Video Article

Force System with Vertical V-Bends: A 3D *In Vitro* Assessment of Elastic and Rigid Rectangular Archwires

Madhur Upadhyay[1], Raja Shah[2], Sachin Agarwal[3], Meenakshi Vishwanath[4], Po-Jung Chen[5], Takafumi Asaki[6], Donald Peterson[7]

[1]Division of Orthodontics, University of Connecticut Health

[2]Private Practice

[3]Department of Orthodontics, University of Melbourne

[4]Department of Orthodontics, University of Nebraska Medical Center

[5]Department of Craniofacial Sciences, University of Connecticut Health

[6]Biomedical Engineering, University of Hartford

[7]Department of Mechanical Engineering, College of Engineering and Engineering Technology, Northern Illinois University

Correspondence to: Madhur Upadhyay at maupadhyay@uchc.edu

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Abstract

A proper understanding of the force system created by various orthodontic appliances can make treatment of patients efficient and predictable. Reducing the complicated multi-bracket appliances to a simple two-bracket system for the purpose of force system evaluation will be the first step in this direction. However, much of the orthodontic biomechanics in this regard is confined to 2D experimental studies, computer modeling/ analysis or theoretical extrapolation of existing models. The objective of this protocol is to design, construct and validate an *in vitro* 3D model capable of measuring the forces and moments generated by an archwire with a V-bend placed between two brackets. Additional objectives are to compare the force system generated by different types of archwires among themselves and to previous models. For this purpose, a 2 x 4 appliance representing a molar and an incisor has been simulated. An orthodontic wire tester (OWT) is constructed consisting of two multi-axis force transducers or load cells (nanosensors) to which the orthodontic brackets are attached. The load cells are capable of measuring the force system in all the three planes of space. Two types of archwires, stainless-steel and beta-titanium of three different sizes (0.016 x 0.022 inch, 0.017 x 0.025 inch and 0.019 x 0.025 inch), are tested. Each wire receives a single vertical V-bend systematically placed at a specific position with a predefined angle. Similar V-bends are replicated on different archwires at 11 different locations between the molar and incisor attachments. This is the first time an attempt has been made *in vitro* to simulate an orthodontic appliance utilizing V-bends on different archwires.

Video Link

The video component of this article can be found at https://www.jove.com/video/57339/

Introduction

An important aspect of clinical orthodontic treatment is the knowledge of the force system produced by multibracket appliances. A clear understanding of the underlying biomechanical principles can help deliver predictable results and minimize potential side effects[1]. Recent years have seen a trend away from placing bends in archwires by building more activation with bracket position and design; however, comprehensive orthodontic treatment still requires placement of bends in archwires. Bends, when placed in different types and sizes of archwires, can create a wide variety of force systems suitable for different types of tooth movement. Although the force systems can become quite complex when multiple teeth are considered, a helpful starting point can involve a simple two-bracket system.

To date, V-bend mechanics have primarily been analyzed in the second order only, utilizing mathematical models[1,2,3,4,5] and/or computer-based analysis/simulations[6]. This has yielded a basic understanding of the force system involved in the second order interaction of the arch wires with adjacent brackets (**Figure 1**). However, these methods impose certain boundary conditions in order to run simulations that might not hold true in actual clinical situations and deviations might occur. Recently, a new *in vitro* model involving force transducers was proposed for measuring three dimensional (3D) forces and moments created by evaluating not only second order archwire-bracket interactions but also in the third order[7]. However, the effect of different types of archwires on the force system at various bend positions along the incisor molar archwire span was not evaluated. Also, the study only involved evaluation of elastic orthodontic archwires, which are not the primary archwires on which tooth movement occurs. Therefore, the aim of this study was to evaluate the force system created by the placement of a V-bend at different locations in rectangular stainless steel and beta-titanium archwires in a 3D set up involving the molar and incisor brackets. Clinicians need to know the force system applied on the dentition when a specific combination of archwire bracket combination is used to fix a malocclusion.

The described technique has been developed to study the orthodontic force system in all the three planes of space, mimicking clinical reality. It is to be understood that it is extremely difficult to measure the force system clinically; therefore, such measurements have to be carried out *in vitro*.

It is assumed that the force system created by a V-bend in the laboratory would be similar if replicated in the patient's mouth. A workflow was created to evaluate how the experimental set up has to be configured (**Figure 2**).

The orthodontic wire tester (OWT) is an innovative product developed by Division of Orthodontics in collaboration with the Bioengineering & Biodynamics Laboratory, UConn Health, Farmington, CT, USA (**Figure 3**). It is designed to accurately mimic the arrangement of the maxillary teeth within the mouth and some intra-oral conditions while providing measurements of the force system created in all the three planes of space. The major mechanical components of the OWT are a Data acquisition device (DAQ), nano Force/Torque Sensors, humidity sensors, temperature sensors, and a personal computer. The testing apparatus is placed in a glass enclosure having temperature/humidity controls. This allows for partial simulation of the intraoral environment. The DAQ serves as the interface for the three sensors: humidity sensor, force/moment sensor, thermistor and the testing apparatus with the sensors situated on a platform (**Figure 3**). These are linked to a software program. The software is a platform and a development environment for visual programming and is used to control different types of hardware. It was chosen to automate the orthodontic wire tester.

A series of aluminum pegs are arranged on the testing apparatus to represent the teeth of the maxillary dental arch. Two of the pegs representing the right central incisor and right first molar are connected to sensors/load cells (S1 and S2). A load cell is a mechanical device that can measure the forces and moments applied to it in all the three planes (x-y-z): F_x, F_y, and F_z; and M_x, M_y, and M_z. The pegs are systematically positioned to create a dental arch form. Each peg is separated from the other by a precisely recorded measurement that is calculated using average tooth widths as observed in patients undergoing orthodontic treatment. The shape chosen for the experiment is an 'ovoid' arch form created from a standardized template.

Protocol

1. Experimental Setup

1. Mark the precise position for the placement of molar tubes and incisor brackets on the aluminum pegs of the OWT by using a customized 'jig'.
2. Bond standard self-ligating brackets with composite material. Light cure for 40 seconds.
3. Insert a 0.021 x 0.025-inch stainless steel (SS) 'ovoid' maxillary archwire into the bracket slots.
4. Place the testing apparatus in the glass chamber.
5. Check for any unintended archwire activation. Any activation of the archwire will automatically create a force system, which will be displayed on the computer screen.
6. Reposition the brackets if any archwire activation is observed. Repeat steps 1.2-1.5.

2. Fabrication of a Template Archwire (Figure 4)

1. Place an archwire (0.021 x 0.025 SS) in the testing apparatus.
2. Use a permanent marker to indicate the following: 1) the midline, 2) a point immediately distal to the incisor bracket (I), and 3) a point immediately mesial to the molar tube (M). Do the same for the contralateral side of the archwire. This is the template arch wire.
3. Transfer the archwire with the marked points to a graph paper.
4. Make a precise replica of the archwire on the graph paper.
NOTE: This graph paper can be used to determine the position of the V-bend for all archwires of the sample.
5. Calculate the perimeter of the arch wire segment (L) from I to M.
6. Now, mark 11 points from I to M. Each point is a future V-bend position.
    1. Label each point from a_0 to a_{10}.
    2. Make sure that each bend position is separated from the other by an equal amount.
7. Obtain a unique number/ratio for each bend position by calculating a/L for each position.

3. Placement of V-bends

1. Take a new archwire from the sample.
2. Place it on the template archwire/graph paper and transfer one of the eleven bend positions bilaterally to the archwire.
3. Use a rectangular archwire plier or a light wire plier to make symmetrical V-bends at both the positions.
4. Place the archwire on a glass slab/flat platform and check the measurement of the angle made by the two ends of the archwire with a protractor.
5. Adjust the ends if necessary so that an angle of 150° is created.
6. Repeat steps 3.1 to 3.5 for all archwires of the sample.

4. Measuring the Force System (Figures 5 and 6)

1. Open the software program for data recording (see **Table of Materials**).
2. Create a new folder for the data to be saved in.
3. Click 'run' to start the software. The program will display each of the three forces and three-moment values at each sensor in real-time.
4. Wait for approximately 10-15 seconds for the fluctuations in data recording software to stop. Ensure that the graph lines on the software for all the components of the force system show a 'flat' line.
NOTE: all six measurements at each sensor will show negligible values (forces < 1 g and moments < 10 g mm).
5. Gently remove the 'testing apparatus' from the platform. Use a Weingart plier to insert an archwire into the molar tubes.
6. Open the door of the incisor bracket with a periodontal scaler.

7. Lift the anterior portion of the archwire and insert it into the bracket slot. Make sure that the midline of the archwire coincides with the midline of the testing apparatus.
8. Return the testing apparatus to the platform and close the door of the glass chamber.
9. Set the temperature at 37 °C. Wait for one minute for the temperature of the glass chamber to adjust.
10. Click the 'start saving' button on the software and allow the software to save/transfer data for at least 10 seconds. Click the 'start saving' button again to end data transfer, then click 'stop'.
    NOTE: Each measurement cycle generates 100 readings over the 10 second period for each component (F_x, F_y, F_z, M_x, M_y, and M_z).
11. Go to the document containing the saved data, and copy/export the data set to a custom designed data analysis spreadsheet (see **Supplementary Table**). Choose the correct V-bend position number and the specific wire sample to insert the data.
12. Repeat steps 4.3 to 4.11 for the 10 archwires of that specific bend position.
13. Now, copy the calculated means and standard deviations for the archwires to a separate spreadsheet to create a graphical representation of the data.
14. Repeat steps 4.2 to 4.13 for all bend positions and types of archwires.
    NOTE: The archwires include, Stainless-Steel (SS) and Beta-Titanium (ß-Ti), with the following sizes: 0.016 x 0.022 inch, 0.017 x 0.025 inch, and 0.019 x 0.025 inch.

5. Error Evaluation

1. Run the computer/software as described in steps 4.1-4.4
2. Remove the 'testing apparatus' from the platform.
3. Obtain a straight length 0.021 x 0.025-inch SS wire. Using a light wire plier, bend one end of the wire into a small hook. Insert the free end of the archwire into the molar tube from the distal side.
4. Place the testing apparatus back on the platform.
5. Attach a known weight (50 g) to the hook. Let it hang freely in the vertical plane by removing any type of interference. Close the door of the glass chamber.
6. Follow steps 4.10-4.11.
7. Repeat steps 5.1-5.6 for the incisor bracket.
8. Enter the Fz values for both the brackets and Mx for the molar tube as 'measured value.'
9. Now apply the equations of equilibrium (see **Supplementary Text**) to calculate the 'expected value.'

Representative Results

The total force and total moment experienced by each sensor at the center of the sensor plate are represented by their three orthogonal components: F_x, F_y, and F_z representing the forces along the x-axis, y-axis, and z-axis, respectively; and M_x, M_y, and M_z representing the moments around the same axes. The initial measurements at the sensors are converted mathematically to the force and moment values experienced by the bracket (**Figure 7**).

A series of graphs displaying the vertical force at the molar (Fz_m) and incisor brackets (Fz_i), moment (mesiodistal tipping) at the molar bracket (Mx_m), and moment/torque (labio-lingual tipping) at the incisor bracket (Mx_i) versus the a/L ratio in relation to the individual tooth coordinate system have been created from the raw data. The a/L ratio represents the mesiodistal position of each V-bend, where 'a' is the distance between the distal edge of the incisor bracket and the apex of the V-bend, and 'L' the distance between the mesial edge of the molar tube and the distal edge of the incisor bracket measured along the archwire (37 mm). An a/L ratio of 0.0 (0 mm /37 mm) represents a bend adjacent to the incisor bracket, and each successive bend (a/L = 0.1, 0.2, *etc.*) is spaced 3.7 mm away from the previous bend ending with a/L = 1.0 (37 mm/37 mm), representing a bend adjacent to the molar bracket. The direction of the force system is indicated by a negative/positive sign. The graphs are grouped by the wire type and size (**Figure 9 and 10**). Each point on the graphs, represent the mean value of ten similar archwires, and the error bars represent one standard deviation above and below this mean. 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.

The vertical forces (F_Z) show symmetric and linear pattern for each of the six wire types (**Figure 8**). Closer the V-bend to either bracket, higher are the vertical forces. As the bend is moved away from the brackets, toward the center, the magnitude of F_Z decreases until a certain point is reached where both forces are approximately zero (neutral zone). As the bend is moved farther beyond this point, F_Z progressively increases. However, the directions of the individual forces (F_{Zm} and F_{Zi}) are reversed. Quantitatively, SS archwires created a significantly greater force system than ß-Ti archwires. Also, higher dimension archwires create larger force systems. Surprisingly, the relative force system created at the two brackets by the archwires both in terms of size and type of archwire is quite similar.

In contrast, the moments (M_X) show a non-linear and asymmetric pattern (**Figure 9**). The flattening of M_{Xi} when V-bends are placed close to the molar tube (a_x/L ratio > 0.6), as well as the reversal of the moment direction in the molar tube (red) from a_x/L of 0.0 to 0.2, was similar for all archwires and perhaps represents a more fundamental nature of archwire-bracket interaction and bracket orientation (second order vs. third order). The ratio of the moment at the two brackets show some specific patterns observed across all archwires tested (**Figure 10**). Bends that are placed close to the incisor (a/L of 0.0-0.3 for ß-Ti and 0.0-0.2 for SS) had both moments in the same direction ($Mx_i/Mx_m > 0$). From a/L of 0.3-0.6 for ß-Ti and a/L of 0.3-0.4 for SS, the moments were opposite in direction ($Mx_i/Mx_m < 0$) (neutral zone). Bends at a/L of 0.6 or greater did not create a significant moment at the incisor (≈0 g mm) but a huge moment was generated at the molar tube ($Mx_i/Mx_m \approx 0$).

Quantitatively, again as with the vertical forces, the magnitude of the moment generated by SS archwire was statistically and clinically greater than those generated by ß-Ti archwires, both with respect to the a/L ratios and the size of the arch wires.

The percent error was calculated by the following equation:

$$\% \; Error = \frac{(Measured \; value - Expected \; value) * 100}{Expected \; value}$$

The % error for weights lesser than 50 g was found to be 5%, and for weights from 50 to 500 g was calculated to be 0.5%.

The neutral zone (equal and opposite bending moments) was found at a/L ratios of 0.3-0.4 for ß-Ti and 0.4-0.5 for SS archwires. At these specific bend locations, the vertical forces are minimal with the moments acting on the incisor and molar brackets opposite in direction. Based on the a/L ratios the force system created by a V-bend between a molar and incisor bracket can be categorized into three different categories (**Figure 11**).

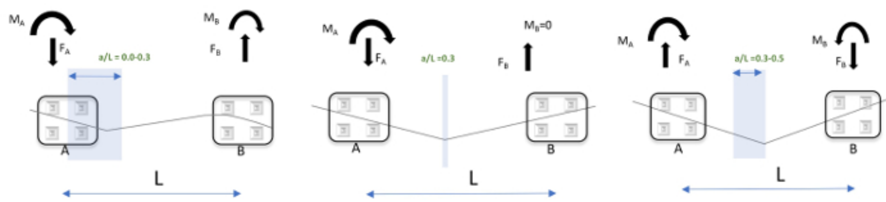


Figure 1: Force system created by two collinear brackets in the second order. L is the distance between the two brackets; a is the position of the V-bend from bracket A; F_A and F_B are the vertical forces created at bracket A and B, respectively; M_A is the Moment at A; M_B is the moment at bracket B. Please click here to view a larger version of this figure.

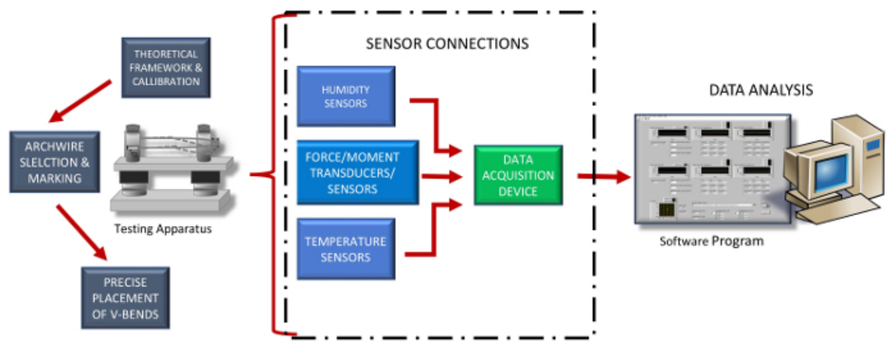


Figure 2: Workflow. Please click here to view a larger version of this figure.

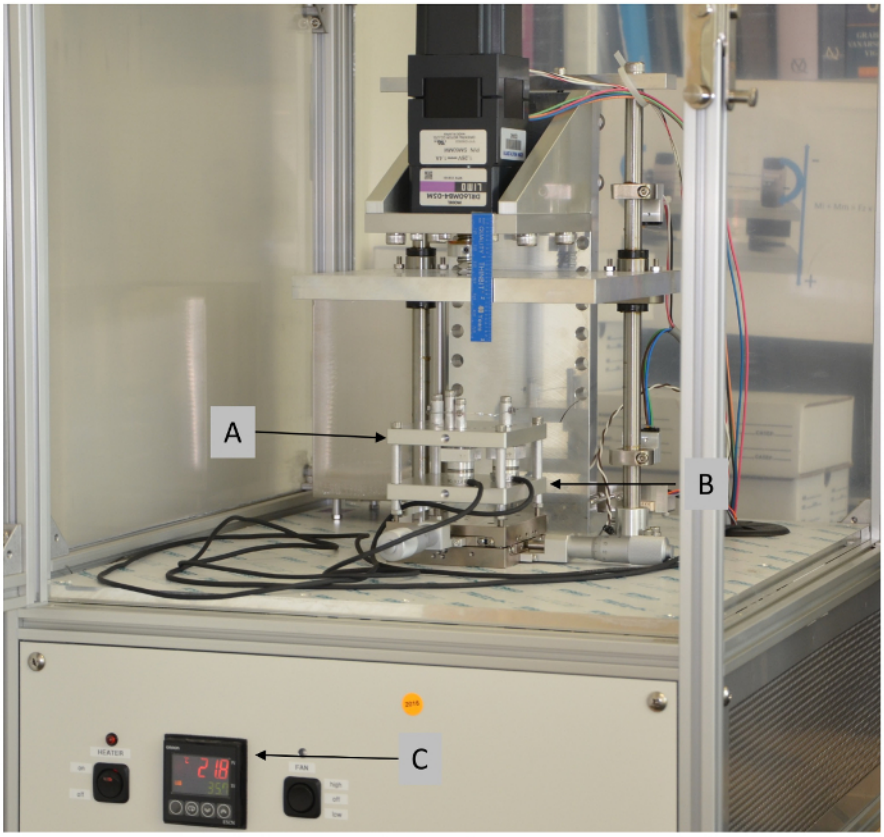


Figure 3: The Orthodontic Wire Tester (OWT). A: Testing apparatus, **B**: measuring platform, **C**: temperature monitor. Please click here to view a larger version of this figure.

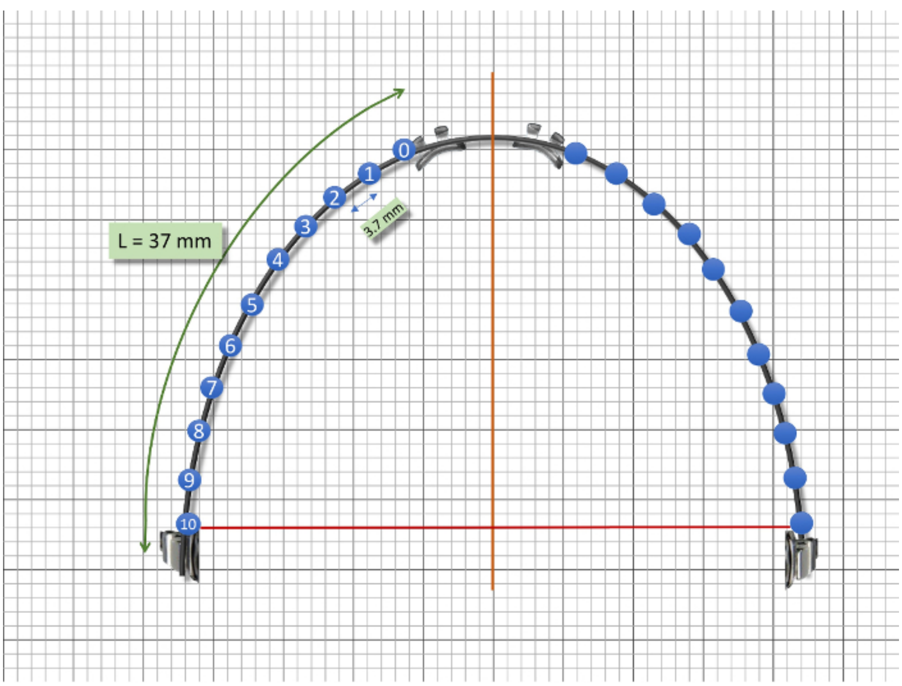


Figure 4: Schematic representation of the bend positions between the two attachments. Every blue dot is a bend location and represents the distance 'a' measured from the incisor bracket along the archwire. There will be 11 different values for 'a' in increments of 3.7 mm. (i.e. blue dot is separated from the adjacent blue dot by 3.7 mm). L is the perimeter length measured from the distal surface of the incisor bracket to the distal surface of the molar tube along the archwire. Please click here to view a larger version of this figure.

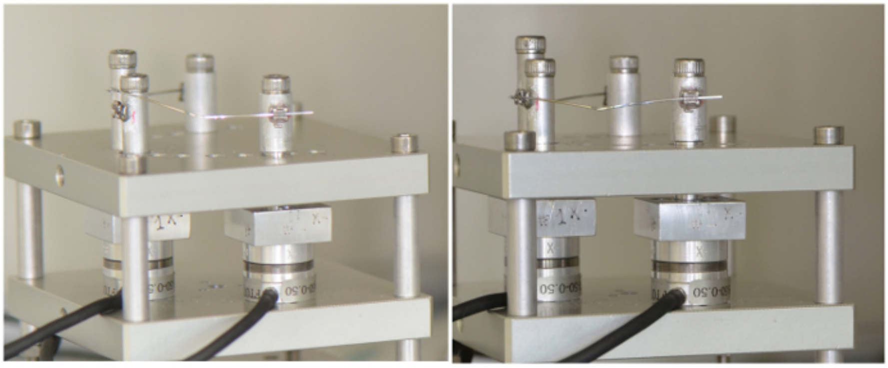


Figure 5: Archwire inserted and held by the brackets on aluminum pegs attached to the sensors. Please click here to view a larger version of this figure.

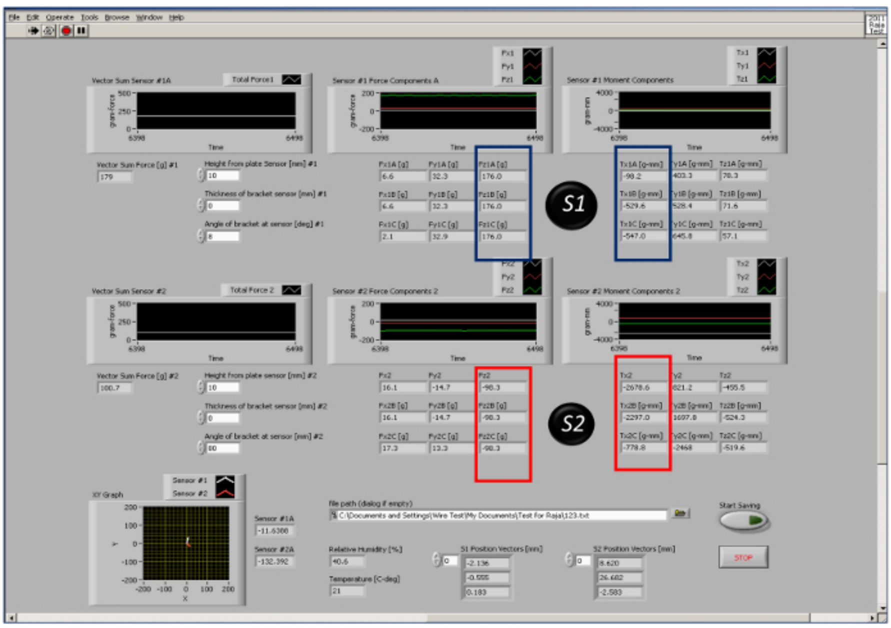


Figure 6: The software program displaying the raw data (in blue and red boxes) obtained from the two sensors (S1 and S2) connected to the incisor and molar brackets. Please click here to view a larger version of this figure.

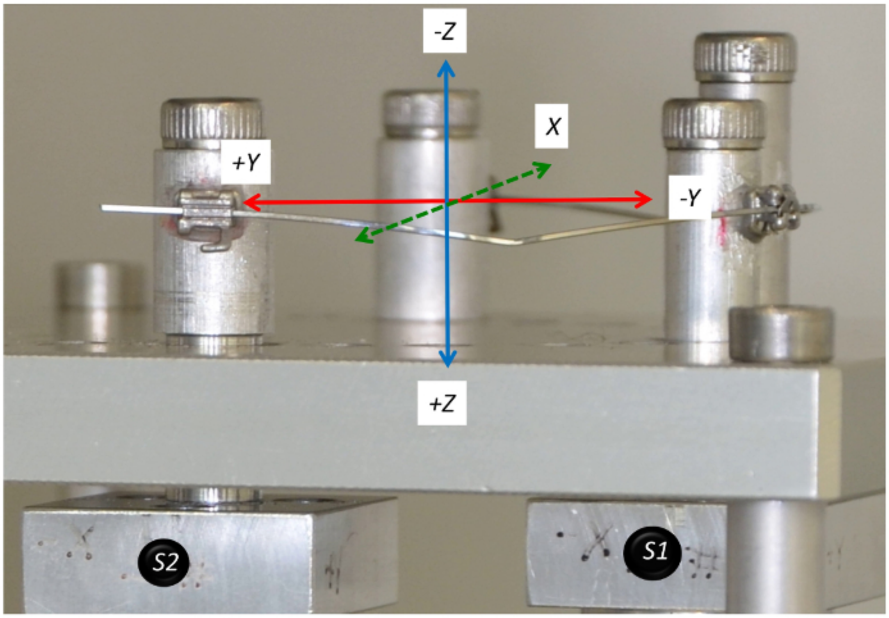


Figure 7: X-Y-Z coordinates and their orientation in relation to the OWT. X: transverse plane; Y: horizontal plane; Z: vertical plane. Please click here to view a larger version of this figure.

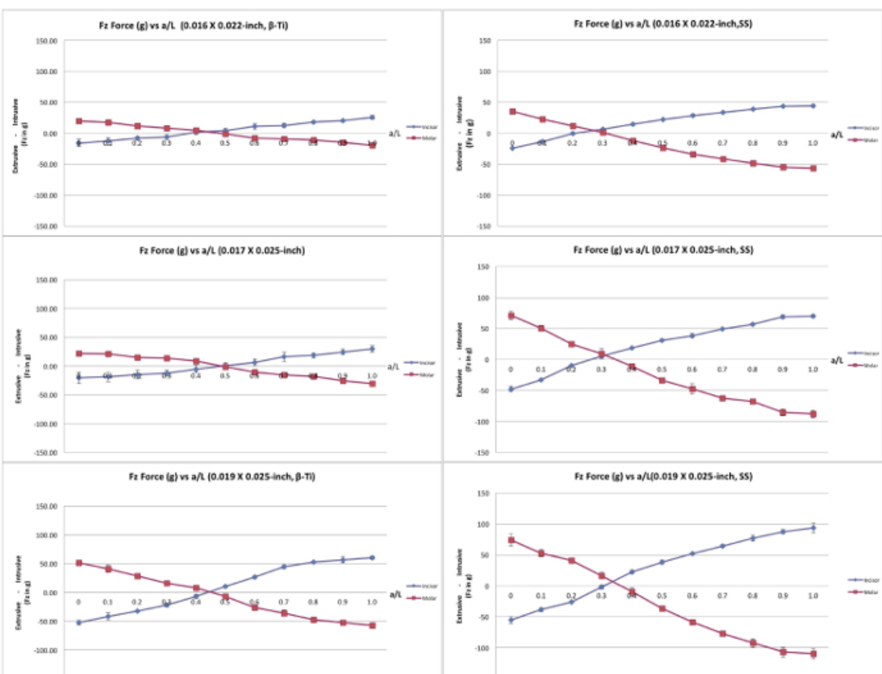


Figure 8: Graphical representation of the vertical force (Fz) at the two brackets. Please click here to view a larger version of this figure.

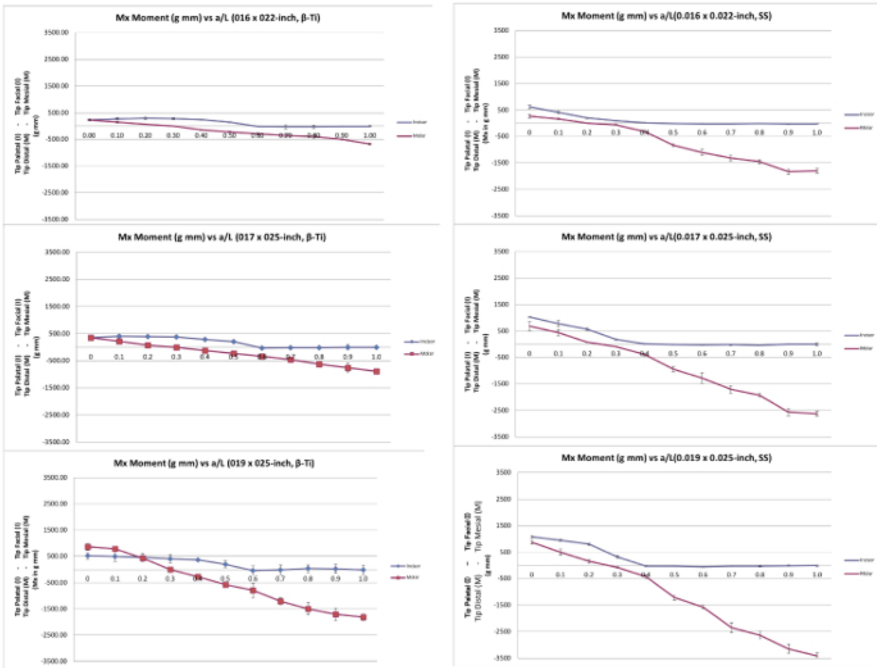


Figure 9: Graphical representation of the moment in the transverse plane (Mx) at the two brackets. Please click here to view a larger version of this figure.

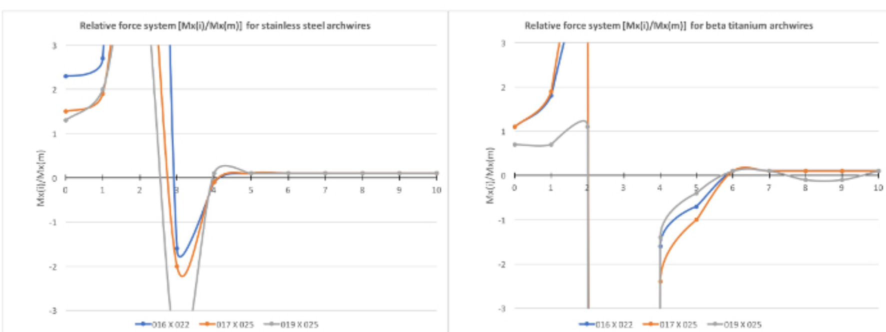


Figure 10: Relative force system across different archwire types and sizes depicted via the ratio of the moments [Mx(i)/Mx(m)]. Please click here to view a larger version of this figure.

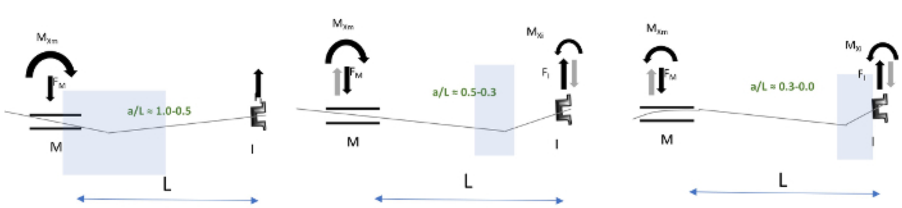
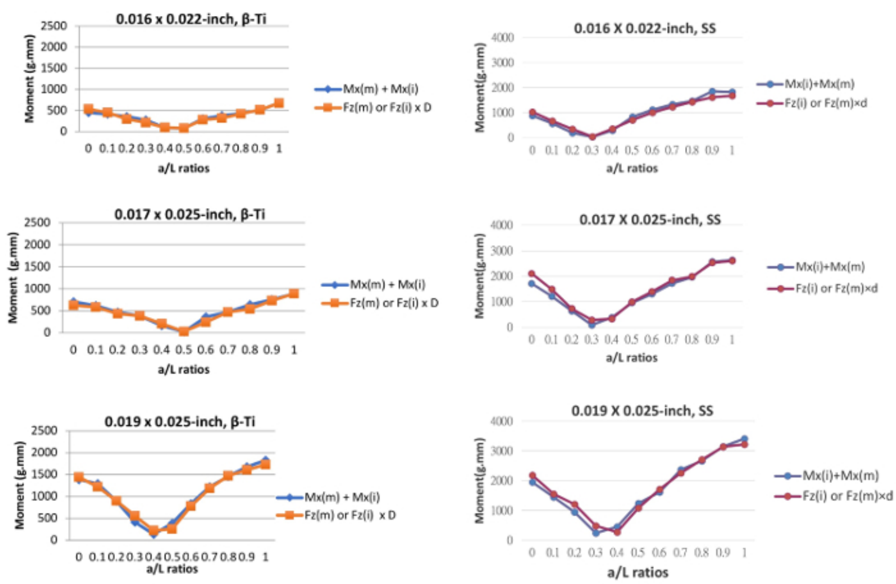


Figure 11: Three distinct force systems from a V-bend. Each zone represents a unique F/M system. The 'blue' shaded region depicts the a/L ratios with similar relative force systems. Please click here to view a larger version of this figure.

Force system	Molar(m)	Incisor(i)
Fz (+)	Intrusive	Intrusive
Fz (-)	Extrusive	Extrusive
Mx (+)*	Mesial tip	Facial/labial tip
Mx (-)*	Distal tip	Palatal/lingual tip
* All measurements were made at the bracket		

Table 1: Sign conventions and direction of the force system.



Supplemental Figure 1: Equilibrium graphs for the moment around X-axis (M*x*). Note: The graphs are only comparing the magnitude of the moments. The direction for $Mx_{(m)}$ + $Mx_{(i)}$ and $Fz_{(m)}$ or $Fz_{(i)}$ x D will always be opposite to each other. Therefore, Σ*Mx*= 0 (See **Supplementary Text**). Please click here to view a larger version of this figure.

Supplementary Text. Please click here to download of this file.

Discussion

Orthodontic archwires have been studied in various ways[8,9,10,11]. They have also been evaluated for various mechanical properties, but they have seldom been analyzed for determining the force system they are going to create[12,13,14,15]. Three-point bending tests are popular for evaluating orthodontic archwires; however, they are generally performed on straight wires devoid of any bends. *In vitro* assessments are generally optimized to look at only 1 or 2 variables at a time which does not allow the outcomes to be readily adaptable to a clinical situation. The focus of this research was to experimentally determine the 3D force systems produced by vertical V-bends placed at different locations along the interbracket distance in rectangular archwires engaged as a 2 x 4 appliance. This protocol differs considerably from the previous methods of analyzing V-bend mechanics. It is the first time that an actual *in vitro* set up has been created utilizing nanosensors mimicking the working of a two-bracket- archwire geometry rather than relying on computer models or finite element methods. This mechanical model not only measures bending moments (second order wire bracket interactions) but also torsional moments (third order wire bracket interactions). No boundary conditions are imposed. In other words, previous studies never accounted for the curvature of the archwire as it goes from the molar to the incisor brackets. Due to this curve, the incisor and molar brackets are not positioned in the same plane, nor are they oriented parallel to one another. This arrangement can add complexity to the analyses of the force systems, which makes them clinically more relevant than those involving just two identical brackets arranged in a straight line and are parallel[3,4].

The functioning of the sensors and the data output can be easily affected by factors like errors from the device, sensor sensitivity, overheating of the OWT, human error in wire activation, bending, ligation, shape, improper wire positioning, deactivation of the wire before final insertion, deformation of the archwire, *etc.* Therefore, it is important to take repeated measurements with new archwires and validate the data by applying the laws of equilibrium. Also, only a few archwires should be inserted for measurement so as to avoid overheating of the OWT.

Each bend position is separated from the other by only 3.7 mm. Therefore, accurate placement of the V-bends along the archwire is also important. Minor deviations from the desired position could radically alter the force system recorded. A custom designed graph paper containing the archwire template with V-bend positions helps in achieving the desired accuracy. Improper bracket positioning on the aluminum pegs could also do the same. Therefore, custom-made precision jigs are used to obtain the position of the bracket if there is a bond failure.

In the event of a bracket getting debonded during experimentation, a new bracket must be precisely placed back in the same spot. Custom designed jigs can help in locating the desired spot. Passive archwires without any bends will have to be used to ensure that the placement of the bracket is correct. If not, it will have to be rebracketed. It is critical not to reuse the debonded bracket as there is an increased likelihood of bracket deformation.

One drawback of the current approach is that only two sensors have been utilized. The addition of more sensors will allow the study of more complex force systems, such as those that include three or more brackets arranged in an arch. Another potential drawback is the inability to simulate the oral environment. Factors such as temperature, saliva, occlusion, and several others could affect the force systems produced. However, at this point is not possible to simultaneously measure the force system and the observed tooth movement at the clinical level.

Computer modeling and simulations involving the use of Finite Element Analysis (FEM) is a rapidly emerging area employed in decoding the biomechanics of various orthodontic appliances[16,17,18,19]. However, one prerequisite to validating these methods is a precise incorporation of complex archwire-bracket interactions and keeping assumptions to a minimum. The archwire-bracket interaction both in the second order and third order are largely unknown, potentially limiting the accuracy of these programs. In order to make the computer simulations better, it is important to first figure out the force system that is present in various clinical situations, generate a sizeable biomechanical database and then make a computer model based on this data set. In other words, better modeling and prediction will require actual experimentation as provided by this protocol.

Disclosures

The authors have nothing to disclose.

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