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Measurement of Forces and Moments in Three-Dimensional Archwires

Dwight Van Buelow
Virginia Commonwealth University

School of Dentistry
Virginia Commonwealth University

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Dr. Steven J. Lindauer, Thesis Director / Program Director Department of Orthodontics

Dr. J. Malcolm Carter, Committee Member, School of Dentistry

Dr. Eser Tufekci, Committee Member, School of Dentistry

Dr. Steven J. Lindauer, Chairman Department of Orthodontics, School of Dentistry

Dr. David C. Sarrett, Assistant Dean – Academic Affairs, School of Dentistry

Dr. F. Douglas Boudinot, Dean of the School of Graduate Studies

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MEASUREMENT OF FORCES AND MOMENTS IN THREE-DIMENSIONAL ARCHWIRES

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

by

DWIGHT V. BUELOW
B.S.E., Princeton University, 1989
D.D.S., Virginia Commonwealth University, 2001

Director: STEVEN J. LINDAUER, D.M.D., M.D.SC.
PROFESSOR AND CHAIRMAN, DEPARTMENT OF ORTHODONTICS

Virginia Commonwealth University
Richmond, Virginia
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Abstract

MEASUREMENT OF FORCES AND MOMENTS IN THREE-DIMENSIONAL ARCHWIRES

By Dwight V. Buelow, D.D.S.

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Major Director: Steven J. Lindauer, D.M.D., M.D.Sc.
Chairman and Professor, Department of Orthodontics

Orthodontic tooth movement occurs in response to the application of controlled mechanical force systems. The purpose of this study was to improve understanding of those force systems by evaluating differences between the resultants of two-dimensional and three-dimensional orthodontic appliance activations. An *in-vitro* model was constructed and three force-moment gauges were used to measure the forces and moments produced. Comparisons were made between two-dimensional and three-dimensional v-bend activations. Measurements were made with both edgewise and ribbonwise wire orientations.

Locations of v-bends resulting in zero moment at the incisor were found to be closer to the molar than the anticipated 1/3 of the distance from molar to incisor, for both two-dimensional and three-dimensional wires. For two-dimensional wires, this v-bend location was found to be approximately ¼, while for three-dimensional wires it was even closer to the molar. Ribbonwise wires, both two-dimensional and three-dimensional, produced forces and moments of greater magnitude than their edgewise counterparts. Further research is required to explain the differences between anticipated and actual results, and to develop more accurate means of modeling orthodontic force systems.

Introduction

Tooth movement occurs in response to externally applied forces and moments. A child's thumb, for example, can provide sufficient force over time to flare the upper incisors. Orthodontic tooth movement involves the intentional application of forces and moments through wires engaged in brackets. The direction of tooth movement is controlled by the system of forces and moments applied, as dictated by the laws of physics and the biological response. In orthodontics, the system is frequently complex, and, if poorly understood, unintentional tooth movements may occur. Burstone and Koenig recognized such "unpredictable and undesirable tooth movement" in 1974, and published an influential analysis of orthodontic forces and moments.[1]

Burstone and Koenig developed a mathematical computer simulation of a straight segment of wire placed in brackets at various angles (Figure 1). They determined the anticipated forces and moments created at each bracket. For example, as shown in Figure 1A, if the brackets were positioned at equal but opposite angles, the computer simulation predicted equal and opposite moments at the two brackets, but no vertical forces. Figures 1B through 1E show other combinations of bracket angles, and the associated moments and forces.

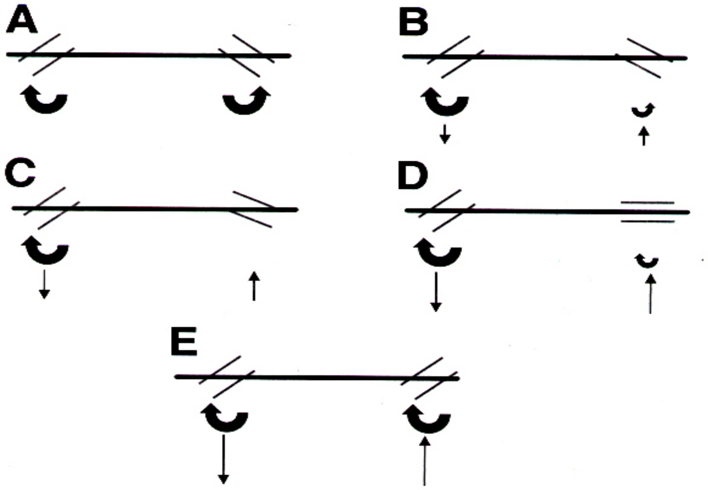

Figure 1. Straight segment of wire in malaligned brackets.

In 1988, Burstone and Koenig used their computer simulation to describe the forces and moments produced by a bent segment of wire engaged in aligned brackets,[2] as shown in Figure 2. The bends illustrated are called v-bends and have various clinical applications. The computer model indicated that a v-bend half way between brackets produced equal and opposite moments at each bracket, with no vertical forces present (Figure 2A). When the v-bend was moved off center and closer to the left bracket (Figures 2B, 2C, 2D), the moment at the left bracket increased. Simultaneously, the moment at the right bracket decreased (Figure 2B), became zero (Figure 2C), and then reversed direction (Figure 2D). The model predicted the moment at the right bracket would be zero when the v-bend was at one third the distance between the right and left brackets (Figure 2C). Vertical forces were present in the directions shown (Figures 2B, 2C, 2D) except when the v-bend was at the half way point (Figure 2A).

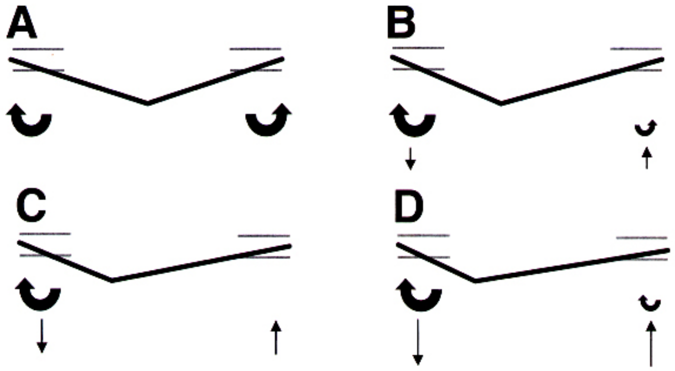

Figure 2. Bent wire in aligned brackets.

Burstone and Koenig's simulation was based on stainless steel wire with a round cross section. They showed that varying the distance between the brackets did not alter the patterns of moments and forces associated with the respective v-bend positions. Furthermore, they implied that the patterns should remain consistent regardless of wire material, stiffness, or cross section, as long as the wire was not permanently deformed.

Similar to the studies of Burstone and Koenig, investigations of orthodontic appliance force systems have typically been limited to two-dimensional models.[3,4,5,6,7,8,9,10] A two bracket system, with all forces and moments acting in a single plane, is the simplest system to analyze. However, some orthodontic applications of v-bends are distinctly three-dimensional.[11,12,13] The commonly used "2x4" appliance is an example, with attachments on the molars and incisors and bilateral v-bends in the premolar or canine area.

While two-dimensional biomechanical interpretations have been applied to “2x4” appliances,[2,14] it is apparent that a more complex three-dimensional analysis is required to predict the resultant force system. For example, while both brackets in a two-dimensional model engage the wire in bending, in a “2x4” appliance the wire acts in both bending and torsion at the molar and incisor attachments. Wires have different properties in torsion versus bending,[15] so the two-dimensional model is inadequate to describe the moments and forces that result from a three-dimensional appliance. Additionally, the principles of static equilibrium must be satisfied not only from the lateral view for a “2x4” appliance, but also from the frontal view. Any two-dimensional model of a three-dimensional system neglects the forces and moments that are out of the plane of analysis.

Recently, *in-vitro* data has been collected from two-dimensional and three-dimensional models.[16] Differences between Burstone and Koenig’s two-dimensional computer simulation and the two-dimensional *in-vitro* data were apparent, as were differences between two-dimensional and three-dimensional *in-vitro* results. The present study continued this work with an improved experimental design. The new *in-vitro* models allowed measurement of forces and moments at all attachment points simultaneously. This alleviated the need to disassemble and reconfigure the model to record measurements separately at each attachment point for a particular wire, and eliminated the error associated with doing so. The present study also investigated the difference between the forces and moments produced by wires with edgewise versus ribbonwise cross section configurations.

Methods

Overview

Orthodontic tooth movement occurs in response to the application of controlled mechanical force systems. The purpose of this study was to improve understanding of those force systems by evaluating differences between the resultants of two-dimensional and three-dimensional orthodontic appliance activations. The influence of varying wire cross section orientation was also evaluated.

In order to measure the force systems produced by two-dimensional and three-dimensional orthodontic archwires, an *in-vitro* model was constructed. Both two-bracket (two-dimensional) and three-bracket (three-dimensional) configurations were used. In the collinear two-bracket configuration, two force-moment gauges (Figure 3, *OrthoMeasure*, Young Research & Development, Inc., Avon, CT) representing an anterior and posterior bracket were mounted on a rigid platform. In the three-bracket configuration, two force-moment gauges were mounted to represent right and left molars, while a third gauge was mounted anteriorly to represent one central incisor.

Vertically-oriented v-bends were placed at five evenly spaced positions along straight wire segments for the two-dimensional configuration and bilaterally along curved archwires for the three-dimensional configuration. The activated orthodontic wires were inserted into the gauges on the model and the resultant force systems were measured. Custom probes were manufactured to allow for measurement of moments and forces in all three dimensions. Resultant vertical forces and moments were recorded at the anterior and posterior attachments for the two-dimensional model and at the molar and incisor attachments for the three-dimensional configuration for each of the appliances tested. The measurements were made with the wire in the edgewise orientation, and also with the wire in the ribbonwise orientation. For each combination of v-bend location and cross section orientation, five wires were fabricated and tested.

Resultant forces and moments at the anterior and posterior attachments were plotted as a function of v-bend position for both the two-dimensional and three-dimensional appliances. To determine differences between force systems resulting from two-dimensional and three-dimensional configurations, the v-bend locations at which vertical forces were zero (corresponding to the point where equal and opposite moments were produced at the anterior and posterior attachments), posterior moments were zero, and anterior moments were zero, were compared.

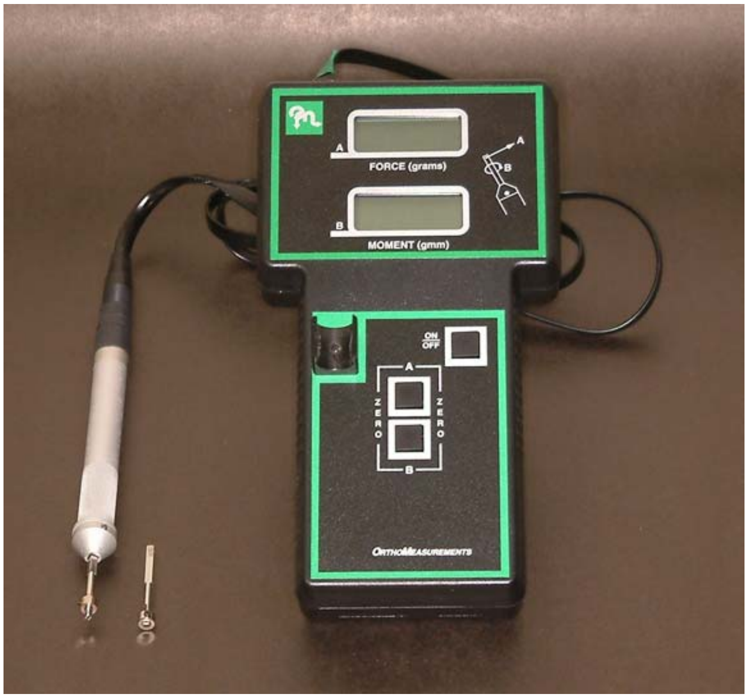

Figure 3. *Orthomeasure* instrument.

Evaluation of Gauge Accuracy

Accuracy of force and moment measurements recorded by each of the three gauges was evaluated. To evaluate force measurements, a 100g weight was suspended from each gauge. Ten trials were performed. T-tests were used to determine whether the recorded values were significantly different than the expected value.

To evaluate the accuracy of moment measurements, a 100g weight was suspended from a segment of wire (0.019” x 0.025” stainless steel in the ribbonwise configuration) fixed to the probe. The distance from the probe tip to the point of suspension was 20mm. Since *Moment = Force x Distance (M=Fd)*, the predicted moment was 2000g-mm. T-tests were again used to determine if predicted and recorded values differed significantly.

Two Dimensional Model

Two gauges were mounted parallel to one-another on a platform such that the slots in the probes were collinear (Figure 4). Collinearity of the probes was confirmed by measuring the forces and moments produced by a straight wire segment. Probes with a press fit connection to the wire were used to remove any play between the slot and the wire. The model was adjusted until the straight segment could be inserted and removed five times without producing forces greater than 5g or moments greater than 50g-mm.

Stainless steel wires (0.017” x 0.025”) were used in both edgewise and ribbonwise configurations. Vertical v-bends of 35 degrees were placed in the wires at predetermined points between the probes. The apices of the v-bends pointed down. The location of the v-bend was defined by an *a/L* ratio with *a* being the distance from the probe to the v-bend, and *L* being the total interprobe distance (37 mm) (Figure 5). V-bends were made in each wire segment at one of five points chosen to divide the straight wire into six equal segments, resulting in a total of five wire shapes (Figure 6). Each wire shape was duplicated five times in the edgewise configuration, for a total of 25 edgewise wires, and five times in the ribbonwise configuration, for a total of 25 ribbonwise wires.

A total of four measurements were made per wire activation: moments (g-mm) and forces (g) at the "molar" and the "incisor." Figure 7 illustrates activation of the two-dimensional model: 7A showing a wire inserted into one probe and lying passive prior to activation, and 7B demonstrating wire activation. Five trials were performed per wire, for a total of 20 measurements per wire, or 1000 measurements in all.

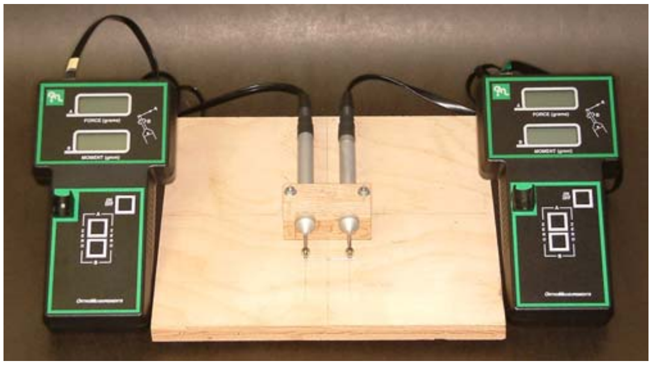

Figure 4. 2-Dimensional model configuration.

Figure 5. 2-Dimensional model: Distance between probes.

Figure 6. 2-Dimensional model: Wire bending.

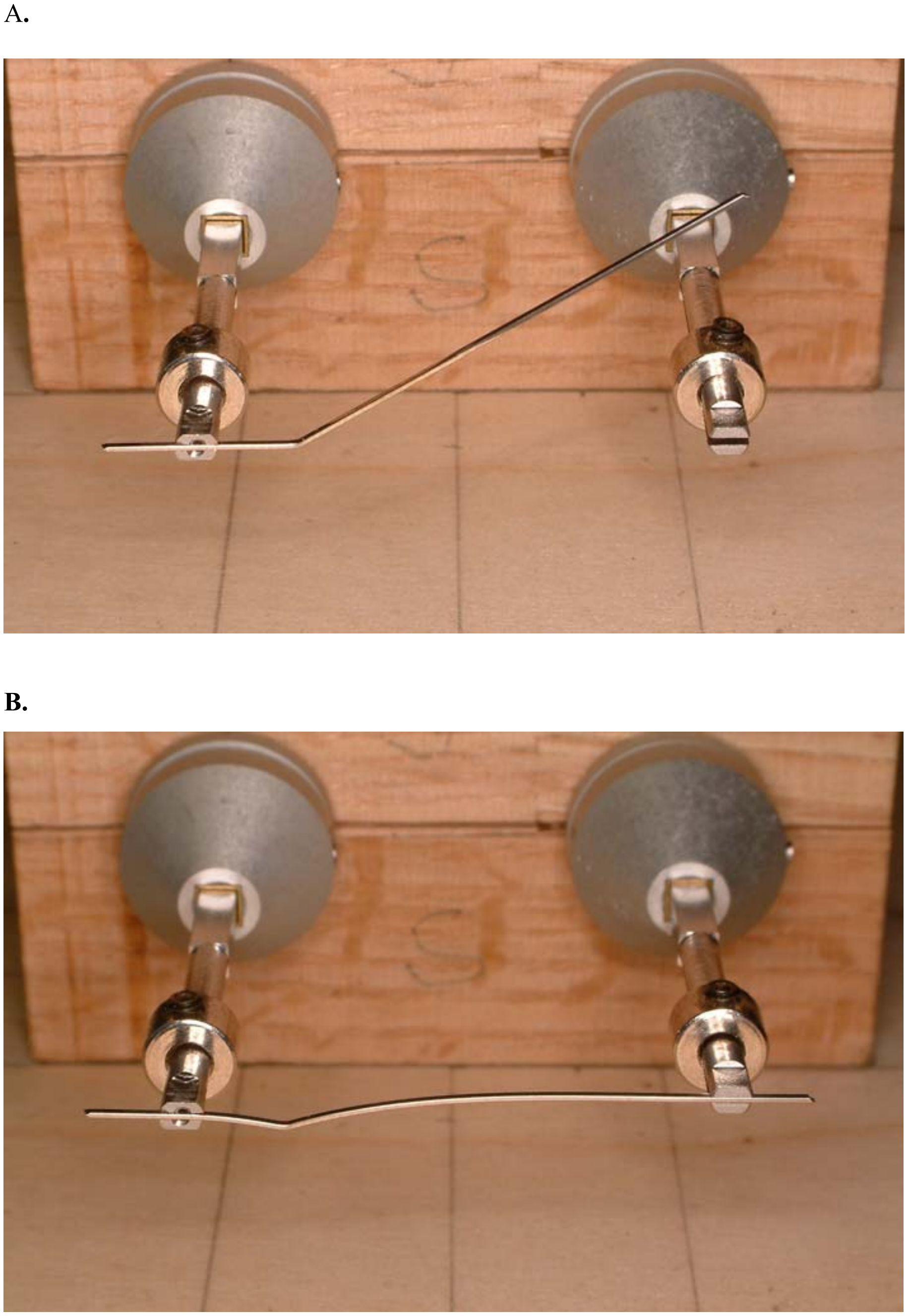

Figure 7. 2-Dimensional model: Measuring moments and forces.

A. Wire is passive prior to insertion.

B. Wire is actively inserted.

Three-Dimensional Model

Three gauges were mounted on a platform such that the probes simulated the positions of two molars and one incisor, a “2 x 1” configuration (Figure 8). The distance from the molar probes to the incisor probe, viewed laterally, equaled 37mm. The intermolar width, the measured distance between molar probes, was 56mm. Probes with a press fit connection to the wire were used to remove any play between the slot and the wire. The model was adjusted until a flat archwire could be inserted and removed five times without producing forces greater than 5g or moments greater than 50g-mm.

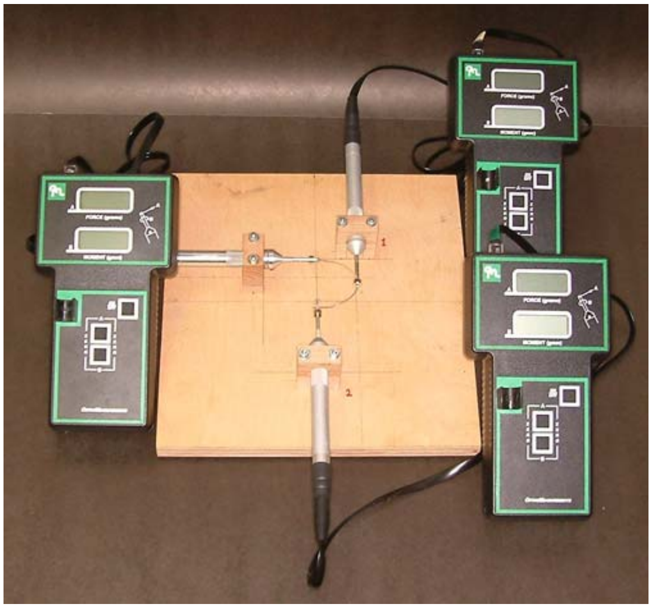

Figure 8. Three-dimensional model configuration.

Stainless steel archwires (0.017" x 0.025") were formed from straight segments in both edgewise and ribbonwise orientations. An "Orthoform III: Ovoid" template was used (3M Unitek, Dental Products Division, Monrovia, CA). Vertical v-bends of 35 degrees were placed in the wires at predetermined points between the molar and incisor probes. The apices of the v-bends pointed down. The location of the v-bend was defined by an *a/L* ratio with *a* being the distance from the molar probe to the v-bend measured along the perimeter of the archwire, and *L* being the total interprobe distance from the molar probe to the incisor probe measured along the archwire perimeter. Bilateral v-bends were made in each archwire at one of five locations chosen to divide the interprobe distance into six equal segments, resulting in a total of five v-bend locations (Figure 9). Each v-bend location was duplicated five times in the edgewise orientation, for a total of 25 edgewise archwires, and five times in the ribbonwise orientation, for a total of 25 ribbonwise archwires.

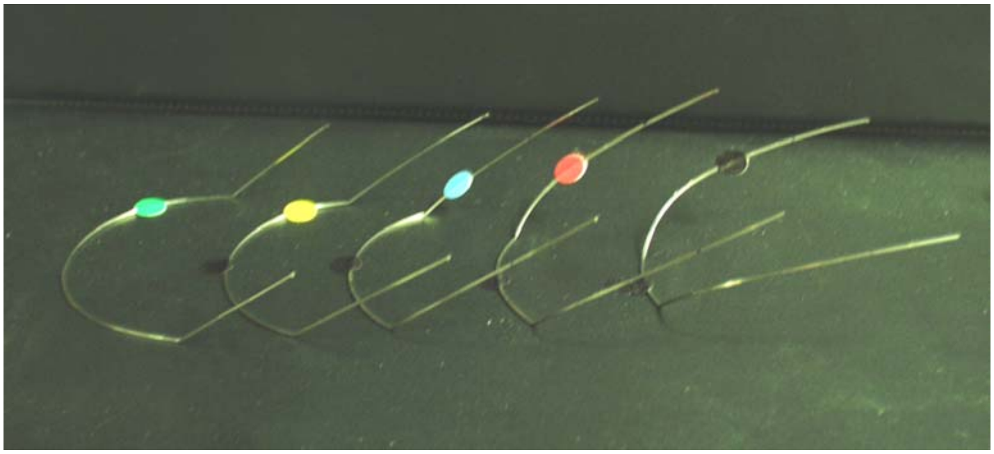

Figure 9. 3-Dimensional model: Wire bending.

A total of six measurements were made per archwire activation: 2nd order moment at the right molar, 3rd order moment at the incisor, 3rd order moment at the left molar, and vertical forces at all three attachments. Figure 10 illustrates activation of the three-dimensional model. Five trials were performed per archwire, for a total of 30 measurements per wire, or 1500 measurements in all.

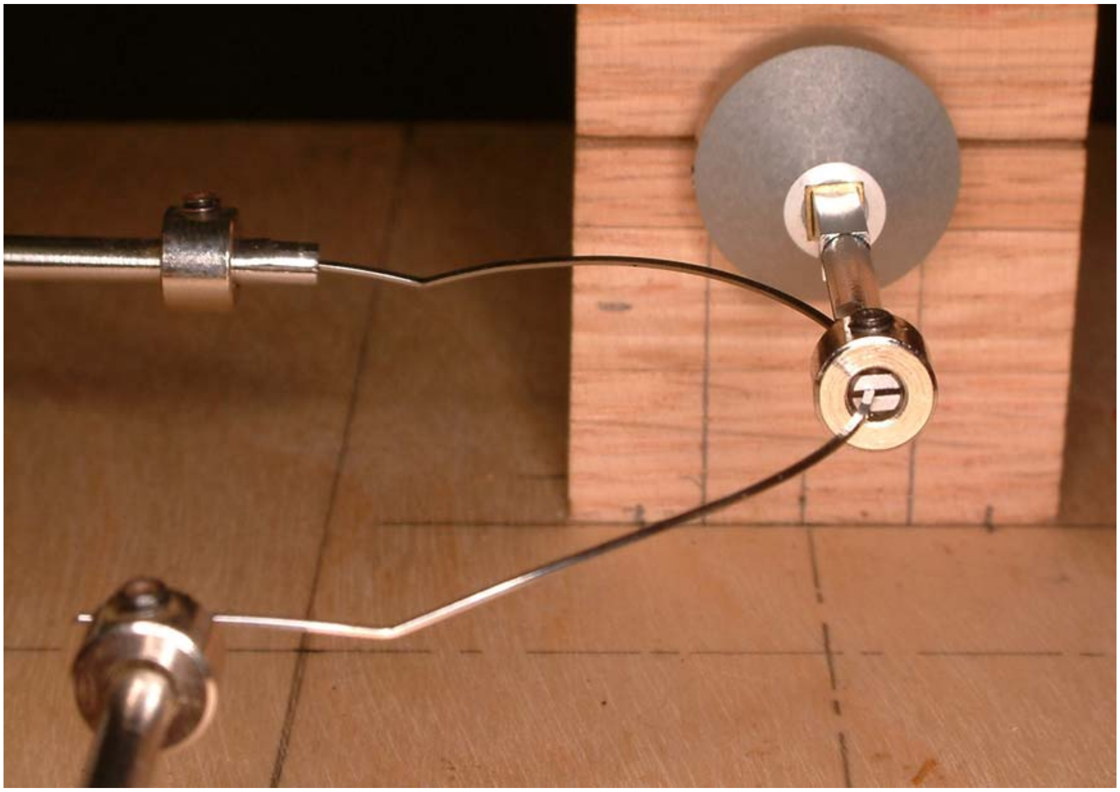

Figure 10. 3-Dimensional model: Measuring moments and forces.

Results

Gauge Accuracy Results

Average forces for ten trials for each of the three gauges are shown in Table I. The means of the readings for gauges #1 and #3 showed no statistically significant difference from 100g. Gauge #2 showed a small but statistically significant difference ($p<0.0001$).

Results of the ten trials for moment measurements are shown in Table II. The mean of the readings for gauge #2 showed no statistically significant difference from 2000g-mm. Gauges #1 and #3 showed statistically significant differences ($p<0.0001$). Note that the standard deviations of all three means were similar, indicating a problem with accuracy rather than precision.

Table I: *OrthoMeasure* Force Accuracy

Gauge #	Actual Weight (g)	Mean Measured Weight (g) (n=10)
1	100	100.5 ± 0.7
2	100	102.6 ± 0.5
3	100	100.0 ± 0.8

Table II: *OrthoMeasure* Moment Accuracy

Guage #	Predicted Moment (g-mm)	Mean Measured Moment (g-mm) (n=10)
1	2000	1865.3 ± 16.5
2	2000	2013.8 ± 20.7
3	2000	2054.3 ± 20.2

Two-Dimensional Results

Average moments and forces recorded at the molar and incisor probes as a result of placing activated edgewise wires with v-bends at various positions between the probes are presented in Table III. The same data for ribbonwise wires follow in Table IV.

Table III: 2-Dimensional Edgewise Data (Average ± Standard Deviation)

Bend Location (*a/L*)	**Force at Molar (g) (n=25)**	**Force at Incisor (g) (n=25)**	**Moment at Molar (g-mm) (n=25)**	**Moment at Incisor (g-mm) (n=25)**
0.17	78.2 ± 3.2	-84.2 ± 4.0	-2650.1 ± 77.2	-501.8 ± 63.6
0.33	38.8 ± 1.2	-40.5 ± 1.3	-1896.9 ± 33.8	320.2 ± 25.9
0.50	-2.8 ± 1.5	1.4 ± 1.6	-1075.6 ± 38.3	1121.1 ± 30.1
0.67	-40.7 ± 1.6	42.8 ± 1.6	-270.0 ± 39.5	1859.0 ± 41.3
0.83	-79.8 ± 3.9	83.2 ± 3.7	607.4 ± 60.3	2543.6 ± 92.1

Table IV: 2-Dimensional Ribbonwise Data (Average ± Standard Deviation)

Bend Location (*a/L*)	**Force at Molar (g) (n=25)**	**Force at Incisor (g) (n=25)**	**Moment at Molar (g-mm) (n=25)**	**Moment at Incisor (g-mm) (n=25)**
0.17	135.1 ± 3.1	-145.5 ± 3.3	-4874.4 ± 82.1	-605.9 ± 44.1
0.33	69.4 ± 2.9	-75.2 ± 3.1	-3598.9 ± 78.4	738.5 ± 41.5
0.50	-0.7 ± 3.5	-1.4 ± 3.7	-2181.3 ± 71.6	2113.3 ± 78.7
0.67	-70.6 ± 2.2	74.0 ± 2.5	-731.8 ± 58.9	3498.0 ± 54.7
0.83	-132.4 ± 4.3	138.0 ± 4.4	598.6 ± 47.4	4651.3 ± 150.1

The edgewise forces and moments, plotted as a function of v-bend position, are depicted in Figure 11 and Figure 12, respectively. Ribbonwise forces and moments are shown in Figures 13 and 14.

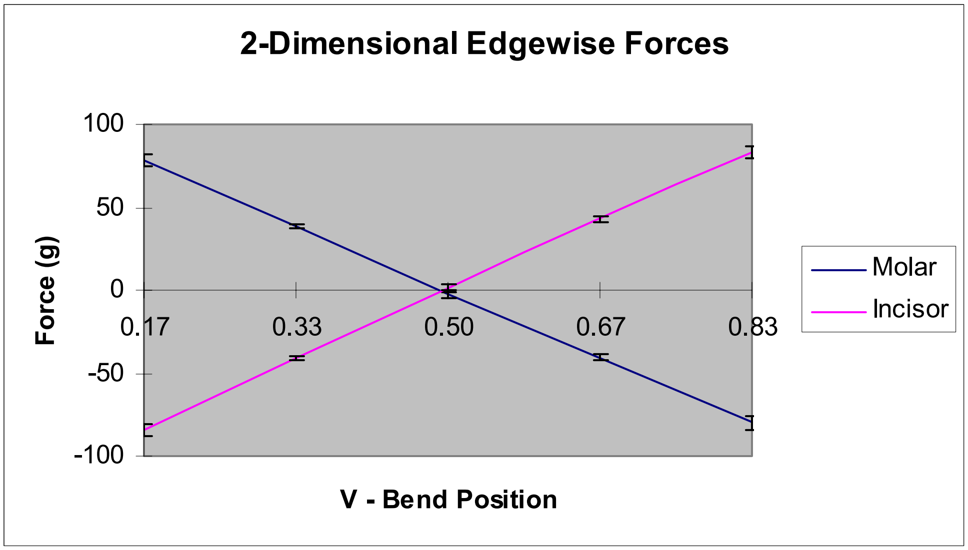

Figure 11. 2-Dimensional model: Edgewise forces as a function of v-bend position.

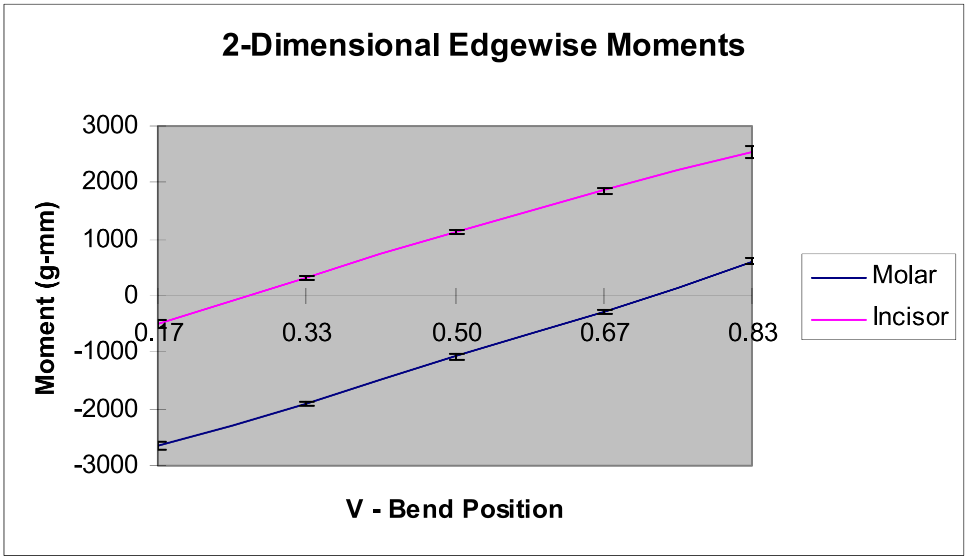

Figure 12. 2-Dimensional model: Edgewise moments as a function of v-bend position.

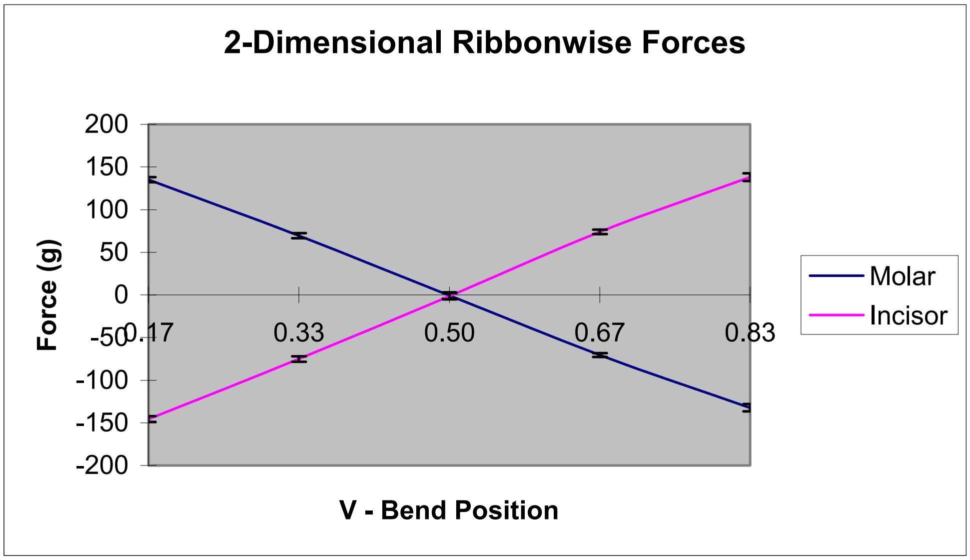

Figure 13: 2-Dimensional model: Ribbonwise forces as a function of v-bend position.

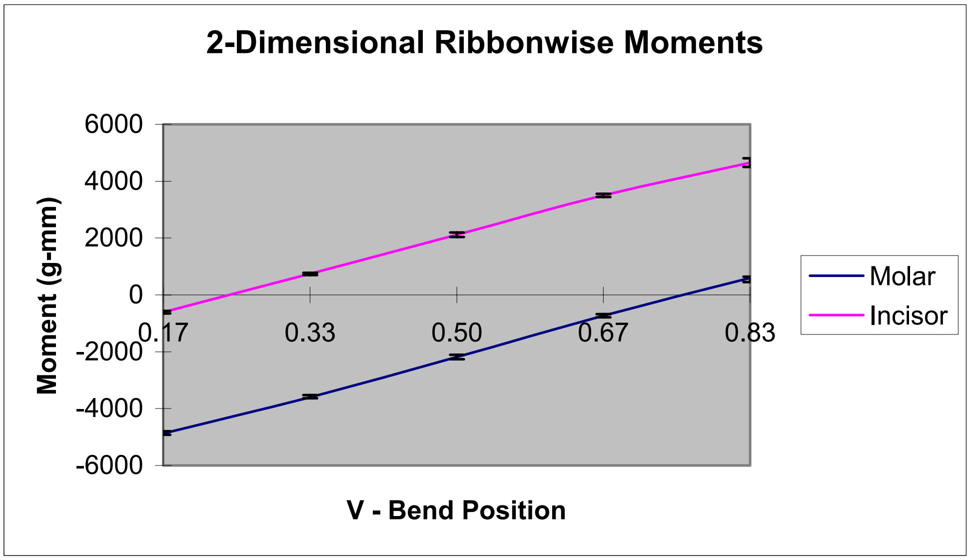

Figure 14: 2-Dimensional model: Ribbonwise moments as a function of v-bend position.

Of particular interest were the intercepts where the vertical forces were zero for the molar and incisor, where the moment at the molar was zero, and where the moment at the incisor was zero. The intercepts were calculated using linear regression. They are presented in Table V for edgewise wires and in Table VI for ribbonwise wires, and are compared to the predicted intercepts based on the mathematical model.[2]

Table V: 2-Dimensional Edgewise Intercepts

	Predicted Intercept (*a/L*)	**Calculated Intercept**
Molar Force = 0	0.50	0.49
Incisor Force = 0	0.50	0.50
Molar Moment = 0	0.67	0.72
Incisor Moment = 0	0.33	0.27

Table VI: 2-Dimensional Ribbonwise Intercepts

	Predicted Intercept (*a/L*)	**Calculated Intercept**
Molar Force = 0	0.50	0.50
Incisor Force = 0	0.50	0.50
Molar Moment = 0	0.67	0.76
Incisor Moment = 0	0.33	0.24

Three-Dimensional Results

Lateral view moments (2nd order at the right molar and 3rd order at the incisor), as well as the 3rd order moment at the left molar, are presented in Table VII for edgewise three-dimensional archwires. Also included are vertical forces for each probe. Table VIII shows the same data for ribbonwise archwires.

Table VII: 3-Dimensional Edgewise Data (Average ± Standard Deviation)

Bend Location (*a/L*)	**Force at Rt Molar (g) (n=25)**	**Force at Incisor (g) (n=25)**	**Force at Lt Molar (g) (n=25)**	**2nd Order Moment at Rt Molar (g-mm) (n=25)**	**3rd Order Moment at Incisor (g-mm) (n=25)**	**3rd Order Moment at Lt Molar (g-mm) (n=25)**
0.17	42.6 ± 3.8	-97.4 ± 8.5	51.0 ± 5.2	-1733.0 ± 60.1	255.0 ± 166.4	529.2 ± 56.9
0.33	19.1 ± 5.0	-43.6 ± 7.4	22.5 ± 2.7	-1169.0 ± 71.3	955.7 ± 203.7	414.8 ± 42.6
0.50	-4.7 ± 3.2	10.8 ± 6.6	-6.9 ± 3.0	-631.6 ± 33.1	1660.6 ± 225.9	284.8 ± 63.5
0.67	-24.5 ± 3.8	58.9 ± 7.9	-32.6 ± 4.7	-75.6 ± 43.9	2102.3 ± 238.4	226.1 ± 43.0
0.83	-49.7 ± 4.5	107.2 ± 10.3	-54.6 ± 7.1	639.2 ± 71.1	2391.9 ± 238.3	132.0 ± 83.3

Table VIII: 3-Dimensional Ribbonwise Data (Average ± Standard Deviation)

Bend Location (*a/L*)	**Force at Rt Molar (g) (n=25)**	**Force at Incisor (g) (n=25)**	**Force at Lt Molar (g) (n=25)**	**2nd Order Moment at Rt Molar (g-mm) (n=25)**	**3rd Order Moment at Incisor (g-mm) (n=25)**	**3rd Order Moment at Lt Molar (g-mm) (n=25)**
0.17	60.8 ± 7.1	-123.3 ± 10.3	58.0 ± 7.7	-2429.4 ± 213.4	450.8 ± 84.3	-30.4 ± 179.9
0.33	39.3 ± 8.8	-75.2 ± 14.0	34.0 ± 7.1	-1952.6 ± 209.4	1095.8 ± 295.6	270.8 ± 178.8
0.50	8.4 ± 5.1	-10.6 ± 10.4	2.8 ± 8.4	-1179.7 ± 140.9	1744.2 ± 323.8	262.0 ± 136.6
0.67	-23.4 ± 6.7	55.5 ± 10.7	-30.9 ± 5.0	-328.6 ± 105.8	2388.9 ± 318.2	189.6 ± 160.8
0.83	-59.6 ± 7.9	123.0 ± 12.0	-61.3 ± 7.0	741.2 ± 213.2	2837.6 ± 194.6	78.8 ± 121.8

The edgewise three-dimensional forces and moments, plotted as a function of v-bend position, are depicted in Figure 15 and Figure 16, respectively. Ribbonwise three-dimensional forces and moments are shown in Figures 17 and 18.

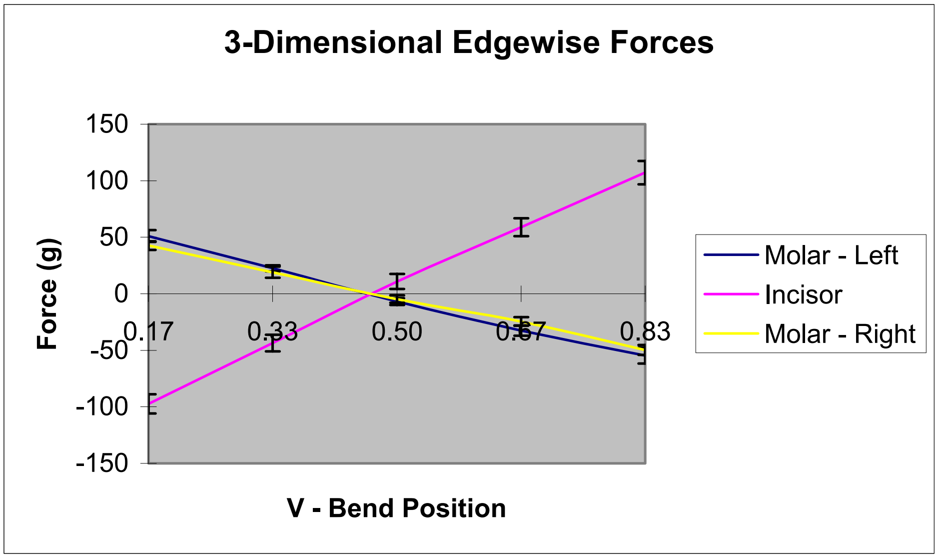

Figure 15: 3-Dimensional model: Edgewise forces as a function of v-bend position.

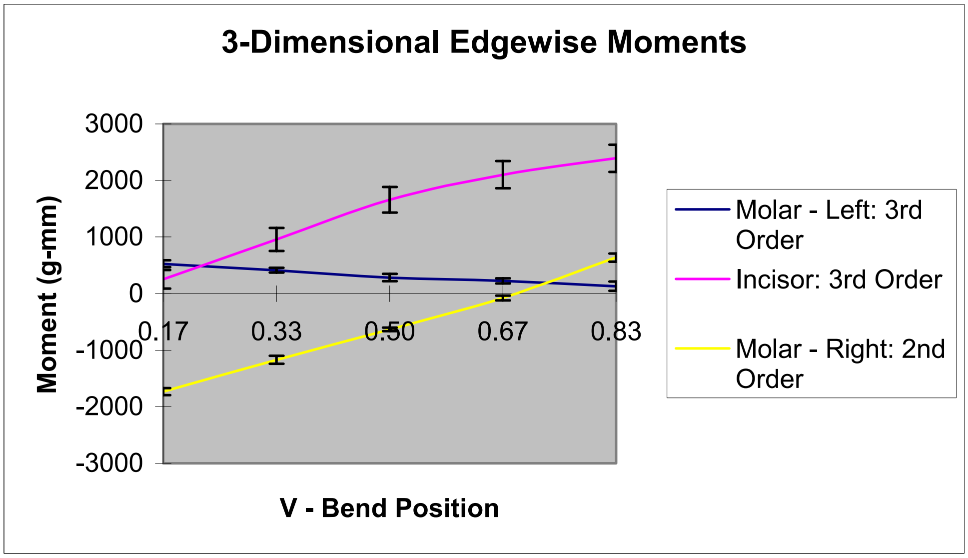

Figure 16: 3-Dimensional model: Edgewise moments as a function of v-bend position.

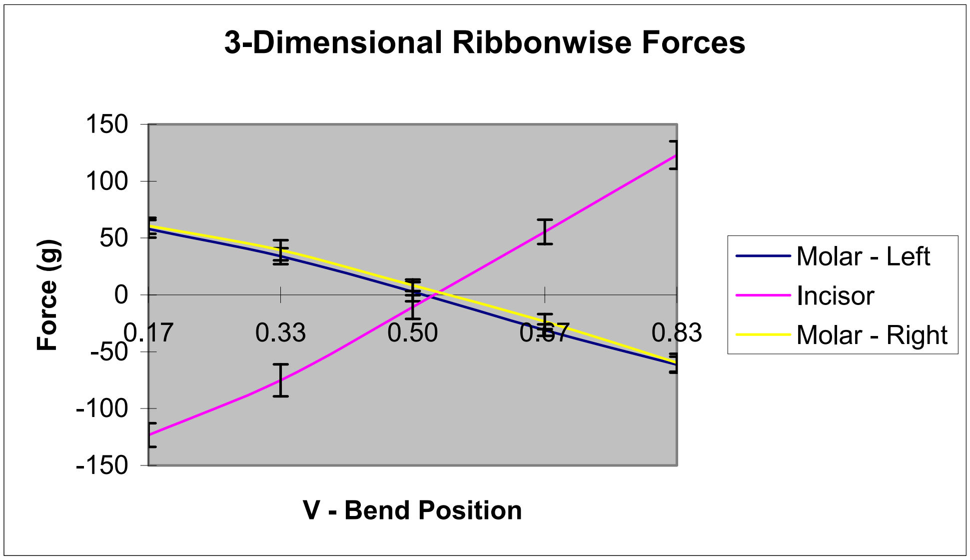

Figure 17: 3-Dimensional model: Ribbonwise forces as a function of v-bend position.

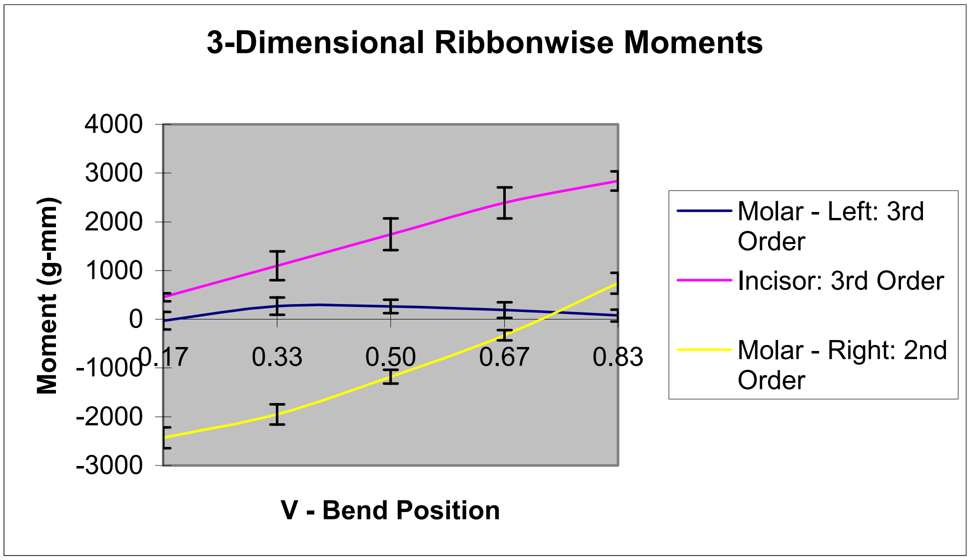

Figure 18: 3-Dimensional model: Ribbonwise moments as a function of v-bend position.

As with the two-dimensional data, of particular interest were intercepts where forces and moments were zero, as seen from the right lateral view. The intercepts were calculated using linear regression. Table IX shows the three-dimensional edgewise calculated intercepts where the vertical forces at the right molar and the incisor were zero, as well as where the second order moment at the right molar and the third order moment at the incisor were zero. The corresponding three-dimensional ribbonwise calculated intercepts are presented in Table X. The calculated intercepts are compared to the predicted intercepts based on the two-dimensional mathematical models.[2]

Table IX: 3-Dimensional Edgewise Intercepts

	Predicted 2D Intercept (*a/L*)	**Calculated Intercept**
Rt Molar Force = 0	0.50	0.47
Incisor Force = 0	0.50	0.48
Rt Molar 2nd Order Moment = 0	0.67	0.67
Incisor 3rd Order Moment = 0	0.33	0.04

Table X: 3-Dimensional Ribbonwise Intercepts

	Predicted 2D Intercept (*a/L*)	**Calculated Intercept**
Rt Molar Force = 0	0.50	0.53
Incisor Force = 0	0.50	0.52
Rt Molar 2nd Order Moment = 0	0.67	0.72
Incisor 3rd Order Moment = 0	0.33	0.03

Discussion

A primary purpose of the present study was to compare two-dimensional *in-vitro* data to Burstone and Koenig's two-dimensional computer model. Differences were found, and it is prudent to consider whether the magnitude of the differences is greater than the experimental error in the *in-vitro* model.

Four sources of possible experimental error were identified and addressed in the present study. First, gauge accuracy was measured. All three gauges recorded forces within 3 grams, or 3%, of the actual 100 gram weight (Table I). Gauge #1 showed an error of 135 g-mm, or 7%, of the predicted 2000 g-mm moment (Table II). As a result, gauge #1 was not used in the two-dimensional model, and was relegated to measurement of the third order moment at the left molar in the three-dimensional model. Gauges #2 and #3 showed moments within 55 g-mm, or 3%, of the predicted 2000 g-mm.

A second possible source of error was the spatial relationship of the probes relative to each other. Before data were recorded, both the two and three-dimensional models were adjusted until passive wires could be placed repeatedly without producing forces greater than 5 grams or moments greater than 50 g-mm. The passive wires were engaged with a press fit connection to the probes, as were the subsequent active wires.

Third, error was undoubtedly present in the placement and size of the v-bends, as well as in the wire properties before and especially after the bends were placed. And finally, subtle differences in the positions of the wires in the probes were anticipated. These last two sources of error were addressed by fabricating five wires for each v-bend location, and then by placing each wire in the probes five times and recording the associated data for each trial. The standard deviations shown in Tables III, IV, VII, and VIII, and the corresponding error bars shown in Figures 11 through 18, reflect the magnitude of these two sources of error.

Burstone and Koenig's two-dimensional mathematical analysis predicted that a v-bend placed midway between brackets produced no vertical equilibrium forces.[2] The present study supports these results. As shown in Tables III and IV, the forces at the molar and incisor when the v-bend location was at $a/L = 0.5$ were close to zero. They were well within the approximately 5 grams of experimental error of the *in-vitro* model setup. Figures 11 and 13 provide graphic evidence of the same data, showing forces essentially zero at $a/L = 0.5$. Finally, Tables V and VI give the calculated zero force intercepts, which are at, or close to, $a/L = 0.5$.

The mathematical analysis also predicted that the v-bend location that results in zero moment at a bracket should be one-third of the total interbracket distance from the opposite bracket.[2] Thus we would anticipate zero moment at the incisor to occur with a v-bend located at $a/L = 0.33$, as shown in Tables V and VI. Likewise, at $a/L = 0.67$, zero moment at the molar would be expected. The present study does not support these v-bend locations. As shown in Table III, for an edgewise wire with a v-bend at $a/L = 0.67$, the moment at the molar was - 270.0 g-mm. This value is much farther from zero than can be explained by the approximately 50 – 55 g-mm of anticipated error in the *in-vitro* model. Also in Table III, the moment at the incisor was 320.2 g-mm when *a/L* = 0.33. Again, the moment is much farther from zero than can be explained by anticipated experimental error. The corresponding ribbonwise data in Table IV shows non-zero moments of - 731.8 g-mm and 738.5 g-mm for the molar moment with a v-bend at *a/L* = 0.67 and the incisor moment with a v-bend at *a/L* = 0.33, respectively. Figures 12 and 14 show the same data graphically, and indicate that v-bend locations resulting in zero moments are significantly farther from the midpoint than Burstone and Koenig predicted. Tables V and VI give calculated zero moment intercepts of *a/L* = 0.27 for the incisor and 0.72 for the molar for edgewise wires, and *a/L* = 0.24 for the incisor and 0.76 for the molar for ribbonwise wires. These results correlate well with previously recorded *in-vitro* data, which showed zero moment intercepts of *a/L* = 0.27 and 0.74.[16]

At least two possible explanations may be proposed for the differences between the two-dimensional zero moment v-bend locations predicted in the mathematical analysis versus those found in the present study. First, wire properties at the v-bend may be altered through deformation. Second, the boundary conditions used in the mathematical model may differ from those present in the current *in-vitro* model. Further research is required to develop two-dimensional mathematical and *in-vitro* models whose data coincide.

In the present study, the three-dimensional data showed intercepts associated with zero forces at the molar and incisor that were somewhat different from the midpoint of the wire. Figures 15 and 17 show that the zero force intercepts for edgewise wires were closer to the molar than the midpoint, while those of the ribbonwise wires were closer to the incisor. Tables IX and X show the calculated zero force intercepts for the three-dimensional archwires.

The three-dimensional zero moment intercepts, as shown in Figures 16 and 18, were also different between edgewise and ribbonwise archwires. Tables IX and X show the associated calculated intercepts. Compared to two-dimensional zero moment intercepts, the three-dimensional values were closer to the molar. Note that obtaining zero moment at the incisor in the three-dimensional model required a bend very close to the molar (a/L = 0.04 for an edgewise archwire).

In both two-dimensional and three-dimensional models, the overall magnitudes of the forces and moments seen from the lateral view produced by ribbonwise wires were consistently greater than for their edgewise counterparts. Tables III and IV show the two-dimensional data, and Tables VII and VIII show the three-dimensional data. This is due to the increased vertical aspect of the cross section of a ribbonwise wire, and the resulting increased resistance to bending.

Conclusion

The important findings of the present study can be summarized as follows:

- Two-dimensional *in-vitro* data conflicts with Burstone and Koenig's two-dimensional mathematical simulation regarding the location of v-bends that yield zero moment at the bracket farther from the bend.
- Forces and moments produced by *in-vitro* three-dimensional archwires differ significantly from *in-vitro* two-dimensional data.
- Ribbonwise *in-vitro* wires produce higher forces and moments than their edgewise counterparts.

A thorough understanding of the mechanical force systems generated by orthodontic wire activations is important for producing efficient tooth movement directed toward achieving predetermined treatment goals. Understanding the three-dimensional forces and moments produced by orthodontic archwires is fundamental to designing orthodontic appliances that will produce predictable tooth movement. Additional research is required to yield two-dimensional mathematical models and *in-vitro* models with coinciding data. Such research will enable the development of more complex models to simulate more complex appliance systems encountered clinically. This knowledge will enhance our ability to study the biologic reactions and tooth movements exhibited in patients as a result of three-dimensional orthodontic appliance activations.

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VITA

Dr. Dwight V. Buelow was born in Bartlesville, Oklahoma on August 3, 1967. He received a Bachelor of Science degree in Mechanical Engineering from Princeton University in 1989. After working for Exxon Corporation as a petroleum engineer in New Orleans, he attended Virginia Commonwealth University School of Dentistry. He earned his Doctor of Dental Surgery degree in 2001 from VCU and subsequently entered the orthodontic residency program at the same institution.