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# Effects of Orthognathic Surgery on Masticatory Muscle Function

Aurelie Majourau

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EFFECTS OF ORTHOGNATHIC SURGERY ON  
MASTICATORY MUSCLE FUNCTION

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D.D.S., Faculte de Chirurgie Dentaire de Paris VII, 1990

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Master of Dental Sciences Thesis


EFFECTS OF ORTHOGNATHIC SURGERY ON  
MASTICATORY MUSCLE FUNCTION

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1993

## DEDICATIONS

To my parents and my grandmother,

To Pierre,

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## **1. INTRODUCTION.**

The adult population seeking orthodontic care has increased considerably over the past ten years. Some patients may have severe types of malocclusion which cannot be successfully treated by orthodontics alone, and, therefore, may require orthognathic surgery as an adjunctive treatment. These patients may have less concern about the cosmetic improvement they might obtain with orthognathic surgery than they may have regarding the functional improvement of their masticatory apparatus following surgery. At the present time, however, there is no quantitative clinical data available to show that orthognathic surgery is justified according to functional criteria, in particular increased bite force brought about by improved muscle function. Therefore, a fundamental question we need to address is whether orthognathic surgery can produce changes in masticatory muscle function, and, if so, the direction and extent of these changes for a particular surgical procedure.

Numerous previous studies have tried to demonstrate the two-way relationship between muscle function and facial form. It is commonly believed that masticatory muscle function can influence and, in turn, be influenced by facial growth and surgically induced changes in skeletal structure. Orthognathic surgery has the potential to affect muscle function in two ways: mechanically, by altering jaw geometry, and physiologically, by changing sensory and

proprioceptive inputs and muscle length. The masticatory muscles may either adapt to these new requirements or, conversely induce adaptation of the associated skeletal structures.

Most previous studies have focused on the effects of the masticatory muscles in relation to surgically induced changes in craniofacial morphology (skeletal adaptation) rather than the influence of the changes in jaw geometry on muscle function (muscle adaptation). This is largely due to the use of wire fixation and intermaxillary fixation (IMF) instead of rigid fixation during orthognathic surgery. In using wire fixation, muscle tension is considered sufficient to reposition the different segments into their stable positions before complete healing of the osteotomy sites; movement of the segments takes place until a biological equilibrium is established between healing and muscle tension. Rigid fixation, by maintaining the contiguous segments together, allows the healing process to take place directly into the osteotomy sites until muscle adaptation occurs. For these reasons, the amount and occurrence of relapse (skeletal adaptation) is considerably decreased in rigid fixation vs. wire fixation (Komori et al, 1987; Ellis et al, 1988, 1990; Will et al, 1989; Satrom et al, 1991).

Studies which evaluated the effects of facial type or orthognathic surgery on maximum voluntary bite force production could not show a relationship between the direction of the bite force change and the structural changes

(Johnston et al, 1984; Proffit et al, 1989). This may be due to the use of a biomechanical model established from a lateral cephalometric radiograph where the localization of muscle vectors from landmarks almost impossible to identify, is quite arbitrary and most often not reflective of the real mechanical advantages. To overcome this lack of consistency, structural changes should be measured by comparing cephalometric measurements from reliable skeletal and dental landmarks before and after surgery instead of simply comparing the presumed mechanical advantages of the different muscles that might result from surgery.

Previous investigators who used EMG measurements to assess and to compare functional characteristics of masticatory muscles have also been inconsistent in their results when seeking to link muscle activity to facial form (Moller et al, 1966; Ingerval et al, 1974; Lowe et al, 1984; Ahlgren et al, 1985). Local electrode conditions and the difficulty in standardizing function result in poor reproducibility of this measurement technique. However, methods using the relationship between EMG activity and bite force which have been shown to be reproducible might minimize this variability problem.

The purpose of this study was to evaluate the variations in maximum bite force as well as the changes in the contribution of the masseter and anterior temporalis muscles to the generation of bite force in relation to surgically induced changes in skeletal morphology.

## **2. BACKGROUND.**

### **2.1. RELATIONSHIP BETWEEN MASTICATORY MUSCLE FUNCTION CHARACTERISTICS AND CRANIOFACIAL MORPHOLOGY.**

Numerous studies have hypothesized that intersubject differences in muscle function can be linked to variations in craniofacial morphology.

#### **2.1.1. Bite force and craniofacial morphology.**

According to Proffit et al (1989), the masticatory apparatus is a classic lever system, with the musculature positioned between the fulcrum at the jaw joint and the point of force application between the teeth. The geometry of this lever system can affect occlusal force directly by varying the mechanical advantages of the muscles (Throckmorton et al, 1984). Individuals with anteriorly located and perpendicularly oriented muscles would be expected to produce the largest bite forces most easily.

In 1989, Sasaki et al evaluated the role of muscle cross-sectional size and lever arm length in bite force production by correlating these variables in 11 healthy patients. Axial and coronal images obtained by magnetic resonance were combined with conventional lateral cephalograms and dental cast data to

reconstruct the craniomandibular morphology in each subject. The cross-sectional sizes of the masseter and medial pterygoid muscles, their lever arms, and the bite-point lever arms were estimated from these reconstructions. Physiological recordings of bite force were made at the first molar by the use of a customized transducer. Despite the fact that craniofacial spatial morphology may differ among the subjects, they found that jaw muscle size alone seems to explain most of the variation in bite force.

These findings are in agreement with those reported by Van Spronsen et al (1992) who showed that differences in the size of the masseter muscle cross-sectional area of long-face and normal subjects might explain, in part, the observed differences in maximum molar bite force.

However, Koolstra et al (1988a) showed that a 10% difference in jaw muscle cross-sections had only a small effect on the magnitude and direction of the molar bite force, whereas modification of jaw muscle orientation profoundly influenced the outcome of biomechanical calculations. Another factor that should be taken into account is the variation of the direction of the bite force (Van Eijden, 1991). If the direction of the bite force differs between long-face and normal subjects, the moment arm of this force will also differ. For example, the length of the bite force moment arm will increase by approximately 20% when its direction changes from ten degrees posteriorly to ten degrees anteriorly (Van

Eijden, 1991).

In the bite force predictions of the Van Spronsen et al study (Van Spronsen et al, 1992), it was also assumed that the intrinsic strength of the jaw muscles of long-face and normal subjects was equal. It has been shown that type I fibers produce less force per unit area than type II a and b fibers (Close, 1972; Burke et al, 1973; Burke, 1981). Therefore, muscles with a high percentage of type I fibers are less powerful than muscles with a predominance of type II fibers. In a normal population, Ringqvist (1973b, 1974) found a significant positive correlation between molar bite force and the proportion of type II masseter fibers. Unfortunately, there is no consensus about the distribution of jaw muscle fiber type in long-face subjects. Finn et al (1980) and Boyd et al (1984) found a high percentage of type I fibers in long- face subjects, whereas Warner (1984) reported the opposite findings and Shaughnessy et al (1989) found no significant relationship between facial type and muscle fiber distribution. The large variation in both fiber-type distribution and fiber size within each skeletal group, as noted by Warner (1984) and Shaughnessy (1989), and the small number of subjects studied, may explain the above cited contradictory results.

Extrapolating the results of studies correlating morphological and biomechanical characteristics, subjects with short mandibles, acute gonial angles, short facial heights, and flat mandibular planes would seem to have the most

efficient muscle configurations (Ringqvist, 1973; Haskell et al, 1986; Proffit et al, 1989). Therefore, such muscles would need to contract less to produce a given amount of bite force or to perform a certain task.

Although the results of these various studies were statistically significant, large individual variations not explained by biomechanical analysis were present. Since bite forces are the result of the combined contraction of several muscles, studies using bite force capability to describe muscle function are limited; they cannot discern the individual characteristics of each of the various muscles involved in generating that force. In order to evaluate the contribution of individual muscles to oral function, many studies have directly measured the electromyographic characteristics of masticatory muscles and compared them with morphological features.

#### 2.1.2. Muscle activity and craniofacial morphology.

The most powerful tool to quantitatively and qualitatively evaluate muscle function is electromyography. This section will review the principles of EMG, findings correlating EMG activity with craniofacial morphology and the limitations of this technique.

##### 2.1.2.1. Basic principles of electromyography.



EMG is an electrical analog of muscle contraction which can be used to quantitatively evaluate muscle contraction. EMG measures the electrical potential between two electrodes placed in or near a muscle. These potentials are generated by the depolarization of the muscle fiber membrane, and are proportional to the contractile strength of the sampled motor units. The shapes and amplitudes of the recorded signal are dependent on the characteristics of the original depolarizations, the distance of the active fibers from the electrode site, and the impedance characteristics of the intervening tissue (Basmajian et al, 1985). EMG activity can be recorded from either intramuscular or surface electrodes which detect the action potentials associated with surrounding motor units. Each type of these electrodes has certain advantages and disadvantages.

Intramuscular electrodes are able to record a more specific and localized signal since they can be placed directly into the desired muscle. The ability to record from deep muscles, inaccessible by surface electrodes, can be accomplished. On the other hand, the range of such recordings is usually limited to muscle fibers in close proximity to the fine wire tip of the electrode. However, this limitation may be varied by changing the length of the insulated tip and controlling the distance between the two recording electrodes.

Surface electrodes may be preferable to record action potentials from superficial muscles; the signals obtained from these electrodes are considered to

be representative of a more substantial part of the muscle and seem to be more reproducible since electrode placement can be visually monitored. Basmajian and DeLuca (1985), have shown that the intrasubject variability of the signal is reduced when it is detected using surface electrodes instead of indwelling electrodes. The non-invasive nature of surface recording is also advantageous for human investigations. Disadvantages may include non-specificity resulting from signals recorded from adjacent muscles, and an increased general noise level due to skin properties.

EMG has been used to study the amplitude and frequency of muscle action potentials, and the behavior, integration, and time relationships of muscle bursts. Extensive kinesiological studies have been undertaken to relate muscle contraction patterns to movements of the mandible (Ahlgren, 1967; Basmajian et al, 1985). Electromyography has also been utilized to record changes in muscle activity resulting from various treatment procedures (McNamara, 1978; Johnston et al, 1984; Moss, 1985) or from craniofacial characteristics (Ingervall et al, 1979).

#### 2.1.2.2. Correlations between EMG activity and craniofacial morphology.

Moller in 1966, conducted an EMG study measuring muscle activity at rest, during chewing and swallowing, and during maximum clenching, in 36 patients. Correlations between masseter, anterior temporalis, posterior temporalis activities,

and dental as well as cephalometric characteristics were examined. At maximal biting, he found increased masseter activity in patients with mandibular prognathism and decreased masseter activity in patients with obtuse gonial angle and steep mandibular plane. Acute gonial angle was also associated with higher anterior temporalis activity during maximal biting. During function, the results were less clear; patients exhibiting a prognathic maxilla showed a significantly higher masseter activity during swallowing.

Ingerval et al in 1974, recorded muscle activity in 52 children aged 9-11 years with normal occlusion in order to determine variations due to facial morphology alone. Muscle activity was recorded with bipolar electrodes; surface electrodes were used for the masseter and the orbicularis oris muscles and hooked wire electrodes were used for the temporalis muscle. Craniofacial morphology was evaluated by cephalometric analysis and dental cast measurements. The clearest correlations between muscle activity and facial morphology were found during chewing and maximal bite. During these functions the amplitudes in the temporal and masseter muscles were larger for children with short lower facial height and a flat mandibular plane.

In 1984, Lowe and Takada examined muscle activity in 18 class I, 25 class II division 1, and 12 class II division 2 patients using canonical correlations of integrated surface EMG with a reduced morphology index based on statistically

determined dependent cephalometric measurements. Muscle activities were compared at rest, intercuspation, clenching, swallowing and maximum jaw opening. The only statistically significant finding was that higher resting level masseter activity was exhibited by patients with short mandibles and steep occlusal planes.

Finn and coworkers in 1984, tried to identify with EMG investigations possible differences in muscle activity between presurgical groups of long faced open-bite and short-faced patients, and normal controls. They used needle electrodes to record the EMG activity at different bite forces (10, 15, 20 Kg.) for the deep masseter and the temporalis muscles. The results showed that the short-faced group had the highest EMG activity during molar bites. They also tended to have higher EMG activity during incisor bites, but there was more variability. They explained these results by differences in fiber morphology between the two groups: since short-faced individuals have muscle fiber atrophy, and since the force a muscle fiber can generate is proportional to the fiber cross-sectional area, short-faced patients must recruit more muscle fibers to produce the same bite force as long-faced subjects. This is reflected in the higher EMG activity of the muscles in short-faced subjects.

Ahlgren et al in 1985, measured EMG activity (with bipolar intramuscular electrodes) of the anterior, middle, and posterior temporalis muscles in 10

subjects with normal occlusion. They correlated the results with cephalometric measurements. At rest, the posterior temporalis muscle showed the greatest activity and during clenching, EMG activity increased in all the components of the muscle; however, no one division showed a clear dominance. Patients with steep mandibular planes exhibited higher overall muscle activity. This finding was in contradiction with the results of previous studies.

Most of these investigations showed large intersubject variability which cannot be explained by morphological differences or biomechanical parameters alone. The inability of these studies to demonstrate strong correlations between muscle function and facial morphology may have been due to three factors: (1) poor experimental design; (2) neural control pattern variability; (3) individual differences in the physiologic properties of the muscles. The use of absolute EMG values to assess the relationship between facial morphology and muscle function made comparison and reproducibility of the experimental results extremely difficult. Many investigators have interpreted EMG data beyond the limitations of the technique.

#### 2.1.2.3. Limitations of EMG.

The validity of the results regarding quantitative evaluation of absolute muscle activity levels by EMG recordings is questionable. Ralston in 1961

showed that peak-to-peak amplitude comparisons of raw EMG signals is inaccurate because of the wave form complexity of the recorded action potentials. As shown by Siegler et al (1985), EMG signal processing, which may include filtering of background noise, rectification, smoothing or averaging, and integration, has been used to quantify muscle contraction over time. However, signal processing does not validate the quantitative comparison of EMG results. Since the magnitude of the recorded signal is dependent on the distance from the generated signal, and on the characteristics of the intervening tissues, amplitudes will inherently vary in the same muscle in different individuals and between muscles of the same individual. Many studies have not considered the contribution of this error; some, like the one conducted by Ingerval et al (1974), have even compared action potentials recorded from muscles using two different types of electrodes.

Poor reproducibility of quantitative EMG measurements has been discussed by several authors. Garnick (1975), showed that even small displacements of the recording electrodes may generate differences in observed quantitative values. The duplication of original conditions is difficult to perform if the electrodes need to be removed and replaced. Changes in skin impedance characteristics may also contribute to the large variability of the results obtained between experimental trials (Angelone et al, 1960).

Difficulty in reproducing quantitative EMG measurements is further complicated when considering functional activities. Many investigators have examined muscle activity at rest, and during mastication and swallowing. These functions are extremely difficult to control. Even simple movements such as clenching or close-open activation may vary in amplitude and firing rate from subject to subject, or even for the same subject at different times. Manns et al (1977), showed that degree of jaw opening and velocity of contraction have significant effects on recorded EMG magnitudes and patterns.

Garnick (1975), demonstrated that the use of absolute EMG measurements to assess muscle activity and the inadequate control of function lead to unreliable and non-reproducible data. Therefore, methods have been developed to minimize the variability problem using the relationship between bite force and EMG activity.

### 2.1.3. EMG/Force function characteristics and craniofacial morphology.

#### 2.1.3.1. Reproducibility of EMG-Force function characteristics.

As early as 1952, investigators have tried to find a quantitative relationship between electrical muscular activity and mechanical muscle tension. Subsequently, a number of studies (Inman et al, 1952; Lippold, 1952) have shown

that a linear relationship exists between the amplitude of the surface EMG signal and isometric tension. The slope of the EMG-tension curve (EMG versus isometric tension plots) represents the average muscle activity increment exhibited per unit of force generated over the range of forces produced. This would indicate that the slope of an EMG-force function curve is more reliable and therefore more reproducible than absolute EMG measurements because it is independent of the thickness or other signal-dampening characteristics between the muscle fibers and the recording electrodes.

Manns et al in 1977, studied the EMG-force function characteristics at different degrees of muscular elongation for the masseter and temporalis muscles. They also showed a linear relationship and observed a link between the steepness of the slope and the amount of elongation. Small elongations (0.5 mm.) were associated with the steeper curves, as opposed to large elongation which were associated with flatter curves (at small and medium elongations, the lower force ranges seem to be regulated by the number of motor units recruited while in the higher force ranges, the increment is mainly due to an increased frequency discharge of the motor units).

Van Eijden et al in 1989, reported in their results that for all muscles (anterior and posterior temporalis, masseter, and digastric) and bite force directions, EMG increased linearly with bite force between 50 N and maximal



voluntary force. They suggested that for each bite force direction, the muscles with the largest mechanical advantages may be more active than the ones with smaller mechanical advantages. In a study done in 1990 on jaw muscle activity in relation to the direction and point of application of bite force, Van Eijden (1990) found that for all bite directions, more muscle contraction was required for production of a constant bite force at the anterior region compared to the posterior region. Therefore, the point of application of bite force in the moment arm does have an influence on muscle function. He also showed that, on average, the activities of the right and left side muscles did not differ in a bilateral vertical bite. Moreover, in a unilateral vertical bite, there were no significant right-left differences.

In 1991, Lindauer et al confirmed the validity of the use of the EMG-force function curves as the most reliable single measurement of the relative contribution of a muscle toward bite force generation. Their results showed that the slope of these curves is a highly reproducible, quantitative, and functionally relevant measurement by which to assess muscle function. Like Manns et al, they reported a dramatic change of the slope characteristics of EMG-function curves with degree of jaw opening (Lindauer et al, 1991, 1993); therefore, they recommended to control this variable as much as possible in studies examining the mechanisms of masticatory muscle function.

#### 2.1.3.2. Correlations between EMG-Force function characteristics and craniofacial morphology.

The wide range of EMG values recorded as a function of isometric bite force found in previous studies suggests that substantial variation in muscle function patterns exists among individuals. Lindauer et al (1989) hypothesized from this finding that variability in muscle function characteristics could be explained by differences in craniofacial morphology. Their study showed a trend toward lower muscle activity changes as a function of bite force in subjects with long mandibles, flat mandibular planes, acute gonial angles and short lower facial heights. This result is in contradiction with previous studies which reported that these types of subjects exhibited the greatest masticatory muscle activity during function; this contradiction was attributed to the lack of function control and the unreliability of the experimental model in the earlier experiments. In Lindauer's study, anatomic and cephalometric measurements demonstrated from a biomechanical point of view that these subjects would have the most efficient muscle orientations for generating bite force. Therefore, it seems logical that in order to produce a certain amount of force, the masticatory muscles in these subjects would need to contract less. It has been shown that these same types of subjects are also able to generate the greatest bite forces (Proffit et al, 1983).

On the other hand, although Lindauer et al. (1989) showed a trend, they

could not demonstrate any statistically significant relationship between EMG-force function characteristics and morphological features; for 2 subjects out of 14, the muscle function data did not conform to predictions based on biomechanical models. They explained the results for these 2 subjects by possible synergistic muscle contractions. For instance, the synergistic contraction of the temporalis muscle to aid a biomechanically unfavorably positioned masseter muscle may decrease the need for that muscle to contract, and may therefore dampen the effects of morphological characteristics on muscle function. According to these authors, this would represent an adaptation of the neural control system for oral function in order to minimize the disadvantageous effects of unfavorable biomechanical situations.

Other parameters correlated with muscle function, for example, the cross-sectional area of the masticatory muscles (Sasaki et al, 1989) as well as their physiological properties may vary considerably among individuals. Thus, if most of these previous studies failed in trying to correlate craniofacial morphology and muscle function at a statistically significant level, it is probably because they were dealing with too many parameters comparing different individuals. For these reasons, it can be beneficial to study the effects of the alteration of the jaw geometry on muscle function i.e. the influence of orthognathic surgery on the EMG-force function characteristics, where each individual subject serves as his or her own control.

Most of the studies which utilized EMG/force function curves to assess and compare muscle function among individuals used normalized values for both EMG activity and maximum bite force values or used raw values for a given bite force. On the other hand, if the maximum bite force values are extremely different from one subject to another, or even worse, for the same subject at two different time intervals due to the effects of a particular treatment, it is not valid to compare the EMG/force curves with force values expressed as percentage. For instance, if a subject is able to generate twice as much bite force after a treatment X with the same muscle contraction, the slopes of the EMG/force curves will be the same if normalized bite force values are used, but will be very different if raw bite force values are used. Therefore, one can compare slope variations only if the raw maximum bite force values are comparable.

## 2.2. RELATIONSHIP BETWEEN ORTHOGNATHIC SURGERY AND MUSCLE FUNCTION.

The relationship between form and function is well documented; but if form is changed by surgery does function adapt and change? Moss in 1985 brought up the question, "is the cause of relapse in some of the surgical cases the consequence of a failure of the soft tissue to adapt to the new form, resulting in a remodeling of the hard tissues and tooth position?" From a physiologic perspective, the concept of adaptation refers to the structural and functional

changes that maintain or enhance functional capabilities in a changing environment. Adaptive change within the muscles and skeletal components of the craniofacial complex are governed by the principles of homeorrhexis, or a constancy of the process by which development comes about, and homeostasis, or the tendency for the system to remain constant. At any one point of time, the stomatognathic system is in a balanced, homeostatic condition. A common consequence of orthognathic surgery is an abrupt and often dramatic change in the length of the muscles and associated soft tissues, and a change of the moment arm of the mandible. Therefore, the short-term and long-term results of orthognathic surgery may depend directly on the process of adaptation and the principles of homeostasis and homeorrhexis as they relate to the ability of the musculo-skeletal structures to achieve a new homeostatic, balanced relation.

#### 2.2.1. Mode of postoperative fixation: its significance on muscle adaptation.

This section will review the literature regarding the influence of the type of post-operative fixation in term of muscle adaptation as well as the interactive effects of mandibular advancement and vertical midface changes on muscle function.

Maxillomandibular fixation (MMF), also called intermaxillary fixation (IMF),

used to be the only technique employed to allow osseous healing to take place post-surgically. This type of fixation consisting of immobilization of the mandible for usually 6 to 8 weeks was accepted as a benign technique in terms of its effects on the masticatory muscles. However, with the advent of alternate techniques of post-operative immobilization of the skeletal segments, such as rigid internal fixation, MMF has been examined more critically.

Mayo et al in 1988, evaluated the histochemical characteristics of masseter and temporalis muscles after 5 weeks of MMF (following surgery) in *Macaca mulatta*. They found that these muscles showed a significant atrophy after the period of immobilization. This atrophy (major decreases in mean cross-sectional fiber area) occurred in both type I-slow twitch and type II-fast twitch fibers indicating that overall recruitment of the muscle and not just of one fiber type of motor unit was affected during fixation.

Some investigators believed that the use of rigid internal fixation during surgery would prevent the severe atrophy of the masticatory muscles that have been demonstrated when mandibular fixation was used (Ellis, 1988; Buckley et al, 1989). In order to test this hypothesis, Ellis et al (1988), compared stimulated molar bite force after mandibular advancement in two groups of adult *Rhesus* monkeys, using MMF in one group and rigid internal fixation without MMF in the other. The results showed that maximum bite force was significantly decreased

in both groups at 6 weeks after the surgery; however, the animals who had rigid fixation alone had significantly greater bite force at 6 weeks post-surgically than the animals who had MMF. However, at the ninth postoperative week, there was no longer any significant difference between the two groups, indicating that the animals in the MMF group recovered after the MMF had been removed (at 6 weeks).

From a review of these studies, it is clear that when a muscle is immobilized, atrophic changes will occur. Moreover, previous studies found that immobilizing a shortened muscle causes more severe changes than immobilization alone (Jokl et al, 1983). This finding indicates that one should strive to maintain the preoperative position of the proximal segment when performing the sagittal ramus osteotomy. Any upward and forward proximal segment rotation after mandibular osteotomy will shorten the masticatory muscles; their immobilization during the period of MMF may cause more extensive irreversible changes within the muscle fibers, leading possibly to some permanent loss of bite force capability. The use of rigid fixation has the advantage of allowing the operator to control accurately the position of the proximal segment and to secure it there reliably. Additionally, when the mandible is allowed to function throughout the period of osseous healing, less myoatrophy will occur. Rigid internal fixation permits the initiation of physiotherapy earlier than when MMF is used, this can lead to a more rapid regain of bulk and strength, and

should be manifested clinically as a smaller reduction in bite force capability.

Many studies have shown that when using MMF, most of the relapse occurred within 6 to 8 weeks following surgery during the period of fixation, and little is seen thereafter. The muscular and soft tissue forces seem to be sufficient to reposition the skeletal segments into their stable positions, since the osteotomy sites are in the process of active remodeling and healing, and do not obtain sufficient antagonist strength to overcome the muscular forces. This finding suggests that once the proximal and the distal segments have become sufficiently healed, relapse ceased. This brings up the question: if the skeletal segments were solidly secured to one another at the time of the surgery, would relapse be prevented?

During the past decade, clinicians tried to find a way of holding the distal segments in their postoperative position until the bones had healed and the soft tissues (suprahyoid complex for mandibular advancement and masticatory muscles for vertical changes) had adapted to lengthening. Shendel and Epker (1980), found a direct correlation between the use of skeletal suspension wire fixation and postoperative stability. Another method to hold the skeletal structures until the muscles and soft tissues have adapted is to use internal rigid fixation at the time of the surgery. Reitzig and Schoorl in 1983, demonstrated that if the bony segments are stabilized in tight contact, primary bone healing takes place



into the osteotomy sites. They compared rigid and semi-rigid fixation in an animal model in which small gaps (0.75 mm.) were created bilaterally in the mandible. At 6 weeks after surgery, the rigidly fixed sides showed no visible external callus and the semirigidly fixed sides showed large visible external callus. The use of rigid fixation has been shown to provide the necessary interfragmentary rigidity to overcome the forces of the musculature complex (Kirkpatrick et al, 1987; Ellis et al, 1988; Satrom et al, 1991). Therefore, with the use of rigid internal fixation, more muscular than skeletal adaptation will take place in order to reestablish after surgery a new biological equilibrium of the stomatognathic system.

#### 2.2.2. Interactive effects of mandibular advancement and setback and muscle function.

##### 2.2.2.1. Mandibular advancement.

The advancement of the mandible is the most common orthognathic surgical procedure performed on the U.S. population (high prevalence of class II malocclusion) and historically considered one of the least stable.

##### 2.2.2.1.1. Effects of the muscles on the stability of mandibular advancement.

Surgical procedures that lengthen the muscles and soft tissues beyond their normal physiologic rest position may significantly increase both active and passive muscle tension and thus, place undue stress on repositioned osseous segments. For this reason, surgeons nowadays prefer to use the bilateral sagittal split osteotomy to advance the mandible in most of the cases, in order to not alter masticatory muscle length. Nevertheless, this procedure generates elongation of the suprahyoid complex and, according to many clinicians, tension produced by the stretched suprahyoid muscles and associate tissues is one of the primary causes of relapse after mandibular advancement.

Ellis and Carlson (1983), tested this hypothesis in performing mandibular advancement in 10 *Rhesus* monkeys with and without suprahyoid myotomy in 5 of each. Lateral cephalometric radiographs with the aid of presurgically implanted bone markers showed a significant amount of relapse in the group without the myotomy during the first 6 weeks, when compared with the myotomy group who showed no relapse.

In contrast, Wessberg and coworkers, in a 1982 analysis of 16 patients from a multicenter sample, found no significant differences between a human control and a myotomy group. Differences between these two studies might be attributed to differences between animal models and humans.

A later study (Carlson et al, 1987) demonstrated that the suprahyoid complex, itself, is elongated with mandibular surgery. Using radio-opaque markers implanted in the suprahyoid muscles in *Rhesus* monkeys, they found that both short term changes and long term adaptations to lengthening of the suprahyoid complex as a result of mandibular advancement occurred primarily within the connective tissues comprising the muscle-tendon and muscle-bone interfaces. However, in 1988 Reynolds et al found that, in contrast to smaller advancements where the adaptive changes occurred at these interfaces, with larger advancements, changes also occurred in the bellies of the muscles. These adaptive changes consist of new sarcomeres incorporated at these interfaces as well as geometric rearrangements of fibers within the muscle (Mc Namara et al, 1978).

Nevertheless, although many studies demonstrated that the musculature does play a significant role regarding the amount of post-operative relapse, instability after mandibular advancement is multifactorial: mode of fixation, surgical technique, magnitude of advancement, and condylar displacement can lead to relapse as various investigators have shown (Lake et al, 1981; Will et al, 1984; Will et al, 1989).

Rigid internal fixation has decreased the amount of horizontal relapse (Satrom et al, 1991). However, with large advancements, there is no question that

the ability of the soft tissues to adapt can be exceeded (Van Sickels et al, 1988). The current fear is that instead of seeing relapse only of the distal skeletal segment, as one did in the past, we will see relapse of the entire mandible with large advancements. The temporomandibular joint may be the site of the posterior translation, distalizing or causing resorption of the condyles (Barer et al, 1987).

In the planning of orthognathic surgical procedures, every effort should be made to maximize adaptations within the soft tissue components of the craniofacial region so as to minimize adaptations occurring in the skeletal structures of the face. It is obvious that beside the use of internal rigid fixation, muscle detachment and reattachment are procedures that can be employed to reestablish functional and skeletal balance in the postsurgical individual, thereby minimizing the amount of relapse. However, one must weigh the advantages of increased stability with the dangers of morbidity. Excessive detachment of the musculature obviously has an effect upon the vascular and nervous supply to the craniofacial complex (McNamara et al, 1978; Bell et al, 1980).

#### 2.2.2.1.2. Effects of mandibular advancement on muscle function.

Dechow and coworkers in 1986, evaluated the extent to which postsurgical masticatory function can be predicted from a model of craniofacial biomechanics

in a group of 63 experimental animals. Maximal stimulated bite force was measured in the molar region in a group of normal *Rhesus* monkeys and in a group that had undergone surgical advancement of the mandible at least one year prior to bite force measurement. The results demonstrated that, on the average, the operated monkeys had a long term loss in bite force relative to the control animals. These results can be understood in mechanical terms as a result of an increase in the length of the moment arm while the lengths of the masticatory muscles remain constant. However, these results indicated a greater and more variable change in bite force than would be predicted on the basis of biomechanical considerations. The surgical procedure used in this study might have had an influence; the detachment and reattachment of the masseter muscle from the ramus of the mandible to expose the bone for subsequent osteotomy may have resulted in muscle fiber destruction or partial denervation. Decrease in bite force then might result from a combination of a decrease in mechanical advantage and iatrogenic damage of the masseter muscle.

Given the change in the mechanical advantage of the masticatory muscles following mandibular advancement, we would expect that these muscles are required to contract more to maintain a masticatory force similar to the presurgical one. It has been well documented that such added loads on muscle result in muscle fiber hypertrophy (Dons et al, 1979).

Proffit et al in a study done in 1989, investigated the effect of surgery on occlusal force. Regarding the mandibular osteotomy, advancement on the average produced a small negative change in the mechanical advantage of the temporalis but a small positive change in the masseter muscle. However, they did not find a correlation between the amount of advancement and the change in mechanical advantage of the temporalis or masseter muscles. According to them, occlusal force is considerably affected by orthognathic surgery but the direction of the change seems to be unpredictable. It does not appear to be related to the change in jaw morphology. However, the technique of the surgical procedure and the mode of fixation were not described in this study; they might have a direct influence on the results obtained.

#### 2.2.2.2. Mandibular setback.

The setback of the mandible is considered as a more stable surgical procedure than mandibular advancement. A number of surgeons, however, have reported some degree of relapse after this procedure. The etiology of relapse, whether wires or screws are used, is thought to be multifactorial: tongue pressure after reduction of tongue space (Simpson, 1974; Moss, 1984), lack of control of the condylar position into the fossa during fixation of the proximal segment (Leonard et al, 1985; Szilagyi et al, 1987), and altered activity and failure of the masticatory muscles to adapt to the repositioned segments (Peppersack et al,

1978; Moss, 1984; Michiwaki et al, 1989), are the most common factors described. The next section will focus on the two last factors cited.

#### 2.2.2.2.1. Effects of the muscles on the stability of mandibular setback.

Kobayashi et al (1986) evaluated the amount of horizontal and vertical relapse in a sample of 44 patients who underwent a sagittal ramus osteotomy for correction of prognathism. Their results indicated that the magnitude of horizontal relapse was proportional to the amount of setback of the mandible. Furthermore, they found that the tendency for relapse was also increased when lateral shift of the mandible occurred at surgery. According to them, the unbalanced tension of the musculature and surrounding soft tissues was the principal factor which affected the stability of the surgical procedure. But, these results are not surprising since they used circumferential wire and MMF methods; the muscles and soft tissues did not apparently adapt in length to the new jaw position.

Most of the studies evaluating the stability of the mandibular setback procedure using only wire fixation and MMF reported a significant amount of vertical relapse. The counterclockwise rotation of the proximal segment as well as the clockwise rotation of the distal segment occurring after surgery were leading to an increased mandibular plane steepness and anterior facial height. (Ridell et al, 1971; Ingervall, 1979; Proffit et al, 1991). Kobayashi et al (1986) did

not show such a significant degree of vertical relapse due to the use of a chin cap for 6 months after the surgery. However, the inferior movement of the symphysis was noticed later when this orthopedic appliance was discontinued. Therefore, the chin cap using only intermittent forces was not efficient enough to induce muscle adaptation in non growing subjects.

Komori et al (1989) found that the degree of inadvertent anteroposterior rotation of the proximal segment at surgery rather than the extent and pattern of surgical repositioning of the distal segment was significantly correlated with the degree of relapse. If the position of the proximal segment is not controlled during the procedure, the pterygomasseteric sling will tend to reposition the condyle in its preoperative location (Michiwaki et al, 1989). Therefore, they recommended the proximal segment be preserved in its exact presurgical anatomic position using an instrument ensuring an accurate control during the procedure.

When rigid internal fixation (RIF) is used to secure the proximal to the distal segment after setback of the mandible, the stability of the vertical dimension has been showed to be superior than when intraosseous wire technique were used (Proffit et al, 1991). This method of fixation allows to overcome the tension of the masticatory muscles and soft tissues on the proximal segment.

Nevertheless, studies found that patients who underwent a bilateral sagittal



split osteotomy (BSSO) with the use of RIF for correction of prognathism showed a significant degree of horizontal relapse (Franco et al, 1989; Proffit et al, 1991).

According to Franco et al (1989), the amount of relapse was proportional to the degree the mandible was set back and due to the change in the spatial arrangement of the muscles and the connective tissue components. Proffit et al (1991) interpreted their results by giving two possible explanations for the forward movement of the chin postsurgically: the first reason, according to them, is the muscular pull which repositions the mandible forward and the second one is the retroposition of the condyles into the fossa during the surgery. If the condyles are pushed too far posteriorly for patient comfort, forward repositioning of the mandible (mainly caused by the contraction of the lateral pterygoid muscle) will be expected postsurgically. This forceful posterior seating of the condyles before applying fixation may be an indication for mandibular advancement to prevent relapse, but should be avoided for mandibular setback.

The results indicated by these different studies show that the stability of the mandibular setback procedure can be highly improved by counteracting the muscular forces by using RIF as a method of fixation associated with an accurate control of the condylar position into the glenoid fossa in order to preserve its preoperative anatomic location.

#### 2.2.2.2.2. Effects of mandibular setback on muscle function.

Astrand in 1974, evaluated the chewing efficiency before and after surgical correction of developmental deformities of the jaws. Almost all the subjects of his surgical sample showed mandibular prognathism. Chewing efficiency was estimated by the capacity to triturate almonds and chewing time was taken as the time it requires to triturate and swallow an almond. All groups with deformities of the jaws were shown to have a significantly lower chewing efficiency and longer chewing time than the control group. According to the patients, the surgery had improved their masticatory ability. However, the patient's opinion could not be confirmed by the results of this study: the masticatory function of the group surgically treated did not show any improvement at 6 months postsurgically. Neither was any difference found between an untreated and a surgically treated group of patients with similar deformities. These results are in contradiction with the finding of Lundberg et al (1973) who demonstrated a change in position of the bolus during chewing after surgical correction of mandibular prognathism. After surgery, the molar area was used more frequently than before. Chewing efficiency might therefore be improved postsurgically. These unexpected results found by Astrand may be explained by different reasons: first, it is extremely difficult to control and reproduce a function such as chewing for an individual. The comparison of this function between individuals and even for the same individual at different periods may not be reliable for the assessment of muscle function. Second, the surgical group underwent different types of surgical procedures. It is therefore impossible to draw any valid conclusions with such a

heterogenous sample. Third, none of the surgical methods which counteract the muscles and soft tissue tensions were described in this study. Therefore, the skeletal structures probably tended to return to their original position leading to an insignificant change in term of muscle function.

Ingervall et al in 1979, studied the changes in EMG activity of the temporal, masseter and lip muscles after surgical correction of mandibular prognathism. They used intracutaneous electrodes for the masseter and temporalis muscles and bipolar surface electrodes for the lips. The muscle activity was recorded in the postural position of the mandible, during maximal bite, during chewing and swallowing of peanuts and during swallowing of water. The postural activity increased during the period of MMF. In agreement with Astrand (1974), they found that the activity during maximal bite before surgery was far below that in individuals with normal occlusion. During MMF, the muscle activity was decreased for maximal bite. This result may be explained by factors as a fear of biting hard, occlusal instability and disuse atrophy. After removal of the fixation, the activity during maximal bite was the same as before surgery and at 8 months, it was higher than presurgically. The number and the duration of chewing cycles necessary to triturate the test food were greater than in normal individuals but decreased as a result of treatment to values close to normal. The results obtained in this study may be questionable in term of their reliability. As a matter of fact, the use of absolute EMG measurements to assess muscle activity and the

inadequate control of function have been shown to lead to unreliable and non reproducible data (Garnick, 1975; Manns et al, 1977). In addition, the use of intracutaneous electrodes by itself is not a reproducible and a reliable method to assess the function of the whole muscle. The control of the electrodes position is so critical that it does not allow comparisons between individuals and for the same individual at different time registrations. Furthermore, when they evaluated the muscle activity during maximal bite, the bite force was not recorded. It would have been more appropriate to compare the muscle activity in function of the bite force produced, to permit normalization of the data and comparison between the subjects and at the different periods (Lindauer et al, 1991).

### 2.2.3. Interactive effects of vertical midfacial changes on muscle function.

Orthognathic surgical procedures designed to reposition the entire maxilla or any of its components may result in stretching or shortening of the muscle fibers, altering the direction of the muscle action, and changing the mechanical advantage of the muscles.

#### 2.2.3.1. Vertical midfacial reduction.

Vertical midfacial reduction produces an autorotation of the mandible by which the elevator muscles may become shortened. Because the muscles are

not lengthened, one would not expect either active or passive distracting forces on the repositioned maxilla from the mandibular musculature. Therefore, it is not surprising that superior repositioning of the maxilla by LeFort I osteotomy is probably the most stable orthognathic surgical procedure (Proffit et al, 1987). However, with the autorotation of the mandible, the biomechanics of the jaw may be altered.

Throckmorton and coworkers (1984) demonstrated in a two-dimensional biomechanical model, that superior repositioning of the maxilla should improve the mechanical advantage of the mandibular elevator musculature. They defined the mechanical advantage of a muscle in terms of the perpendicular distance from condyle to muscle over the perpendicular distance from condyle to load. Indeed, the major effect of raising the maxilla is to decrease the distance between the point of bite and the condyle. They showed that since the insertions of the masseter and temporalis muscles are closer to the condyle than the molars, the amount of movement of these points during autorotation is less than the movement at the molars. Thus, the moment arms of the muscle are less affected by the rotation than is the moment arm for bite load. They demonstrated that the impaction of the maxilla resulted in an increased mechanical advantage for the temporalis muscle, while the mechanical advantage of the masseter muscle stayed the same: the moment arm for the masseter muscle decreased at approximately the same rate as that of the bite force. The reverse is true when

the maxilla is repositioned inferiorly.

Theoretically, long-faced individuals who have undergone correction of vertical maxillary excess should, therefore, be better able to produce occlusal forces given a constant muscular activity. Unfortunately, clinical investigations have not been able to corroborate these hypotheses. Johnston and coworkers (1984), evaluated a small sample of individuals with vertical maxillary excess using EMG and bite force measured before and after superior repositioning of the maxilla. Half the subjects had substantial decreases in EMG activity for a given bite force, and half had increases; only one patient reached the values predicted by the biomechanical model.

Proffit and colleagues in 1989, measured bite force before and at various intervals after superior repositioning of the maxilla in 9 patients. They found great variability in occlusal force after surgery. Further, the calculated change in mechanical advantage of the masseter and temporalis muscles using Throckmorton's model was very small postoperatively. No patient showed a change in mechanical advantage greater than 10%. Once again, although bite force was affected by this surgical procedure, the magnitude and direction of the changes were unpredictable.

The high variability obtained in these studies could be explained by many

parameters that were not taken into account: the patients differed in the extent of deformity, age, and body weight. Further, it was not possible to quantify the effects of postoperative immobilization of the mandible by MMF. Additionally, maxilla impaction was often associated with mandibular surgery. Another possible reason for the observed variability in bite force could be alterations in the size or fiber distribution of the masticatory muscles. However, in 1989 Boyd et al, in a study of 2 patients with vertical maxillary excess on whom preoperative and postoperative biopsies were analyzed, have shown that the histochemical characteristics of the superficial masseter muscle undergoes minimal change in fiber distribution or fiber size after superior repositioning of the maxilla. Of note was the lack of any changes in the muscles, such as fiber atrophy or pathologic changes that might adversely affect function. They concluded that autorotation of the mandible resulting from maxillary surgery had no clinically significant effect on the fiber composition of the elevator muscles.

Because the data regarding the functional consequences of superior repositioning of the maxilla are highly variable, the only conclusion drawn from these studies is that patients probably will not be any worse functionally as a result of this surgery, and some may be improved.

#### 2.2.3.2. Vertical midfacial augmentation.

Vertical midfacial augmentation produces an autorotation of the mandible (in the clockwise direction) which should decrease the mechanical advantage of the masticatory muscles according to Throckmorton's (1984) biomechanical model.

This autorotation may also stretch the mandibular elevators and create increased stress on the inferiorly repositioned maxilla and the interpositional bone graft. Clinical investigations have reported that vertical midfacial augmentation is an extremely unstable procedure, with relapse rates of zero to hundred percent (Bell et al, 1981; Quejada et al, 1987). This high relapse tendency may be due to a lack of adaptation of the masticatory muscles to the new jaw geometry.

Studies using bite opening appliances (McNamara et al, 1978; Yellich et al, 1981; Carlson et al, 1983) showed that the stretched mandibular elevator muscles cause marked anterior and superior displacement of the maxilla and severe dental intrusion in adult monkeys even when no surgery has been performed on the maxilla. Further proof of the role of the masticatory muscles in relapse was the finding that myotomy of the pterygomasseteric sling reduces the amount of maxillary displacement. However, Faulkner and coworkers (1978) showed that the lengthening of muscles by the introduction of a bite opening appliance resulted in an adaptation of fiber length by addition of new sarcomeres.



The main reason which can explain the great amount of instability of this surgical procedure is that most of the previous clinical investigations did not use rigid internal fixation to secure the skeletal segments together; indeed, when the skeletal segments are not rigidly secured, the masticatory muscles stretched beyond their resting length, tending to move the maxilla back to its original position until the healing process was achieved. Therefore, more skeletal than muscular adaptation occurs to reestablish homeostatic conditions.

Ellis and colleagues (1989), designed an experimental investigation on 18 adult female monkeys to test the following hypotheses: (1) preadaptation of the mandibular elevator muscles to an increased length by the use of a bite opening splint will help to reduce relapse tendencies post-operatively; (2) myotomy of the elevator muscles will help to reduce relapse tendencies, and (3) more stable means of fixation will help to counter the forces of the elevator muscles on the interpositional bone graft and thereby reduce relapse tendencies. The results demonstrated that the mandibular elevator muscles do play a significant role in relapse after inferior repositioning of the maxilla. They showed that a combination of rigid fixation along with myotomy and preadaptation of the elevator muscles improve stability. However, a combination of these methods may not be necessary in the clinical setting. Indeed, animal studies differ from clinical studies in many points. First, patient compliance is always a significant factor in determining surgical success; the monkeys could not be taught to avoid

development of occlusal forces in the postoperative period. Second, the amount of midfacial augmentation must be taken into consideration: in the clinical setting, it is unusual to augment the midface the degree to which the animals were downgrafted. Further, patients with vertical midface deficiency usually have an increase in the interocclusal freeway space into which the maxilla can be repositioned.

### 2.3. SUMMARY.

Taking into account the findings of the studies which examined the relationship between craniofacial morphological characteristics and bite force ability, long face individuals with a long mandible, an obtuse gonial angle, and a steep mandibular plane, present a less efficient muscle configuration to produce bite force.

Conversely, individuals with a short facial vertical dimension, a short mandible, an acute gonial angle, and a flat mandibular plane have the most efficient craniofacial characteristics and are able to generate very high bite force levels (Ringqvist, 1973; Throckmorton, 1980, 1985; Proffit, 1983; Haskell et al, 1986). Individuals with large muscle cross-section, anteriorly located and perpendicularly oriented muscles would also be able to produce higher bite forces (Koolstra et al, 1988a; Sasaki et al, 1989; Van Spronsen et al, 1992).

Therefore, one can expect that changes in these different craniofacial parameters as a result of surgery (mandibular advancement, mandibular setback, facial height reduction, facial height augmentation) would produce predictable changes in bite force and EMG levels. Unfortunately, none of the clinical studies reviewed showed a consistent change in bite force or EMG activity for a given surgical procedure.

The reason of this lack of correlation between structural skeletal changes and masticatory muscle function may be due to different factors: (1) measurement of muscle mechanical advantage, relying on skeletal radiographic landmarks extremely difficult to identify, assumes that muscle orientation and location are always the same for a particular facial type; (2) difficulty in standardizing function; (3) failure to control degree of jaw opening; (4) use of non customized bite blocks to record maximum bite force; (5) failure to control local EMG electrode conditions; (6) variations in the direction of the bite force; (7) lack of homogeneity of the samples regarding surgical technique; (8) complex neurophysiologic adaptations that may occur after surgery and compensate for the structural changes in jaw geometry.

The functional changes of the masticatory muscles can be studied in two ways: (1) by comparing bite force ability, and (2) by comparing muscle contraction characteristics before and after surgery. Comparisons can be made

for both absolute and relative changes in bite force presurgically versus postsurgically, using quantitative force measurements. Muscle contraction effects can be determined by comparing the absolute maximum EMG values and the slopes of the EMG/Force function curves pre and postsurgically.

There are, however, some inherent limitations in this type of investigation: First, for maximum bite force measurements, the fear of biting hard and the soreness of the maxillo-mandibular complex may lead to an inaccurate recording of the true physiologic maximum, especially immediately postsurgically; second, due to the difficulty of controlling local conditions, the comparison of absolute EMG values may not be a reliable method to assess changes in muscle contraction. However, if the changes observed are considerable and consistent for a given surgical procedure, this method can be utilized at least to estimate the relationship between structural changes and muscle function. Finally, the comparison of the slopes of the EMG/Force function curves can only be made if the bite force levels are comparable among patients and for the same patient at the different recording times.

### **3. OBJECTIVES AND HYPOTHESES.**

The overall objective of this study was to determine the effects of surgically changing mandibular length and facial vertical dimension on maximum voluntary bite force and on the functional characteristics of the masseter and anterior temporalis muscles in different orthodontic patient populations. These effects were measured six weeks and six months postsurgically.

The specific aims of this study were to:

(1) Measure and compare the maximum voluntary bite force generated at the molar and incisor areas during isometric contraction before orthognathic surgery (T0), and at six weeks (T1), and at six months (T2) postsurgically.

(2) Compare the functional characteristics (absolute EMG activity and slopes of EMG/Force function curves) of the masseter and anterior temporalis muscles during isometric contraction at (T0), and at (T1), and (T2).

(3) Verify the structural changes brought about by surgery by comparing the cephalometric measurements at (T0), immediately after surgery (T1), and at (T2), and relate those to changes in

maximum voluntary bite force and masseter and anterior temporalis muscle function.

The following hypotheses were tested:

(1) There is a relationship between presurgical facial type and maximum bite force and EMG levels.

(2) Absolute maximum bite force levels change postsurgically, at both the molar and incisor regions. The direction and extent of these changes are linked to a given surgical movement.

(3) The contribution of the masseter and temporalis muscles to the generation of bite force changes postsurgically, and that these directions and extent of these changes can be predicted by post-surgical changes in craniofacial morphology.

## **4. MATERIALS AND METHODS.**

### **4.1. SUBJECTS.**

The subject sample consisted of fifteen patients who had undergone orthognathic surgery at the University of Connecticut Health Center (UCHC). These patients were studied immediately before surgery (T0), and at 6 weeks (T1) and 6 months (T2), postsurgically. All subjects had undergone presurgical and postsurgical phases of orthodontic treatment at UCHC in order to optimize "functional" and aesthetic outcomes. For every subject, their orthodontic appliance was present throughout the study period to eliminate the introduction of another variable to the study. Decisions concerning diagnosis and type of surgery to be performed were made jointly by the orthodontics and oral surgery attending staff. The surgical movements (horizontal and/or vertical directions) had to be more than three millimeters. The patients were older than eighteen years of age, and did not show any signs of potential growth. Patients who had congenital craniofacial syndromes, traumatic injuries or previous orthognathic surgery were excluded from this study.

### **4.2. SURGICAL PROCEDURES.**

Patients who were candidates for a bilateral sagittal split osteotomy (BSSO)

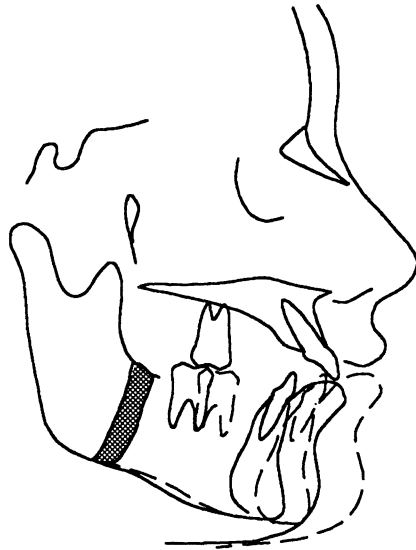
with or without a LeFort I osteotomy (LFIO) were selected for this study.

The choice of the surgical procedures was made in order to evaluate the influence of lengthening the moment arm on the masseter and temporalis muscles, and to study the effects of shortening or lengthening these muscles on muscle function.

A BSSO was performed to advance or setback the mandible (Figs. 1a & 1b). Changes in the anterior facial height (AFH) were achieved by either altering the mandibular plane angulation with a BSSO (Figs. 2a & 2b), repositioning the maxilla with a downgraft LFIO (Fig. 3a) or a LFIO impaction (Fig. 3b), or a combination of both BSSO and LFIO.

Model surgery and a surgical occlusal splint made in acrylic were used for every patient in order to permit optimal control during the surgical procedure. The splint was removed approximately at six weeks postsurgically. The bony segments in all these procedures were secured by internal rigid fixation and the intermaxillary fixation (IMF) period following surgery was minimum or nonexistent.



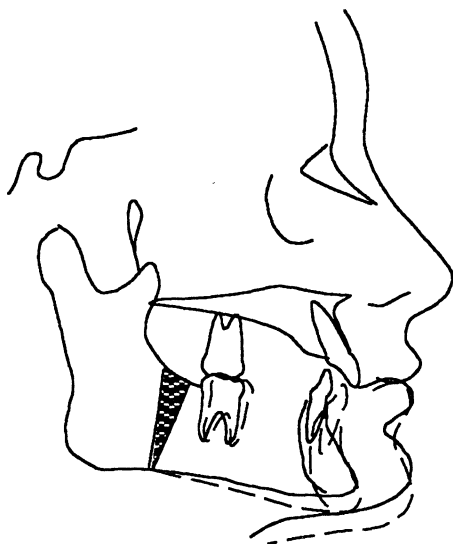


a. Mandibular advancement.



b. Mandibular setback.

Fig. 1. Variations of the mandibular length with a bilateral sagittal split osteotomy (BSSO).

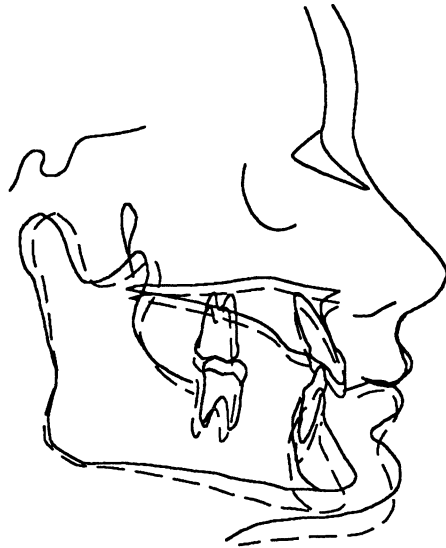


a. AFH augmentation by clockwise rotation of the mandibular distal segment.

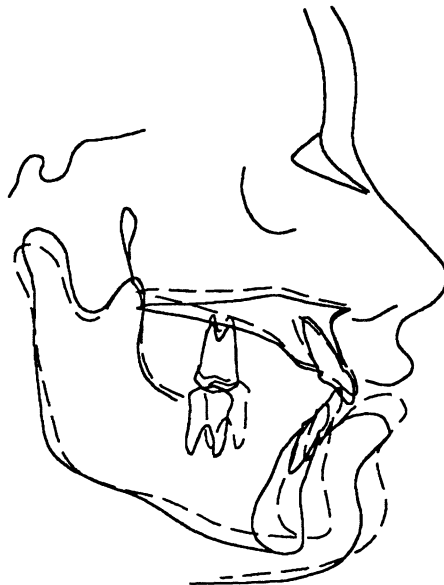


b. AFH reduction by counterclockwise rotation of the mandibular distal segment.

Fig. 2. Variations of the anterior facial height (AFH) by altering mandibular plane angulation with a BSSO.



- a. AFH augmentation by a downgraft LeFort I osteotomy (Clockwise autorotation of the mandible).



- b. AFH reduction by a LeFort I osteotomy impaction (Counterclockwise autorotation of the mandible).

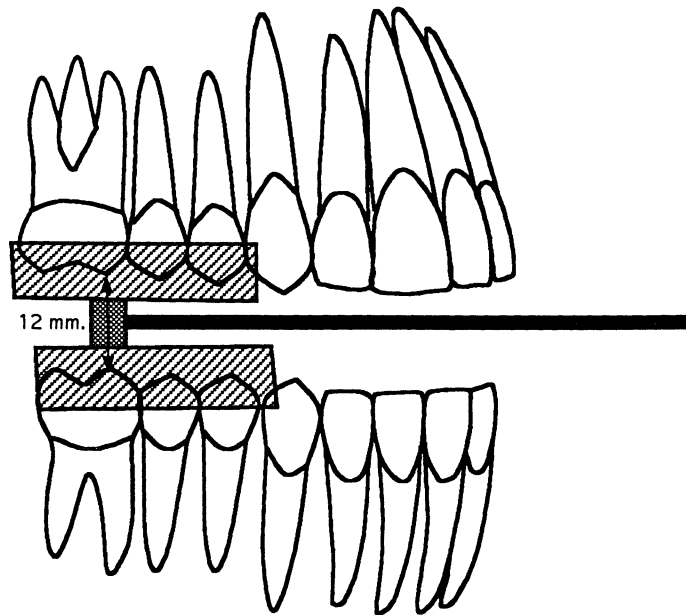
Fig. 3. Variations of the AFH with LeFort I osteotomies.

### 4.3. DATA RECORDING AND ANALYSIS PROCEDURES.

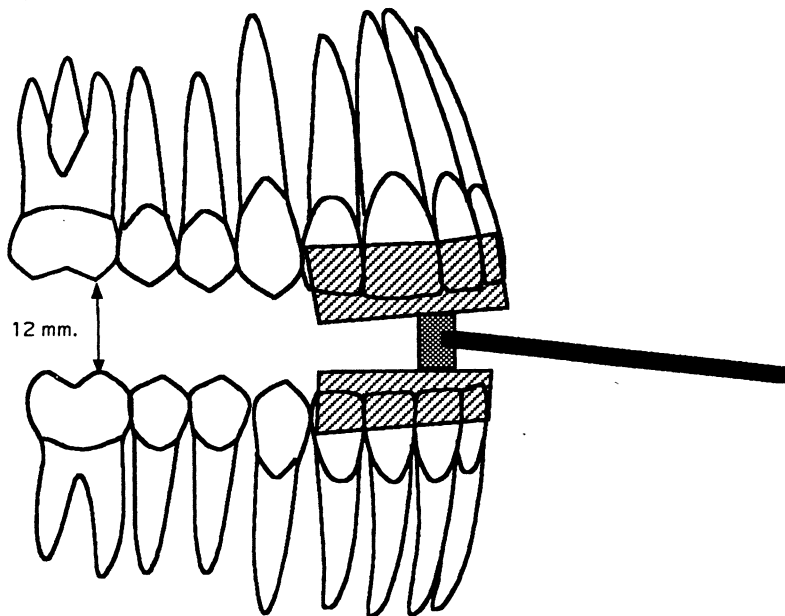
#### 4.3.1. Force measurements.

Force measurements for each subject were obtained using a force transducer system (Kistler, 5400) that included a miniature quartz transducer (6.0 mm. diameter and height) imbedded in a specially constructed bite block at both the molar and incisor regions, producing a 12 mm. jaw opening (Figs. 4a & 4b). In this system, the force applied to the transducer acts on a quartz element through two face plates. The longitudinal force effects on the two face plates induce a proportional electrostatic charge in the quartz element. A charge amplifier serves as both a power source and conditioning amplifier for the quartz element and outputs a force-proportional dc voltage that is recorded on a separate channel of the instrumentation tape recorder.

The bite blocks were made with a material from the polyester family (TAK, Hydroplastic) that has the property to be softened in hot water (165 F); after manipulation during the plastic period, the material becomes unbreakable after five minutes or instantly when placed in cold water. This material, which has been tested for safety, does not need any mixing or polymerizing and can be directly placed in the patient's mouth at the plastic stage.



a. Posterior customized bite block with force transducer.



b. Anterior customized bite block with force transducer.

Fig. 4. Force measurement device.

The bite blocks were constructed for the molar region (unilaterally) and the incisor region at one unique jaw opening of 6 mm. measured at the mesio-buccal cusp of the first maxillary molar. Therefore, the mandibular plane angulation remained the same for measurements at both the molar and incisor bites. The interposition of the force transducer between the two separate components of the bite block (each one for the maxillary and mandibular arches respectively) produced a total disocclusion of 12 mm. at the molar area. The fabrication of two separate parts independent to each other facilitate the measurement of absolute maximum bite forces.

Each site was lined with a layer of soft wax in order to protect the brackets and arch wires during the construction of the bite blocks. A solid gauge made out the same material was first fabricated and placed at the contralateral side in order to achieve an 8 mm. disocclusion measured with a bow divider at the mesio-buccal cusp of the first maxillary molar. Then, the two components (separated by a rectangular piece of wax 1 mm. in height), were placed during their plastic stage between the maxilla and the mandible, and the patient was asked to bite until reaching the gauge placed at the contralateral side. At this stage, the material (which was still transparent) permitted the identification and the marking of the maxillary first molar as well as the maxillary and mandibular midlines on the bite blocks. Then, before the material was totally set, the rectangular piece of wax was removed. At this time, the force transducer was

inserted between the superior and inferior components of the bite block at the previously marked molar area and maxillary midline for the posterior and anterior bite blocks, respectively. After confirming that the subject was not deviating his mandible forward or laterally, he was asked to bite very gently on the force transducer in order to create a slight groove on the bite blocks (0.5 mm. deep for each component). This groove permitted the patient to hold the force transducer at the exact same location and to keep the same mandibular position during the experiment. The superior and inferior parts were then taken out, placed in cold water, and reintroduced into the mouth to verify their fit.

#### 4.3.2. Electromyography.

All recordings for both the superficial masseter and anterior temporalis muscles were made using commercially available bipolar surface electrodes (Sensormedic Miniature) that were attached to the skin using double sided adhesive tape. Placement for both muscles was aided by palpation. Based on current practice, superficial masseter location is determined as an area midway along a line connecting the inferior border of the zygomatic arch at the zygomaticotemporal suture to the gonial angle. The anterior temporalis site was determined by having the subject clench and retrude the mandible. Electrical impedance at sites of electrode contact was reduced by light abrasion and application of a saline gel. Lateral photographs were taken of the electrode sites

for purposes of documenting and replicating locations for subsequent recordings. The raw EMG signals were led from the electrodes by insulated wires to two differential input amplifiers (CWE, 831) where they were amplified using a gain of 1000. The signals were band pass filtered between 2-2000 Hz to remove movement artifacts and high frequency noise. The data signals for each muscle were then stored on a digital audio tape cassette recorder (TEAC, RD-111T). Figure 5 shows a schematic representation of the recording system.

#### 4.3.3. Data acquisition and processing.

The EMG activity and bite forces were recorded at ten different levels ranging from the maximum voluntary bite force (MVBF) to ten percent of this value in ten percent decrements. Each level of force was visually controlled and monitored on the oscilloscope by the investigator. After this step, all data processing was performed on an IBM PS/2, Model 70 microcomputer, using a commercially available data acquisition and analysis hardware and software system (Crisal PC, Version 2.5). The EMG signals and the dc force signal were played back through the data recorder through an analog-to-digital converter at a sampling rate of 2 KHz. The data, in 2 second sample sizes, were demultiplexed and stored as raw data files. Each raw data file was then digitally high-pass filtered at 2 Hz to remove any dc offset voltages.



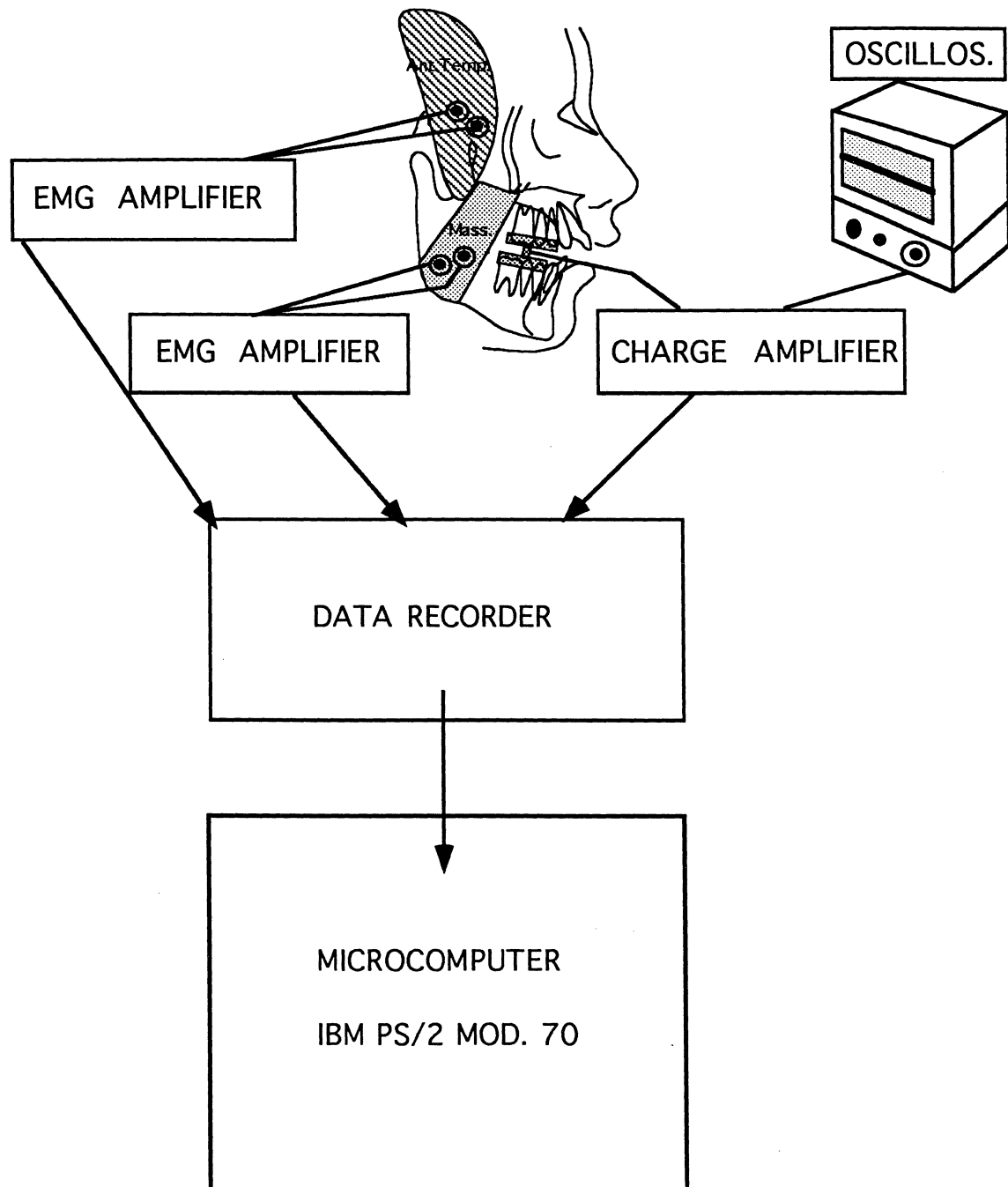


Fig. 5. Data acquisition and processing.

The power density spectrum and RMS power level for each 2 second sample was then calculated with the results stored in a separate analysis file. The power density spectrum was readily displayed on the monitor and plotted on graphics printer. The RMS and Total power values were output in numerical form.

#### 4.3.4. Determination of Changes in Skeletal Structure.

Standard lateral cephalometric radiographs were taken at UCHC at (T0), immediately after surgery and (T2), to measure the structural changes achieved by the surgical procedures, as well as the stability of those changes. These radiographs were traced, superimposed on the anterior cranial base, and analyzed by the same individual. Sixteen skeletal and dental landmarks (Fig. 6) were used in order to measure eighteen linear (Fig. 7) and nine angular (Fig. 8) measurements from an X-Y coordinate system (Table 1). For the lateral cephalometric radiograph taken immediately after surgery, the mandible was first traced separately and autorotated closed around an arbitrary axis located 5 mm. above Articulare until reaching posterior occlusal contact in order to compensate for the presence of the surgical occlusal splint.

A biomechanical model was not used in this study because of the difficulties encountered by others investigators to define precisely and reliably the mechanical advantage of the muscles and moment arms.

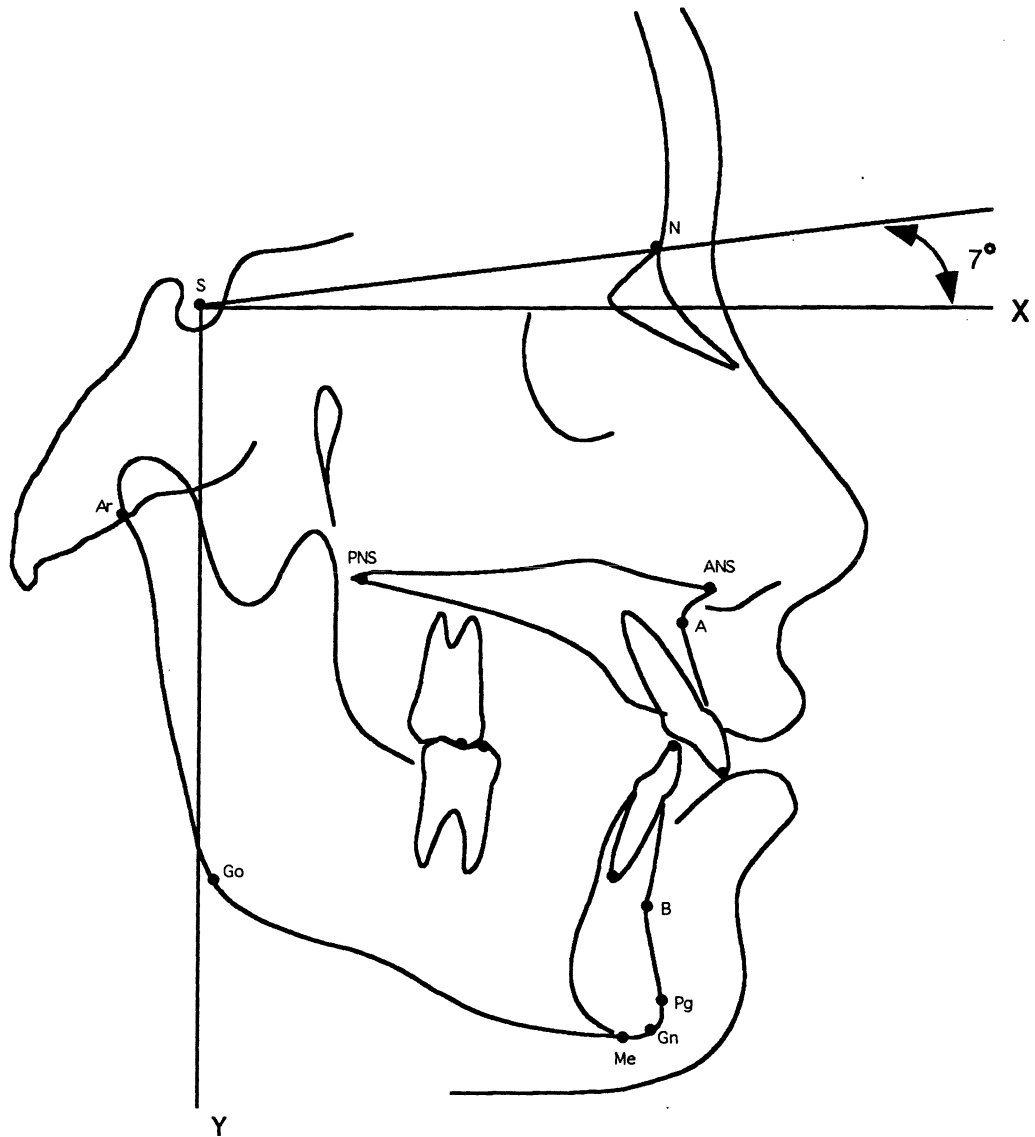


Fig. 6. Cephalometric landmarks.

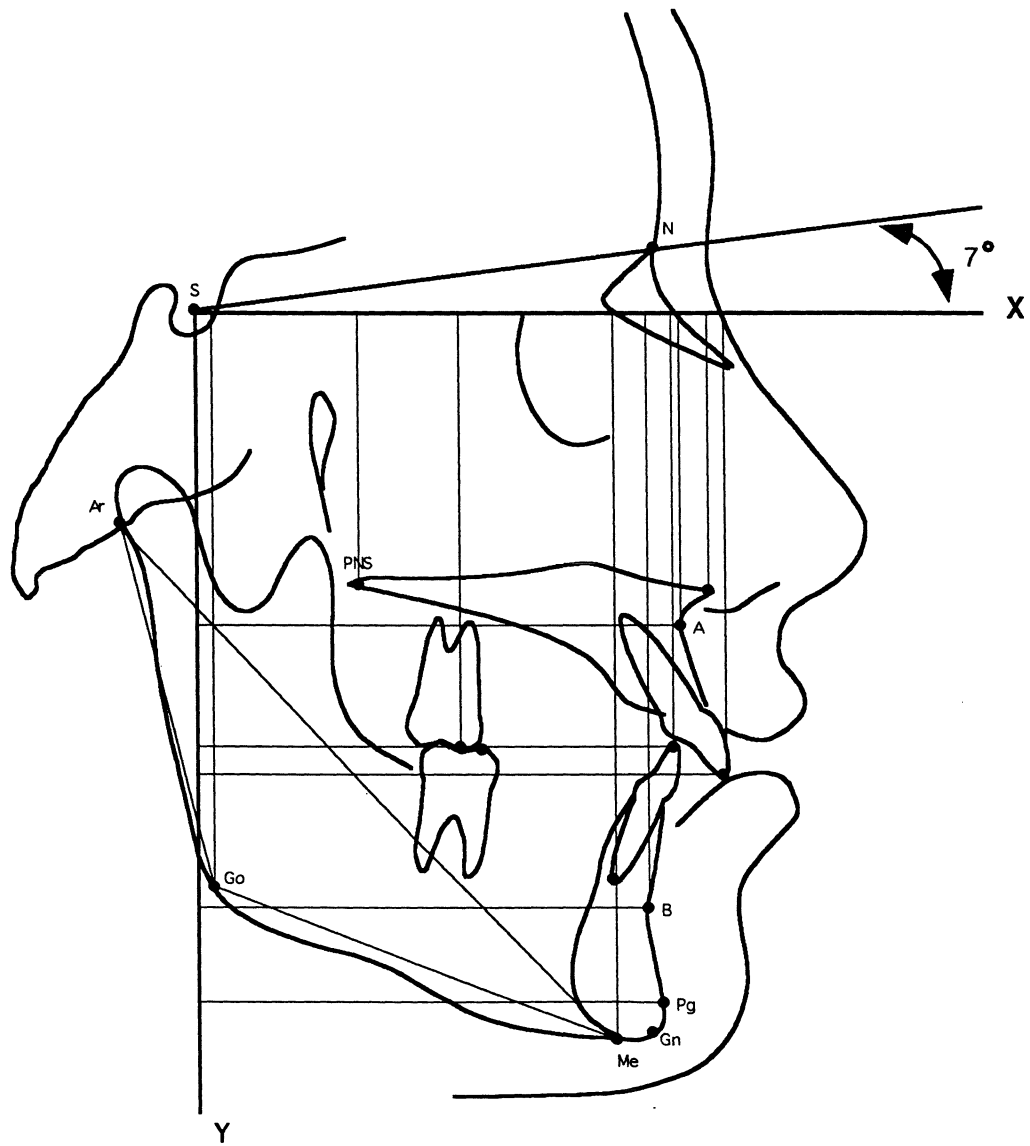


Fig. 7. Linear measurements.

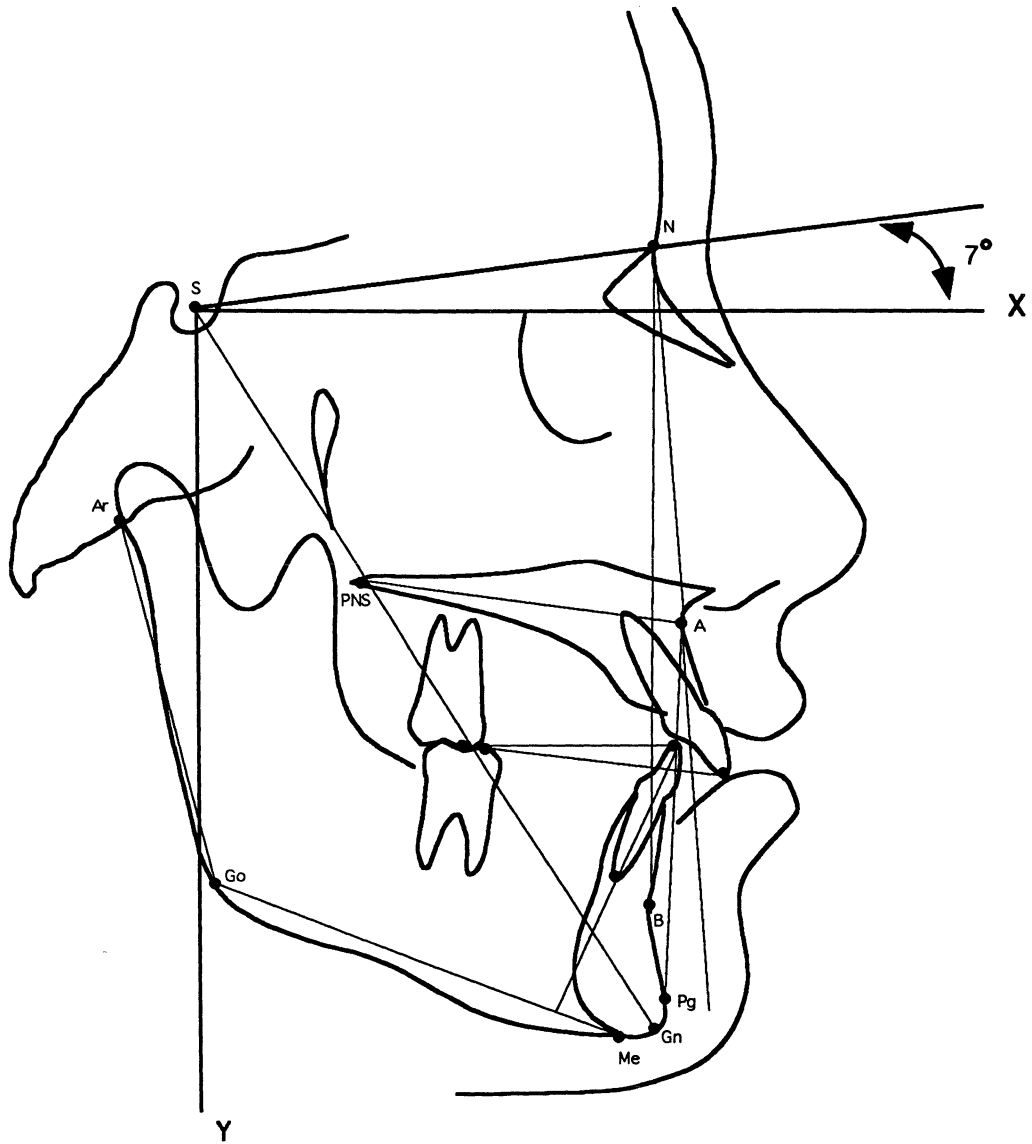


Fig. 8. Angular measurements.

| LINEAR     |            |          | ANGULAR   | RATIOS    |
|------------|------------|----------|-----------|-----------|
| horizontal | vertical   | absolute |           |           |
| Point A    | Point A    | Ar - Me  | N-A-Pg    | NANS/NMe  |
| ANS        | ANS        | Ar - Go  | SNA       | ANSMc/NMe |
| Mx I edge  | PNS        | Go - Me  | Pal plane |           |
| Point B    | Mx I edge  |          | UOP       |           |
| Pg         | Mx M (MBC) |          | SNB       |           |
| Md I edge  | Point B    |          | Md plane  |           |
|            | Me         |          | Y axis    |           |
|            | Md I edge  |          | Ar-Go-Me  |           |
|            | Go         |          | LOP       |           |

Table 1. Cephalometric measurements.

The cephalometric data permitted us to determine the following parameters: (1) presurgical mandibular morphology and facial height; (2) surgical changes of the mandibular length, anterior and posterior facial height, and mandibular plane angle; (3) extent of the surgical movement; (4) surgery on mandible, maxilla, or both. These different parameters allowed to group the subjects in different categories.

#### 4.3.5. Data analysis.

##### 4.3.5.1. Subject classification.

The fifteen patients were grouped in different categories according to their presurgical morphological type and, the direction of the surgical movements. The limited number of subjects did not permit classification according to the extent of surgical movement. Since the cephalometric analysis revealed only insignificant changes in posterior facial height, only anterior facial height and mandibular characteristics were used to identify the groups. The patients were divided into four presurgical morphological types: (1) retrognathic mandible (9 observations), (2) prognathic mandible (5 observations), (3) short anterior facial height (2 observations), and (4) long anterior facial height ( 10 observations). The same subjects were also divided into six surgical categories: (1) mandibular advancement (10 observations), (2) mandibular setback (4 observations), (3)

anterior facial height reduction (9 observations), (4) anterior facial height augmentation (5 observations), (5) mandibular plane angle reduction (10 observations), and (6) mandibular plane angle augmentation (3 observations).

#### 4.3.5.2. Bite force.

The distribution of patient showing: (1) an increase of maximum voluntary bite force (MVBF), (2) a decrease of MVBF, and (3) no change of MVBF, postsurgically, was compared to the expectation of no change if surgery was not performed. These frequencies were tested for significance with a non parametric analysis (Fisher's Exact Test).

Absolute values of MVBF for both molar and incisor were compared at (T0), (T1) and (T2). The differences between (T0), (T1), and (T2) were expressed as a percentage of the bite force at (T0) for each individual group in order to normalize the data. The relationship between molar and incisor bite forces was studied by comparing the ratio of molar bite force/incisor bite force at (T0), (T1), and (T2). All these differences were tested for significance within each group with a t-test, and between the groups with an analysis of variance (General Linear Models procedure, SAS).



#### 4.3.5.3. EMG/Force Function curves.

For each subject for whom the maximum voluntary bite force values were comparable (less than 10% different) at (T0), (T1) and (T2), plots of bite force versus EMG (RMS power) were constructed for each muscle for the molar and/or incisor bites. Linear regression analysis was used to construct EMG-force function curves that were compared in term of slope variations at (T0), (T1) and (T2). Procedures outlined by Lothar Sachs (1984) were employed to determine whether differences between the presurgical and postsurgical slopes were statistically significant.

#### 4.3.5.4. Electromyographic activity.

Raw maximum EMG activity values of the temporalis and masseter muscles for molar and incisor bites were compared at (T0), (T1), and (T2). Differences from (T1) to (T0), and (T2) to (T0) were expressed as a percentage of the presurgical EMG activity for each group. Ratios of temporalis / masseter muscle activity for both molar and incisor were compared to evaluate the changes in the contribution of each muscle to the bite force; t-tests were used to determine if the changes of these variables were statistically significant within groups, and a univariate analysis of variance was used for between-group comparisons.

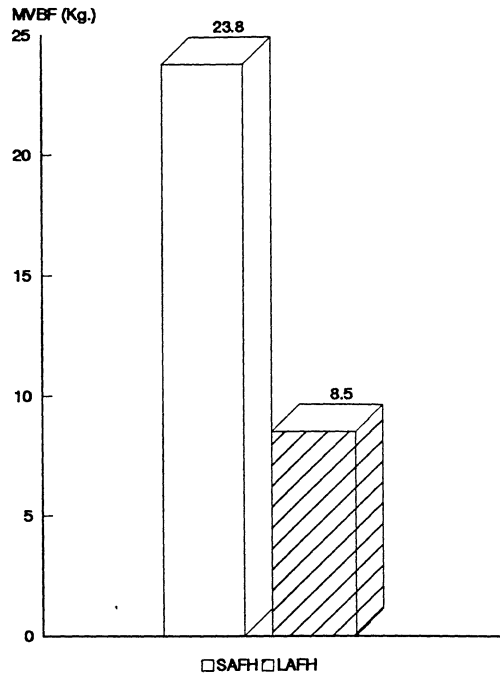
## **5. RESULTS.**

The short-term results at 6 weeks postsurgically were inconsistent and probably erroneous because of the patient's fear of biting hard due to relative soreness of the jaws. In most of the subjects, the maximum voluntary bite force recorded at 6 weeks was very low and probably did not reflect a true physiologic maximum but more a psychological limitation in order to avoid pain. For this reason, we disregarded the results obtained at 6 weeks and examined only the presurgical and the 6 months postsurgical comparisons.

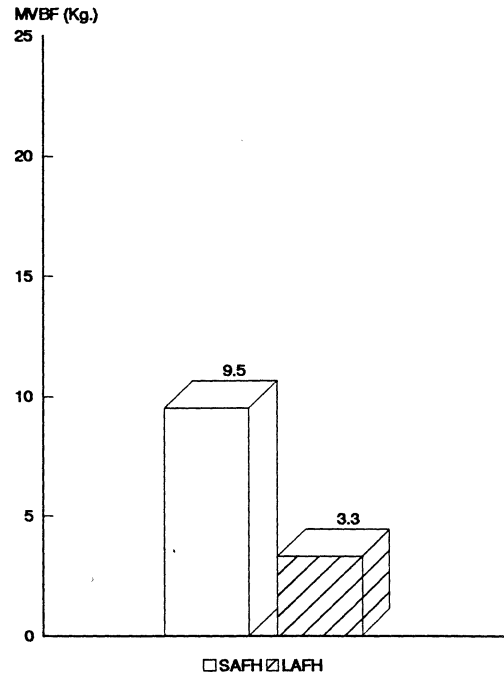
### **5.1. BITE FORCE.**

#### **5.1.1. Relationship between presurgical craniofacial morphology and maximum bite force.**

The short and long anterior facial height groups showed statistically significant differences for both molar and incisor bite force presurgically (Figs. 9a & 9b). The molar and incisor bite forces were much greater for the short anterior facial height subjects (SAFH) than for the long anterior facial height ones (LAFH). Mean maximum bite force levels were 23.8 kg for (SAFH) and 8.5 kg for (LAFH) at the molar and 9.8 kg and 3.3 kg at the incisor, respectively.

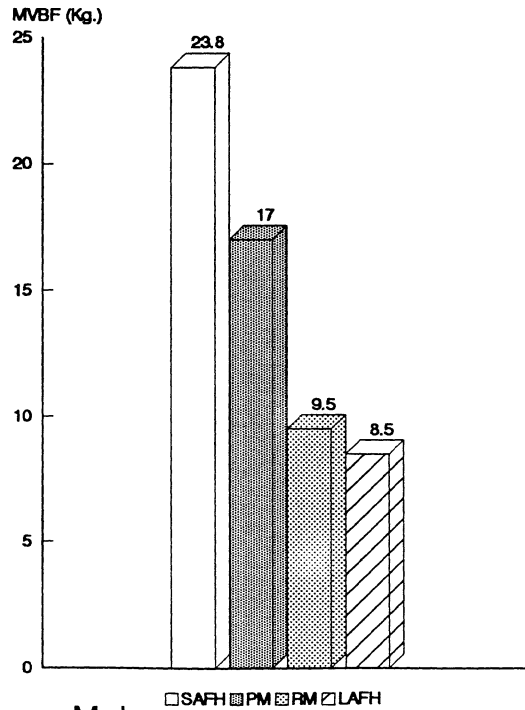


a. Molar ( $p < .0042$ )

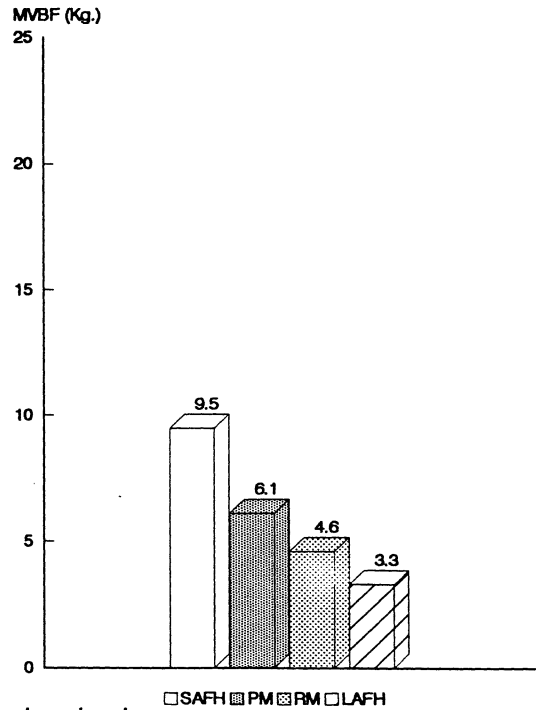


b. Incisor ( $p < .0296$ )

Fig. 9. Presurgical maximum voluntary bite force (MVBF) differences between SAFH and LAFH groups for molar and incisor bites.



a. Molar



b. Incisor

Fig. 10. Presurgical MVBF for LAFH, RM, PM, and SAFH groups, for molar and incisor bites.

Maximum bite forces decreased in the following order: (1) long anterior facial height (LAFH), (2) retrognathic mandible (RM), (3) prognathic mandible (PM), and (4) short anterior facial height (SAFH) (Figs. 10a & 10b). However, no statistically significant differences were found between the RM and the PM groups.

The ratio of the molar bite force / incisor bite force was approximately equal to 3.0 for the four groups. The molar bite force levels were therefore about three times greater than the incisor ones.

#### 5.1.2. Postsurgical changes in maximum bite force.

The results in this section are described according to the two different ways that were used to group the subjects: (1) presurgical skeletal morphology, and (2), surgical procedures.

##### 5.1.2.1. Postsurgical changes in maximum bite force based on presurgical skeletal morphology.

A non parametric analysis (Fisher's Exact Test) was used first to determine the distribution of patients who showed: (1) an increase of MVBF, (2) a decrease of MVBF, and (3) no change of MVBF, postsurgically, in comparison to the expectation of no changes if surgery was not performed. The results expressed

as frequencies are displayed in Table 2. For the SAFH group, 2 out of 2 subjects showed a decrease in molar MVBF (-20% to -48.6%); 1 showed a decrease in incisor MVBF (-25%) and 1 showed no significant change. For the LAFH group, 8 out of 10 showed an increase in molar MVBF (+17% to +567%) and 2 showed a decrease (-66.7% to -71.4%); for incisor MVBF, 5 out of 10 exhibited an increase (+50% to +350%), 2 showed a decrease (-33.3% to -50%), and 3 showed no change. For the RM group, 6 out of 9 had an increase in molar MVBF (+33% to +567%), and 3 had a decrease (-20% to -71.4%); for incisor MVBF, 5 out of 9 showed an increase (+50% to 316.7%), 3 showed a decrease (-25% to -50%), and 1 showed no change. For the PM group, 3 out of 5 had an increase in molar MVBF (+17% to +78.6%), and 2 had a decrease (-17% to -66.7%); for incisor MVBF, 2 out of 5 showed an increase (+92% to +350%), and 3 showed no change.

This analysis revealed that orthognathic surgery produced a highly statistically significant change in the number of patients whose mean bite force either increased or decreased after surgery for the LAFH and RM groups ( $P < .003$ ). This change was positive, especially for molar bites. The range of MVBF increase, expressed as a percentage of the presurgical MVBF, was extremely wide, going from approximately + 20% to + 600% for molar bites, and + 50% to + 350% for incisor bites.

|              |     |     |     |
|--------------|-----|-----|-----|
| SAFH (n = 2) | (+) | (-) | (=) |
| Molar MVBF   |     | 2   |     |
| Incisor MVBF |     | 1   | 1   |
| LAFH (n =10) | (+) | (-) | (=) |
| Molar MVBF   | 8   | 2   |     |
| Incisor MVBF | 5   | 2   | 3   |
| RM (n = 9)   | (+) | (-) | (=) |
| Molar MVBF   | 6   | 3   |     |
| Incisor MVBF | 5   | 3   | 1   |
| PM (n = 5)   | (+) | (-) | (=) |
| Molar MVBF   | 3   | 2   |     |
| Incisor MVBF | 2   |     | 3   |

Table 2. Postsurgical changes of maximum voluntary bite force (MVBF). Frequency distribution for groups based on presurgical facial morphology. (+): increase of MVBF; (-): decrease of MVBF; (=): no change of MVBF.

The SAFH group showed a negative change in the mean molar MVBF (34.3% decrease from original MVBF) and the LAFH and RM groups showed an increase of 81.9% and 126.1%, respectively. The PM group showed only a relative small increase (13.8%) (Fig. 11). For incisor forces, the SAFH group showed a decrease of 15.8% in MVBF; the RM, PM, LAFH groups showed comparable increases of 76.1%, 82.7%, and 87.1% respectively, from their original incisor MVBF (Fig. 11). The ratio of molar MVBF/incisor MVBF decreased for the PM and SAFH groups. It increased for the RM group and stayed stable for the LAFH group. However, none of these changes was statistically significant, probably because of either the small N (for example, SAFH, N=2), or the large within-group standard deviation.

#### 5.1.2.2. Postsurgical changes in maximum bite force based on surgical procedures.

The distribution of patients showing either an increase, a decrease, or no change in MVBF, closely followed the one obtained by grouping the subjects according to their presurgical craniofacial morphology with some exceptions. The results expressed as frequencies are given in Table 3. Out of the 9 subjects who had an anterior facial height reduction (AFHR), 7 showed an increase in molar MVBF (+17% to +567%), and only 2 showed a decrease (-17% to -66.7%); for incisor MVBF, 5 out of the 9 had an increase (+50% to +317%), 1 exhibited a

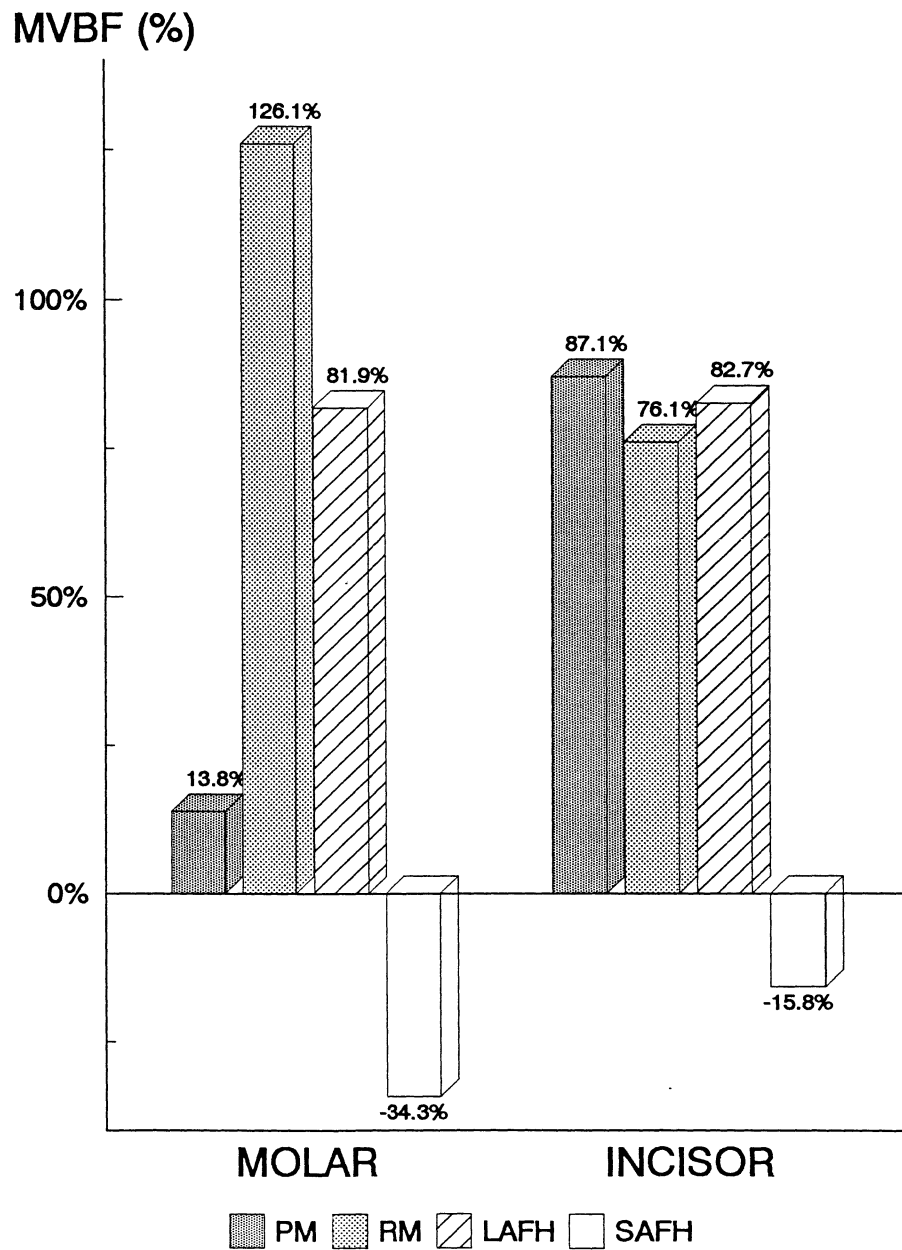


Fig. 11. Mean postsurgical changes in molar and incisor MVBF for the groups based on presurgical morphology (SAFH, LAFH, RM, PM). (Changes are expressed as percentage of the presurgical MVBF values).



|              |     |     |     |
|--------------|-----|-----|-----|
| AFHA (n = 5) | (+) | (-) | (=) |
| Molar MVBF   | 2   | 3   |     |
| Incisor MVBF | 2   | 2   | 1   |
| AFHR (n = 9) | (+) | (-) | (=) |
| Molar MVBF   | 7   | 2   |     |
| Incisor MVBF | 5   | 1   | 3   |
| MA (n = 10)  | (+) | (-) | (=) |
| Molar MVBF   | 6   | 4   |     |
| Incisor MVBF | 5   | 3   | 2   |
| MSB (n = 4)  | (+) | (-) | (=) |
| Molar MVBF   | 3   | 1   |     |
| Incisor MVBF | 2   |     | 2   |
| MPAA (n = 3) | (+) | (-) | (=) |
| Molar MVBF   | 1   | 2   |     |
| Incisor MVBF | 1   | 1   | 1   |
| MPAR (n=10)  | (+) | (-) | (=) |
| Molar MVBF   | 7   | 3   |     |
| Incisor MVBF | 5   | 2   | 3   |

Table 3. Postsurgical changes of maximum voluntary bite force (MVBF). Frequency distribution for groups based on surgical procedures. (AFHA): anterior facial height augmentation; (AFHR): anterior facial height reduction; (MA): mandibular advancement; (MSB): mandibular setback; (MPAA): mandibular plane angle augmentation; (MPAR): mandibular plane angle reduction; (+): increase of MVBF; (-): decrease of MVBF; (=): no change of MVBF.

decrease (-50%), and 3 had no change. For the group who had a reduction of their mandibular plane angle (MPAR), 7 out of 10 showed an increase in MVBF (+17% to +567%), and 3 had a decrease (-17% to -71.4%); for incisor bites, 5 out of 10 exhibited an increase (+50% to +350%), 2 showed a decrease (-33.3% to -50%), and 3 had no change. One can note that the mandibular plane angle reduction (MPAR) group has a similar distribution to the anterior facial height reduction (AFHR) group; this result is consistent since most of the long anterior facial height subjects had a reduction of the mandibular plane angle via a BSSO in order to decrease their anterior facial height. Out of the 10 subjects who had a mandibular advancement (MA), 6 exhibited an increase in molar MVBF (+17% to 433.3%), and 4 showed a decrease (-17% to -71.4%); for incisor bites, 5 had an increase (+50% to +317%), 3 had a decrease (-25% to -50%), and 2 had no change. Out of the 4 patients who had a mandibular setback (MSB), 3 showed an increase in molar MVBF (+57% to +567%), and 1 showed a decrease (66.7%); for incisor bites, 2 had an increase (+50% to +350%), and 2 had no change. However, for the subjects who had an anterior facial height augmentation (AFHA) as well as the ones who had an augmentation of their mandibular plane angle (MPAA), the distribution did not match the one observed for the short face subjects (SAFH): for the 5 subjects who had an AFHA and the 3 who underwent a MPAA, the change in molar or incisor MVBF went in either direction.

For molar biting, all the groups showed an increase in the mean MVBF

after surgery (Fig. 12). The MSB group showed a very large increase (158.9% of the presurgical MVBF); the MA, AFHA, and AFHR groups showed an increase in MVBF of 56.8%, 74.4%, and 88.4% respectively. For incisor biting, all the groups showed more than a 50% increase in MVBF after surgery (Fig. 12). The MVBF augmentation was more homogenous among the groups for incisor bites than for molar bites. The ratio molar MVBF/incisor MVBF decreased for the MA, AFHA, and MPAA groups. It greatly increased for the MSB group (3.6  $\rightarrow$  5.4), and slightly for the AFHR and MPAR groups (Fig. 13). Again, however, none of these differences was statistically significant.

## 5.2. EMG ACTIVITY

### 5.2.1. Relationship between presurgical craniofacial morphology (SAFH, LAFH, PM, RM) and presurgical maximum EMG activity.

The presurgical maximum EMG activity during molar bites was statistically significantly different ( $p < .02$ ) for the SAFH and LAFH groups (Fig. 14).

The temporalis muscle seemed to contribute more than the masseter muscle to the generation of MVBF for the RM and LAFH groups for molar bites (Fig. 15a.). Conversely, the masseter muscle seemed to contribute more than the temporalis muscle for the SAFH group for incisor bites (Fig. 15b.).

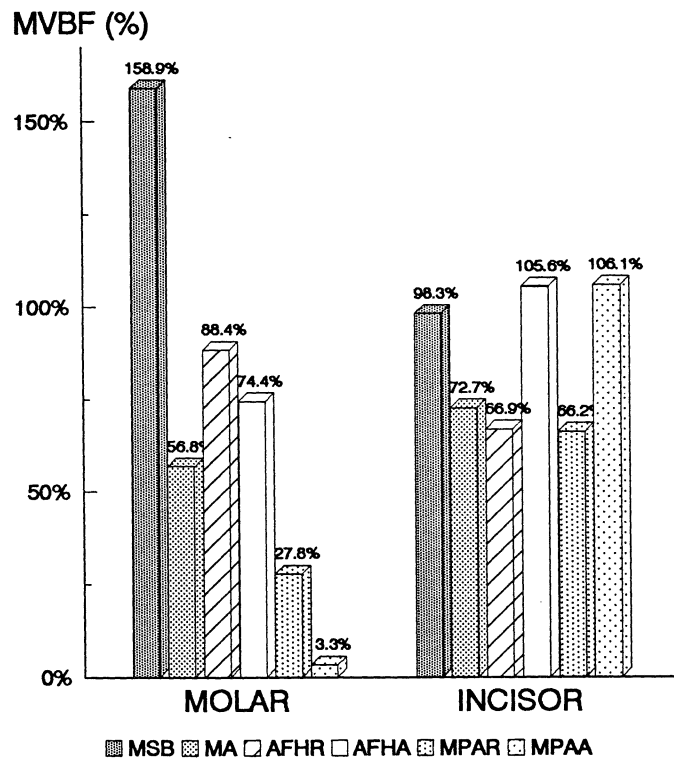


Fig. 12. Mean postsurgical changes in molar and incisor MVBF for the groups based on surgical procedures (AFHA, AFHR, MA, MSB, MPAA, MPAR).

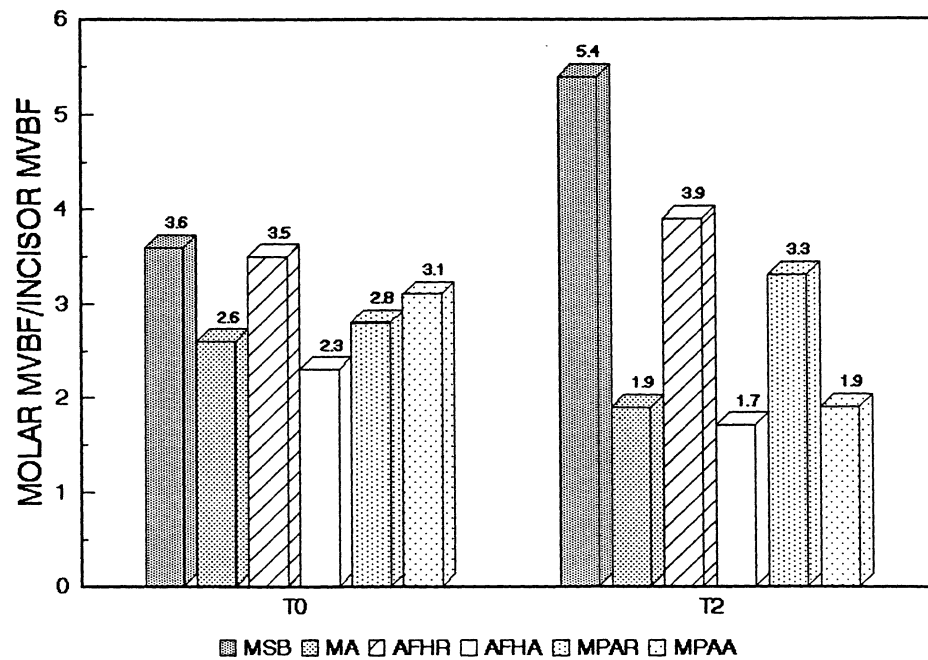


Fig. 13. Ratio molar MVBF/incisor MVBF. T0-T2 differences for the groups based on surgical procedures.

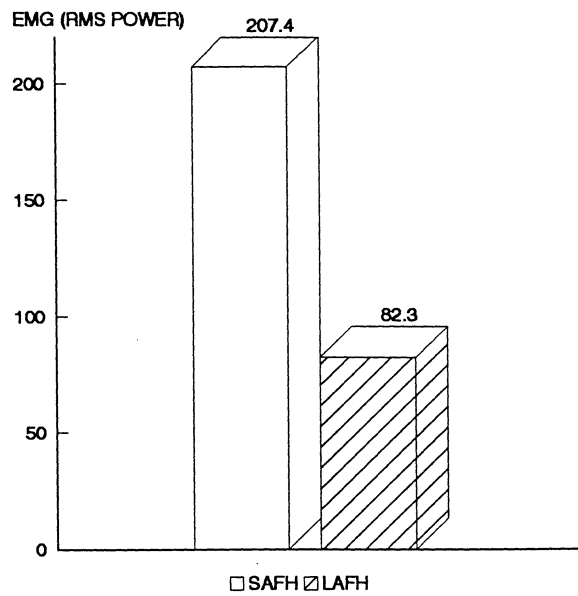
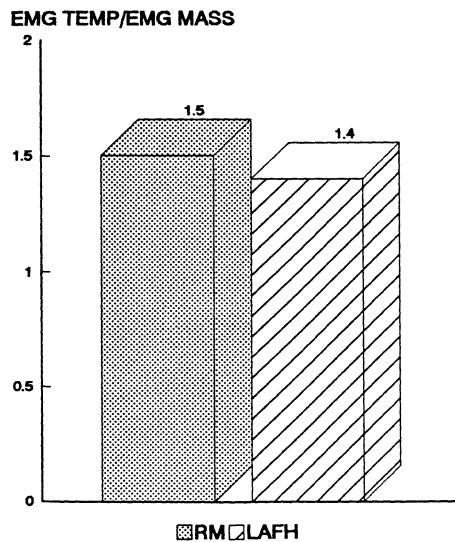
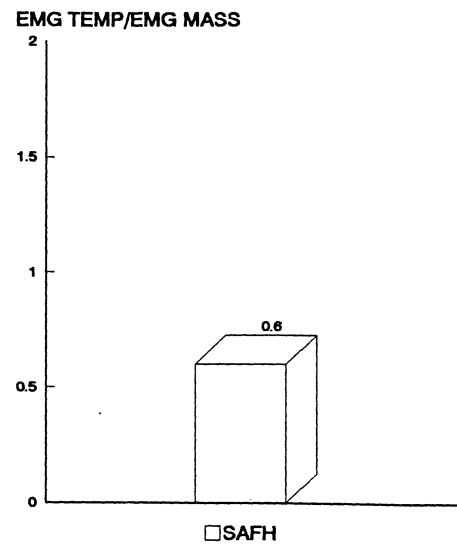


Fig. 14. Differences in presurgical maximum EMG activity during molar bites for SAFH and LAFH groups. ( $p < .02$ ).



a. Molar



b. Incisor

Fig. 15. Contribution of temporalis muscle vs. masseter muscle to MVBF generation.

### 5.2.2. Postsurgical changes of EMG activity.

Based on presurgical morphology, the SAFH group showed a decrease in the mean maximum EMG activity levels for the masseter muscle for both molar (-72.7%) ( $p < .032$ ) and incisor (-42.7%) bites, and for the temporalis muscle only for incisor bites (-12.6%). The other groups showed a general increase in maximum EMG activity. The contribution of the temporalis muscle to the generation of MVBF tended to increase relative to the contribution of the masseter muscle for molar bites for the SAFH group (Fig. 16).

Based on surgical procedures, a decrease in maximal EMG activity levels was reported for the MPAA group for the masseter muscle for molar bites. Otherwise, a general increase in maximal EMG activity levels was noted. The contribution of the temporalis muscle to MVBF seemed to increase relative to the contribution of the masseter muscle, especially for molar bites for the MPAA group (Fig. 17). The only exception was for the AFHA group, where the temporalis muscle's contribution to MVBF reduced slightly for both molar and incisor bites.

Although these trends were consistent for the different groups, the differences were not statistically significant except for the SAFH group for the masseter muscle at molar bites. Again, as with the comparisons for the other

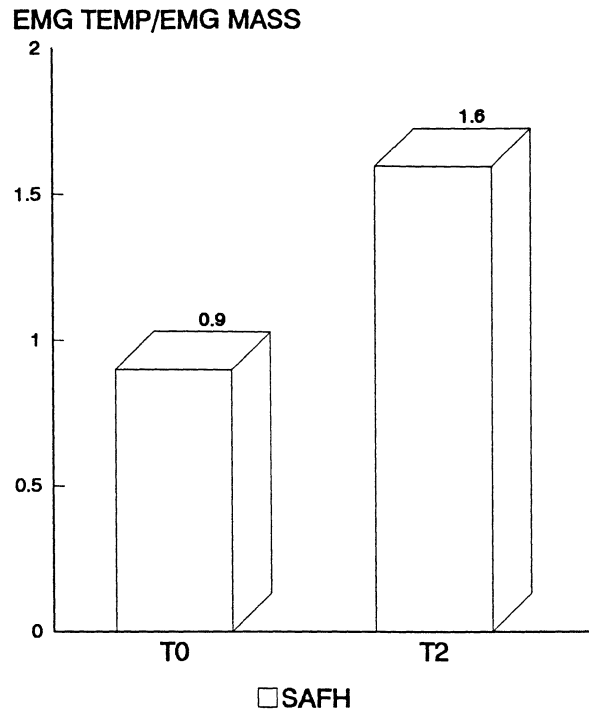


Fig. 16. Differences in the contribution of temporalis muscle vs. masseter muscle to molar MVBF between T0 and T2. SAFH group.

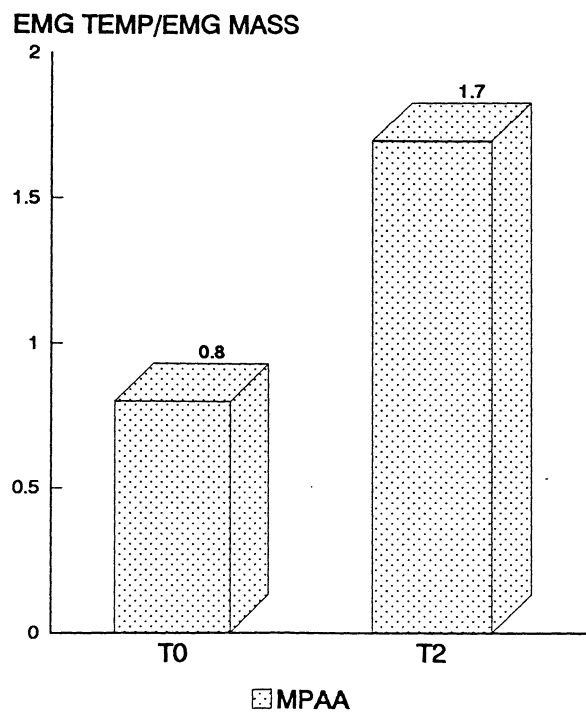


Fig. 17. Differences in the contribution of temporalis muscle vs. masseter muscle to molar MVBF between T0 and T2. MPAA group.

groups, the N was small (for example, MPAA, N=3) and the standard deviations were large.

### 5.3. EMG/FORCE FUNCTION CURVES.

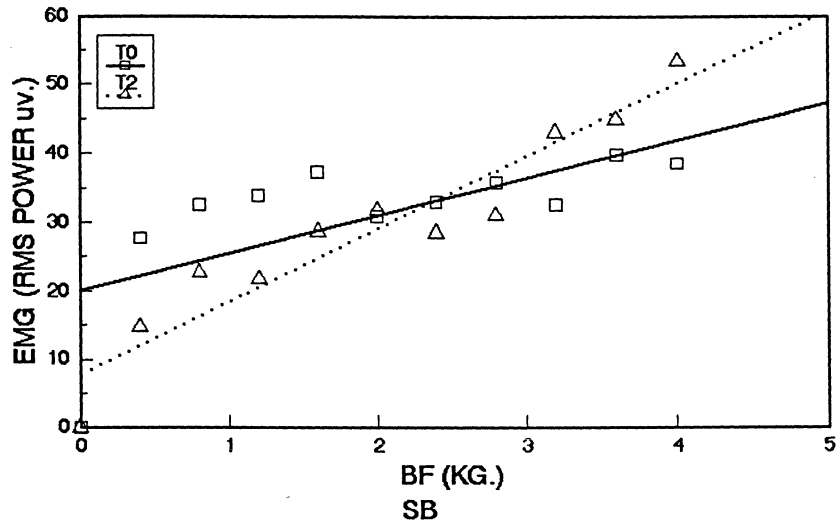
A regression analysis of the slopes of the EMG/Force function curves was performed for each of the four subjects who had comparable MVBF at T0 and T2 (+/- 10% difference). However, these four subjects had comparable bite force levels between T0 and T2 for the incisor bites only. Three of the four subjects (RS, RE, and SB) belonged to the same presurgical craniofacial morphology groups (LAFH, PM) and underwent the same type of surgical procedures (AFHR, MPAR, MSB). One of the four subjects (BH) had the opposite presurgical facial type (SAFH, RM), and the opposite surgical movements (AFHA, MPAA, MA).

Three out of the four subjects (RE, SB, and BH) showed highly statistically significant differences in the slope of the EMG/Force curves for both temporalis and masseter muscles between T0 and T2 ( $p < .001$ ) (Figs. 18, 19, and 20). One subject (RS) tended to show a change in the slopes for the masseter muscle but did not show statistically significant differences for either temporalis or masseter muscles between T0 and T2 (Fig. 21).

For the masseter muscle, the slope was statistically significantly decreased



**TEMPORALIS  
INCISOR**



**MASSETER  
INCISOR**

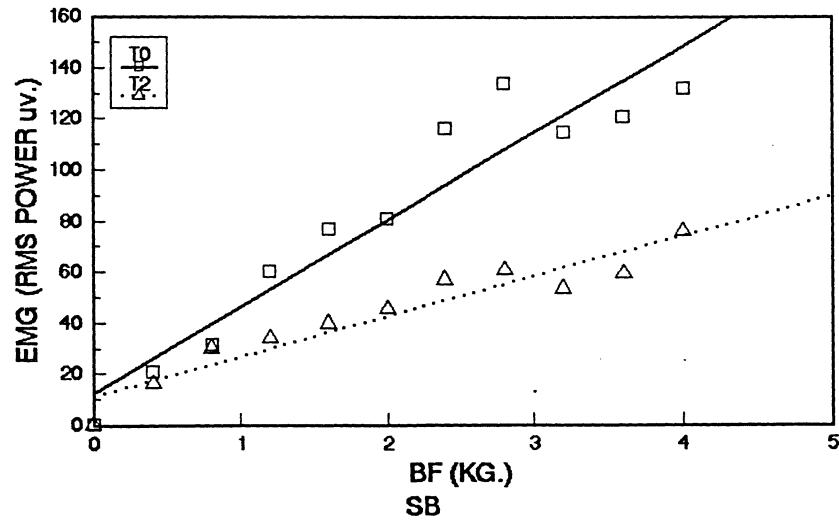
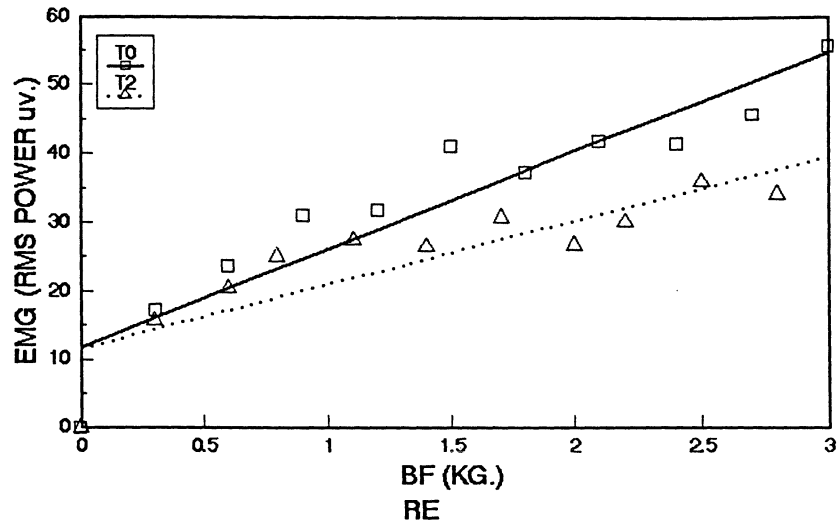


Fig. 18. Subject SB. EMG / Force function regression curves for temporalis and masseter muscles, (slopes variations T0 - T2,  $p < .001$ ).

**TEMPORALIS  
INCISOR**



**MASSETER  
INCISOR**

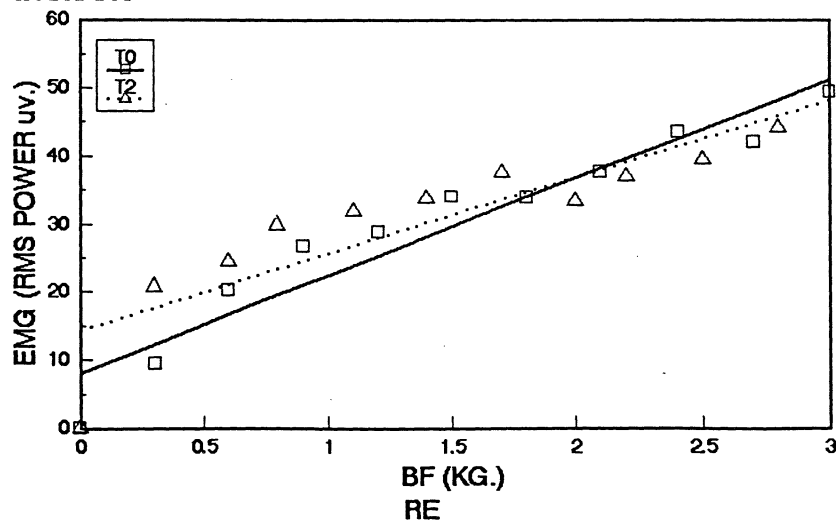
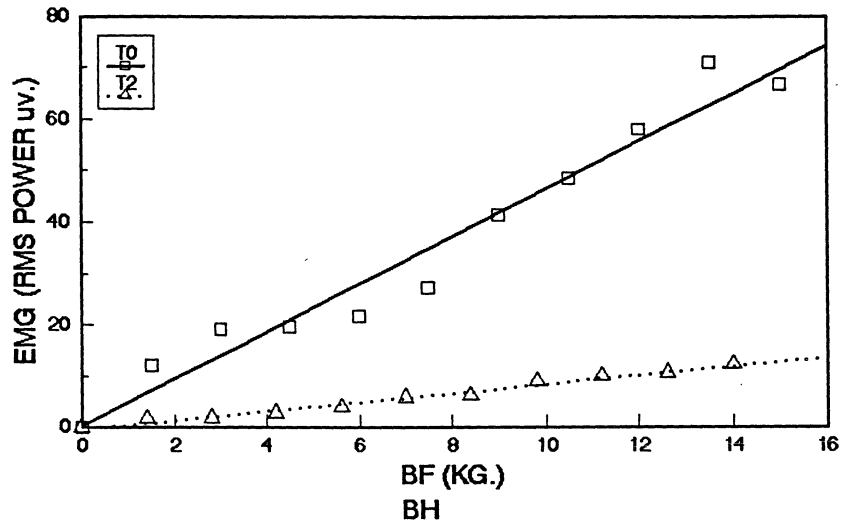


Fig. 19. Subject RE. EMG / Force function regression curves for temporalis and masseter muscles, (slopes variations T0 - T2,  $p < .001$ ).

**TEMPORALIS  
INCISOR**



**MASSETER  
INCISOR**

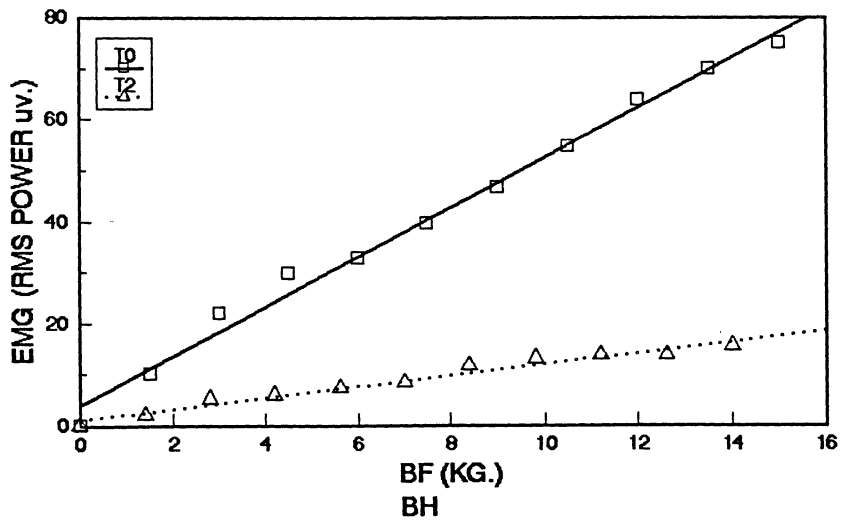
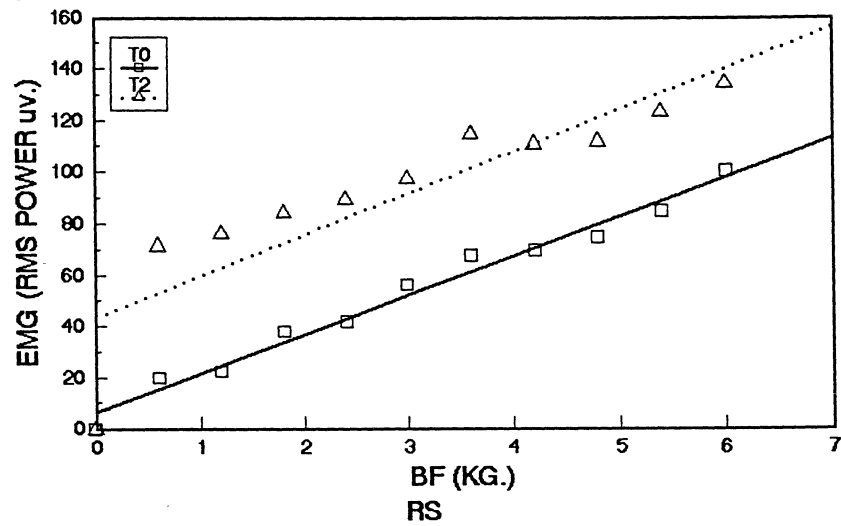


Fig. 20. Subject BH. EMG / Force function regression curves for temporalis and masseter muscles, (slopes variations T0 - T2,  $p < .001$ ).

**TEMPORALIS  
INCISOR**



**MASSETER  
INCISOR**

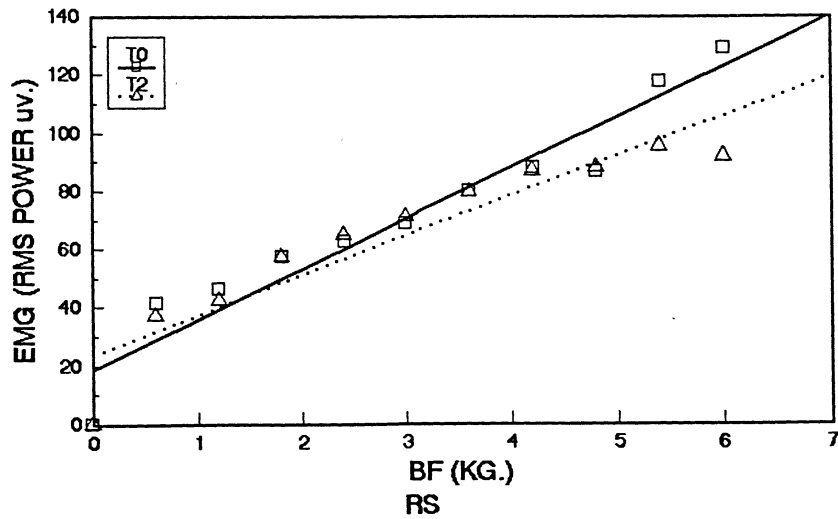


Fig. 21. Subject RS. EMG / Force function regression curves for temporalis and masseter muscles, (slopes variations T0 - T2).

postsurgically for subjects RE, SB, and BH, and tended to be reduced for subject RS, meaning that the average increase in EMG activity per unit of force over the range of bite forces studied decreased as a result of surgery. The contribution of the masseter muscle to bite force production was therefore statistically significantly decreased for high force levels after surgery for subjects RE, SB, BH, and tended to be reduced also for subject RS.

For the temporalis muscle, subjects RE and BH showed a statistically significant decrease in the steepness of the slope after surgery; thus, they had lower increases in EMG activity with force, meaning that the contribution of the temporalis muscle to bite force was decreased postsurgically for high force levels. Conversely, subject SB showed a significantly steeper temporalis slope after surgery, showing a greater increase in EMG activity with force and an increase in the muscle's contribution to bite force at high force levels. Subject RS showed no change in the contribution of the temporalis muscle to bite force.

These results showed that orthognathic surgery significantly affected the way in which a muscle contributes to the generation of bite force, but the way in which it does so is unpredictable. This suggests that the adaptive response to structural change is individual.

## **6. DISCUSSION.**

The purpose of this investigation was to examine: (1) the relationship between presurgical facial type and maximum voluntary bite force and EMG activity, (2) postsurgical changes in maximum voluntary bite force, (3) postsurgical variations in the contribution of the masseter and anterior temporalis muscles to the generation of bite force, and (4) the relationship of these changes to surgical movements and presurgical craniofacial morphology.

### **6.1. Relationship between presurgical facial type and maximum bite force and EMG activity levels.**

The differences found in presurgical maximum voluntary bite force (MVBF) and maximum EMG activity levels between the short and long face groups were consistent with the findings of other investigations (Ringqvist, 1973; Throckmorton et al, 1984; Haskell et al, 1986; Proffit et al, 1986; Van Eijden et al, 1991). These findings confirm that, as predicted, short face individuals can produce greater levels of bite forces than long face individuals. This can be explained by the fact that short face individuals have a flatter mandibular and lower occlusal plane than long face individuals, so that the direction of the bite force increases the mechanical advantage of muscles (Van Eijden, 1971). The more anteriorly positioned masseter muscle in short face individuals might also increase the

mechanical advantage of the muscle (Koolstra et al, 1988).

However, while we found statistically significant higher molar and incisor bite force levels and molar EMG activity in the short face group compared to the long face one, we did not find significant differences between the retrognathic and prognathic mandible groups. Further, the prognathic mandible group tended to have higher MVBF than the retrognathic mandible one. This can be explained by the fact that biomechanical variations are not the only factors involved in masticatory muscle function; other parameters such as muscle cross-sectional area and orientation, and individual neural control pattern have also been suggested to play an important role (Sasaki et al, 1989; Van Spronsen et al, 1992; Koolstra et al, 1988a; Lindauer et al, 1991).

For the four presurgical groups we found that the molar bite force levels were about three times greater than the incisor ones. This is consistent with the current biomechanical models of the jaw because for molar bites the point of force application is closer to the fulcrum (condyle) than it is for incisor bites. The bite force moment arm is therefore reduced and the mechanical advantage of the muscles is increased (Throckmorton et al, 1984; Proffit et al, 1989).

## 6.2. Postsurgical changes in maximum voluntary bite force.

The positive change in MVBF observed for the long face subjects who had a surgical reduction of their anterior facial height could have been predicted from a biomechanical point of view. Throckmorton et al (1984) demonstrated in a two-dimensional model that the effect of maxillary impaction is to decrease the distance between the point of force application and the condyle. But they only found an increased mechanical advantage for the temporalis muscle; the mechanical advantage of the masseter muscle remained the same. Proffit et al (1989) measured MVBF in 9 subjects after a LeFort I maxillary impaction. They found that the postoperative change in the mechanical advantage of the masseter and temporalis muscle was very small, and that the direction of the change in MVBF was unpredictable. However, in our sample, the long face subjects underwent a counterclockwise rotation of the distal segment of the mandible by a BSSO to reduce the vertical dimension; this type of surgical movement changed the direction of the bite force considerably; Van Eijden et al (1991) showed that the length of the bite force moment arm decreased by approximately 20% when its direction changed from ten degrees anteriorly to ten degrees posteriorly. This might explain why our results differ from the ones found in previous clinical investigations (Johnston et al, 1984; Proffit et al, 1989) which used only a LeFort I maxillary impaction to decrease the vertical dimension.

Unexpectedly, our retrognathic patients who had a mandibular advancement also showed a positive change in MVBF. This suggests that



biomechanical considerations alone are unable to explain variations in MVBF (Dechow et al, 1986; Proffit et al, 1989). Physiologic properties of muscles and muscle fibers may vary postsurgically in a very individual way. Another factor may also be that there were no statistically significant differences between the MVBF of the retrognathic and prognathic mandible groups.

The biomechanical differences described by Throckmorton et al. (1984) may not be as important as the consideration of the direction of the bite force (Van Eijden et al, 1991): mandibular plane as well as lower occlusal plane angle differences commonly associated with differences in anterior facial height might have more influence on MVBF outcome than antero-posterior dimension. This is probably why the mean molar and incisor MVBF changes from T0 to T2 expressed as a percentage of the original force showed a general increase for all groups except for the short face subjects who had an augmentation of the vertical dimension. These MVBF variations were much higher than the ones described by previous investigations. This might be due to: (1) an optimal control of jaw opening and antero-posterior position by the use of customized bite blocks; (2) a more accurate recording of true MVBF; (3) the utilization of normalized values from the original MVBF of each group. However, we also found a high standard variation within the groups which makes prediction of the magnitude of the MVBF changes difficult to determine on an individual basis.

Orthognathic surgery seems to produce differential effects on molar and incisor bites as shown by the changes in molar MVBF/incisor MVBF ratio: it considerably increased for the subjects who had a mandibular setback and an anterior facial height reduction and decreased for the ones who had a mandibular advancement or an anterior facial height augmentation. This finding can be explained biomechanically by the fact that changes in facial height were achieved by a variation of the mandibular plane which produces a more dramatic effect on the molar bite force direction than the incisor one.

### 6.3. Postsurgical variations in the contribution of the masseter and anterior temporalis muscles.

#### 6.3.1. Maximum EMG activity levels.

Surgery tended to produce an increase in maximum EMG activity levels for all groups except the short face subjects; the EMG activity increase is in agreement with Astrand's (1974) and Ingervall's (1979) findings. However, these results should be interpreted with caution given the extremely high standard deviation found within the different groups.

The results regarding the individual contributions of the temporalis muscle and masseter muscle to generate bite force are also predictable. For the short

face subjects and those who underwent an augmentation of the mandibular plane angle via a BSSO, the contribution of the temporalis muscle to MVBF production increased relative to the masseter muscle's contribution for molar bites postsurgically. This pattern has also been described previously in long face individuals (Moller, 1966; Lindauer et al, 1990).

#### 6.3.2. Slopes of the EMG/Force function curves.

The results of this study showed that orthognathic surgery had a statistically significant effect on the contribution of the anterior temporalis and masseter muscles to bite force generation for three out of four subjects studied.

The average increase in EMG activity with bite force for the masseter was decreased at high force levels postsurgically for all four subjects, with the decrease statistically significant for three. These results might be explained by the fact that the masseter muscle was either more efficient postsurgically or that other muscles changed their contributions. However, even though these muscles all changed their contribution patterns, they did not do so in a predictable fashion.

From a biomechanical point of view, we might expect that the temporalis muscle contribution to bite force should increase as part of the adaptive process. However, only one subject showed a significant increase in the temporalis muscle

postsurgical slope, two subjects showed a significant decrease, and one showed no change. This result is in agreement with the findings of Lindauer et al (1989) who did not find consistent associations between masseter and temporalis muscle activity tradeoffs as a function of force. Other muscles such as the lateral and medial pterygoid muscles not examined in our study, may increase their contribution to bite force at high force levels as a compensatory mechanism. These possible complex trade-offs among the different muscles may explain why subject BH showed a decrease in the slope of both temporalis and masseter muscles. According to the surgical movements that he underwent (mandibular advancement, anterior facial height augmentation) and to his presurgical facial type (retrognathic mandible associated with a short anterior facial height), we could have expected an opposite result. On the other hand, the decrease in the masseter slope observed in SB, RE, and RS who had the same type of surgery (mandibular setback and anterior facial height reduction) and belonged to the same presurgical groups (prognathic mandible with long anterior facial height) could have been predicted from a biomechanical point of view: the counterclockwise rotation of the mandibular distal segment changed the direction of the bite force in a favorable way, increasing the muscle mechanical advantage (Van Eijden, 1991). For these subjects, the decrease in the slope may be due to an improvement of the physiological properties of the masseter muscle, showing less activity increments at high force level than they did presurgically. However, for one of these subjects (SB), a significant increase in temporalis slope at high

force level was observed, suggesting a potential compensation in order to produce the same bite force. However, the direction of the changes in the slopes could not be predicted from the type of surgery, even though three subjects who had similar surgical procedures showed the same direction of changes in the slopes for the masseter muscle. In contrast, the fourth subject whose change was also significant had the opposite surgical procedure. Thus, whether a patient's adaptation to a new structural environment is determined by biomechanical properties or neuromotor strategies, is probably determined, itself by the individual patient.

#### 6.4. Grouping factors.

Another factor to consider is the method used to classify the patients into different categories. It is obvious that such a categorization is artificial and might be misleading; our small sample size did not allow us to group the subjects according to a single surgical movement. For example, we could not isolate the influence of mandibular setback alone on bite force and muscle function because this procedure was associated in most cases with corresponding changes in anterior facial height. On the other hand, the use of combined surgical movements is nowadays common in order to correct complex maxillo-mandibular deformities; the overlap of the different categories then may not be a problem but, on the contrary, be useful to better understand the effects of "real world" surgical

procedures.

The size of our sample also did not permit us to evaluate the extent of the surgical change; therefore, borderline subjects who may have had a relatively small change in either direction were in the same group as patients who had more severe facial deformities. Since the variations in maximum voluntary bite force and EMG activity from T0 to T2 were expressed as a percentage of the presurgical values of each group, the results could be biased. For example, of the five subjects who underwent an anterior facial height augmentation (AFHA), two only had more than 5.0 mm. increase, and the presurgical bite force and EMG activity levels were significantly different for these two subjects compared to the other three. This resulted in an increase in the range of bite force and EMG values , magnifying the postsurgical changes. This was one of the reasons why we also categorized the subjects according to their presurgical facial type in order to increase the chances to find significant differences and to see the influence of the original condition on bite force and muscle function.

## **7. SUMMARY AND CONCLUSIONS.**

This study showed that there was a statistically significant relationship between anterior facial height and presurgical maximum voluntary bite force (MVBF) for both molar and incisor bites, and maximum EMG activity levels for molar bites. For all groups, the presurgical molar MVBF was three times greater than the incisor MVBF.

The surgical procedures produced statistically significant positive changes in MVBF for the long face subjects who had a reduction of their anterior facial height and the retrognathic patients who underwent a mandibular advancement. A negative change in molar MVBF was observed for the short face subjects who had an augmentation of their anterior facial height. The mean molar and incisor MVBF changes from T0 to T2 expressed as a percentage of the presurgical MVBF showed a general increase for all groups except the short face subjects. However, the variation observed within groups was high. Surgery seemed to have a differential effect on molar and incisor bite forces: the ratio of molar MVBF/incisor MVBF decreased for the subjects who had a mandibular advancement or an augmentation of their anterior facial height. For the most part, it increased for the patients who had a mandibular setback with a reduction of their anterior facial height.

Surgery tended to produce an increase in maximum EMG activity levels for all groups except the short face subjects, who showed decreased EMG activity levels postsurgically (statistically significant result only for the SAFH group for the masseter muscle at molar bites). Again, the variation from the mean values within the groups was high.

A change in the contribution of the masticatory muscles to bite force was observed for the short face subjects as well as for the subjects who underwent a clockwise rotation of the mandibular distal segment: the contribution of the temporalis muscle to the generation of (MVBF) increased relative to the masseter muscle's for molar bites.

The steepness of the slopes of the EMG/Force function curves for the temporalis and masseter muscles were statistically significantly different postsurgically for 3 out of 4 subjects who had comparable MVBF at T0 and T2, suggesting a physiologic adaptation to their new jaw geometry. At high force levels, the masseter muscle contributed significantly less to produce the same bite force postsurgically, suggesting that either it was more efficient or that the contribution of other muscles contributions changed. However, the contribution of the temporalis muscle at high force levels increased significantly for only one subject, was reduced for two subjects and unchanged for one. These changes in muscle contraction patterns could not be explained by biomechanically-derived



parameters alone. Apparently, individual neuromuscular variations in response to orthognathic surgery makes a prediction of change in the relative contributions of the temporalis and masseter muscles difficult to determine.

Based on the results of this study, several conclusions can be drawn:

(1) A statistically significant relationship exists between facial morphology and the ability to generate bite force.

(2) Orthognathic surgery significantly affects a patient's ability to generate bite forces, with apparent differential effects on molar and incisor force levels.

(3) Orthognathic surgery significantly affects the relative contributions of the anterior temporalis and masseter muscles in generating bite forces.

(4) The direction and extent of changes in bite forces and the way in which the muscles contribute to those changes cannot be predicted on the basis of biomechanical factors alone.

This study revealed the importance of both biomechanical and neuromuscular parameters on bite force ability and muscle contraction. The

biomechanical parameter which seemed to be the most reliable predictor was the change in bite force direction associated with changes in anterior facial height.

However, the changes observed could not always be fully explained by changes in jaw geometry alone. A very individual adaptive process of the neuromuscular system seems to take place after orthognathic surgery, making it difficult to predict specific changes in function as a response to any given surgical procedure.

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