A MECHANICAL MODEL FOR THE RESOLUTION OF FORCES PRODUCED BY SYMMETRIC AND ASYMMETRIC HEADGEAR

David J. Birdwell D.D.S.

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INTRODUCTION

The use of extraoral traction as a means of effectively applying a distally directed force during orthodontic treatment has become somewhat of a standard within our profession. Headgear today are commonly employed for purposes of anchorage or direct forces for orthodontic and or orthopedic movements. Three main categories exist based on the direction of the traction; high pull, straight pull, and cervical. Each, obviously has advantages and disadvantages depending on the desired effect and the desired compliance of the patient.

Numerous variations of outerbow and inner bow designs exist but the fundamental purpose of all is to deliver the desired direction of force with minimal deterious effects. Variations of every conceivable positioning of the outerbow in relation to the inner bow have been reported to effectively produce the desired effect upon the maxillary first molars. Various designs have also been presented to attempt to effectively produce unequal or asymmetric forces on the right and left sides. The effectiveness of the various designs has been reported but the findings are not all in agreement.

The question of relative effectiveness of various designs and configurations has been approached by numerous investigators. Some have used only clinical impressions as their bases, others using theoretical or mechanical models. Theoretical models have proven difficult to obtain a high level of accuracy due to the complexity of dealing with a nonrigid body. While each offers its own unique advantages and disadvantages, for the purpose of quantifying the various force components produced by various headgear designs, it is the author's opinion that a well designed mechanical model should provide this type of information most accurately. The mechanical model should have the capabilities and flexibility to measure the various force components created when a certain headgear design is employed.

The original intent of this project was to redesign a mechanical model that was constructed a number of years previously by Marenda to determine the effectiveness of various asymmetric headgear designs.[18] Marenda's model allowed measurement of anterio-posterior and medio-lateral forces. Our desire was to elaborate on this and incorporate the capability of measuring the intrusive-extrusive force and the moments commonly referred to as tip and torque on each maxillary first molar. As the project progressed it was deemed necessary to fabricate an entirely new mechanical model that would accurately allow these measurements and at the same time provide more precise data regarding the anterio-posterior and medio-lateral forces.

While our main interest, initially, was in asymmetrically designed headgears, an effort was made to create a mechanical model that could be effectively used to universally study other headgear designs as well. Because of the wide spectrum of past literature concerning headgears, we will limit our literature review to that concerning the unilateral or asymmetrical design.

This project will involve the design, fabrication, and calibration of a mechanical model to allow the measurement of the various forces and moments produced when a headgear is employed. A preliminary analysis of one symmetrical and one unilateral headgear design will also be completed.

REVIEW OF THE LITERATURE

The use of an extraoral appliance for the purpose of supplying a posteriorly directed force to move maxillary teeth can be traced back to Norman W. Kingsley.[1] Original headgear designs can be found in some of his early works dating back to 1866 and apparently this was a widely used technique until the early 1900's. Case[2] also advocated the use of headgear in the early 1900's but at this time its use was waning, being largely discarded for E.H. Angle's "new philosophies" of the day, utilizing intermaxillary reciprocal anchorage.[3]

After a quarter of a century of quiescence , the use of a headgear was again revived by men such as Oppenheim[4], who found many of the effects of intermaxillary anchorage undesirable. Oppenheim utilized what would be considered today a design similar to a high-pull or headcap headgear and found the appliance to be quite efficient in supplying a distally directed force to the maxillary molars. Gould[5] in a later article discussed the same case that Oppenheim used in his earlier report. He notes that not only did the headcap provide a distal movement of the maxillary molars but it did so without distal tipping. Gould indicates that at the end of treatment the molars actually had a mesial inclination. Although, these early reports are based entirely on clinical impressions as opposed to a well controlled study, considerable value has sprouted from these men and their reports.

Epstein[6] in 1946 was one of the first to evaluate the effects of headgear cephalometrically. Although his methods and measurements are not as well refined as those of today, his findings have merit historically. He observed that the upper molar was found posterior to its original position when related to the cephalometric plane, S-N.

His prevailing idea was apparently that the upper molar remained steady while other structures, namely the mandible with its teeth, continued to progress downward and forward in growing individuals. An astute observation on Epstein's part and by some considered to this day to be the most beneficial effect of headgear.

Kloehn[7] is credited with providing the major impetus for the resurgence in the use of headgear. His report of cases utilizing a cervical neckstrap, which he designed and popularized, showed clinical effects of his appliance. Kloehn advocated the ease of construction and use of his design. The distal force provided by this design is fully accepted. The extrusive force on the upper molar provided by this type of headgear design is probably regarded to be the major disadvantage of the cervical headgear. The clinical significance of this force component is still debated today and regarded as the deciding factor on whether to use a cervical neckstrap as opposed to another design. Even with this possible deterious effect, Kloehn's cervical headgear has continued to hold its popularity among modern day practioners. In a recently published poll, headgear of the Kloehn type was reported to be routinely used by approximately 40% of the responding clinicians.[8]

Subsequently, a variety of methods have been designed to employ an extraoral force in conjunction with almost every type of orthodontic appliance. The primary use of extraoral force can be still be categorized into two main uses: (1) to correct dental arch relationships and (2) as anchorage to support teeth that would be displaced while other movements are being carried out. Variations of these uses include situations where a force may need to be eccentrically applied to one molar, such as class II subdivision cases.

In 1953, Baldridge presented a paper entitled, "Construction and Use of Unilateral Headcap with Report of Cases".[9] Two cases were presented in which his unilateral headcap design had been used. Baldridge's original design consisted of a conventional inner bow and outer bow but the soldered connection of the two was offset to the side where the greater force was desired. The finished models showed both molars in a class I relation, however, no explanation as to the theoretic design was provided. With subsequent research and theoretical models, Baldridge's original design was shown to be inaccurate but there still is some debate as to whether the theoretic models do accurately fit the clinical picture. This report did spark the minds of several investigators as to the possibility of utilizing headgear for unilateral forces.

The following year (1954) Block constructed a mechanical model to evaluate the effect of Baldridge's design.[10] Block constructed three headgear with the inner bows made of .045 stainless steel. The inner bows were identical but the position that the outer bow was soldered varied from the midline, to the area of the canine, to the area of the second bicuspid. His mechanical model consisted of elastics to direct the force posteriorly, as the neckstrap. To counter and evaluate this force, elastics were also attached anteriorly to jackscrews. The jackscrews were then activated to return the headgear to its original position. This provided a somewhat qualitative assessment of force distribution since no actual measurements were recorded. Block's findings agreed with Baldridge's and he concluded that the further the solder joint was offset the greater the unilateral force on the side of the solder joint.

Gould[11], in 1957, provided an explanation for the mechanical forces created by the use of a headgear appliance. He addressed both symmetrical and asymmetrical designs. Gould's contribution includes an explanation of the two main types of motions created by headgear on the tooth: (1) translation and (2) rotation. Gould explains how the direction of the force and the relation of the force to the tooth's center of resistance influence whether the movement of the tooth includes pure translational forces and or moments creating rotation of the tooth. Gould in his paper diagramed how the position of the outer bow could be altered to provide the forces desired by the clinician.

Subsequent clinicians have expanded on Gould's original work and provided diagrams and analogies to relay these original concepts.[12,13,14] (fig. 1-2) Gould exhibited an accurate understanding of the basic forces produced by a headgear appliance and he too accepted Baldrige's inaccurate design for a unilateral appliance.

Haack and Weinstein published their first article discussing the mechanics associated with headgear traction in 1958.[15] They discussed the need to keep both the principles of biologic and physical sciences in mind when analyzing the headgear system: "Simply put, the movement of a tooth is the biologic response to the application of a force."[11] They reported that some previous studies had been inaccurate in their understanding of these forces and had only added confusion. Haack and Weinstein provided an intelligible explanation of the forces in static body systems by the use of the three fundamental equations of coplanar equilibrium.

1. The sum of the forces in the X direction equals zero.
2. The sum of the forces in the Y direction equals zero.
3. The sum of the moments about any point equals zero.

With their theoretic models, they demonstrated that the prime consideration in the design of eccentric headgear is the angle formed by the ends of the elastic straps tangent to the neck. The geometry of these angles can be manipulated in such a way that the bisector of that angle passes closer to the molar where the increased unilateral force is desired. Clinically, this can be accomplished by lengthening the outer bow on one side relative to the other. By doing this, a lateral force component is also introduced to the system. A complete discussion of the theoretic design will be reserved for a later time in this paper.

Haack and Weinstein theorized that the design proposed by Baldrige[8] in an earlier work would not provide a true eccentric force in a static model design: "In a statically determinate problem, the internal configuration of a rigid body does not affect the distribution of the external forces on the body". In the same paper they tested their theoretic models with a mechanical model utilizing Dontex tension

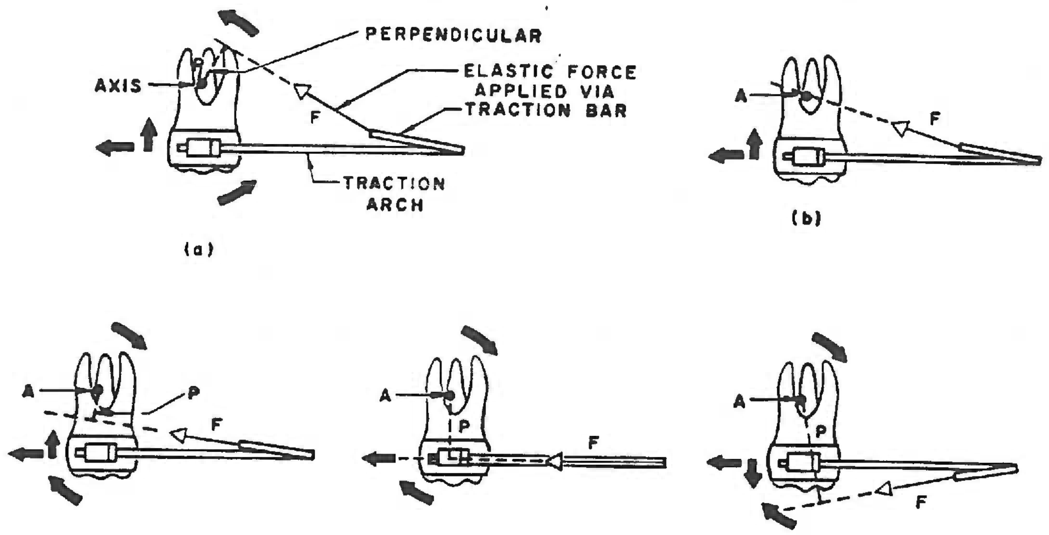


Figure 1. - Motion of upper right molar under headcap anchorage. Approximate position of center of resistance at A. Heavy straight arrows indicate directions of translational movements; curved arrows indicate tipping displacemets.[11]

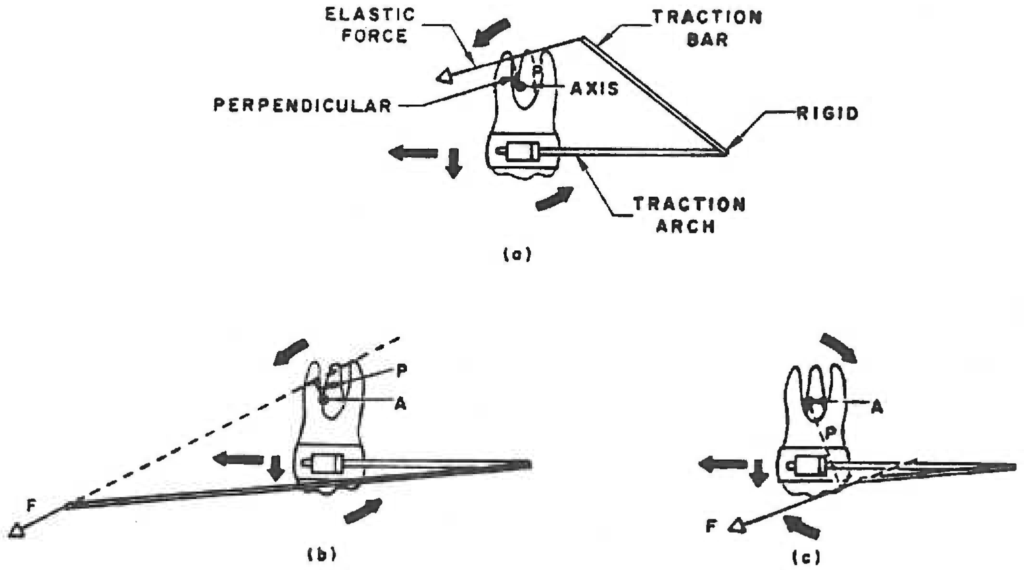


Figure 2. - Motion of upper right molar with cervical anchorage. Heavy straight arrows indicate directions of translational forces; curved arrows indicate tipping displacements.[11]

gauges to measure the distally directed force vector of a headgear applied to a dentiform model. Their findings were commensurate with those that they had theorized. They proposed that the only truly eccentric headgear is one in which the bisector of the angle created by tangents of the neck strap does not lie equal distance from the right and left molars.

Haack and Weinstein provided the following suggestions with regard to the use of an asymmetrical design:

> 1. The differential in length of arms of face-bow need not be great, only sufficient to alter the geometry so that the resultant bisector crosses the molar closer to the more anteriorly positioned molar than to the other. Excessive difference in arms lengths could increase the lateral forces.
> 2. The diameter of wires can be increased for greater rigidity; it is suggested that the arch wire be 0.055 inch and the face-bow 0.075 inch.
> 3. The arms of the face-bow should clear the cheeks so as not introduce more undesirable lateral forces.[11]

Drenker, in 1959, agreeing with Haack and Weinstein's model of force description further explained the system of forces by the use of simple trigonometry. The force produced by the traction on the neck strap (T) can be divided trigonometrically into component forces by using the angle O created by the relation of T to the sagittal plane. The posteriorly directed force is equal to TcosO. In an eccentrically designed system the right and left O's are of different magnitudes, therefore creating unequal values for the distal force components on the right and left side. By creating a design with different right and left O's the line of action is moved off the center sagittal plane and closer to one molar where the increased distal force is desired. Drenker also added that by bending the long arm of the face bow out away from the patient the force difference is increased due to a larger difference in the O angles. Also, deducing from this relation of the right and left O's and their component force vectors it can be easily seen that when right O does not equal left O a resultant lateral force is also introduced to the system.

Baldridge, not convinced that his original design was flawed, conducted a clinical experiment to prove the effectiveness of his offset solder joint. He tested his original design, a symmetrical design, and a power arm design by placing open-coil springs on the inner bow of a patients headgear to which a stop had been soldered to prevent the springs from sliding forward. If unequal forces were created at the molars he deduced that the springs would be compressed different amounts. To his disappointment, he found the springs were not compressed different amounts on the offset solder joint or the symmetrical design.[16]

Kloehn in 1961 published another paper of his clinical successes utilizing his cervical headgear design.[17] Kloehn states, "The essential requisite for successful treatment with any extraoral appliance is sufficient force, applied over sufficient time, in the desired direction." This paper, also of a qualitative nature, surely further embedded the use of this increasingly popular appliance.

From the early 1960's the literature concerning headgear appliances can be said to have taken two avenues; (1) an emphasis on cephalometric and model evaluation to determine the direct effectiveness of headgear designs on the patient, including distalization of molars and influence upon growth direction, and (2) studies with theoretic and laboratory models to evaluate the forces generated with various headgear designs. The latter is the avenue this review will follow since it is felt this project would also be included with this group.

In 1963 Haack[18] published a subsequent article discussing the mechanics of headgear. He presented mathematical calculations for the unilateral headgear design with one arm longer than the other. He applied actual numerical numbers to the dimensions and vector quantities to the forces. His calculations showed that by lengthening one arm an inch and one half it was possible to obtain 2.86 times the force on that side. He also calculated the net lateral force that is introduced with this type of headgear design.

Marenda in an unpublished thesis at the University of Oregon, devised an eloquent but simple mechanical model to verify the theoretical models of Kloehn headgear forces.[19] Marenda studied one symmetrical headgear design and four various asymmetrical designs including the controversial offset solder joint and the one arm lengthened designs. All were constructed with an outer bow of .063 inch and an inner bow of .045 inch in dimension. Each design was tested ten times with forces ranging linearly from 100 to 1100 grams. Marenda's conclusions, contrary to Haack and Weinstein, showed the offset solder joint to be efficient in delivering an unilateral force throughout the whole range of forces applied, whereas the design with one arm lengthened by one and one half inches was not efficient in delivering an appreciably eccentric force unless the lengthened arm was also bent outward one and one quarter inches. Marenda concluded that although Haack, Weinstein, and Drenker's theoretic models in analyzing a headgear design are correct when considering a rigid body, the use of rigid body mathematical calculations may not accurately describe the asymmetric headgear in the wire diameters most often used clinically. With these smaller wire diameters flexion of the inner and outer bows may be of a significant amount to alter the forces diagrammed.

Several authors have contributed articles which help with our understanding of the forces involved in headgear systems by presenting visual and mathematical diagrams that expand on those previously mentioned. These will be presented for sake of our basic understanding. Let us first proceed with some fundamental definitions of the mechanical principles involved:

> Center of Resistance. That point in a body through which the resultant of constraining forces acting upon it may be considered to act. A fixed point within a body dependent upon its shape and support.

Center of Rotation. The center of rotation of a body is that point around which the body will rotate or tip. The center of rotation of a body can be changed dependent upon external force application.
Force Resolution. Forces may be resolved into component vectors which in a single plane of space are at right angles to each other.
Line of Action (Line of Traction). The line of action of a force is usually represented by an arrow and is the direction in which the force acts.

Burstone in 1962 clarified that the point of greatest resistance or the center of resistance of the upper first molar tooth is located in the middle third of the root near the junction with the cervical third, approximately at the trifurcation of the roots.[20] When the line of action of an applied force passes through the center of resistance, no tipping of the tooth will occur. The tooth will, however, tip if the force does not pass through the center of resistance. The tipping takes place around the center of rotation which is not a fixed position on the tooth and will vary according to the relationship of the line of action of the force to the center of resistance of the tooth. (fig. 3)

The force system involved in the Kloehn headgear is considered active in three mutually perpendicular planes (fig. 4):

a. Sagittal plane in which the distal force component acts.
b. Coronal plane in which the vertical force component acts.
c. Transverse plane in which the lateral force component acts.

In a headgear system where the force does not pass through the center of resistance of the tooth, a tipping component or moment is also present in each of these three planes.

Gould, Oosthuizen et al., Greenspan, Jacobsen, Baldidni, and Hershey et al. have clearly shown diagrammatically and mathematically the effects of various outer bow configurations.[4,21,22,23,24] Oosthuizen defines the line of traction of the force as, "... that line connecting the point of origin of the force to the attachment on the outer bow." and "The site of the point of origin of the force is relatively fixed by the position of the neckstrap..." They state that the inclination of the line of traction can be altered only by

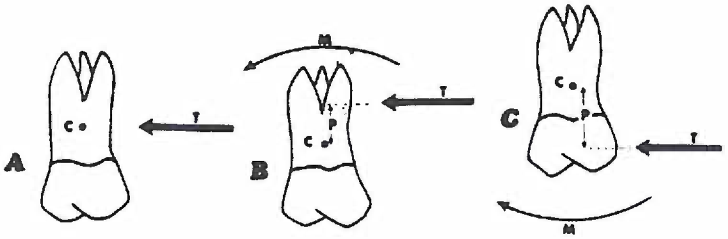


Figure 3. - C, Center of resistance. T, Tension (line of action of force). P, Perpendicular distance. M, Moment.[13]

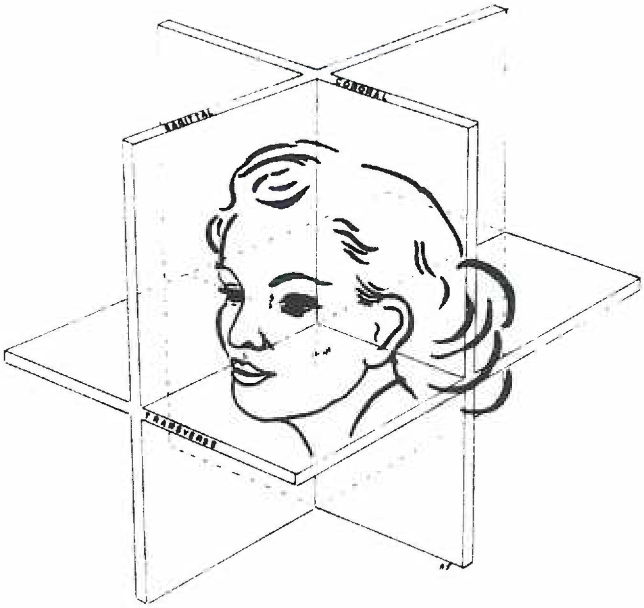


Figure 4. - Three planes of space in which headgear forces may act.[13]

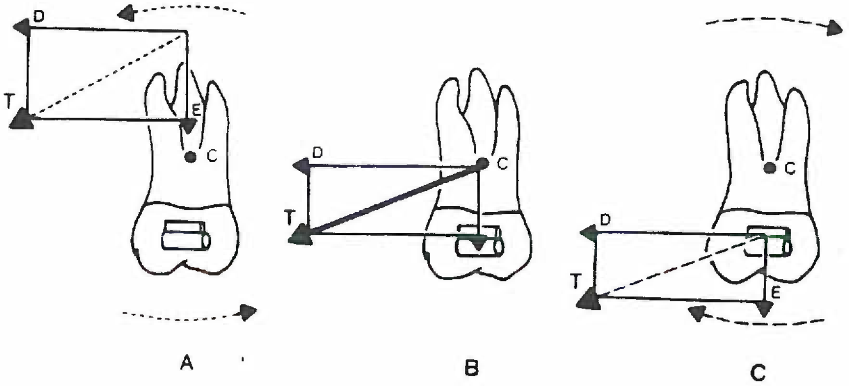


Figure 5. - The extrusive component is present with mesial crown tipping (a) no tipping (b) and also with distal crown tipping (c).[21]

variations in the position of the outer bow hooks either by lengthening and shortening or by bending them up or down. A line of traction passing superiorly to the center of resistance will produce a counter clockwise tipping or distal <u>root</u> tipping of the tooth whereas a line of traction passing inferiorly to the center of resistance will produce a clockwise rotation or distal <u>crown</u> tipping.

Variations in the length of the outer bow as stated above will effect the relation of the line of traction to the center of resistance. The very short outer bow (shorter than the first molar tube) is not versatile when used with a cervical strap since it is not possible to achieve a line of traction which passes through or above the center of resistance. Therefore this appliance is limited to producing a distal crown tipping effect. The tipping force created can be defined in the following equation:

$$M = T \times P$$

Where M is the moment produced, T is the tension in the neckstrap, and P is the perpendicular distance from the center of resistance to the line of traction.[17] As can be seen from this equation the tipping force generated increases proportionately to the distance the line of traction is moved away from the center of resistance. When the line of traction lies at the center of resistance, $P = 0$ and no tipping force is present. A medium length and a long outer bow can be constructed to pass through, above, or below the center of resistance.

The position of the outer bow in relation to the point of origin of the force will vary the extrusive force that is present. As long as the line of traction has a positive slope, an extrusive force will be present. Since the center of resistance of the tooth is positioned superiorly to the point of origin of the force a positively sloped line of traction is seen unless the outer bow is bent down so that the hooks lie at the same level as the neck strap. This obviously introduces a large distal crown tipping moment. Conversely, when the outer bow is bent upward in relation to the center of resistance the steepness of the slope of the line of traction is increased and the extrusive force vector is increased. The extrusive force with a Kloehn headgear can exist with the outer bow positioned above, at, or below the center of resistance. Mathematically this can be viewed by the resolution of the line of traction force into right angle Y and X axis components. Consider angle phi created by the intersection of the line of traction with the transverse plane. In the parallelogram of forces:

Line of traction = hypotenuse of the triangle
Extrusive force (E) = Tsin phi
Distal force (D) = Tcos phi

If T is constant then E is directly proportional to sin phi and D is directly proportional to cosine phi. Obviously the distal force provides the most valuable clinical significance. (fig. 5)

In the transverse plane the forces can also be resolved to gain an appreciation for the effects of various designs in the X and Z axis. Two slightly different mathematical analysis have been used to describe the relation of the inner and outer bow forces. Both will be reviewed for the sake of completeness. Note, however that both of these models were only two dimensional and include forces in the X and Z axis and exclude any force components or effects in the y axis (intrusive-extrusive). We must first define a number of items prior to reviewing these analysis. The labeling of forces, planes, and points have been homogenized into the following list from both analyses that will be reviewed. (fig. 6-7)

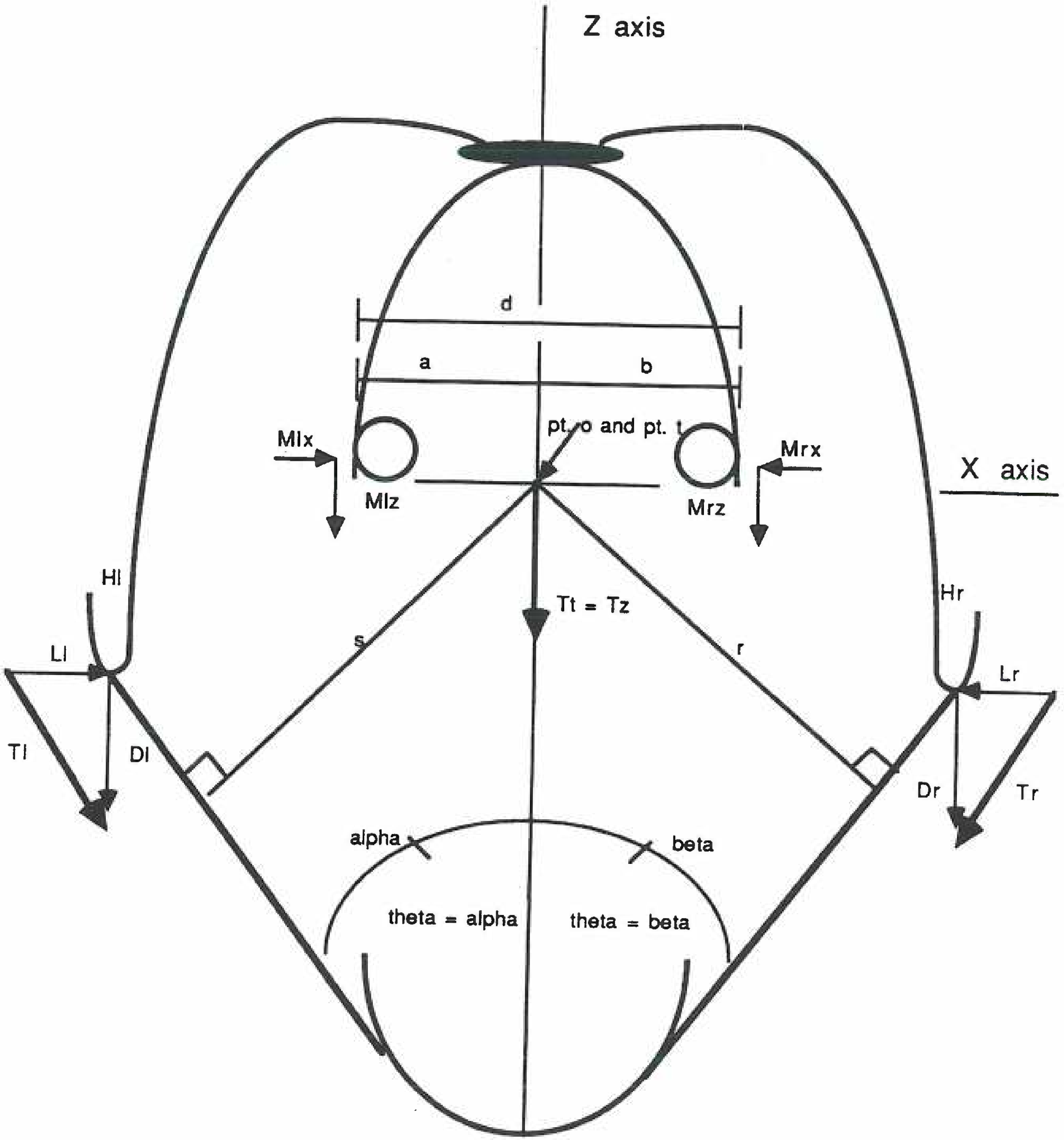
We can first label the planes and points:

X = the axis passing through the distal terminal end of each inner bow and perpendicular to Z.
Z = the axis of the intersection of the midsagittal plane and the transverse plane.
o = the point of intersection of the X axis and the Z axis.
t = the point of intersection of the X axis and the resultant force (T_t). Note: In a symmetrical design pt. t = pt. o
h_r= right outer bow hook. (point of right force application)
h_l= left outer bow hook. (point of left force application)

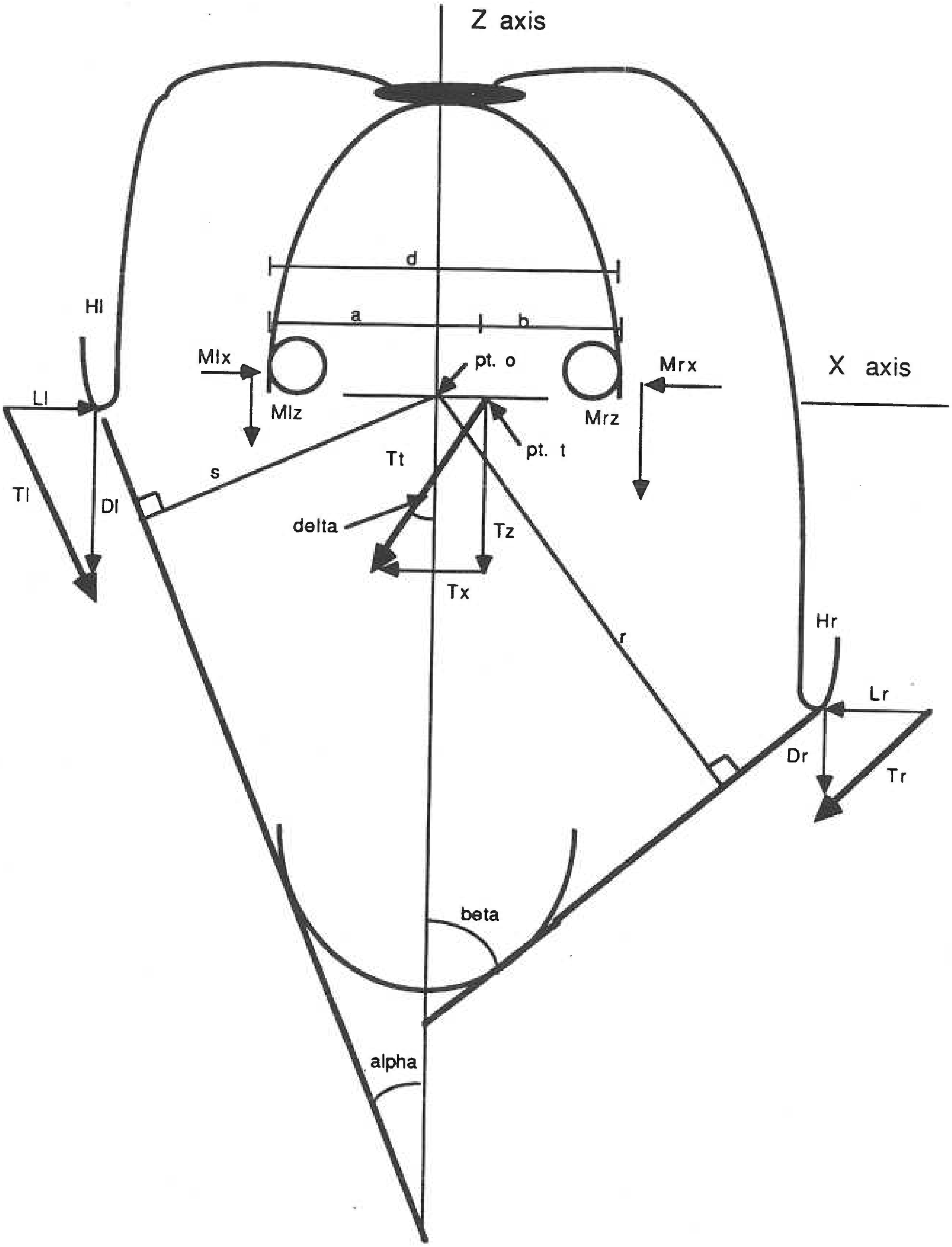
And the forces involved:

T_r = right line of traction. (force at right hook)
T_l = left line of traction. (force at the left hook)
$T_t = T_r + T_l$ (resultant force bisects angle formed by T_r and T_l)

SYMMETRIC HEADGEAR (fig. 6)



ASYMMETRIC HEADGEAR (fig. 7)



And the resolved forces at the headgear hooks are:

D_r = right posterior force component
D_l = left posterior force component
L_r = right lateral force component
L_l = left lateral force component
T_x = net lateral force
T_z = net anterio-posterior force
T_y = net intrusive-extrusive force

And the forces exerted at the molars are:

M_{lz} = left posterior force
M_{rz} = right posterior force
M_{lx} = left lateral force
M_{rx} = right lateral force
*reactive forces designated as (-) i.e. $-M_{lz}$

Force vectors will be consider positive when acting down and or to the right. Forces acting up and or to the left will be considered negative in value.

The following letters represent distances:

a = distance from the left molar tube to point T on the X axis.
b = distance from the right molar tube to point T on the X axis.
d = distance separating the two molar tubes on the X axis.
r = perpendicular distance between T_r and point o.
s = perpendicular distance between T_l and point o.

And let:

alpha = the angle formed by the intersection of T_l and the Z axis.
beta = the angle formed by the intersection of T_r and the Z axis.
theta = the bisecting angle of the angle formed by T_l and T_r.
delta = the angle that T_t intersects the Z axis.

We will first consider the mathematical model presented by Oosthuizen et al.[17] We will consider symmetric models. An asymmetric mathematical analysis will be covered at a later time in this paper. As defined earlier, T is the force applied at the outer bow hooks, h_r and h_l. Since an equilibrium is reached in the neckstrap, $T_r = T_l$. In a symmetric design, Alpha and Beta, the angles formed by the force T and the Z axis, are also equal and can be used to calculate the resolved distal and lateral force components using simple trigonometry:

$$L_l = T_l \text{ sin alpha}$$
$$D_l = T_l \text{ cos alpha}$$
$$L_r = Tr \text{ sin beta}$$
$$D_r = T_r \text{ cos beta}$$

Since the lateral force components act in mutually opposing directions, if they are equal as in a symmetric design the net lateral force (T_z) is zero. This can be described by:

$$T_x = T_l \text{ (sin alpha)} + T_r \text{ (sin beta)}$$

The distal force (T_z) can be described by:

$$T_z = T_l \text{ (cos alpha)} + T_r \text{ (cos beta)}$$

And since Alpha = Beta and $T_l = T_r$:

$$T_z = 2(T_l)\text{(cos alpha)}$$

From this it can be seen that the total distal force is inversely proportional to the size of alpha and beta since the cosine of an angle decreases from a value of one at 0^o to a value of zero at 90^o.

By using our knowledge of the mathematical description of a moment:

$$\text{Moment} = \text{Force} \times \text{Distance}$$

We can calculate D_l and D_r from knowing T_l and T_r and the perpendicular distance of these forces from point o. These distances will be the right perpendicular (r) and the left perpendicular (s). We can calculate the moments about o produced by T_l:

$$M_l = T_l \times s$$

And knowing that also:

$$M_l = D_l \times .5(d)$$

It follows that:

$$D_l = \frac{T_l \times s}{.5(d)}$$

The same holds true for the right side and combining both sides gives us:

$$D_l - D_r = \frac{T\ (s - r)}{.5(d)}$$

Since in practice the line of traction (T) must always cut a tangent to the outside of the neck, the distances s and r are in a direct relation to the sine of the angles alpha and beta. As the angle increases so does the length of r and s. Therefore by increasing the angulation of the line of traction to the midline axis on one side, greater force will be exerted on the molar on the same side. If the angulation of the line of traction is the same on the right and left side then in the above equation (s - r) would equal zero and no net moment would exist but a straight net distal force passing through point o. (fig. 6)

Hershey et al.[21] presented a slightly different mathematical model to analyze the forces involved in the transverse plane which they derived from Haack and Weinstein's earlier work.[11] If we consider the bisecting angle, theta, formed by the intersection of T_l and T_r and the resultant force T_t, it will be noted that T_t intersects the X axis at point t. (fig. 7) In a symmetrical headgear this will lie at the midpoint along the X axis between the right and left molars (point t will be coincident with point o) and T_t will be coincident with the Z axis.(fig. 6) T_t will also be equal to T_z since no net lateral force component exists. In an asymmetric design T_t will not be coincident with the Z axis and point t will lie closer to one molar than the other.

First let us again review the equations of coplanar equilibrium:

$$\_F_x = 0$$
$$\_F_z = 0$$
$$\_M = 0$$

We can apply these equations to derive the relation of the forces at the outer bow hooks and the molars as follows:

$$\_F_x = 0$$
$$T_x + (-M_{lx}) + (-M_{rx}) = 0$$

And to apply the equation for the moments a point must be selected to view the forces. We will select the left molar for simplicity but any point may be selected. Each moment as stated earlier is equal to the force times the distance from the point selected. The equation for the moments involved:

$$\_M = 0$$

$$(T_z)(a) + (-M_{rz})(d) = 0$$

Solving this equation for M_{rz}:

$$M_{rz} = \frac{(T_z)(a)}{d}$$

Substituting this into the equation for the sum of the forces in the z axis, we get:

$$T_z + (-M_{lz}) + \left[-\frac{(T_z)(a)}{d}\right] = 0$$

$$M_{lz} = T_z + \left[-\frac{(T_z)(a)}{d}\right]$$

$$M_{lz} = \frac{(T_z)(b)}{d}$$

It can be seen that if the resultant force is coincident with the Z axis then $a = b$ and $M_{lz} = M_{rz}$. From this it can be deduced that if the distance that the resultant force T_z lies from the right and left molars along the x axis is not of equal distance, the force at each molar in the Z axis direction will not be the same. The distal force component at each molar is directly related to the ratio of the distance that the molar lies from point t, the point that the resultant force intersects the X axis, and inversely related to the distance between right and left molars.

We can now take this knowledge and digress for a moment to look at the force T_t. By again using the right triangle axiom we can determine that:

$$T_t = (T_l + T_r)(\cos \text{theta})$$

If angles alpha and beta are equal and T_r and T_l are equal in magnitude then T_t will be coincident with the Z axis. T_t will intersect the Z axis at some angle, delta. In a symmetrical design alpha equals beta therefore the angle delta will equal 0^o. Remembering that the cosine $0^o = 1$ and the sine of $0^o = 0$. The distal and lateral components of T_t can be expressed as:

$$T_z = T_t\ (\cos \text{delta})$$
$$T_x = T_t\ (\sin \text{delta})$$

By substitution we can derive:

$$T_z = (T_l + T_r)(\cos \theta)(\cos \delta)$$
$$T_x = (T_l + T_r)(\cos \theta)(\sin \delta)$$

And the forces at the molars are equal to:

$$M_{lz} = \frac{(T_l + T_r)(\cos \theta)(\cos \delta)(a)}{d}$$
$$M_{rz} = \frac{(T_l + T_r)(\cos \theta)(\cos \delta)(b)}{d}$$
$$M_{lx} = \frac{(T_l + T_r)(\cos \theta)(\sin \delta)(a)}{d}$$
$$M_{rx} = \frac{(T_l + T_r)(\cos \theta)(\sin \delta)(b)}{d}$$

The traction forces on the right and left straps will for the majority of instances reach an equilibrium with each other and be of equal magnitude.

Since theta is the bisecting angle of alpha plus beta:

$$\text{theta} = \frac{\text{alpha} + \text{beta}}{2}$$

We can derive the value of delta if we know alpha and beta:

$$\text{delta} = \frac{\text{alpha} + \text{beta}}{2} - \text{alpha}$$

In a symmetric design, alpha = beta and therefore delta = 0. Therefore by knowing the magnitude of the traction forces at the right and left straps and the values for alpha and beta, it is possible to compute the values of forces at the right and left molars in the transverse plane in a two dimensional model.

EXPLANATION OF UNILATERAL HEADGEAR

We will utilize information from the previous models discussed to arrive at what is felt to be an appropriate explanation of how a unilateral force can be created. Although our laboratory model will enable us to measure the forces resolved into all three orthogonal directions, we will contain our theoretical explanation to a description of the forces in two dimensions. Our explanation will also be reserved to treating the inner and outer bows of the headgear as rigid bodies.

A theoretical evaluation derived from the earlier work of Haack and Weinstein [14] will be used to discuss an asymmetric headgear design. We will utilize the same definitions and background information provided in the review of the literature for the sake of brevity. (fig. 7)

We can assume that the scalar quantity of the tractional force delivered at each end of the neck strap will be equal due to the sliding ability of the strap on the neck. It is important to remember that in a unilateral design by the positioning and length of the outer bow the direction of the tractional forces, T_l and T_r, will not be the same. Let us explain this in mathematical terms.

As stated earlier, the angles formed by the left and right lines of traction intersection with the Z axis constitute angles alpha and beta. If these angles are of equal value then the bisecting vector and the resultant force T_t are coincident with the Z axis and the distal force at each molar tooth will be equal. If however alpha does not equal beta then the bisecting vector, T_t, will not be coincident with the Z axis and a differential force will be exerted at the right and left molar. T_t will intersect the Z axis at a given angle, delta, which can be described by:

$$\text{delta} = \frac{\text{alpha} + \text{beta}}{2} - \text{alpha}$$

And T_t can be described as:

$$T_t = (T_r + T_l)(\cos \text{theta})$$

The force T_t can be resolved into its distal and lateral components, T_x and T_z.

$$T_z = T_t(\cos \text{delta})$$
$$T_x = T_t(\text{sine delta})$$

As we discussed in the literature review, the force exerted at the right and left molars is directly proportional to the ratio of distance a to b, the distance from the two molars that T_t intersects the X axis.

The following equations can be calculated from the equations of coplanar equilibrium as was done in the previous section of this paper:

$$M_{lz} = \frac{(T_z)(b)}{d}$$
$$M_{rz} = \frac{(T_z)(a)}{d}$$

From this it can be seen that the distal force at the molars is directly related to a and b:

$$\frac{M_{lz}}{M_{rz}} = \frac{b}{a}$$

We can see that the size of angle delta is a function of the difference in the magnitude of angles alpha and beta:

$$\text{delta} = \frac{\text{alpha} + \text{beta}}{2} - \text{alpha}$$

As the magnitude difference between alpha and beta increases the size of delta will increase and the position of point t on the X axis will change in turn varying the proportional lengths of a and b.

We can also look at the lateral force component which can be described mathematically by:

$$T_x = T_t \text{ (sin delta)}$$

The lateral force is a function of the sine of delta. As delta increases, slowly, the value of the net lateral force increases quickly, because the sine of a low angle increases rapidly when the angle increases only slightly. Therefore the value of the net lateral force increases substantially when a magnitude difference between alpha and beta is created.

In summary, to create an asymmetric force application to the molars a difference in the angle of tangency of the right and left force applications to the neck must be created. In doing this a net lateral force is created directed towards the side of less distal force.

The following equations which were presented in the previous section can be used to view the respective forces at the right and left molars:

$$M_{lz} = \frac{(T_l + T_r)\text{(cos theta)(cos delta)(a)}}{d}$$

$$M_{rz} = \frac{(T_l + T_r)\text{(cos theta)(cos delta)(b)}}{d}$$

$$M_{lx} = \frac{(T_l + T_r)\text{(cos theta)(sin delta)(a)}}{d}$$

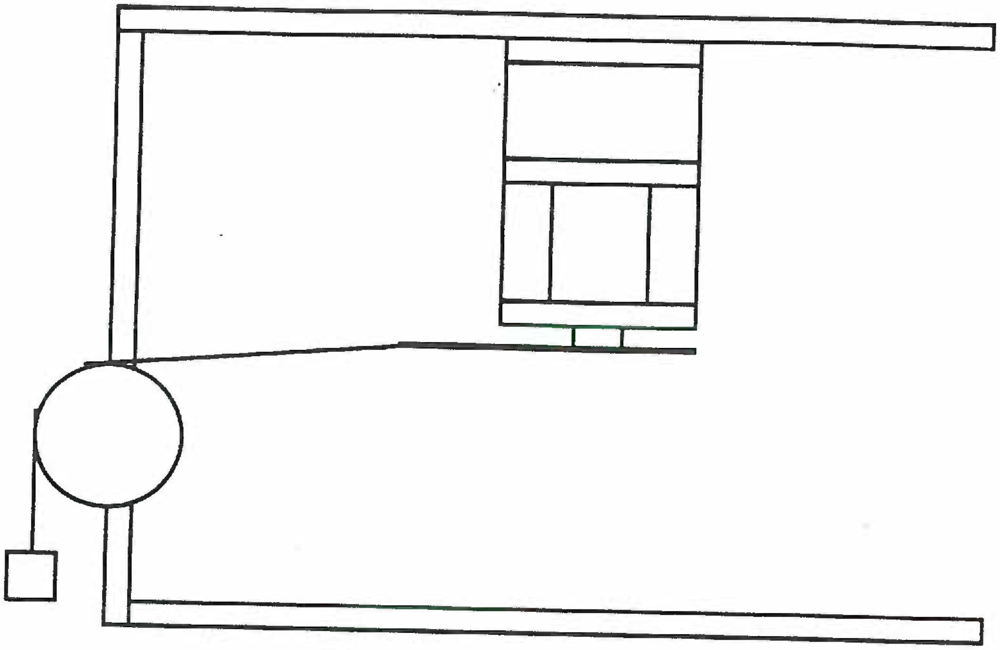
$$M_{rx} = \frac{(T_l + T_r)\text{(cos theta)(sin delta)(b)}}{d}$$

MATERIALS AND METHODS

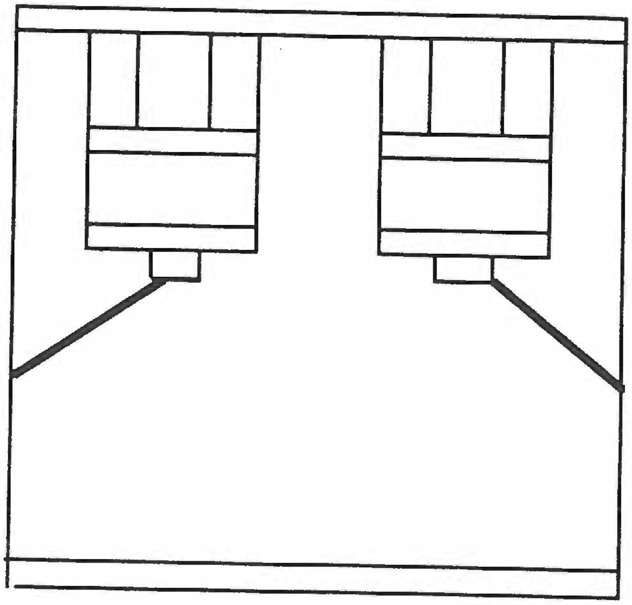
A mechanical model capable of measuring the relative forces delivered to the molar teeth by various symmetrical and asymmetrical headgears was designed and constructed.(fig. 8-9) Special emphasis was placed on designing a laboratory model that would be capable of meeting the needs for analyzing various headgears and outerbow configurations in future studies.

Whereas previous models have investigated the forces delivered in the distal (anterio-posterior) and lateral directions, to our knowledge a model has not been constructed that enabled the measurement of the before mentioned force components in conjunction with the forces delivered in an intrusive - extrusive plane. The model for this investigation was designed and constructed with the intention of providing a means of measuring relative forces at the anchorage molars in the distal, lateral, and intrusive/extrusive directions. This model also will allow measurement of moments created at the anchorage molars in the planes commonly referred to as tipping (mesio-distal) and torquing (bucco-lingual).

The model utilizes a commonly employed engineering tool, the strain gauge to measure the various force components created at the molar teeth. The strain gauge can be used to measure the strain (the internal deformation per unit length) in a given structure by an applied force. Stress can be defined as the internal resistance of a body to an applied force. The stress and strain are related by the formula STRESS = STRAIN x MODULUS OF ELASTICITY. With the calibration of the strain gauges to known forces applied, the gauges can then be used to determine each of the force vectors of interest when a given load is applied.



(fig. 8) Side view of Headgear Force Analyzer



(fig. 9) Front view of Headgear Force Analyzer

Strain gauges were employed on various pieces of feeler stock, positioned to resolve the total force into the relative forces of interest. When a specific headgear design is engaged on the model, strain gauge readings from some 32 strain gauges are recorded which provide data from which can then be calculated the stress and or force in specific directions.

The dimensions of the model were selected to approximate those of an average adolescent. Because of the large variation that exists in each individual this model can only be thought of as an illustration of the relative forces that a particular headgear design can produce and is not intended to provide specific force values that will be produced by a given headgear, clinically. It is important to remember that since the resultant force vectors are related to the magnitude and direction of the forces applied and also the various dimensions of the individual patient a wide variation can exist from individual to individual.

Several dimensions were obtained from information provided from previous reports. The portion of the model representing the maxillary first molars was constructed so as to measure the moments produced at the center of resistance of the fore mentioned teeth. This point was found to lie at the level of the root trifurcation or approximately 12 mm apically to the occlusal surface. The distance the molar teeth would be positioned from the neckstrap location in both the Z axis and the Y axis was not readily available. Therefore 10 active orthodontic patients currently wearing a cervical headgear were measured and a mean dimension for both the distal and inferior placement of the neck strap simulation was obtained. This dimension for the anteroposterior dimension was calculated to be 80mm. The dimension for the inferior placement of the neckstrap in relation to the maxillary first molar occlusal surface was calculated to be 13mm. These two dimensions of the mechanical model were designed to be changeable if future studies should warrant. The maxillary first molar intra-arch dimension was set at 61mm measured from buccal tube to buccal tube. The dimension from center of tooth to center of tooth was recorded at 47mm.

The bonded resistance strain gauge is a commonly employed engineering tool to measure stress. The gauge consists of a grid of very fine wire or a thin metallic foil bonded to an insulating backing called a carrier matrix. Several other types of strain devices are also used but this is by far the most common. The gauge utilizes the electrical characteristic that electrical resistance is proportional to the strain. The electrical resistance of the bonded strain gauge varies linearly with strain. The carrier matrix is attached to the specimen with an adhesive. A commercially prepared cyanoacrylate recommended for this purpose was used in this study. When the specimen is loaded, the strain in its surface is transmitted to the grid material by the adhesive and carrier system. The strain in the specimen is found by measuring the change in the electrical resistance of the grid material. The bonded strain gauge is quite often connected to a Wheatstone bridge circuity, because of this configuration's outstanding sensitivity. The Wheatstone bridge consists of a four sided electrical circuit with each side containing a resistor. A current is passed through the circuit and a voltmeter connected across the "bridge" registers any difference between the two sides. When the bridge is balanced, no net difference exists between the right and left sides of the bridge. This can be expressed in the formula:

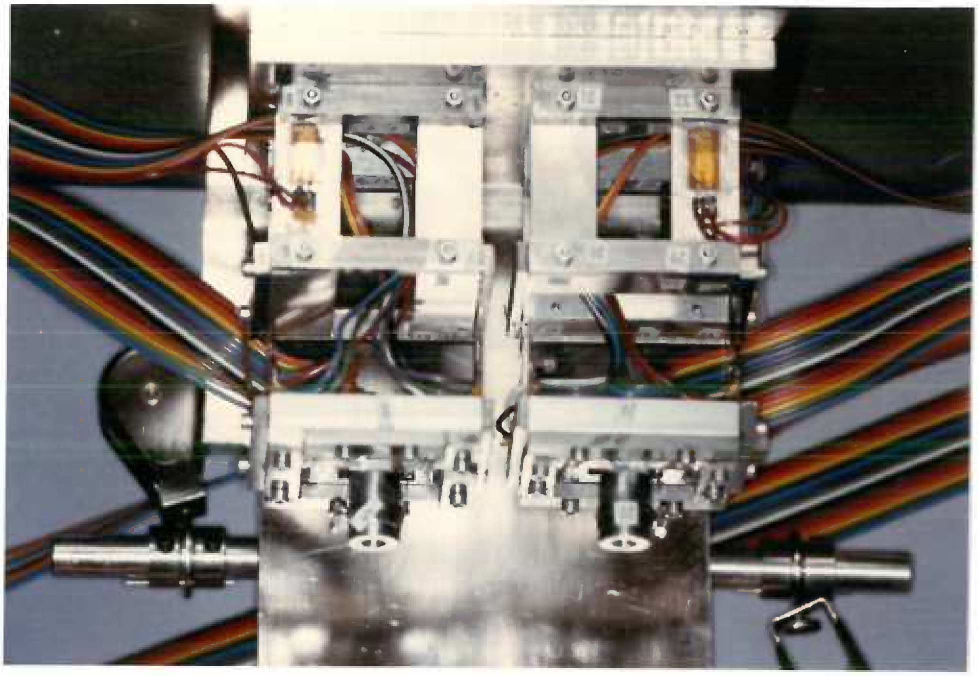
$$V_{out} = Vi_n\left[\frac{R_3}{R_3 + R4} - \frac{R_2}{R_1 + R_2}\right]$$

Where R is equal to each of the resistors on each side and V is equal to the voltage in and out.

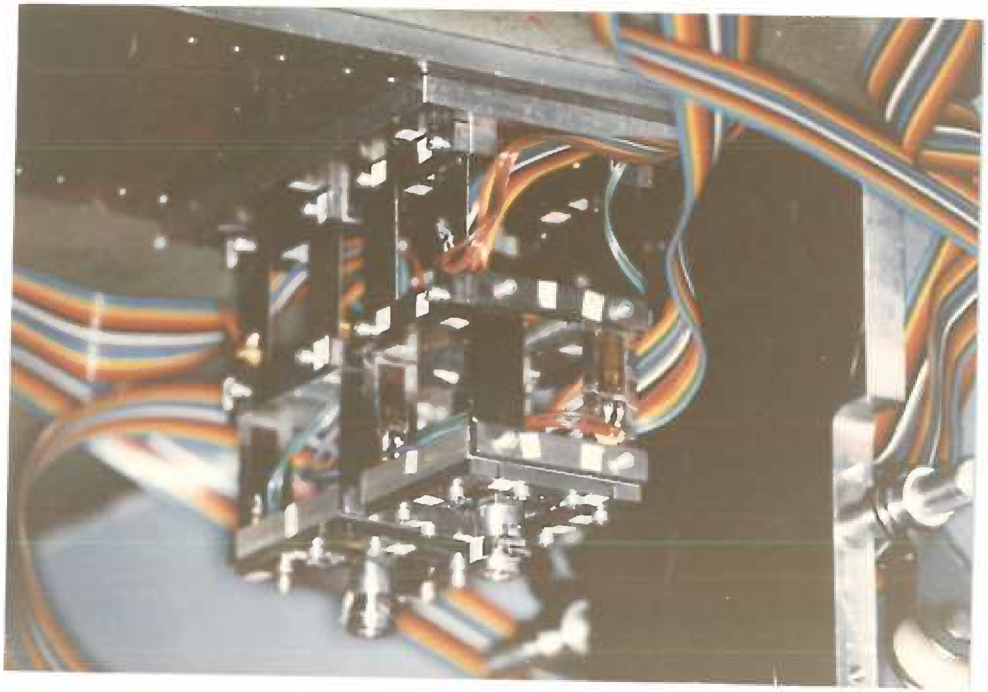
The strain gauge is substituted into one of the sides and if the bridge is initially balanced, when a given strain is applied to the specimen containing the gauge it will be registered on the voltmeter. From previous calibration the amount of stress can then be calculated that occurred to create a given change in resistance in the gauge. The strain gauge can be a highly sensitive tool and small changes in strain can be recorded allowing accurate measurements of the stresses involved in a given specimen. It is also possible to incorporate a strain gauge into each side of the Wheatstone bridge, provided all sides have the same size gauge so as to keep the bridge balanced when the gauges are unstrained. By constructing the Wheatstone bridge from strain gauges on all four sides certain advantages exist. One, the effects of temperature upon the highly sensitive gauges can be eliminated, two, the sensitivity of the bridge is increased, and three, unwanted force components can be eliminated from the readings by allowing gauges positioned on opposite sides of the bridge to cancel each other out.

The model was designed with a series of eight vertical one inch pieces of feeler stock arranged in a series of two tiers from which each simulated tooth was suspended by two horizontal pieces of feeler stock. A strain gauge was attached to each segment of feeler stock. (photographs 1-4) The vertical segments were positioned to measure the forces produced in the medio-lateral and anterio-posterior directions. The highest tier was positioned to measure the anterio-posterior forces and was made of .010 inch feeler stock 1/2 inch wide. The second tier was positioned to measure the lateral forces and was constructed of .008 inch x 1/2 inch feeler stock. The two horizontal segments arranged in a cross were positioned to record intrusive and extrusive forces along with moments in the buccolingual and mesiodistal direction. These were constructed of .008 inch feeler stock 1/4 inch wide. The simulated tooth was attached to these two horizontal segments 12mm below the occlusal surface to record the moments at the average level of the center of resistance on the maxillary first molar teeth. As mentioned previously, strain gauges were configured properly to negate any temperature change effects upon the bridge sensitivity.

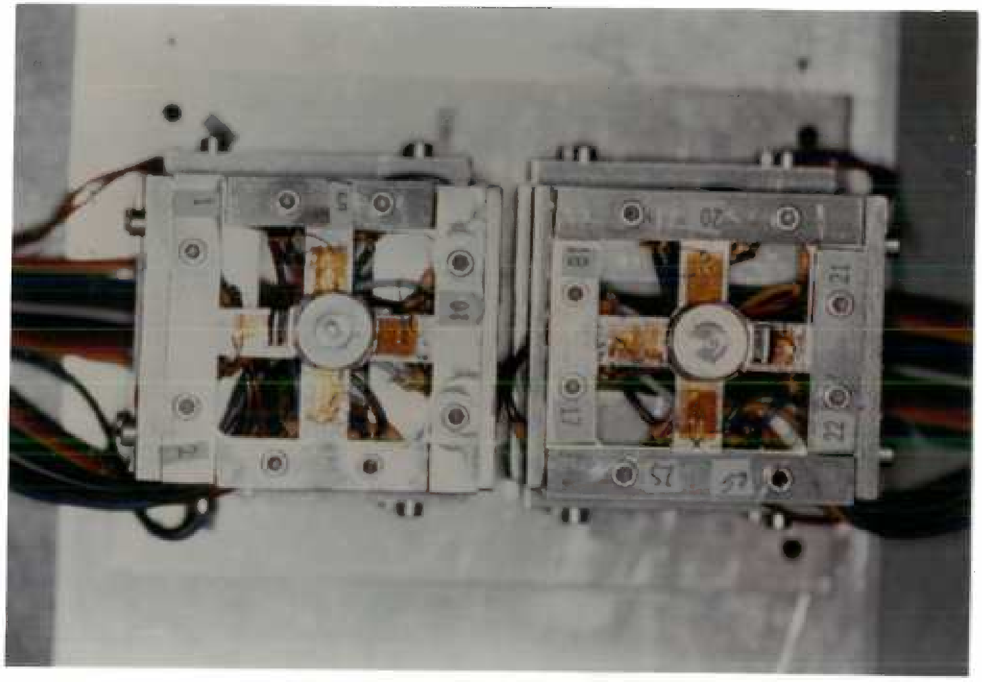
The gauges used in the construction of this model were obtained from Omega Engineering. Two sizes were used; 16 smaller gauges (5.0mm x 3.2mm) were attached to the horizontal cross members of feeler stock from which the simulated teeth were suspended and 16 larger gauges (8.3mm x 4.7mm) were attached to the vertical pieces of feeler stock.



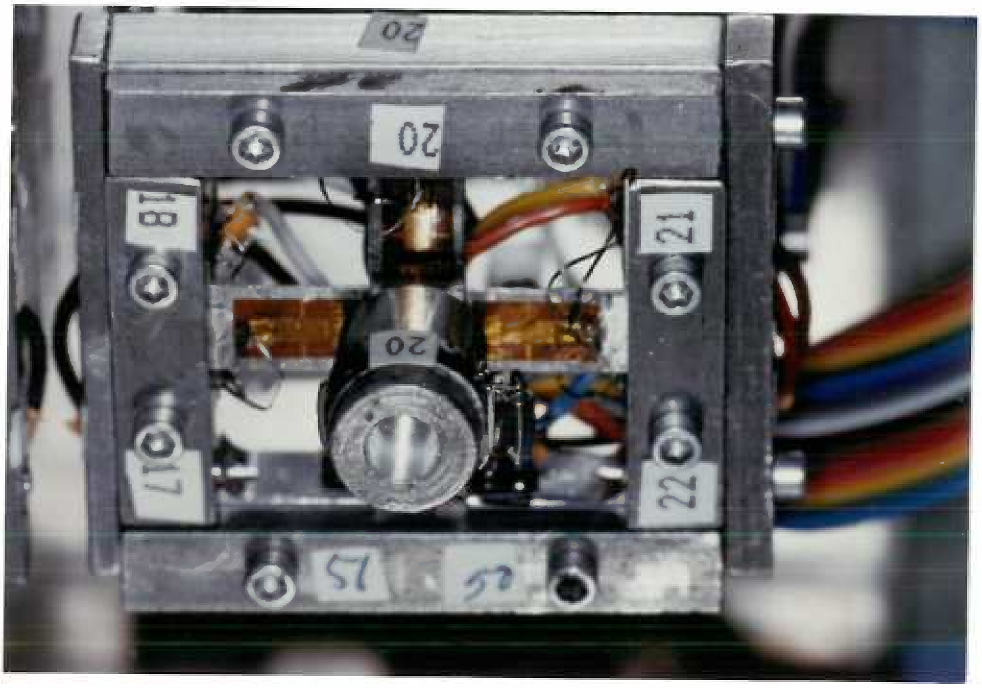
Photograph 1: Anterior view of the feeler stock and strain gauge assembly.



Photograph 2: Medio-lateral view of the feeler stock and strain gauge assembly.



Photograph 3: Inferior view of the feeler stock, strain gauge, and tooth assembly.



Photograph 4: Inferior view/close up of the feeler stock, strain gauge, and tooth assembly.

The smaller gauges had the following technical characteristics: gauge factor = 1.99 +/- 1%, resistance = 120ohms +/- 0.2%. The larger gauges had the following technical data: gauge factor = 2.02 +/- 1%, resistance = 120ohms +/- 0.2%.

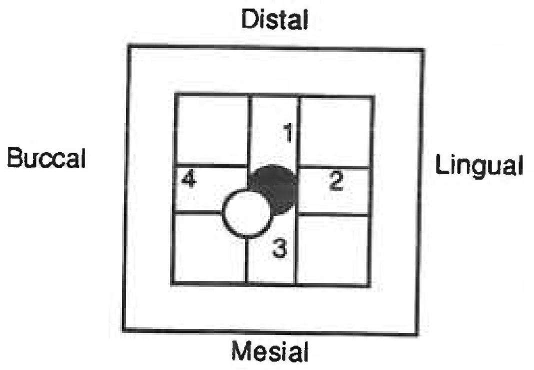
The gauges were connected to a switching mechanism in the appropriate Wheatstone bridge configurations to allow relative ease in recording the measurements. The switching mechanism also allowed the balancing of each bridge by providing a balancing resistor for each bridge configuration. The eight Wheatstone bridges configured to measure anterio-posterior, medio-lateral, bucco-lingual torque, and mesio-distal tip all consisted of four gauges (one per side of the bridge). The two Wheatstone bridges configured to record intrusive-extrusive forces consisted of eight gauges each. The two appropriate gauges were hooked in series on each side of the bridge. Wiring diagrams are included to represent the color coding of wires to each gauge position and the location of each gauge on the feeler stock.(figs. 10-11) Wheatstone bridge configurations are shown.(fig. 12) Each gauge was assigned a number denoting position and two letters denoting right or left and top or bottom. For example gauge 6TL is located in position 6 (underneath side of horizontal cross member) on the top left. (figs. 10-12)

Because information about both the intrusive-extrusive forces and the moments about the first molars was needed, care was taken to wire the gauges in a manner that would provide this information. In the majority if not all headgears, both a intrusive-extrusive force and moments about the center of resistance exist simultaneously. Because of this, it was necessary to configure the bridges in a manner that would separate one from the other. This was accomplished by configuring the gauges so that the effect of the intrusive-extrusive force would be eliminated in the readings of the bucco-lingual and mesio-distal torque and vice a versa the effects of the moments would be eliminated from the intrusive-extrusive force. By utilizing gauges on all four sides of the Wheatstone bridge this could be accomplished.

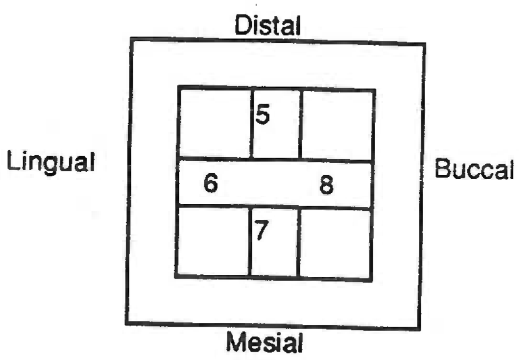
LEFT SIDE WIRE CODINGS (FIG10)

Blue Green	Yellow Orange	Red Brown	Black White	Gray Purple	Blue Green	Yellow Orange	Red Brown
1LT	5LT	2LT	6LT	3LT	7LT	4 LT	8LT

Top Superior View

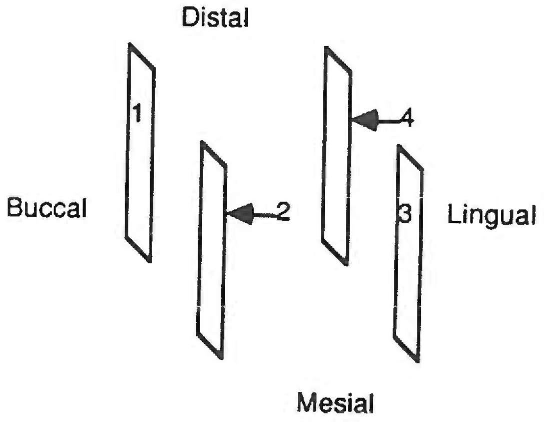


Top Inferior View

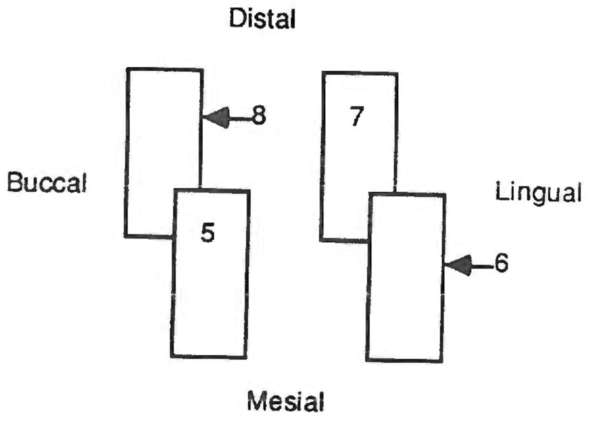


Blue Green	Yellow Orange	Red Brown	Black White	Gray Purple	Blue Green	Yellow Orange	Red Brown
8LB	7LB	1LB	4LB	3LB	2LB	6LB	5LB

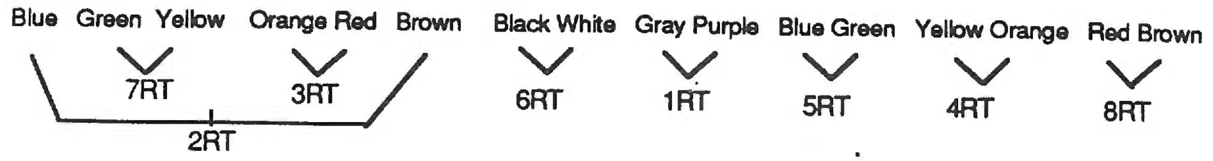
Middle Tier



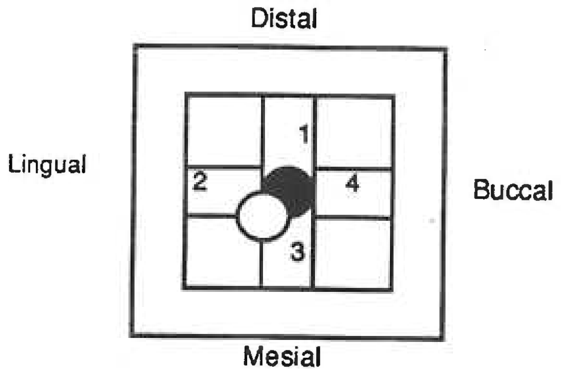
Upper Tier



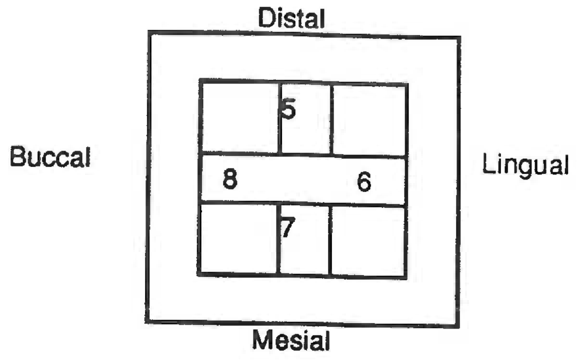
RIGHT SIDE WIRE CODINGS (FIG. 11)

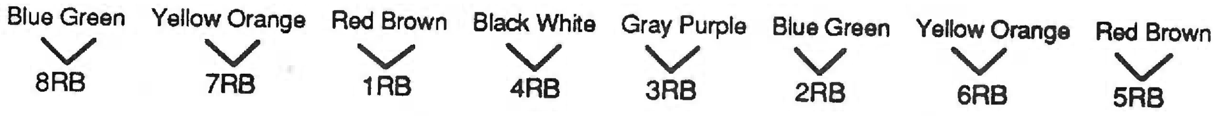


Top Superior View

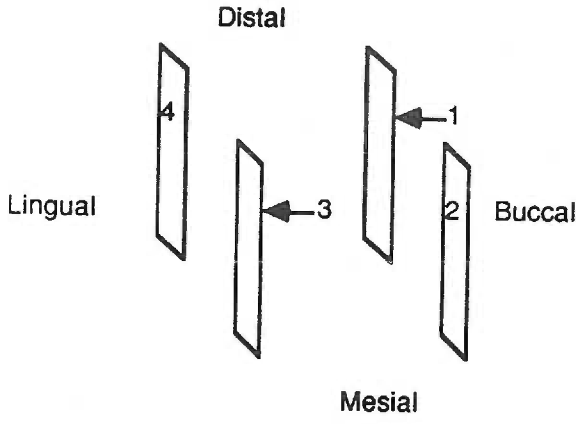


Top Inferior View

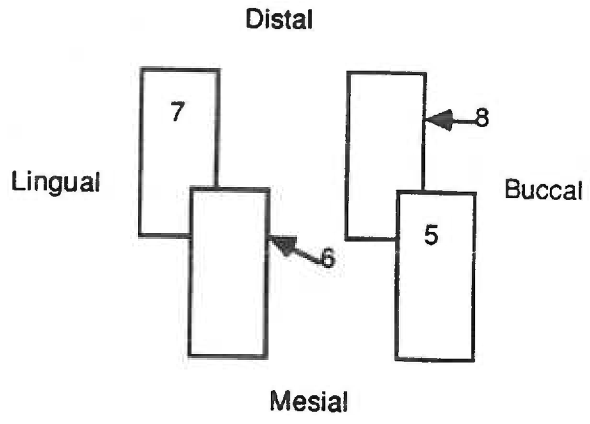




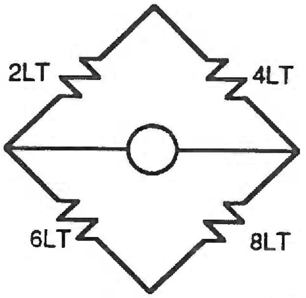
Middle Tier

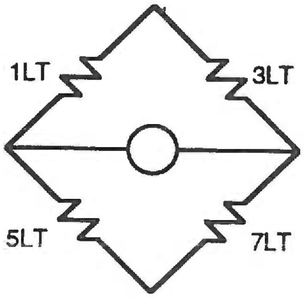


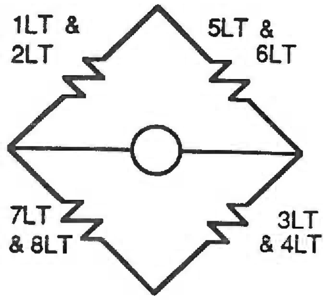
Upper Tier

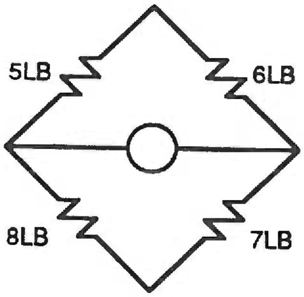


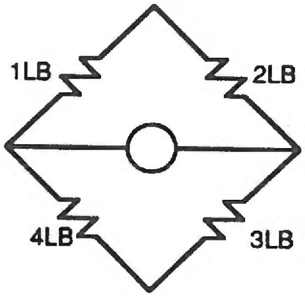
WHEATSTONE BRIDGE CONFIGURATIONS (FIG.12)

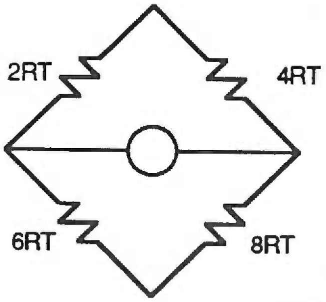

Bridge #1
Left Bucco-lingual
Torque

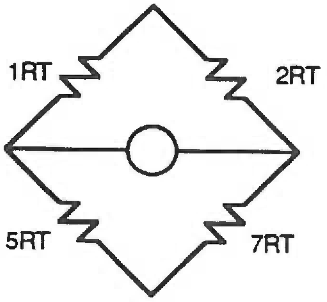

Bridge #2
Left Mesio-distal
Tip

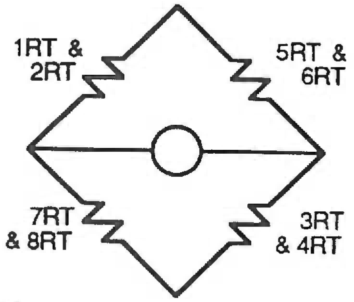

Bridge #3
Left Intrusive-Extrusive

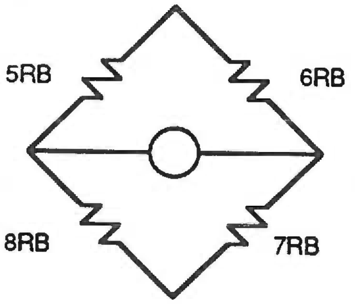

Bridge #4
Left Anterio-Posterior

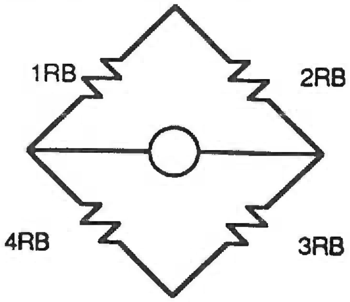

Bridge #5
Left Medio-Lateral


Bridge #6
Right Bucco-Lingual
Torque


Bridge #7
Right Mesio-Distal
Tip


Bridge #8
Right Intrusive-Extrusive


Bridge #9
Right Anterio-Posterior


Bridge #10
Right Medio-Lateral

The switching mechanism was then connected to the Sanborn Strain Gauge Amplifier. When a transducer, in our case the various Wheatstone bridges, is connected to the Strain Gauge Amplifier, the amplifier provides an excitation voltage to the transducer. The transducer returns a signal voltage to the Strain Gauge Amplifier. The variation in the signal voltage that is returned is interpreted by the Sanborn and moves the galvanometer stylus up or down on the recording paper to show the direction and magnitude of the load applied to the bridge.

The entire system was then initially balanced by using an internal capacitor and resistor in the Sanborn, then each bridge was balanced by using an additional variable resistor located in the switching device. This allowed switching from one bridge to the next without requiring rebalancing of the entire system. A series of known forces were then applied, independently, to each portion of the model to calibrate the stylus deflection of the galvanometer. Known forces in the range of the anticipated forces were applied to each portion to achieve an accurate calibration. These force values are listed in table 1. On the four gauges where a moment was being observed, a known weight was applied at a distance of 12mm from the center of the bracket. The moment was then calculated from the force times the distance. Because of the difficulty in applying forces in the proper direction to calibrate the machine after fabrication, measurements were made in only one of each two possible directions of deflection. The assumption was made that the galvanometer deflection would be equal in either direction therefore the deflection could be measured in only one of the two possible directions and then used to represent both possible force directions. A negative value was assigned to galvanometer deflections that occurred to the right of zero and positive values were assigned to galvanometer deflections to the left. By chance, all calibration measurements resulted in a positive deflection of the galvanometer needle. The following lists the direction of each calibration;

COMPONENT FOR CALIBRATION	DIRECTION OF CALIBRATION
Anterio-posterior	Anterior
Medio-lateral	Lateral
Intrusive-extrusive	Intrusive
Bucco-lingual torque	Lingual torque
Medio-distal tip	Distal tip

After completion of the calibration runs, the deflections noted were recorded and plotted for each Wheatstone bridge. (table 1) A regression analysis (table 2) was performed and the regression line was plotted on each graph representing the galvanometer deflection for each applied force. (graphs 1-10)

The stylus deflection closely approximates a linear relation to the load applied and by calculating the linear equation of each regression line, the resultant force in each of the measurable directions can be calculated by knowing the galvanometer deflection. The linear equation is represented by:

$$Y = aX + b$$

Where Y is equal to galvanometer deflection, a is the slope of the line or X coefficient, X is the force applied, and b is the y intercept or constant.

We can then solve for X:

$$X = \frac{Y - b}{a}$$

A headgear design can now be placed upon the model and by recording the stylus deflection from each Wheatstone bridge, the force vector in each direction at question can be measured.

The neckstrap of the headgear was simulated by two pulleys positioned 4.5 inches apart to simulate the dimension of the neck. A chain was attached to the outer bow and fed over the pulley and then attached to a weight to simulate the amount of force applied at each end of the neckstrap.

A conventional symmetric headgear was constructed by using a graph paper underlay to assure right and left arch symmetry. This was first placed on the model and measurements were taken when a traction force of 400gms per side was applied to each side. The outerbow was positioned

at the same level as the center of resistance of the tooth (12mm above the occlusal surface). The data was analyzed to first check the validity of the mechanical design.

A swivel arm unilateral facebow checked for arch symmetry was also placed on the model and measurements were recorded. A traction force of 400gms per side was used and the swivel arm was on the right side.

TABLE 1: WHEATSTONE BRIDGE CALIBRATIONS

BRIDGE NUMBER	BRIDGE PURPOSE	APPLIED FORCE (gms)	APPLIED MOMENT(gms-mm)	GALVANOMETER DEFLECTION	REGRESSION LINE VALUE	BRIDGE CONSTANT	BRIDGE X COEFFICIENT
1	LEFT BUCCO-LINGUAL TORQUE	50	600.0	32.5	34.36	5.500	0.577
		100	1200.0	66.0	63.21		
		200	2400.0	120.0	120.93		
2	LEFT MESIO-DISTAL TIP	50	600.0	20.0	23.20	4.492	0.374
		100	1200.0	42.0	41.91		
		200	2400.0	84.0	79.32		
		500	6000.0	190.0	191.57		
3	LEFT INTRUSIVE EXTRUSIVE FORCE	20		1.4	1.54	0.057	0.074
		50		4.0	3.77		
		100		7.4	7.49		
4	LEFT ANTERIO-POSTERIOR FORCE	100		34.0	36.60	5.238	0.314
		200		68.0	67.95		
		300		100.0	99.31		
		500		168.0	162.02		
		600		194.0	193.38		
		700		220.0	224.74		
5	LEFT MEDIO-LATERAL FORCE	20		8.2	8.25	0.872	0.369
		50		18.2	19.31		
		100		38.0	37.74		
		200		77.0	74.62		
		300		110.0	111.49		
6	RIGHT BUCCO-LINGUAL TORGUE	50	600.0	28.0	29.00	4.500	0.490
		100	1200.0	55.0	53.50		
		200	2400.0	102.0	102.50		
7	RIGHT MESIO-DISTAL TIP	50	600.0	28.0	33.33	10.513	0.456
		100	1200.0	56.0	56.15		
		200	2400.0	110.0	101.79		
		500	6000.0	236.0	238.72		
8	RIGHT INTRUSIVE-EXTRUSIVE FORCE	20		1.2	1.11	-0.651	0.088
		50		3.6	3.75		
		100		8.2	8.14		
9	RIGHT ANTERIO-POSTERIOR FORCE	100		24.0	21.52	-5.190	0.267
		200		48.0	48.24		
		300		70.0	74.95		
		500		130.0	128.38		
		600		158.0	155.10		
		700		180.0	181.81		
10	RIGHT MEDIO-LATERAL FORCE	20		5.8	4.07	-1.992	0.303
		50		13.2	13.17		
		100		26.2	28.33		
		200		58.0	58.65		
		300		90.0	88.98		

TABLE 2: BRIDGE CALIBRATIONS-REGRESSION ANALYSIS

```
                 WSB01
Constant                                          5.5
Std Err of Y Est                         3.4743961449
R Squared                                0.9969033062
No. of Observations                                 3
Degrees of Freedom                                  1

X Coefficient(s)          0.5771428571
Std Err of Coef.          0.0321666579
```

```
                 WSB02
Constant                                 4.4923076923
Std Err of Y Est                           4.15840206
R Squared                                0.9979770347
No. of Observations                                 4
Degrees of Freedom                                  2

X Coefficient(s)          0.3741538462
Std Err of Coef.          0.0119115743
```

```
                 WSB03
Constant                                 0.0571428571
Std Err of Y Est                         0.2828427125
R Squared                                0.9955817378
No. of Observations                                 3
Degrees of Freedom                                  1

X Coefficient(s)          0.0742857143
Std Err of Coef.          0.0049487166
```

```
                 WSB04
Constant                                 5.2380952381
Std Err of Y Est                          4.054685708
R Squared                                0.9976170921
No. of Observations                                 6
Degrees of Freedom                                  4

X Coefficient(s)          0.3135714286
Std Err of Coef.          0.0076626357
```

```
                 WSB05
Constant                                 0.8715361446
Std Err of Y Est                         1.7505191427
R Squared                                0.9987286904
No. of Observations                                 5
Degrees of Freedom                                  3

X Coefficient(s)          0.3687198795
Std Err of Coef.          0.0075951758
```

```
                 WSB06
Constant                                          4.5
Std Err of Y Est                         1.8708286934
R Squared                                0.9987520799
No. of Observations                                 3
Degrees of Freedom                                  1

X Coefficient(s)                  0.49
Std Err of Coef.          0.0173205081
```

```
                 WSB07
Constant                                10.5128205128
Std Err of Y Est                         7.1826000578
R Squared                                 0.995952317
No. of Observations                                 4
Degrees of Freedom                                  2

X Coefficient(s)          0.4564102564
Std Err of Coef.          0.0205742669
```

```
                 WSB08
Constant                                -0.6510204082
Std Err of Y Est                          0.181827458
R Squared                                0.9986935765
No. of Observations                                 3
Degrees of Freedom                                  1

X Coefficient(s)          0.0879591837
Std Err of Coef.          0.0031813178
```

```
                 WSB09
Constant                                -5.1904761905
Std Err of Y Est                         3.3558761541
R Squared                                0.9977506931
No. of Observations                                 6
Degrees of Freedom                                  4

X Coefficient(s)          0.2671428571
Std Err of Coef.          0.0063420098
```

```
                 WSB010
Constant                                -1.9918674699
Std Err of Y Est                         1.7320739942
R Squared                                0.9981606155
No. of Observations                                 5
Degrees of Freedom                                  3

X Coefficient(s)          0.3032228916
Std Err of Coef.          0.0075151458
```

TABLE 3: SYMMETRIC HEADGEAR (400 GM/SIDE)

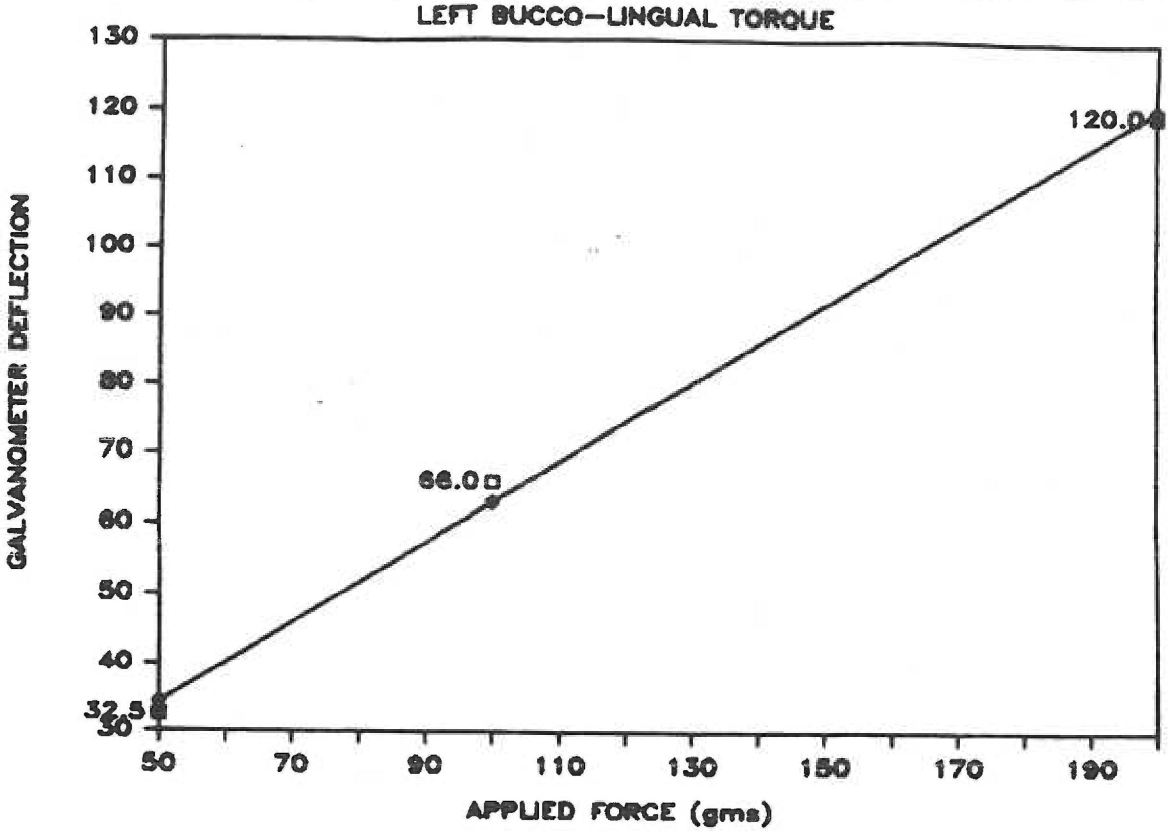
BRIDGE NUMBER	BRIDGE PURPOSE	RESULTANT FORCE (gms)	RESULTANT MOMENT (gms)	GALVANOMETER DEFLECTION
1	L. bucco-ling. tor	61.16	734.0	40.8
2	L. mesio-dis. tip	495.81	5949.7	190.0
3	L. intrusive-extr.	63.85		-4.8
4	L. anterio-post.	493.55		-160.0
5	L. medio-lat.	60.56		-23.2
6	R. bucco-ling. tor	41.43	497.1	24.8
7	R. mesio-dis. tip	310.00	3720.0	152.0
8	R. intrusive-extr.	146.10		-12.2
9	R. anterio-post.	438.68		-112.0
10	R. medio-lat.	49.44		-13.0

TABLE 4: ASYMMETRIC HEADGEAR (400GMS/SIDE)

BRIDGE NUMBER	BRIDGE PURPOSE	RESULTANT FORCE (GMS)	RESULTANT MOMENT (gms)	GALVANOMETER DEFLECTION
1	L. bucco-ling. tor	111.76	1341.1	-70.0
2	L. mesio-dis. tip	220.52	2646.2	87.0
3	L. intrusive-extr.	28.85		-2.2
4	L. anterio-post.	286.26		-95.0
5	L. medio-lat.	111.54		42.0
6	R. bucco-ling. tor	70.41	844.9	39.0
7	R. mesio-dis. tip	437.08	5244.9	210.0
8	R. intrusive-extr.	143.83		-12.0
9	R. anterio-post.	618.36		-160.0
10	R. medio-lat.	55.38		-14.8

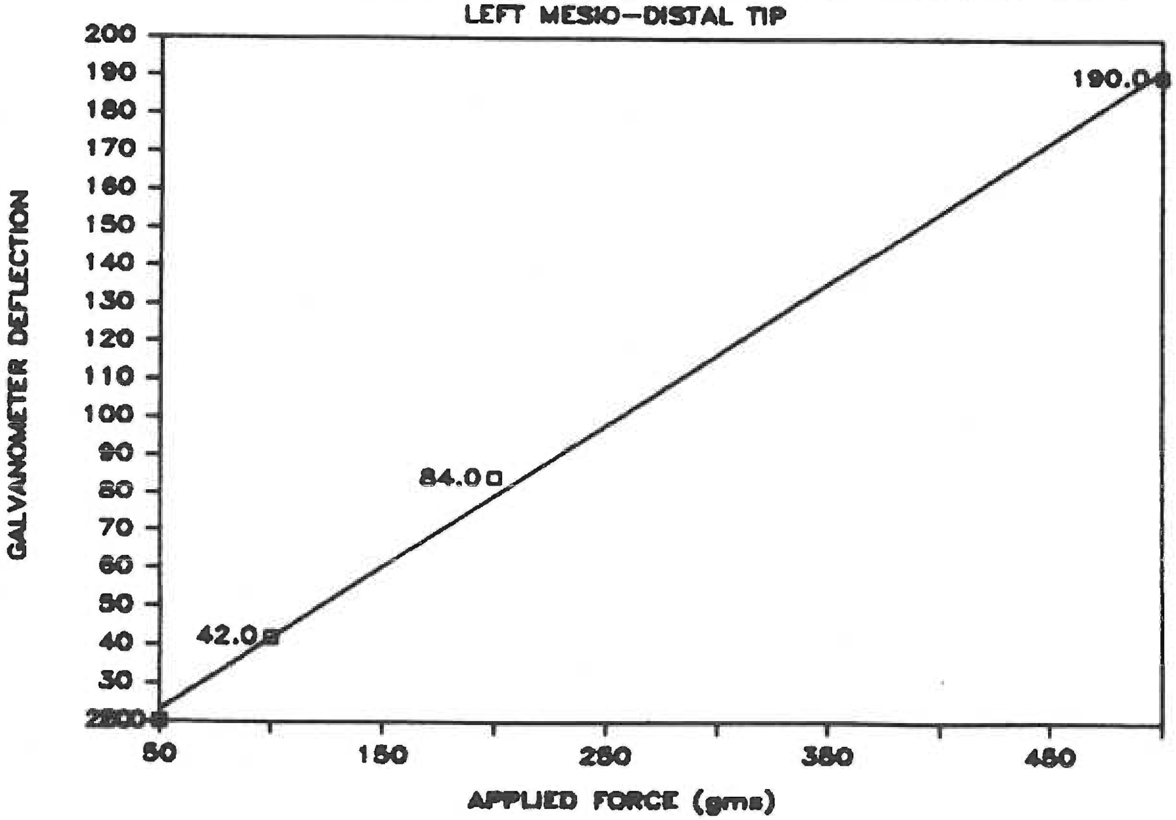
WHEATSTONE BRIDGE #1 CALIBRATIONS

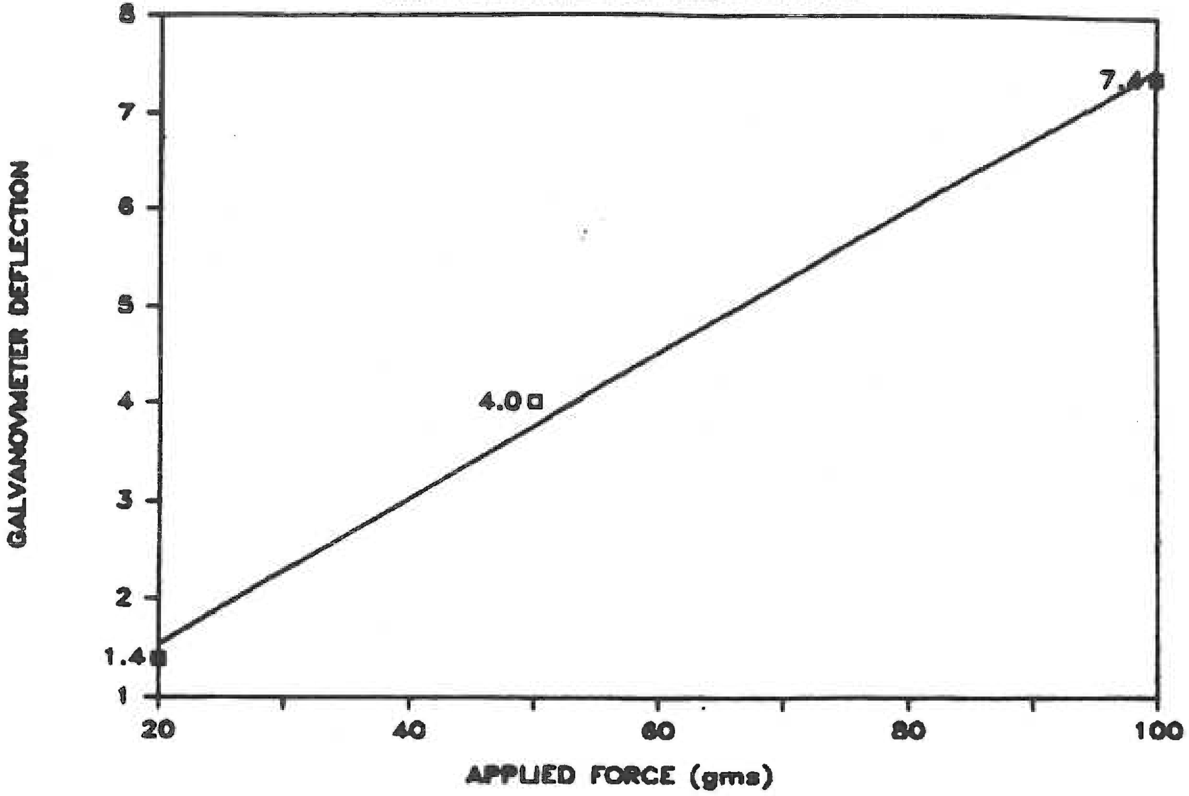
LEFT BUCCO-LINGUAL TORQUE



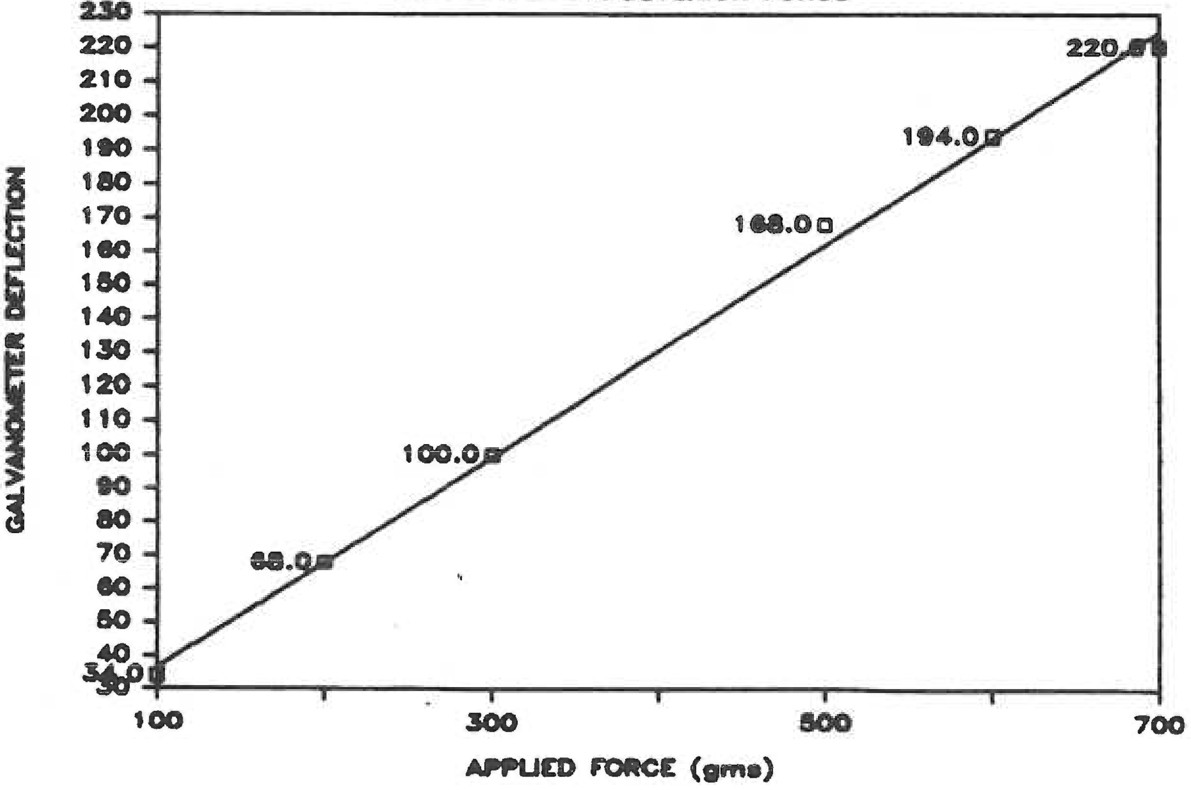
WHEATSTONE BRIDGE #2 CALIBRATION

LEFT MESIO-DISTAL TIP




WHEATSTONE BRIDGE #3 CALIBRATION

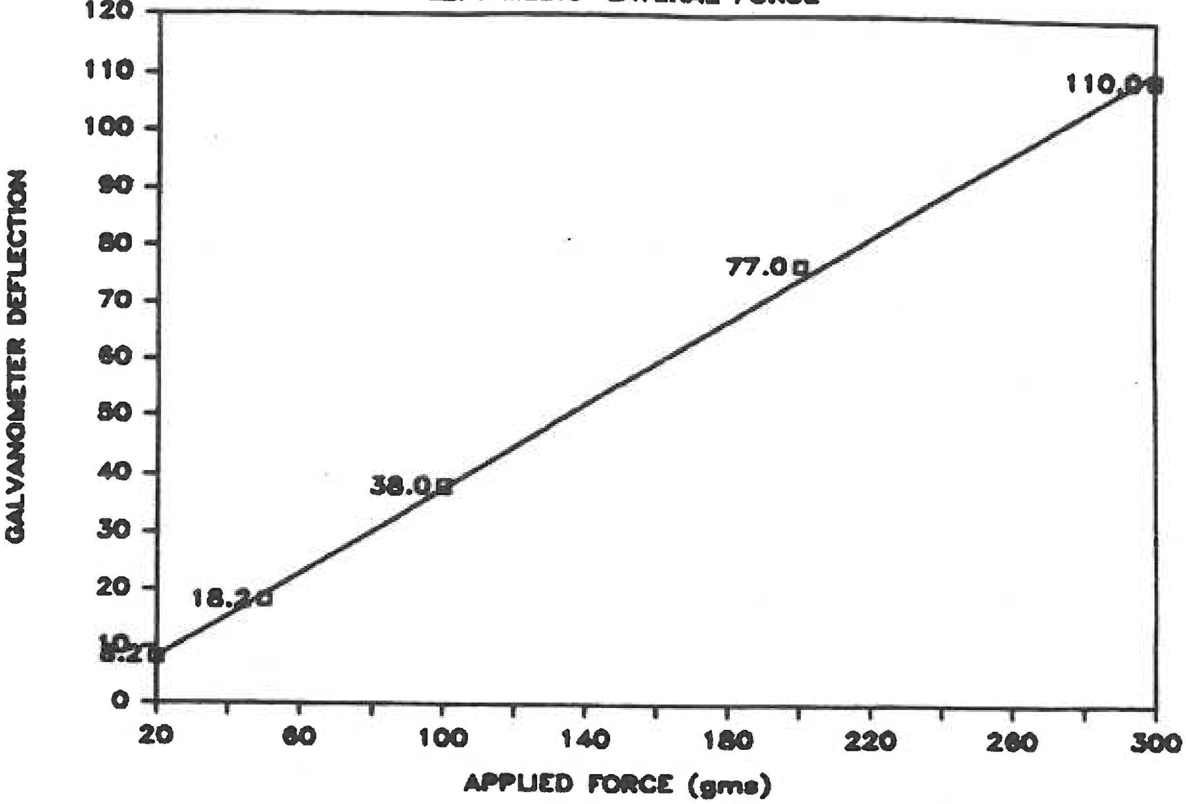
LEFT INTRUSIVE-EXTRUSIVE FORCE


WHEATSTONE BRIDGE #4 CALIBRATION

LEFT ANTERIO—POSTERIOR FORCE

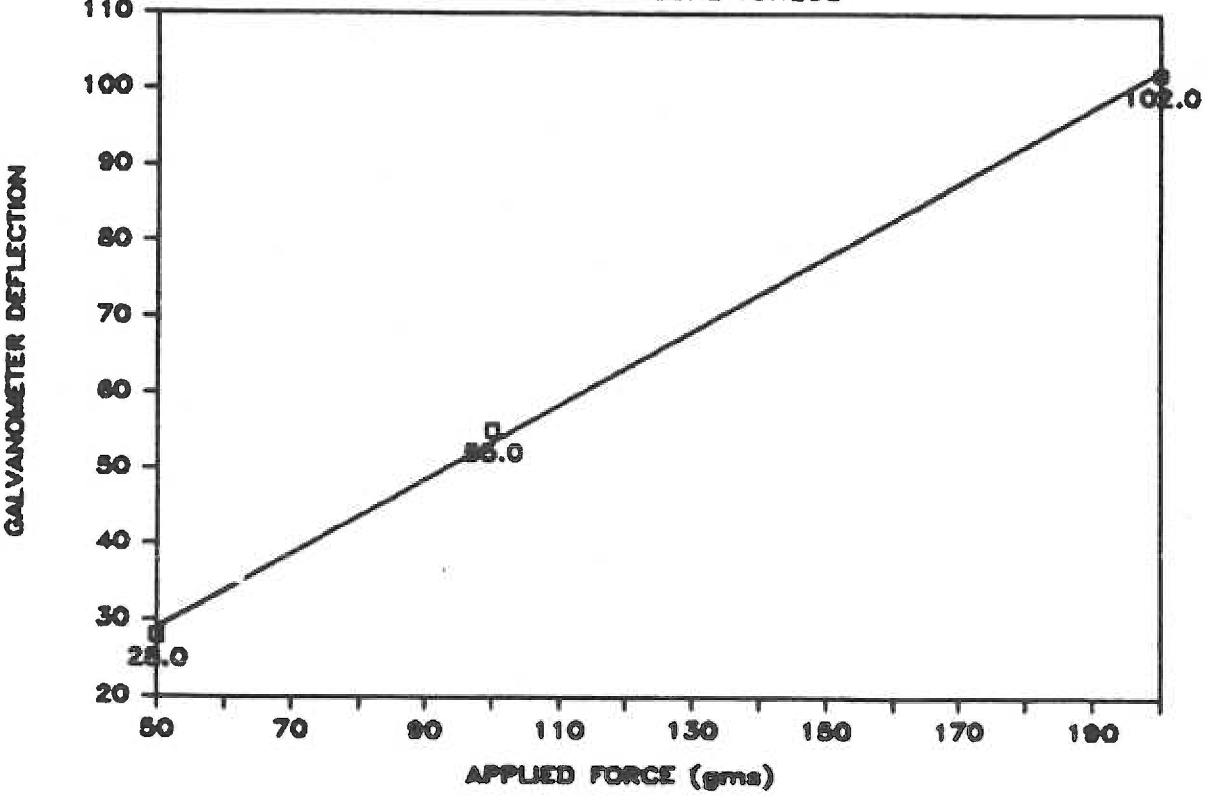
WHEATSTONE BRIDGE #5 CALIBRATION

LEFT MEDIO-LATERAL FORCE

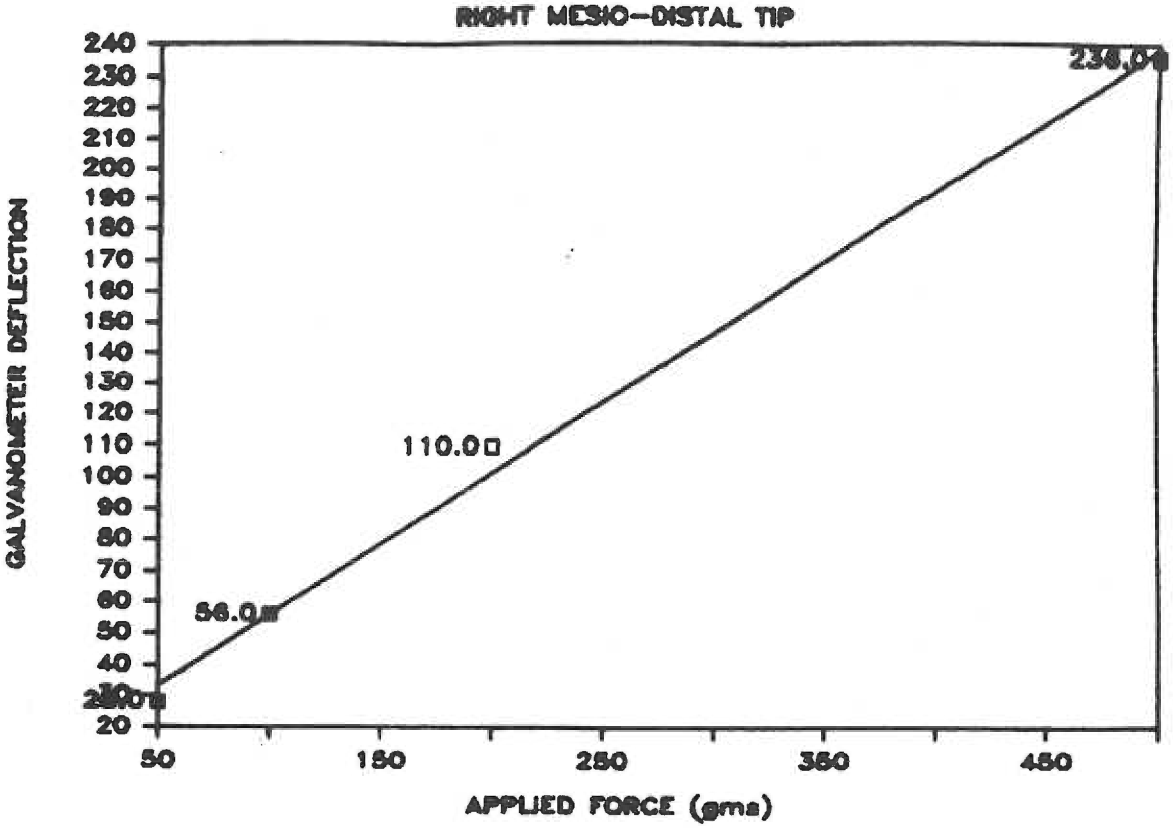


WHEATSTONE BRIDGE #6 CALIBRATION

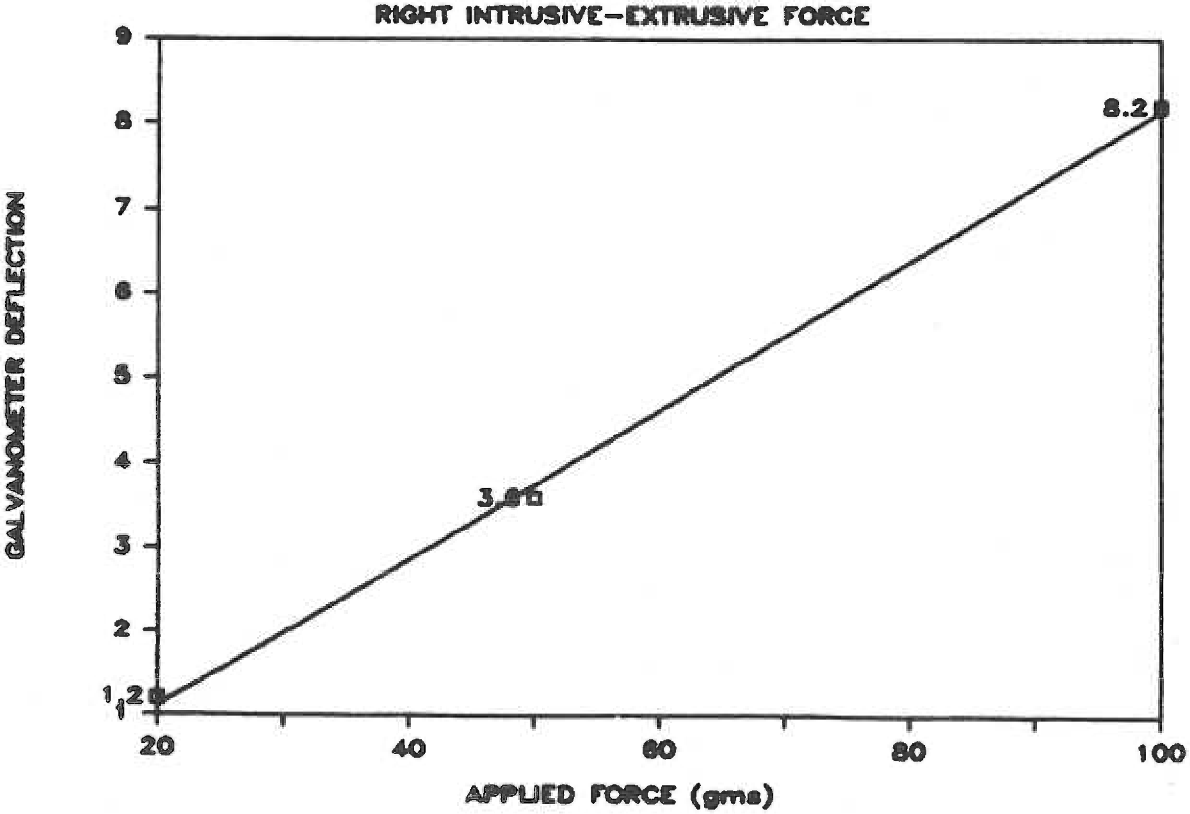
RIGHT BUCCO-LINGUAL TORQUE



WHEATSTONE BRIDGE #7 CALIBRATION

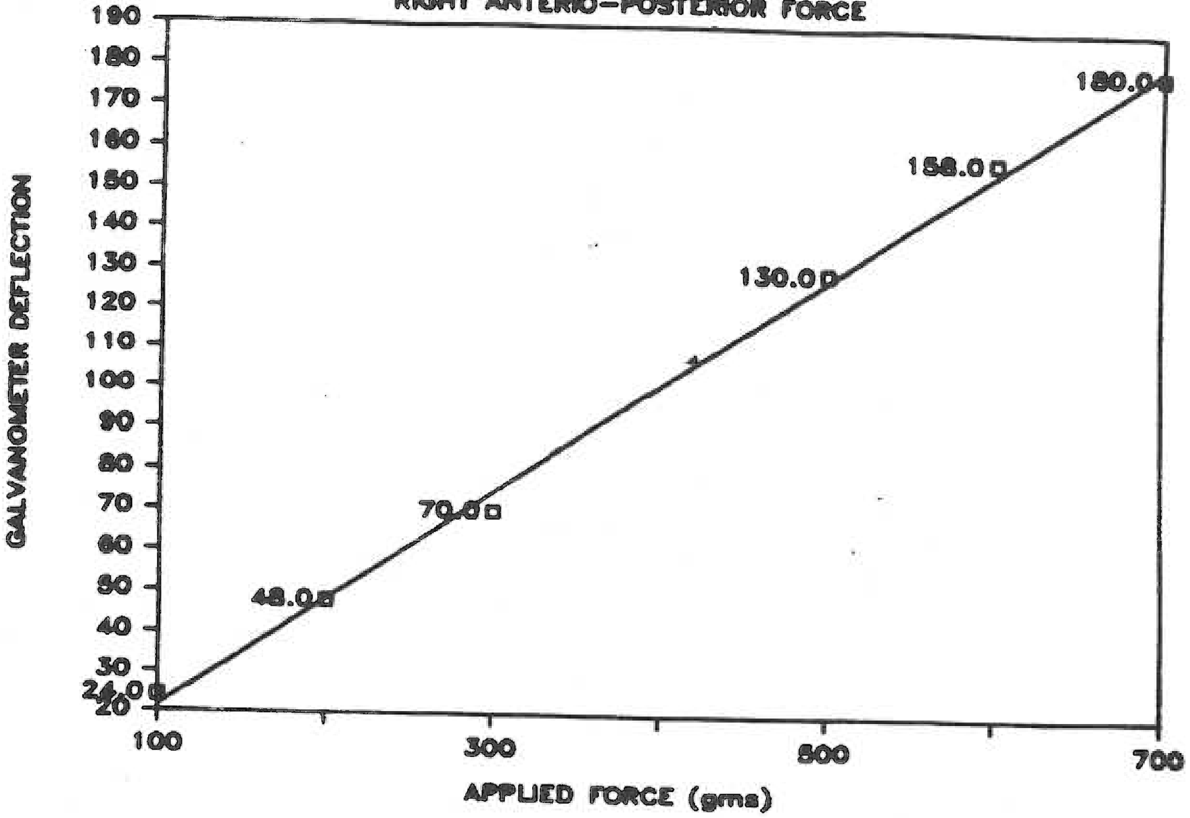


WHEATSTONE BRIDGE #8 CALIBRATION



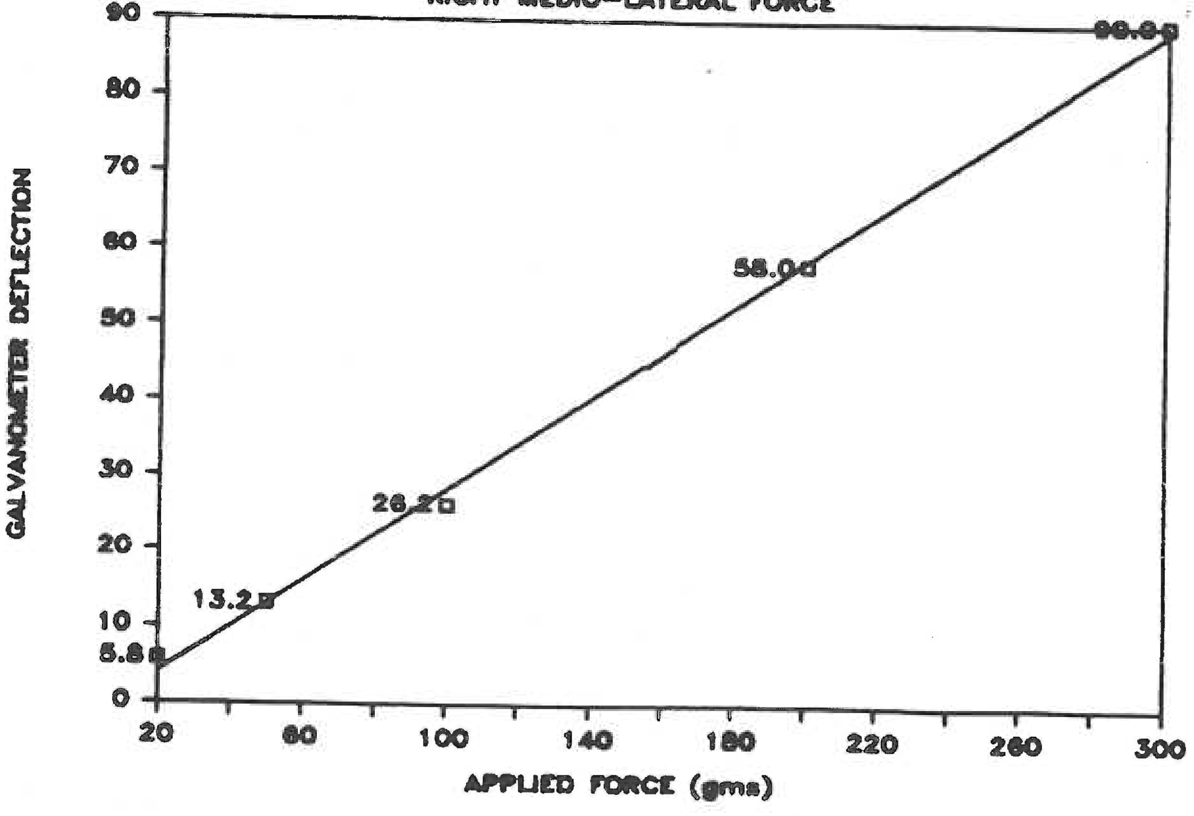
WHEATSTONE BRIDGE #9 CALIBRATION

RIGHT ANTERIO-POSTERIOR FORCE



WHEATSTONE BRIDGE #10 CALIBRATION

RIGHT MEDIO-LATERAL FORCE



DISCUSSION

The fabrication of the mechanical model became an involved project with numerous modifications to design being required as the fabrication evolved. The final design appears to have promise in its usefulness to further study headgear designs and their resultant forces.

Because of the complexity of the force system in a nonrigid body, such as a headgear bow, an analyzer of this type should be a valuable tool in resolving the various forces produced. Obviously, until the analyzer can accurately and repeatedly produce consistent results its use is negligeable. The trial runs utilizing the symmetric and asymmetric designs provided insight into the accuracy of the design as it exists today. From viewing the calculated forces for each component forces it became apparent that some areas of error in our calibration or design might still exist. Noting the forces recorded on the tables 3 and 4 we see that the component force values total more than the applied force of 400gms per side. Obviously this is not possible due to the fact that each of the component forces is equal to the applied force times the cosine or sine of an angle. At the same time, however, if we view the data recorded from the asymmetric facebow, we see that our model has recorded significantly different force values for the right and left sides with the relative amounts agreeing with the direction and magnitude that asymmetric designs have previously been shown to produce. Our findings show a relative greater distal force on the right side than the left, as would be expected. The medio-lateral registration shows a net medial force on the right and a net lateral force on the left. These also are in agreement with the direction of forces anticipated in an asymmetric design.

In viewing our calibration data and the scatter plots with regression lines overlaid, we see that each bridge appears to have a quite linear response with regards to galvanometer deflection to applied force. Table 2 demonstrates a high level of correlation with the R^2 values for each bridge being greater than .99. Because of this data, it is felt that the accuracy and reproducibility with this model is achievable but additional time will be required to refine those areas that may be contributing to the errors in force values.

A possible explanation of this error may involve a discrepancy in the calibrated force per unit deflection for each bridge. The most logical fault lies in the error of assuming that the deflection would be equal in both directions of force for each bridge. Because of possible inherent stresses in the gauges and or beams it is quite probable that the galvanometer deflection may be unique for each direction of the force. Further calibrations of each bridge in the direction of forces not previously calibrated will be required to rule out this oversight on my part.

Because of a design modification that was required to enable proper function of the Wheatstone bridges recording the bucco-lingual torque, the mesio-distal tip, and the intrusive-extrusive force, the model as it exists today is slightly cumbersome in measuring each of these galvanometer recordings. At present, it is necessary to disconnect the gauges from bridges 1, 2, 6, and 7 on the switching device and then reconnect them in a different configuration for the bridges 3 and 8. The addition of some type of simple switching device would remedy this problem, purely by adding to the ease of operation.

In the initial trial runs, the headgear force analyzer appears to exhibit significant sensitivity in resolving the forces into the desired components. The only area which could possibly be improved would be in the intrusive-extrusive force component where, due to the type of deflection this force produces in the feeler stock, force increments less than approximately 20gms will not be visible on the most sensitive setting of the Sanborn amplifier.

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