Muscle Equilibrium: Fact or Fancy

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INTRODUCTION

Even a cursory review of the orthodontic literature is quite sufficient to impress us with the fact that the exploration of the biological principles pertinent to orthodontic practice has been essentially confined to the hard tissue structures, *i.e.*, to the bone and teeth. No wonder that our understanding of the soft tissue behavior and, especially, the behavior and equilibrium of the musculature has remained fairly rudimentary. For the same reason we seem to display greater skills in the actual correction of malocclusion than the subsequent retention of the achieved results.

Generally, it is assumed that a period of retention of eighteen to twenty-four months duration *somehow* produces a state of labiolingual muscular equilibrium within the new, orthodontically-established configuration of dentoalveolar structures. This is, unfortunately, not always the case. However, many of our retention failures could be prevented if an objective method for measuring muscular behavior were available. Such a "myometric" system would provide us with a quantitative framework of reference against which a patient's muscular pattern could be evaluated in the same manner as his skeletal pattern which we routinely assess against cephalometric norms.

The concept of equilibrium of labiolingual muscular environment can be traced to Tomes[1] who in 1873 suggested that "the agency of the lips and tongue is that which determines the position of the teeth." This view has been endorsed, since, by many orthodontists[2-10] who, according to Graber[9], have become "aware of the important role of musculature in maintaining the stability of the treated results or in effecting changes in arch size, shape, and tooth position when the mechanically-determined orthodontic result is not in balance with environmental forces and structures." The long period of empirical and intuitive acceptance of the equilibrium theory ended abruptly, however, with the advent of "myometric"[11-15] and electromyographic[16,17] orthodontic research.

When Winders[11] employed strain-gauge transducers to measure the forces exerted on the dentition by the perioral and lingual musculature, he found that the tongue was capable of exerting more pressure on the dentition than the buccal musculature. Consequently, he has implied that there was no "balance of the musculature between the buccal and lingual sides of the dentition" and that the "balance of muscular forces can be questioned."[11] This notion seemed to be supported by Kydd[13] who, similarly, reported that the pressures exerted by the tongue were greater than those exerted by the lips.

A theory that the "action of the tongue is more important than the lips and cheeks"[18] and that "these forces may not be equal" has been, presumably, further strengthened by clinical observation of patients with congenital facial paralysis, complete or partial aglossia or tongue enlargement. These cases have been said to indicate that the lack of lip activity associated with the facial palsy does not affect the configuration of dentoalveolar structures,

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Presented at the meeting of the Midwestern Component of the Edward H. Angle Society of Orthodontia, Dorado Beach, Puerto Rico, January, 1968.

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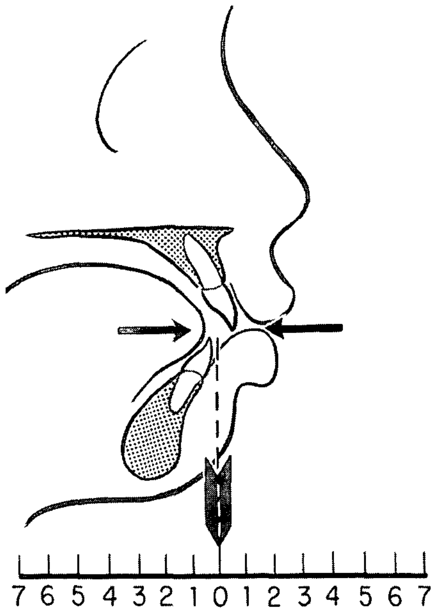

Fig. 1 A condition of static equilibrium of perioral and intraoral musculature in an untreated case of Class II, Division 1 malocclusion.

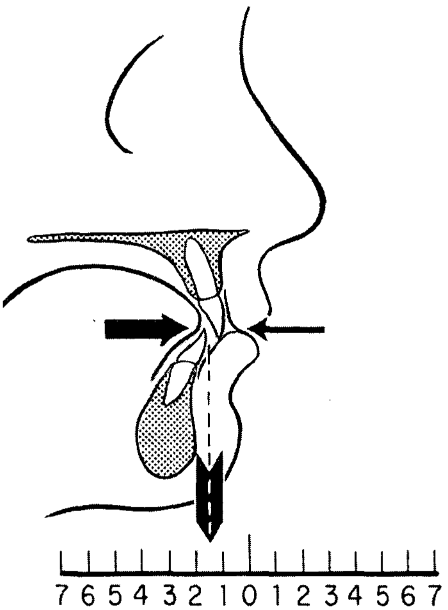

Fig. 2 Dentoalveolar structures moved orthodontically to a new position; an unbalanced system of muscular forces produced.

while the tongue is a potent factor which greatly influences the position of teeth.[18-20]

In recent years a supposition that there is actually no equilibrium between the intraoral and perioral muscular forces[11] worked its way into orthodontic journals[18,21] and textbooks[22] and is being treated as if it were a demonstrated fact. The objective of this paper is to re-evaluate the concept of equilibrium, or lack of equilibrium, of the perioral and intraoral muscular forces from the standpoint of (1) the laws of Newtonian mechanics, (2) a cybernetic theory of feedback and physiological adaptation, and (3) the principles of biophysical behavior of muscle.

KINETIC CONSIDERATIONS

A body remains at rest or in uniform motion until acted upon by an unbalanced set of forces (Newton's first law). This simple truism has a universal application. Thus, for example, a stable Class II, Division 1 malocclusion (Fig. 1) represents a state of static equilibrium. This means that our hypothetical null-position occupied by the dentoalveolar structures is associated with a balanced set of labiolingual forces. When dentoalveolar structures are moved orthodontically to a new position, they encroach upon the intraoral muscular space and become subjected to an unbalanced system of forces (Fig. 2) which tends to restore a state of equilibrium and, therefore, can produce a relapse of malocclusion.

Figure 3 illustrates an inanimate system of forces into which we have built many mechanical characteristics of organized living systems. The scheme may, consequently, simulate kinetic behavior and feedback processes encountered in the fields of orthodontics or orthopedics. Our simulation model (Fig. 3) displays the following elements: *A rigid body,* in this case a ball,

Fig. 3 Simulation model: the ball (dentoalveolar structures) occupies a position of static equilibrium (null-position) determined by the gravity and the enveloping flow of water jets (muscular forces).

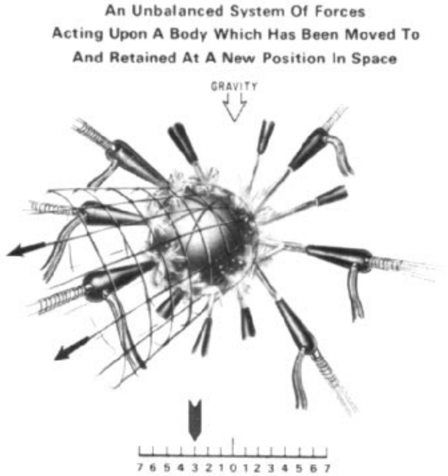

Fig. 4 Simulation model: state of equilibrium disarrayed by orthodontic treatment.

suspended in a three-dimensional space in a state of equilibrium determined by a direct action of water jets and a remote action of gravitation. The position occupied by the ball represents the point in space in which (1) the vector sum of all external forces acting upon it is zero; (2) the sum of the moments of all the forces acting about any single axis is zero, and; (3) the vector sum of all inertia forces and torques acting upon it is also, separately, zero. Our ball is meant to portray and simulate the dentoalveolar structures and, similarly to dentoalveolar structures, it does not represent an ideal rigid body because of its limited plasticity. However, for the purpose of kinetic analysis the assumption of rigidity seems to be permissible. The position in space occupied by the rigid body can be determined in relation to a linear reference system (null-position in Fig. 3).

Water hoses provided with recoiling mechanisms represent the second component of our scheme and are meant to depict and simulate the behavior of the oral musculature. A combined length of the recoiling device and water hose nozzle symbolizes the muscle length which is determined by the intensity of water jets (motor action) and the passive action of the springs (tonus). Our water hoses do not deliver equal nor constant outputs and, therefore, they typify a great variety of force-time relationships characteristic for muscular performance.

When a body which has been in a state of static equilibrium is moved to a new position in space (Figs. 2 and 4), it becomes subjected to an unbalanced system of forces and, therefore, it experiences a linear acceleration which tends to return it to its initial position in space (Fig. 5). According to the Newton law of action and reaction the forces exerted on the first body (the ball) by the second body (water jets) should be equal and opposite to the forces exerted on the second body by the first one (Fig. 6). However, in a biological system, and particularly, in a skeletomuscular system, the reciprocal forces exerted by the hard tissues upon the muscle do *not* produce an equal and opposite response. This can be shown on our simulation model where the reactive forces exerted upon water jets by the ball are not transmitted to

Fig. 5 Rigid body "relapses" to null-position.

water hose nozzles. Consequently, a reciprocal position readjustment of the ball and the water hose nozzles cannot be anticipated and, after a period of retention, the ball would return to its initial position in space (Fig. 5). Our simulation model suggests, therefore, that encroaching upon the muscle space does not produce a direct muscle readjustment.

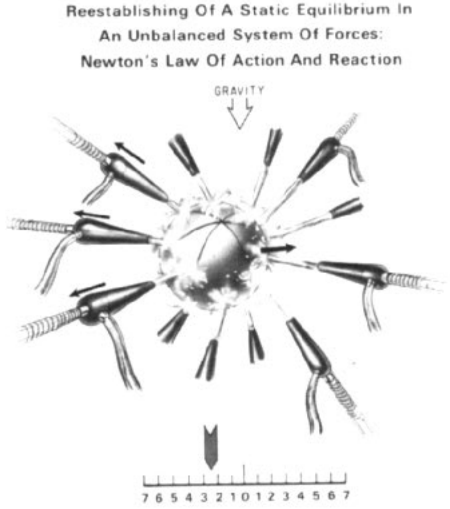

Fig. 6 The implied direct counteraction generated by the rigid body actually *does not occur* in our system, symbolizing the fallacy of the concept of environmental determinism.

CYBERNETIC FEEDBACK THEORY

The configuration illustrated in Figure 6 reflects the fallacy of the concept of environmental determinism. This traditional notion of environmental control of both the reflex action and motor learning (1) suggests a pattern of physiological feedback directly controlled by the extrinsic stimuli, and (2) denies the existence of an intrinsic self-regulatory homeostatic mechanism. This supposition corresponds to the situation depicted in Figure 6 which portrays a direct mass action of the ball upon water hoses.

A field of science which deals with animate and inanimate feedback mechanisms and control systems (cybernetics) has been introduced by Wiener.[23] An experimental cybernetic theory[24,25] of the physiological control of the skeletal motor system interprets motor activity and motor learning as self-regulated processes rather than a series of stimulus-controlled reflexes. Furthermore, the cybernetic feedback theory rejects as meaningless the ideas of association, conditioning and reinforcement. Instead, the theory proposes that the receptor inputs and muscular movements are continuously regulated by response-generated feedback signals which enhance behavioral integration (Fig. 7). Such a concept of motor-sensory self-regulation differs from the traditional assumption that sensory perception and motor activity should be viewed as two independent processes.

For a better understanding of the cybernetic regulation of muscular system, a short review of the biophysical principles of muscular behavior should be presented. Muscle may be viewed[26] as a physical entity composed of three functionally, though not structurally, distinct elements: (1) a contractile element, (2) a series elastic component, and (3) a parallel elastic component (Fig. 8). On stimulation, contractile

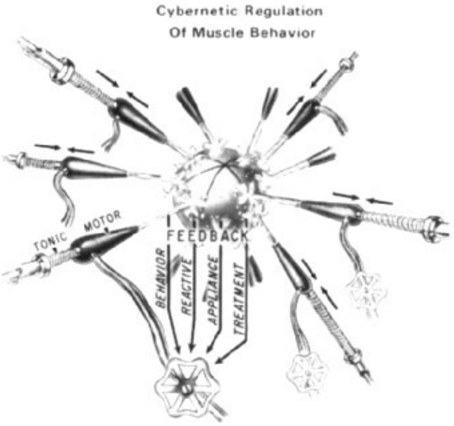

Fig. 7 Simulation model: four feedback circuits control the intensity of water jets (motor action); the passive accommodation of the springs (tonus) is determined by (1) reactive forces generated by water jets (active contraction), and (2) stiffness of the springs (parallel tonic system).

element (CE) becomes activated and generates a contractile force. The resulting active shortening of the contractile element causes a passive elongation of the series elastic component (SEC). Consequently, an internal force is produced at the points of attachment of the muscle.

The contractile element together with a coupled series elastic component does not contribute to the resting tensions of the muscle; the latter are controlled primarily by the parallel elastic component. Recently, it has been be proposed[27] that the parallel elastic component should be viewed as a ratchet device for the setting of equilibrium of muscle tension and length (Fig. 9). This parallel system has been labeled "tonic" because it satisfied "the definition of being capable of altering the state of the muscle without dependence on the maintained release of energy by the contractile process."[27] According to this scheme, muscle tonus is a function of (1) passive accommodation of muscle length, and (2) active contraction. Passive accommodation is produced by slippage of the ratchet in either direction in response to sustained physical force applied to the muscle. Active contraction, in addition to activating the contractile element, produces rapid resetting of the parallel elastic component to the resting length and erases the plastic set established during passive equilibrium of tension. These biophysical principles (tonus and motor action), as well as the concept of an intrinsic self-regulatory mechanism (waterknobs) controlled by the response-generated feedback signals, have been incorporated in the model of cybernetic regulation presented in Figure 7.

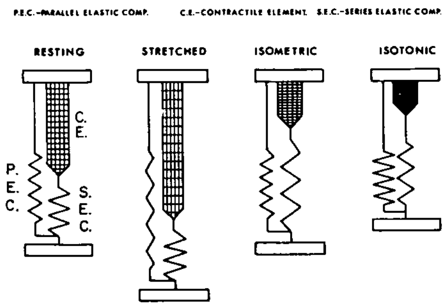

Fig. 8 Model of muscle components.

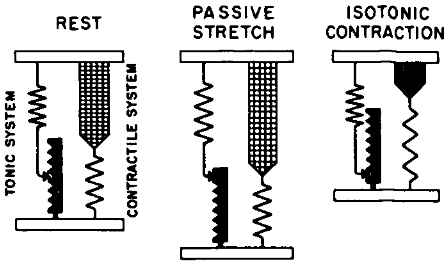

Fig. 9 Model of muscle machine.

A normal individual receives feedback information generated by his bodily movements (*reactive feedback*). When an individual is subjected to an active orthodontic treatment and subsequent retention, the sources from which he receives the feedback information become multiplied. In addition to a reactive feedback he receives a *feedback from the appliance,* a feedback from the changing configuration of dentoalveolar structures or *treatment feedback,* and finally, a feedback generated by the altered muscular behavior pattern or *behavior feedback* (Fig. 7). It is essential that the appliance feedback, treatment feedback and behavior feedback, which are produced by the orthodontic treatment, be coherent with the reactive feedback which represents the residual motor control mechanism.

According to the *neurogeometric principle* of cybernetic regulation, brain cells do not act as synaptic conductors but as direction-specific detectors sensitive to spatial differences in stimulation. Therefore, responses are not triggered by discrete, unitary sensory inputs but by stimulus differences on sensory surfaces. In fact, the oral cavity has been likened to a single sense organ deriving information about shape, texture and motion through the synthesis of input information from receptors of several types.[28]

The oral mucosa, lips, and tongue are richly supplied with receptors.[29] The constantly changing, relative positions of oral structures produce great mobility of these receptors, so that the sensory feedback patterns needed to control the response are being continually displaced relative to each other. Orthodontic patients are able to adapt to conditions of spatial displacement of the sensory feedback within the normal range. However, when the magnitude of feedback displacements brought about by orthodontic treatment exceeds the breakdown threshold, perception becomes distorted and muscular performance deteriorates. That is why certain tongue restraining devices, such as "spikes," may actually produce detrimental results. When the established patterns of feedback control are lost or distorted, the patient attempts to use those sources of control which are most readily available, *i.e.,* motor systems or sensory avenues most closely approximating those which have been displaced. This produces substitute sensory guidance and substitute movements which may be, in some instances at least, less desirable than those present before treatment.

During active treatment and the period of retention a cumulative motor-sensory memory record is established with predictive significance for control of muscular performance in the future. One of the major shortcomings of orthodontic science is our inability to determine or predict whether such cumulative memory record of learned muscular behavior pattern (1) will produce a condition of static equilibrium in the orthodontically-established normal occlusion, and (2) when it is sufficiently well established to persist, *i.e.,* not to become extinguished when retention is discontinued. Fortunately, our expanding knowledge of muscle biomechanics and the recent advances in the field of transduction of physiological events promise great progress in the area of "orthodontic myometrics," so that in the not-too-distant future, *we may be actually attempting to estimate objectively how much retention our patients require.*

BIOMECHANICAL CONSIDERATIONS

On the basis of our model of muscle machine (Figs. 7 and 9) which, in fact, can be tested experimentally, muscular performance can be assigned to three distinct, observable categories:

1. Dynamic (strength in action).
2. Static isometric.
3. Static tonic.

Strength in action (isotonic) involves shortening (concentric contraction)[30] or lengthening (eccentric contraction)[30] of the muscle and is greatly determined by such variables as (1) excursion, (2) load, and (3) velocity. *Static isometric strength* is exemplified by an effort used, for example, for holding of weights or pushing against unyielding resistances. *Passive tonic forces* are produced by a constant slight tension over normal skeletal muscle at rest which is brought about by the intrinsic elastic properties of muscle tissue. This constitutes an important nonneural element of the proprioceptive mechanism which permits the maintenance of our posture with a minimum expenditure of energy.[31]

I wish to suggest that all daily activity is maintained by a continuous shift or combination of various kinds of muscular performance, *i.e.,* the dynamic, static-isometric and static-tonic performance. Only the sum of these efforts, maintained over various periods of time, can be viewed as a valid criterion for determination of the balance of forces. Despite the fact that dynamic intraoral forces may be indeed greater than the corresponding perioral forces, the sum of all opposing muscular forces acting upon a separating body must be in balance, or movement of the body occurs. Therefore, if orthodontic results are to be stable, the behavioral pattern of perioral and intraoral musculature must produce a condition of static equilibrium of forces. Even minor muscular forces of such low values as 1.68g, if not balanced by equal opposing forces, have been shown to be capable of moving teeth.[32]

A clinical determination of static equilibrium is extremely difficult for a number of reasons: (1) Muscular force-system encompasses at least three levels of muscular performance, *i.e.,* the dynamic, static-isometric and tonic performance; (2) the magnitude, direction and the point of application of oral muscular forces are not easily determined, and (3) muscular forces do not represent a steady-state condition and, in fact, a great variety of force-time relationships can be observed. Consequently, quantitative measurement of oral muscular forces must be viewed as a gross approximation only. With these limitations in mind let us now examine the merits of the available clinical tools which can be employed for measuring muscular forces, *i.e.,* the electromyography and electrodynamomography.[33,34]

First let us consider electromyography. The relation between integrated action potential in human muscle and its static isometric tension is directly linear.[35,36] Otherwise, EMG may be viewed as a valid index of isometric tension. Such linear relationship between electromyogram and the tension cannot be observed, however, when the muscle is allowed to change greatly in length. Moreover, EMG cannot be viewed as an index of dynamic muscle performance because muscle excursion, speed and load greatly influence the recorded amplitude.

Another restriction of the EMG is, of course, the fact that it does not reflect the magnitude of passive static forces (tonus), since normal muscle at rest, despite constant slight tension, receives no nerve impulses. The background activity frequently observed in muscle fibers at rest is said to be due to the amplifier noise or tissue noise. Actually, the same "activity" can be observed when electrodes are placed over the patella, obviously a nonmuscular site.[37] In view of these limitations EMG methods may easily lead to proliferation of conjectures as to the pattern of muscular behavior.

Electrodynamographic techniques employ strain-gauge transducers to convert mechanical energy to electrical energy. As the transducer is subjected to a strain, its electrical resistance changes proportionally to the magnitude of forces causing the strain.

By means of EDG, all three pre-

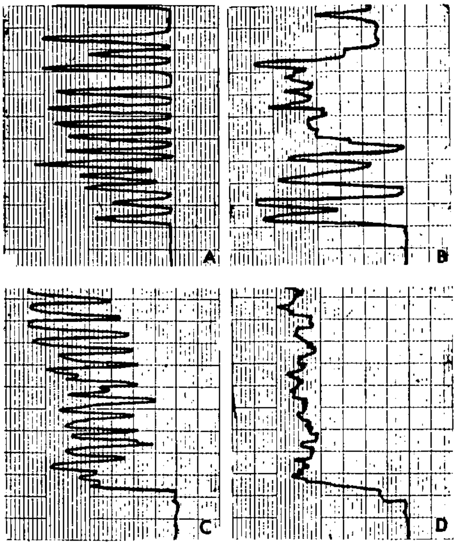

Fig. 10 Discordance of force-estimations determined by two different methods: The magnitude of forces recorded in graph D will be found twice as great as that in graph A when expressed in terms of curve-areas *per unit of time.* Forces A and D must be viewed as similar in magnitude, however, when expressed in terms of average curve amplitudes.

viously defined categories of muscular performance can be recorded. However, various theories advancing balance or imbalance of labiolingual forces on the basis of strain-gauge measurement of muscular effort must be approached with great caution, since the results of these "myometric" studies are usually reported in grams. This has far-reaching implications because the unit of force is, in fact, not a gram but a *dyne.* Dyne belongs to the centimeter-gram-second system and therefore, includes a *time dimension.* Figure 10 illustrates the importance of this consideration.

I wish to emphasize the fact that the balance of labiolingual forces is not determined by the intensity of labial and lingual forces at a few transient moments. Muscular performance does not conform to a steady-state condition and, therefore, muscular balance must be viewed as a product of force and time.[38]

The existing evidence seems to suggest that the *contractile* forces exerted by the tongue may be indeed greater than those exerted by the lips,[11-13] while the lingual *tonic* forces may be less significant than the labial tonic forces. This relatively secondary importance of perioral contractility could account for the reported[18,19] absence of malocclusion associated with congenital facial paralysis. In fact, facial palsy and the resulting muscular disuse may be causing a reduction of the size of the involved muscles (absence of eccentric contraction) and thus, an actual increase of perioral tonus. In this manner the overall sums of the force-time products of labial and lingual musculature remain equal, and a state of muscular equilibrium is *de facto* maintained.

The importance of the labial and buccal *tonic* forces for counterbalancing the dynamic forces exerted by the tongue became further evident when the perioral muscular tensions were measured by means of strain-gauge transducers placed in the modiolar region of the oral vestibule[39] (Fig. 11). That investigation revealed a characteristic pattern of tonic forces in various classes of malocclusion, while the pattern of contractile labiobuccal forces showed no interclass differences (Table 1). The plastic property of the muscle, which can produce a "tonic set" at various muscle lengths, could probably account for these findings.

It should be reiterated that according to our model (Figs. 7-9), tonic forces are a function of both passive accommodation of muscle length (stretching or shortening) and active contraction. Consequently, objective recording of tonic forces may, to some degree at least, reflect an interplay of both the motor-sensory as well as the "parallel" muscular mechanisms. These biomech-

TABLE 1

Characteristic pattern of tonic forces in various classes of malocclusion.

RATIO OF MAXILLARY TO MANDIBULAR VESTIBULAR FORCES						
CLASS OF MALOCCLUSION	CONTRACTILE FORCES MAXIL.	MAND.	RATIO	TONIC FORCES MAXIL.	MAND.	RATIO
I	155	222	0.70	88	49	1.79
II/1	116	167	0.69	101	22	4.59
II/2	121	144	0.84	58	39	1.48
III	114	126	0.90	55	63	0.87
OPEN BITE	138	149	0.93	88	146	0.60

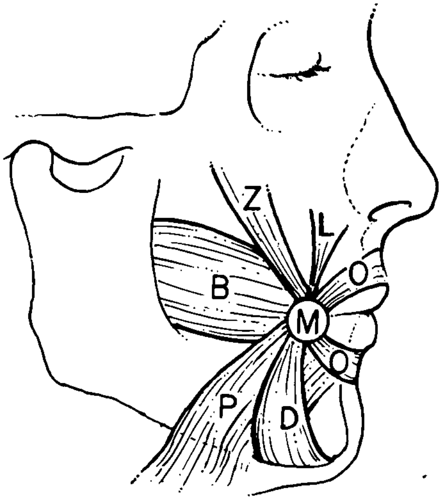

Fig. 11 Muscular modiolar configuration. B, buccinator; Z, zygomaticus major; C, caninus (levator anguli oris); O, orbicular oris; T, triangularis (depressor anguli oris); P, platysma-risorius complex; and M, modiolus.

anical properties of muscular behavior may justify acceptance of the tonic forces as an index of muscular accommodation. In fact, the ratio of maxillary to mandibular tonic forces observed in the previous studies[38-40] appears to resemble very closely the corresponding values of IMA* which integrates both tonic and contractile forces. I wish to propose that this ratio be called an Index of Tonic Accommodation or ITA (Table 2), so that:

$$\text{ITA} = \frac{\text{Max. Vestibular Tonic Forces}}{\text{Mand. Vestibular Tonic Forces.}}$$

TABLE 2

Comparison of IMA and ITA scores in various classes of malocclusion.

CLASS OF MALOCCLUSION	IMA[1]	ITA[2]
I	2.44	1.79
II/1	6.33	4.59
II/2	1.77	1.48
III	0.96	0.87
OPEN BITE	0.63	0.60

[1] Index of Muscular Accommodation
[2] Index of Tonic Accommodation

From the point of view of a clinical application ITA offers many significant advantages over IMA, since it does not require recording of the contractile forces which are difficult to measure objectively. The simplicity of ITA recording techniques (Fig. 12) should allow clinical employment of the electrodynamographic methods for a serial registration of the pattern of perioral tonus before, during and following active treatment. Of course, further cross-sectional and longitudinal studies are needed to verify the reliability of the observed ratios and the validity of

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$$\text{IMA} = \frac{\text{Mandibular}\,\dfrac{\text{Contractile Forces}}{\text{Tonic Forces}}}{\text{Maxillary}\,\dfrac{\text{Contractile Forces}}{\text{Tonic Forces}}}$$

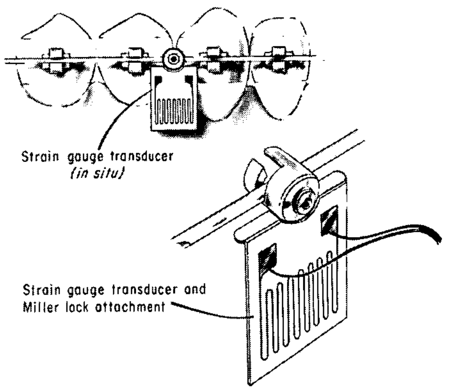

Fig. 12 Transducer assembly modified for electrodynamographic recording in orthodontic practice.

the ITA index as an indicator of muscular performance and muscular adaptation.

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