# On An Equilibrium Theory Of Tooth Position

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## STATEMENT OF PROBLEM

Both in clinical orthodontics and in the study of growth and development of the dentition, an understanding of the effects of the enveloping musculature upon the conformation of the dental arches into which the individual elements of the dentition fit is of great importance. Considerable subject matter has been written concerning these effects. For the most part such writings are based upon uncontrolled clinical observations. There are presently few references based upon precision measurements of movements of teeth induced by a natural muscular environment or describing the stabilizing influence of this environment.

Controlled study of tooth movement under the influence of those forces naturally imposed by surrounding tissues is not easily accomplished and the quantitative measure of the forces imposed by such environmental elements is quite difficult. Whether or not an equilibrium theory of tooth position can be accepted as fact may very largely depend upon the development and implementation of such controlled experiments. Acceptance of unsubstantiated theory regardless of its popularity on a basis of "it stands to reason" can hardly be considered scientifically proper.

For the past four years the Graduate Department of Orthodontics at the University of Nebraska has, through the efforts of graduate students and staff and with the support of grants from the National Institute of Health, Patterson-Hettinger Fund, and the Graduate Research Council of the University, concerned itself with experimentation designed to either confirm or discredit such an equilibrium theory. Evidence accumulated through those experiments is now thought to be sufficiently conclusive to warrant preliminary publication.

## I THEORETICAL CONSIDERATIONS

### EQUILIBRIUM

When any body is acted upon by forces exerted by surrounding bodies it is said to be in equilibrium if the resultants of all such forces and all moments in consequence of such forces are equal to zero.

The consequence of such equilibrium is a state of rest or of uniform motion, i.e., motion of zero acceleration. In the discussion to follow the state of rest is the one of primary concern. Conversely, if a body is not accelerated, which is

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certainly the case of a body in a state of rest, it can be concluded, without question, that this body is in a state of equilibrium and that the resultant forces and moments are zero.

The body in question is an element of the dentition. The forces thereon may be exerted by adjacent musculature, adjacent elements of the dentition, occluding elements of the dentition, other interposed materials, i.e., food bolus, thumb, fingers, etc., and of particular importance, the forces exerted on the root of the dental element by the surrounding bone acting through the periodontal ligament. It is to be noted that all of the first-mentioned forces exerted upon the tooth are exerted upon the crown, and that the last-mentioned forces are exerted upon the root. If a tooth is in equilibrium, and if the forces exerted upon the crown thereof have zero resultant, the equilibrium of the tooth as a whole does not require the development of forces upon its root. Likewise, if forces exerted upon the tooth crown do not in themselves produce equilibrium, then equilibrium must be achieved by reactive forces exerted upon the root through the medium of the periodontal ligament thus causing pressures and tensions to be built up in this very important tissue.

In light of the above-mentioned theoretical considerations it may be hypothesized that the individual elements of the dentition are in a state of equilibrium. At any instant this equilibrium may involve not only intraoral forces acting upon the tooth crown, but also forces exerted upon the root of the tooth by its surrounding bony structure through the periodontal ligament. Since such forces in the periodontal ligament are the initiating factors in tooth movement, whether these forces are of orthodontic or non-orthodontic origin, this "equilibrium position" must be such that the average distributed force over any reasonably extended period of time at any point in the periodontal ligament is zero. The "equilibrium position" of a tooth is thus a position from which it will not be moved by the natural environmental forces acting thereon. Conversely, if a time-linked resultant force were to exist in the periodontal ligament, the tooth would be expected to move to a position relieving this condition.

The above hypothesis may be referred to as the "equilibrium theory of tooth position," and the following experiments have been conducted to test its validity.

## II Review Of Literature

Literature concerned with tooth position and its relationship to muscular environment has its basis in subjective clinical observations. The resultant concepts, while alluding to equilibrium, usually do so with some degree of superficiality. While there is recognition, too, of a three dimensional field of this equilibrium, emphasis has been on the plane of occlusion.

Brodie[1,2] and Graber[3] stress the "muscle drapery" or "buccinator mechanism," a continuum of muscle surrounding the dental arches, and the muscular tongue mass inside the dentition. This relationship suggests a dentition trapped within a muscle force system.

Fischer[4], in taking issue with the "sanctity of the full complement of teeth", concludes that, "the primary factors in establishing dental occlusion and articulation as well as the movements of the condyle in the glenoid fossa are the forces exerted by the muscles surrounding the teeth and the ligaments supporting the mandible that limit these forces." Rogers[5], by continually sponsoring the "myofunctional therapy" concept of tooth movement, alludes, at least indirectly, to muscle forces and equilibrium positions.

Both Brodie[6] and Moyers[7] refer to the dimension of time as a contributor to this equilibrium picture. "As the teeth of the deciduous set begin to erupt and as their alveolar process is formed to accompany them, the contact is broken between cheeks and lips on the one hand and the tongue on the other. The teeth, once they emerge from their bony crypts, are completely at the mercy of their muscular environment so far as their buccolingual and labiolingual positions are concerned. Their arrangement will be determined by the equilibrium between the tongue on the inside and the lips and cheeks without. This condition obtains throughout life." Moyers is in general agreement in stating: "A change in muscular environment around a tooth will cause the tooth to move through the bone until it is again in balance. Change in quality, quantity or sequence of muscle contraction will be reflected in tooth position . . ."

A British group, Rix[8,9], Ballard[10], Gwynne-Evans[11], and Hovell[12] has, in recent years, given emphasis to the role of the surrounding musculature in the determination of dental arch morphology.

Brodie further discusses hypertonicity and hypotonicity with implications of increased muscle tensions and relaxed or "flabby" muscle tensions respectively. Whether these muscle tonus conditions are reflected in a dental arch of rotated and crowded units or in one with spacing between the teeth, the over-all dental picture again is a unique presentation of the equilibrium of the whole system.

Schwartz[13], in postulating an "orthofield" defined as a physicobiological continuum surrounding the dentofacial complex, says, "It can be thought of as consisting of the sum total of the forces which play upon the denture at any time in the life cycle of the individual."

There is recognition of components of force acting in the occlusal plane in addition to those directly the result of the outside envelope and the inside tongue mass.

Repeated references are made to "an anterior vector of force" associated with tooth migration or tipping in an anterior direction. However, the usual explanations of these "anterior vectors" are conspicuous by lack of either affirmative evidence or regard for basic phyical principles.

The influence of vertical forces on the equilibrium position of the dentition, too, has been noted. Some suggest that these forces originate in the system of musculature concerned with movements of the mandible. Moyers[14] states, "In the vertical plane the teeth are maintained up to the level of the occlusion plane by the alveolar growth influence."

Observations of various dentofacial dyscrasias have suggested further evidence of tooth position—muscle environment relationship. Jackson[15] states: "The influence of the deranged neuromuscular complex upon the dentoalveolar structures, continuing over a period of time, brings about the maldevelopment by causing a loss of equilibrium in the functional unit formed by the skeletal framework of the maxilla and mandible and their muscular attachments. The variation in the normal tonus of the muscles of the face, most often hypertonic, as is often present in cerebral palsy, and the perversion of the muscular actions associated with the acts of swallowing and speech, characteristic clinical features of cerebral palsy, are important from an etiological standpoint as causes of malocclusion and arch deformities."

Brash, McKeag, and Scott[16] cite literature concerned with cases of muscular dystrophy and facial paralysis with accompanying asymmetries of dental arches.

Cases of congenital aglossia evidence extreme constriction of dental arches, especially in the mandible[17,18]. There is evidence, too, of an underdevelopment of the mandible proper.

The relationship of upper incisors to postural position of upper and lower lips has long been recognized. Recently, Sclare[19] again emphasized the influence of the "trapped lower lip" on the position of the upper incisors. Both the position of the lower lip to the incisors and the lip muscular tonicity are important factors in the inclination and spatial relationship of the incisors.

Townend[20], in evaluating Class II malocclusions of a set of monozygotic twins, found that in one the lower lip was trapped completely behind the upper incisors, whereas, in the other, the lower lip covered the incisal third of the upper central incisors. The axial inclinations of the incisors in the two subjects were markedly different.

The constancy of individual arch dimensions as related to time again fortifies the tooth position-muscle environment theory. Riedel[21], in evaluating a series of twenty-two treated orthodontic cases some time out of retention and in which the mandibular canine width was maintained or expanded, found that in all cases there was either a maintenance of or return to the original dimension. Riedel cites two other collections of cases long out of retention which further support the concept of stability of both the intercanine and intermolar dimensions.

Scott[22] is in disagreement with the concept of the determination of the dental arches by the influence of the surrounding musculature. He postulates on fetal material observations that this encompassing soft tissue adapts itself to the position of the teeth.

Brodie[13], who recognizes the muscle influence on size and form of the dental arch, but who disagrees with the inviolability of original arch dimensions, suggests that the muscle pattern at one age is no indication of what the muscle pattern will be at a later age.

Scott[24] further states: "It would seem that the hypothesis that arch form and tooth position are determined primarily by muscle action, is certainly not established to the extent postulated by some of its upholders, in that the role of the musculature requires further study before this hypothesis can be accepted even in a modified form."

However, Scott does suggest that muscle action is important in the natural alignment of displaced teeth without further treatment, once space has been made available in the dental arches. He states that it should not be difficult to design specific experiments to measure the effort of natural muscle forces on displaced teeth.

Attempts to quantify the muscular forces around the dentition have led to the use of several instruments. Schlossberg[25], using electromyographic techniques, compared perioral and suprahyoid muscle activity in five individuals with normal occlusion and five with Class II malocclusions. The mentalis activity was more pronounced in the Class II group than in the normal one with a positive correlation between this activity and the severity of the malocclusion. Both groups showed reproducible constant rest positions.

The manometer was the instrument of choice for another series of muscle force measurements. Feldstein[26] determined a maximum force of 3.5 gms. exerted on the buccal surface of the right molar in twenty-five individuals with Class I molar relationship. In the article referred to here, Feldstein does not report on sufficient data for significant conclusions.

Stevens[27], using a manometer with a flexible bulb transducer, attempted to evaluate the range of force directed on the labial and lingual surfaces of maxillary and mandibular central incisors of Class II, Div. 1 malocclusions. In all three positions, occlusion, rest and swallowing, the correlation coefficient between lingual and labial muscular pressures was insignificant. In swallowing, the lingual pressure exceeded the labial pressure in all persons tested.

Kydd[28], using a manometer, evaluated maximum forces exerted on the dentition by the perioral and lingual musculature. The greatest maximum pressure of 8.05 pounds per square inch was on the lingual aspects of the upper incisors, and the least maximum pressure of 1.3 pounds per square inch was exerted by tongue against the lower first and second molar region. Lip pressures were 4.4 pounds per square inch. Kydd concluded: 1) that either the forces of the lips or the tongue, if unopposed, were capable of moving teeth, 2) that the hypothesis that the force of tongue from within the dental arches is normally compensated for by action of lip and cheek musculature was not substantiated, and 3) that other balancing forces were thought to exist.

The limitations and inherent errors of the manometer pressure system led to the development of the strain gage techniques. Alderisio[29] suggested the use of a base plus a wire resistance strain gage which was inserted into the mouth. The apparatus, which incorporated a multiple leg bridge circuit, was initially balanced, and readings were recorded under active and passive muscular conditions. His results suggested little or no pressure, active or passive, on the canine area, but progressively increasing pressure toward the molar region. The increase in differential between passive and active forces was also progressive from canine to molar regions.

Winders[30], using this strain gage technique, with a series of exercises, measured ranges of forces applied to the dentition by perioral and lingual musculature. His conclusions suggested that: 1) there is no apparent increase in pressure on the buccal surface of maxillary first molar or on the labial surface of maxillary central incisors during swallowing activity, 2) there is an increase in pressure on the lingual surface of the mandibular first molar during the swallowing act, 3) there appears to be more pressure exerted on the dentition by the tongue than by the buccal musculature during speech, 4) there is more pressure exerted by the tongue on the dentition during maximum effort than by the buccal musculature, 5) the tip of the tongue is capable of exerting the most force, with the side of the tongue, upper lip and cheek following in that order. Winders further concluded that the apparent imbalance of lingually and buccally directed muscle forces acting on the dentition indicates that the position of the teeth is dictated primarily by the skeletal base. It is further suggested that other forces needed for equilibrium might be forces of occlusion, lingual inclination of teeth, design of roots, and their attachment to the alveolus.

Subsequent investigation by Winders[31] concerned muscular forces on the dentition during swallowing. He found no statistically significant correlation between swallowing pressures and anteroposterior position of teeth.

Graber[32], in reviewing Winder's conclusions, admitted that the maximum functional force values of tongue versus perioral muscles did not represent a system of mean values and could not be representative of the mean equilibrium picture.

Dixon[33] used a free-sliding (buccolingually) pontic embedded in a viscous plastic base (chewing gum) on a partial. By positioning this pontic buccally or lingually out of the line of the natural dental arch, and allowing the subject to wear the partial overnight, he noted that there was no uniformity of final position of pontic to arch configuration.

Muscle tissue has the property of extensibility or elasticity. Muscle has been identified as a "biological" elastomer. King and Lawton[34] defined elastomers as "substances exhibiting long range elastic behavior. Ordinarily they contain long macromolecules, so randomly twisted and intermeshed that any disturbance in one direction is communicated in all directions." Biologic elastomers are "the high polymers of body cells which for the most part are long protein macromolecules, whose structure may vary according to the numerous possible arrangements of their structural units, the amino acids. These long molecules occur in a variety of forms, progressing from randomly twisted threads to crystalline networks. In general, the properties of various tissues are attributable directly to their molecular structures, and it is expected that variations in orientation and crystallinity go hand in hand with variations in function." They feel the most outstanding and most easily observed characteristic of rubber and other elastomers is their long-range reversible extensibility. Rubber-like substances also exhibit plasticity depending on the amount of stretch and the temperature. This phenomenon gives rise to relaxation (decay of stress at constant extension) and to creep (increase in length at constant load). Many tissues of the body display long-range reversible extensibility, relaxation and creep. In most body tissues at rest, the macromolecules are partially oriented and therefore the tissues may show limited long-range reversible extensibility. This is particularly true of relaxed, isolated whole muscle where, in addition to the oriented molecules of myosin, highly oriented collagenous tissue also is present.

Buchthal[35] found that extensions up to 200% of rest length were possible for an isolated muscle fiber. Ramsey and Street[36] have reported contractions of 20% from rest length in an isolated muscle fiber. These findings certainly suggest a great range of extensibility, as well as a modest range of contractibility.

Granting some knowledge concerning muscle extensibility, its stress-strain pattern during extension has not been clearly defined. If it behaves like rubber, as some suggest, what type stress-strain curve may be expected? King and Lawton state that "rubber-like materials when stretched from their thermodynamically most probable state often yield S-shaped stress-strain curves." Kesson[37] demonstrated that the sigmoid pattern is characteristic of muscle tissue when stretched from the contracted state. In contrast to this, King and Lawton state that "when muscle tissue is stretched from the relaxed state, the pattern is different; the stress-strain curves have no inflection points and have long been considered hyperbolic."

Brisbin and Allen[38] investigated the elasticity of muscle in the frog, crab, and lobster, finding their data to conform to the logarithmic law $E = k (\log W) + c$ where E is the extension, W the stretching force, and k and c are constants. This law was found by them to hold for both striated and smooth muscles. They stated that muscle did not conform to a hyperbolic law of elasticity, but rather to a logarithmic one. They also demonstrated several linear parts in each of their stress-strain graphs indicating nonconformity to Hooke's law.

Bull[39] studied the elastic properties of several protein materials. He produced stress-strain curves; among those of interest were (a) ox ligamentum and (b) nylon stocking. The stress-strain curves of these materials do not conform to Hooke's law and are not unlike those of Brisbin and Allen for the frog, crab, and lobster.

Buchthal and Rosenfalck[40], commenting on noncontracting muscle or resting muscle, state, "it has an elasticity which is similar to that of rubber; a small force is sufficient for its elongation, and it can be stretched without material plastic changes up to about double its equilibrium length. It displays a non-Hookean elasticity, its stress increasing relatively more than its strain."

## III Measurement Of Differential Buccolingual Force In The Bicuspid Area

A subject was found with an edentulous area limited to the upper right second bicuspid and first molar but with an otherwise sound dentition. After some experimentation it was determined that a differential force transducer could be built in such a way and of such small size as to make possible its installation within the molar pontic of a partial restoration for this subject. The bicuspid pontic of this restoration was mounted on the sensitive element of the transducer to measure the magnitude of the unbalanced force in the buccolingual direction. The sensitive element of this transducer consisted of a copper cantilever flexural member 1/8 inch wide, 1/32 inch thick and about 1/2 inch long to which 1/16 inch gage length wire resistance electric strain gages were cemented. These electric strain gages were so located and wired as to be self temperature compensating. A buccolingual force applied to the bicuspid pontic caused slight bending of the flexural member and, as a result, induced strains on the surfaces of that member which were detected by the strain gages in terms of changes in the resistances thereof. These changes in resistance caused changes in the characteristics of a bridge circuit which in turn could be recorded on a moving paper tape by an oscillograph. Deflections of the pen line on the oscillograph tape were interpreted in terms of grams of force after suitable calibration tests. Figure (III-1) is a drawing showing three views of the partial restoration and its internal construction.

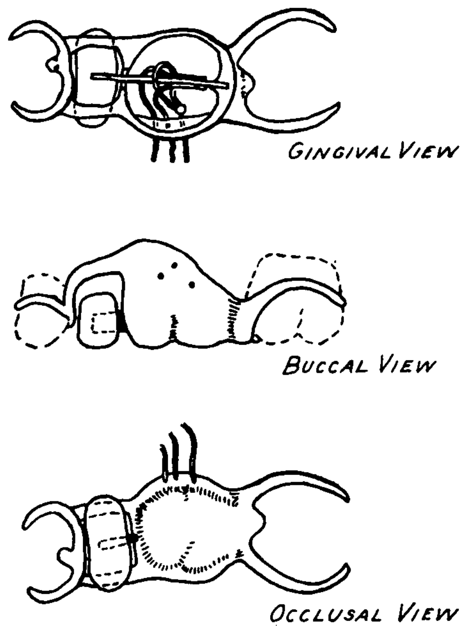


**Fig. III-1 Three views of partial restoration with transducer for buccolingual force measurements.**

The experiments were conducted in the following manner. The partial restoration was fitted in the subject's mouth and the zero force position was determined so that the pen line could be adjusted to the center of the paper tape. The subject then proceeded through a short series of exercises, the effects of which were recorded on the moving paper tape. The exercises were as follows:

1. Relax to permit the subject to acclimate to the presence of the foreign object.
2. Traverse the inside of the dental arches with tongue to bring the tip of the tongue into contact with the lingual surfaces of the teeth.
3. Produce the effect of sucking by puckering the lips with the teeth slightly ajar and evacuating the oral cavity as if sucking through a straw.
4. Read a short paragraph.
5. Swallow three or four times using accumulated saliva with which this subject was abundantly supplied.

Between exercises the subject always returned to the initial relaxed position.

The series of exercises was repeated with each of five bicuspid pontics. Each of these pontics, while of uniform buccolingual dimension, had a different buccolingual position varying from 2 mm lingual version to 2 mm buccal version by 1 mm increments. The midrange of these five pontics was, in the opinion of the investigators, in the normal buccolingual position of the bicuspid which it replaced. Figure (III-2) shows the partial restoration with the pontic located 2 mm in buccal version.

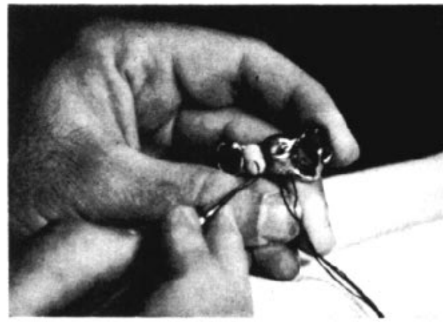

**Fig. III-2 Partial restoration with force-measuring pontic 2mm in buccal version.**

In Figure (III-3) are shown three recording tapes from the phase of the exercises in which the subject was asked to run his tongue around the inside of the mouth. Each of these tapes is labeled as to pontic position. The exercise was repeated three times on each tape. Note that in tape (a) where the pontic was 2 mm to the buccal, traversing the inside of the mouth with the tongue had very little effect. In tape (b), the normal pontic position, the effect of the above exercise is considerably more pronounced. In tape (c), where the pontic was 2 mm to the lingual, the effect is seen to be still more pronounced. In fact, the maximum displacements of the pen line represent not the magnitude of the buccally-directed differential force, but the limit to which the pen could be deflected. It would seem from these observations that, in this particular case at least, the influence of the tongue in pushing the second bicuspid in a buccal direction is definitely related to the buccolingual position of this tooth and such influence is much greater when the tooth is displaced 2 mm lingually than when it is displaced a like amount buccally. Furthermore, this buccally-directed influence is greater in the case of the lingually-displaced tooth and much less in the case of the buccally-displaced tooth than it is in the case of the tooth in normal position.

In some instances, however, the results of these experiments are much less easily interpreted. In Figure (III-4) are shown five tapes from the phase of the exercises in which the subject was asked to create a partial vacuum in the oral cavity to suck the cheeks against the teeth. As in the previous case the exercise is repeated three times on each tape segment. It is noted that the five tape segments corresponding to the five pontic positions show no great differ-

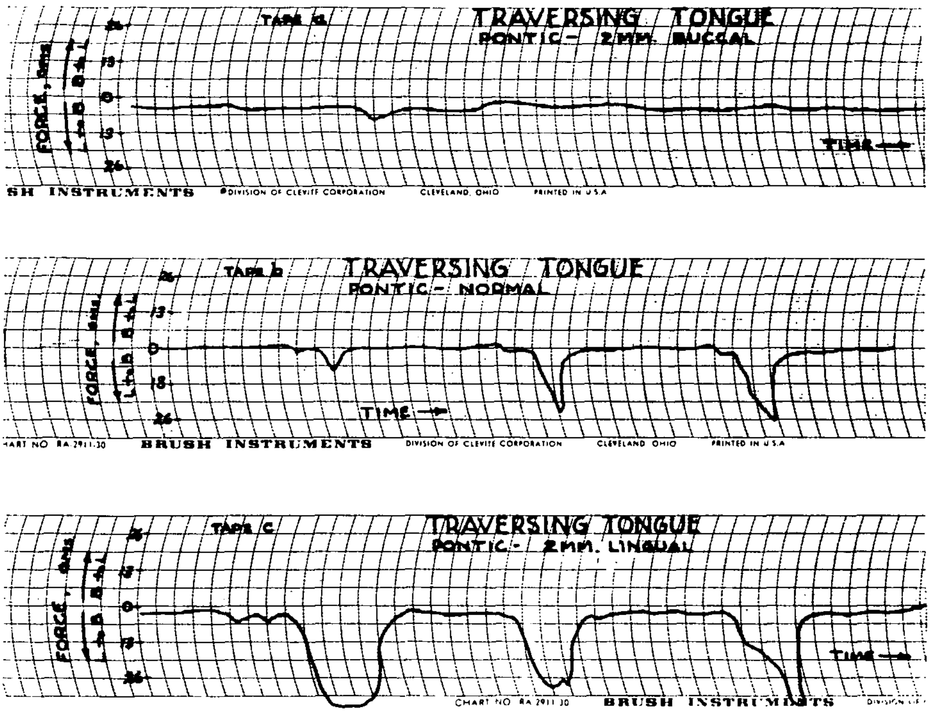


Fig. III-3 Recording tapes for tongue traversing exercise.

ence in lingually-directed force because of this exercise. Furthermore, there seems to be no discernible pattern attributable to the variation in pontic position. Just as it was improper to draw a definitive conclusion on the basis of a single sample in the case of the previous exercise, it is improper here to conclude that the pontic position has no effect on the magnitude of the lingually-directed force. On the other hand, these oscillograph tapes may reflect the general situation. The lingually-directed force in this case is caused by atmospheric pressure exerted on the outside of the cheeks, the buccal muscles being in the passive state. Under these circumstances the cheek tissues are very pliable and conform readily to the shape of the dentition. It may be altogether reasonable that the amount of the buccolingual pontic deviation used here was not sufficient to test conformability of the cheek tissues thus yielding the fairly uniform results for all five pontic positions.

In view of the fact that the above results were obtained from only one subject and cannot therefore be considered as conclusive in themselves, further discussion and the drawing of conclusions will be deferred to the end of this paper where these results can be considered along with results of other experiments to give a better overall picture of the environmental complex to which the teeth are subject.

## IV Multiple Positions of Stability

One of the principal stumbling blocks on the road to acceptance of an "equilibrium theory" of tooth position, arch shape, etc., is the fact that it is clinically obvious that there is, in many

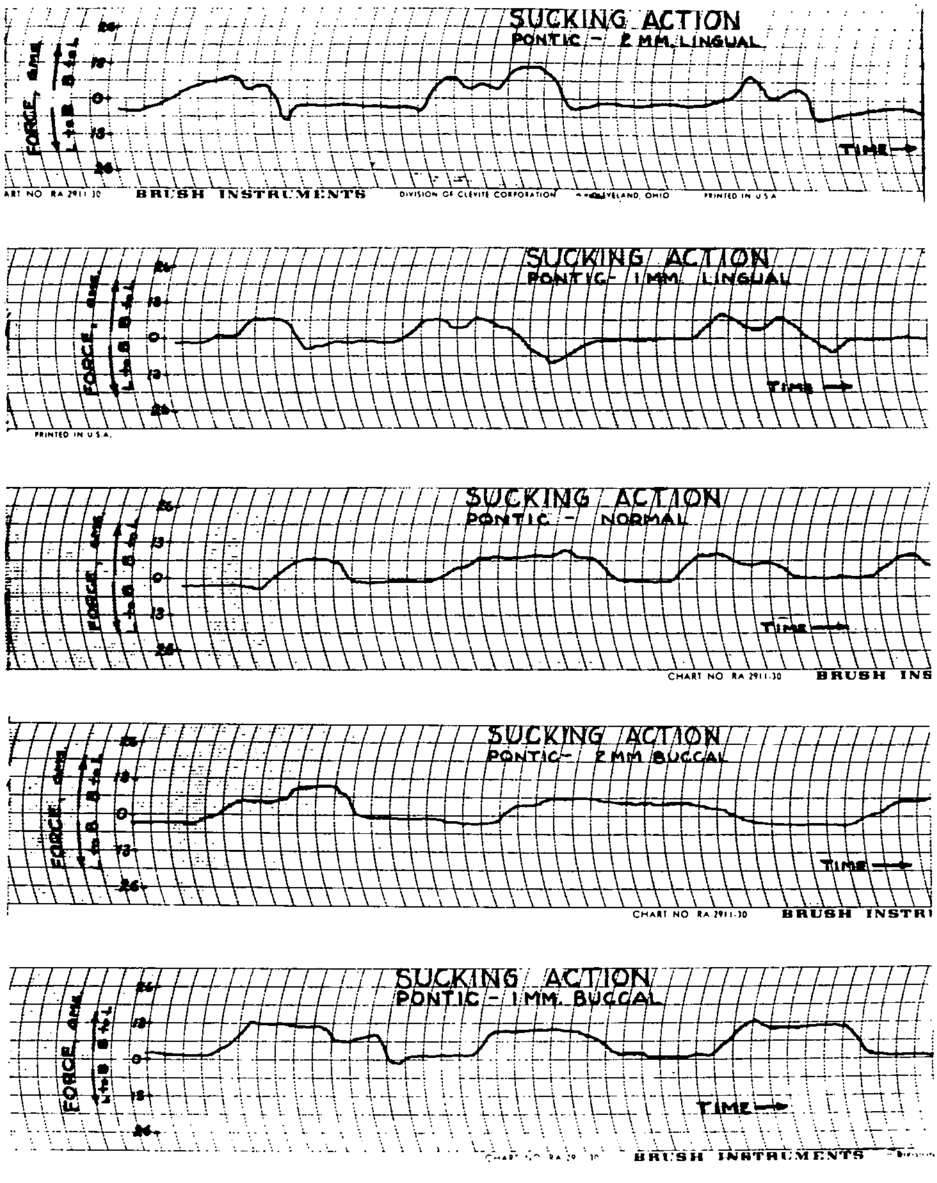


**Fig. III-4 Recording tapes for sucking exercise.**

cases, more than one stable configuration in which the teeth may arrange themselves while under the influence of normal perioral environment.

Actually, the possible existence of more than one stable position of equilibrium does not contradict the "equilibrium theory". Positions of stable equilibrium of any static body are determined by the state of potential energy of the system consisting of the body and its pertinent surroundings. If only one position of minimum potential energy exists, this will be the only stable position of the body. If more than one such minimal energy position

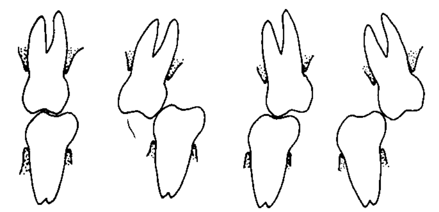


Fig. IV-1 Four possible stable positions of molar buccolingual relationship.

exists, however, each of these positions will be a stable one. This principle must apply to teeth as well as to other material bodies. This minimum energy concept of stable equilibrium position must be considered an integral part of an "equilibrium theory" of tooth position. In the case of the teeth the potential energy considered must be that stored in the surrounding muscular tissue. A frequently observed example of this multiple equilibrium position phenomenon is molar crossbite. In this case, at least, four such stable buccolingual positions may be recognized (Figure IV-1).

In each of the three illustrated instances of malocclusion the extant tooth relationship may be seen to be stable, since it will not change of itself, while the position of proper occlusion is also one of stability for, if it were not, the treated crossbite would always relapse. The possibility of more than one position of stable equilibrium exists in areas other than the one just discussed. In order to confirm experimentally the possible existence of at least two positions of stable equilibrium for the maxillary central incisors, the following experiment was conducted.

A model of the sagittal cross section of the maxillary central incisor and upper and lower lip region was constructed. The object was to study the relationship between the angle of incisor protrusion and the deformation of the labial tissue. In order to have a dimensionless measurement of labial deformation, this deformation was also measured in terms of angle, ($\Theta_1$ for lower lip and $\Theta_2$ for upper lip) (Figure IV-2).

Since energy stored in an elastic medium is a direct function of the square of the deformation of the medium, the sum of the squares of the deformations $\Theta_1$ and $\Theta_2$ was considered to be directly related to the energy stored in the prototype soft tissue. The model used here does not purport to be a model of any particular prototype person, nor is it capable of representing local deformation of soft tissue or the energy stored thereby. However, the model makes acceptable representation of the gross deformation of the soft tissue involved.

By varying the angle, $\alpha$, (Figure IV-2) corresponding variations in the lip angulations $\Theta_1$ and $\Theta_2$ were determined. The sum $\Theta_1^2 + \Theta_2^2$ was plotted on a graph against $\alpha$ as an independent variable.

If a position of stability for the maxillary central incisors other than the normal position were to exist, it would necessarily be represented by a second minimum on the graph so constructed. Figure IV-3 shows such a graph constructed from data taken

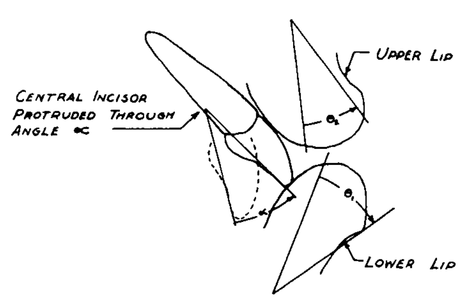


Fig. IV-2 Relationship of protrusive angles as measured on the sagittal cross section model.

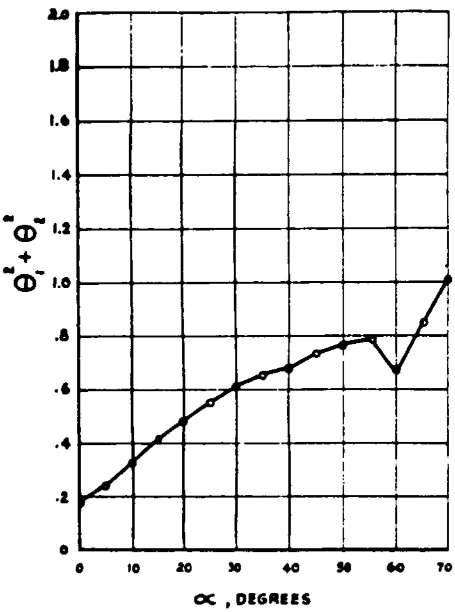


Fig. IV-3 Graph of $\theta_1^2+\theta_2^2$ vs. $\alpha$ showing secondary position of stability.

from the model described above. A secondary position of stability for the maxillary central incisor is a consequence of the second minimum on this graph. This position corresponds to the frequently observed "trapped lower lip." It is entirely possible, however, that a different vertical relationship between the incisal edge of the maxillary central and the lower lip could result in the existence of but one position of stability. Here the oral fissure would be at a lower level than the incisal edge of the maxillary incisor. This situation might be considered typical of a profile exhibiting a comparatively long upper lip. If the maxillary incisor does not contact the lower lip, it is obvious that this tooth cannot "trap the lip". Figure (IV-4) illustrates the graphing of such a situation. It is obvious that there is no second minimum $\theta_1^2+\theta_2^2$ position. This smooth continuous curve is representative of the storage of energy in

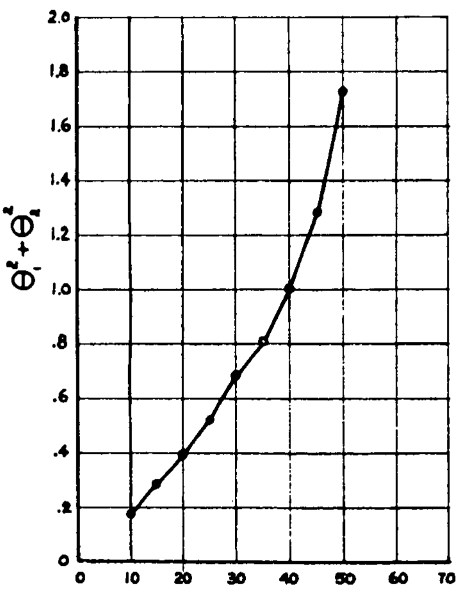


Fig. IV-4 Graph of $\theta_1^2+\theta_2^2$ vs. $\alpha$ showing no lower lip effect. No secondary position of stability.

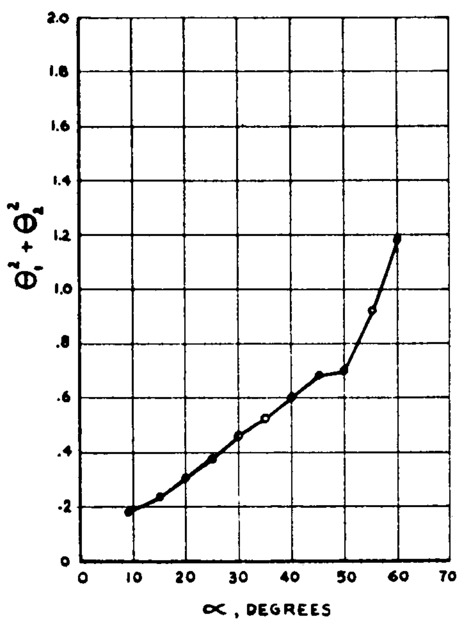


Fig. IV-5 Graph of $\theta_1^2+\theta_2^2$ vs. $\alpha$ showing lower lip effect insufficient for secondary position of stability.

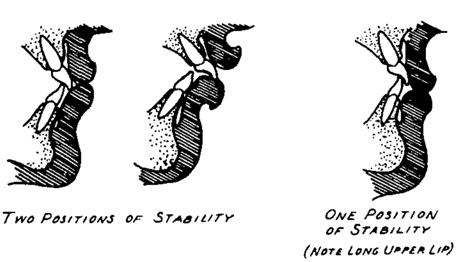


**Fig. IV-6 Sketch of sagittal cross section showing dual positions of stability as opposed to a unique position of stability.**

the upper lip only. Between these two previously described extreme situations there may exist relationships of the maxillary centrals to the lower lip in which the teeth contact the lower lip, but the $\Theta_1^2+\Theta_2^2$ curve does not exhibit a second minimum. (Figure IV-5). Here the interference with the lower lip has caused an irregularity in the curve, but there is no second minimum position associated with this irregularity. In terms of clinical observation this would represent a case in which the strong influence of the upper lip overcomes the relatively weak influence of the lower one. Figure (IV-6) shows a sketch of sagittal cross sections of the three lip-tooth relationships described above.

## V Measurement Of Forces On The Anterior Teeth

Another approach to understanding the influence of the labial musculature on the incisor position entails the use of a strain gage force measuring device. The device is comprised essentially of a plastic body, wire clamps, transducer bar, pontic, and two SR-4 strain gages. It resembles a maxillary retainer and has a transducer bar in the midline of the palate (Figures V-1, V-2). The electrical details of this device are the same as those described in the section of this paper dealing with the measurement of differential buccolingual force in the bicuspid area.

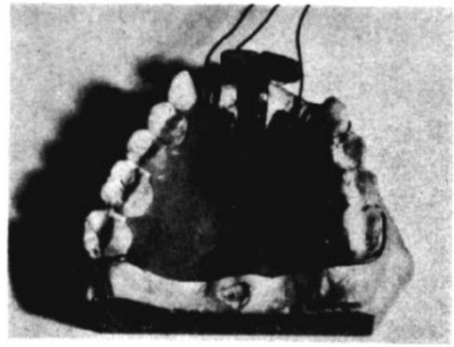

**Fig. V-1 Transducer device for measurement of forces on maxillary central incisors.**

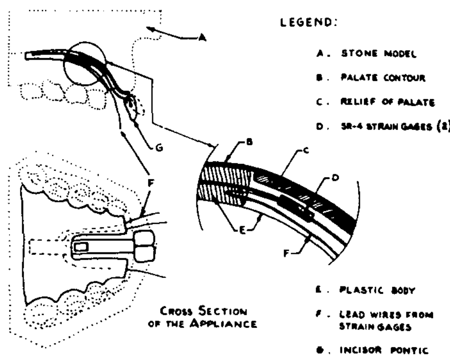


**Fig. V-2 Sketch showing construction details of device in Figure V-1.**

Construction of the appliance required subjects to have an edentulous area corresponding to the two central incisors to provide room for instrumentation. All these subjects evidenced Class I molar relationship with acceptable overjet and overbite. After seating the device in the mouth and balancing the bridge circuit each subject was instructed to perform three positive effort exercises: purse, pucker and lower lip thrust. The use of such standardized exercises makes possible a comparison of the forces acting upon the sensitive pontic for various angulations of this pontic for the same individual. The purse exercise consisted of pressing the lips together with the teeth in occlusion and with the contact between

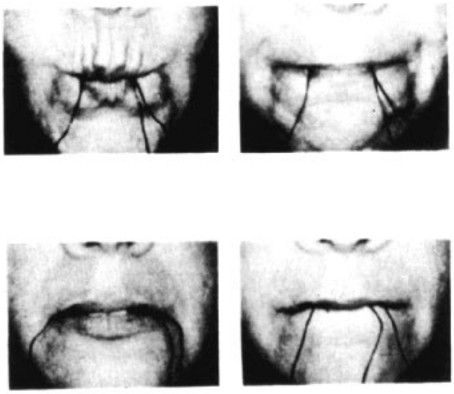

Fig. V-3 Frontal view of patient performing: upper left, pucker; upper right, purse; lower right, lower lip thrust; and lower left, post-effort rest exercises.

the lips extending anteriorly to the vermillion border. The pucker exercise consisted of "drawing up" the circumoral musculature with the teeth in occlusion. The lower lip thrust consisted of opening the mouth to a position where the lower lip could be placed between the maxillary and mandibular incisors. With the lip moistened it was allowed to roll anteriorly past the incisors and pontic to meet the upper lip. The teeth were brought into occlusion in the latter phase of this movement (Figure V-3). After termination of each positive effort the subject was instructed to permit the facial musculature to assume a relaxed or passive position. This position was termed the post-effort rest position. During all phases of the exercises the tongue was retracted to remain out of contact with the transducer bar.

The force exerted normally to the labial surface of the pontic was recorded on the oscillograph recording tape during the positive effort exercises and the subsequent post-effort rest positions. Each exercise was repeated several times as can be seen on the sample

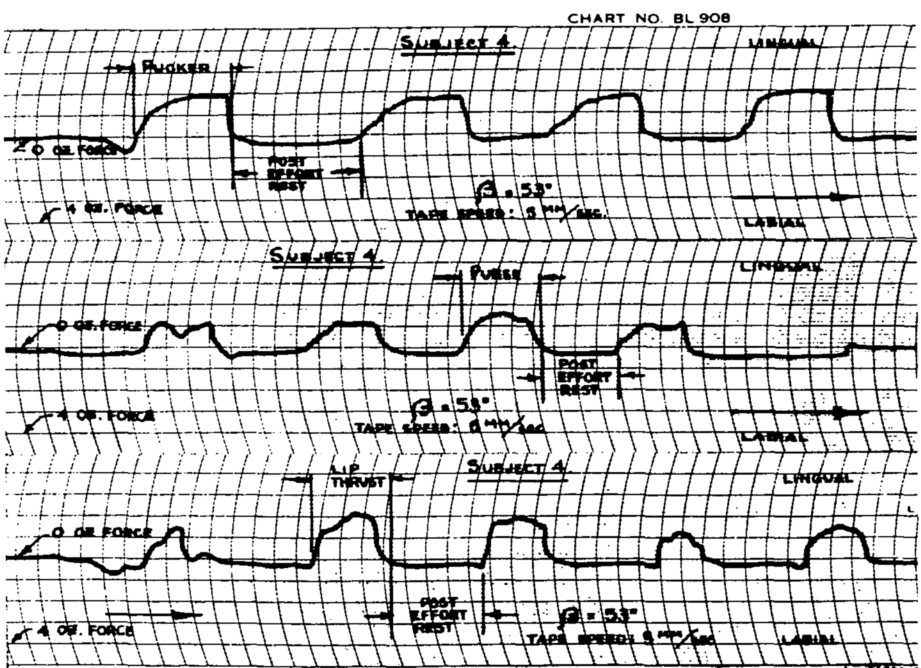


Fig. V-4 Recording tapes showing force measurements for the three positive effort exercises.

tapes in Figure V-4. After each exercise was completed, the angulation of the labial surface of the pontic, measured with respect to the occlusal plane, was altered by bending the transducer bar. The series of exercises was repeated for five different angulations. These angulations were measured by attaching a strip of lead foil on the labial surface of the central incisor pontic and on the occlusal surface of the posterior teeth. A lateral radiogram showed this x-ray-opaque material as two fine lines from which the angulation could be measured.

Four subjects were studied in the manner described above. The results of two of these studies are described here. These have been chosen because of the widely different interpretations of the results in these cases.

Subject one was a thirty-four-year-old white female with moderate upper lip thickness and length. Data is shown graphically in Figure V-5.

Looking first to the results of the positive effort exercises, it can be seen that pucker and lip-thrust maximum forces vary little in the range between seventy-three and fifty degrees. The purse exercise shows a maximum at about sixty-five degrees. As may be seen by comparison with the next subject, this is a fairly indefinite pattern displaying little tendency for stability at any single angulation. The post-effort rest forces on the other hand show two minimum force positions which could correspond to stable equilibrium configurations. One of these is in the sixty-five to seventy-three degree range and the other is at about fifty degrees. These points represent a concentration of the force patterns at minimum levels. The considerable difference in force scale values between the two graphs of Figure V-5 should be noted. The importance of the rest forces should not be treated in this proportion, however,

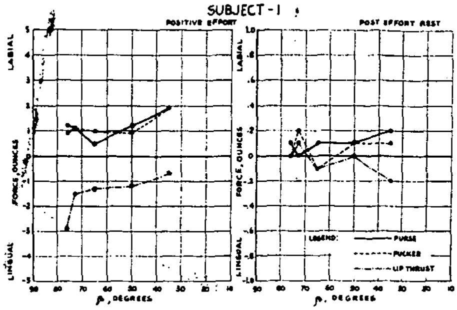


Fig. V-5 Forces vs. angle $\beta$ for subject one.

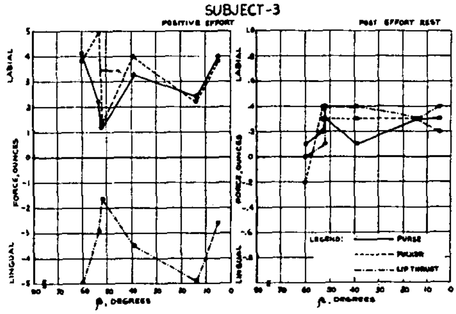


Fig. V-6 Forces vs. angle $\beta$ for subject three.

since these are of longer duration than the positive effort forces.

Subject three was a fifteen-year-old white male with a long and thick upper lip. Data is shown graphically in Figure V-6.

In the case of this subject the positive effort forces show a single distinct minimum at fifty-two degrees. Furthermore, the post-effort rest forces exhibit their only composite minimum at about the same angle. It appears that there is only one position of stability for the maxillary incisors of this subject.

## VI Measurement Of Buccal Forces In The Bicuspid Region

The measurement of cheek extensibility is an indicator of the elastic quality of the cheek and an estimator of the force exerted upon the buccal surfaces of the maxillary bicuspids.

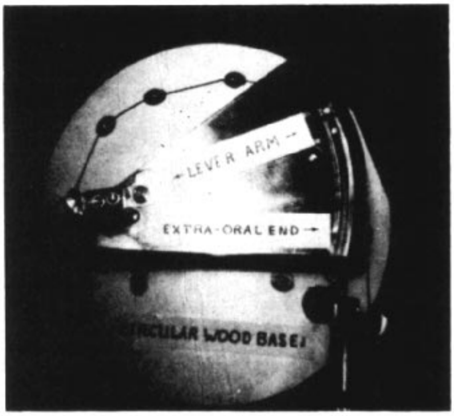


Fig. VI-1 Plan view of force-deformation instrument for testing cheek extensibility.

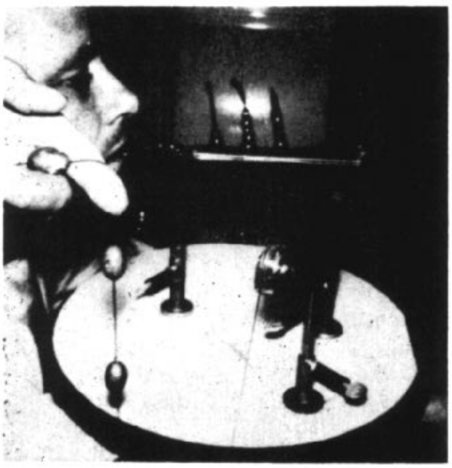

Fig. VI-2 Force-deformation instrument in use.

A force-deformation instrument (Figure VI-1) was designed so that calibrated weights added to the extraoral end of a lever would be transmitted to the internal cheek surface by the intraoral end of the lever. The stainless steel base plate on which the lever was pivoted was asymmetrically hourglass in shape and formed the basic biteplate and recording base. The smaller end of this plate was adjustable to accommodate dental arches of various widths. As a bite plate base it insured stability during the experiment. The intraoral end of the lever was a convex steel button 6.6 mm in diameter which contacted the internal cheek surface.

The weight was applied to the extraoral end of the lever by a small nylon cord. Eight weights spaced two and three quarters inches apart on the nylon cord were calibrated with their respective proximal portion of the cord to twenty-five grams each. This design permitted a rapid, easy method of applying successive uniform increments of force to the lever (Figure VI-2). As each weight was added to the extraoral arm of the lever, it moved this lever clockwise in a horizontal plane until the button on the intraoral arm deformed the internal cheek surface just enough to balance the weight. This deformation was then a measure of the elasticity or extensibility of the cheek tissues and could be recorded by the amount of rotation of the lever.

The following steps describe the procedure used to obtain and analyze data on cheek extensibility.

1. The subject was seated and instructed to grip the intraoral plate (covered with soft wax and gauze) between the teeth so that the button on the lever was positioned opposite the buccal embrasure of the maxillary first and second bicuspids. This procedure for gripping involved the muscles of mastication allowing the perioral and buccal tissue to remain relaxed.

2. The cheek was retracted and a measurement taken from the most lateral surface of the button to the buccal surface of the bicuspid tooth. This distance, referred to as the initial distance (i.d.), represented the amount the tissue had been deflected from the buccal surface of the bicuspids by interposing the button.

3. With the cheek again relaxed against the button, a zero starting mark was scribed on a transparent plastic sheet fastened on the base plate and under the movable lever. The first lead weight was allowed to hang free and to de-deform the cheek as the pointer indicator moved to the subject's right. The effect of the weight registered an immediate deformation followed by a secondary deflection or deformation. The total deformation was recorded by marking along the pointer after all pointer movements had ceased for at least ten seconds.

The same procedure was used to record deformation for each of the eight successive weight increments. The procedure outlined above was carried out on a sample of forty-eight Caucasian subjects. The age range of the sample was from nine to fifty-six years with the mean age 24.5 years and a standard deviation of 7.08 years. The sex distribution was six females and forty-two males.

The force displacement data of each subject, obtained as described above, were plotted in regular rectangular coordinates as shown in Figure VI-3. The relationship between force and displacement as exhibited in this graph is obviously nonlinear. The nature of the nonlinearity exhibited suggests that a semilogarithmic plotting of the data should yield a straight line. In accordance with this observation the data of each subject were also plotted in semilogarithmic coordinates, that is, the logarithm of the force was plotted against the deformation, Figure VI-4.

Two interesting results are obtained by the analysis of these semilogarithmic graphs. First, the straight line relation-

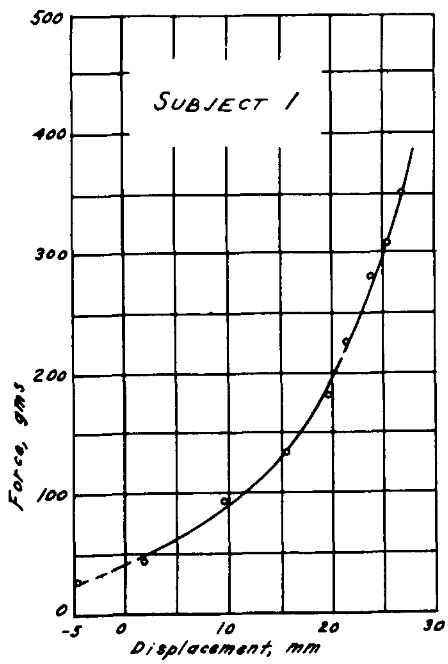


Fig. VI-3 Graph showing relationship of force and displacement of cheek in uniform rectangular coordinates.

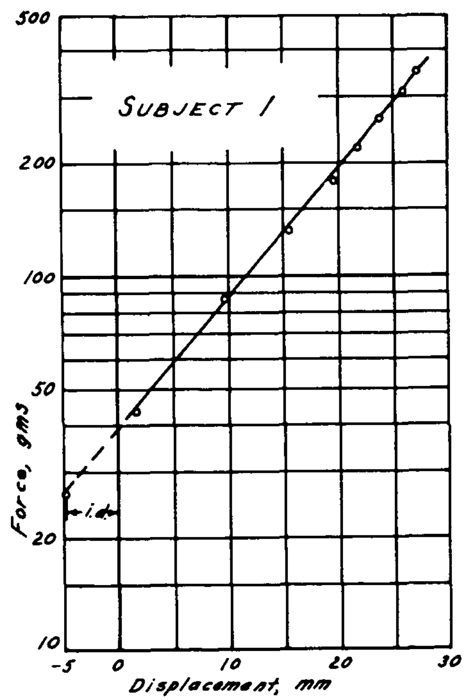


Fig. VI-4 Graph showing the same data as Figure VI-3 but plotted in semilogarithmic coordinates.

ship exhibited can be extrapolated to the left to compensate for the "initial distance" mentioned above. The ordinate of this straight line curve at this point is the logarithm of the force which would be exerted by the musculature against an area of tooth surface equal to the area of the interposed button. By dividing this force by the area of the button, the average pressure of the buccal musculature in the bicuspid region may be determined.

Second, the rate of change of the force, with respect to the displacement of the buccal tissue at the buccal surface of the biscuspid, can also be determined. This rate of change is best described as the "stiffness" or elastic index of the tissue. It is felt that this quantity is of considerable interest in the analysis of muscle forces exerted on the teeth. The stiffness is actually the rate with which the force exerted by the cheek on the surface of the biscuspid increases with the buccal displacement of that tooth. Designating the stiffness by E, the following formula may be used for its determination:

$$E = \frac{\log_e \frac{F_1}{F_0}}{\Delta_1} F_0$$

Where $F_0$ is the force at the tooth surface, $F_1$ is the force at any arbitrary displacement $\Delta_1$. $\mathrm{Log}_e$ indicates natural logarithm. This stiffness can also be expressed in terms of pressure by dividing by the area of the button.

The extrapolated force from the forty-eight subjects showed a range of 15.5 to 34.5 gm. The mean was 24.19 gm and the standard deviation was 4.022 gm.

The stiffness ranged from 1.27 to 3.0 gm/mm. The mean was 1.94 gm/mm and the standard deviation was .308 gm/mm.

The extrapolated pressure was .7 $gm/mm^2$ and the stiffness in terms of pressure was .057 $gm/mm^3$.

The magnitudes of force and stiffness reported here may at first seem startlingly large. However, it must be remembered that this observed force on the buccal surface is equilibrated by forces exerted by a very active muscle, the tongue.

## VII Tooth Movement Caused By Unbalanced Muscular Forces

In each of the previously described experiments the principal concern has been for the measurement of forces acting upon certain elements of the dentition, or for the development of fundamental philosophical aspects of the "equilibrium theory" of tooth position. As yet, no measurements of the actual movement of teeth subjected to the natural intraoral forces have been reported.

In order to examine the movement of a tooth as it seeks an equilibrium position in the dentomuscular complex, it must first have its equilibrium upset, for a tooth which is in its equilibrium position cannot be expected to move. The research described in the following paragraphs is concerned with measuring the buccolingual movement of upper and lower first bicuspids, the natural equilibrium positions of which have been disturbed by the attachment of a gold onlay extension on either the buccal or lingual surface. (Figure VII-1). This gold extension effectively increases the buccolingual dimension of the bicuspid but places all this increase on one side of the tooth. Ideally, if the natural stiffness and functional activity of the musculature on the two sides (buccolingual) of the tooth were precisely the same, the expected equilibrium position of the tooth would be shifted by one-half the thickness of the extension. If the stiffness and functional

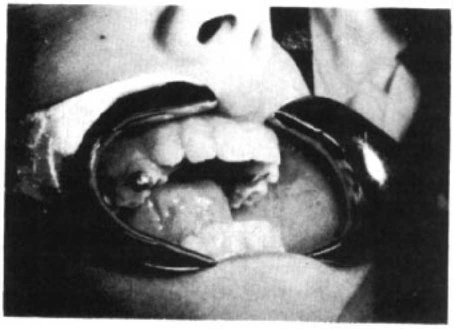

**Fig. VII-1 Gold extension onlay applied to the buccal surface of a first bicuspid.**

activity are not symmetrical, the shift of the equilibrium position might be somewhat more or less than half the thickness of the extension and would be correlated to the relative stiffness and functional activity of the two sides. It should be noted that equilibrium itself is dependent on the *balance of forces* on the two sides of the tooth and does not require equality of tissue stiffness and functional activity. This phase of the research is not concerned with the relative stiffnesses but with testing the hypothesis that the teeth will tend to move toward new equilibrium positions when the old equilibrium positions are upset.

Since it may be expected that the movement of teeth under light force conditions will be rather slow, it is necessary to make precise measurements of the change of tooth position. Such gross measurements usually made by use of calipers and scale would not be of sufficient sensitivity. In this study measurements of movement were made with a dial indicator, precise to the nearest one-thousandth part of an inch. Of course, precise measurements must be made relative to a stable datum. An acrylic splint was constructed to fit all teeth of one arch, except teeth to be modified as described above, or those used as experimental controls. These acrylic splints were fitted with appropriately spaced brass inserts against which the dial indicator could be positioned while measurements were made. The splint, dial indicator, and method of measurement are indicated in Figures VII-2 and VII-3.

Eight subjects, ranging in age from nine to sixteen years, were selected from patients scheduled for four bicuspid extractions as part of their orthodontic treatment. In each subject two first bicuspids were modified by a gold onlay extension 2mm thick of the type described previously. The arch and quadrant locations of the modifications, as well as the surfaces to be modified, were selected at random. The unmodified first bicuspids in each subject were

**Fig. VII-2 Acrylic splints in place showing cutouts for modified and controlled teeth, showing brass inserts for positioning dial indicator.**

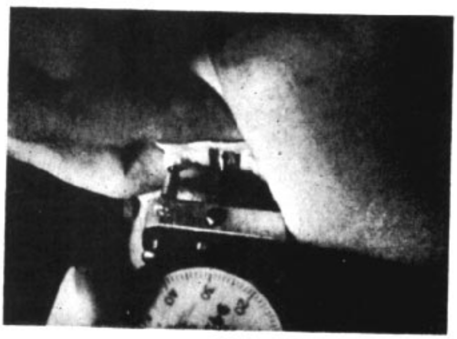

**Fig. VII-3 Dial indicator being used to measure movement of a modified maxillary first bicuspid.**

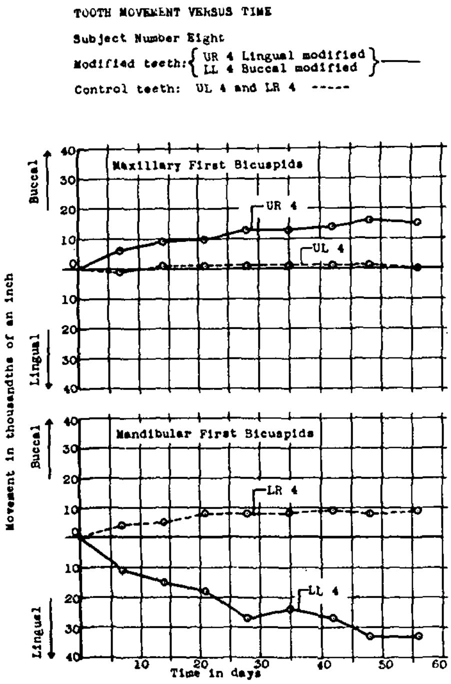


Fig. VII-4

used as controls. In order to insure complete freedom of movement for both modified and control teeth, the proximal and occusal contacts were relieved.

An initial measurement of the location of each modified and control tooth was made at the time of the attachment of the modifying onlays. Thereafter, new measurements of this buccolingual position were made at intervals of one week, for a period of eight weeks. In order to best display the data, graphs were plotted showing the movement of each tooth (modified or control) as a function of the elapsed time. Graphs for four representative subjects are shown in Figures VII-4,5,6,7.

Figure VII-4 shows the graph of the tooth movements of subject number eight. In the maxillary arch the right first bicuspid was modified by an extension on the lingual surface. As evidenced on the graph, this tooth experienced a fairly steady movement in the buccal direction totaling .015 in. at the end of eight weeks. The average rate of movement was approximately .002 in. per week. The control tooth (left first bicuspid) showed minor fluctuation during the test, but at the end of eight weeks was found to have moved not at all. In the mandibular arch the left first bicuspid was modified by an extension on the buccal surface. This tooth experienced a somewhat unsteady movement in the lingual direction totaling .033 in. at the end of eight weeks, an average rate of lingual drift of .004 in. per week. In this case the control, the right first bicuspid, moved a total of .009 in. in the buccal direction at the end of eight weeks. Most of the movement of this control tooth (.008 in.) occurred in the first three weeks.

Figure VII-5 shows the graph of the tooth movements of subject number four. In the maxillary arch the modification was on the lingual surface of the right first bicuspid. Here the movement totaled .030 in. in the buccal direction at the end of eight weeks, an approximate rate of .004 in. per week. The control tooth underwent somewhat irregular fluctuations, but at the end of eight weeks had moved only .002 in. in the buccal direction. The mandibular left first bicuspid, modified on its buccal surface, moved .022 in. in the lingual direction in eight weeks. This was an average rate of about .003 in. per week. The corresponding control tooth, lower right first bicuspid, experienced more movement than any of the previously discussed controls, .014 in. in eight weeks. This much movement of a control tooth should be subjected to critical analysis. It may be exactly what it appears to be, .014 in. drift in the lingual direction. However, the same apparent effect might be the result of mesial or distal drift made possible by relief of the contact points which would result in a lateral movement of the curved contour of the tooth under the measuring point of the dial indicator (Figure VII-3). This latter viewpoint will be reinforced by the analysis of the behavior of the control teeth in the next subject discussed.

In Figure VII-6 are graphed the tooth movements of subject number seven. In this case both modified teeth were in the maxillary arch, the left first bicuspid being extended on the lingual surface and the right first bicuspid on the buccal surface. The left first bicuspid moved .009 in. to the buccal during the eight weeks duration of the test. The right first bicuspid moved .022 in. to the lingual during the same period of time. The control teeth (mandibular first bicuspids) evidenced quite different behavior. The right one moved a net total of only .002 in. in eight weeks. However, the left control tooth moved .024 in. in the same time. Most of this motion (.020 in.) occurred in the last three weeks, after the exfoliation of the adjacent second deciduous molar, at the end of the fifth week of the test period. This control tooth was observed to have undergone a marked *distal* drift in these last three weeks, and it was the behavior of this tooth and the apparent reading of *lingual* movement on the dial indicator that suggested the explanation of the control tooth movement mentioned in connection with the previous subject.

Figure VII-7 graphs the results of tests on subject number one. The maxillary left first bicuspid was modified by an extension on the buccal surface. This tooth underwent a lingual drift of .018 in. during the eight week test period. During the same time the con-

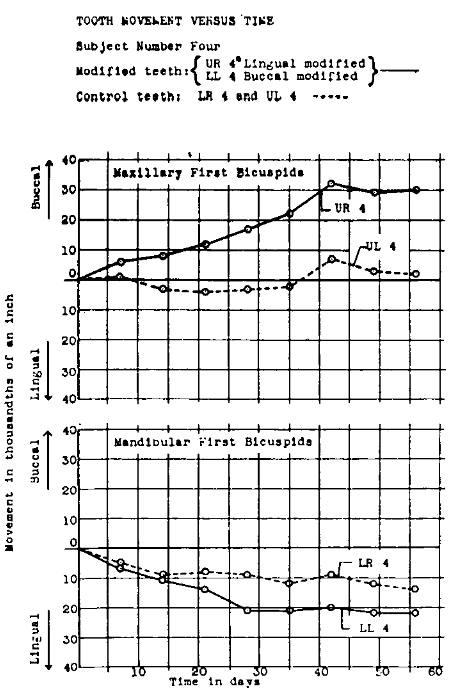


Fig. VII-5

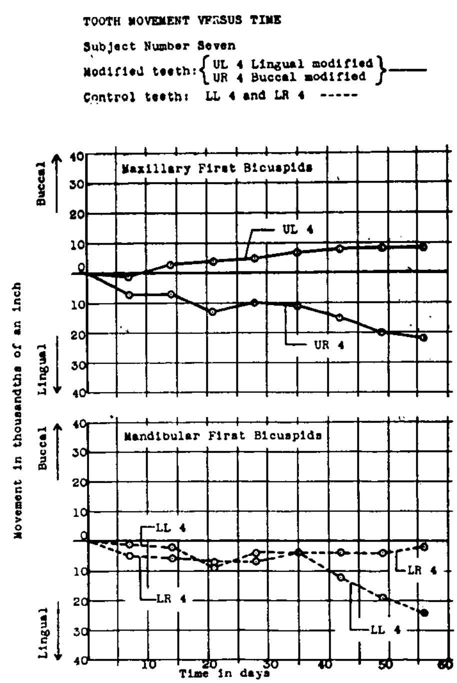


Fig. VII-6

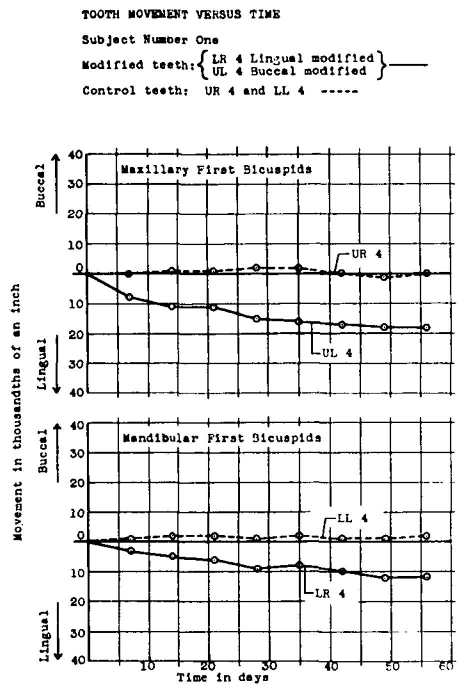


Fig. VII-7

trol tooth in the same jaw (right first bicuspid) underwent no net movement. The control tooth in the mandibular arch (left first bicuspid) moved but .002 in. buccally. The lingually modified right first bicuspid, however, moved .012 in. in the *lingual* direction. It should be noted that this is not in the direction of expected motion. This abnormal movement was noted early in the eight week test period and the case was the subject of careful scrutiny. Since it seemed desirable to locate the passive position of the tongue with the mandible and tongue in physiological rest position, it was decided to probe lightly through the embrasures adjacent to the first bicuspid with a swab stick, the end of which was moistened with gentian violet. The marks made by this probing were consistently found to be on the *inferior* surface of the edge of the tongue. This marking pattern suggested that the resting tongue exerted a gingival or downward directed force on the top of the gold extension. Such a force would tend to tip the crown of the tooth inward. The steadiness of the motion experienced by this tooth certainly indicates that, whatever its cause, it was not of a vagarious nature. Further study of this problem on a group of subjects not reported here shows that this effect is more likely to be related to the occlusal relationship of the upper and lower teeth. The forces of mastication rather than the force exerted by the resting tongue mass may be the source of the observed movement.

## VIII Discussion And Conclusions

The experiments described in the body of this report have been concerned with the development and testing of an "equilibrium theory of tooth position" and with the associated problems of stability. At this point it would be well to restate the fundamental tenets of this equilibrium hypothesis.

Each unit of the dentition is in equilibrium with its surroundings at any instant. The surroundings must be considered in toto, that is, they must include adjacent teeth, the tongue, the buccolabial musculature, the bone and intervening periodontal ligament, and the occluding teeth or interposed matter. In enumerating elements surrounding individual teeth, consideration must also be given to foreign objects, i.e., thumb, fingers, orthodontic appliances, etc.

The equilibrium position of a tooth will be one for which the effects of those random forces, which form a consistent pattern of application to the crown area, will be self negating. That is to say, the effect of such forces that would tend to permanently displace a tooth in a certain direction will be counteracted in the effects of forces tending to displace the tooth in the opposite direction. It should be noted that each tooth is in equilibrium with its surroundings at any instant whether or not it is in an equilibrium position. Thus the term "equilibrium position" should not be confused with the term "equilibrium".

If there is superimposed upon the crown of a tooth which is in an equilibrium position, as previously described, a system of forces the resultant of which is not equal to zero, it is hypothesized that the tooth in question will in time be permanently displaced to a location which satisfies the above-mentioned definition of an equilibrium position.

In addition to considering those factors which determine an equilibrium position, it is also necessary to consider the stability of such positions and the conditions under which equilibrium positions may be stable or unstable. Equilibrium positions, as previously defined, need not necessarily be stable positions. Fundamentally, the stable position is differentiated from the unstable one by the level of the potential energy stored in the surroundings of the tooth. Since relatively little energy can be stored in the bony structure due to its great stiffness, most of this storage will take place in the surrounding soft tissue, principally in the musculature. Equilibrium positions will always be positions of maximum or minimum potential energy. Those characterized by maximum potential energy are intrinsically unstable, while those which have minimum potential energy are stable. Furthermore, since there may be several positions for which the potential energy is a minimum, there will likewise be as many stable positions of the tooth in question. In general, a body subjected to a small displacement from a stable position of equilibrium will return to the stable position upon removal of the displacing force. Correspondingly, a body displaced from an unstable position of equilibrium will not return to this position but will instead move to a stable equilibrium position.

Reference has been made to the superimposition of a system of forces on the crown of a tooth. If the resultant of this system is not equal to zero, then the equilibrium of the entire tooth (for the tooth must always be in equilibrium) requires that an equilibrating system of forces act upon the root of the tooth. These reactive forces are supplied by the bone through the medium of the periodontal ligament and in the final analysis are the factors which initiate osteoblastic and osteoclastic action and the concomitant tooth movement.

## CONCLUSION 1.

*Forces exerted upon the crown of the tooth by the surrounding soft tissue may be sufficient to cause tooth movement in the same manner as that produced by orthodontic appliances.*

In the experiments described in Part III recording tapes from various exercises show distinctly different patterns of force exerted upon the second bicuspid pontic, dependent upon the buccolingual position of that pontic. In all cases a two millimeter lingual displacement of the pontic appreciably increased the influence of the outward-pushing tongue on the force pattern. A two millimeter buccal displacement of the pontic decreased the influence of the tongue on the force pattern. Buccal and lingual displacements of the pontic seemed less definitely connected to the influence of the cheek musculature on the force pattern. It would be improper to draw conclusions based exclusively on the extremes of the differential forces exhibited on these tapes because these extreme forces do not act continuously and the frequency and duration of these extremes are dependent upon factors associated with the individual subject. Of more importance than these extreme force values would be a factor which might be best referred to as the mean effective differential force associated with the displacement. The fact that such mean forces as are associated with two millimeter displacements are sufficient to cause tooth movements is shown by the results of the experiments described in Part VII.

Experiments of a similar nature to those described in Part III but concerned with the maxillary centrals are discussed in Part V. Here the displacement of the teeth in question is accomplished not by bodily movement of the pontic but by change of the axial inclination. Furthermore, the two muscular elements involved here are the upper and lower lips. Examination of the typical graphs reveals the varying influence of these muscular elements upon positive effort forces and post-effort rest forces associated with variations in axial inclinations. Here it can be seen that forces exerted by the muscular elements tend to push the maxillary centrals toward angulations for which the forces will be minimized and a balance achieved. In some of the cases studied more than one equilibrium position was in evidence.

## CONCLUSION 2.

*Each element of the dentition may have more than one position of stable equilibrium within the system composed of the natural oral environment.*

From clinical experience alone it is widely recognized that teeth can be moved from positions amply demonstrated as stable, by years of relatively stationary existence, to new positions where they once again assume the characteristics associated with a stable state. In some instances however, the treated dentition is observed to "relapse". This tendency to relapse is rather easily understood in terms of an "equilibrium theory of tooth position," but the explanation for the success of certain orthodontic procedures involving extensive tooth movement is not nearly so obvious. It is this point which has caused many orthodontists to discard the "equilibrium theory of tooth position" altogether.

In the experiments described in Part IV a model was constructed to test for the possibility of the existence of more than one position of equilibrium of the maxillary central incisors. It was found that for certain relationships between the geometry of the soft tissue and bony structures as approximated by the model, there was more than one position of minimum energy. Such minimum energy positions are always associated with positions of stable equilibrium. Furthermore, it was noted that for other geometric relationships only one stable position existed.

Examination of the graphs accompanying Part V shows the tendency in one case for the forces on the pontic to cause movement to either of two distinct positions, while in the other case these forces seemed to dictate convergence upon a single position. Thus the possibilities of both more than one or only one position of stability are substantiated by this test.

## CONCLUSION 3.

*Differential forces, even when they are of small magnitude, if applied over a considerable period of time can cause important changes in tooth position.*

In the experiments described in Part VII the only alteration in the force system acting upon the tooth during the experiment as compared with the force system acting upon the tooth prior to the experiment must be attributed to the presence of the 2 mm gold onlay extension. It is reasonable to assume that these teeth were initially in positions of stable equilibrium. The constancy of the arch configuration and tooth position prior to the experimentation is suggested by 1) the relative lack of movement of the control teeth, and 2) the excellent fit of the acrylic splint from week to week during the time of the experiment.

In support of conclusion number 3 it should be noted that, with the exception of the lingually modified mandibular bicuspids, the movements of the first bicuspids under the influence of the 2 mm onlay extensions lay in the range of 7 to 33 thousandths of an inch with a mean of 19 thousandths. Over a period of eight weeks this magnitude of movement can hardly be considered sensational, but it is important also to consider the magnitude of the forces involved. While there are not direct data as yet available for lingual forces, the increment of force exerted by the buccal extension may be estimated from the results of the tests on buccal tissue stiffness described in Part VI. Referring to the data for subjects 12 and 14, Figure VI-5, (representing maximum and minimum stiffnesses) the increment of force associated with a 2 mm buccal extension may be seen to be in the range of 3 to 7 gm. Using the mean stiffness of 1.94 gm/mm., the mean increment of force can be estimated as approximately 4 gm.

These forces are from *one-fourth* to *one-tenth* of those generally recommended as *minimum* forces for orthodontic treatment (Reitan[41], Burstone[42]).

Thus, differential forces much smaller than those ordinarily used in orthodontic treatment can, with protracted application, produce easily measured displacements.

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