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Force-System Generated by Rigid Archwires with V-bends: A 3-D Analysis of Varying Activations

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Force-System Generated by Rigid Archwires with V-bends: A 3-D Analysis of Varying Activations

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Acknowledgements:

We are not now that strength which in old days
Moved earth and heaven, that which we are, we are;
One equal temper of heroic hearts,
Made weak by time and fate, but strong in will
To strive, to seek, to find, and not to yield.
{Last few lines of Ulysses- Alfred, Lord Tennyson}

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To save myself the embarrassment of not being able to express my gratitude completely and since the best is saved for the last, I thank Dr. Po-Jung Chen here. He became an indispensable part of our team and it would not be an exaggeration for me to say that this project would have been impossible to complete without him. I thank him for his passion, selflessness and most of all for being the best research partner and friend I could have ever hoped for.

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Abstract

Background: Previous analysis of V-bend mechanics has been in two dimensions, although all orthodontic appliances are 3 dimensional (3D) in nature. **Purpose**: To produce clinically relevant data for the force system with V-bends placed in stainless steel archwires of 4 different sizes. **Research design**: Three V-bend angles of 12º, 20º and 30º placed at 11 different locations obtained from a theoretical framework from previous data was used. Multi-axis force transducers mimicking a 2x4 appliance were used to measure the force-system in the x, y &z planes. **Results**: The data obtained did not conform to the previous 2D studies. The force system increased at the two brackets (P<0.5) with increasing wire size & activation. Torsional & bending moments created unique force systems at each bracket. **Conclusions**: This 3D analysis provides critical information on V-bend activation & application. A model for determining the force system is described, that will allow for easier translation of the data to actual clinical practice.

Introduction:

The scientific basis of clinical orthodontics is based on the knowledge of a variety of different fields. From bone biology to growth, comprehension of the basic mechanisms and patterns of the craniofacial region is essential for the clinician to be able to provide optimum care. However, a thorough understanding of the force systems of the various appliances that are used in day to day clinical practice is at the helm of this knowledge. Sound biomechanical principles can help the clinician achieve predictable treatment results and minimize potential side effects thereby the ability to provide efficient and effective treatment[1].

Multi bracket appliances are commonly used in orthodontics to move teeth. Such appliances exert a three-dimensional (3D) force/moment (F/M) system on each bracketed tooth. The quantitative knowledge of the F/M system therapeutically applied to the individual teeth is of utmost importance for accurate control of their 3D translations and rotations. However, the force system generated by such appliances is complex and statically indeterminate. One way of circumventing this problem is to reduce the multi-bracket system into less complicated basic units.

The two - bracket system is the simplest mechanical system, which offers a basic building block for understanding more complex forces systems from multi-bracketed appliances. Additionally, the two bracket arrangement on the

molar and the incisors is used commonly in clinical practice to achieve desired tooth movement. This is done usually by placing a 'V' bend in the wire connecting the two brackets (molar and incisor). Some examples of such use are, when the clinician is trying to achieve/ maintain incisor torque control during space closure[2] or is aiming to flare the upper incisors to achieve correction of anterior crossbite.

A study of the orthodontic literature reveals that the force/moment system of the two- bracket geometry has been studied, but, only in one plane of space. The two brackets that were studied were parallel and colliner- such as two premolar brackets[3]. In addition, the results obtained were based on mathematical models. Though this information lays the foundation to several biomechanical concepts, it does not provide the accurate force/ moment systems for the two bracket arrangement that are used in common clinical situations (as described in the above examples) which involve the incisor and a molar bracket. This arrangement, between the molar and incisor is now non-colliner or in more than one plane.

Traditionally the principles of two bracket geometry was thought as universal and applied to all two bracket situations without considering the change in dimension that is brought about by including the incisor bracket. In addition as these methods were not experimental models, they imposed certain boundary conditions for running the simulations which might not hold true in

actual clinical situations and deviations might occur. Therefore, the rationale for the current study was to experimentally research and establish the force/moment mechanics of a two bracket system that has a non- collinear and non- parallel arrangement.

Background:

Drs. Burstone and Koenig in 1974 studied the force systems of an ideal archwire when engaged in two nonaligned brackets[4]. This was followed by the authors studying the two bracket arrangement when 'V" bends and step bends were placed in the wire that was engaged in aligned brackets[3]. Further studies were also done, where, similar bends were placed but the amount of deflection of the bend was increased[5]. They also tested if their results held true if wires of different modulus of elasticity were used[6].

The results of all the above studies were similar and were outlined using six possible geometries or force/ moment systems. It is important to observe that the six geometries are representative of a continuum of possible configurations and force systems between the two brackets. Through experimentation Upadhyay et al[7] have further summarized these configurations into three systems that are detailed using the figures below.

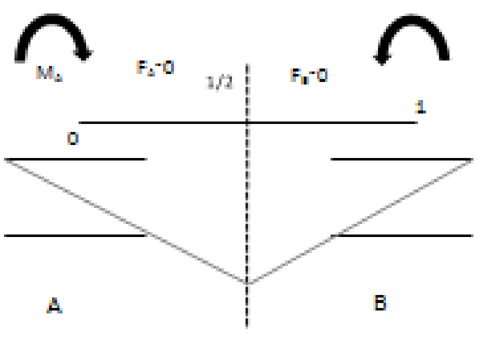


Figure: 1

Fig 1: Depicts the scenario where the bend is placed exactly between (the halfway point) the two brackets –A and B. Two equal and opposite moments are created with the forces cancelling out. The term that has been coined for this position of the 'V'' bend is - ***Neutral point***.

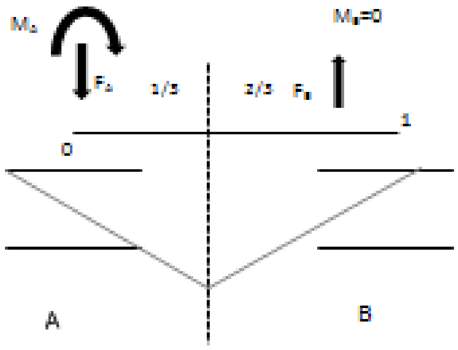


Figure: 2

Figure 2 depicts the situation where the bend is moved towards one of the brackets-in this case bracket A. This causes the moment on bracket A to increases and on the other bracket (Bracket B) to decrease. If the bend is moved to a particular point i.e. 1/3rd the distance from bracket A, it was noticed that the moment becomes zero at B. This was called the ***Dissociation point***.

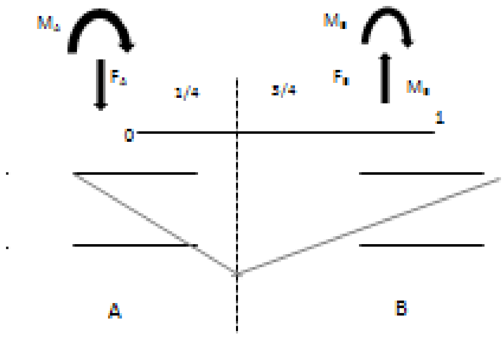


Figure: 3

Figure 3 depicts the force system between the two brackets in which the bend is further moved towards bracket A. This shift causes the moment to reappear at bracket B but in the same direction as that of bracket A. This was termed the ***Reversal point***.

Two very important inferences can be drawn from the three geometries described above.

1. We see a dramatic change in the moment produced in bracket B with changes in the position of the V bend. Therefore these specific positions carry notable clinical relevance and application. Therefore, these points are called ***Critical points***.

2. Due to the virtue of the brackets being in the same plane, the brackets A and B are mirror images of each other and flipping them just reverses the moments and forces between the two brackets but essentially the geometries and the critical points will remain the same.

The results of these studies though commonly applied in clinical practice and used as scientific basis of explaining force/ moment systems of various appliances have several drawbacks:

1. Only one plane, the second order was considered and the two brackets that studied were collinear & parallel in arrangement.

2. Perfect symmetry was assumed - this the brackets and consequently the force/ moment system were mirror images and interchangeable between the two brackets.

3. The Force moment systems were not obtained experimentally. Mathematical models were used based on which calculations were made.

4. Assumptions regarding the properties and behavior of the wire were made in conjunction with the mathematical model.

5. It was also assumed that the wire was completely free to slide within the brackets, and thus, any effects of friction and mesiodistal forces were ignored.

Isaacson et al[8] recognized some of these drawbacks and hypothesized that the effects produced by a 3-D rectangular wire with a single vertical V-bend will produce moments and forces different from those reported for the same bend in a 2-D system. Using an FEM model of a 2x2 appliance system they found that the curves of the 3-D system are not symmetrical nor centered around a neutral point at an a/L ratio (similar to the neutral point) of 0.5 as reported for 2-D systems. However, in spite of finding a clear difference between the two systems they concluded that the data, while significantly different from the data developed by previous two-couple models, did not radically modify the clinical use of arch wires. They also had several limitations to their study such as, testing only one arch wire at one given angulation of Δ= 0.5mm.

More recently, Upadhyay et al, at the University of Connecticut have been conducting experiments in an attempt to understand and quantify the force system generated in a 3D two bracket set up involving the molar and incisors with vertical V-bends. The first set of experiments using Beta Titanium archwires of various dimensions at a 30 degree angulation has been recently published.[7]

Rationale:

The rationale for the current study is outlined below:

1. Majority of studies have used a 2 D set up to explain the force system generated by 3D arch wires and brackets.

2. The force system generated for a large or a small deflection 3D set up, has not been qualitatively or quantitatively defined.

The question that we are addressing in this study is -"Is it possible for us to clinically predict what moments and forces are generated, when we place a bend (Small / Large) in any position between the incisor and molar bracket"?

Aims / Objectives and hypothesis:

1. To quantify- the F/M system generated by the orthodontic arch wire undergoing large and small deflections in a 2x4 appliance set up.

2. To quantify the variation in the F/M system for different arch wire sizes.

3. To compare the consistency of our results- (primary qualitatively) with previous theories on the ‘v’ bend principle.

Both, a null and alternate hypothesis were defined for the study. The null hypothesis was essential as the previous studies on two bracket systems have had universal clinical applicability for the last few decades and we wanted to experimentally examine if we arrived at the same results. However, based on theoretical modeling of a 2x4 bracket arrangement we realized that we need a clearly defined alternate hypothesis.

Null hypothesis:

1. There is no difference in the Force / Moment system generated in a 2D set up when compared to a 3D set up mimicking a 2x 4 appliance.

2. There is no difference in the qualitative description of the F/M system between a large and a small deflection set up.

3. There is no different in the qualitative description of the F/M system between different arch wire sizes.

Alternate Hypothesis:

1. There will be a difference in the Force / Moment system generated in a 3D set up mimicking a 2 x 4 when compared to a 2D set up.

2. There will be a difference in the qualitative description of the F/M system between a large and a small deflection set up.

3. There will be a difference in the qualitative description of the F/M system between different arch wire sizes.

Materials and Methods:

It will be discussed under the following headings:

1. Theoretical framework

2. Actual experimentation

Theoretical framework was established in order to determine the various angles that were incorporated into the study. Estimating the large and small deflection based on information from the previous studies involved certain trigonometric calculations.

The first angulation or what was called small deflection, was based on the previous paper by Busrstone et al[3]. The paper defined the deflection using a delta value in millimeters. The angle of deflection (θ) was calculated using the formula: $\tan \theta = \sin \theta / \cos \theta = a/b$. If a, b and c are the sides of a right angled triangle as shown here.

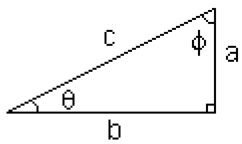


Figure: 4

When we consider a symmetric ‘V’ bend placed in a wire engaged in two parallel collinear brackets at a distance of 7mm with each other, with a delta

value of 0.35mm, we get a right angled triangle as depicted at the half way point in figure 5.

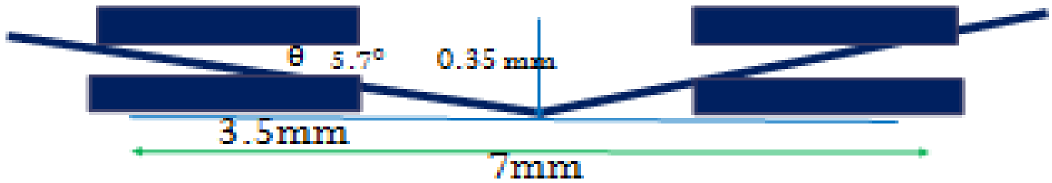


Figure: 5

Using the above mentioned formula the angulation can be calculated as follows:

$\tan \theta = 0.35/ 3.5$

$\tan^{-1} = 5.7°$

$2\ \theta = 11.4°$

Therefore angle of 11.4° which was rounded of to 12° was used as the 'small' deflection or the <u>first angulation</u> that was to be tested in various positions. This angulation is an obvious choice as this was the original angulation used and formed the basis for our current understanding of the force/ moment system in the two bracket arrangement. Testing this angulation would let us compare our results with previous results.

The other component that was analyzed about the 'small' deflection angulation of 11.4° is why was it was their angle of choice. In order to find the reasoning behind this we needed to calculate the critical contact angle (θc)[8] that was produced by an 0.016 inch wire in a bracket with a slot height of 0.022 inches.

$$\tan \theta c = \frac{\text{Bracket Height- Wire Height}}{\text{Bracket Length}}$$

For 0.016" wire in 0.022" bracket

= 0.558- 0.381 mm/ 3.5mm

$\tan^{-1} = 3^{\circ}$

Therefore, for a 0.016 inch wire to achieve a two point contact in a bracket that had an occluso- gingival height of 0.022inches, the bend has to be at least 3° as shown in figure 6.

Figure: 6

The next step in creating the theoretical framework was to calculate the critical contact angle for the incisor bracket which is in a different plane of space as compared to the molar/ premolar bracket and therefore contact changing the dimension in which the wire contacts the bracket[10,11]. The critical contact angle for the incisor bracket of 0.022 inch height and 0.028 inch depth can calculated using this formula:

$$\tan \theta c = \frac{\text{Bracket Height- Wire Height}}{\textbf{Bracket depth}}$$

$\tan^{-1} = 12^{o}$

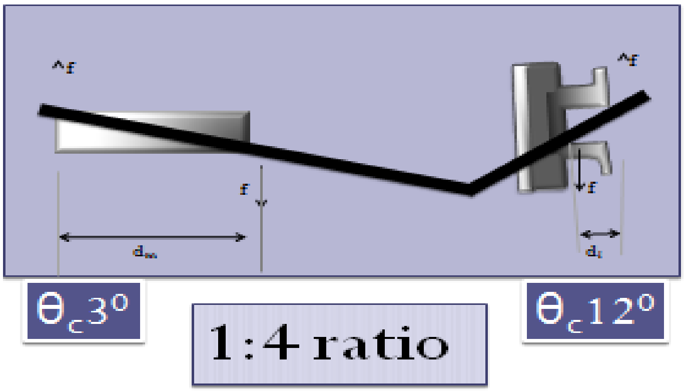


Figure: 7

Figure 7 visually demonstrates the difference in the in the two critical contact angles (of the molar and the incisor brackets) and we can also see that the same bend we placed before does not make a 2 point contact at the incisor bracket as we are now looking at the bracket in a different plane. We also get the same result mathematically by substituting the bracket length with bracket depth. The

critical contact angle was calculated 12° for the incisor bracket. This is four times that of the critical contact angle of the molar. It was also an incidental finding that this ratio remains 1: 4 for all wire dimensions.

Based on the above calculation we derived the value for the *second angulation* as 20°. This was because θc of the molar was 3° and the θc of the incisor is 12° adding up to a total of 15°. We rounded it to 20° for two reasons. First, to have a discernible difference between the first angulation and the second. Secondly, based on our critical contact angle calculations we wanted it to be sensitive enough for our measuring system to be able to detect the force/ moment system.

The *third angulation* or the large deflection was set at 30°. This angle was determined based on the two previous angulations. It needed to be substantially larger than what we termed as 'small' deflections. Additionally, previous studies have used it, it forms an ideal choice for comparison and most importantly this is a commonly used angle in clinical practice. Therefore, the results will have direct clinical application. Therefore the three angles to be used are: Bend angulation: 168°,160°, 150°.

Materials used in the actual experimentation:

Arch-wires which will be used:

1. Experimentation arch wire- 0.016 inch Stainless Steel (SS) wire- round dimension - this dimension was used in previous studies and will this act as

control wire. Additionally, since it is a round wire, we expect to eliminate any torque values at the incisor thus providing us with additional control.

2. Experimental arch wire - 0.016 x 0.022- inch SS

3. Experimental arch wire - 0.017 x 0.025- inch SS

4. Experimental arch wire - 0.019 x 0.025- inch SS

All of these arch wires will be procured in the maxillary arch ovoid form from Ortho Arch Company.

The testing apparatus[12]:

The testing apparatus consisted of a series of aluminum pegs arranged to represent the teeth in a maxillary dental arch. Two of the pegs (those representing the right central incisor and right first molar) were connected to sensors which have the ability to measure forces and moments in three dimensions: Fx, Fy, and Fz; and Mx, My, and Mz. These sensors were ATI NANO 17 SI-50-0.5 F/T sensors. The twelve pegs, representing the maxillary teeth up to the first molars, were arranged in the shape of a dental arch using a predefined ovoid arch form. The pegs were positioned along the arch such that when brackets are adhered to them, the bracket slots would follow the arch form. The distances between the pegs were calculated using average tooth widths. Once the pegs were secured to an aluminum plate, a set of self-ligating brackets- Empower series from American Orthodontics, were bonded to both

central incisor pegs using a composite resin, and both first molar pegs were bonded with single tubes. The slot dimension for all teeth was 0.022 inches x 0.028 inches. A full dimension stainless steel wire was used as a jig to align the brackets and ensure that they were bonded in a neutral position, meaning they would express zero tip and zero torque. Theoretically, any arch wire in the specific shape of maxillary ovoid arch form should lie passively when engaged into the brackets. Finally, the sensors were connected to a computer to record the readings, and the entire apparatus diagram of the apparatus was placed in an enclosed chamber as is shown in Figure 8.

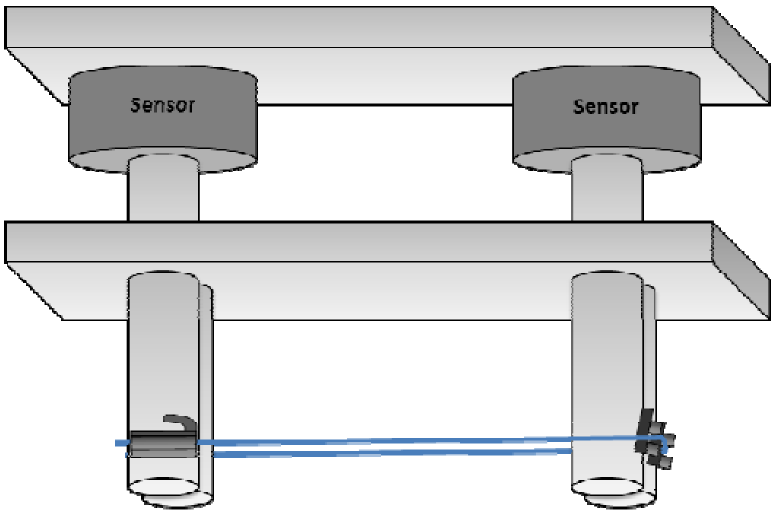


Figure : 8

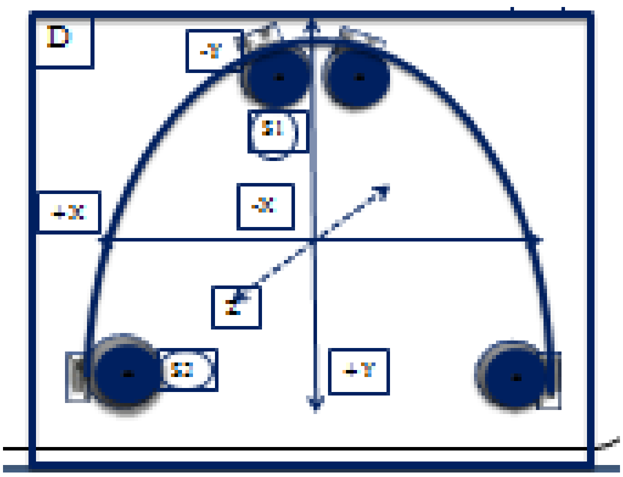


Figure : 9

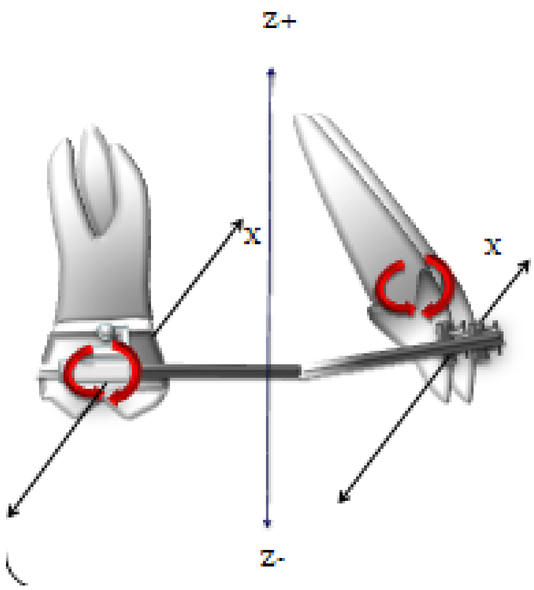


Figure : 10

Figure 9 and figure 10 illustrate the axes along which the 3- dimentinal measurements are going to be recorded.

Table 1 - The movements in orthodontic clinical terms in each axes. One can also see from this table that our concentration is focused on with forces and moments in Z and X axes.

F/M System	Molar (M)	Incisor
Fz (+)	Intrusive	Intrusive
Fz (-)	Extrusive	Extrusive
Mx (+)	Mesial Tip	Facial / labial tip
Mx (-)	Distal Tip	Palatal/ lingual tip

Bend positions:

It was decided that the V-bends would be placed in 11 positions on the arch wire. The bend position represented by a/L ratio, where a is the position of the bend in relation to the incisor bracket in relation to L - the length of the wire. Using the formula the perimeter of the parabola (in our case the wire) was calculated to be 37mm. As there are to be 11 bends each successive bend is to be placed at 3.7mm from the other. The bends can be represented thus: the first bend closest to the incisor bracket will have an a/L ratio of 0/ 37, therefore

zero and the fourth bend can be calculated 3.7 x 3 which would be 11.1 /37, therefore 0.3 mm from the incisor bracket.

This is diagrammatically depicted using blue dots on the arch wire in Figure 11.

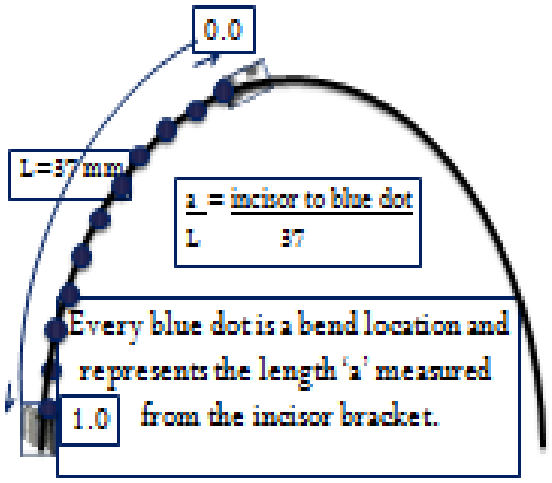


Figure 11

A total of 1500 wires will be tested as we have four dimensions of wires 0.016 inch, 0.016 x 0.022 inch, 0.017 x 0.025inch & 0.019 x 0.025 inch Stainless Steel. Each wire size would be tested for each of the 11 positions, 1 times each for every wire size at 3 angulations.

Experimental Procedure:

The F/M system measured at each sensor was represented by their three orthogonal components. Fx, Fy, and Fz represented the force components while Mx, My, and Mz represented the moments along the x, y and z axes, respectively.

1. Before any wire was engaged in the brackets, the software program was set the "zero point" of both sensors. At this time, the software program displayed each of the three force and three moment values at each sensor in real time and all six measurements at each sensor were confirmed to be negligible values (forces < 1 g and moments < 1 g·mm) before continuing.
2. One wire sample was engaged into the first molar and central incisor brackets, representing a 2x2 appliance. The wire was held in place using the passive self-ligation system on the central incisor brackets.

Figure 12 shows an example of a wire inserted into the testing apparatus both before and after it has been engaged into the incisor bracket.

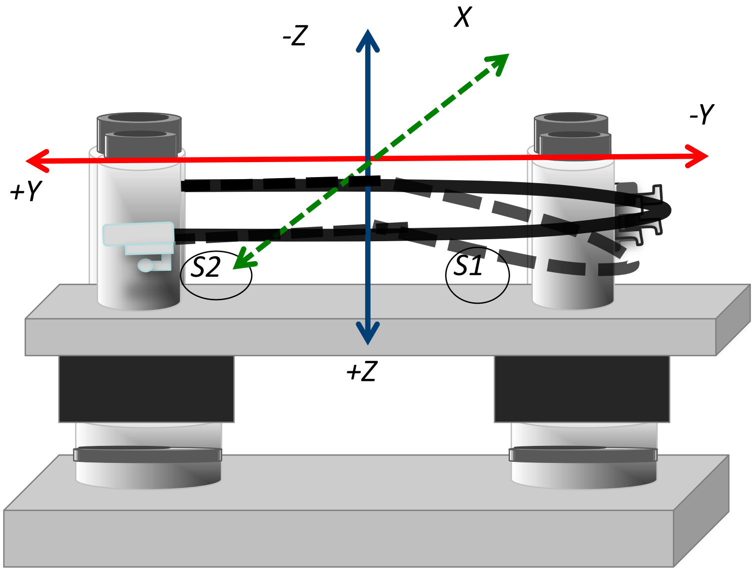


Figure 12

3. The recording feature of the software program was run for a five second measurement cycle, in which the three force and three moment components from each of the two sensors was recorded. Each cycle generated 5 readings over the five second period for each component. (Fx, Fy, Fz, Mx, My, Mz). Thus, for each individual wire sample, there were twelve associated measurements (six components at two sensors) with 5 readings per measurement, and these were recorded to a Microsoft Excel spreadsheet.
4. The wire sample was removed from the apparatus, and the computer program was stopped.
5. Steps 1-4 were repeated for each wire sample.

For each combination of wire specifications: Wire angulation, Wire dimension, and position of v-bend), ten samples were measured, which resulted in a total of 1500 wires tested.

Analysis:

A clinical coordinate system was set up for the two brackets at the incisor and molar positions. Archwire symmetry was assumed and only the right half of the archwire was modeled. A global coordinate was chosen and the values recorded were at the sensor. The force was measured in Newton (N) but converted into gram-force or gram (g) for convenience.

For the purpose of analysis we specifically focused on: the vertical forces at the molar (Fzm) and incisor brackets (Fzi), the second order rotation (mesio-distal tipping) at the molar bracket (Mxm) and the third order rotation (labio-lingual tipping) at the incisor bracket (Mxi). Moments generated in one plane have negligible effect on those generated out of plane[13]. Therefore our analysis was limited to only Fz & Mx.

Statistical Methods:

Descriptive statistics were used for this study. Statistical analyses were performed using Graph Pad Prism (GraphPad Software, Inc., La Jolla, CA). Individual statistical analyses were performed for Fz and Mx. Analyses of variance (ANOVA) were used to examine differences in the curves for the force and moment components across the four arch wires and three angulations.

Error data:

Different loads were applied over the z-axis of both the sensors. For weights lesser than 50g, the error was found to be 5%. The average error for weights from 50g to 500g was calculated to be 0.5%. The percent error was calculated by the following equation:

$$\% \text{ Error} = \frac{\text{Actual value} - \text{Expected value} * 100}{\text{Expected Value}}$$

Here the expected values were the known weights and observed results were the actual values.

Results:

For each individual wire sample, 50 readings over a five second period were recorded for each component (Fx, Fy, Fz, Mx, My, and Mz) at each sensor (incisor and molar). Any variations among the 50 values in a particular set were negligible ($p>0.05$) as they represented very minute fluctuations in the electronics of the sensor or software program. The standard deviations for the mean values were < 0.75 g for the forces and < 5 g·mm for the moments.

Ten samples were tested for each combination of wire specifications (wire deflection, wire dimension, and position of v-bend) to take into consideration variations caused by factors such as operator error, slight differences in wire insertion or activation, and differences in the exact position or angle of the v-bends for each wire sample. Thus, for each group of ten wire samples with the same specifications, the mean and standard deviations were calculated for each force and moment component in both coordinate systems. Each point on the graphs shown below represents the mean value of the ten wire samples in that group, and the error bars represent one standard deviation above and below this mean.

Although, close attention was paid to the sign convention for each force and moment component when applying mathematical calculations and checking for equilibrium, when it comes to clinical applicability, it is not relevant to

consider the force system in those terms. Rather, it is simpler to imagine the forces and moments by the type of tooth movement that would likely occur. For example, + Fz and - Fz forces are better understood as extrusive and intrusive forces, respectively. Thus, each of the graphs is labeled to describe the direction of tooth movement likely to occur above or below the horizontal axis, and the positive and negative signs can be ignored. A point close to the horizontal axis (either above or below) signifies a force or moment with a low magnitude, and a point farther from the horizontal axis (either above or below) signifies a force or moment with a higher magnitude. Furthermore, for each of the graphs, a line representing the incisor bracket is paired with a line representing the molar bracket. These pairings were based on which combination of force or moment components at both of the brackets were most closely related when considering that the force system is in equilibrium.

Figures 13 – 18 show a series of graphs displaying the magnitude and direction of a particular force or moment component versus the a/L ratio in relation to the individual tooth coordinate system. The graphs are grouped by the amount of deflection placed on the wire: 12°, 20° and 30°. Within each figure there are four graphs for each wire size (0.016 inch, 0.016 x 0.022 inch, 0.017 x 0.025inch & 0.019 x 0.025 inch Stainless Steel), and a total of eight graphs representing both moment and force of each bend angle.

The vertical axes are labeled with the direction of tooth movement above and below the horizontal axis. The lines on the graphs are color coded to distinguish the incisor bracket and molar forces and moments and they are labeled with (I) or (M), respectively. The horizontal axes are labeled with the a/L ratio from 0 to 1.0. The lines represent the average values for each bend point, with the standard deviations reflected around each a/L point.

An overall comparison of the effect of archwire size on the force system showed that with increasing both the wire size and the amount of wire deflection both Fz and Mx increased at the two brackets (Figures 13-18). Thereby quantitatively 0.019x 0.025 inch wire bent at 30 ° produced the largest forces and moments for any given a/ L ratio. Within each archwire type, the bends closest to the incisor produced lesser force and moment as compared to the bends at the same distance from the molar tube. Also, as the bend was moved towards the molar bracket, as the a/L ration approached 0.2- 0.3 there was a reduction in the force and moment generated at the individual brackets. Analysis of the Fz curves showed vertical linear symmetry (around the horizontal axis) for the molar and incisor lines. However, the Mx curves did not reveal a symmetrical relationship in any plane. The molar bracket curves were linear, while the incisor bracket curves flattened off as the bend approached the molar bracket.

The alternate hypothesis was accepted. There was a difference in the force/moment system generated in a 3D set up mimicking a 2 x 4 appliance system when compared to a 2D set up. No symmetry was found between the force system at S1 and S2 i.e they were not interchangeable unlike the force system found in collinear brackets. The torsional and bending moments created their own unique force systems at each bracket. The point of dissociation, point of reversal and the neutral points were not consistent with a 2D description of the two- bracket force system

Figure 13: Force graph for 12°

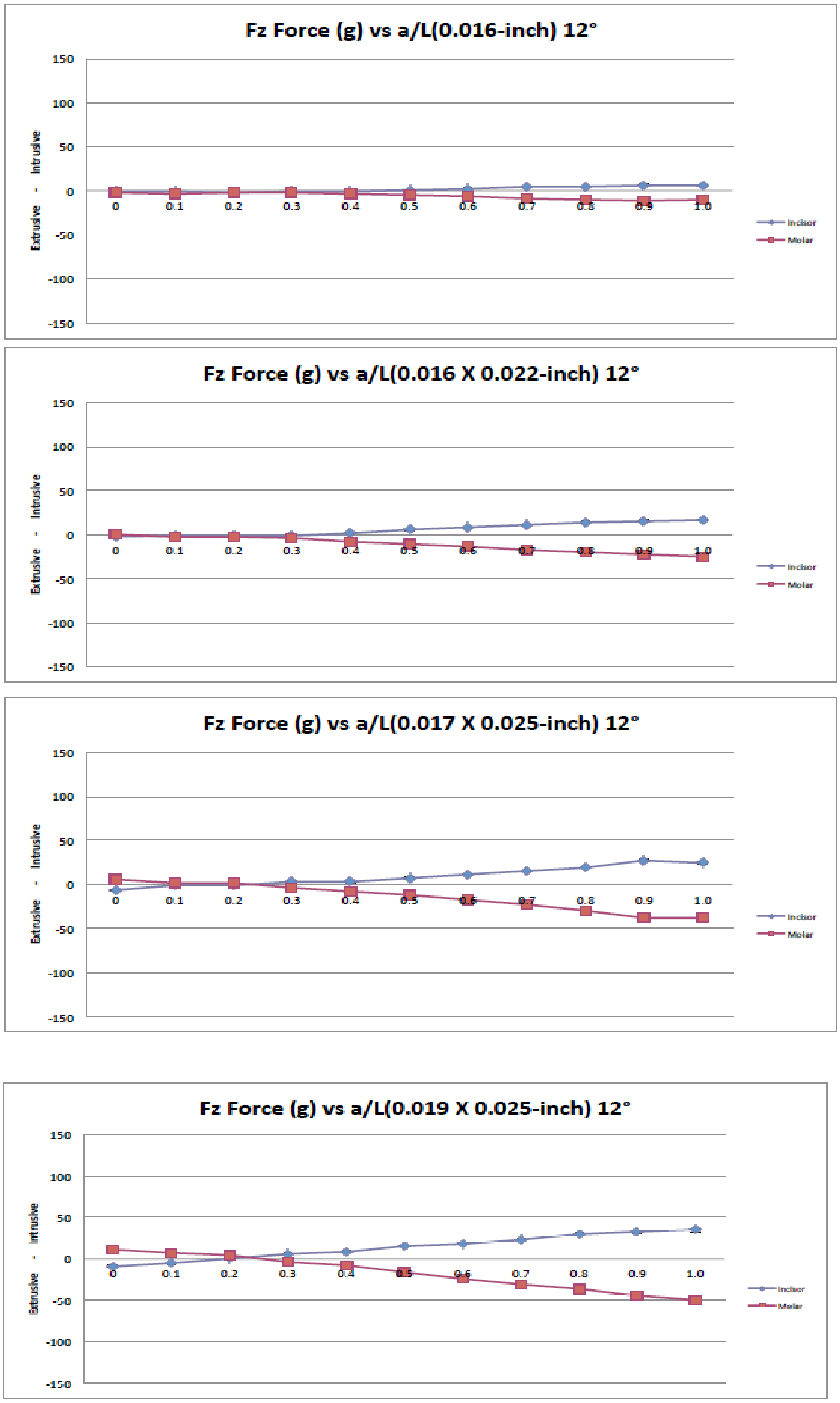
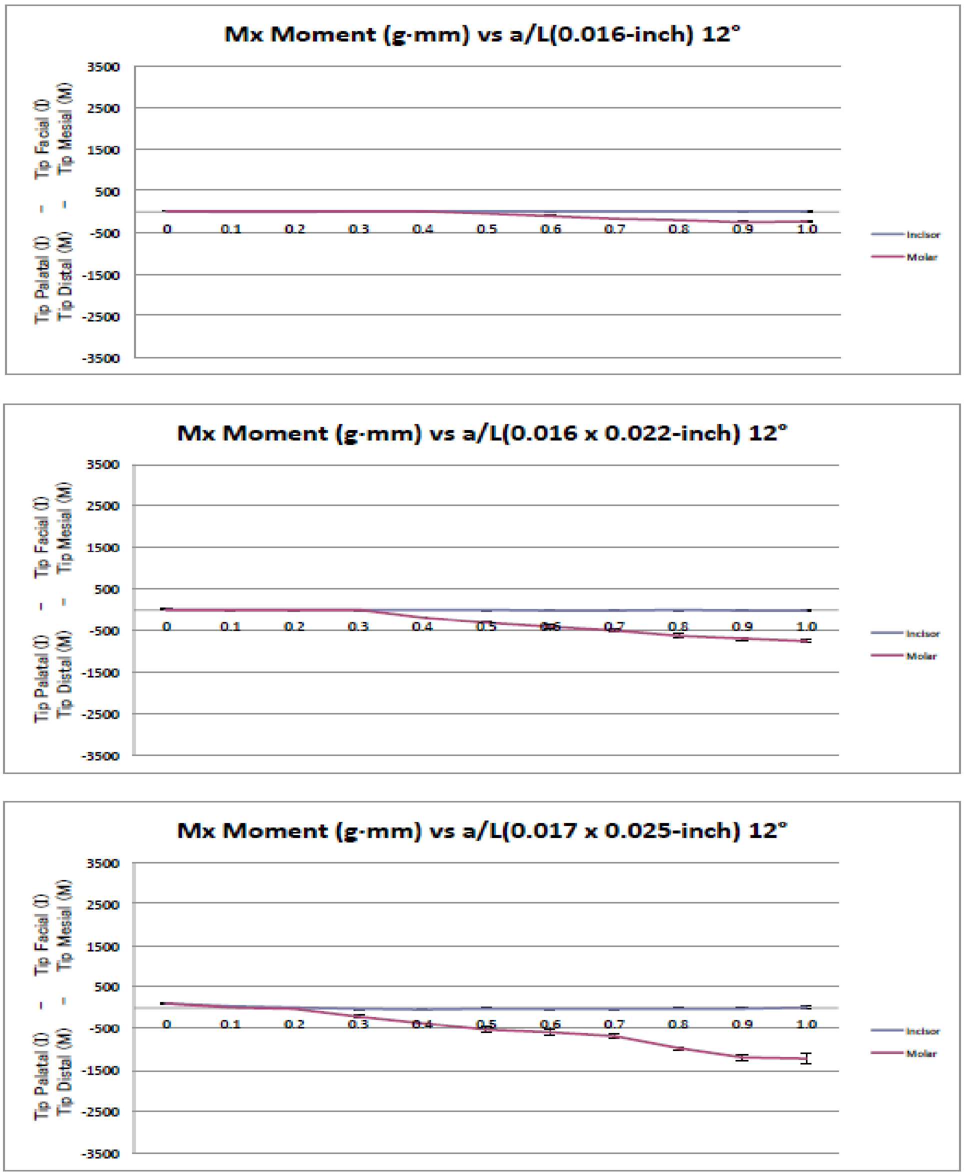


Figure 14: Moment graph for 12°



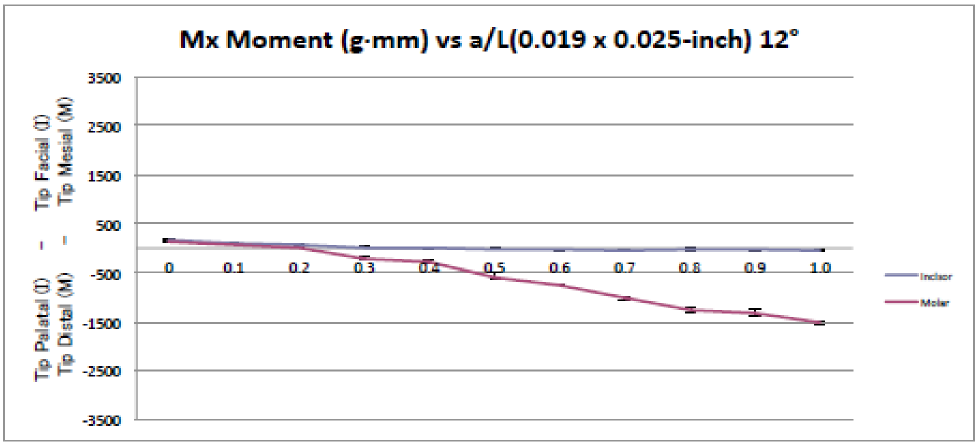
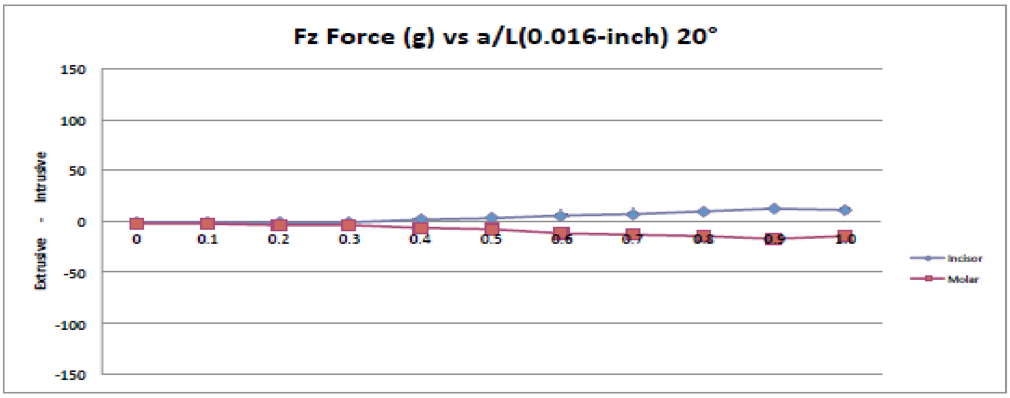
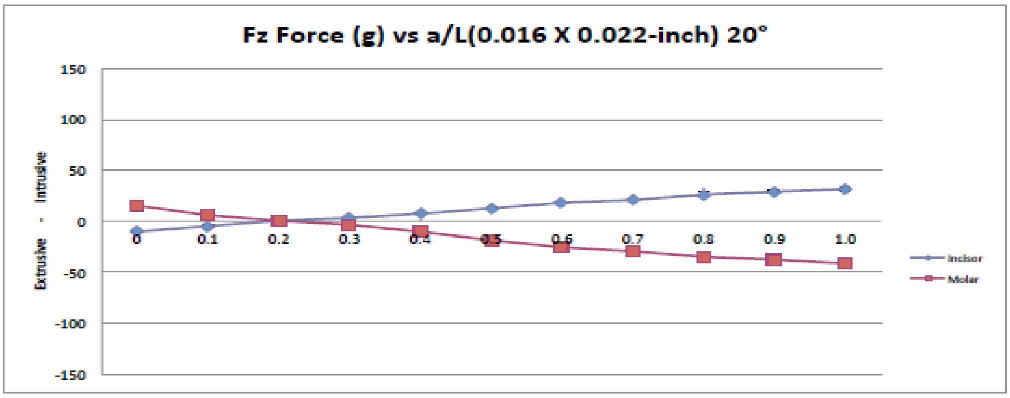
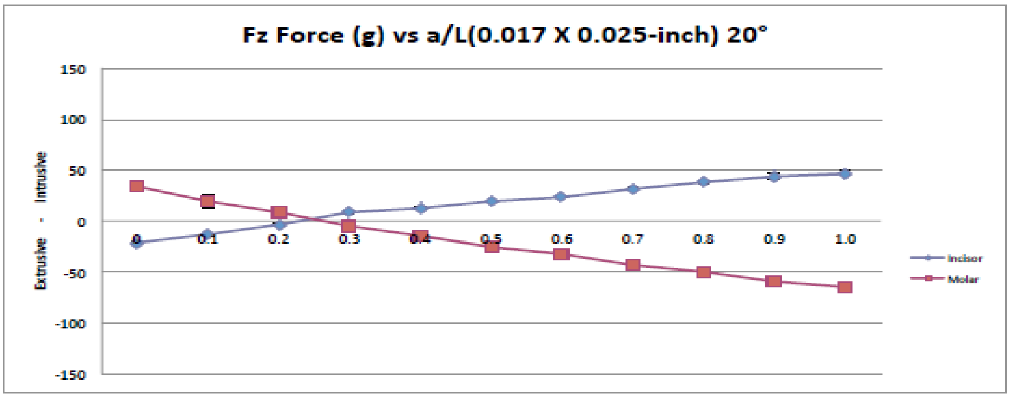


Figure 15: Force graph for 20°


Fz Force (g) vs a/L(0.016-inch) 20°
150
100
50
0
-50
-100
-150
Intrusive - Extrusive
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Incisor
Molar


Fz Force (g) vs a/L(0.016 X 0.022-inch) 20°
150
100
50
0
-50
-100
-150
Intrusive - Extrusive
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Incisor
Molar


Fz Force (g) vs a/L(0.017 X 0.025-inch) 20°
150
100
50
0
-50
-100
-150
Intrusive - Extrusive
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Incisor
Molar

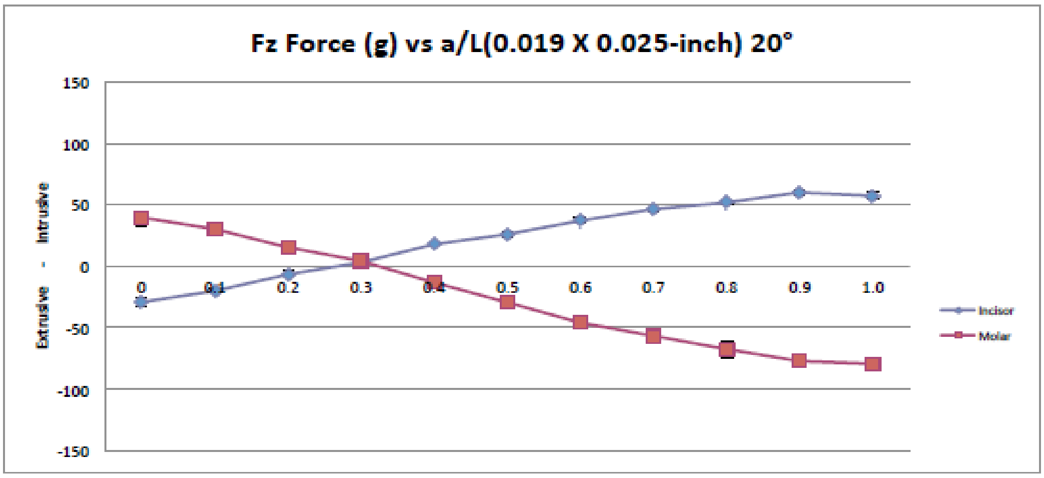

Fz Force (g) vs a/L(0.019 X 0.025-inch) 20°
150
100
50
0
-50
-100
-150
Intrusive - Extrusive
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Incisor
Molar

Figure 16: Moment graph for 20°

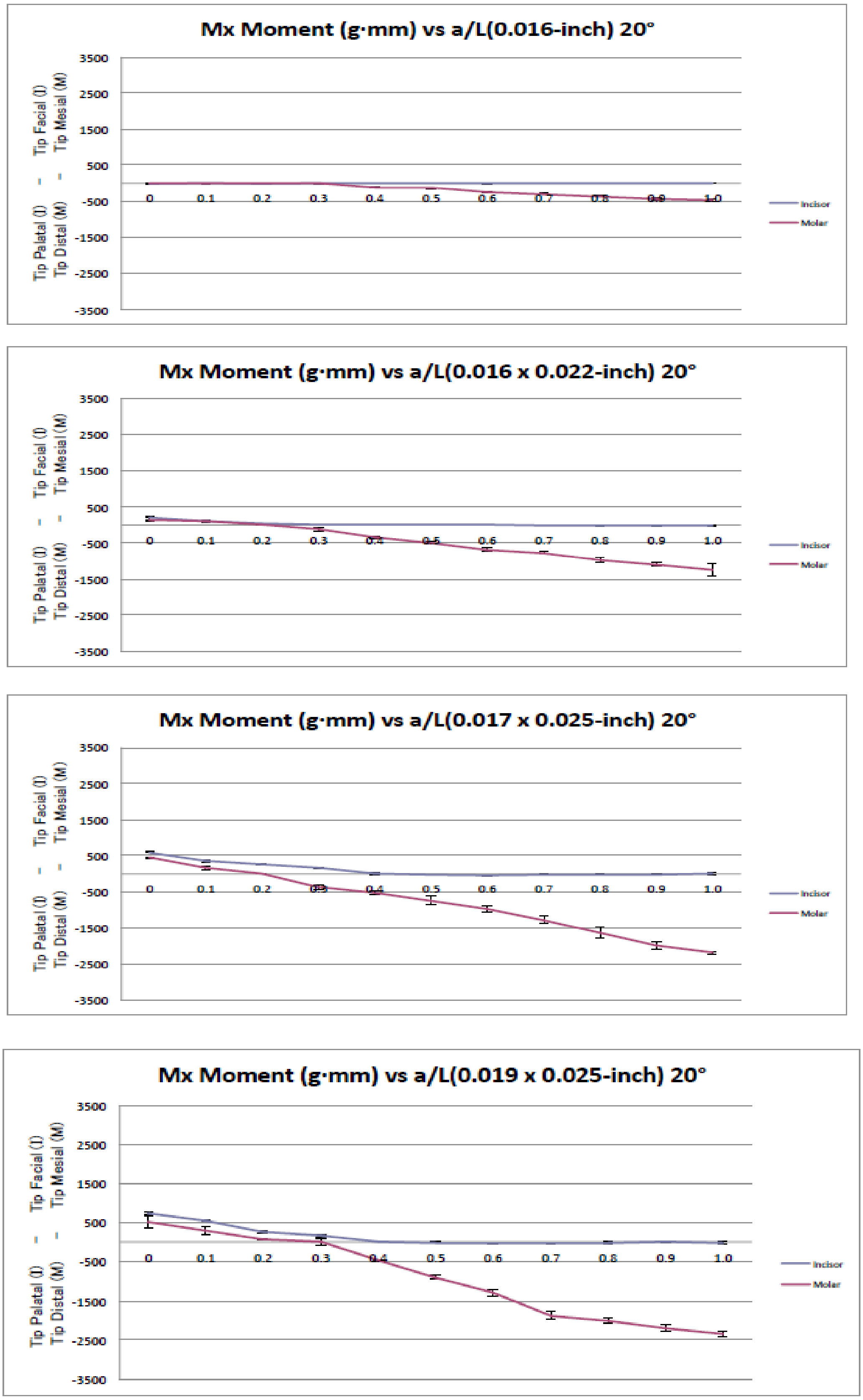


Figure 17: Force graph for 30°

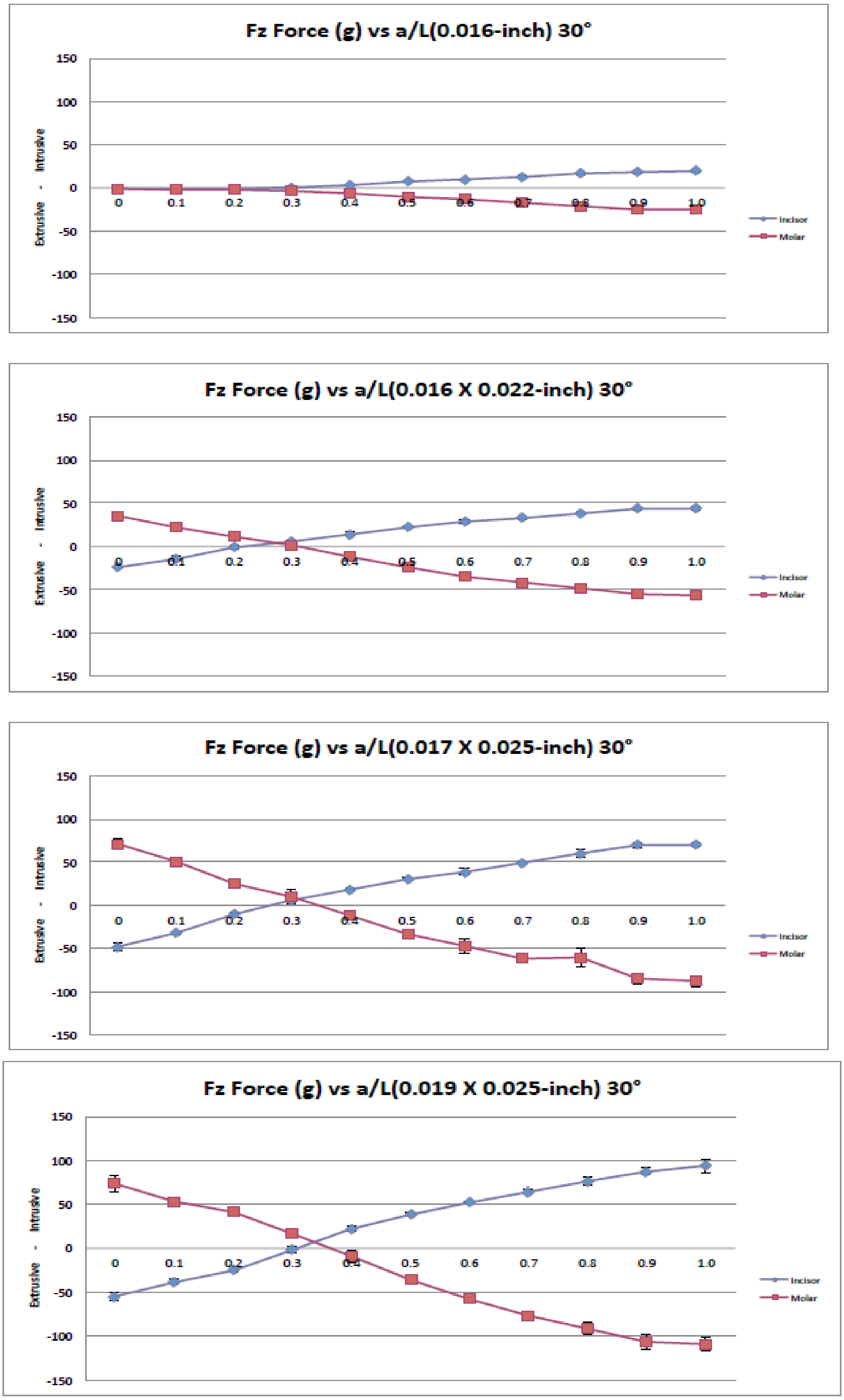
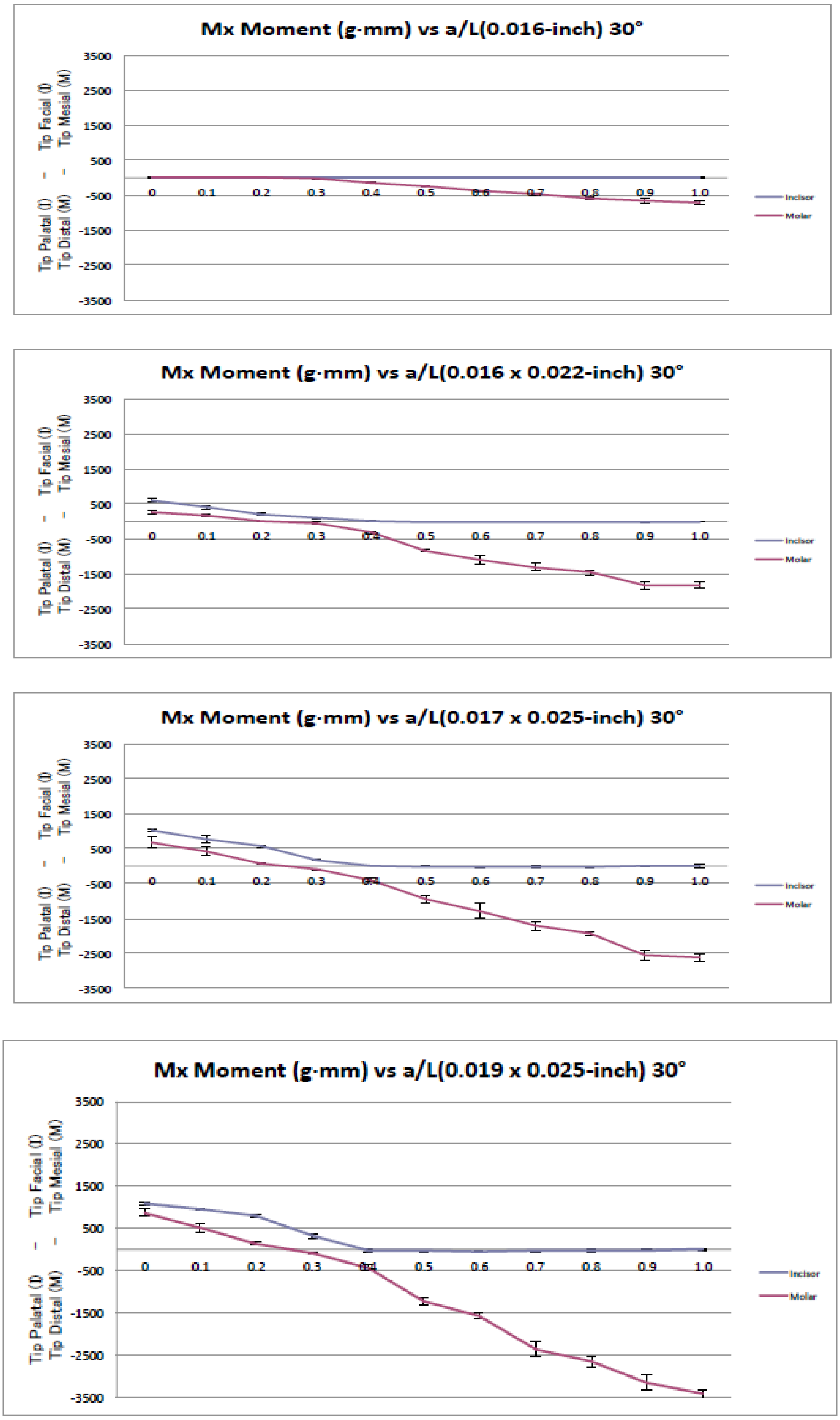


Figure 16: Moment graph for 30°



Discussion:

The focus of this research was to experimentally determine the 3D force systems produced by vertical v-bends of three different amounts tested on wires of four different dimensions with the bends placed at eleven different locations along the interbracket distance of an archwire engaged in a 2x2 appliance.

The methodology of the present study differed from the previous analyses of V-bend mechanics in many ways. This was an in –vitro experimental study rather than employing computer models[3-6] or finite element method[8]. Not only bending moments (second order wire bracket interactions) but also torsional moments (third order interactions) were analyzed at the two brackets. No boundary conditions were imposed.

The results showed significant deviations from the previous data. In symmetrical brackets (Figure 1- 3) the brackets are in the same plane therefore their respective critical contact angles for creating a moment due to a couple is similar. However in our set up the molar bracket was engaged in the second order while the incisor was in the third order, thereby differing significantly in their critical contact angles (Figure 5-7). This asymmetry was primarily responsible for the asymmetrical nature of the force system between the two brackets.

The change in position of the V- bend across the different archwire dimensions produces a distinctive pattern as seen in the graphs (Figure13, 15, 17). The Fz increases both for the incisor and molar as the bend moves towards the molar bracket. This is due to the larger couple produced at the molar bracket and the ease with which the critical contact angle is breached on the molar tube. Again due to the same phenomenon the vertical forces decrease to zero and even start reversing in direction at a/L ratio of greater than 0.3 (Figure13, 15, 17).

The interpretation of the moment graphs further illustrates the non- linear and asymmetric nature of our results in comparison with the previous data. When the V-bend was moved toward the incisor bracket (a/L <0.3) as expected the moment at that bracket (Mxi) increased while it decreased at the molar bracket (Mxm)(Figure 16 , 18). At an a/L of 0.2-0.35 (based on the wire dimension and bend angle) , point of dissociation for the molar was obtained (Mxm≈ 0). Any further decrease in the a/L ratio i.e. movement of the bend towards the insior, resulted in the reversal of the direction of Mxm i.e. it was now in the same direction as Mxi, similar to the results of previous studies. The reversal of moment is a result of the bending properties of the wire in the second order[3]. Bending close to the incisor bracket causes the wire to reverse its direction of curvature as it enters the molar tube (Figure 19). Interestingly as the

V-bend approached closer to the incisor bracket (a/L <0.3) even the magnitude of the moments became similar with Mxm almost equivalent to Mxi.

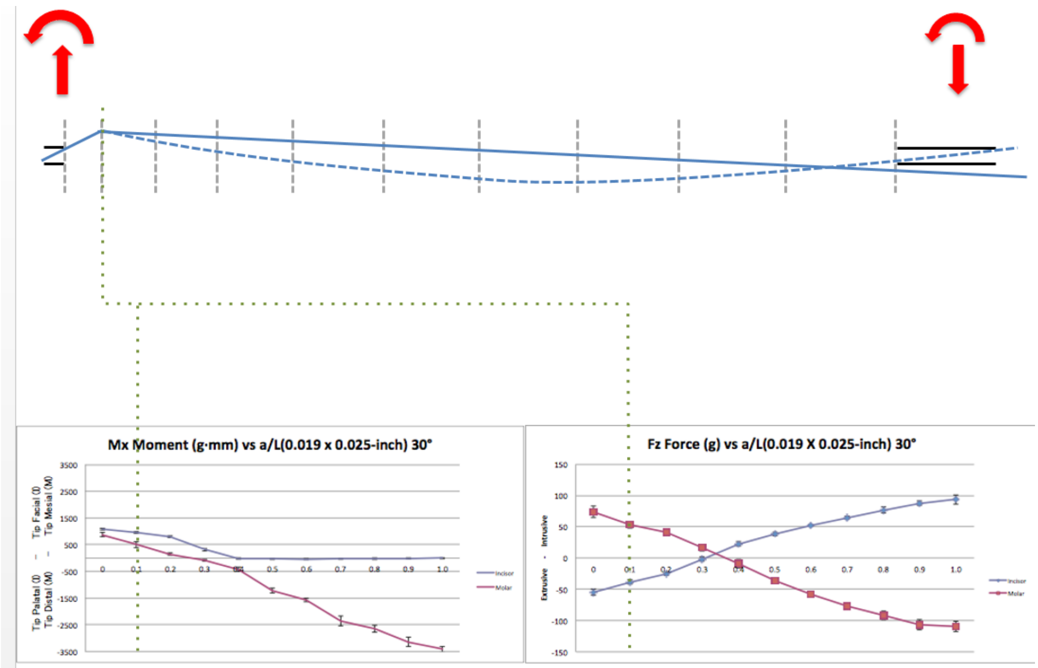


Figure 19

The reversal of the moment never occurs in the incisor bracket. (Figure 20) This discrepancy is due to the second order engagement of the archwire in the molar tube versus third order engagement in the incisor bracket. The moments created at either bracket are a function of the couple forces at the edges of the bracket and the distance between them. This distance is much greater for the molar bracket (bracket length) as compared to the incisor (bracket depth) because of their orientation. This leads to the conclusion that the incisor bracket will have a smaller moment unless the bend is placed sufficiently close to it so that the couple forces are very high, partially offsetting

the lack of distance between them. However high magnitude of couple forces within the bracket slot can increase the local stress on the archwire causing permanent deformation of the anterior leg of the archwire. This was reflected in our experiment by the flattening of the Mxi curve for all archwires.

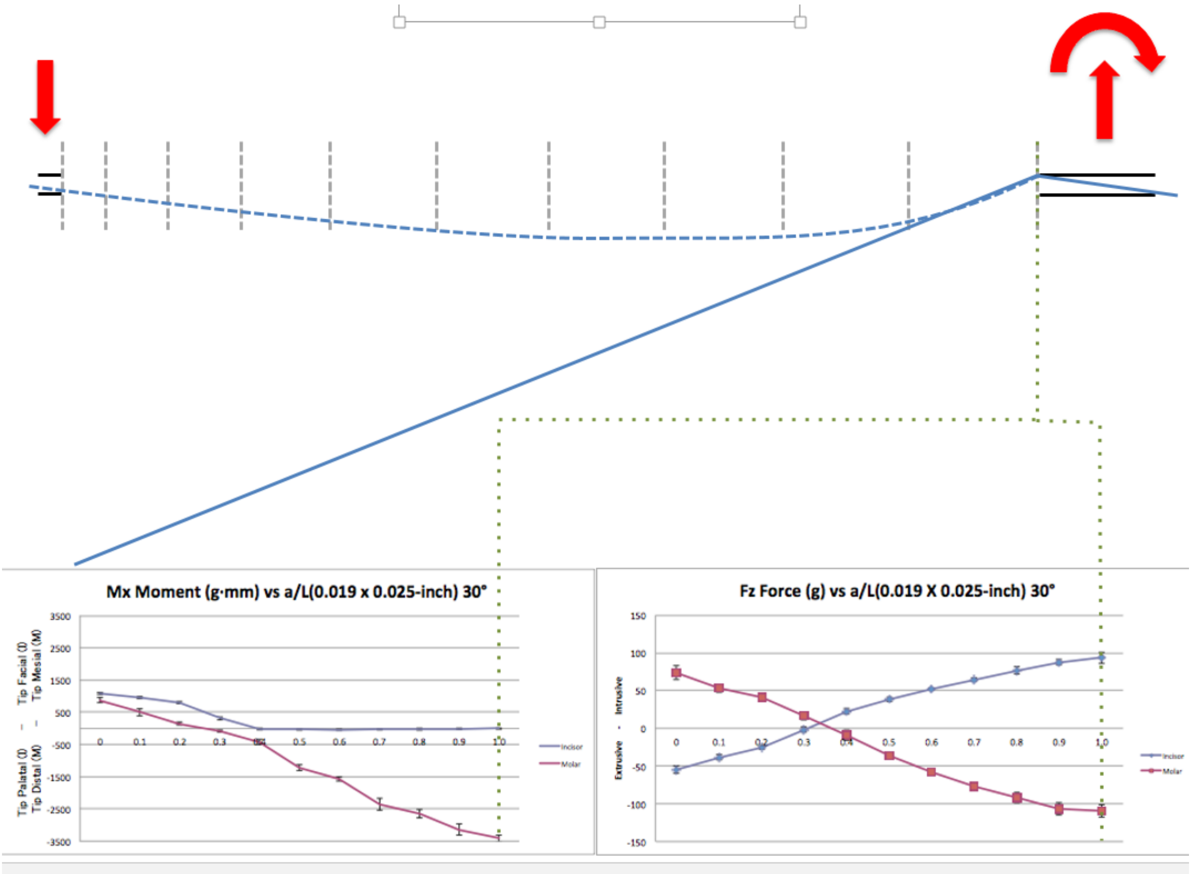


Figure 20

Moment due to a couple tends to increase with an increase in the angle of entry of the archwire into the bracket slot as seen in previous studies and mathematical analysis. The bends placed at a/L of 0.0 -0.3 do not appreciably

change the angle of entry of the wire into the incisor bracket as the bends are primarily in the transverse plane (x-axis) as opposed to the anterio-posterior plane (y-axis) due to the curvature of the wire . When the bend was moved progressively closer to the molar bracket (a/L >0.5) Mxm increased, while Mxi decreased. The point of dissociation for the incisor was observed at an a/L of approximately 0.4, however a point of reversal was not observed i.e. Mxi never reversed in direction as predicted by the 2D model. Instead it became flat (non-linear) and remained close to 0 gm.mm through a/L of 0.4 to1. In other words, the moment on the incisor decreases considerably as the bend is moved away from it but never reverses in direction. Perhaps a more acute bend (<150 degrees) placed very close to the molar bracket is required to reverse the moment direction at the incisor bracket.

The neutral point was found at a/L of 0.2 for wires of either smaller dimensions or smaller bend angles moving up to 0.3- 0.4 for thicker wires with higher deflections. However, they consistently displayed a tendency to be located toward the incisor bracket (Figure 13- 18). Equal and opposite moments in such a set up are only created when the bend is moved closer to the incisor bracket so that the wire is able to engage the edges of the incisor bracket in the third order and generate a moment opposite in sense to that on the molar bracket. Interestingly a projection of the 3D two-bracket set up on a 2D plane further exaggerates this ‘off centering’ of the V-bend (Figure 21). An a/L ratio

of 0.5 when viewed from a buccal perspective is actually located 11.3 mm from the incisor bracket and 18.2 mm from the molar bracket. This has never been taken into consideration in previous renderings of a similar set up.

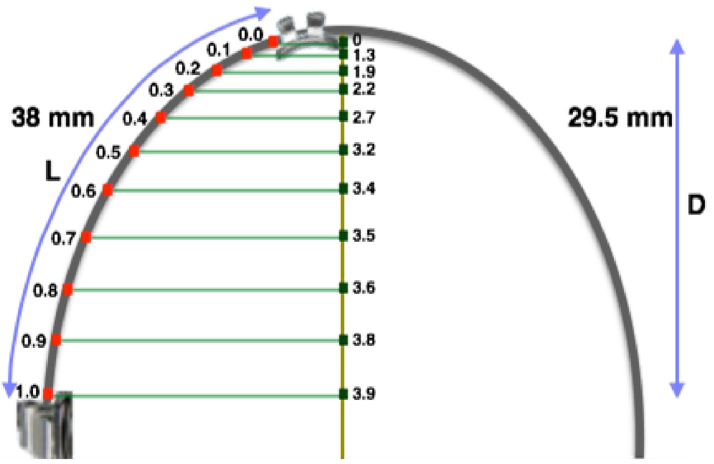


Figure 21

Clinical relevance:

The new 3 D understanding of the two bracket force system leads to some interesting clinical interpretations. Bend placed in a rectangular arch wire of at least 20° at an a/L ratio of 0.0 to 0.3 produces a Mxi and Mxm in the same direction (Mxi / Mxm >0). From a/L of 0.2 to 0.4 (depending on wire size and bend angulation) the moments were opposite in direction (Mxi / Mxm <0). Any bend placed at an a/L of 0.4 or greater created a very small moment at the incisor and a relatively larger moment at the molar tube (Mxi/Mxm ≈0). The synthesis of this data into three distinct F/M systems provides critical insight

into the clinical application of torque/moment over the incisor and molar (Figure 22).

The three zones represented in Figure 22 demonstrate the asymmetry and variation in the force system. Clinical examples are:

1. In situation one- any bend placed upto 15 mm mesial to the molar bracket will not produce any significant moment due to couple at the incisor bracket for the purpose of tipping or torque control.

2. If equal and opposite moments are to be produced the bend cannot be at the center of the two brackets but rather has to be skewed significantly towards the incisor bracket.

3. If we need incisor torque control or flaring the bend has to be very close to the incisor bracket (a/L of 0-0.3) on a relatively full size rectangular wire. This bend zone is also ideal when molar protraction is planned.

4.

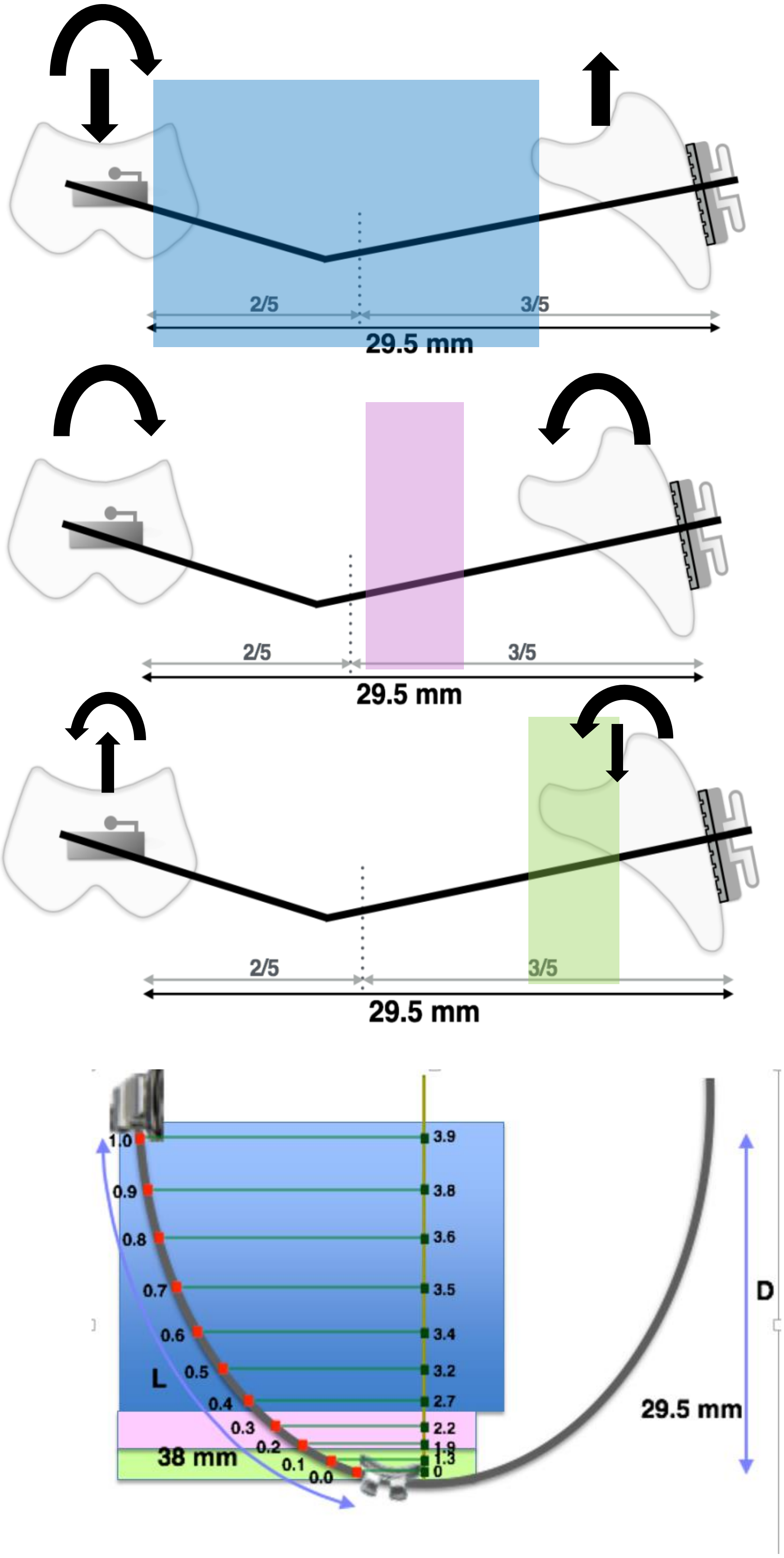

2/5
3/5
29.5 mm
2/5
3/5
29.5 mm
2/5
3/5
29.5 mm
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
L
38 mm
3.9
3.8
3.6
3.5
3.4
3.2
2.7
2.2
0
D
29.5 mm

Figure 22

Conclusions:

1. **A new model for a two bracket force system has been presented which has more universal scope and might have far reaching clinical applications.**
2. The F/M system obtained in this 3D set up was significantly different from previous 2D interpretations.
3. The *force system pattern* created by varying the degree deflection was similar between the different archwire sizes.
4. Changing both the archwire size and the amount of deflection produced significant differences in the magnitude of the force system

Appendix:

The conditions of coplanar (one plane) equilibrium state that sum of all the forces and moments in any plane are zero. The two bracket set up described should therefore satisfy the conditions of equilibrium. Here, the assumption is that the arch is symmetrical, therefore the force system is symmetrical between the right and left sides.

A) Solving for the forces in the vertical axis (z):

$\Sigma F_z^{\rightarrow} = 0.$

Also, $\Sigma F_z^{\rightarrow} = F_z^{\rightarrow}(m) + F_z^{\rightarrow}(i)$

Here, $F_z^{\rightarrow}(m)$ and $F_z^{\rightarrow}(i)$ are vertical forces on the molar and incisor brackets respectively

B) Solving for the moments around the transverse axis (x):

$\Sigma M x\rightarrow = 0$

Or, $Mx\rightarrow(m) + Mx\rightarrow((i) = F_z^{\rightarrow}(m)$ or $F_z^{\rightarrow}(i) \times D$

Here, $Mx\rightarrow(m)$ and $Mx\rightarrow(i)$ are the moments of couple at the molar and incisor brackets around the transverse axis.Please note that $Mx(i)$ and $Mx(m)$ are two unequal couples. Therefore the entire system will have a tendency to rotate in one direction. To maintain equilibrium an additional pair ofequal and opposite forces is oriented to rotate the whole system in an equal and oppositedirection given by the equation: $F_z^{\rightarrow}(m)$ or , $F_z^{\rightarrow}(i) \times d$.

References:

1. Burstone C. Orthodontics as a science: the role of biomechanics. Am J Orthod Dentofacial Orthop 2;117:598-6.

2. Nasiopoulos AT, Taft L, Greenberg SN. A cephalometric study of Class II, division 1 treatment using differential torque mechanics. Am J Orthod Dentofacial Orthop 1992;11:276-28.

3. Burstone CJ, Koenig HA. Creative wire bending--the force system from step and V bends. Am J Orthod Dentofacial Orthop 1988;93:59-67.

4. Burstone CJ, Koenig HA. Force systems from an ideal arch. Am J Orthod 1974;65:27-289.

5. Koenig HA, Burstone CJ. Force systems from an ideal arch--large deflection considerations. Angle Orthod 1989;59:11-16.

6. Ronay F, Kleinert W, Melsen B, Burstone CJ. Force system developed by V bends in an elastic orthodontic wire. Am J Orthod Dentofacial Orthop 1989;96:295-31.

7.Upadhyay M, Shah R, Peterson D, Asaki T, Yadav S, Agarwal S.Force system generated by elastic archwires with vertical V bends: a three-dimensional analysis. Eur J Orthod. 216; Jun:1-7.

8. Isaacson RJ, Lindauer SJ, Conley P. Responses of 3-dimensional arch wires to vertical v-bends: comparisons with existing 2-dimensional data in the lateral view. Semin Orthod 1995;1:57-63.

9. Kusy RP, Whitley JQ. Assessment of second-order clearances between orthodontic archwires and bracket slots via the critical contact angle for binding. Angle Orthod 1999;69:71-8.

10. Kang BS, Baek SH, Mah J, Yang WS. Three-dimensional relationship between the critical contact angle and the torque angle. Am J Orthod Dentofacial Orthop 23;123:64-73.

11. Joch A, Pichelmayer M, Weiland F. Bracket slot and archwire dimensions: manufacturing precision and third order clearance. J Orthod 21;37:241-249.

12. Venkatesan A. Automation of Orthodontic Wire Tester for Performing Three Point Bending Tests. University of Connecticut :DigitalCommons@UConn 211:Master's Theses.

13. Raboud, D.W., Faulkner, M.G., Lipsett, A.W., Haberstock, D.L. (1997) Three dimensional effects in retraction appliance design. American Journal of Orthodontics and Dentofacial Orthopedics,112, 378-392.