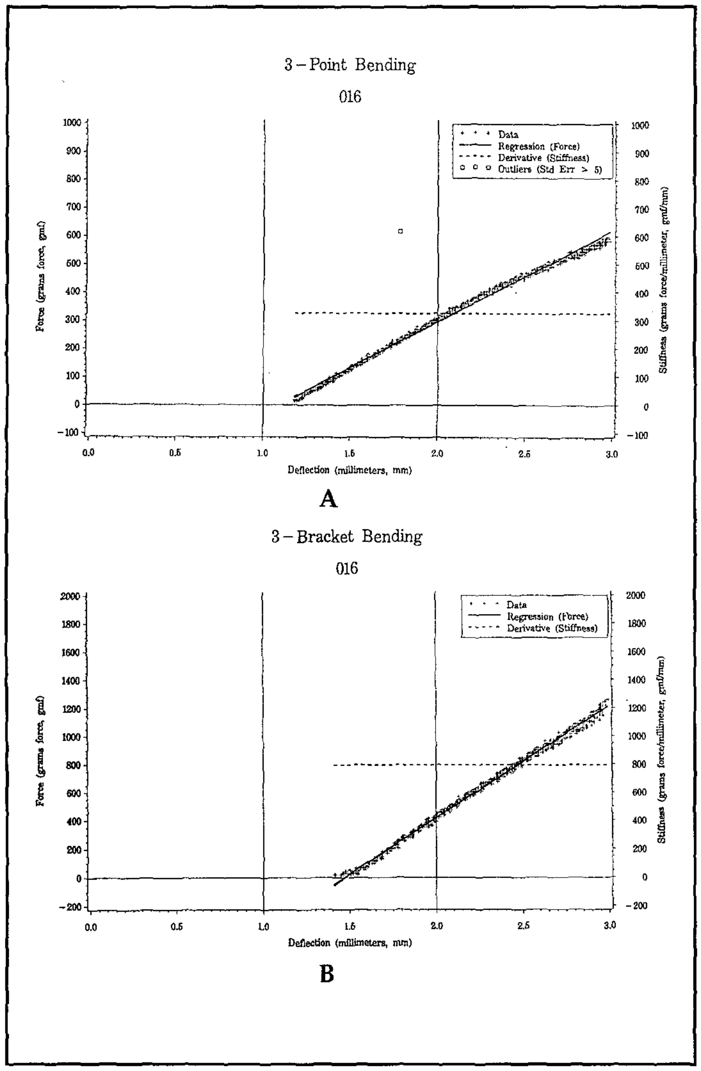
	1 mm				2 mm				3 mm		
Wire type	Mean	SD	Grp.	Wire type	Mean	SD	Grp.	Wire type	Mean	SD	Grp.
N 017x025 9s	46.3	9.3	A	N 021x025	-211.2	214.2	A	N 017x025 9s	111.4	51.3	A
N 021x025 9s	96.2	9.8	AB	N 021x025 9s	-77.9	13.2	AB	016x016 8s	153.3	129.8	A
0175 6s	127.6	13.7	ABC	N 018	-19.8	37.5	ABC	0175 3s	160.3	160.4	A
016x016 8s	182.7	10.4	ABCD	N 016	-16.0	12.9	ABC	N 016x016	185.2	78.2	A
N 016x016	184.7	9.6	ABCD	N 016x016	11.5	15.1	ABC	N 016	199.3	63.9	A
N 016	186.3	7.7	ABCD	N 017x025 9s	12.4	7.5	ABC	N 018	211.3	142.6	A
0175 3s	248.1	19.1	BCDE	N 017x025	18.8	15.2	ABC	0175 6s	220.5	123.7	AB
0215 6s	259.5	54.0	BCDE	0175 6s	43.1	16.8	ABC	N 017x025	339.9	101.5	AB
016x016 3s	280.9	71.1	CDE	0175 3s	65.3	29.5	ABC	N 021x025 9s	376.8	63.7	ABC
N 018	284.3	11.2	CDE	016x016 8s	91.2	20.4	ABC	017x025 8s	416.9	174.9	ABC
017x025 9s	285.3	17.8	CDE	0215 6s	96.3	56.4	ABC	016x061 3s	431.4	192.4	ABCD
N 017x025	303.5	11.8	DEF	021x025 8s	141.5	113.9	BCD	017x052 9s	434.7	235.8	ABCD
021x025 9s	330.2	161.9	DEF	021x025 9s	146.7	82.0	BCD	0215 6s	503.3	341.7	ABCD
017x025 8s	338.1	15.5	DEF	017x025 8s	170.7	24.9	BCD	016	795.7	15.0	ABCDE
0215 3s	367.4	327.4	EF	017x025 9s	180.5	29.1	BCD	017x025 3s	1130.6	314.8	BCDE
021x025 8s	373.5	408.3	EF	0215 3s	233.9	184.8	BCD	021x025 8s	1132.0	681.2	BCDE
N 021x025	454.9	161.3	F	016x016 3s	276.0	27.0	CD	018	1263.5	24.5	CDE
017x025 3s	459.7	172.3	F	017x025 3s	468.7	61.3	DE	016x016	1285.3	24.6	CDE
016	795.7	15.0	G	016	795.7	15.0	E	021x025 9s	1331.5	602.6	DE
018	1263.5	24.5	H	018	1263.5	24.5	F	0215 3s	1474.4	1162.9	E
016x016	1285.3	24.6	H	016x016	1285.3	24.6	F	N 21x025	3564.4	3314.1	F
021x025 3s	1307.9	254.8	H	021x025 3s	2083.5	1376.1	G	017x025	4489.3	121.1	G
017x025	4489.3	121.1	I	017x025	4489.3	121.1	H	021x025	8896.3	148.8	H
021x025	8896.3	148.8	J	021x025	8896.3	148.8	I				

Note: The stiffness for wire 021x025 3s was not reported at 3 mm of deflection because several of the test specimens reached the capacity of the load cell prior to reaching 3 mm, thus influencing the polynomial regression at this deflection.

stiffness values obtained in the three-bracket mode, there were fewer significant differences among the wire samples. For single-strand wires of both alloys, stiffness increased with an increase in wire size. The exception was for the nickel-titanium wires at 2 mm of deflection in the three-bracket bending test in which stiffness did not change. For multistrand wires, there was a trend for higher stiffness values with increase in wire size, but it was not consistent.

Generally, when the alloy and number of strands were held constant and the size of the wire increased, stiffness also increased. However, this trend weakened with incorporation of multiple strands. The single-strand 016x016 and the 018 stainless steel wires had near equal stiffnesses that were not significantly different from each other (P<0.05) in either bending mode. In the three-point bending mode, with respect to the stiffness of the 016 wire, the 016x016 and 018 wires were about 1.5 times as stiff, the 017x025 about 3.0 times, and the 021x025 about 7.8 times as stiff. These results were similar to those of Kusy and Dilley.[5] In the bracket-bending mode, the 016x016 and 018 wires were 1.6 times as stiff as the 016 wire, about 5.6 times for the 17x025, and about 11.2 times for the 021x025 wire. Differences in stiffness were greater in the bracket mode of bending when comparing large cross-section wires with 016 than for the same comparisons made in three-point bending mode.

In three-point bending at 1 and 2 mm of deflection, the rank order of nickel-titanium wires by stiffnesses closely followed that of cross-sectional area, similar to results from stainles steel wires. However, at 3 mm of deflection, this order varied slightly in that stiffnesses of the 016 and 018 wires were not significantly different. For the same nickel-titanium wires tested in the bracket bending mode, an increase in stiffness with an increase in cross-sectional size was seen only at 1 mm of deflection. At 2 mm, there was no sig-



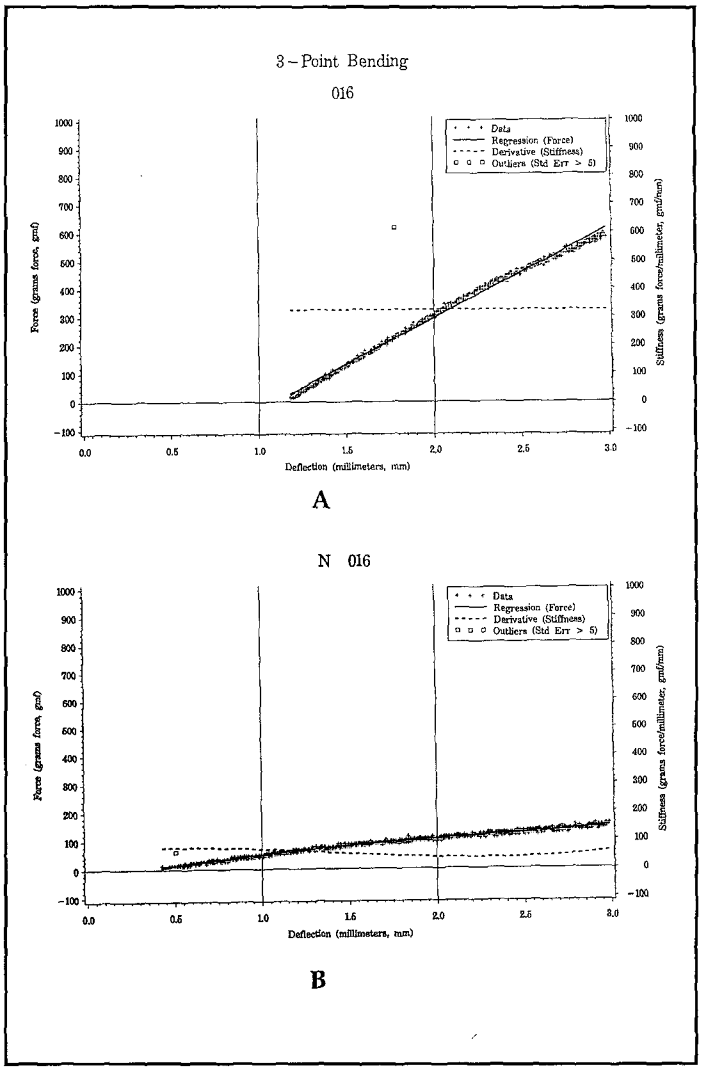


Figure 4

Figure 5

Figure 4
Comparison of force- and stiffness deflection plots between three-point and three-bracket bending modes of 0.016-inch stainless steel wire during unloading from 3.0 mm to 0.0 mm.

Figure 5
Comparison of force- and stiffness deflection plots between 0.016-inch stainless steel and nickel-titanium wires in three-point bending mode during unloading from 3.0 mm to 0.0 mm.

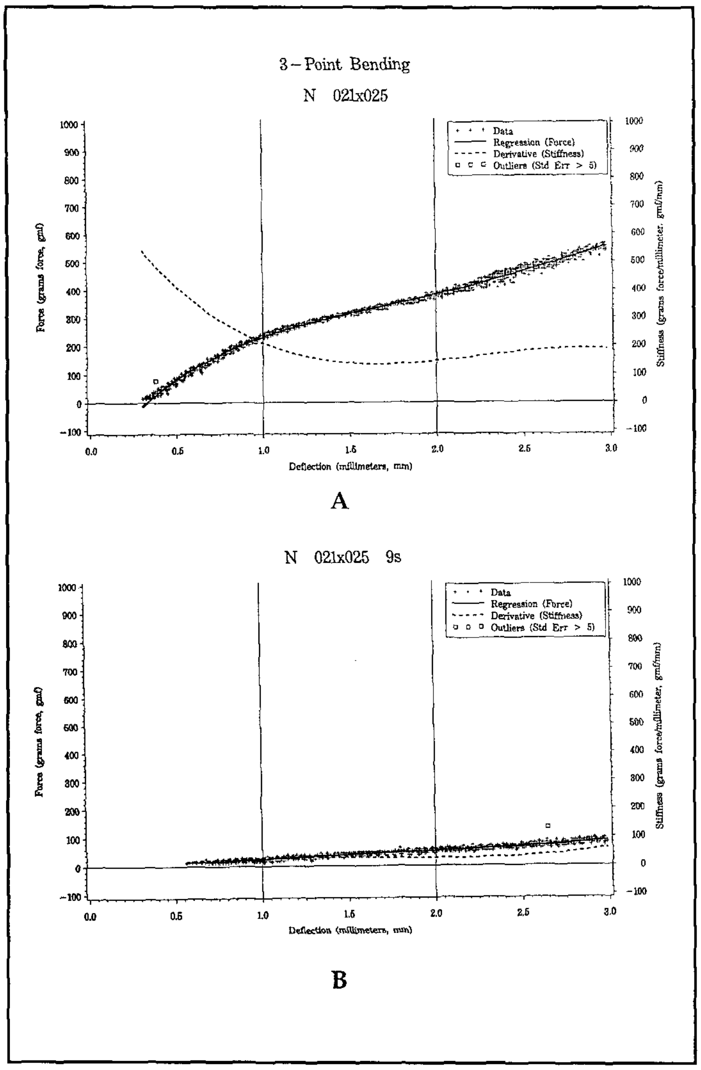
nificant difference with an increase in size, and at 3 mm, the mean stiffness values showed an increase with increasing size.

Alloy (stainless steel vs. nickel-titanium)

The stiffnesses of the stainless steel wires were significantly greater than those of the nickel-titanium wires, regardless of size or number of strands. When comparing stainless steel and nickel-titanium alloys of similar sizes and numbers of strands, the stiffnesses of stainless steel wires were significantly greater than those of the nickel-titanium wires by 3.5 to 7 times. Figure 5 compares the force- and stiffness-deflection plots for single-strand stainless steel and nickel-titanium 016 wires from the three-point bending test. Other investigators have reported similar results. Goldberg et al.[14] found the flexure modulus of elasticity of stainless steel to be about 4 times that of nickel-titanium. In addition, Kusy and Stevens[6] also reported the elastic moduli of stainless steel to be 3 to 5 times that of the nickel-titanium alloys. With respect to stiffness, Kusy and Dilley,[5] who used a three-point bending test, found the stiffness of 0.016 inch stainless steel to be 5.7 times that of an 0.016 inch nickel-titanium wire.

Number of strands

Generally, as the number of strands increased, the stiffness decreased, regardless of the test mode employed or the amount of deflection. Exceptions included the eight- and nine-strand stainless steel wire samples from which the stiffnesses were not significantly different from one another, and from those of the nickel-titanium wires. Figure 6 compares the force- and stiffness-deflection plots for solid and nine-strand 021x025 nickel-titanium wires in the three-point bending test. Figure 7 compares the force- and stiffness-deflection plots for the three- and nine-strand 017x025 stainless steel wires in the three-bracket test.



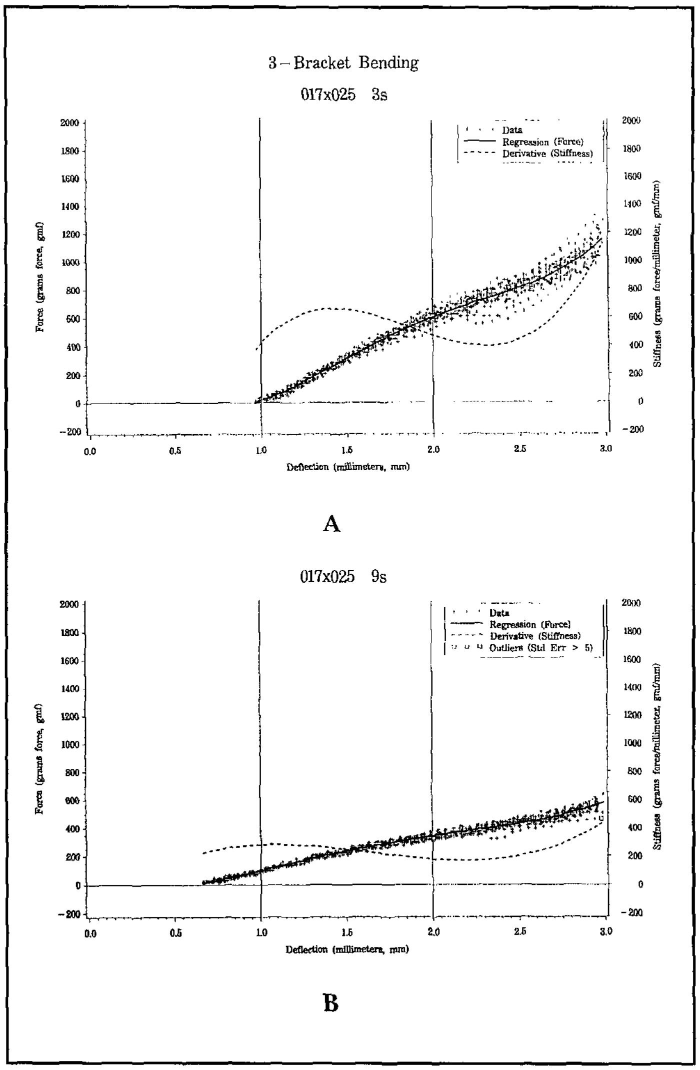


Figure 6

Figure 7

Summary and conclusions

Unloading curves were nonlinear for many of the multistrand stainless steel and for all the nickel-titanium wires. It was not possible to define a single value of stiffness or slope of the bending plot for these wires. These results have supported the use of the polynomial regression method used in this investigation to determine the stiffnesses of these wire samples over a range of deflections. This methodology allows the evaluation of the instantaneous stiffness in standard mechanical tests and for orthodontic appliance systems.

The results of this investigation have shown that wire stiffness can be altered not only by size but also by varying the number of strands and the alloy composition of the wire. This supports the concept of variable modulus orthodontics, which suggests changing stiffness by changing the elastic modulus rather than changing the wire size. The stiffnesses noted at different deflections for the multistrand stainless steel wires were variable in contrast to the constant stiffnesses recorded for the single-strand stainless steel wires. Wire selections in clinical practice should include considerations of the alloy type, wire cross-section, and number of strands. All three factors are found to have a profound influence on wire stiffness.

Figure 6
Comparison of force- and stiffness-deflection plots between solid and nine-strand 0.021 x 0.025 nickel-titanium wire in three-point bending mode during unloading 3.0 mm to 0.0 mm.

Figure 7
Comparison of force deflection and stiffness deflection plots between three-strand and nine-strand 0.017 x 0.025 inch stainless steel wire in three-bracket bending mode during unloading 3.0 mm to 0.0 mm.

E-mail addresses
manville-duncanson@uokhsc.edu
joydeep-ghosh@uokhsc.edu
ram-nanda@uokhsc.edu
frans-currier@uokhsc.edu

Author Address
Ram S. Nanda
University of Oklahoma
College of Dentistry
Departments of Orthodontics and Dental Materials
1001 S.L. Young Blvd.
Oklahoma City, OK 73190

Jay M. Oltjen, former graduate student, University of Oklahoma College of Dentistry.

Manville G. Duncanson Jr., professor and chair, Dept. of Dental Materials, University of Oklahoma College of Dentistry.

Joydeep Ghosh, assistant professor, Dept. of Orthodontics, University of Oklahoma College of Dentistry.

Ram S. Nanda, professor and endowed chair, Dept. of Orthodontics, University of Oklahoma College of Dentistry.

G. Frans Currier, professor, Dept. of Orthodontics, University of Oklahoma College of Dentistry.

References

1. Thurow RC. Edgewise orthodontics. 4th ed, St. Louis: Mosby, 1982: 16-25, 48-9, 56, 62, 219-33.
2. Adams DM, Powers JM, Asgar K. Effects of brackets and ties on stiffness of an archwire. Am J Orthod Dentofac Orthop 1987; 91:131-136.
3. Waters NE, Houston WJB, Stephens CD. The characterization of arch wires for the initial alignment of irregular teeth. Am J Orthod 1981; 79:373-389.
4. Burstone CJ. Variable-modulus orthodontics. Am J Orthod 1981; 80:1-15.
5. Kusy RP, Dilley GJ. Elastic property ratios of a triple-stranded stainless steel archwire. Am J Orthod 1984; 86: 177-88.
6. Kusy RP, Stevens LE. Triple-stranded stainless steel wires - evaluation of mechanical properties and comparison with titanium alloy alternatives. Angle Orthod 1987; 57:18-32.
7. O'Brien WJ. Orthodontic wires, dental materials: Properties and selection. Chicago: Quintessence, 1989:22-23, 381-94.
8. Kapila S, Sachdeva, R. Mechanical properties and clinical applications of orthodontic wires. Am J Orthod Dentofac Orthop 1989; 96:100-109.
9. Burstone CJ, Qin B, Morton JY. Chinese NiTi wire-a new orthodontic alloy. J Orthod 1985; 87:445-52.
10. Khier SE, Brantley WA, Foumelle RA. Bending properties of superelastic nonsuperelastic and nickel-titanium orthodontic wires. Am J Orthod Dentofac Orthop 1986; 90:1-10.
11. Miura F, Mogi M, Ohura Y, Hamanaka H. The super-elastic property of the Japanese NiTi alloy wire for use in orthodontics. Am J Orthod Dentofac Orthop 1986; 90:1-10.
12. Miller I, Freund JE. Probability and Statistics for Engineers. 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 1977: 306-12.
13. SAS/STAT user's guide, Version 6, 4th ed, Vol. 2, SAS Institute, Inc, Cary, NC, 1989, p 891-996.
14. Goldberg AJ, Morton J, Burstone CJ. The flexure modulus of elasticity of orthodontic wires. J Dent Res 1983; 62:856-858.