MUSCULO-SKELETAL ADAPTATION TO DISTURBANCES OF THE CRANIO-FACIAL COMPLEX

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ABSTRACT

This study has addressed the possible relationships between the structure and function of the masseter and temporalis muscles and the skeletal morphology of the human face and jaws. Furthermore, it has noted how these muscles respond to surgical correction of facial deformities, and whether this has any relevance regarding surgical stability.

42 patients scheduled for surgical correction of vertical facial deformities were subjected to investigations designed to record the structure and function of masseter muscle, and the function of temporalis muscle. These were repeated over a one year review period. Muscle structure was investigated using ATPase histochemical techniques, whilst muscle function was recorded through electromyography, mandibular kinesiography and occlusal force measurement. Skeletal and dental form was measured from digitized lateral skull cephalometeric radiographs. Where appropriate the results were compared to those from a matched control group (20 patients) with normal skeletal facial morphology.

The results showed a significant reduction in the size of type II fibres in patients with a long face morphology and this was reflected in the reduced occlusal force generated by such individuals. Canonical correlation analysis showed that a reduced type II fibre contribution to the relative fibre cross-sectional area influenced the anterior vertical relationship of the mandible to the cranial base ($p \leq 0.001$), but no other aspect of facial form. Facial morphology did not significantly influence muscle structure.

Surgery resulted in a reduction in Intermediate fibre incidence and vertical surgical stability correlated with the incidence of Intermediate fibres prior to operation ($r = -0.94$, $p \leq 0.001$). Muscle adaptation was observed over the review period ranging from almost immediate adaptation in the clinical rest position of the mandible relative to the maxilla, through to more gradual adaptation in the physiological rest position and range of mandibular mobility

extending over a 12 month period.

The measures of muscle function indicated reciprocal activity between masseter and anterior temporalis in maintenance of mandibular rest position. Non-invasive studies of muscle function showed good correlation with type II fibre size and percentage total cross-sectional area but gave little information regarding type I fibres, the sub-groups of type II or Intermediate fibres.

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List of abbreviations used throughout the text

The following commonly used abbreviations will appear throughout the text:

EMG	-	Electromyography
ATP	-	Adenosine triphosphate
ATPase	-	Adenosine triphosphatase
SS	-	Sagittal split osteotomy of the mandible
LFI	-	Le Fort I osteotomy of the maxilla
SFG	-	Short face group
LFG	-	Long face group
RVD	-	Resting vertical dimension
TESP	-	Trans-cutaneous electrically stimulated position
SD	-	Standard deviation of the mean
SE	-	Standard error of the mean
95% CI	-	95% confidence interval
r	-	Pearson correlation coefficient
ANOVA	-	One-way analysis of variance
ns	-	Not statistically significant
GTCO[3]	-	Superscript indicates manufacturer listed in appendix

INTRODUCTION

The question as to the principal factors responsible for the control of cranio-facial growth has resulted in a swing of the pendulum back and forth between the genetic and environmental theories. Of the environmental factors, the form and function of the muscles of mastication have been suggested as possible regulatory mechanisms influencing the final form and relationships of the maxilla and mandible, especially in the vertical dimension (Møller, 1966).

The question whether abnormal facial form affects muscle structure and function or whether abnormal muscle form and activity affects facial morphology remains unanswered. However, regardless of how abnormal dento-skeletal form occurs there is no doubt that the dental, skeletal and muscular components are in a state of functional balance. Orthodontic or surgical correction of dento-facial form is likely to alter the musculo-skeletal relationship and may result in muscle activity abnormal for the individual which could potentially lead to relapse.

It was considered that further information could be ascertained regarding form, function and musculo-skeletal adaptation by studying patients presenting for the surgical correction of facial deformity. If abnormal facial growth in the vertical dimension is a direct result of abnormal muscle, then unless that muscle is capable of adaptation, surgical correction of the deformity should theoretically relapse, which may to some extent lend weight to the argument in favour of muscle as an environmental factor controlling growth.

Alternatively, if surgical stability were followed by adaptation of muscle structure and function to a more 'normal' level, then this would perhaps suggest that the muscle picture was secondary to the genetically determined bony relationship.

The aims of this study were three-fold. Firstly, to investigate the possible relationships between the structure and function of human masseter muscle and the function of the temporalis muscle with respect to the corresponding facial form in the vertical dimension. Secondly, to study the changes occurring in the structure and function of the masseter muscle in conjunction with surgical alteration of vertical facial imbalance. Thirdly, to consider to what extent the results of non-invasive studies of muscle function reflect muscle structure.

All patients attending the facial deformity and orthognathic clinics of the Eastman Dental Hospital between February 1987 and August 1988 were screened for an obvious discrepancy in vertical facial form as revealed by inspection.

A total of 66 patients was identified of whom 54 agreed, at least initially, to take part in the study having had the full protocol explained. As will be seen, several patients exercised their prerogative to withdraw, particularly in the later stages. Despite attempts to the contrary, it proved impossible through technical and logistical reasons to record information for every patient at the prescribed stages of the study. Therefore the number of participants involved in each aspect of the investigation will be identified in the text.

All investigations in this study received the approval of the Research and Ethical Committee of the Eastman Dental Hospital and Institute of Dental Surgery.

Chapter 1

GENERAL LITERATURE REVIEW

Facial growth in the vertical dimension

i) Vertical facial balance

In order to maintain a normal relationship between the mandible and the maxilla and cranial base, anterior and posterior facial growth must remain in balance. If the vertical increase at the facial sutures and alveolar processes is greater than at the condyle, the mandible rotates in an opening or backward manner. Conversely, if condylar growth exceeds the sum of vertical anterior growth then a closing or forward rotation will occur (Schudy, 1965; Isaacson *et al.*, 1971). Depending upon the location and relative extent of the vertical growth imbalance, the centre of rotation will vary from the incisal edge, the teeth in the buccal segments or the temporo-mandibular joint.

ii) Theories of vertical facial growth

Scott (1953, 1957) considered that facial growth was primarily under genetic control and that growth of the associated soft tissues occurred secondarily to that of the osseous tissue. Although soft tissue function could influence the form and structure of a particular bone at certain sites, for example the size of muscular processes, growth in length of a bone was considered to be largely independent of its use (Scott, 1957).

In complete contrast to these views, Moss (1962, 1964) proposed that whilst genetic factors initiated bone formation, subsequent growth of any bone was ultimately determined by function. This so-called "functional matrix" was later sub-divided into two types. The "periosteal" matrix was considered responsible for determining bony topography and the "capsular" matrix for spatial location of a part. According to Moss (1968) enlargement of the nasal and oral airways resulted in expansion of the oro-facial capsule which carries the mandible downwards and forwards away from the cranial base. The maxilla responds by expansion in order to maintain an articulation

between the mandible and base of skull. The spheno-occipital, nasal and condylar cartilages were not, therefore, considered primary growth centres but sites at which growth occurred in response to functional demands.

Moss (1981) further developed his theories by suggesting that both "genomic" and "epigenetic" factors are necessary for cranio-facial growth. As such, since the genome does not contain sufficient information to regulate all subsequent development, additional epigenetic information is self-generated concomitant with the attainment of increasing structural and functional complexity.

It is very difficult to either prove or disprove the theories as proposed by Moss. Severe criticism of much of the supportive evidence was levelled by Johnston (1976) and one must question whether evidence from essentially pathological conditions can be applied to explain a normal developmental process.

Mills (1983) stated that the mechanisms behind anterior or posterior growth rotations have never been adequately explained.

Björk (1969) considered that condylar growth direction together with muscular forces were important as aetiological factors. Since muscle and ligamentous attachments have a finite working length, the author felt that they were capable of directing growth of the mandibular body such that when vertical mandibular growth exceeded horizontal development, the attachments at or near the gonial angle converted the vertical growth direction into an anterior rotation. Björk (1969) also considered the magnitude of the masticatory forces significant in relation to growth rotations, referring specifically to the observations of Møller (1966) using electromyography. These results indicated a greater activity in the elevator muscles during maximum biting and simulated chewing in those cases exhibiting an anterior or closing rotation compared to those with an opening or backward rotation. These results have been subsequently supported by several authors both electromyographically (for example Moss, 1980) and

by occlusal force measurements in adults (Proffit *et al.*, 1983).

iii) Extreme vertical facial dysplasias

Whilst all individuals exhibit some degree of forward or backward rotational growth of the face and jaws, the effect is normally small and frequently masked. Occasionally, however, the degree of rotation may be particularly marked such that anterior rotations are characterized by some of the morphological features seen in the "short face syndrome " (Opdebeeck and Bell, 1978) whilst posterior rotations display features characteristic of the "long face syndrome" (Schendel *et al.*, 1976). The term syndrome is used in these situations as it allows a more complete description of the facial, skeletal and dental characteristics of a given facial type and its variants rather than relying upon more exclusive but somewhat inaccurate designations of single parameters, for example "low or high angle" cases (Bishara and Augspurger, 1975; Opdebeeck and Bell, 1978).

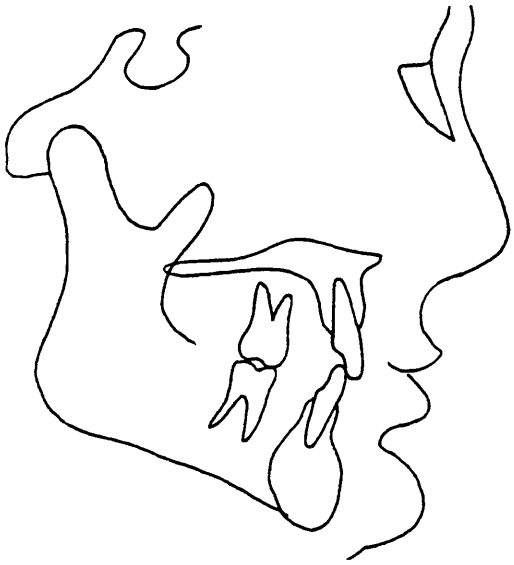
iv) The short face syndrome

Opdebeeck and Bell (1978) studied cephalograms of 27 untreated adult Caucasians which had been selected on the basis of a clinical impression of a reduced face height. The authors concluded that two sub-groups of the clinically recognizable facial type were evident (figure 1). Sub-group 1 was characterized by a long ramus, a sharply reduced cranial base to mandibular planes angle, and a relatively normal ratio of upper to lower anterior face heights measured as percentages of the total anterior face height.

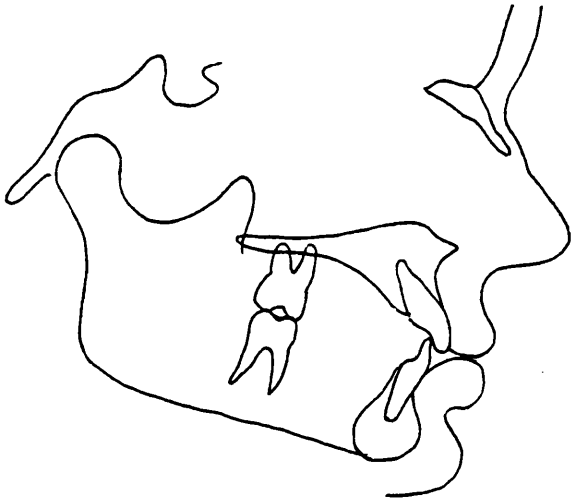
By way of contrast, sub-group 2 was characterized by a short ramus, a slightly reduced cranial base to mandibular planes angle, a facial proportion index of approximately zero and a reduced posterior maxillary height designated as vertical maxillary deficiency.

Figure 1 - Sub-groups of the short face syndrome

(after Opdebeeck and Bell, 1978)



Sub-group I show a reduced sella nasion - mandibular planes angle, a long ramus, a normal posterior maxillary dento-alveolar height and a facial proportions index which approximates 10. (see page 61)



Sub-group II is characterized by a reduced sella nasion - mandibular plane angle, a short ramus, vertical maxillary deficiency and a facial proportions index which approximates zero.

v) The long face syndrome

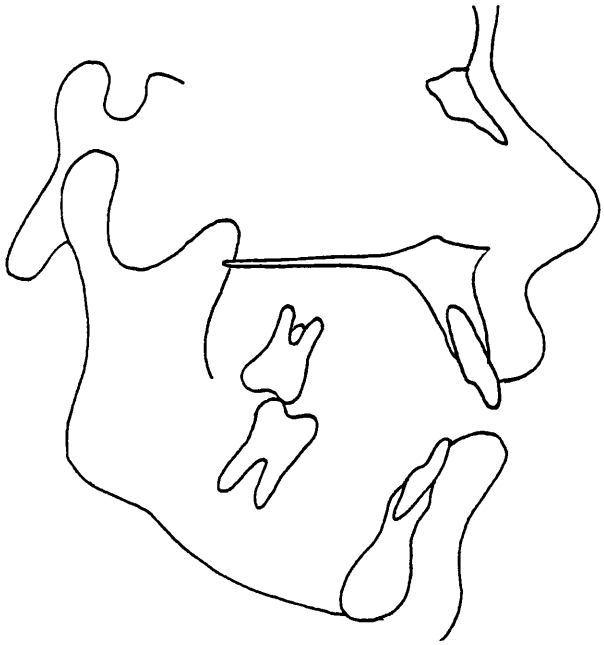
According to Schendel *et al.* (1976) the term "long face syndrome" was used to unify the various and more specialized titles of this specific facial deformity (for example; high angle case, adenoid face or vertical maxillary excess) under one facial type.

Whilst there may be common aesthetic abnormalities (for example, excessive exposure of maxillary teeth and gingivae, especially on smiling) it was only following cephalometric analysis of 31 Caucasian patients that the commonly recurring skeletal and dento-alveolar features were identified. These included an increased total anterior facial height and specifically an increased lower face height which correlated with excessive development of the maxilla in the vertical direction. Dental open and closed bites are two variants of the syndrome. Open bites were noted in those patients with a normal ramus height whilst an increased ramus height was seen in those patients in which a positive overbite existed. Other features were common to both sub-groups, namely a high mandibular plane to cranial base angle, and excessive exposure of the maxillary incisors despite the upper lip length being within normal limits.

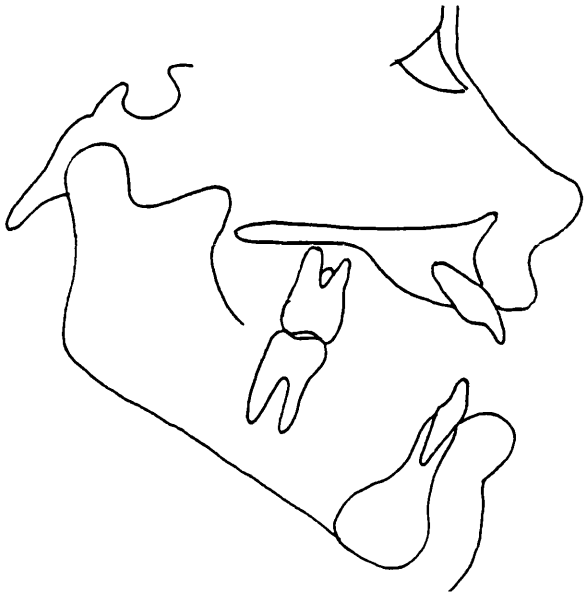
In a later study Opdebeeck *et al.* (1978) attempted to sub-divide patients with the long face syndrome using the same parameters used in the sub-classification of the short face syndrome (figure 2). As a consequence sub-type I was characterized by a long ramus, vertical maxillary excess, a slightly increased sella nasion to mandibular plane angle and an extremely long face. By way of contrast, sub-type II was characterized by a short ramus height, a posterior dento-alveolar height that was within normal limits, a moderate increase in lower anterior facial height but a markedly increased sella nasion to mandibular plane angle. Clearly there are differences between the two classifications and in many cases there may be features of both sub-types. For that reason sub-divisions of the long and short face groups will be avoided in the present study.

Figure 2 - Sub-groups of the long face syndrome

(after Opdebeeck *et al.*, 1978)



Sub-group I is characterized by a slightly increased sella nasion - mandibular planes angle, an extremely long face, a long ramus and vertical maxillary excess.



Sub-group II is characterized by a greatly increased sella nasion - mandibular planes angle, a moderate increase in lower anterior face height, a normal or short ramus and a normal posterior dento-alveolar height.

vi) Theories of abnormal vertical growth

a) Genetic influence

The relative role of genetics in the development of abnormal vertical growth has never been fully established. Hunter (1965) in a study on like-sexed twins demonstrated that vertical cephalometric variables showed a relatively stronger genetic dependence than variables in the horizontal dimension. Subsequently, Lundstrom (1984) although initially opposing this view later reversed this opinion and concurred with Hunter's findings (Lundstrom and McWilliam, 1987).

b) Environmental factors

The role of naso-respiratory function and head posture

The functional influence of oral and nasal respiration on facial form has been extensively investigated. Brühn (1927) suggested that anterior open bites probably resulted from irregular growth of the facial skeleton accompanying chronic pharnygitis. Furthermore, Bennett (1931) discussed the inter-relationship between enlarged adenoids and associated mouth breathing with the incidence of anterior open bites, which he ascribed to increased posterior vertical maxillary growth. Ricketts (1968) confirmed the high incidence of anterior open bites in patients with hypertrophic adenoids describing the collective features as the "Respiratory Obstruction Syndrome".

Abnormal vertical patterns of growth have been created in Rhesus monkeys by initiation of mouth breathing following gradual nasal obstruction with silicone plugs (Harvold *et al.*, 1973). An increase in lower anterior face height as well as an increased tendency to anterior open bites was noted compared with a control sample. The results were, however, extremely variable and in many cases mandibular prognathism rather than vertical defects ensued. These variable effects were also evident in a later study by

Vargervik *et al.* (1984).

Solow and Tallgren (1976) observed that the posture of the head in relation to the cervical column was related to cranio-facial morphology. In cases where the head was extended, the face was retrognathic and the mandibular planes angle as well as the anterior and total facial heights were large. Subsequently, Solow and Kreiborg (1977) suggested that factors which may affect the adequacy of the nasal airway could result in a posterior extension of the head, which in turn would stretch the soft tissues, namely the muscles and fascia, passing between the cranium and the mandible and as a result initiate differential forces on the skeleton and hence a change in morphology.

Linder-Aronson (1979) demonstrated that enlarged adenoidal tissue induced mouth breathing which in turn demanded a low tongue position. With the need to maintain an airway the head extends and as a consequence the lower facial height and vertical facial angles increased with an associated high incidence of anterior open bite, V-shaped maxillary arch forms and frequent crossbites in the buccal segments. In a five year follow up study following adenoidectomy the experimental group was observed to return to more "normal" features with reduction of the extended head posture, a decrease in the maxillary-mandibular planes angle and an increase in upper arch width (Linder-Aronson, 1979).

The studies of Linder-Aronson have been criticized by Vig *et al.* (1981) who found no significant difference in nasal resistance between individuals with normal facial proportions and those with an increased face height. Similarly Turvey *et al.* (1984) in a study of patients attending for surgical correction of a "long face" found increased nasal resistance in only 37% of cases. As Turvey *et al.*, (1984) pointed out, the factor controlling the resistance to nasal air-flow is governed by the inner aspect of the anterior nares (the liminal valve) and not by factors further posterior in the naso-pharynx.

The role of masticatory musculature

The classifications of vertical morphology described above are very similar to the two vertical skeletal variants described by Sassouni (1969) as skeletal deep bite and skeletal open bite. Of the factors considered in the aetiology of the two groups, he drew attention to the differing activity occurring in the posterior vertical chain of muscles (masseter, medial pterygoid and temporalis) as noted electromyographically by Møller (1966) as well as through his own gnathodynamic measurements. The differing anatomical relationship of the muscle attachments to the dentition prompted the suggestion that in deep bite cases the anterior attachment of the muscles on the mandible is such that the molars are directly under the vertical impact of masticatory function.

Throckmorton *et al.* (1980) commented that several factors could produce the observed differences in muscle activity and specifically bite force between the skeletal types. These could include; the total muscle size, differences in muscle morphology and variations in mechanical advantage of the adductor muscles of the jaw.

The inter-relationship between muscle weakness and progressive facial divergence has been reported by Proffit *et al.* (1968) and by Kreiborg *et al.* (1978) who documented the increasing facial heights in patients with progressive muscular dystrophy.

The therapeutic effect of increasing muscle force in growing individuals with morphological features of a developing long face was observed in a pilot study by Ingervall and Bitsanis (1987). During a one-year experimental period 13 children, aged 7 to 12 years, were asked to chew a resin gum for at least two hours per day. The results showed an overall increase in muscle strength and a tendency towards an anterior or closing rotation of the mandible.

Structure and function of masticatory skeletal muscle

i) General anatomy

The muscles of mastication are voluntary skeletal muscles of the mesoderm of the first branchial arch. Transplantation experiments and auto-antibody studies undertaken on quail embryos have shown that the myogenic cells originate from the paraxial mesoderm and become associated and interspersed with mesenchymal cells of neural crest origin (Noden, 1988).

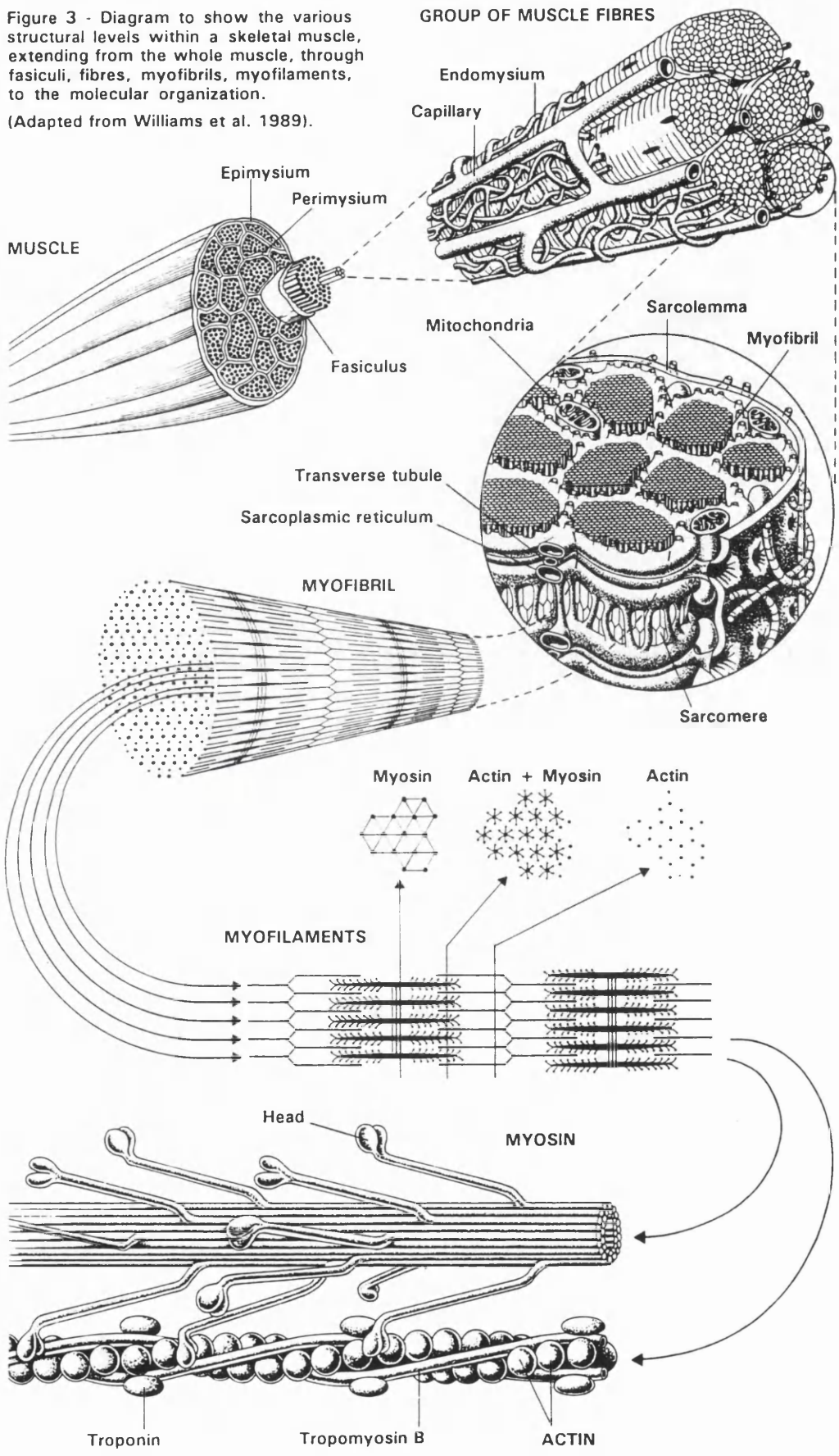
The various stages of development of these cells to form mature muscle fibres remain uncertain but it is generally agreed that discrete muscle condensations appear with alignment and fusion of myoblasts forming multinucleate myotubes. Almost immediately after fusion, myofilaments begin to be assembled which ultimately form myofibrils with highly organized sarcomeres that continue to enlarge and accumulate myofibrils throughout the embryonic period.

The myofibrils first appear near the centre of the cell and further myofilaments are added to the outside of existing ones, such that the nuclei become displaced towards the periphery of the fibre. It is at this stage that the architecture of the muscle is formed as tendons and connective tissue septa become evident as well as the arrangement of muscle fibres (McClearn and Noden, 1988).

The structural architecture of the whole muscle (figure 3) consists of a number of fasciculi or groups of fibres each surrounded by a connective tissue envelope (the perimysium). Each fibre is a single cylindrical, elongated cell of varying diameter encased in a delicate envelope of loose connective tissue (the endomysium). The sarcoplasm of each cell contains groups of longitudinally running myofilaments or myofibrils composed of either the fibrous protein myosin (thick myofilaments) or the globular proteins actin and troponin (thin myofilaments). The actin filaments consist

Figure 3 - Diagram to show the various structural levels within a skeletal muscle, extending from the whole muscle, through fasiculi, fibres, myofibrils, myofilaments, to the molecular organization.

(Adapted from Williams et al. 1989).



of two chains of globular units in the form of a long double helix with the smaller troponin molecules attached at intervals along its length by means of tropomyosin molecules present in the groove between the two actin chains. In transverse section each myosin filament is surrounded by six actin filaments in a regular hexagonal pattern (Hanson and Huxley, 1955).

The arrangement of the thick and thin myofilaments produces the characteristic sarcomere pattern of cross striations seen on electron microscopic examination, with the thick myosin filaments forming the dark A bands and the thin actin filaments forming the lighter I bands.

Surrounding the myofilaments is the sarcotubular system consisting of the T system and the sarcoplasmic reticulum. The T system of transverse tubules extends from the membrane of the muscle fibre and runs between the A and I bands. This tubular system is responsible for rapid depolarization from the cell membrane to all the constituent filaments such that all parts of the muscle fibre can be stimulated to contract more or less simultaneously producing the characteristic 'twitch'.

The sarcoplasmic reticulum forms a drape around each of the filaments and is concerned with calcium storage and movement, and muscle metabolism.

Mitochondria with densely packed cristae lie between the myofibrils (figure 3) with their incidence varying according to the type of muscle fibre. According to Hess (1970), mitochondria are more plentiful in slow rather than fast twitch muscles so providing the energy source to resist fatigue.

Most skeletal muscles, including the muscles of mastication, exhibit a mixture of two types of fibres, designated slow and fast twitch. The fibre type is determined by the frequency of neural activity supplied by the terminal branches of the nerve fibre or axon whose cell body is in the anterior horn of the grey matter of the spinal cord (Riley and Allin, 1973).

This cell body, the axon running down the motor nerve and its terminal

branches together with all the muscle fibres supplied by that nerve constitute a motor unit (Liddell and Sherrington, 1925). The number of muscle fibres served by one axon varies according to the degree of finesse involved in a particular muscle action. The finer the degree of muscle movement and hence control required, the fewer the fibres per motor unit (Henneman *et al.*, 1965).

Carlsöo (1958) recorded the mean number of muscle fibres per motor unit as 640 for masseter and 936 for temporalis. For comparative purposes Møller (1966) quotes 5 fibres per motor unit in the rectus oculi and 1900 per motor unit in the gastrocnemius muscles.

Wyke (1974) described a mixture of small and large motor units in the supra- and sub-mandibular muscles. The small units being found predominantly in the sub-mandibular group. He suggests that the small (phasic) units are involved in the production of rapid mandibular movements whilst the larger (tonic) units are used for postural regulation and sustained biting.

Muscle fibres belonging to one motor unit exhibit a remarkable homogeneity in their properties with similar histochemical profiles. The contractile response of whole skeletal muscles represents an average response of the individual fibre types that constitute that particular muscle (Henneman and Olson, 1965).

ii) Skeletal muscle fibre types

For many years muscles were classified according to their gross anatomical appearance. Initially, this was on the basis of colour with a differentiation into highly vascular red muscles and less vascular pale or white muscles.

Following the work of Engel (1962) muscle fibres were classified histochemically by staining for myofibrillar adenosine triphosphatase (ATPase), and particularly on the basis of the stability of this staining

reaction with variations in pH. Under alkaline conditions those fibres with a low (weakly staining) myofibrillar ATPase activity were designated type I fibres, whilst those presenting a strong staining intensity were designated type II fibres. Bárány (1967) noted that the myosin ATPase activity was indicative of the contractile speed of the muscle fibres. Subsequently, Brooke and Kaiser (1970) noted that when frozen muscle sections were pre-incubated in acid, a complete reversal of the staining pattern occurred with type I fibres, whereas type II fibres showed only a partial change. Consequently the classification was expanded to include sub-divisions of type II fibres. With pre-incubation at pH 4.6 those fibres which demonstrated a complete inhibition of staining reactivity were designated type IIa fibres. Following pre-incubation at pH 4.3, fibres which had shown a strong reaction at pH 4.6 but now showed a weak response were designated type IIb. A third sub-type of type II fibre, the IIc fibre shows a residual positive reaction at pH 4.3 but becomes negative at a pH below 3.9. Brooke *et al.* (1971) have suggested that type IIc fibres may be a precursor of the other muscle fibre types.

The intensity of staining for specific enzymes of the glycogenolytic and glycolytic metabolic pathways gives an indication of the capacity of the fibre to contract in the absence of oxygen. Conversely, oxidative enzymes give an indication of the muscle's aerobic capacity and hence its ability to resist fatigue providing a blood supply is maintained.

Recognition of these biochemical properties led to the classification of Peter *et al.* (1972) inferred from the staining characteristics of rabbit and guinea pig muscle in a myosin ATPase (pre-incubation pH 9.4) and a Dihydronicotinamide adenine dinucleotide (NADH) diaphorase preparation. Fibres were described as: SO (ie. slow oxidative, equivalent to type I fibres, staining light with ATPase and dark with NADH), FOG (ie. fast oxidative glycolytic, staining dark in ATPase and intermediate in NADH) possessing both high aerobic and anaerobic capacity, equivalent to type IIa fibres, and FG fibres (ie. fast glycolytic with high ATPase and anaerobic capacity, equivalent to type IIb fibres, staining dark in ATPase and light in NADH).

An alternative sub-division was proposed by Burke *et al.* (1971) based on the mechanical response of all the muscle fibres of a motor unit when their motoneurone was stimulated by a single electrical pulse (contractile response) and to a sustained train of stimuli (contractile fatigue response). Fibres are classified as: S (slow and fatiguable), FR (fast and fatigue resistant) and FF (fast but rapidly fatigued).

It is evident from the above that several classifications of muscle fibre types exist and this has undoubtedly led to confusion in the past. A comparison of the various classifications and the physiological properties of muscle fibre types is presented in table I.

With regard to the masticatory musculature the picture is clouded even further since Ringqvist (1971,1973c) has reported the presence of fibres (ATPase IM) presenting an intermediate staining intensity for myofibrillar ATPase at alkaline pH and claims this as evidence of the unique structure and function of these muscles. Although similar findings have been observed by Serratrice *et al.* (1976) the incidence of such fibres was extremely variable. Dubowitz and Pearse (1960) whilst observing these fibres, especially in animal muscle, did not delineate them as a separate fibre type. Indeed, the authors felt that such findings may indicate a technical artifact as it was difficult to assign such fibres to an equivalent group using an alternative classification.

Billeter *et al.* (1980) employed an immunohistochemical technique using specific antibodies to fast and slow myosins as a means of investigating the correlation between fibre type and myosin isoforms in human limb muscles. They concluded that whilst type I fibres contained mainly slow myosin and type II fibres fast myosin, type IIc fibres contained both fast and slow myosins in variable proportions. Similar results were observed for the muscles of mastication by Thornell *et al.* (1984) with both ATPase Intermediate and type IIc fibres containing both slow and fast myosins in variable amounts.

Table I - A comparison of the classifications and physiological properties of human skeletal muscle fibre types.

Classification				
Brooke and Kaiser (1970)	I	IIa	IIb	IIc
Peter *et al.* (1972)	SO	FOG	FG	-
Burke *et al.* (1971)	S	FR	FF	-
Properties				
Contraction rate	slow	fast	fast	-
Oxidative capacity	high	> IIb	low	-
Force tension	low	< IIb	high	-
Fatigue rate	slow	slow	fast	-
Function	posture or slow repetative movt.	fast repet. movt.	explosive movt. or max. tension	? trans-itional

The myosin molecule consists of two heavy molecular weight and four light molecular weight polypeptide chains. Billeter *et al.* (1980) suggested that the histochemical ATPase activity was determined by the heavy and not the light chains. It is feasible, as suggested by Thornell *et al.* (1984), that all the various degrees of staining and reactions in masticatory muscle fibres may be explained by a continuum of various proportions of slow and fast myosin, heavy as well as light chains.

The heterogenous distribution of the various myosin isozymes has been

confirmed by Butler-Browne *et al.* (1988) with many masseter muscle fibres containing more than one myosin type. Furthermore, they have shown that mature human masseter muscle in addition to adult fast and slow myosin contains two proteins characteristic of developing muscle. The presence of these neo-natal myosin heavy chains and embryonic light chains were particularly related to the ATPase Intermediate and type IIc fibres giving further evidence that these fibres may serve a functionally adaptive role.

iii) Skeletal muscle growth and regeneration

The final number of fibres within a muscle is reached some time before birth. Subsequent growth in length is as a result of an increase in the number of sarcomeres added primarily at the ends of the muscle fibres where fusion of myoblasts continues. Further growth in diameter occurs through the addition of myofilaments around the periphery of the myofibril up to a critical size whereupon the fibril splits longitudinally into two myofibrils (Williams *et al.*, 1989). These processes continue into post-natal life and some myoblast cells persist into adult life as satellite cells.

The fibre diameter is greatly affected by activity, such that exercise leads to fibre hypertrophy, whereas disuse results in atrophy (Rowe and Goldspink, 1969). Fibre atrophy also occurs following denervation being replaced by fibrous connective tissue.

Human skeletal muscle is capable of limited regeneration following injury, although the exact mechanism remains unclear. According to Carlson (1973) following damage and removal of the necrotic material by multinucleate cells, nucleated cylinders of cytoplasm and the basement membrane remain intact. These cylinders fuse and grow back inside the basement membrane to form a myotube. Satellite cells are also believed to be involved in the process, possibly fusing at the ends of the existing cytoplasm to form part of the new fibre (Bischoff, 1975).

iv) The connective tissue component

Types I and III collagen fibres are major contributors to the connective tissue element of muscle structure. Type I collagen fibres form long thick bundles which are virtually inelastic, whilst type III collagen forms a loose reticular arrangement. Two other collagen types are present but in smaller proportions; type IV which forms a macromolecular network ideally adapted to the highly flexible and mechanically stable sheet-like structure of the basement membrane, and type V collagen present as small fibres around the muscle cells (Kuhn, 1986).

The role of collagen in muscle development and regeneration has, until recently, been largely neglected. Bailey *et al.* (1979) have demonstrated through *in vitro* studies that collagen substrate is important in the promotion of myoblast differentiation, whereas several authors (for example Carlson, 1973) have stressed the importance of the presence of the basement membrane for myotube orientation during the regeneration of damaged muscle.

v) Muscular contraction

The contraction of skeletal muscle is initiated by membrane depolarization at the motor end-plate. The resultant action potential is transmitted to all fibrils by way of the T system with a corresponding release of calcium ions from the sarcoplasmic reticulum. Calcium initiates the contraction by binding to the troponin molecules, and the troponin/calcium complex in turn activates actin permitting the development of cross-linkages between the actin and myosin molecules at the myosin heads. The contractile response is a result of repeated forming, breaking and reforming of cross-linkages between the actin and myosin molecules. This interaction requires a continual source of energy provided by the hydrolysis of adenosine triphosphate (ATP) by myofibrillar adenosine triphosphatase (ATPase).

According to Faulkner *et al.* (1978) the general sequence of energy flow

during contraction is:-

1. Immediate hydrolysis of ATP with the release of high energy phosphate bonds.

2. Within milliseconds, the re-synthesis of ATP from adenosine diphosphate (ADP) and creatinine phosphate begins.

3. Within seconds, the glycolytic pathway is activated to provide energy for the first forty seconds of contraction. This extra source of energy from anaerobic glucose breakdown permits muscular exertion of greater magnitude but of limited duration.

4. Gradually over the first 60-90 seconds energy from mitochondrial oxidative phosphorylation provides an increasing proportion of the steady rate energy requirements.

It is apparent, therefore, that muscle fibres with a high mitochondrial density are more resistant to fatigue compared with fibres possessing a low density.

vi) The gross anatomy and functions of masseter and temporalis muscles

The muscles of mastication to be considered in this study are masseter and temporalis. Their anatomy and function are as described by Williams *et al.* (1989).

Masseter

Masseter muscle is a quadrilateral shaped muscle composed of three superimposed layers which blend anteriorly.

The **superficial** layer is the largest and arises from the thick aponeurosis from the zygomatic process of the maxilla and from the anterior two-thirds of the lower border of the zygomatic arch. The fibres pass downwards and backwards to be inserted into the angle and the lower half of the lateral surface of the ramus of the mandible.

The **middle** fibres arise from the deep surface of the anterior two-thirds of the zygomatic arch and lower border of the posterior third and are inserted into the middle of the ramus of the mandible.

The **deep** fibres arise from the deep surface of the zygomatic arch and are inserted into the upper part of the ramus and coronoid process of the mandible.

The principal action of the masseter muscle is to elevate the mandible with a small effect in lateral and protrusive movement and minimal activity in the rest position. The relative involvement of the different fibre layers during functional movements of the mandible has been fully elicited through electromyographic studies (Vitti and Basmajian, 1977).

Temporalis

The fan shaped muscle arises from the whole of the temporal fossa except that part formed by the zygomatic bone, together with the deep surface of the temporal fascia. The anterior and posterior fibres converge to attach, via a tendon, to the medial surface, the apex and the anterior and posterior borders of the coronoid process and the anterior border of the ramus of the mandible nearly as far as the last molar tooth.

The anterior fibres elevate the mandible and the posterior fibres whilst providing a backward pull during closing specifically draw the mandible back after protrusion. Electromyography suggests the muscle is active during forced elevation of the mandible but not in slow elevation (Vitti and Basmajian, 1977).

Musculo-skeletal adaptation

Adaptation can be defined as those structural and physiological changes which serve to maintain functional homeostasis or to enhance functional capabilities in a changing environment (Faulkner *et al.,* 1978).

McNamara (1972) proposed that with regard to the musculo-skeletal system, adaptation could occur at four sites:

i) Within the central nervous system

The development of altered neuromuscular feedback appears to be one of the earliest and most rapidly occurring adaptive mechanisms. Minor alterations in the position of the skeletal attachments of the oro-facial muscles or changes in muscle length have profound effects on the muscles of mastication (Carlson *et al.*, 1982). Golgi tendon organs and proprioceptors within the periodontal membrane and temporomandibular joint provide feedback through the central nervous system regarding the spatial relationship of the maxilla and mandible.

ii) Within muscle

Adaptation can take place within muscle through the geometric rearrangement of fibres, and/or changes in both sarcomere number and length, and/or changes in muscle physiology through the distribution of fibre types, their metabolic capabilities and their resultant contractile properties.

The fact that muscle geometry is the result of functional needs and is not simply genetically determined has been shown through changes in fibre length, cross-sectional area and fibre arrangement occurring normally during growth, with advancing age and, for example, in response to plaster immobilization (Maxwell *et al.*, 1974). When muscles are maintained in a lengthened position it is possible for the insertions of individual muscle fibres

to migrate so returning the fibre length to normal whilst maintaining the increased length of the muscle as a whole (McNamara *et al.*, 1978).

Sarcomere length appears to be stable within a given muscle. One possible explanation of this could be that following stretching of a muscle, the reduced overlap of the actin and myosin filaments and the corresponding reduction in the number of cross-bridges (Goldspink, 1972), is perceived through proprioceptors with a resultant contraction of the muscle so pulling the altered segments back to their original position. Alternatively, sarcomere length could be re-established by the addition of sarcomeres within the stretched fibre at either the muscle/tendon junction (Speidel, 1938) or at the end of individual fibrils (Crawford, 1954).

Adaptive changes in muscle physiology have been shown to occur under varying circumstances. Faulkner *et al.* (1971, 1972) and Maxwell *et al.* (1973) for example, have demonstrated a reduction in the oxidative capacity of skeletal muscle fibres with age, whereas an increase occurs in response to endurance training. Similarly a change occurs from fast to slow myosin in response to age (for example, Karpati and Engel, 1968) and as a result of cross-innervation (Bárány and Close, 1971). With specific regard to physiological adaptation of the muscles of mastication, Carlson and Poznanski (1982) reported the findings of their associated research team using the rhesus monkey as their animal model. Myofibrillar ATPase activity, oxidative capacity and cross-sectional area were studied for masseter and temporalis muscles following a reduction in functional length, through dental extraction, and an increase in functional length through bite opening appliances.

Biopsies from eleven adult female rhesus monkeys rendered edentulous up to five years previously were compared with specimens taken from an age and sex matched control group. The results indicated that the masseter and temporalis muscles responded to the reduced facial vertical dimension, the reduced functioning length and altered masticatory function in that there was a reduced percentage of type I fibres and an increase in type II fibres

with a significant reduction in oxidative capacity. Although the proportions of all fibre types were affected, only type I fibres showed a significant change in size through a reduction in cross-sectional area.

The type I fibre atrophy was believed to indicate a decrease in the load resisted by the slow fibres brought about by a decreased role in the maintenance of mandibular posture, decreased masticatory effort or both.

The effect of increasing the vertical dimension was studied in adult female rhesus monkeys by means of an intra-oral bite-opening appliance designed to create an 18 - 20 mm interincisal opening and an 8 to 10% stretch in masseter muscle (Carlson *et al.*, 1982). The results indicated the relative stability of the masseter and temporalis muscles with respect to fibre percentage composition. Those monkeys who received an appliance but underwent a bilateral masseter myotomy and surgical reattachment of the muscle again showed some atrophy of type I fibres.

In discussing the results of these animal experiments Carlson and Poznanski (1982) expressed the view that the appearance of a particular type of myofibrillar ATPase seems to be a result of neural influence primarily and therefore was determined relatively early in development. A change in fibre proportion was more likely to be due to splitting of type II fibres and not a transformation of the type of ATPase synthesized by the muscle fibres as suggested by Rowe and Goldspink (1968). The general conclusion, therefore, was that muscle fibres reflect alterations in function rather than being the primary determinant of function.

iii) <u>At the muscle- tendon and muscle- bone interfaces</u>

Both the muscle-tendon and muscle-bone interfaces are active sites of adaptation since the interface itself is composed primarily of collagen fibres. In the case of the muscle-bone interface two general types of attachment are evident- periosteal and tendinous. Periosteal attachments are characterized by a blending of the muscle fibres with the fibrous outer layer

of the periosteum from which collagen fibres pass into the cortical bone. The bone surface beneath the attachment may be either depository or resorptive depending upon the local circumstances of bone or muscle growth (Enlow, 1975).

In tendinous muscle attachments the muscle fibres blend with collagen fibres of the tendon itself which acts as a link of variable length between muscle and bone. Like the muscle-bone interface, the muscle-tendon interface is an extremely active site of growth and of adaptation to biomechanical forces which alter the muscle length itself.

iv) Within bone

Two major non-pathological adaptations can occur within or between bones following surgical alteration of facial form. Firstly, a change in the spatial orientation of bones which may act as origins or insertions of muscles may affect the functioning length of the associated musculature and secondly, localized bony remodelling which will affect the size and shape of individual bones. Both of these forms of adaptation may compromise the surgical result leading to relapse. The aspects of relapse relevant to the present study will be discussed in the next section.

The techniques and stability of the surgical correction of vertical facial deformities

Surgical techniques devised to correct cranio-facial and dento-facial deformities have been reported since the early 19th century. However it was the development of the versatile sagittal split osteotomy of the mandible (Trauner and Obwegeser, 1957) and the downfractured Le Fort I osteotomy of the maxilla (Bell, 1975; Epker and Wolford, 1975) that has now enabled the treatment of an extensive range of deformities.

When assessing patients for orthognathic surgery it is essential to consider the deformity in all three planes of space. Vertical deformities can occur on any class of antero-posterior skeletal pattern. Furthermore, it is important to appreciate that antero-posterior and vertical movements of the maxilla will have a secondary effect on the spatial location of the mandible. This rotational effect (autorotation) may or may not be aesthetically desirable. It is, therefore, common for combinations of surgical techniques to be undertaken in order to produce the most aesthetic, efficiently functioning result.

With regard to vertically deficient facial abnormalities, surgical techniques may include maxillary inferior repositioning with or without advancement, and /or a forward sliding mandibular osteotomy with or without anterior segmental surgery and genioplasty.

Similarly, abnormalities incorporating an increased vertical height may require corrective procedures ranging from a reduction genioplasty through to a maxillary impaction in combination with a sagittal osteotomy of the mandibular ramus and /or genioplasty.

When considering the stability of the various procedures it is therefore appropriate to consider them both in isolation and in combination.

i) Isolated maxillary procedures

a)Vertical repositioning

Inferior repositioning of the maxilla has the reputation of being one of the least stable orthognathic procedures. Relapse reported in the literature has been shown repeatedly to be extremely variable. Bell and Scheidman (1981), for example, noted relapse in 11 patients to vary from 0 to 100%, with a mean of 31%, whilst Wolford and Hilliard (1981) reported a range of 20 to 70%. Numerous attempts have been made to augment the stability of the result including pre-operative muscle lengthening splints, inter-positional bone grafts, the use of threaded Steinmann pins into the zygomatic buttress and rigid intra-osseous fixation techniques (Welch, 1989). Several of these modified techniques have failed to eliminate relapse, perhaps not surprisingly as they clearly demonstrate a lack of understanding of the adaptive abilities of muscle and bone. Several authors, therefore, recommend overcorrection to allow for relapse. Bell and Scheidman (1981), for example, recommend adding 2mm to the ultimate desired vertical change, whilst Freihofer (1981) suggests a 50% overcorrection.

In contrast to inferior repositioning procedures, maxillary impaction techniques have been reported to be generally stable. Studies by Bell and McBride (1977), who analyzed the results of 41 patients with vertical maxillary excess treated by Le Fort I osteotomy, and Schendel *et al.*(1976), who reported on 30 patients studied over one year following surgery, both showed minimal post-operative movement, and that which did occur was found to be in the same direction as that achieved at surgery. More recently Proffit *et al.* (1987) examined 61 patients who underwent superior repositioning of the maxilla. During fixation,if the posterior maxilla were to move, it was generally more likely to intrude rather than relapse inferiorly. The posterior maxilla was vertically stable in 90% of cases. The anterior maxilla also moved superiorly during fixation and remained stable in 80% of cases. The analysis showed no difference when comparing one-piece maxillary osteotomies to multiple segmental procedures.

b) Maxillary advancement

Individual modifications to surgical techniques and methods of fixation preclude direct comparison of stability studies following Le Fort I maxillary advancement.

Aranjo *et al.* (1978) reported relapse of between 31 and 68% of the advancement when this was undertaken without bone grafting, compared to a second group of ten patients where relapse varied from 0 to 5% when grafts were placed between the tuberosity and pterygoid plates. Rather surprisingly, the authors then concluded that routine use of bone grafts was not indicated with notable exceptions, for example, cleft palate deformities.

Teuscher and Sailer (1980) followed the progress of 16 patients for a minimum of one year following advancement and reported virtually no change in maxillary position. Similar findings were reported by Horster (1980) who recommended the routine use of bone grafts and rigid plate fixation. Luyk and Ward-Booth (1985) emphasized that adequacy of fixation was of prime importance for stability rather than grafting, but the study only examined four patients for a period of three months.

Carlotti and Schendel (1987) reported excellent stability in 16 of 18 cases stabilized by a variety of techniques. They commented that any skeletal changes which did occur were complete within 5 months of surgery, but that dental compensations could continue for at least 12 months.

ii) Isolated mandibular procedures.

a) Mandibular advancement.

Welch (1989), in a comprehensive review of studies, both animal and human, reported relapse ranging from 22 to 50%.

McNeil *et al.* (1973) postulated that condylar distraction from the glenoid

fossa and a posteriorly directed soft tissue force and muscle pull as being the two mechanisms for relapse. More recently Wessberg *et al.* (1982a) added the method and duration of fixation as being important. As a consequence attention has focused on the use of rigid fixation techniques, as a means to control the proximal segment, and the effect of the suprahyoid musculature. Animal investigations by Ellis *et al.* (1988) and human studies by Barer *et al.* (1987) have found total stability. However, the size of the advancement may still be significant as Van Siskels *et al.* (1986) found consistent relapse despite rigid internal fixation in cases where the advancement exceeded 6mms.

b) Mandibular set-back.

Despite the numerous surgical procedures available to setback the mandible, comparatively few authors have addressed the post-operative stability.

Reitzik (1974, 1980) in a study of 50 cases treated by a variety of ramus and angle procedures studied skeletal change up to one year following surgery. Antero-posterior relapse was noted in 50% of cases. Similar findings were noted by Vijayaraghaven *et al.* (1974) in a study of 16 sagittal split osteotomies where relapse of up to one-third of the surgical correction occurred in 50% of cases one year following surgery.

In the 1974 study Reitzik observed an increase in anterior face height in 90% of his cases with a resultant variable degree of anterior open bite which he attributed to disruption of the pterygo-masseteric sling.

Morrill *et al.* (1974) found horizontal relapse in 17 of 22 patients one year following surgery but surprisingly found that the remaining 5 cases showed a continued posterior movement. Surgery also resulted in an increase in the mandibular plane angle and this angle continued to increase post-surgically.

Hunt (1980) in a study of 30 cases who had undergone sagittal split correction of mandibular prognathism employing minimal rotation found the

results as a whole to be stable, the relapse occurring being neither statistically nor clinically significant. This was in contrast to a later unpublished study by the same author in which surgery produced marked changes in both anterior and posterior face height. Vertical relapse was significant in the majority of cases.

iii) Simultaneous bimaxillary procedures.

Stability studies of simultaneous bimaxillary procedures have produced a whole spectrum of results when compared to single-jaw osteotomies. LaBanc et al. (1982), for example, analyzed 100 consecutive cases and concluded that there was an increased incidence of relapse when compared to single-jaw surgery. Quejada *et al.* (1987) found no difference in stability, whereas Brammer *et al.* (1980) in a study of 12 patients treated with maxillary impaction and advancement combined with mandibular advancement found a strong correlation between superior repositioning of the posterior maxilla and decreased mandibular relapse. They concluded that the decreased facial height resulting from the impaction maximized the autorotational advancement of the mandible thereby reducing the absolute forward movement of the mandible required.

The variation in response between individuals is highlighted by close examination of the least stable group included in the study of Hiranaka and Kelly (1987). Three patients were treated by an inferior and anterior movement of the maxilla together with a mandibular setback. One patient had complete relapse, one had no post-operative change and one showed continued downward movement.There was no correlation between the change in posterior face height and relapse.

In conclusion it is apparent that certain osteotomy procedures are more stable than others. Currently, however, there is no way to predict which patients will remain stable and, if post-operative movement is to take place in which direction that movement will occur. Furthermore, although bimaxillary procedures are finding an increasing prominence in orthognathic

surgery, it is still unclear whether all deformities that require two-jaw procedures should be treated as a combined operation or staged separately (Welch, 1989).

Summary

This literature review has, so far, briefly discussed the general aspects of cranio-facial growth, especially in the vertical dimension, the possible causal mechanisms of abnormal growth and the surgical techniques available, together with their success rates, for the correction of extreme vertical facial abnormalities.

The muscles of mastication have been cited as one of the factors whose structure and function may influence cranio-facial development. Certainly it is apparent, from the fairly limited information available, that these muscles may exhibit a structure which could possibly be considered to be fairly unique amongst other human skeletal muscles, but the question as to whether their structure and, perhaps, function affect facial morphology remains, to a large extent, unanswered.

Furthermore, although it is evident that skeletal muscles possess the ability to adapt to functional needs, it is not apparent whether this is true for all individuals and yet this is an essential requirement if surgical correction of facial abnormalities is to prove successful and remain stable.

i) Overall aims of the investigation

The overall aim of this series of investigations is to provide further information into the role of the muscles of mastication in determining facial form and in particular how those muscles adapt or respond to the surgical rehabilitation of individuals with diverse facial abnormalities in the vertical dimension.

ii) The assessment of masticatory function

Techniques to assess masticatory muscle function include electromyography, the analysis of mandibular movement (kinesiography), the measurement of certain physiologic correlates of muscle contraction, such as occlusal bite force, and invasive techniques such as the histochemical characterization of the muscle fibres themselves.

These methods of investigation will form the basis for the individual aspects of this study and will provide an overall view as to the structure and function of the muscles of mastication.

Histochemical analysis has the obvious disadvantage of requiring surgical excision of muscle tissue and, therefore, may be limited in its acceptance by patients. To date there have been only two published studies (Ringqvist, 1973b and Shaughnessy, 1986) which have correlated histochemical characteristics with occlusal force. Furthermore, only Shaughnessy (1986) has attempted to discover whether other non-invasive measurement techniques could provide similar information regarding muscle metabolic characteristics. As data will be collected by both invasive and non-invasive techniques correlation of that data will form the final aim of this study.

For ease of presentation the various investigations will be presented separately in individual chapters, following which the results will be brought together and discussed.

Statistical methods used throughout the studies.

Two computer packages, Minitab Release 7[1] (1989) and SAS System for Statistical Analysis[2] were used to analyze the data accumulated in the various studies.

The data were first tested to ensure they conformed to a normal distribution using either plots of Normal Score Transformations or the Shapiro-Wilk test. Descriptive statistics included the sample mean ($\bar{x}$), standard deviation (SD) and standard error of the mean (SE) as well as the 95 % confidence interval (95% CI). Where the data were not normally distributed the median and inter-quartile (¼-ile) limits were noted.

Prior to undertaking comparative statistical analysis, the variances of the samples were compared using Snedecor's Variance Ratio Test (F test).

In those situations where the data were normally distributed and the F statistic not exceeded, comparative analysis involved either the paired or un-paired two-tailed *t* test. Multiple comparisons were made using the one-way analysis of variance (ANOVA). Relationships between sets of data were analyzed using the Pearson correlation coefficient (*r*) and where appropriate either linear regression or step-wise multiple regression. Where relationships between multiple variables with varying inter-dependence were being assessed, data reduction was first undertaken through Principal Component Analysis (PCA) and the relationships between the groups of variables studied through Canonical Correlation Analysis. More detail regarding these two analyses will be given in the appropriate part of the text.

Where the requirements for parametric statistical analysis were not met, the data were analyzed using either the Wilcoxon Signed Rank test for paired data or the Mann-Whitney U test for un-paired data as appropriate. Comparisons between several groups were made using the Kruskal-Wallis

test.

When assessing the systematic and random errors involved in the study design, both the Dahlberg error (Dahlberg, 1940) and the coefficient of reliability (Houston, 1983) were noted.

The minimum level of significance (α level) accepted throughout the studies was 0.05 (*), considered to be moderately significant. Levels of 0.01 (**) were considered as significant and 0.001 (***) designated as highly significant. A lack of statistical significance was designated as (ns).

Chapter 2

THE CEPHALOMETRIC ASSESSMENT OF THE STUDY CASES

Cephalometric Investigations

Each of the succeeding chapters in which masticatory muscle structure and function is examined by differing investigative techniques will correlate those findings with facial form as measured by lateral skull cephalometric radiography. It is pertinent, therefore, to describe the cephalometric measurement techniques used.

i) Material

Serial lateral skull cephalometric radiographs were taken as part of the routine evaluation of patients attending the combined orthodontic / oral surgery clinics at the Eastman Dental Hospital. Radiographs of those adult Caucasian patients assessed clinically as possessing a vertical facial abnormality as part of their overall facial deformity were included. However, those patients exhibiting facial deformities as part of more complex syndromes, cleft palate deformities, endocrine disorders or those with other obvious pathologies including disorders of the temporo-mandibular joint were excluded.

Cephalometric assessment was based on radiographs taken immediately prior to operation, at the removal of intermaxillary fixation and approximately one year later.

ii) Method

Tracings were made of the lateral skull radiographs using a 4H pencil and fine grain, high quality tracing paper. Tracings were carried out in a darkened room using a frame to eliminate excess light and facilitate landmark identification. The complete series of radiographs of one patient was traced on the same occasion but in a randomized order so as to reduce systematic error (Houston, 1983). No more than six radiographs were traced on any one occasion in order to minimise error due to operator fatigue.

The tracings were then digitized using a GTCO^3 Digitizer linked to a micro-computer for data storage and subsequent statistical analysis. The di gitizing programme was written by Dr P. Furness.

iii) Cephalometric landmarks and measurements

The following cephalometric landmarks were digitized from the tracings (figure 4) and unless otherwise stated are as described by Krogman and Sassouni (1957).

S - Sella. The midpoint of the sella turcica determined by inspection.

N - Nasion. The most anterior point on the fronto-nasal suture.

Or - Orbitale. The most inferior point on the bony orbital margin.

ANS - Anterior nasal spine. The tip of the anterior nasal spine. If this point was not clear the base of the spine was bisected.

PNS - Posterior nasal spine. The tip of the posterior spine of the palatine bone of the hard palate. If this point was not clear, the base of the spine was bisected.

A - Point A (Sub-spinale). The deepest midline point on the maxilla between anterior nasal spine and the alveolar crest.

B - Point B (Supra-mentale). The most posterior point on the outer contour of the mandible between pogonion and the alveolar crest.

UA - Upper incisor apex. The apical point of the most anterior upper incisor.

UE - Upper incisor edge. The incisal edge of the most anterior upper incisor.

LE - Lower incisor edge. The incisal edge of the most anterior lower incisor.

LA - Lower incisor apex. The apical point of the most anterior lower incisor.

UM - Upper molar cusp. The tip of the mesiobuccal cusp of the upper first molar.

LM - Lower molar cusp. The tip of the mesiobuccal cusp of the lower first molar.

Pg - Pogonion. The most anterior point on the bony chin.

Me - Menton. The most inferior point on the bony chin.

Go - Gonion. The most posterior inferior point at the angle of the mandible. This point was determined by constructing and bisecting the angle formed by the tangents to the lower and posterior borders of the angle of the mandible. Where the bisector met the contour of the mandible was deemed to be gonion.

Ar - Articulare. The point of intersection of the posterior border of the mandibular ramus and the inferior border of the base of the skull (Björk, 1947).

Po - Porion. The uppermost contour of the ear-post sited in the external auditory meatus.

In order to minimise the error associated with tracing the incisors, templates of the upper and lower incisors were constructed for each individual case, by selecting the best incisor projection from the patient's radiographic sequence.

Where bilateral landmarks produced a double image, the midpoint between those images was chosen in order to reduce enlargement error (Baumrind and Frantz, 1971a).

In many cases following surgery involving a sagittal split osteotomy, up to four shadows may be evident in the angle region of the mandible (figure 5). In such cases gonion constructions were drawn for each shadow and the midpoint of the constructions being ultimately recorded as gonion for that film.

Figure 4 - Cephalometric landmarks.

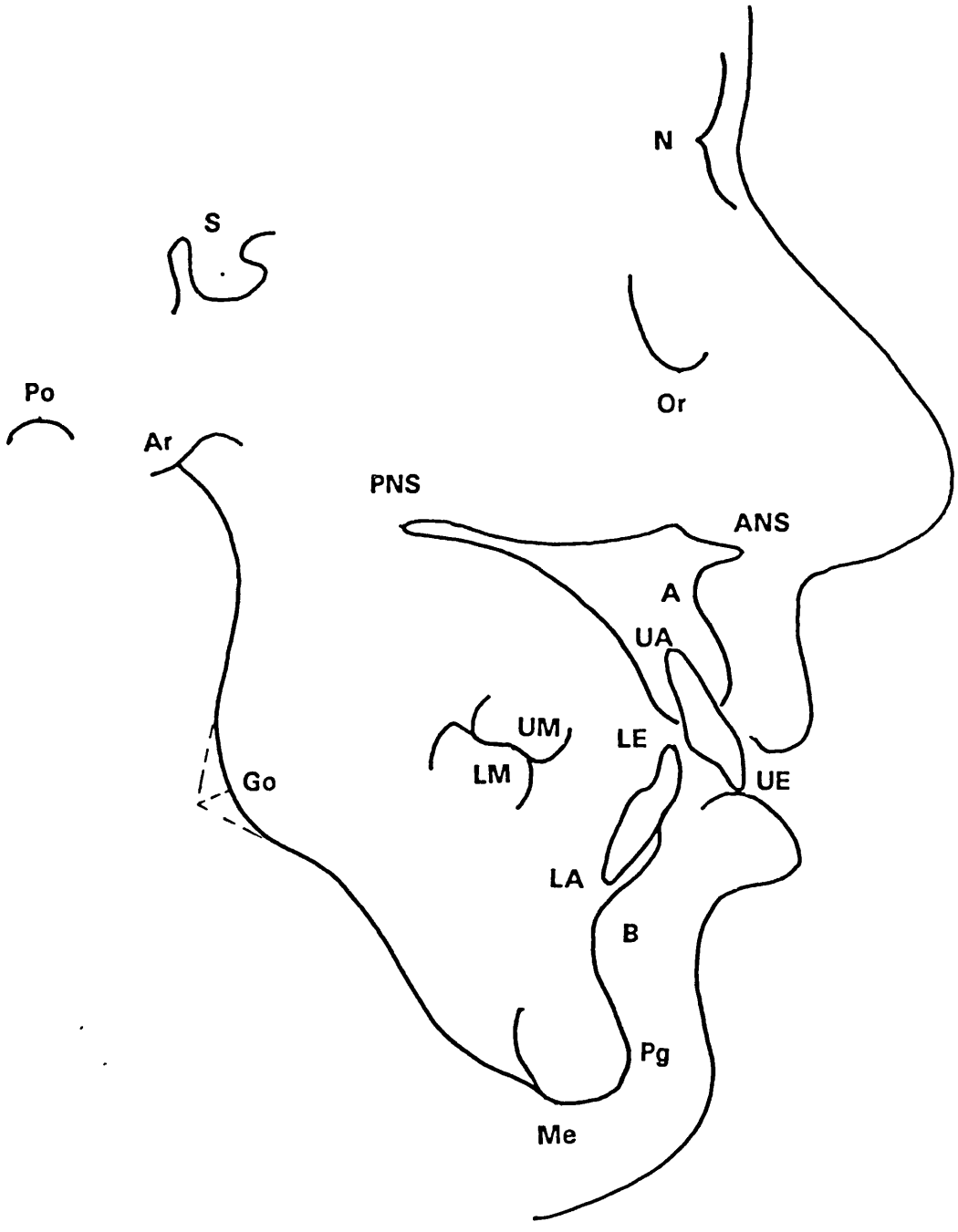
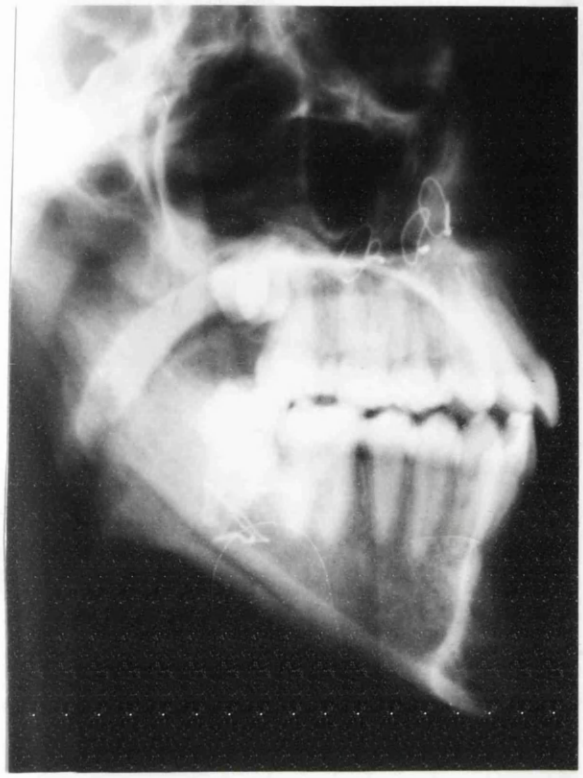


Figure 5 - Photograph of a post-operative lateral skull radiograph illustrating the difficulty of gonion location.



Using the digitized coordinates the computer calculated 14 angular measurements (figures 6 and 7):

1. **SNA** -The angle at N between the S-N line and a line from N to point A. The angle of maxillary prognathism.

2. **SNB** -The angle at N between the S-N line and a line from N to point B. The angle of mandibular prognathism.

3. **SNPg** -The angle at N between the S-N line and a line from N to pogonion.

4. **SNmax.** -The angle formed by the intersection of the S-N line and the maxillary plane (a line extended through points ANS and PNS).

5. **SNmand.** -The angle formed by the intersection of the S-N line and the mandibular plane (a line extended through menton and gonion).

6. **FMPA** -The angle formed by the intersection of the Frankfort plane (a line passing through orbitale and porion) with the mandibular plane.

7. **MM** -The angle formed by the intersection of the maxillary and mandibular planes.

8. **NSAr** -The angle at sella between the S-N line and a line from N to articulare. The saddle angle.

9. **SArGo** -The anterior angle at articulare between lines from Ar to gonion and Ar to sella. The joint angle.

10. **ArGoMe** -The superior angle at gonion between lines from Go to articulare and Go to menton. The gonial angle.

11. **UImax** -The angle formed by the intersection of the long axis of the upper incisors (UE to UA extended) and the maxillary plane.

12. **UISN** -The angle formed by the intersection of the long axis of the upper incisors and the S-N line.

13. **LImand** -The angle formed by the intersection of the long axis of the lower incisors (LE to LA extended) and the mandibular plane.

14. **LISN** -The posterior angle formed by the intersection of the long axis of the lower incisors and the S-N line.

and 13 linear measurements (figures 8 and 9):

15. **UAFH** -The upper anterior face height. The distance between point N and the maxillary plane measured along a perpendicular to the maxillary plane.

16. **LAFH** -The lower anterior face height. The distance between Me and the maxillary plane measured along a perpendicular to the maxillary plane.

17. **UPFH** -The upper posterior face height. The distance between S and the maxillary plane measured along a perpendicular to the maxillary plane.

18. **LPFH** -The lower posterior face height.The distance between Go and the maxillary plane measured along a perpendicular to the maxillary plane.

19. **TAFH** -The total anterior face height measured as the sum of the upper and lower anterior face heights.

20. **TPFH** -The total posterior face height measured as the sum of the upper and lower posterior face heights.

21. **UADH** -The upper anterior dental height measured as the perpendicular distance from the maxillary plane to UE.

22. **UPDH** -The upper posterior dental height measured as the perpendicular distance from the maxillary plane to UM.

Figure 6 - Cephalometric angular measurements.

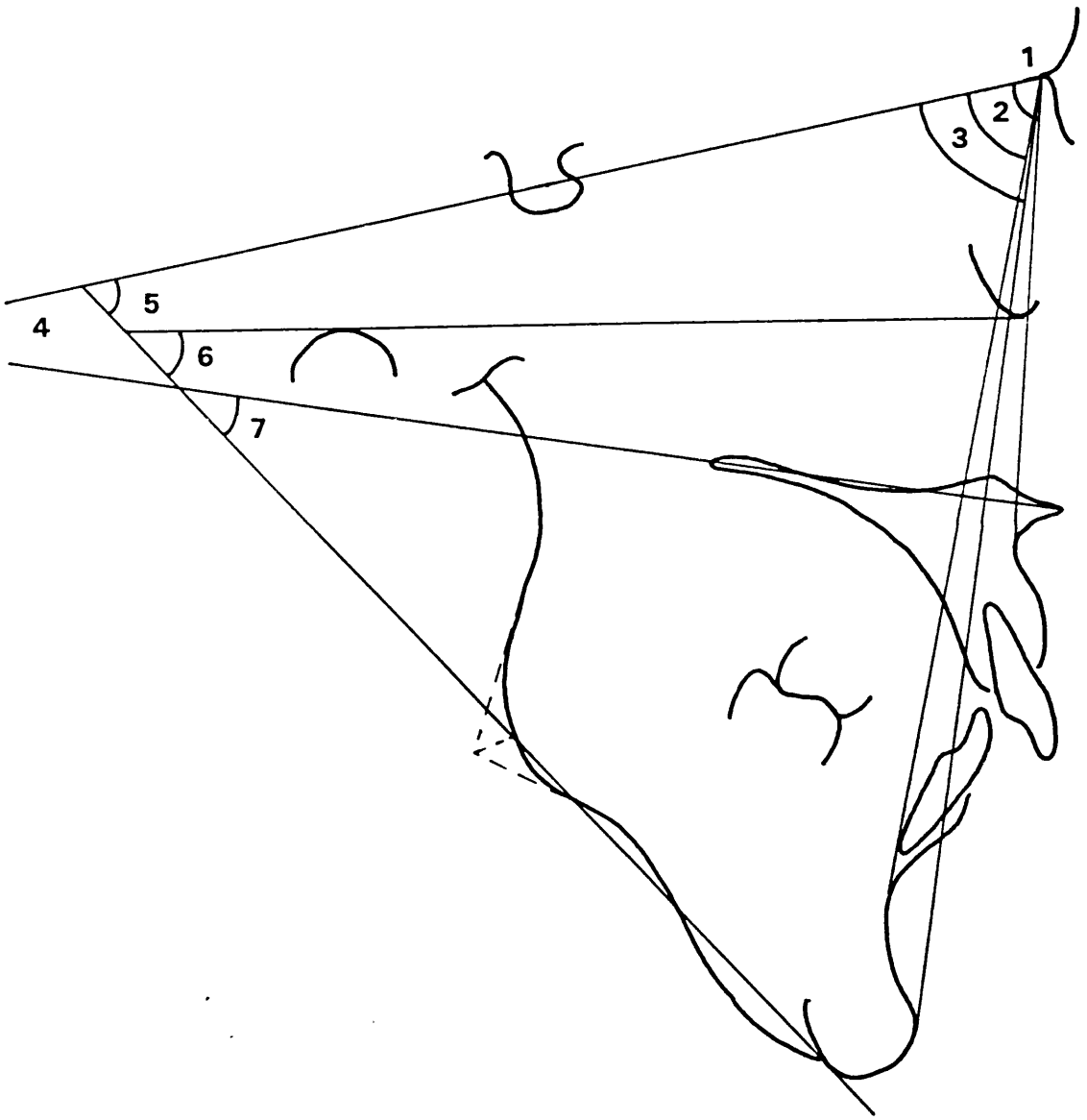
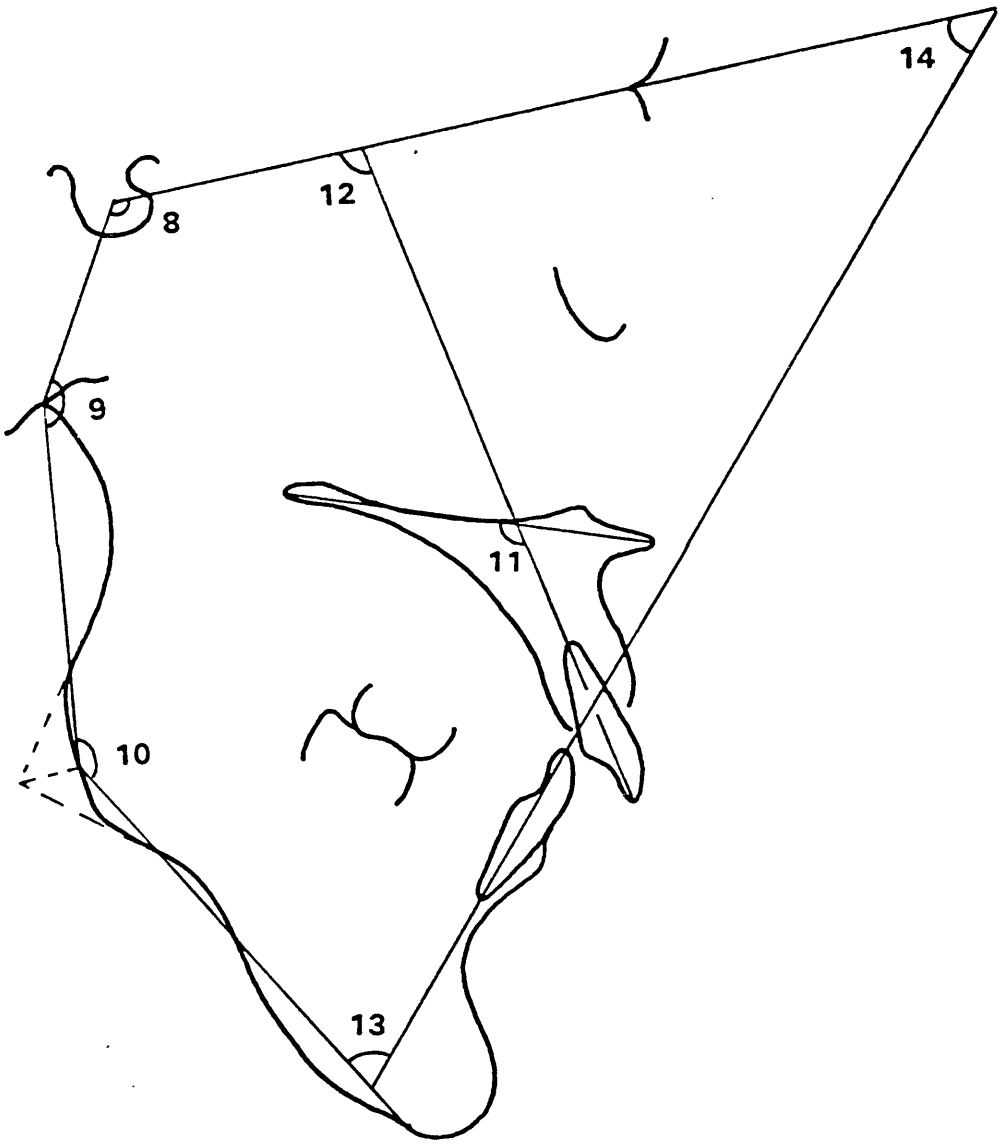


Figure 7 - Cephalometric angular measurements cont[d].



23.**LADH** -The lower anterior dental height measured as the perpendicular distance from the mandibular plane to LE.

24.**LPDH** -The lower posterior dental height measured as the perpendicular distance from the mandibular plane to LM.

25.**ML** -The mandibular length measured as the distance between the points Pg and Ar.

26.**RH** -The mandibular ramus height measured as the distance between points Go and Ar.

27.**Body** -The mandibular body length measured as the distance between points Go and Pg.

The two remaining linear measurements were made relative to a vertical reference line passing through sella and drawn at 98 degrees to the S-N line.

28.**OJ** -Incisor overjet measured as the difference in horizontal distance of perpendiculars from the reference line to UE and LE.

29.**OB**-Incisor overbite measured as the vertical distance along the reference line between perpendiculars from that line to UE and LE.

Finally three proportional measurements were recorded:

30.**%LAFH** -The LAFH expressed as a percentage of the TAFH.

31.**%LPFH** -The LPFH expressed as a percentage of the TPFH.

32.**FPI** -The facial proportions index as described by Opdebeeck *et al.* (1978) and derived from subtracting the upper anterior facial proportion from the lower (both being expressed as a percentage of the TAFH). For normal vertical proportions this figure would be 10, ie 55% - 45%. A figure less than 10 would indicate a short face tendency, whilst a figure greater than 10 would indicate features of a long face.

Figure 8 - Cephalometric linear measurements.

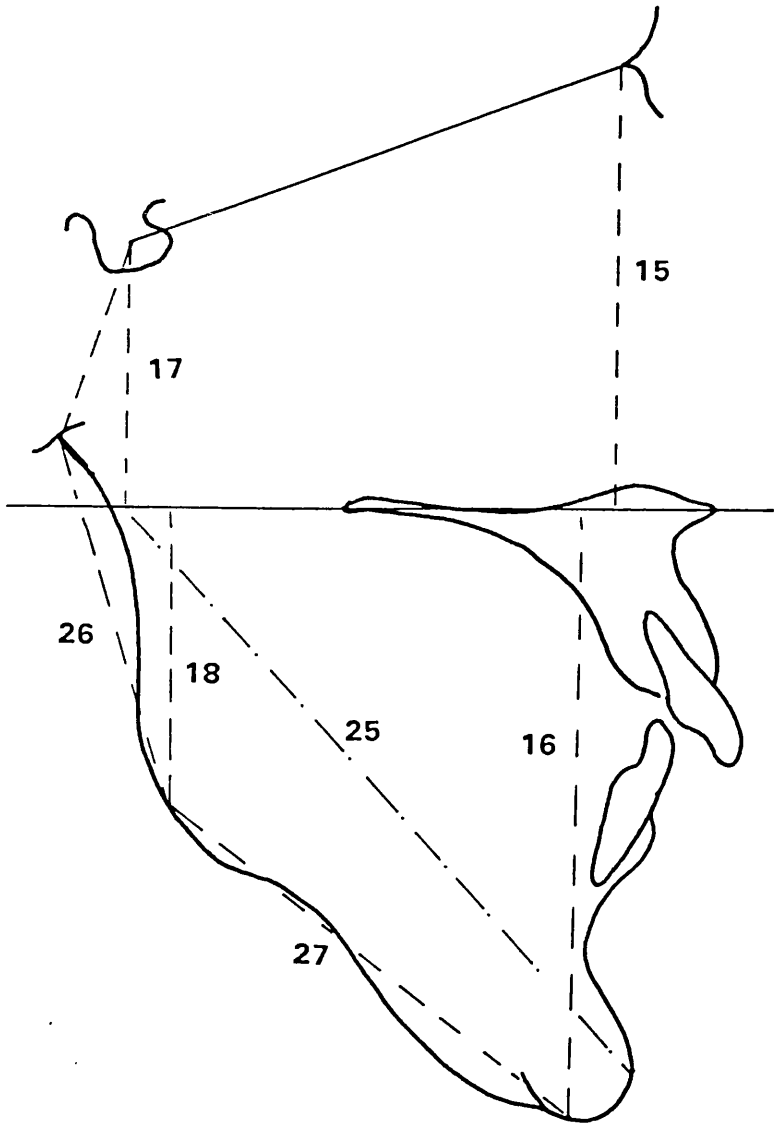
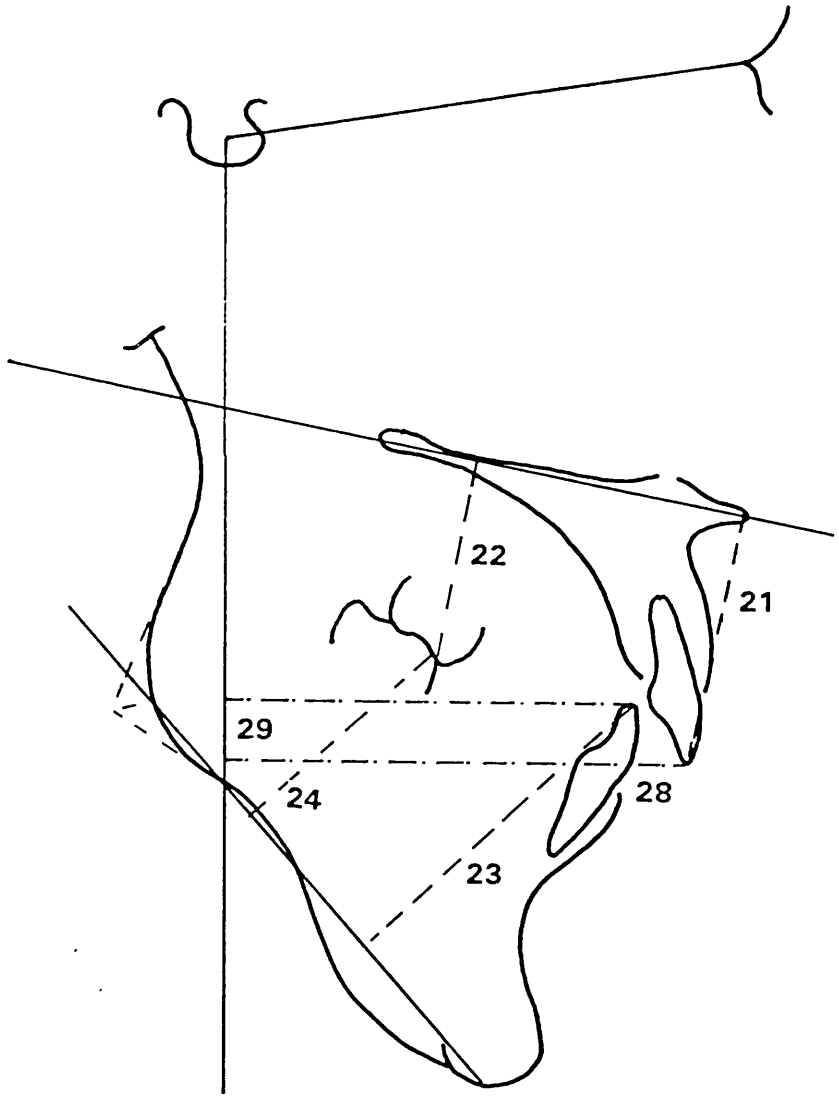


Figure 9 - Cephalometric linear measurements cont[d].



iv) Masticatory muscle orientations

Throckmorton *et al.* (1980) have suggested that the activity of the muscles of mastication may be related to the geometric arrangement of those muscles relative to the occlusal plane.

In order to evaluate the orientation of the muscle fibres to both the morphology of the facial skeleton and the dentition, seven additional cephalometric points were identified to help establish the origins and insertions of the superficial masseter and temporalis muscles. These points were based on the study by Takada *et al.* (1984) in which the muscle attachments were identified by direct comparison of dry skulls and radiographs of the same skulls. The additional points were (figure 10):

33.**Sor** -Supraorbitale. The most anterior point on the intersection of the inferior surface of the roof of the orbit and its lateral contour.

34.**KR** -Key ridge. The lowermost point on the contour of the anterior limit of the infratemporal fossa.

35.**AGo** -Antegonion. The highest point on the notch of the lower border of the ramus where it joins the body of the mandible.

36.**C1** -Coronoid point 1 - The most inferior point on the anterior contour of the coronoid process.

37.**C2** -Coronoid point 2 - The most superior point on the anterior contour of the coronoid process.

38.**C3** -Coronoid point 3 - The most superior point on the posterior contour of the coronoid process.

39.**C4** -Coronoid point 4 - The most inferior point on the posterior contour of the coronoid process.

Figure 10 - Additional cephalometric points used in the muscle orientation study.

The points representing the origins and insertions of the muscles were then taken as follows (figure 11):

Point IM -The insertion of the superficial masseter muscle taken as the midpoint of a line joining AGo to Go.

Point AT -The origin of anterior temporalis muscle taken as the midpoint between the intersections of the S - N line with the contours of the greater wing of the sphenoid bone and the anterior limit of the infra-temporal fossa.

Point PT -The origin of the posterior temporalis muscle taken as the midpoint between SOr and Or projected on a perpendicular to the Frankfurt plane (Or - Po) at Po.

Point PC -The insertion of the temporalis muscle taken as the midpoint of a line bisecting the angle formed between lines joining C1 to C2 and C3 to C4, and a line parallel to the Frankfurt plane passing through KR.

Having established the lines of action, the orientation angles between the muscles and the upper and lower occlusal planes were calculated, the occlusal plane being defined as a line joining the incisor edge with the molar point (figure 12).

40.**UOPMASS** and 41.**LOPMASS** -The superficial masseter angulation measured as the anterior angle formed between the upper or lower occlusal plane and a line parallel to the line connecting KR and AGo through IM.

42.**UOPAT** and 43.**LOPAT** -The anterior temporalis angulation measured as the anterior angle formed between the occlusal planes and a line through PC and AT.

44.**UOPPT** and 45.**LOPAT** -The posterior temporalis angulation measured as the anterior angle formed between the occlusal planes and a line through PC and PT.

Figure 11 - Derived points representing the origin and insertions of the masticatory muscles.

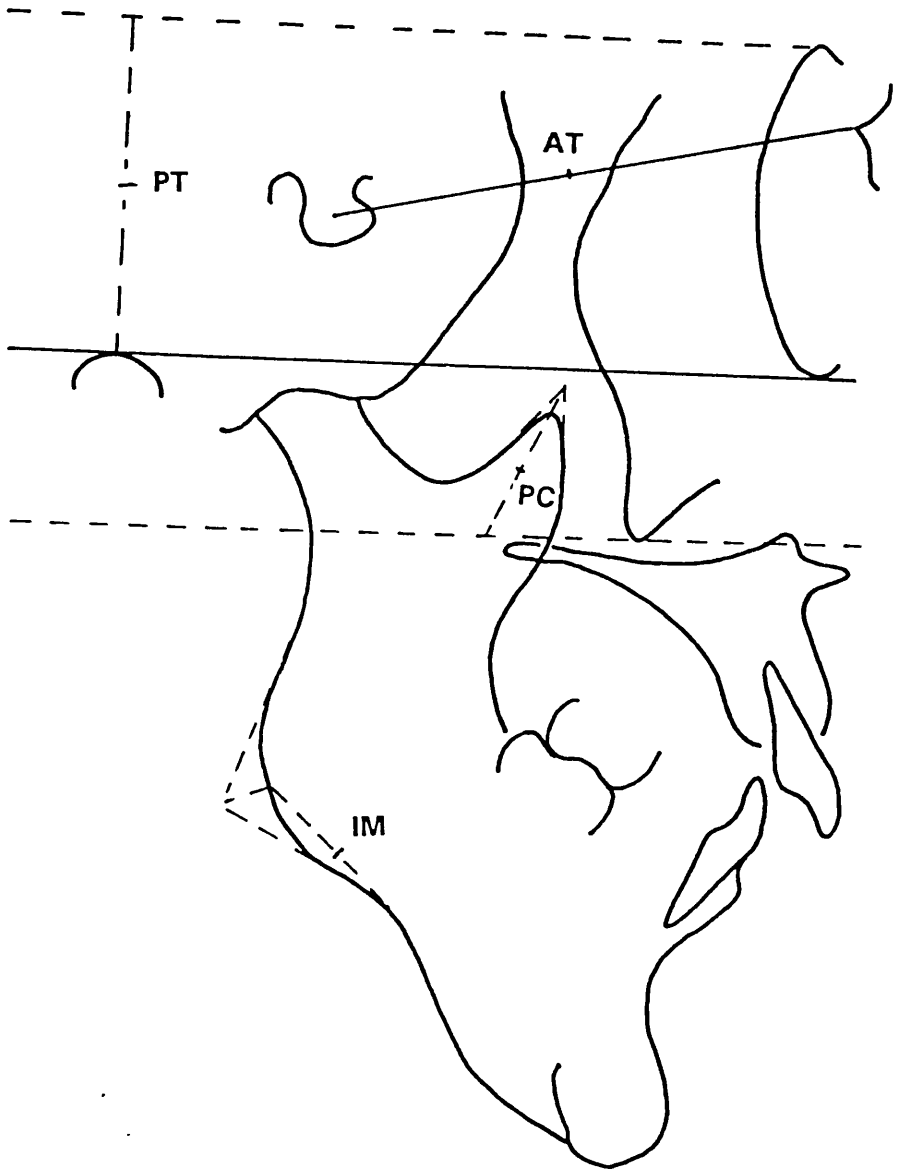
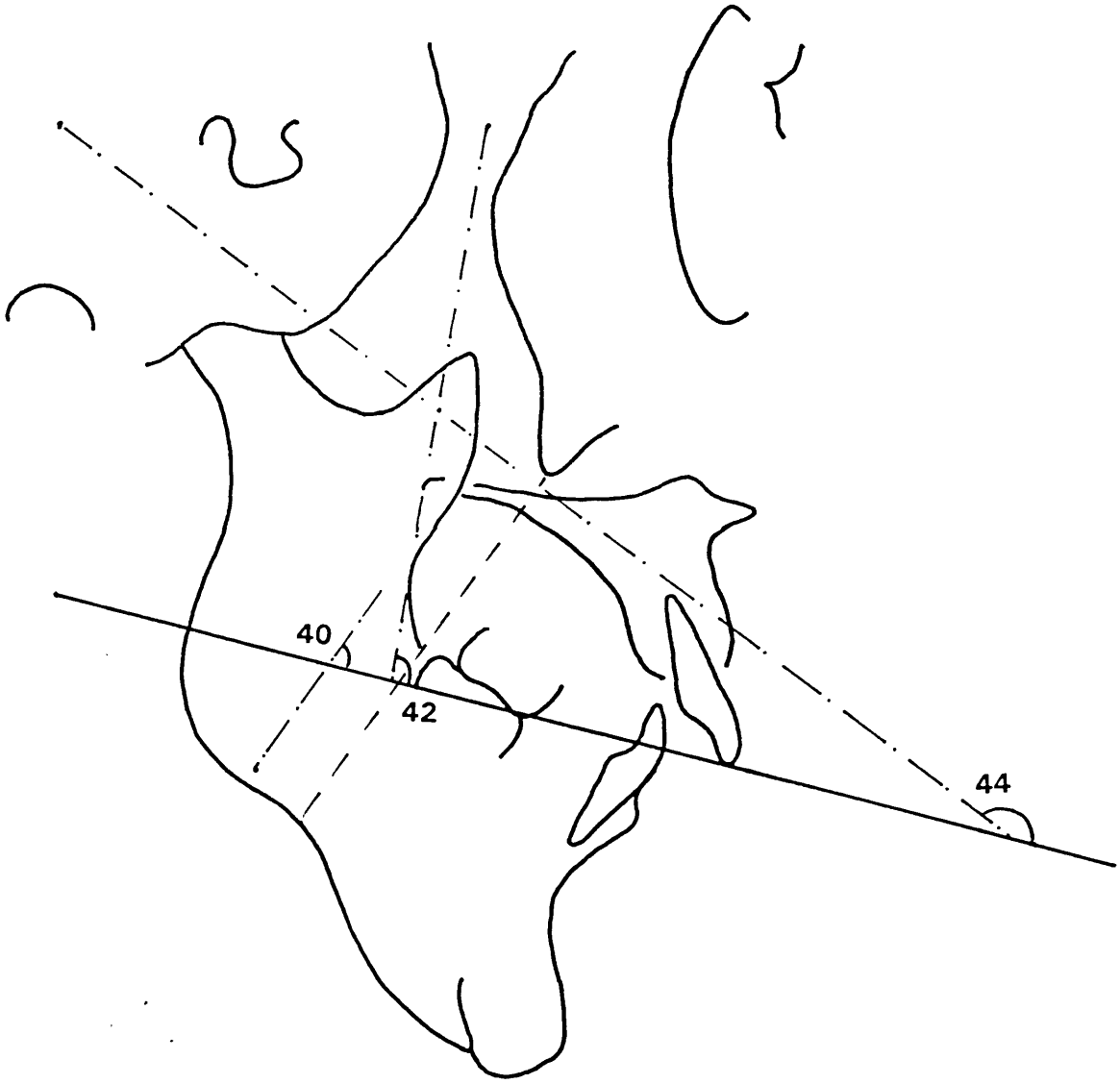


Figure 12 - The masticatory muscle orientation angles.



v) The error of the method of cephalometric techniques

Three sources of error are evident when undertaking cephalometric techniques (Baumrind and Frantz, 1971a).These can be considered as:

a) Errors of radiographic technique and projection error

b) Errors in landmark identification and location

c) Measurement error.

Errors of radiographic technique and projection error

All the radiographs used in this study were produced to a standardized procedure. However, any radiographs which displayed obvious malpositioning of the head in the cephalostat were rejected.

Projection errors are inevitable when producing two dimensional shadows of three dimensional objects from a non-parallel X-ray beam. Points in the mid-sagittal plane are least affected whereas bilateral landmarks will undergo differential enlargement. When two images of bilateral structures were identified, the midpoint between the respective landmarks was registered in order to minimize the enlargement error.

In order to compare the results of this study with those of other workers it was necessary to incorporate a correction factor (0.93) into the computer programme to take into account the magnification of the linear distances recorded.

Errors in landmark identification and location

It has been demonstrated that each landmark has its own characteristic and often elliptical envelope of error. Errors of identification were reduced by using, whenever possible, measurements from landmarks in their most reliable plane. Some points, notably the incisor apices are notoriously difficult to locate and in these cases templates were constructed from the most clearly identifiable radiograph in that particular patient's series. Points

which lie on curves with large radii (for example, gonion) show a tendency towards greater error but this was minimized by using constructed landmarks where possible.

All points on the tracing were digitized using the two pass method. Points were rejected by the computer if the difference between the two passes exceeded 0.2 mm.

Measurement Error

Since all measurements were calculated by the computer, this source of error was eliminated.

a) Assessment of the overall error of the method for the cephalometric study.

In order to establish the overall error of the method thirty radiographs were selected at random by an independent observer and coded. The author then produced repeat tracings which were subsequently digitized. A comparison of the linear and angular measurements recorded on the two occasions gave an indication of the combined systematic and random errors involved in the study. The overall error of the method was calculated according to the formula of Dahlberg (1940). In addition, the coefficient of reliability gave an indication of the error variance in relation to the total variance of the measurement, and the paired *t* test was indicative of the systematic error (Houston, 1983).

b) Results

The results for each of the linear and angular measurements involved in the study are shown in table II.

Whilst the results of the error study for the cephalometric variables are within acceptable limits, they are generally higher than the majority of

Table II - Errors of the method for the cephalometric variables

	Dahlberg error	Coefficient of reliability	*t* test
Angular measurements			
SNA	0.50	99.3	ns
SNB	0.64	99.1	ns
SNPg	0.81	98.2	ns
SNmand	0.56	99.3	ns
SNmax	0.64	97.9	ns
MM	0.73	99.2	ns
FMPA	0.83	99.4	ns
NSAr	1.42	97.4	ns
SArGo	1.32	95.5	ns
ArGoMe	0.64	99.4	ns
UImax	0.72	99.4	ns
UISN	1.10	99.3	ns
LImand	0.53	99.6	ns
LISN	0.73	99.5	ns
Linear measurements			
UAFH	0.64	93.2	ns
LAFH	0.81	99.3	ns
UPFH	0.90	99.7	ns
LPFH	0.77	99.5	ns
TAFH	0.68	99.2	ns
TPFH	0.43	99.2	ns
UADH	0.92	96.4	ns
UPDH	0.53	92.9	ns
LADH	0.59	96.2	ns
LPDH	0.47	99.4	ns
ML	0.84	99.8	ns
RH	0.66	99.3	ns
Body	0.64	98.6	ns
OJ	0.56	95.8	ns
OB	0.47	99.3	ns
%LAFH	0.70	99.6	ns
%LPFH	1.17	99.5	ns
FPI	0.50	93.7	ns
Muscle orientation angles			
UOPMASS	1.18	97.0	ns
LOPMASS	1.94	90.8	ns
UOPAT	1.28	92.0	ns
LOPAT	1.01	98.9	ns
UOPPT	2.77	92.5	ns
LOPPT	2.12	94.9	ns

cephalometric studies undertaken within the same department, including those by the author (for example Hunt, 1980). It must be stressed, however, that the random selection of radiographs for inclusion in the error study would inevitably include those of patients who had experienced extensive bimaxillary surgery making landmark identification more difficult. The coefficient of reliability was greater than 90% and therefore considered acceptable.

Houston (1983), whilst discussing types of error which may occur during orthodontic measurement stresses the importance of the terms validity and reproducibility. In the present investigation one must question whether the method described for determining the muscle orientation angles forms a valid representation of the true lines of action of the muscles. Recent advances in computerised tomography and magnetic imaging techniques would provide a more valid and realistic approach but unfortunately such techniques were not available when the study was designed. In the absence of a better alternative it was decided to proceed with the approach described but to view the results with caution.

From the point of view of reproducibility the results of the repeat measurements were surprisingly precise bearing in mind the large number of geometric constructions, each with their own source of error, required to establish the orientation angles. The size of the Dahlberg error was acceptable bearing in mind the size and range of the recorded angles but certainly care would need to be taken when considering changes in the orientation angles with treatment or time. Unfortunately, Takada *et al.*(1984) fail to quote figures for the method error in the technique described and therefore it is impossible to draw what would have been useful and essential comparisons.

vi) Classification of patients according to facial type

For some sections of this study it was appropriate to sub-divide the patients, on the basis of their facial morphology, into long and short face groups. It is apparent, however, that although the two groups are well recognized clinical entities, they cannot be differentiated on the basis of any single cephalometric variable, but rather by a pattern of variables.

The cephalometric studies of the "long face syndrome" (Schendel *et al.*, 1976) and the "short face syndrome" (Opdebeeck and Bell, 1978) highlighted those features which are most commonly at variance from "normal". Consequently it was decided to classify the patients in this study using a weighted points system based upon the values of eight cephalometric variables considered by the above authors as being significant features of vertical facial type.

These variables were :

1. SN-Mand
2. MM
3. ArGoMe
4. TAFH
5. %LAFH
6. FPI
7. UPDH
8. OB

The total score was derived from the number of standard deviations that the individual's variables differed from established "normal" figures having made the necessary adjustment for the magnification. A positive score was taken as indicative of a long face whilst a negative score resulted in the patient being ascribed to the short face group.

In the absence of a matched control group the "normal" figures were taken as a compilation of those given by Riolo *et al.* (1974), Broadbent *et al.* (1975), Opdebeeck and Bell (1978) and Mills (1982).

It is appreciated that this approach is open to criticism on at least two counts. Firstly, the normal or control figures should, ideally, be taken from

the same population and matched for aspects such as age and sex. Unfortunately, lateral skull radiographs of such patients were not available and it was considered unethical to produce them. Secondly, Baumrind and Frantz (1971b) have indicated that in order for observed differences to be considered as real (that is biological rather than due to measurement error), the observed difference should be at least twice the standard deviation of the estimating error. In view of the small number of variables considered in this section, the total number in the sample, and the relative severity of the vertical deformities, application of the suggested approach would have failed to provide a clear delineation. Consideration of the pattern of multiple variables rather than single parameters, whilst not overcoming the problem, improved the likelihood of the characterization being correct.

Chapter 3

MASSETER MUSCLE - HISTOCHEMICAL STUDIES

i) The fibre profile of the human masseter muscle

To date, the published information relating to the fibre profile of the human masseter muscle is sparse and open to criticism on several counts. Comparisons of previous studies are very confusing due to variations in sample selection criteria, biopsy sites, fibre classification systems and the format of the results.

a) Critique of previous investigations

One of the earliest investigations of muscle fibre types was by Wachstein and Meisel (1955) who used specimens taken from rats and rabbits as well as human autopsy material. Unfortunately the results were somewhat meaningless as the data was pooled and not presented as species specific (Ringqvist, 1974a).

Whilst several investigations have been based upon human biopsy material (Ringqvist, 1971; 1973b; 1973c; 1974a; 1974b; Ringqvist *et al.*, 1982; Boyd *et al.*, 1984; Shaughnessy, 1986) several studies have used human autopsy material (Finn *et al.*, 1980a; Vignon *et al.*, 1980; Eriksson, 1982; Eriksson and Thornell, 1983) whilst others have mixed autopsy and biopsy material (Serratrice *et al.*, 1976; Thornell *et al.*, 1984).

Although Eriksson (1982) has shown the reliability of fibre typing in specimens taken within several days of death, there is no evidence to suggest that fibre size is directly comparable between biopsy and autopsy material. Indeed, Goldspink *et al.*(1973) reported a reduction of fibre diameter of approximately 15% within 24 hours of death.

Another confusing factor is that whilst a few studies looked specifically at material from subjects with both normal dental and skeletal relationships

(Vignon *et al.*, 1980; Eriksson and Thornell, 1983) and other workers have studied groups with specific skeletal abnormalities (for example Ringqvist, 1973c; Boyd *et al.*, 1984) several studies have been based upon samples taken from subjects with varying states of the occlusion (Ringqvist, 1974a), or varying skeletal and dental relationships (Serretrice *et al.*, 1976; Finn *et al.*, 1980b; Shaughnessy, 1986).

A lack of stringent sample selection criteria has resulted in studies which are not sex specific (for example Ringqvist, 1973c; Boyd *et al.*, 1984) and have included wide age ranges (Serratrice *et al.*, 1976; Vignon *et al.*, 1980). Furthermore, many studies are based on very small sample sizes (for example Finn *et al.*, 1980a; Ringqvist *et al.*, 1982; Eriksson, 1982 who all used five patients only).

A frequently occurring criticism of many previous studies is the lack of information presented relating to the exact location of the biopsy site. Eriksson and Thornell (1983) have shown that regional variations in muscle structure do exist. It is, therefore, of paramount importance to be specific when describing a biopsy site in order to avoid misinterpretation. For example, a statement that "samples were taken from the superficial bundle of fibres..." does not indicate whether these were from the superficial or deep aspect of the anterior or posterior fibres of the superficial bundle. Finn *et al.* (1980a) described the results of biopsies from the deep masseter, whereas the same group of workers (Boyd *et al.*, 1984) later described results obtained from the deep surface of the superficial masseter. The authors expressed surprise as to the discrepancy in results which would suggest that either they were unaware of the regional variation study of Eriksson and Thornell (1983) which would seem unlikely, or that the anatomical source of the biopsies in the two studies was in fact consistent, in which case the description of that source was inadequate.

A further reason for confusion with regard to the findings of previous studies arises from the use of different histochemical fibre type nomenclatures. Thus, Boyd *et al.* (1984), used the classification described

by Peter *et al.* (1972) with division of fibres into slow oxidative, fast glycolytic and fast oxidative glycolytic. Several other workers (for example Serratrice *et al.*, 1976; Vignon *et al.*, 1980; Eriksson and Thornell, 1983) employed the classification described by Brooke and Kaiser (1970) with the grouping of fibres into either type I or type II with sub-divisions of the latter.

As Shaughnessy (1986) pointed out, even more confusing is the fact that some workers have claimed to be using the Brooke and Kaiser (1970) classification although their actual application appears to involve different naming systems within that classification. Eriksson and Thornell (1983) noted the reactivity of fibres at various pH levels but their interpretation of a type IIa fibre could be classified as a type IIb fibre by other workers. The critical pH of the ATPase reaction is not identical from one study to another and this may result in different classifications of the same fibre type between studies.

Measurement techniques have also varied between workers. Ringqvist (1974b), for example, used sliding callipers to measure fibres from prints of enlarged photomicrographs, whereas Eriksson (1982) employed a particle size analyzer and Boyd *et al.* (1984) digitized photographs of sections on a summagraphics data tablet.

With the exception of Eriksson (1982) the error of the measurement method used in the various studies has not been reported.

Finally, the description and format for presentation of the results is often confusing, with differing terminology used by different workers. Ringqvist (1974b), for example described fibre size using measurement of the "smallest diameter" as well as the percentage distribution of fibres. Eriksson (1982),however, estimated the fibre diameter from its cross-sectional area and presented his results as the relative frequency of the fibre types, mean fibre diameter and the relative fibre cross-sectional area. The terms "relative distribution of fibres" and "percentage proportion" quoted by Boyd *et al.* (1984) and used synonymously, correspond to the term relative or

percentage cross-sectional area as described by Eriksson (1982).

b) Studies of human masseter muscle fibre profile

The first quantitative investigation into the histochemical fibre types in human masticatory muscle was by Ringqvist in 1971. A pooled sample of 12 biopsies taken from the masseter and temporalis muscles of 6 males and 6 females showed the presence of both type I and smaller but more numerous type II fibres. Unfortunately the exact site of the biopsies was not reported.

In a subsequent study (Ringqvist, 1973c) based on 17 subjects with mandibular prognathism, where samples were taken from the middle and deeper portions of the masseter muscle, fibres with an intermediate staining reactivity were demonstrated in addition to the type I and II fibres. Like type I fibres, the Intermediate fibres exhibited a strong or moderate NADH tetrazolium reductase reaction, a strong ATPase reaction after acid pre-incubation, and a weak ATPase reaction after alkali pre-incubation. However, like type II fibres they showed a strong phosphorylase reaction. The author suggested that such fibres may represent a type I fibre in the process of being transformed into a type II fibre or *vice versa* and as such this supported the conclusions of Guth and Yellin (1971) that muscle cells have the potential for adaptation to changing functional demands.

Unlike Ringqvist (1973c), the presence of Intermediate fibres could not be demonstrated in the middle and deep bundles of fibres in a mixed autopsy and biopsy study by Serratrice *et al.* (1976). However, their existence was confirmed in 6 out of 10 samples taken from the superficial bundle. Vignon *et al.* (1980) similarly noted the presence of Intermediate fibres in autopsies from superficial masseter. Furthermore, whilst there was no correlation between the incidence of type I and Intermediate fibres, a negative relation was found between the percentage of type II and Intermediate fibres.

Eriksson (1982) noted that Intermediate fibres were present in five different

sites within masseter muscle following biopsies obtained from 5 individuals with normal intermaxillary relations and complete dentitions. Furthermore, the classical staining reaction for type IIa fibres was only noted in one subject. This latter finding supported a similar observation by Vignon *et al.* (1980) and led to the suggestion that Intermediate fibres were possibly most closely allied to type IIa fibres. Ringqvist *et al.* (1982) disagreed with this view and suggested that Intermediate fibres were probably most closely related to IIc fibres. This association between type IIc and Intermediate fibres has been supported by immunocytochemical evidence in that both types of fibre contained a mixture of fast and slow myosins in variable amounts (Thornell *et al.*, 1984) and that both fibres show myosin isoforms characteristic of developing muscle (Butler-Browne *et al.*, 1988)

The findings regarding the relative proportion of type I and type II fibres has varied extensively in previous studies. Ringqvist (1971) noted that type II fibres constituted 65% of the fibre types in the specimens examined, whereas in a later study (Ringqvist *et al.*, 1982) greater variation was noted with type I fibres representing 14 - 44%, Intermediate fibres representing 7 - 19% and type II fibres constituting 37 - 79%.

By way of contrast, Eriksson (1982) and Eriksson and Thornell (1983) reported that in addition to inter-individual variation, obvious intra-muscular variability occurred. Whole fascicles or large groups of type I fibres could be seen as well as groups of only type IIb fibres. However, their studies reported an overall type I fibre predominance of 61.6 - 71.8% in four different areas of masseter, with equal relative frequency in the posterior superficial portion of the muscle.

Previous studies have shown greater overall consistency of results with regard to relative fibre size. Serratrice *et al.* (1976) reported that the relative size of type I and II fibres varied with the site of the biopsy. The most striking disparity occurred in the superficial bundle where the type I fibres had a much larger diameter compared to the type II fibres. Unfortunately it is impossible to report exact figures as those quoted were not consistent

throughout the paper. The size disparity between the type I and type II fibres was apparently less evident in the middle and deep bundles.

In a later autopsy study by the same investigative team (Vignon *et al.*, 1980) 18 samples were taken from the superficial fibres of masseter, the subjects being aged between 17 days and 87 years old. The material was divided into two groups according to age with 13 years taken as the cut-off point. The mean diameter of type I and type II fibres in the adult group was given as 38.4μm (S.D. ± 11.2) and 16.1μm (S.D. ± 8.2) respectively. This size discrepancy was not evident in the very young specimens but by 2.5 years a difference of up to 5 μm was noted.

Eriksson (1982) found the type I fibres to be larger than type II fibres in all sites except the intermediate zone. The range of the results was large, however, with the diameter of type I fibres varying between 10 - 90 μm and the type II fibres ranging from 10 - 60 μm.

A more detailed investigation of the fibre population of masseter muscle was undertaken by Eriksson and Thornell (1983). Autopsy material was examined from 5 subjects with samples taken from the anterior and posterior aspects of the superficial fibres, the anterior and posterior aspects of the deep fibres as well as from the intermediate or middle fibre bundle. The mean fibre diameter of the type I fibres (43.9 μm) was larger in all sites than the type II fibres (31.0 μm). The various types of fibre did not differ significantly in diameter between the various parts of the muscle. The estimated percentage of the total fibre cross-sectional area attributed to type I fibres ranged from 70.2 % in the posterior aspect of the superficial fibres to 87.9 % in the anterior aspect of the deep fibres.

It is evident from the above that information regarding the fibre profile of the human masseter muscle in healthy subjects with normal skeletal and dental relationships is limited and often contradictory. A summary of the findings is presented in table III. It was considered desirable, therefore, to undertake an investigation to obtain further information on fibre profiles using

techniques which would ultimately be involved in the main study.

Table III - A comparison of previous studies of masseter profiles in normal subjects

Study	Type I		Type II	
	mean fibre diameter	% comp.	mean fibre diameter	% comp.
Ringqvist 1971	-	35	-	65
Ringqvist *et al.* 1982	-	14 - 44	-	37 - 79
Eriksson and Thornell 1983	-	61.6 - 71.8	-	-
Vignon *et al.* 1980	38.4	-	16.1	-
Eriksson 1982	10 - 90	-	-	-
Eriksson and Thornell 1983	43.9	-	31.0	-

ii) The histochemical profile of masseter muscle in patients with diverse vertical facial morphology

To date, very few studies have examined the masseter muscle fibre profile in patients with specific vertical skeletal facial deformities, and indeed those reported have emanated from the same centre, by the same research team. Nevertheless there has been variation in their observations.

Finn *et al.* (1980a, 1980b) examined deep masseter muscle biopsies in individuals with long and short face syndromes, and compared their findings with biopsies from control subjects with normal facial morphology. The initial study (Finn *et al.*, 1980a) was only based on 3 patients in each group and presumably these same individuals were included in the slightly larger samples in the later report (Finn *et al.*, 1980b). The ultimate sample size included 10 long faced individuals, 8 short faced subjects and 10 control biopsies. The authors reported that, compared to the controls, the short faced patients demonstrated type II fibre atrophy, whereas the long faced patients showed hypertrophy of both type I and type II fibres.

These results were in contrast to the findings of later reports of 9 patients with vertical maxillary excess (Boyd *et al.*, 1984; Gonyea *et al.*, 1985) where biopsies were taken from the deep surface of the anterior aspect of the superficial masseter.

The mean fibre area for the slow oxidative fibres was 1784 μm^2 as compared with 1654 μm^2 for the fast oxidative glycolytic, and 1269 μm^2 for the fast glycolytic fibres. It should be noted, however, that large variation occurred in fibre area for all fibre groups. The type II fibres as a whole (FOG and FG) were predominant accounting for 55.4% of the distribution of the fibres. Combining mean fibre area and percentage distribution, the type I (SO) fibres contributed slightly more (51.9%) to the total fibre cross-sectional area of the muscle.

It is evident that, as mentioned by Gonyea *et al.* (1985), there is a definite

need for further investigations, based on larger sized samples, into the fibre profile in patients with vertical skeletal discrepancies.

iii) The adaptation of masseter muscle to surgical correction of facial deformity.

The effect of orthognathic surgery on the masseter muscle fibre structure, as assessed through histochemical investigation has again received little attention in the literature.

Bell (1985) reported the response to surgical correction of vertical maxillary excess in five patients, four women and one man, with a mean age of 24.4 years. All patients underwent a Le Fort I osteotomy to intrude the maxilla, with three patients experiencing an additional mandibular advancement procedure. In all instances intermaxillary fixation was applied although this was not standardised in duration. Biopsies were taken from the deep surface of the anterior aspect of the superficial masseter muscle at surgery and at least six months later (mean = 8.5 months).

The pre-operative fibre profile was reported as being consistent with that of an earlier publication, which is not surprising as, whilst actual figures are not quoted, one strongly suspects that the data was from the same source. In four of the five patients the slow oxidative (type I) fibres predominated and, in all but one individual, they were also the largest fibre as measured in terms of cross-sectional area. Post-operative biopsies showed a shift in fibre predominance from slow oxidative (type I) to fast glycolytic (type IIb) in all patients. The change in percentage of fast oxidative glycolytic fibres (type IIa) was extremely variable.

Fibre size also changed following surgery and this appeared to be related to the surgical procedure. Patients who experienced maxillary surgery alone were noted to show an increase in the area of type II fibres, whereas the three patients who underwent bimaxillary surgery showed a reduction in fibre size. In one patient this was limited to the type IIb fast glycolytic

group, whilst all fibre groups were affected in the other two individuals. It is important to bear in mind, however, the small sample size upon which these observations were made.

Statement of the problem and aims of the histochemistry studies

In view of the very limited and frequently contradictory reports in the literature relating to the histochemical fibre profile of human masseter muscle in individuals with both normal and abnormal facial morphology, the paucity of reports which have investigated whether or not there is any relationship between masseter muscle structure and cranio-facial form and the total lack of information relating the histochemical response following one specific form of corrective surgery, a series of investigations was devised to throw further light on all these aspects.

The aims of the studies were therefore:

1) To confirm a technique for histochemical fibre typing of human masseter muscles in our laboratory and to determine the reproducibility of that technique.

2) To establish whether a single biopsy could be considered representative of the histochemical profile of the whole muscle.

3) To determine the histochemical profile of subjects with normal antero-posterior and vertical facial morphology using the specific histochemical technique and fibre classification.

4) To determine the histochemical profile of patients with either increased or decreased vertical facial morphology and to compare these with the fibre profile of normal subjects.

5) To determine whether there is any correlation between masseter muscle

structure and skeletal form, especially in the vertical dimension.

6) To ascertain the response of the masseter muscle fibres to surgical correction of vertical facial deformity by a Le Fort I impaction of the maxilla and sagittal split osteotomy of the mandible.

Method

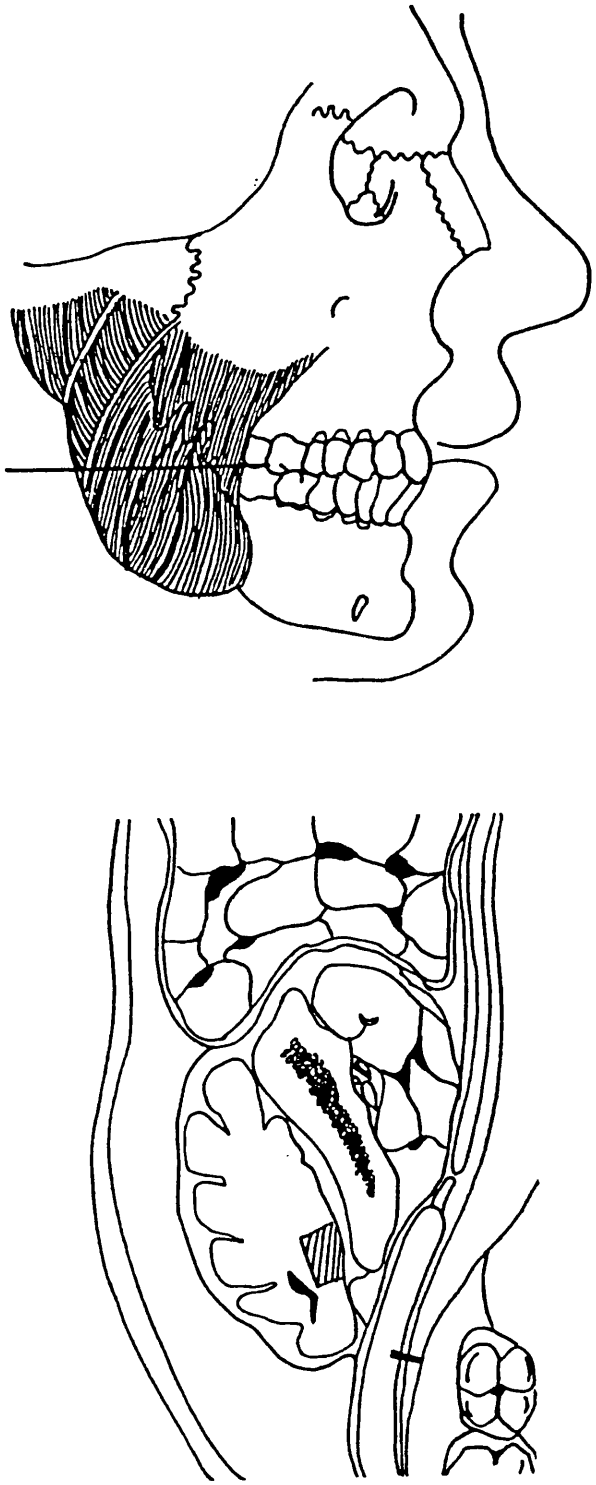
Masseter was chosen as the muscle for histolochemical investigation for several reasons. Firstly, it is an elevator muscle of the mandible believed to be active during posture as well as during isometric biting activity. Secondly, access to the muscle is readily available during orthognathic procedures involving the mandibular ramus, and thirdly, results would be available to enable comparison of some aspects of the study with the findings of previous workers.

i) Masseter muscle biopsy technique

All muscle biopsies were taken at the start of any operative procedure and before excessive manipulation of the mandible had occurred. In those cases where the biopsy was taken under local anaesthesia, care was taken to ensure that the nerves were blocked at a site remote, being proximal and high, to the biopsy site.

The biopsies were taken through intra-oral incisions at the level of the third molar teeth. Having reflected the mucosa and identified the anterior edge of the ascending ramus,the muscle fibres were partially detached from the lateral surface of the mandible. Specimens measuring 3mm x 2mm x 2mm were removed from the anterior leading edge and deep surface of the masseter muscle (figure 13) with the largest dimension always taken in the long axis of the muscle in order to aid orientation. The biopsies therefore consisted of muscle taken from the anterior and deep surface of the superficial fibre bundle up to and including the middle fibres.

Figure 13 - Diagrammatic representation of the masseter muscle biopsy site.



The specimens were removed from the deep surface of the anterior part of the superficial masseter muscle at the level of the occlusal plane (the hatched area on the lower diagram).
Adapted from Bell (1985).

Care was taken to ensure the constancy of biopsy site as well as avoiding any tendinous insertions. All biopsies were taken by the same surgical team. No attempt was made to maintain the muscle specimen at its original length as results of a previous electron microscopy study (Round *et al.*, 1982) have shown the sarcomeres to be fully and consistently relaxed.

ii) Histochemical fibre typing techniques

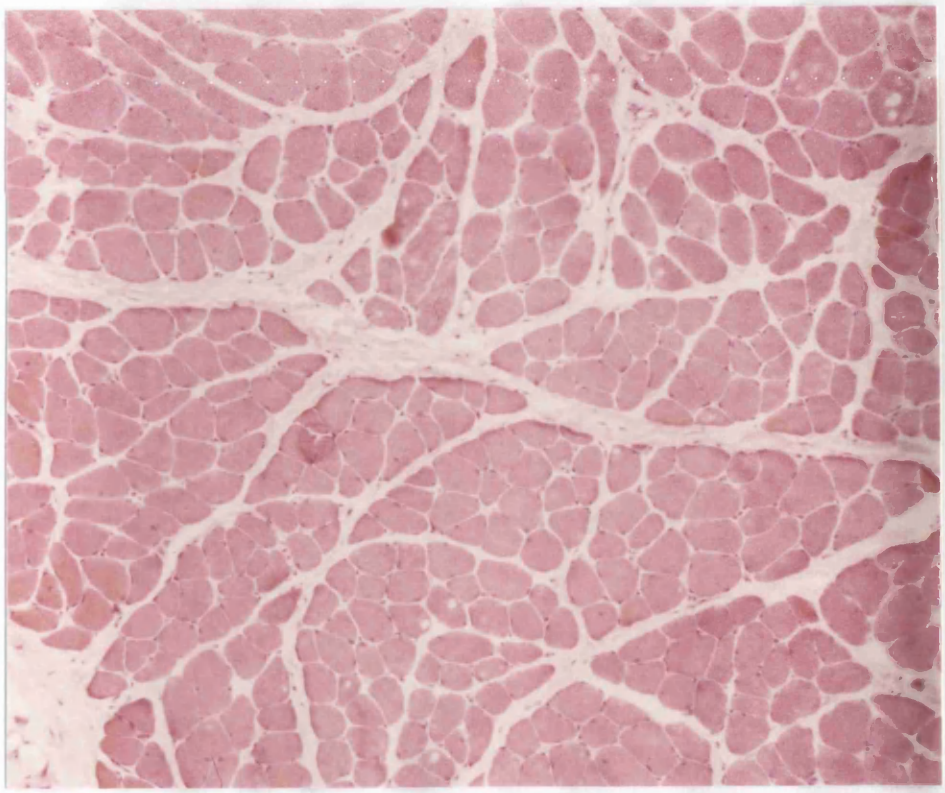
Once taken, the specimens were orientated under the microscope and mounted on a cork disk using OCT[4] mounting compound following which they were frozen by dropping into iso-pentane cooled to -196°C in liquid Nitrogen. The specimens were coded, by a technician, to enable blind analysis thereby reducing bias. Finally, the frozen specimens were stored in liquid Nitrogen until required for analysis.

Sequential sections of 4μ thickness were cut on a cryostat and subjected to the following histological and histochemical analyses:

a) Routine Haematoxylin and Eosin stain. (figure 14)

This was undertaken as a control in order to check the quality of the biopsy material, that no damage or distortion of the tissue had occurred during the freezing process, and that the muscle fibres did not exhibit any inherent pathology.

Figure 14 - Haematoxylin and Eosin stained section

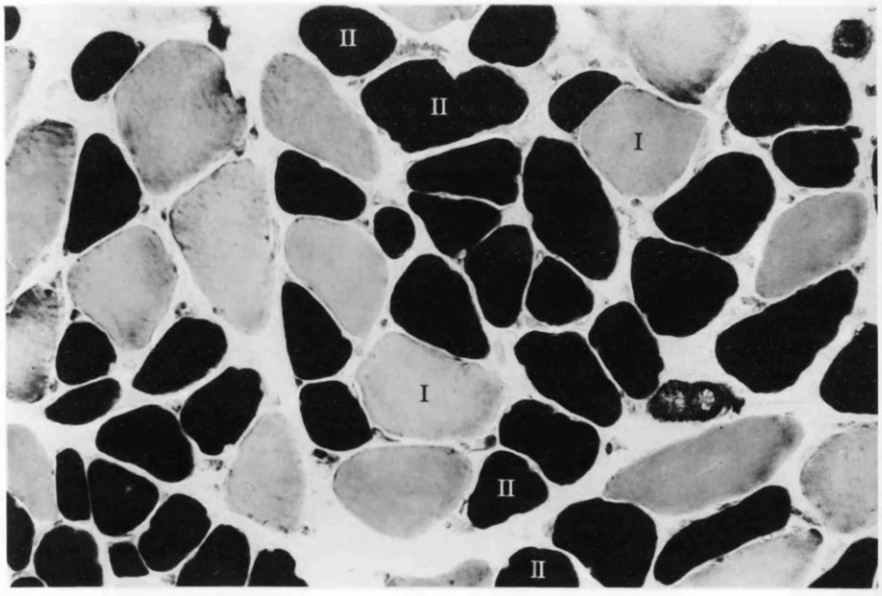


H and E sections showing normal tissue architecture with no evidence of freezing damage and no evidence of pathology. Magnification x 187

b) Routine ATPase activity at pH 9.4 (Engel,1962). (figure 15)

The 4μ cryostat sections were placed on a clean, dry coverslip and air dried, prior to incubating for 30 - 60 minutes at 37°C in a working solution of 5mg Adenosine 5' triphosphate dissolved in water, together with 10ml of buffered calcium chloride. The details of all the buffers and solutions are given in Appendix A. The sections were then washed 3 times for a minimum period of 2 minutes each in a 1% solution of calcium chloride prior to being transferred to a 2% solution of cobalt chloride for 2 one minute washes. The sections were then rinsed well in distilled water prior to staining in a freshly prepared 1% ammonium sulphide solution for 30 seconds. Finally, the stained sections were rinsed and mounted. This provided the basic division into type I and II fibres with type I fibres pale staining and type II fibres staining dark.

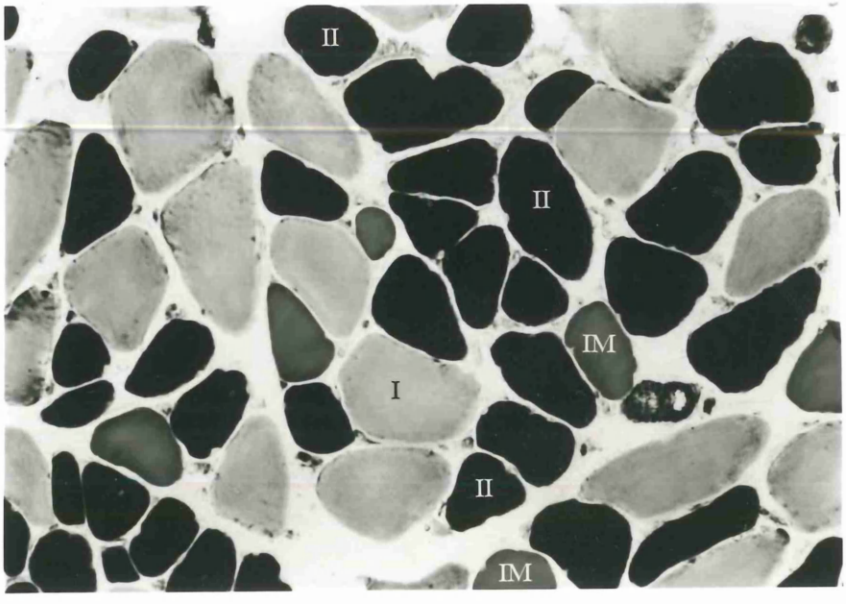
Figure 15 - ATPase staining reaction at pH 9.4 - Type I and II fibres



The type I fibres are pale staining in contrast to the darkly staining type II fibres. Magnification x 270

In the early studies, fibres with an Intermediate staining response were classified according to their most closely allied fibre type. However, with increasing experience and minor improvements in technique, especially more meticulous rinsing procedures, it was considered that they could be classified reliably in their own right (figure 16).

Figure 16 - ATPase staining reaction at pH 9.4 - Intermediate fibres



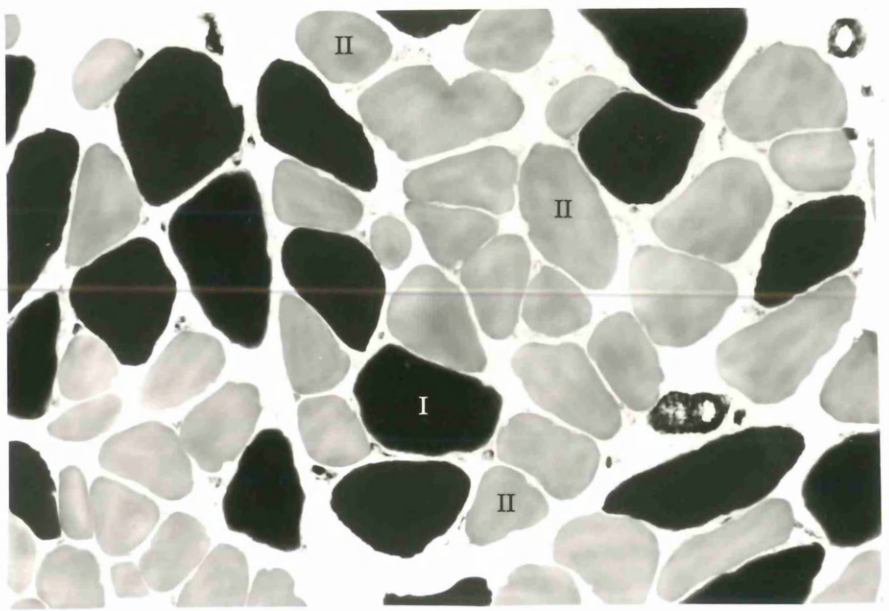
In addition to the pale staining type I fibres and darkly staining type II fibres, fibres with an intermediate staining intensity can be identified. Magnification x 270

c) Reverse ATPase activity at pH 4.6 and 4.3 (Brooke and Kaiser, 1969).

The sections were preincubated in acetate buffer at pH either 4.3 or 4.6 as appropriate for 15 minutes at 37°C. Again, the details of the buffers are listed in Appendix A. Subsequently, they were rinsed with the ATP working solution used at pH 9.4 but diluted to twice its volume with distilled water prior to following the procedure as outlined above. Examination of these two sections enabled the differentiation of the two sub-types of type II fibres.

At pH 4.6 the type I fibres stain very dark, whilst the type II fibres demonstrate a light staining intensity (figure 17).

Figure 17 - ATPase staining reaction at pH 4.6

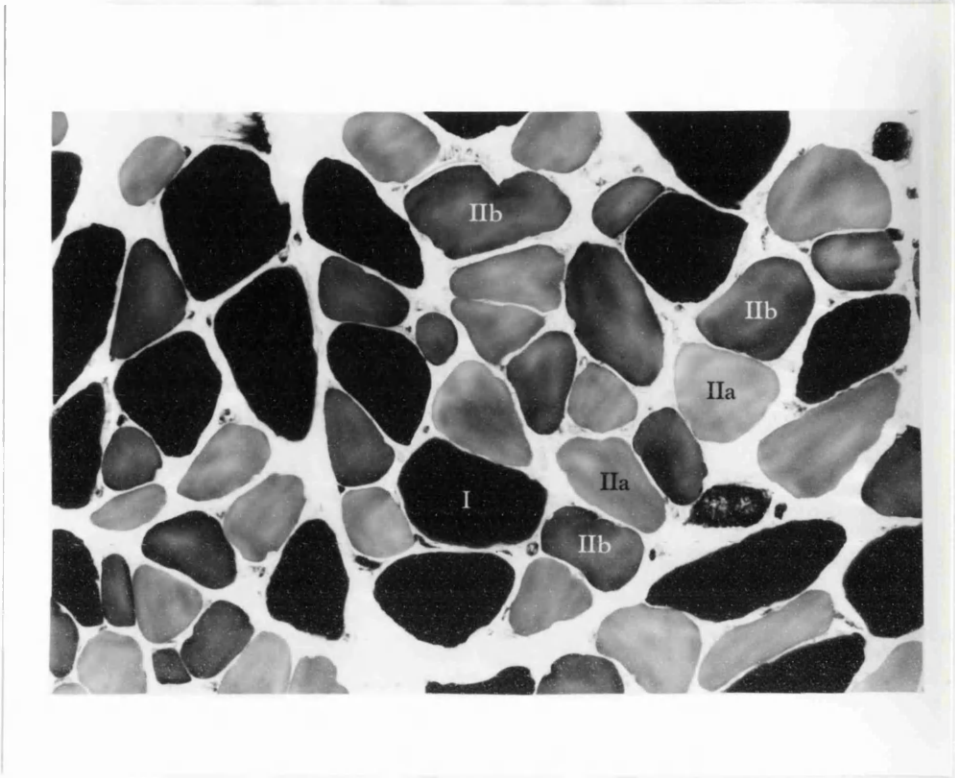


The reversal of the staining intensity observed at pH 9.4 is demonstrated with the type I fibres now darkly staining in contrast to the paler type II fibres. Magnification x 270.

At pH 4.3, the sub-type IIa remain relatively light staining whilst the IIb fibres take up an intermediate intensity between the type I and IIa fibres.

Of all the histochemical procedures employed, the reverse ATPase method proved technically to be the most difficult. Consequently, in some instances it was considered inappropriate to include data based upon rather inconclusive staining responses and the results were, therefore, restricted in those cases to the basic classification into type I and II fibres. As such the number of cases where type II sub-groups were recorded was less than for the basic fibre typing.

Figure 18 - ATPase staining reaction at pH 4.3



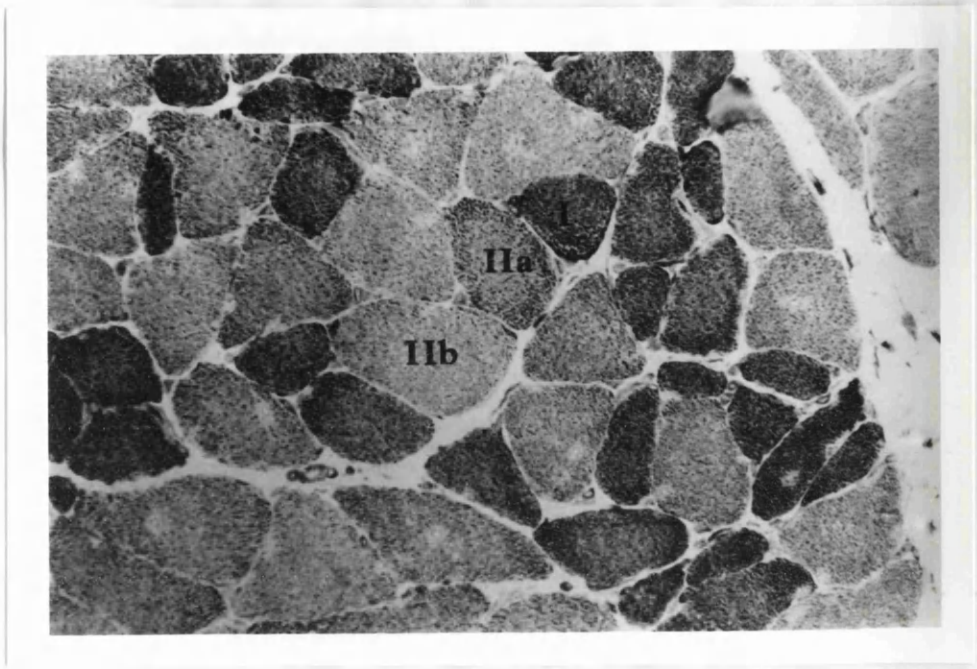
At pH 4.3, the type IIa fibres remain relatively pale staining whilst the IIb fibres are between the type I and IIa fibres in appearance. Magnification x 270.

d) NADH tetrazolium reductase response (Nacklas *et al.*, 1958). (figure 19)

The sections were incubated for 10 minutes at 37°C in a working solution of buffered Nitroblue tetrazolium to which NADH had been added. Subsequently, they were rinsed in distilled water and fixed in 20% Formalin for 10 minutes. Finally, the sections were washed in distilled water and mounted in glycerine jelly.

This response helped to confirm the fibre types identified by the ATPase reactions in sequential sections.

Figure 19 - NADH tetrazolium reductase staining reaction



The NADH response helped to confirm the type II sub-groups, with the type IIa fibres intermediate in staining intensity between the dark type I fibres and the paler IIb fibres. Magnification x 270.

iii) Measurement of fibre area and percentage distribution.

It has become generally accepted that of the numerous methods available for the assessment of muscle fibre size, planimetric methods are considered to be the most accurate (Adams *et al.*, 1968). Fibre areas in this study were assessed using a Reichert-Jung MOP-1[5] measuring device linked to a microcomputer and digitizing tablet (Jones *et al.*, 1980), as illustrated in figure 20.

Figure 20 -The Reichert-Jung MOP-1 system

The image of the muscle fibres was digitized by the drawing pen with the resulting coordinates stored stored by the microprocessor as well as giving a print-out of the mean and distribution of the respective fibre areas.

The sections were examined using a binocular microscope with a drawing tube attachment so permitting the image of the muscle specimen and the image of the digitizing tablet to be superimposed.

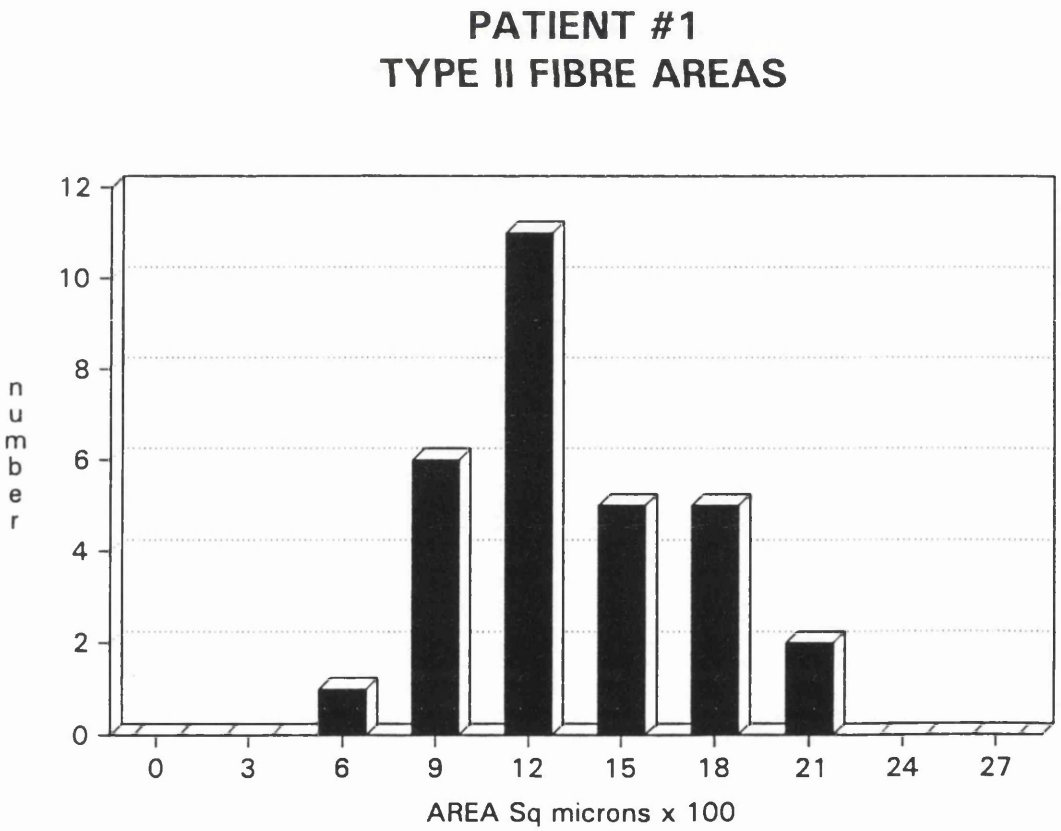
The microscope and side arm were calibrated at the start of each recording session using a Vernier slide with a x25 objective and x10 eye-pieces. The magnification of the side arm was adjusted such that 0.1mm on the Vernier slide was equivalent to 20mm on the tablet. The side-arm magnification factor (x200) was stored by the microprocessor consequently allowing a read out of the true fibre area in μm^2. This magnification was found to provide a conveniently sized image suitable for tracing by the drawing pen. Only those fibres considered visually to be cut in transverse section were

traced and measured. A minimum of 30 type I and 30 type II fibres were measured from a minimum of five different fields throughout the section and the results averaged in order to establish the mean area together with the standard deviation for each fibre type of a particular patient. The MOP-1 system also provided a printout of the distribution of the fibre areas in the form of a histogram (figure 21).

The percentage distribution of the fibres was assessed by counting 100 fibres and classifying them accordingly. This was repeated for a minimum of five fields throughout the section and the results averaged. Once again, the overall mean distribution of the fibre types was calculated for a particular patient group.

Where appropriate, the measuring procedure was repeated for the reverse ATPase sections in order to establish the type II fibre sub-group populations.

Figure 21 - Example histogram of muscle fibre area distribution



A histogram was produced for each fibre type from each field of 30 fibres giving the distribution of fibre areas in 300 Sq. micron increments.

iv) Error of the method and reproducibility of the typing technique and analysis

In order to assess the error of the method and the reproducibility of the measurement of fibre area and percentage composition, 10 biopsy specimens, previously frozen and stored in liquid nitrogen, were selected at random, reprocessed and remeasured not less than one month following the original measurement.

The overall error of the method (δ) was obtained according to the formula described by Dahlberg (1940), and the coefficient of reliability and the paired *t* - test gave an indication of the random and systematic errors respectively.

a) Results

The results are presented in table IV. The reproducibility of the technique proved satisfactory in most cases. The random error associated with the measurement of type IIa fibres and the assessment of Intermediate fibres in the early part of the study, meant that the results with regard to these fibres should be viewed with extreme caution before drawing conclusions. The paired *t* - test showed that the systematic error was acceptable with the exception of early techniques for the assessment of those fibres designated as Intermediate fibres.

In the early studies, as mentioned previously, the Intermediate fibres were not considered as a separate entity but grouped as either type I or type II fibres depending upon their relative staining intensity. With greater experience and minor improvements in technique the ability to reliably classify Intermediate fibres improved to the extent that they were considered in their own right in the later studies. The overall error of the method showed the measurement of fibre area to be within ± approximately 150 μm^2. In view of the size of the fibres (see later) this error was considered to be entirely satisfactory. Similarly, the assessment of

relative percentage fibre composition was considered acceptable.

Table IV - Error of the method of biopsy analysis

	Dahlberg error	Coefficient of reliability	*t* test
Fibre area (μm^2)			
Type I	151	91.6	ns
Type II	156	96.9	ns
Type IIa	59	85.8	ns
Type IIb	114	96.5	ns
Type IM	74	95.2	ns
Percentage composition (%)			
Type I vs Type II	3	90.7	ns
Type IIa vs Type IIb	5	95.4	ns
Type I and II vs Type IM (early)	19	71.2	*
Type I and II vs Type IM (late)	7	89.7	ns

Study 1 Whole muscle study

Some doubt arises as to whether a single biopsy presents a truly representative picture of the architecture of the whole muscle. In other words, would slight variations in biopsy site produce differing results regarding muscle fibre size and relative proportions?

Previous histochemical studies based on autopsy material have shown that regional variations occur within the masseter muscle for both fibre size and relative proportion (Serratrice *et al.*, 1976; Eriksson, 1982; Eriksson and Thornell, 1983).

Prior to embarking upon establishing data for both the control patients and the experimental groups, a pilot study was undertaken with the following aims: Firstly, to confirm the regional variation between the superficial and deep fibres, and secondly to ascertain whether variations occur between biopsies taken from within a particular region.

i) Material

The material consisted of a whole right masseter muscle, removed within 12 hours of sudden death from a male Caucasian aged 50 years. The consent of the relatives was sought and agreed, and supported the written request of the deceased that his organs be used for transplantation or scientific research. The donor possessed a full complement of teeth and had no known head or neck pathology.

The reliability of autopsy material for histochemical fibre typing obtained within 12 hours of death has been confirmed (Eriksson, 1982).

The muscle was carefully dissected from its origins and insertions together with the associated parotid gland and duct in order to aid orientation.

ii) Method

A total of 8 biopsies were removed representing two sites within the superficial aspect of the superficial fibre group, four from the deep aspect of the superficial fibres, around the area normally accessed in clinical *in vivo* biopsy studies of the masseter muscle, and the remaining two from the deep aspect of the deep fibre group.

The specimens were orientated, frozen, sectioned, stained and analyzed in the same manner as previously described.

Within each biopsy three different fields representing a minimum of 30 type I and 30 type II fibres were examined enabling the recording of the mean fibre area and percentage composition of the type I and type II fibres for each field. From these results the overall mean fibre area and relative composition was calculated for each anatomical region of the masseter muscle.

iii) Results

The overall results are presented in Appendix B, whilst the group mean results are shown in Tables V and VI. The statistical analysis included a one-way analysis of variance (ANOVA) as well as Student's *t* test for both paired and unpaired data.

Biopsies taken from the superficial aspect of the superficial bundle of fibres showed both type I ($p \leq 0.01$) and type II fibres ($p \leq 0.001$) to be significantly smaller than their deeper counterparts. However, there were no significant differences in mean fibre area between biopsies taken from the deep aspect of the superficial bundle and the deep fibres.

Similarly there were highly statistically significant ($p \leq 0.001$) differences in relative percentage composition between the superficial aspects compared to the deeper structures. In the superficial biopsies, type

II fibres predominated ($\bar{x}$ = 52 %)

Table V - **Regional variations in muscle fibre area**

	Type I				Type II			
Anatomical site	mean area	SD	SE	95% CI	mean area	SD	SE	95% CI
Superficial/ Superficial (SS)	1261	171	70	1081-1441	924	203	83	711-1137
Deep/ Superficial (DS)	1523	129	37	1441-1605	1511	130	37	1428-1594
Deep (D)	1552	106	43	1440-1664	1599	125	51	1468-1731

Units : Sq microns.

Significance:	**Type I**			**Type II**		
	SS	DS	D	SS	DS	D
SS	-	**	**	-	***	***
DS	**	-	ns	***	-	ns

Table VI- Regional variation in muscle fibre distribution

Anatomical site	Type I mean %	Type I 95% CI	Type II mean %	Type II 95% CI	SD	SE
Superficial/ Superficial (SS)	48.0	44.6-51.4	52.0	48.6-55.4	3.2	1.3
Deep/ Superficial (DS)	53.6	51.9-54.9	46.4	45.0-47.9	2.3	0.7
Deep (D)	54.8	53.8-55.9	45.2	44.1-46.2	1.0	0.4

Units : %

Significance:

	Type I			Type II		
	SS	DS	D	SS	DS	D
SS	-	***	***	-	***	***
DS	***	-	ns	***	-	ns

whilst in the deeper areas type I fibres were more abundant ($\bar{x}$ = 54 %). Again, there was no significant difference in percentage composition between the deep aspects of the superficial bundle and the deep fibres.

These results only partially support the findings of Serratrice *et al.* (1976) in that although they found type II fibre predominance in the superficial aspects, the discrepancy was not as obvious as in the present study (4 % cf.10 %). Furthermore, Serratrice *et al.* (1976) noted a 6 % predominance of type II fibres in the deep aspects of the masseter muscle. Interestingly, the authors observed that biopsies taken from areas between the superficial and deep bundles showed a 9% predominance of type I fibres, a result which more closely resembles the mean percentage observed in this study for biopsies taken from the deep aspect of the superficial fibres (53.4 %).

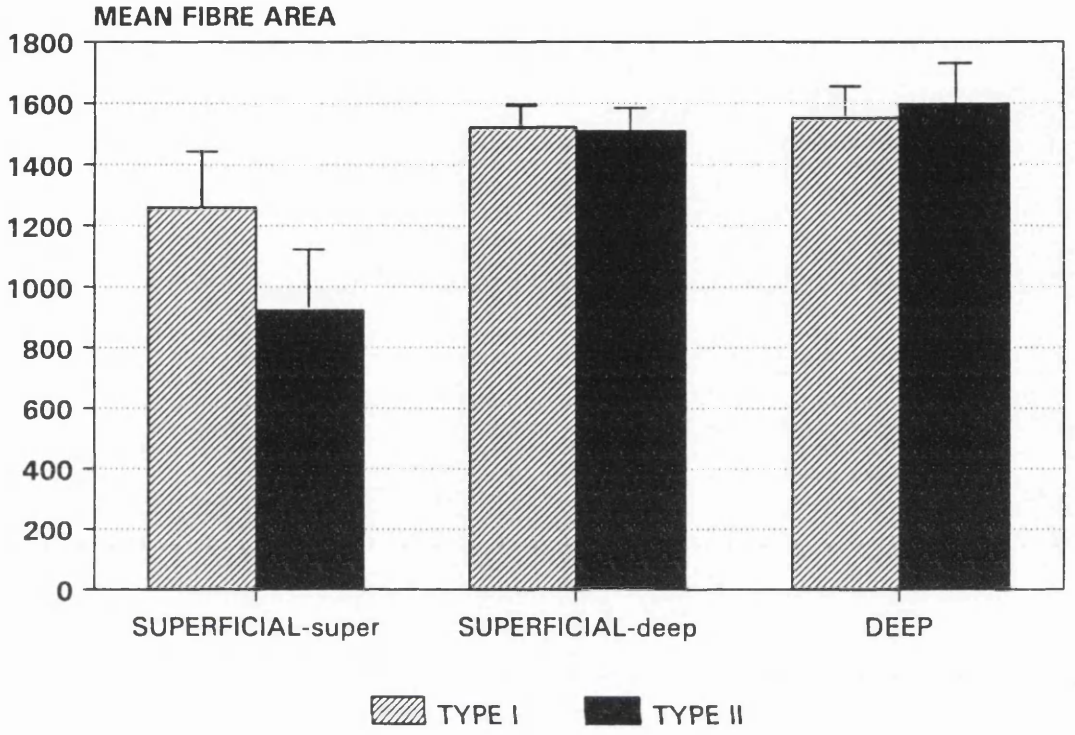
With regard to variations between different fields and between biopsies taken within the same anatomical region, there were no significant differences between the results for either fibre size or percentage composition in both the deep superficial and the deep areas.

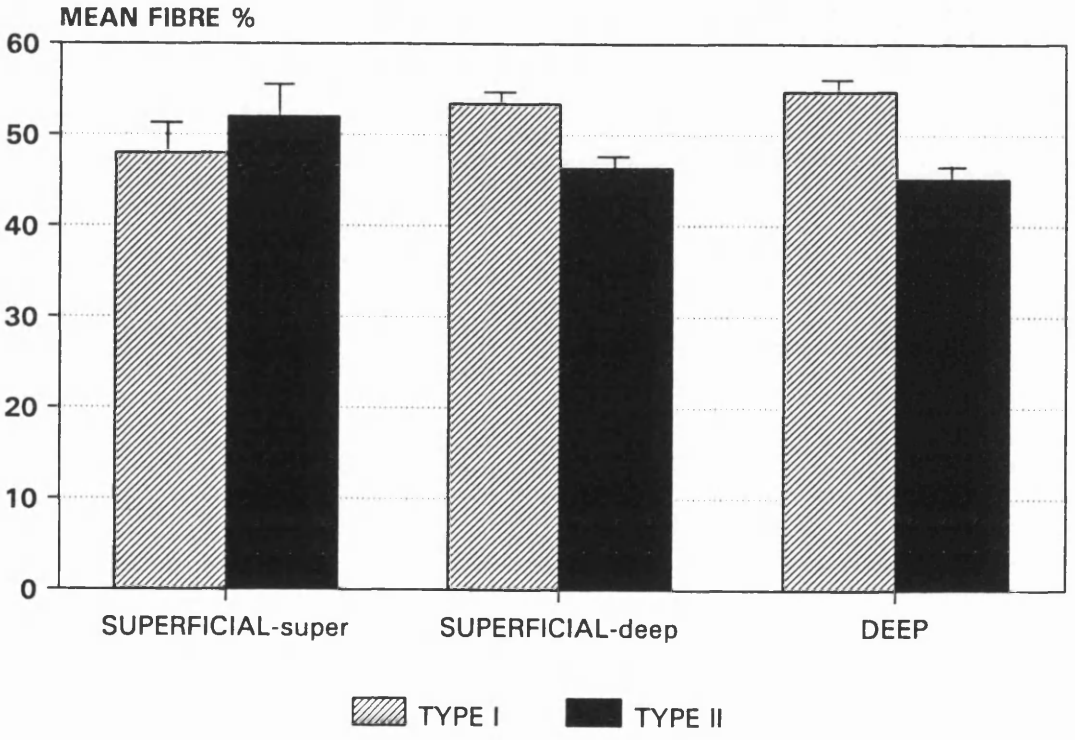
Similarly, the mean fibre size was consistent between the two sites from the most superficial fibres but variation did occur in fibre composition ($p \leq 0.05$).

In conclusion, the results confirm the findings of previous studies by Serratrice *et al.* (1976), Eriksson (1982) and Eriksson and Thornell (1983) in that regional variations in fibre size occur within the masseter muscle. However, there was no significant difference between samples obtained from the same anatomical region. It was considered that providing regional anatomical boundaries are adhered to, a single biopsy can be representative of the muscle fibre profile of that region. This is especially true for the deeper aspects of the masseter muscle. Therefore, it is likely that any variation in fibre profile occurring either between individuals or within individuals on different occasions should be indicative of the variation of

muscle morphology and physiology at that time, rather than as a result of minor variations in biopsy site.

Figure 22 - Regional variation in fibre areas and percentage composition





Study 2

The masseter muscle fibre profile in subjects with normal skeletal and dental relationships

In view of the variation in results which has been reported regarding the masseter fibre profile in patients with normal cranio-facial morphology, it was felt necessary to establish "normal" or control data for such patients using the techniques of the present study.

i) Subjects

20 Caucasian patients due to have their unerupted third molar teeth removed under general anaesthesia consented to a muscle biopsy at the time of surgery. The subjects consisted of 10 males and 10 females aged between 17 and 30 years, with a mean age of 19.6 years. No patients gave a history of neuromuscular disease, habits,bruxism or temporomandibular joint dysfunction. All patients exhibited normal relationships of the mandible to the maxilla antero-posteriorly, vertically and laterally, as well as good quality dentitions as assessed by inspection. With the exception of four patients, each of whom had four first premolars removed as part of minimal orthodontic intervention, all patients possessed a full complement of teeth.

ii) Method

The biopsies were processed and measured according to the technique previously described. The mean areas and standard deviations for each fibre type for the male and female groups, as well as the entire pooled control sample were established. Subsequently, the computer produced a histogram for each patient demonstrating the number and distribution of fibres within a particular area range as previously described (figure 21). When all 20 patients had been recorded, the histograms were pooled to form a megahistogram for each fibre type for the entire control group (figure 23) in the manner described by Serratrice *et al.* (1976).

Dubowitz *et al.* (1985) has emphasized that in biopsy studies where fibre histograms do not correspond to a normal distribution curve or which are skewed, it is important to ascertain the deviation in fibre distribution. Consequently it is important to state the variability coefficient. This coefficient is derived from the expression:

$$\frac{\text{standard deviation} \times 1000}{\text{mean fibre size}}$$

Any fibre type with a variability coefficient of greater than 250 is considered to demonstrate abnormal variability in size of the fibres.

The percentage composition of the fibre types was determined as before. Once again, the overall mean distribution of the fibre types was calculated for the male and female groups as well as for the pooled sample. Finally, the relative percentage contribution of each fibre type to the total cross-sectional area, determined from the products of the mean areas and percentage compositions, was ascertained.

The above procedure was then repeated for the acid reversal sections in order to classify the type II fibres into the type IIa and IIb sub-groups. Unfortunately the sub-division of type II fibres was limited to only 8 patients.

iii) Results

The overall figures for the individual mean fibre areas, percentage compositions and percentage cross-sectional areas are presented in Appendix C together with the comparison of the groups according to sex.

The material for this aspect of the study was derived from biopsies of 10 male and 10 female subjects. However, there was no significant difference observed between the sexes for any of the parameters measured. On this basis, the results were pooled to form a control group of more meaningful size.

Table VII shows the combined male and female group figures together with the statistical comparisons. Figures 23 to 25 present the mean group results diagrammatically.

The inability to observe any sex difference with regard to type I and II mean fibre area, relative percentage composition and relative percentage cross-sectional area, supports the findings of Ringqvist (1971, 1974b) with regard to masseter muscle. This differs, however, from findings related to limb muscles in which the cross-sectional dimensions were found to be smaller in females than in males (Edstrom and Nystrom, 1969; Brooke and Engel, 1969).

Although there was no statistically significant difference between the type II sub-groups, the very small sample size severely limits further discussion.

Considering the entire control sample, the mean area of the type I fibres was 1771 μm^2 (95% CI 1601 to 1940 μm^2). This compared with an average fibre area for the type II fibres of 1909 μm^2 (95% CI 1735 to 2083 μm^2), a difference which was not statistically significant.

As discussed earlier, it is difficult to draw exact comparisons with the findings of previous studies due to variations in biopsy site. Eriksson and Thornell (1983) observed that type I fibres were larger than type II fibres in all sites examined. However, Serratrice *et al.* (1976) and Eriksson (1982), despite noting a large size disparity in the superficial fibres, observed a more equal fibre diameter in the middle or intermediate zone, the area most probably allied to the present study. Unlike the findings of Eriksson (1982), who noted large variations in the diameter of both fibre types, the range of areas in the present study was reasonably consistent. The variability coefficients were low at 203 and 194 for the type I and II fibres respectively.

The results of this study showed a significant difference ($p \leq 0.05$) between the relative percentage composition of the type I and II fibres,

Table VII - The histochemical profile of the control group

20 patients

Fibre area	Type I	Type II	Sig
mean	1771	1909	ns
SD	361	371	
SE	81	83	
Var. coeff.	203	194	
95% CI	1601-1940	1735-2083	
% Composition			
mean	45.4	54.6	*
SD	7.3	7.3	
SE	1.6	1.6	
95% CI	42.0-48.8	51.2-58.2	
% X-sect.area			
mean	43.6	56.4	**
SD	8.5	8.5	
SE	1.9	1.9	
95% CI	39.6-47.6	52.4-60.3	

8 patients

Fibre area	Type IIa	Type IIb	Sig
mean	1848	2007	ns
SD	492	500	
SE	174	176	
Var. coeff.	266	249	
95% CI	1437-2260	1589-2426	
% Composition			
mean	28.6	26.0	ns
SD	6.5	4.7	
SE	2.3	1.7	
95% CI	21.8-35.4	22.0-30.0	
% X-sect. area			
mean	28.5	27.9	ns
SD	5.7	5.0	
SE	2.0	1.8	
95% CI	23.3-32.8	23.9-32.1	

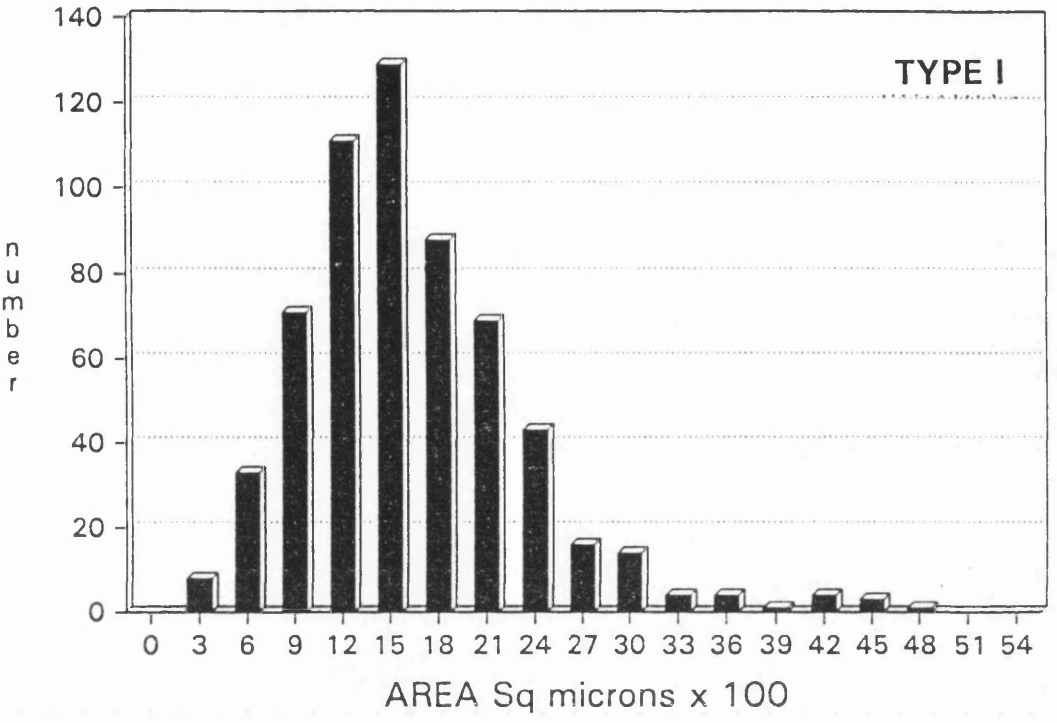
with the latter predominating on average by 9.2% (95% CI 2.3 to 15.9%). Serratrice *et al.* (1976) noted a 6% predominance of type II fibres in the deep aspects of the muscle, but in contrast to the present study, they noted a 9% type I fibre predominance for biopsies taken from the deep aspects of the superficial fibres. It should be emphasized however, that Serratrice *et al.* (1976) included patients with varying skeletal relationships and differing states of the occlusion.

The percentage fibre cross-sectional area showed significant type II fibre predominance ($p \leq 0.01$) accounting for 56.4% of the total fibre area, which was on average 12.8 % (95% CI 4.8 to 20.7%) more than the type I fibres. These results are again at variance to the findings of Eriksson and Thornell (1983) who observed type I fibre predominance in all sites studied.

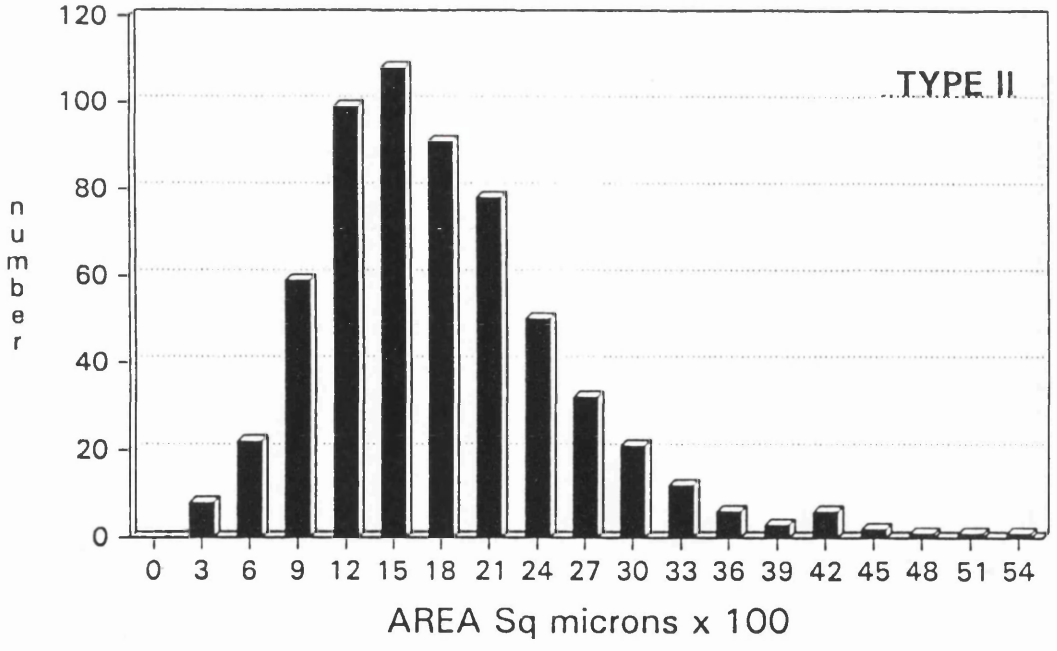
As already mentioned, difficulties with laboratory techniques limited the number of biopsy samples available for assessment of the sub-types of type II fibres. However, from the 8 samples measured the mean area of the type IIa or FOG fibres was 1848 μm^2 (95% CI 1437 to 2260 μm^2), whereas the mean area of the type IIb or FG fibres was slightly greater, but not significantly so, measuring 2007 μm^2 (95% CI 1589 to 2426 μm^2). The variability coefficients displayed reasonable consistency.

The IIa fibres were present in similar frequency to the IIb fibres forming 52% of the type II fibres measured, although it should be noted that the range was relatively large, varying from 47 - 65%. Overall, the mean incidence of types I, IIa and IIb fibres was 45.4%, 28.6% and 26% respectively.

Figure 23 - Histogram of control group fibre areas - types I and II



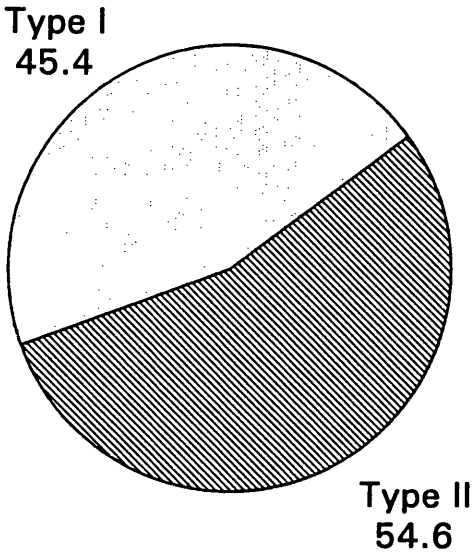
20 patients



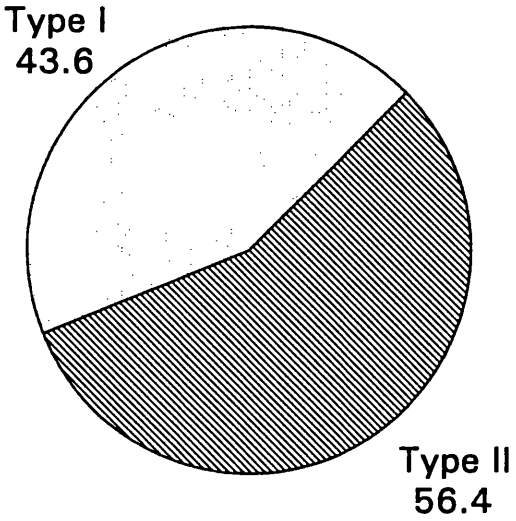
The histograms demonstrate that there was no significant difference between the relative size of type I and type II fibres within the control sample.

Figure 24 - Control group fibre percentage composition and total cross-sectional area - types I and II

FIBRE PERCENTAGE COMPOSITION

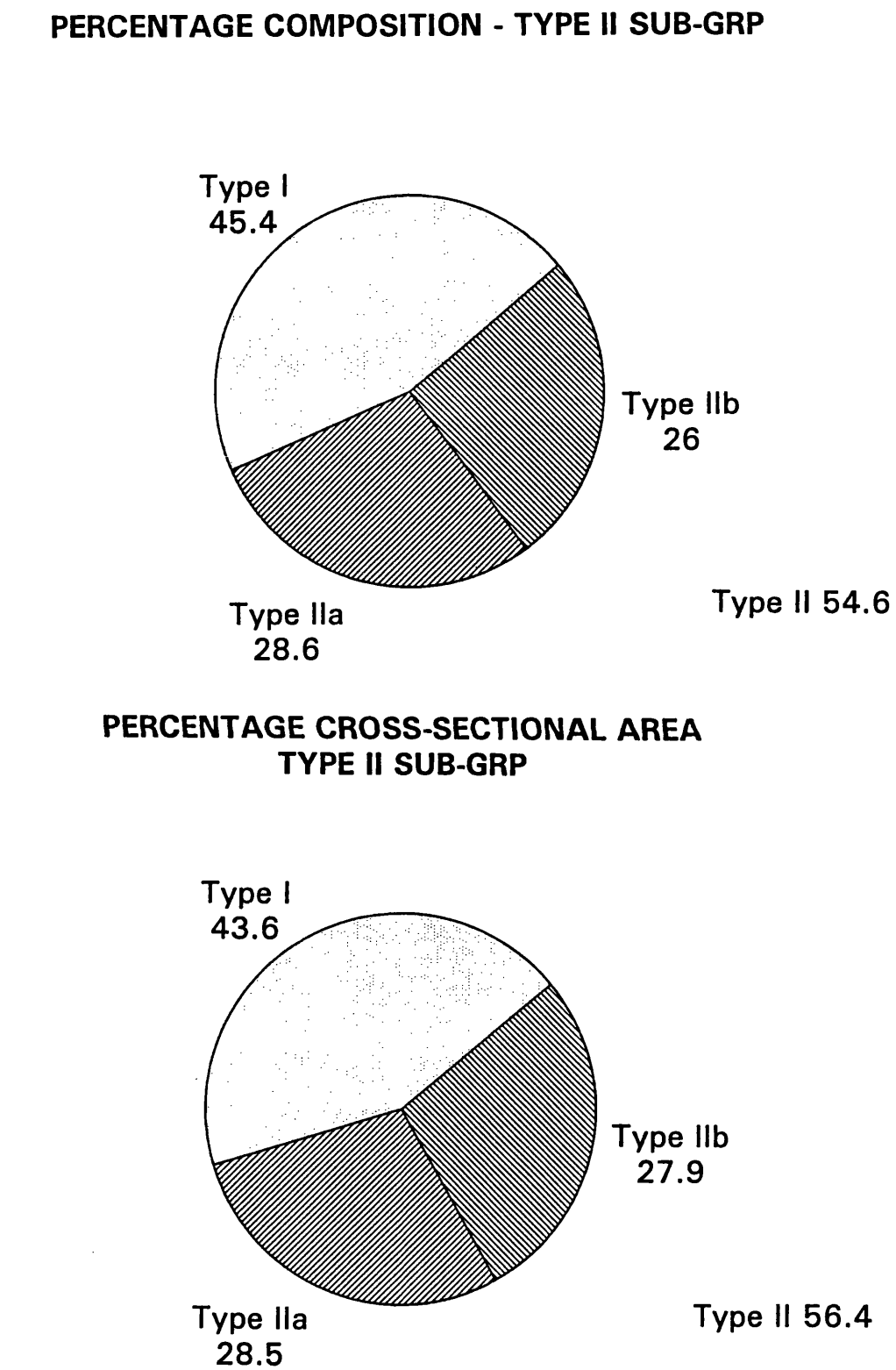


FIBRE PERCENTAGE CROSS-SECTIONAL AREA



The overall contribution of the type II fibres to the total fibre percentage cross-sectional area was significantly ($p \leq 0.01$) greater than that of the type I fibres.

Figure 25 - Control group fibre percentage composition and total cross-sectional area - sub-groups IIa and IIb



There was no significant difference between the type II sub-groups for either percentage composition or overall contribution to the total fibre cross-sectional area.

Variations in nomenclature of fibre types makes comparison of these findings with those of earlier investigators somewhat difficult. Serratrice *et al.*(1976), for example, reported the presence of type IIb, IIc and Intermediate fibres in their mixed autopsy /biopsy study, commenting that IIa fibres were an unusual finding in the superficial aspects of the masseter muscle. As mentioned earlier the histochemical techniques followed in this investigation gave inconsistent results regarding Intermediate fibres or IIc fibres. It is feasible that fibres assessed as IIa in the present study could be interpreted as Intermediate fibres by other workers. The metabolic properties of fibres assessed as type IIa were confirmed whenever possible by examination of serial sections stained using the NADH reductase reaction.

Study 3

The histochemical profile of masseter muscle in patients with diverse vertical facial morphology

In view of the paucity of data relating to the masseter muscle fibre profile in humans with abnormal vertical skeletal relationships, the following investigation was undertaken to provide further information in this respect.

i) Subjects

Of the 54 patients who ultimately proceeded to surgery for the correction of a facial deformity involving a change in the vertical dimension, 42 patients consented to a masseter muscle biopsy at the time of surgery. Of the 42 patients, 25 (15 females, 10 males) were identified as long faced individuals (see page 73) where surgery was planned to reduce the vertical skeletal dimension. Similarly, 17 patients (10 females, 7 males) were identified as possessing short faces requiring an increase in skeletal dimensions in the vertical plane. The mean age of the whole group was 23.3 years (95% CI 21.5 to 25.1 years).

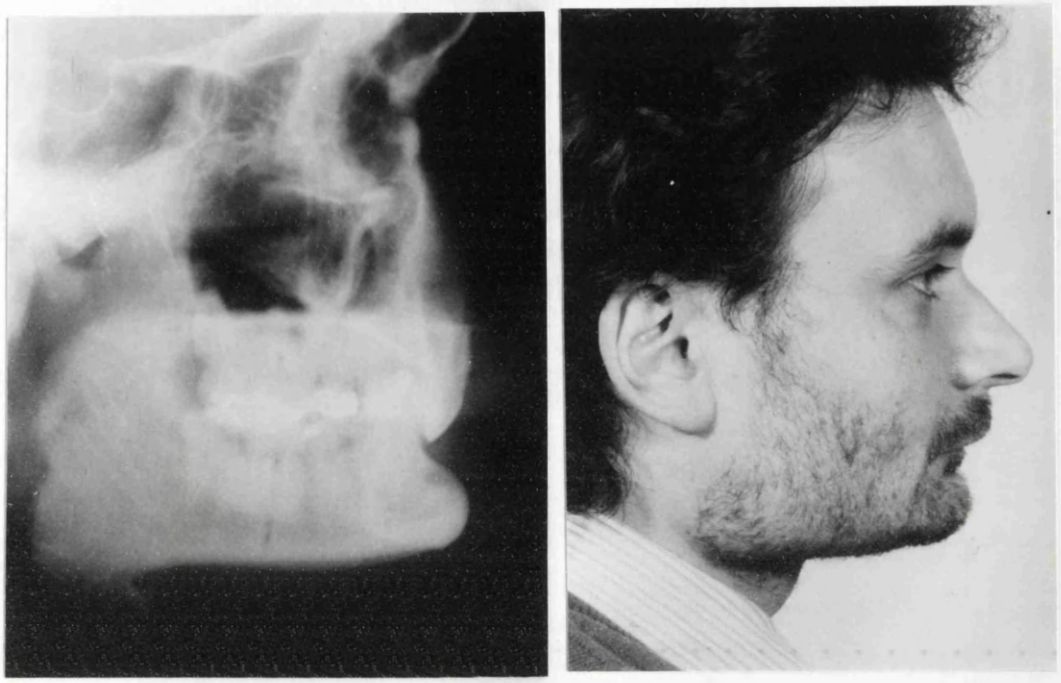
ii) Method

The biopsy technique, together with the preparation of the specimens and their subsequent measurement followed exactly the same procedure as detailed previously. For the first 6 months of this part of the study, all the sections were both prepared for analysis and measured by the author. However, for the latter 12 months, the specimens were prepared for analysis by Miss A. Geraerts from the Metabolic laboratory at University College Hospital, London. In all cases the morphometric analysis was undertaken by the author. In order to check that there was no discrepancy in the results obtained for specimens prepared by the two workers, 6 biopsies previously prepared by the author were subsequently recut by Miss Geraerts and analyzed. The variation in the results was well within the error

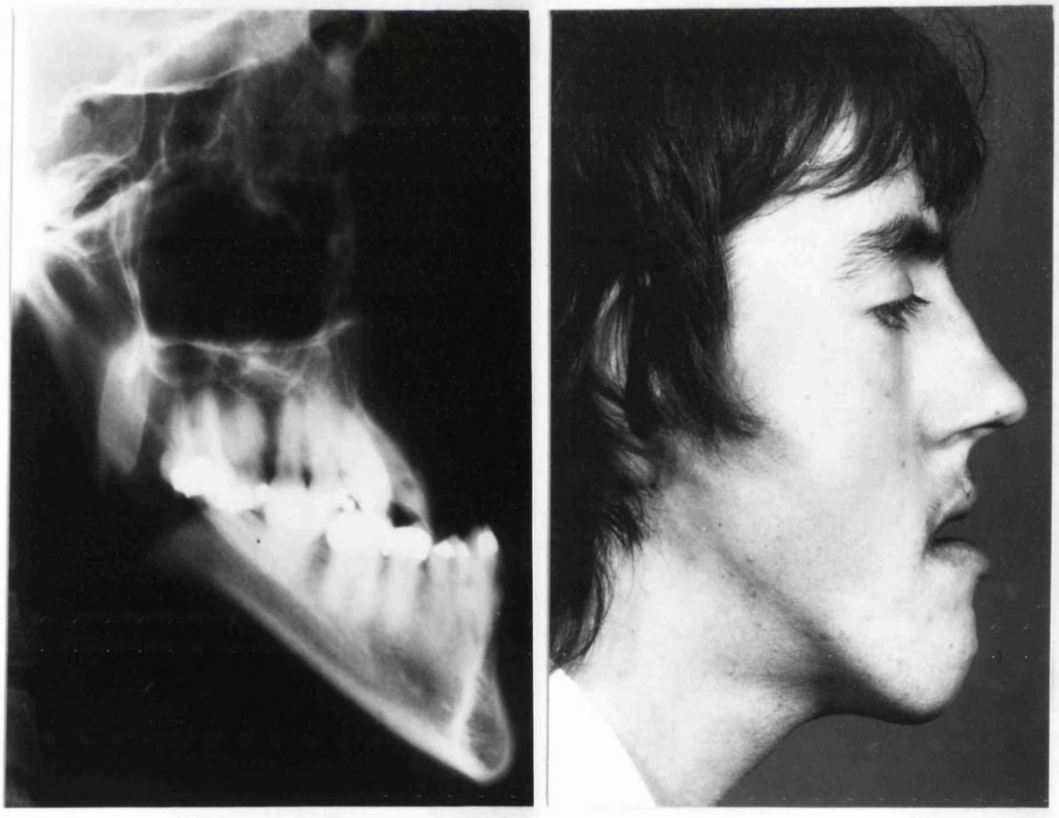
of the method listed on page 98.

Figure 26 - Typical features of patients with short or long faces.

A short face patient



A long face patient



iii) Results

The detailed results for the short and long face groups, together with group comparisons based on patient's sex are presented in Appendix D. The type II fibre sub-classification was available for 12 of the 17 patients in the short face group and 20 of the 25 patients in the long face group. As the only significant difference between the male and female patients in either group occurred with regard to the mean type I fibre area for the long faced individuals ($p \leq 0.05$), it was felt justifiable to pool the sexes to form skeletal groups of more meaningful size.

The overall mean fibre areas, relative fibre percentage composition and percentage cross-sectional areas, together with the variation coefficients are presented in tables VIII and IX, and figures 27 to 32.

A comparison between the control and study groups was made using the one-way analysis of variance (ANOVA) for the parametric data or the Kruskall-Wallis test (K-W) for non-parametric data as appropriate. The results are presented in table X as well as in diagrammatic form in figure 34.

Table VIII- The histochemical fibre profile of the short face group

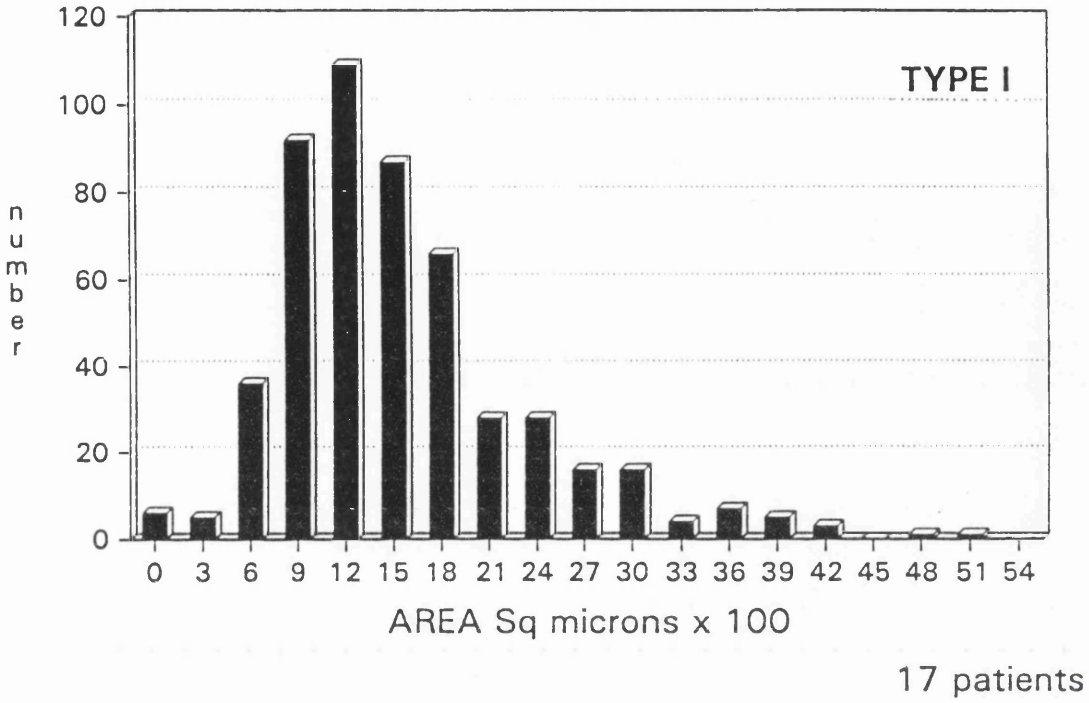
17 patients

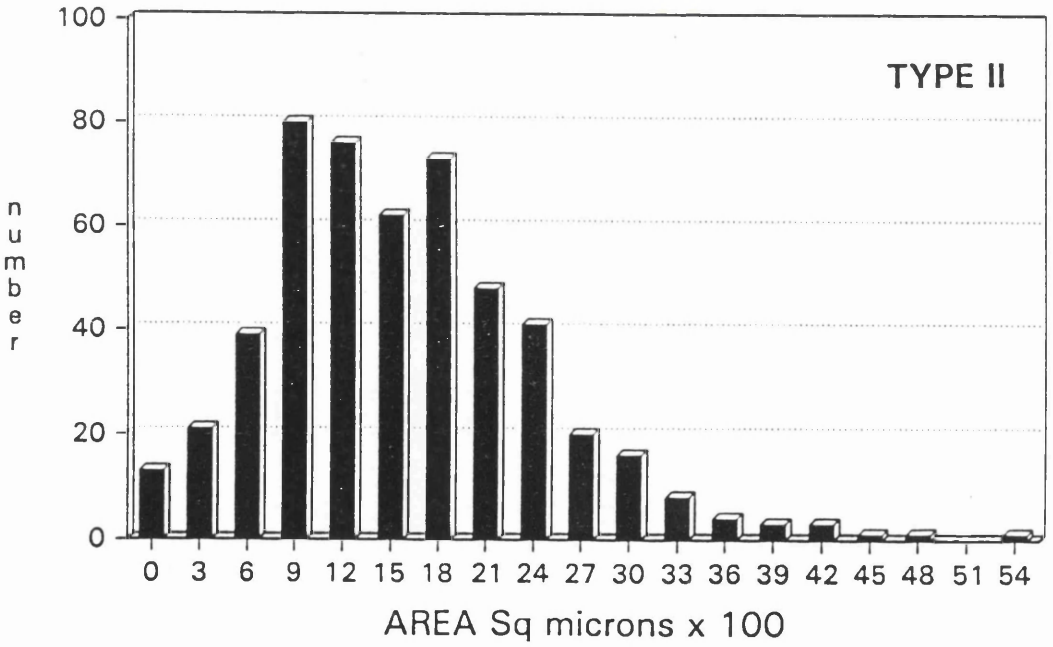
Fibre area	Type I	Type II	Sig
mean	1705	1718	ns
SD	383	529	
SE	93	28	
Var. coeff.	224	307	
95% CI	1508-1902	1446-1990	
% Composition			
mean	45.8	54.2	*
SD	7.8	7.8	
SE	1.9	0.9	
95% CI	41.8-49.8	50.2-58.2	
% X-sect.area			
mean	46.2	53.8	ns
SD	9.6	9.6	
SE	2.3	2.3	
95% CI	41.2-51.1	48.8-58.8	

12 patients

Fibre area	Type IIa	Type IIb	Sig
mean	1565	1640	ns
SD	727	689	
SE	209	199	
Var. coeff.	464	420	
95% CI	1103-2027	1201-2078	
% Composition			
mean	27.9	26.3	ns
SD	12.2	7.6	
SE	3.5	2.2	
95% CI	19.8-36.0	21.3-31.3	
% X-sect.area			
mean	27.5	26.3	ns
SD	13.4	9.0	
SE	3.9	2.6	
95% CI	18.4-36.6	20.1-32.5	

Figure 27 - Histogram of short face group fibre areas - types I and II

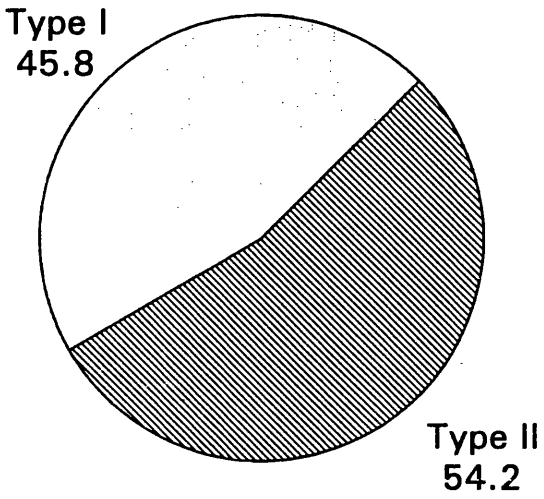




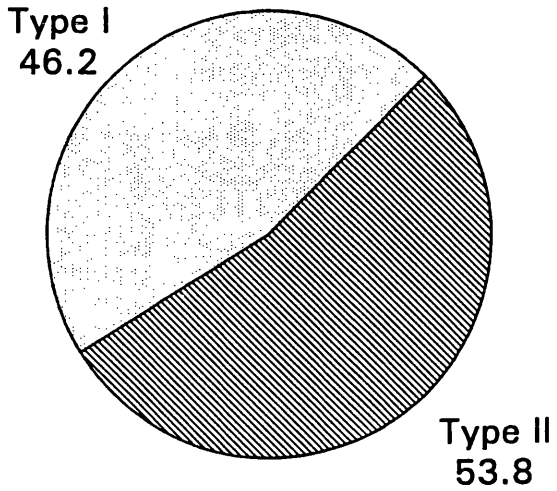
There was no significant difference between the relative size of the type I and type II fibres.

Figure 28 - Short face group fibre percentage composition and total cross-sectional area - types I and II

FIBRE PERCENTAGE COMPOSITION

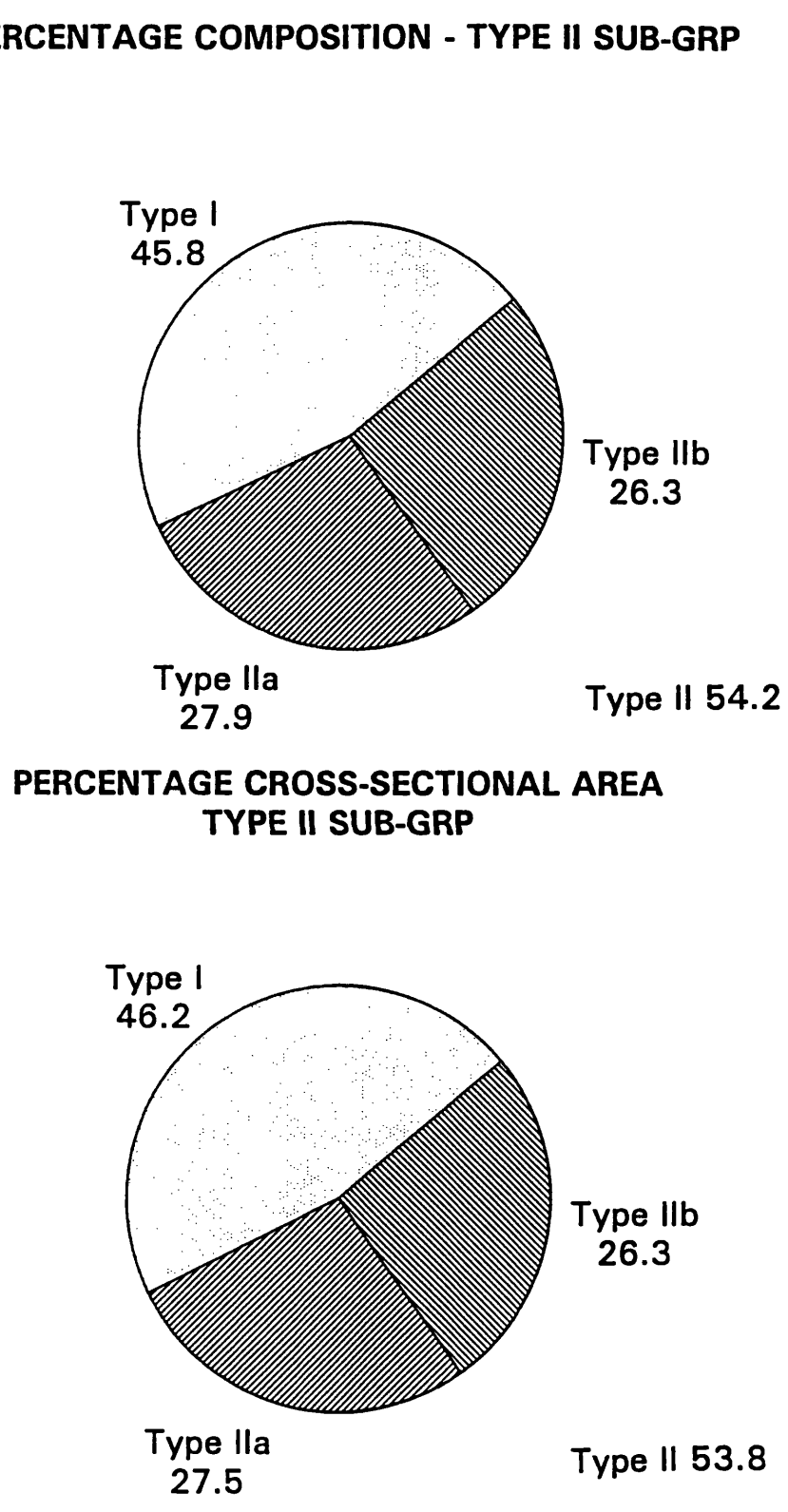


FIBRE PERCENTAGE CROSS-SECTIONAL AREA



Although the type II fibres were present in a significantly higher percentage ($p \leq 0.05$), their overall contribution to the total cross-sectional area was not significant.

Figure 29 - Short face group fibre percentage composition and total cross-sectional area - sub-groups IIa and IIb



There was no significant difference in either the percentage composition or the percentage total cross-sectional area between the sub-groups.

Table IX - The histochemical fibre profile of the long face group

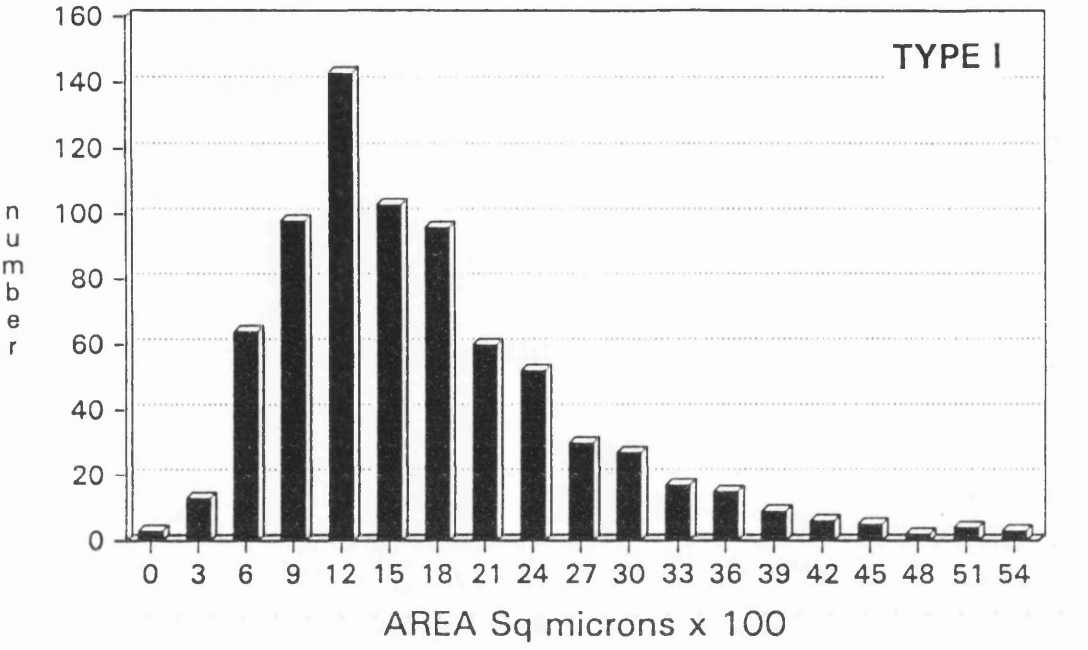
25 patients

Fibre area	Type I	Type II	Sig
mean	1880	1131	***
SD	527	median 808	
SE	105		
Var. coeff.	280	646	
95% CI	1662-2097	¼ile 619 -1491	
% Composition			
mean	58.2	41.8	**
SD	10.7	10.7	
SE	2.1	0.1	
95% CI	53.8-62.7	37.3-46.2	
% X-sect.area			
mean	71.5	28.5	***
SD	11.8	11.8	
SE	2.4	2.4	
95% CI	66.7-76.4	23.6-33.3	

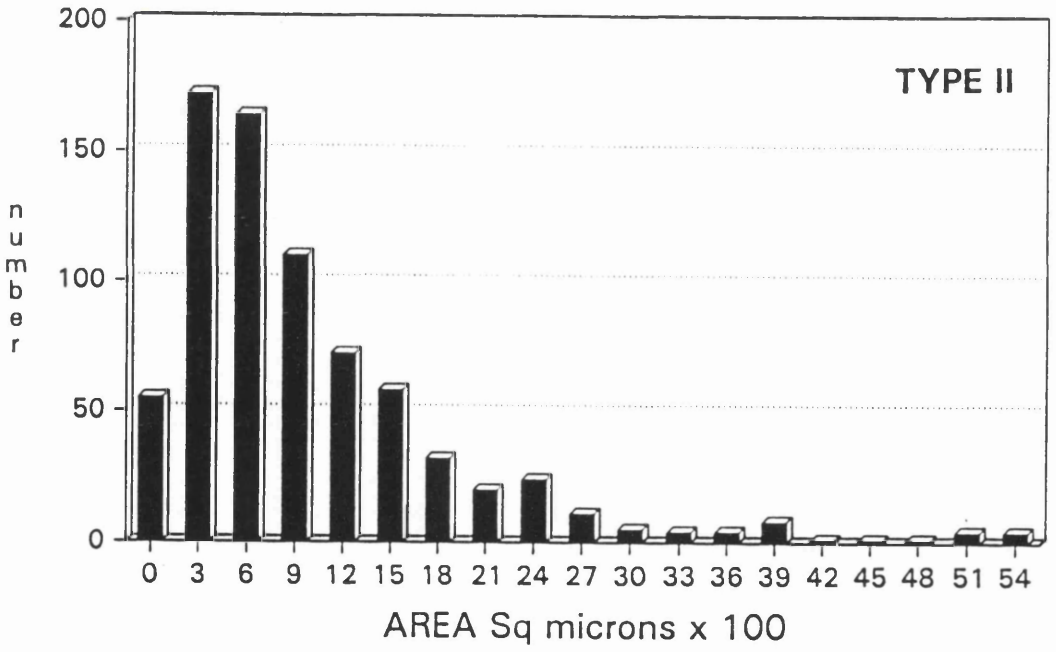
20 patients

Fibre area	Type IIa	Type IIb	Sig
mean	1020	1162	ns
median	629	862	
inter ¼ile	493-1138	649-1421	
Var. coeff.	882	658	
% Composition			
mean	23.3	18.5	*
SD	9.2	5.6	
SE	2.0	1.2	
95% CI	19.0-27.6	15.9-21.2	
% X-sect.area			
mean	14.8	13.7	ns
SD	median 11.4	5.2	
SE		1.2	
95% CI or inter ¼ ile	7.1 - 20.6	10.9 - 15.8	

Figure 30 - Histogram of long face group fibre areas - types I and II



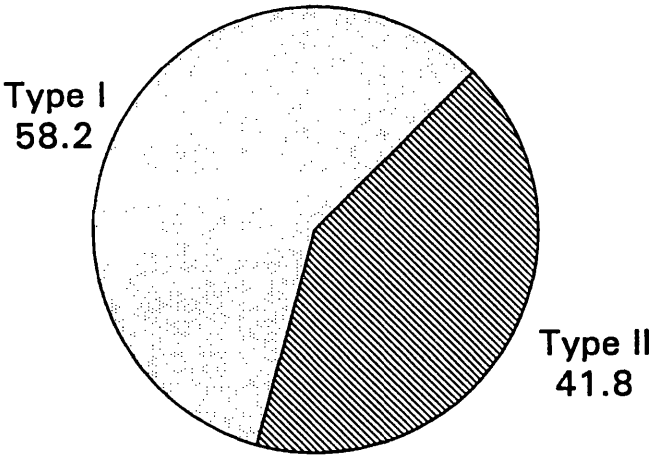
25 patients



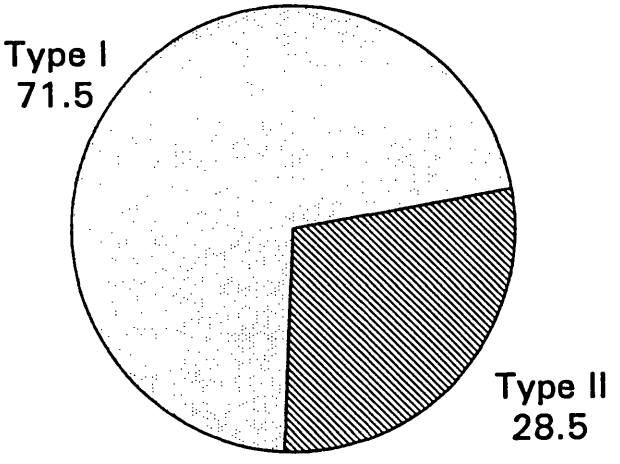
The type II fibre area was highly significantly smaller ($p \leq 0.001$) than the type I fibres.

Figure 31 - Long face group fibre percentage composition and total cross-sectional area - types I and II

FIBRE PERCENTAGE COMPOSITION

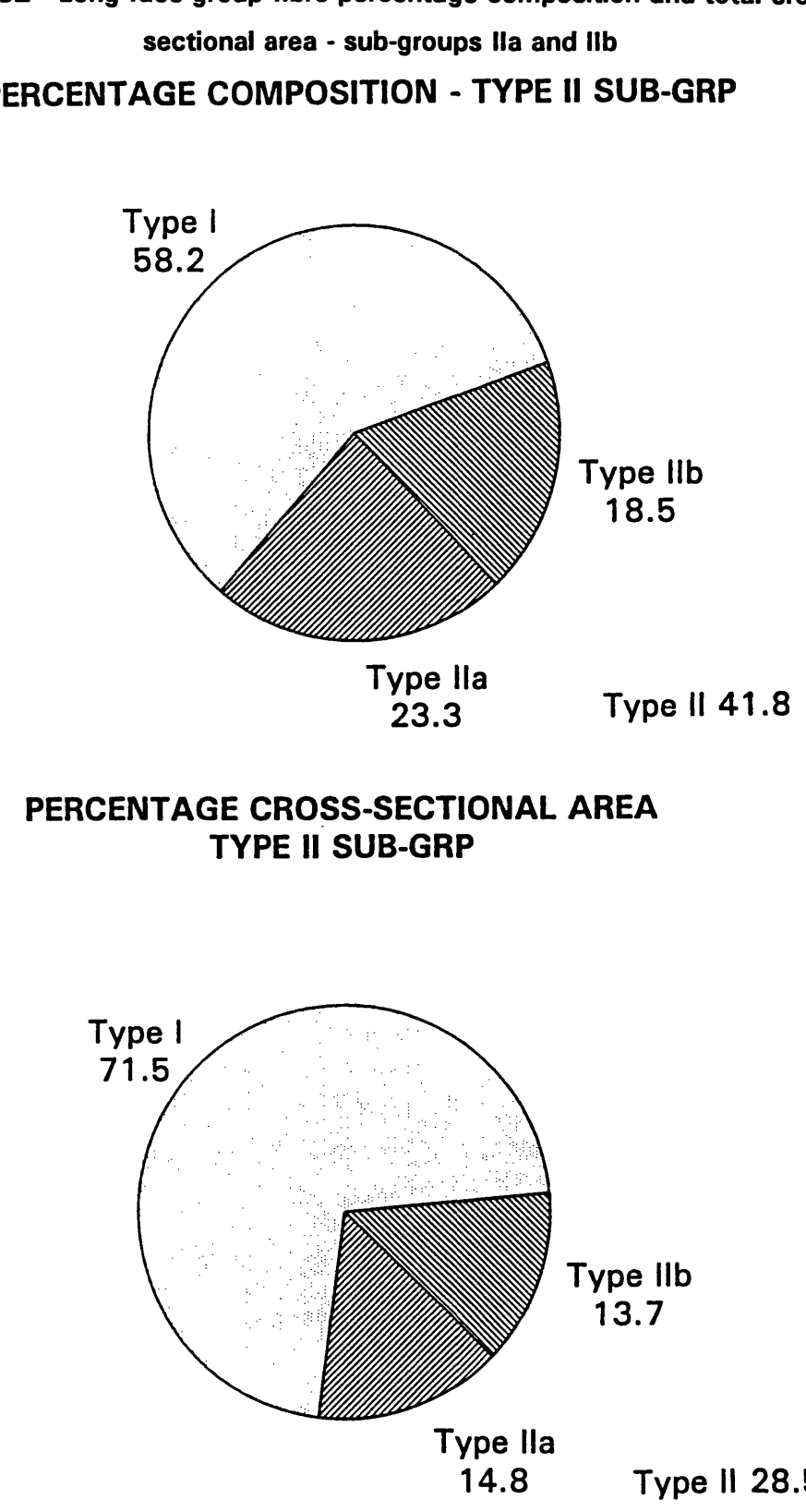


FIBRE PERCENTAGE CROSS-SECTIONAL AREA



The overall contribution of type I fibres to the percentage total fibre cross-sectional area was highly significantly greater ($p \leq 0.001$) than the type II fibres.

Figure 32 - Long face group fibre percentage composition and total cross-sectional area - sub-groups IIa and IIb



Although the type IIa fibres formed a greater percentage of the type II fibres ($p \leq 0.05$), there was no significant difference between the IIa and IIb fibres as to their respective contribution to the total fibre percentage cross-sectional area.

Table X - Comparison between control and experimental groups

	ANOVA or K-W	SF v Ctl	LF v Ctl	SF v LF
Type I area	ns	ns	ns	ns
Type II area	***	ns	***	**
Type I %	***	ns	***	***
Type II %	***	ns	***	***
Type IIa area	*	ns	*	*
Type IIb area	**	ns	**	*
Type IIa %	ns	ns	ns	ns
Type IIb %	**	ns	**	**
Type I % X-sect area	***	ns	***	***
Type II % X-sect area	***	ns	***	***
Type IIa % X-sect area	**	ns	**	*
Type IIb % X-sect area	***	ns	***	***

Key: ANOVA - Analysis of variance for parametric data

K-W - Kruskall-Wallis test for non-parametric data

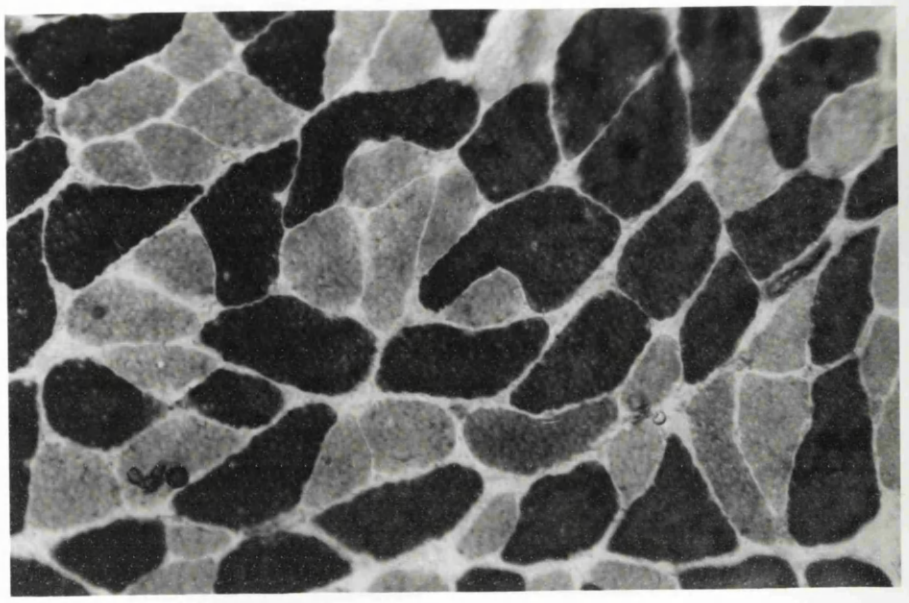
SF - Short face group

LF - Long face group

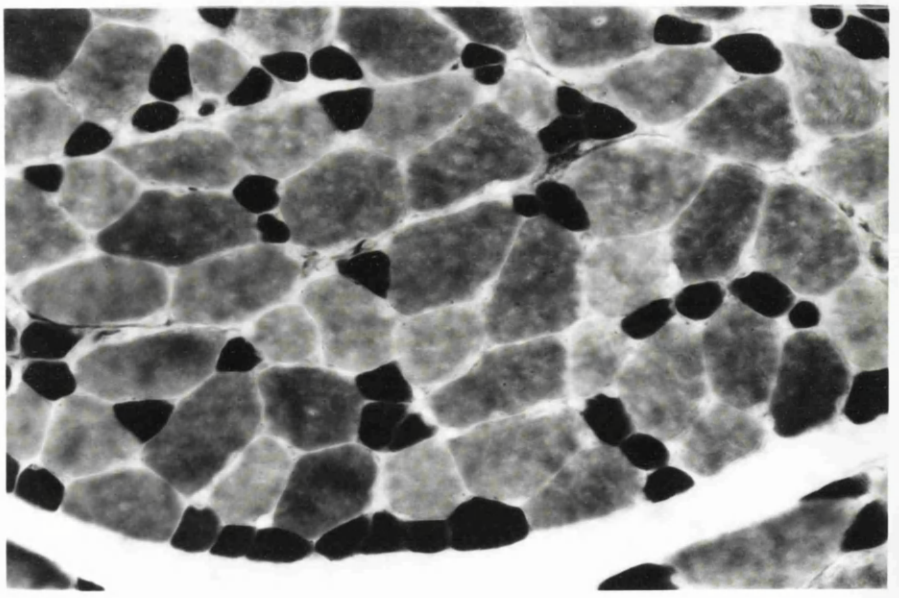
Ctl - Control group

Figure 33 - Example sections from the experimental groups (pH 9.4)

Short face sample



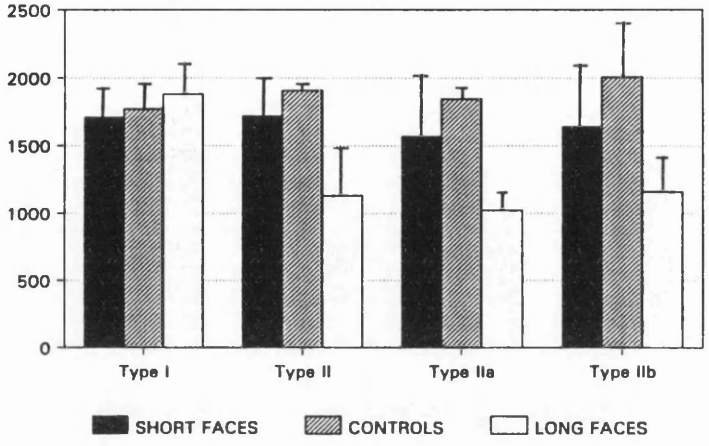
Long face sample



The short face section shows type II fibres to be present in a slightly greater proportion, whereas the long face section shows type II fibres of a highly significantly ($p \leq 0.001$) reduced size.

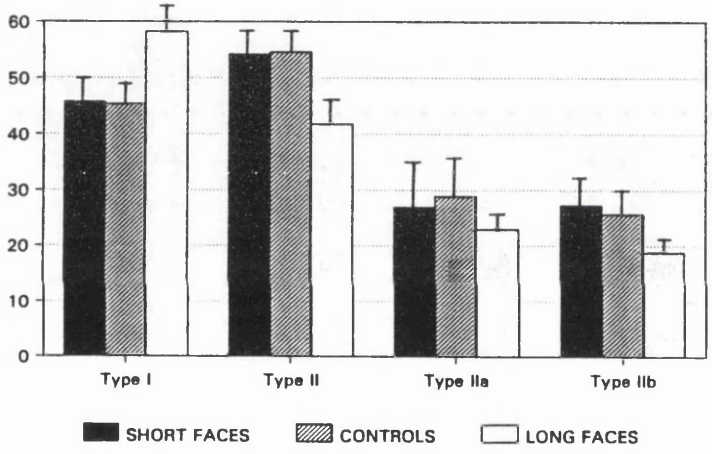
Figure 34 - Comparison of control and experimental groups

Mean fibre areas



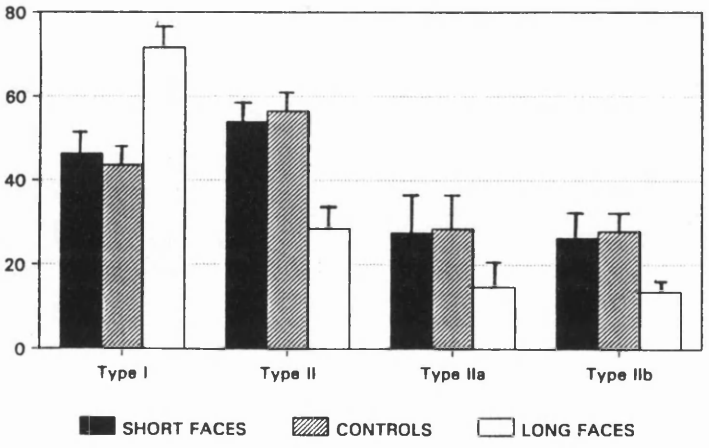
UNITS - Sq Microns

Mean fibre percentage composition



UNITS - %

Mean fibre percentage total cross-sectional area



UNITS - %

a) Short face group

Considering the type I and type II fibres, there was no significant difference in the mean areas, although the type II fibres were present in a slightly greater proportion ($p \leq 0.05$). The mean figures for fibre area, percentage composition and relative cross-sectional area were very similar to the corresponding values for the control sample.

Although the average figures for the type IIa and type IIb fibres were slightly smaller than the controls, the differences were not statistically significant. The 95% confidence intervals were large indicating the wide variation between individuals. Furthermore the variability coefficients were high indicating a wide range of fibre size within samples.

Similarly, although the percentage cross-sectional area of the type IIa fibres was reduced in comparison to the controls, individual variation was high and hence the mean differences were not significant.

Finn *et al.* (1980b) commented that the short faced patients in their study demonstrated type II fibre atrophy. Unfortunately, their figures were not quoted, nor indeed any reference as to the significance levels reached. It is, therefore, impossible to draw comparisons with the results of this study.

b) Long face group

There was a highly significant difference between the size and a moderately significant difference in proportions of both the type I and type II fibres in this sample.

The type I fibres were of comparable size to the controls and the variation in fibre area was reasonably low. This was in contrast to the type II fibres which were relatively atrophic with a mean area of 1131 sq. microns, but with a large area variability, the coefficient being 646. These results support the findings of Boyd *et al.* (1984) for biopsies taken from the same

anatomical site. However, whereas Boyd *et al.* (1984) noted that the fast glycolytic or type IIb fibres were predominantly affected, the present investigation showed both sub-groups of the type II fibres to be equally atrophic, but again with large individual variations. The percentage of type IIa fibres was not significantly different from that in the control group but the percentage of type IIb fibres was reduced to a highly significant extent. Consequently, considering the overall contribution of the type IIb fibres to percentage cross-sectional area, there was a highly significant reduction compared to both the control and short face group.

With regard to the percentage composition of fibres, the type I fibres accounted for 58.2 % of the population. This result is in contrast to the study of Boyd *et al.* (1984) who noted a 55.4 % predominance of type II fibres. Considering the mean fibre areas and their relative composition, the type I fibres in this study accounted for 71.5 % of the total fibre cross-sectional area.

When considering the relationship between muscle fibre profile and skeletal form it is important to remember the metabolic properties of the respective fibre types which constitute a specific muscle. As has been mentioned, type II fibres are capable of fast action but are easily fatigued, whereas type I fibres are responsible for more sustained activity, for example, posture. If muscle composition and activity influence facial form to any extent, it is more likely to be effected through the slow acting type I fibres rather than through the less frequently recruited type II fibres. As there was no significant difference between the experimental and control groups, the size of type I fibres *per se* cannot be important in influencing vertical facial form. However, there were highly significant differences in the contribution of type I fibres to the total cross-sectional area of the muscles, between the long faces and both the control and short face groups. The relative size and contributions of the fibres can be more easily visualized in figure 34.

With regard to the question as to why there should be a significant difference between the long faced individuals and the controls but not so for

the short faces, several answers could be considered. Firstly, it would be important to compare the relative severity of the skeletal abnormalities. The long face group may be more disparate from 'normal' compared to the short faces. Secondly, it is feasible that muscle function and efficiency is more 'normal' in the short faced individuals with a tendency towards a level occlusal plane. Conversely, subjects with high maxillary-mandibular planes angles tend to have acute angles between the long axes of the premolar and molar teeth leading to a less functionally efficient masticatory system with the generation of reduced biting forces. The results of the bite force study will help to clarify this point.

Study 4

The correlation of masseter muscle structure with facial form

It was apparent from the previous study that there were highly significant differences in the structure of masseter muscle in groups of individuals classified according to vertical facial form. The purpose of this study was to elucidate possible relationships between the aspects of muscle structure and specific features of cranio-facial form.

i) Subjects, material and method.

As mentioned in study 3, forty-two patients scheduled for orthognathic correction of facial deformities consented to a muscle biopsy at the time of surgery. The patients were all Caucasian and consisted of 17 males and 25 females with a mean age of 23.3 years (95% CI 21.52 to 25.15 yrs).

Specimen preparation and fibre quantification was as described previously with fibre classification limited to type I and II.

The cephalometric assessment was based on tracings of lateral skull radiographs taken as part of the pre-surgical preparation of the case. Linear and angular skeletal and dental variables were recorded as well as the orientations of the lines of muscle action relative to the occlusal planes. The patient sample was considered as a whole and not subdivided according to facial type, as in the previous study, for the purpose of identifying specific cranio-facial parameters which may relate to specific aspects of muscle structure.

ii) Statistical Analysis

Principal component analysis

When considering cranio-facial form it is important to realise that very few, if any, of the variables measured on a lateral skull radiograph can be

considered as totally independent. It is, therefore, important to consider associations between the collective components of form rather than individual parameters. A principal component analysis reduces the number of variables to a smaller new set of variables which are linear combinations of the original data set but which contain most of the relevant information.

A principal component analysis was undertaken on 29 of the original 32 cephalometric skeletal and dental variables, the mathematically derived facial proportions being excluded. Table XI lists the eigenvalues of the correlation matrix as well as the difference between successive eigenvalues, the proportion of the variance explained by each eigenvalue, and the cumulative proportion of the variance explained.

Table XI- Eigenvalues of the Correlation Matrix for the cephalometric variables

Principal Comp.	Eigenvalue	Difference	Proportion of variance	Cumulative proportion
#1	9.67	4.60	0.33	0.33
#2	5.07	0.51	0.17	0.51
#3	4.56	2.08	0.16	0.67
#4	2.48	0.99	0.09	0.75
#5	1.49	0.17	0.05	0.80
#6	1.32	0.08	0.05	0.84
#7	1.24	0.26	0.04	0.89
#8	0.98	0.43	0.03	0.92
#9	0.55	0.08	0.02	0.94
#10	0.47	-	0.02	0.96

It can be seen from the above that the first 6 or 7 components account for

84 and 89 % respectively of the variance, with subsequent components adding little (less than 4%) each. Subsequent analysis can, therefore, be based on the first 7 principal components as little extra information is likely to be gained by adding the remainder.

From the table of eigenvectors (table XII) it is possible to ascertain those skeletal and dental variables which, in the presence of the other variables, act as the major contributors to variations in facial form.

Table XII - Eigenvectors of the 7 principal components of facial form

	PRIN #1	PRIN #2	PRIN #3	PRIN #4	PRIN #5	PRIN #6	PRIN #7
SNA	-.09	.18	-.09	-.29	-.08	.19	.51
SNB	.03	.36	-.25	-.00	.00	.01	.14
SNPg	-.01	.40	-.18	-.06	-.06	-.09	.10
SN-mand	.29	-.20	-.15	.03	.00	.11	-.16
SN-max	.07	-.13	-.09	.47	.07	.17	-.47
MM	.26	-.17	-.13	-.16	-.04	.05	-.04
FMPA	.27	-.08	-.19	-.05	-.06	.10	.10
NSAr	-.11	-.20	-.12	.38	-.22	-.01	-.16
SArGo	.16	-.07	.09	-.25	.52	-.13	.06
ArGoMe	.19	-.01	-.28	.03	-.31	.21	.04
UI-max	-.11	.16	-.07	.21	.33	.48	-.09
UI-SN	-.14	.22	.04	.06	.34	.38	-.06
LI-mand	.24	.12	-.16	.07	-.05	-.16	-.33
LI-SN	.02	.35	-.04	.05	-.06	-.31	-.37
UAFH	.15	-.04	.25	-.04	.02	.38	-.21
LAFH	.31	.02	.04	.03	.02	-.02	.06
UPFH	.07	.07	.26	-.43	-.09	.16	-.21
LPFH	.02	.21	.26	.31	-.07	-.09	.30
TAFH	.31	.01	.12	.02	.02	.11	-.03
TPFH	.06	.21	.38	-.06	-.12	.03	.08
UADH	.26	-.08	.15	-.08	-.10	.03	.01
UPDH	.28	.09	.04	.01	-.10	.10	.04
LADH	.21	-.08	.16	.17	.10	-.01	.29
LPDH	.15	-.09	.22	.13	.18	-.30	.27
ML	.23	.26	.07	.09	-.10	.07	-.08
Ramus	.01	.20	.32	.08	-.33	.13	.02
Body	.18	.23	.11	.09	.34	-.15	-.17
OJ	-.15	-.18	.23	-.15	-.12	.04	-.09
OB	-.24	-.05	.18	.00	-.10	.02	-.13

The first principal component shows the highest positive loadings for 8 variables: SN-mand. plane, Max.- mand. plane, Frankfort-mand.plane and lower incisor - mand. plane angles; both lower and total anterior face heights and the upper anterior and posterior dental heights. There is also an important negative loading related to the extent of the overbite. These factors can, therefore, be considered as a general index of the vertical relationship of the mandible to the base of the skull.

The second component gives the highest weightings to the angles SNB, SNPg and SN - lower incisor as well as mandibular length. These factors can be considered as representative of the antero-posterior relationship of the mandible to the base of skull.

The third component shows the highest weightings for upper, lower and total posterior face heights as well as ramus height and upper anterior face height. All five of these variables have a positive loading whereas there are also important negative loadings for size of the gonial angle . These results give an index of the vertical relationship of the posterior part of the mandible.

The fourth principal component introduces the vertical relationship of the maxilla, whilst the fifth and sixth components stress the posterior facial angles and the position of the teeth in the overall pattern of facial form.

It is also important to appreciate that if a large number of correlations are being considered simultaneously then at a significance level of 5%, for example, 5 out of every hundred individual correlations will appear significant by chance. The canonical correlation procedure was adopted in this study in an attempt to reduce the possibility of chance significant findings.

Canonical Correlation Analysis

Canonical correlation is a technique for analyzing the relationship between several *x* variables and several *y* variables simultaneously. In the first part of this study the first seven principal components of facial form were correlated with the histological variables of fibre areas, percentage distribution and overall cross-sectional area. The three mathematically derived variables excluded from the principal component analysis were also correlated with the histological variables.

iii) Results

The relationship between the principal components of facial form and muscle structure

The linear correlations between the first seven principal components of cranio-facial form and the individual variables of masseter muscle structure were generally low, with the exceptions of the relative percentage of the total cross-sectional fibre area (+0.62 for type I, -0.62 for type II).

The first and second canonical correlations were 0.82 and 0.67,both of which were higher than the linear correlations between the variables. The first canonical coefficient was significant at the $p \leq 0.01$ level, whereas the second and all that followed were not significant.

Examination of the standardized coefficients indicated that the first canonical variable for the cranio-facial variables was primarily weighted in favour of the first principal component,which has been shown previously to represent the relationship of the mandible to the base of the skull in the vertical dimension. Similarly, the first canonical variable for the muscle structure variables was heavily weighted towards the percentage fibre total cross-sectional areas, over and above the other individual variables. The canonical structure indicated that the percentage total cross-sectional area of type II fibres was a suppressor variable meaning that the greater the

Table XIII - Correlation coefficients between the principal components of facial form and muscle structure

	Area I	% I	Total I	Area II	Total II	% X-sect. area
PRIN#1	0.12	0.37	0.35	-0.40	-0.52	-0.62
PRIN#2	0.03	-0.13	-0.02	-0.09	0.05	0.05
PRIN#3	0.07	-0.28	-0.01	0.12	0.22	0.23
PRIN#4	0.12	-0.37	-0.14	0.15	0.23	0.24
PRIN#5	0.08	0.04	0.12	0.21	0.14	0.11
PRIN#6	0.07	0.09	0.08	0.06	0.03	-0.06
PRIN#7	-0.05	0.12	-0.01	-0.06	-0.08	-0.08

Canonical correlations

	Canon. Coeff.	Coeff.^{2}	Eigen.	Sig.	Prop^n. of var. of form expl^d.	Prop^n. of var. of muscle expl^d.
1st.	0.82	0.67	2.07	**	0.10	0.19
2nd.	0.67	0.43	0.76	ns	0.16	0.30

Canonical redundancy analysis - Squared multiple correlations

	Area I	% I	Total I	Area II	% II	Total II	% X-sect I	% X-sect II
1st canon. variable of facial form	0.01	0.13	0.11	0.15	0.13	0.25	0.37	0.37
	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7	
1st canon. variable of muscle	0.60	0.01	0.00	0.02	0.02	0.00	0.03	

contribution of the type I fibres to the total fibre cross-sectional area of the muscle, the greater the tendency towards a long face form.

The canonical redundancy analysis showed neither of the first pair of variables was a good overall predictor of the opposite set, the proportions of the variance explained being 0.10 and 0.19. The squared multiple correlations showed that the first canonical correlation for the muscle variables was a good predictor of anterior vertical facial form (60%) but was somewhat meaningless in terms of prediction of the other facial dimensions including, somewhat surprisingly, the third principal component ie. the relationship between the posterior part of the mandible and the cranial base. These results are supported by the simple correlation coefficients between the percentage total cross-sectional area of the type I and II fibres and the percentage anterior and posterior facial heights (table XIV).

Breaking the first principal component of facial form down into its constituent elements showed that the canonical variable of muscle structure could be considered a predictor as follows:

SNmand.	51%
MM	65%
FMPA	44%
LI mand.	29%
LAFH	56%
TAFH	48%
UADH	46%
UPDH	46%

The variables constituting vertical form were, however, relatively poor predictors of muscle structure (37%).

Table XIV - Linear correlations with the mathematically derived measures of vertical form, together with their significance.

	%LAFH	%LPFH
Type I area	0.01	0.04
Type I %	0.41 **	-0.35 *
Total type I	0.26	-0.21
Type II area	-0.36 *	0.17
Type II %	-0.42 **	0.35 *
Total type II	-0.50 ***	0.26
% Total X-sect area type I	0.57 ***	-0.31 *
% Total X-sect area type II	-0.57 ***	0.31 *

In the second part of the study the histological variables were correlated with the orientation of masseter muscle relative to the occlusal planes and finally the masseter and temporalis muscle orientations were related to the principal components of facial form.

The relationship between masseter muscle structure and the orientation of masseter muscle relative to the occlusal planes.

The linear correlations between the structure and orientation variables were low to moderate with the highest being 0.61 between the angulation of the muscle relative to the lower occlusal plane and the relative contribution of the type I and II fibres as a percentage of the total fibre cross-sectional area.

The first canonical correlation was slightly higher at 0.68, which was significant ($p \leq 0.01$). The standardized coefficients were heavily weighted towards percentage cross-sectional area for the structural variables and LOPMASS as was to be expected from the linear correlation results. The incidence of type I fibres, the size , incidence, total fibre cross-sectional area and percentage of the total cross-sectional area of the type II fibres, all acted as suppressor variables. Similarly , UOPMASS was a suppressor variable for the orientation variables.

Overall, only 22% of the variation in muscle structure could be predicted from the orientation of the muscle.

The relationship between the masticatory muscle orientations and facial form.

Linear correlations between the principal components of cranio-facial form and the orientations of the muscles of mastication showed large variation but the three highest values were 0.72 (Prin 1 vs LOPMASS), 0.69 (Prin 1 vs LOPAT) and 0.54 (Prin 1 vs LOPPT). The first canonical correlation was higher than the individual linear coefficients at 0.85, which was highly significant ($p \leq 0.001$). The standardized coefficients showed that the first canonical variable for the muscle orientations was a weighted difference for UOPMASS and LOPPT subtracted from LOPMASS, and the canonical structure indicated that both UOPMASS and LOPPT were suppressor variables. The redundancy analysis showed that the percentage of the

Table XV - Correlation coefficients between masseter muscle orientation and the muscle structure

	UOPMASS	LOPMASS
Area I	0.16	0.01
% I	0.20	0.48
Total I	0.23	0.29
Area II	-0.30	-0.37
Total II	-0.33	-0.51
% Total X- sect. area II	-0.42	-0.61

Canonical correlations

	Canon. Coeff.	Coeff.^{2}	Eigen.	Sig.	Prop^n. of var. of struct. expl^d.	Prop^n. of var. of orient^n. expl^d.
1st	0.68	0.46	0.86	**	0.22	0.28
2nd	0.45	0.21	0.26	ns	0.24	0.36

Canonical redundancy analysis - Squared multiple correlations

	Area I	% I	Total I	Area II	% II	Total II	% X-sect. I	% X-sect. II
1st canon. variable of orientation	0.00	0.29	0.08	0.12	0.29	0.26	0.37	0.37
	UOP MASS	LOP MASS						
1st canon. variable of structure	0.14	0.42						

Table XVI - Correlation coefficients between the muscle orientation angles and the principal components of facial form.

	UOPMASS	LOPMASS	UOPAT	LOPAT	UOPPT	LOPPT
PRIN #1	0.47	0.72	0.42	0.69	0.18	0.54
PRIN #2	0.07	0.03	-0.31	-0.22	-0.10	-0.11
PRIN #3	-0.23	-0.32	-0.15	-0.26	-0.27	-0.33
PRIN #4	0.02	0.06	0.03	0.07	-0.01	0.10
PRIN #5	-0.21	0.04	-0.09	0.14	-0.31	0.01
PRIN #6	-0.09	0.04	-0.03	0.09	-0.26	-0.10
PRIN #7	0.05	0.07	0.15	0.13	0.18	0.24

Canonical correlations

	Canon. Coeff.	Coeff.^{2}	Eigen.	Sig.	Prop^n. of var. of form expl^d.	Prop^n. of var. of angle expl^d.
1st	0.85	0.72	2.59	***	0.10	0.32
2nd	0.58	0.34	0.52	ns	0.15	0.42

Canonical redundancy analysis - Squared multiple correlations

	UOP MASS	LOP MASS	UOP AT	LOP AT	UOP PT	LOP PT	
1st canon. variable of facial form	0.19	0.59	0.18	0.60	0.02	0.35	
	PRIN1	PRIN2	PRIN3	PRIN4	PRIN5	PRIN6	PRIN7
1st canon. variable of muscle orientation	0.57	0.00	0.09	0.00	0.03	0.02	0.00

orientation angles explained by overall facial form was 32% whereas the amount of overall form explained by the angles was only 10%. In terms of prediction, the first canonical variable could predict 57% of vertical facial form, but no other aspect of form. The first canonical variable of form was a reasonable predictor of the LOPMASS (59%) and the LOPAT (60%).

Study 5

The response of masseter structure to orthognathic surgery

Advances in surgical technique have greatly enhanced the likelihood of the bony relationships remaining stable following orthognathic correction of facial deformity. Similarly, whilst it is now well recognised that certain movements of the mandible and/ or maxilla are more stable than others, there still remains instances where the position and relationships of the skeletal elements fail to respond in an expected manner following surgery. This includes cases where, despite an anticipated favourable surgical change, relapse is seen to occur in the post-operative period, or alternatively, cases which exhibit remarkable stability despite an anticipated unfavourable surgical movement.

The exact cause for these inconsistencies remains the subject of conjecture but several factors have been cited including variations in surgical technique, the extent of the surgical movement and the method of skeletal fixation employed.

It is generally agreed that whenever surgery changes the skeletal relationships, the muscles related to those skeletal elements must adapt to those relationships. As has already been discussed, muscle adaptation can occur through several different ways. Included in these is an alteration in the muscle fibre profile (Carlson and Poznanski, 1982).

As discussed on page 84, the study by Bell in 1985 represents the only

report to date which has investigated the changes occurring in human masseter structure following orthognathic surgery, and this was based on a sample of only five patients. It was considered,therefore, that further information was required in order to improve our understanding of surgical stability.

Table XVII - Details of patients involved in the follow-up biopsy study.

	Number (n)	Age (yrs) mean	Age (yrs) 95% CI	Review period (yrs) mean	Review period (yrs) 95% CI
Total	12	22.3	19.2 to 25.4	1.0	1.0 to 1.1
Males	7	22.8	18.1 to 27.6	1.0	0.9 to 1.1
Females	5	21.5	15.4 to 27.6	1.1	0.9 to 1.2

i) Subjects, material and method

12 patients who had previously agreed to a muscle biopsy at the time of corrective surgery consented to a repeat biopsy approximately one year later. The details of the patients are shown in table XVII. All patients were from the original long face group and underwent surgery designed to reduce the overall skeletal vertical dimension. Surgery in all cases consisted of a Le Fort I procedure combined with a sagittal split osteotomy of the mandible to either produce or maintain a class I occlusion. All patients were put in inter-maxillary fixation for a period ranging from 6 to 8.5 weeks. The repeat biopsies were carried out under local anaesthesia but care was taken to ensure that the nerves were blocked at a point some distance from the biopsy site. The biopsy was removed from a part of the muscle as close to the original site as possible, but purposefully avoiding any obvious scar

tissue.

The samples were processed and measured in the same manner as previously described but improvements in technique now led to a reliable recognition and quantification of those fibres described as being of an Intermediate type. For comparison purposes sections from the pre-operative blocks, which had been stored in liquid nitrogen were recut, processed and measured. The preparation of all the sections for this study was undertaken by Miss A. Geraerts of the Metabolic Unit at University College Hospital, London. All measurements were undertaken by the author.

ii)Results

Examination of the pre-operative fibre profiles of the twelve patients confirmed the results of study 3, in that the size of the type I fibres was generally larger than the type II fibres, bearing in mind that all patients belonged to the long face group. Unlike study 3, Intermediate fibres were classified in their own right rather than according to their most closely allied fibre type. Consequently, the percentage distribution of fibres pre-operatively was at variance to that shown in the earlier study. As can be seen from tables XVIII and XIX, the incidence of Intermediate fibres was variable with a range from 2 to 21 %, and appeared to be at the equal expense of both the type I and II percentages noted in study 3.

Table XVIII - The mean figures for fibre area, percentage distribution and percentage of the total cross-sectional area before and after surgery

	Pre-op				Post-op			
	mean	SD	SE	95% CI	mean	SD	SE	95%CI
AREA (Sq. microns)								
Type I	1831	358	103	1603 to 2058	1532	294	85	1345 to 1719
Type II	1296	751	217	818 to 1773	1327	699	202	883 to 1771
Type IM	1440	386	111	1195 to 1685	1453	359	104	1240 to 1698
% Composition								
Type I	51.5	6.1	1.8	47.6 to 55.4	55.0	4.9	1.4	51.9 to 58.1
Type II	37.0	7.1	2.0	32.4 to 41.4	41.0	5.5	1.6	37.4 to 44.3
Type IM	12.0	6.1	1.8	7.7 to 15.5	4.0	2.3	0.7	2.6 to 5.6
% X- Sect". area								
Type I	60.7	13.9	4.0	51.9 to 69.5	59.8	13.7	4.0	51.1 to 68.5
Type II	29.1	14.3	4.1	20.0 to 38.1	36.2	13.8	4.0	27.4 to 45.0
Type IM	10.3	5.4	1.6	6.8 to 13.8	4.0	1.8	0.5	2.8 to 5.1

Table XIX - The percentage distribution of fibre types before and after surgery

	Type I		Type II		Type IM	
Patient no.	**Pre-**	**Post-**	**Pre-**	**Post-**	**Pre-**	**Post-**
1	55	52	43	46	2	2
2	54	60	29	36	17	4
3	57	58	36	40	7	2
4	53	61	28	37	19	2
5	40	50	39	44	21	6
6	52	54	40	43	8	3
7	43	46	51	51	6	3
8	42	48	42	48	16	4
9	54	58	39	39	7	3
10	56	58	30	33	14	9
11	57	57	28	35	15	8
12	55	58	38	39	7	3
Overall means	**51**	**55**	**37**	**41**	**12**	**4**

The effects of surgery on the fibre profile was marked, with large variations both within and between individuals. It is noticeable, however, that in all cases, surgery was associated with a reduction in type I fibre area, with a range of approximately 4 to 45 % of the original size. Bearing in mind that all patients had bimaxillary surgery, these results partially support the findings quoted by Bell (1985) who noted a reduction in type I fibre area in one of the three patients operated upon for vertical maxillary excess.

Type I fibre atrophy can represent both a physiological or pathological change. Examination of the sections in this study failed to show any evidence of loss of cell architecture of the muscle fibres, such as angular fibres or fibre clumping indicative of atrophy of neurogenic origin as may occur, for example, following denervation and reinervation. In one or two cases there was some evidence of localized phagocytic infiltration apparent on the haematoxylin and eosin slides but this remained a minor observation. More commonly type I fibre atrophy occurs as a result of reduced activity. This has been reported in several studies including immobilization of human limbs (for example Sargent *et al.,* 1977; Sale *et al.,* 1982) and in the muscles of mastication in monkeys following intermaxillary fixation (Mayo *et al.,* 1988) or rendering them edentate (Maxwell *et al.,* 1980). Furthermore, it has been shown that the atrophic process accelerates if the muscle is immobilized at a length shorter than its resting length (Tabary *et al.,* 1972).

The magnitude of the mean reduction in size of the type I fibres was approximately 16 %, which was significant at the $p \leq 0.05$ level, but the range was large. It is feasible that this may represent a variation in the length at which the muscle was immobilized during fixation and the corresponding reduction in facial height with the muscle acting at a length less than its original resting length. To test this hypothesis, the reduction in area was correlated with two previously established cephalometric variables; the changes in ramus height and total posterior face height occurring at surgery. The correlations were only moderate at 0.42 and 0.57 respectively indicating that the change in posterior skeletal dimension was only associated with 17 and 32 % of the type I atrophy.

The percentage distribution of type I fibres decreased in one patient, remained static in one patient but increased in the remainder. Overall the percentage of type I fibres increased on average by 4 %. As this tended to offset the reduction in fibre size, the contribution of the type I fibres to the total fibre cross-sectional area did not change to any significant extent. These results are at variance to those of Bell (1985) who noted an average

reduction of 15 % of type I fibre percentage cross-sectional area.

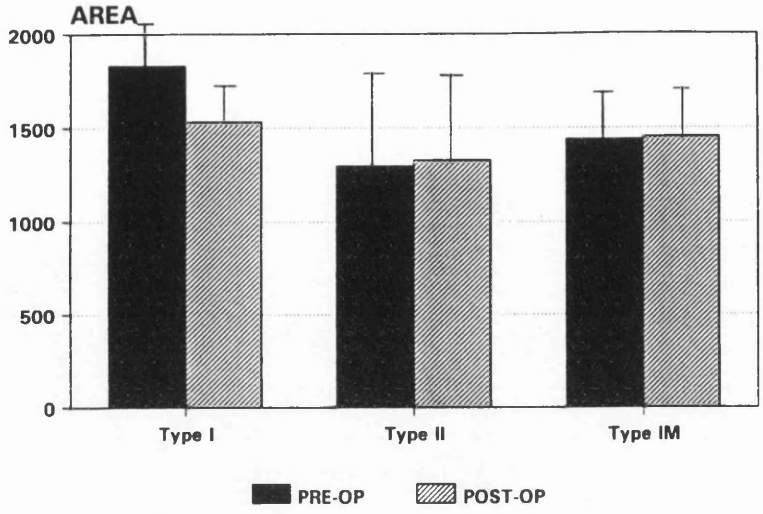
At first glance it would appear that the results are also in disagreement with the findings of Mayo *et al.* (1988) in their study of monkeys following surgery and intermaxillary fixation, who reported that type I fibres accounted for up to 75% of the cross-sectional area at the end of the experimental period. It should be noted, however, that unlike the present study, Mayo *et al.* classified those fibres with intermediate ATPase activity as type I fibres.

With regard to Intermediate fibres it is interesting to note that not only did they hold a variable presence pre-operatively but that their incidence dropped in all but one of the cases following the review period. Their overall contribution to the percentage cross-sectional area dropped on average from 10 % to 4 % with virtually no change in fibre size.

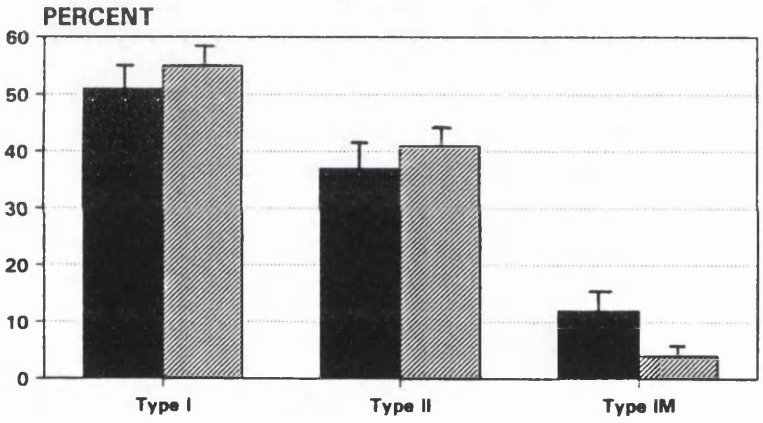
The response of the type II fibre areas was far more variable both in magnitude and direction. The range was large with one patient showing a mean reduction in area of almost 42 % of the pre-operative size whilst another patient showed fibres which had increased in size by over one and a half times the original area.

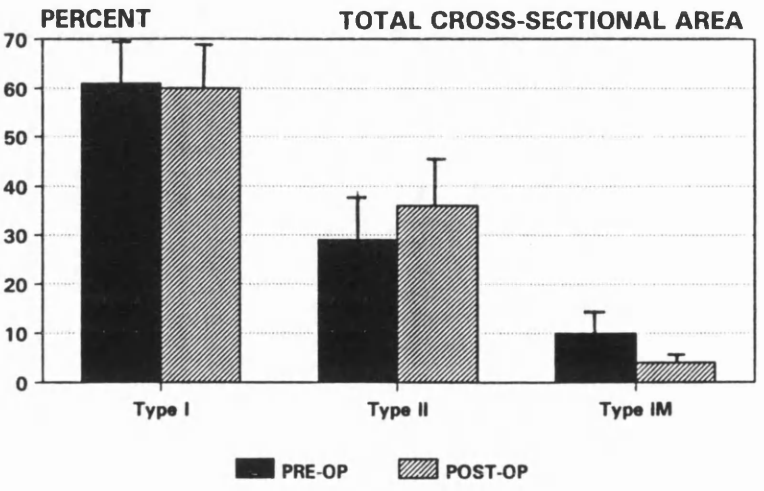
Considering the group as a whole, the mean change was neither clinically nor statistically significant. The mean percentage composition, however, showed an increase from 37 to 41 % with the effect that the overall percentage contribution to the fibre cross-sectional area also increased from 29 to 36 %. In view of the variation in response within a sample of this size it is not surprising that the overall difference in total cross-sectional area was not significant.

Figure 35 - The change in fibre areas, incidence and percentage total cross-sectional area following surgery.



UNITS -Sq microns



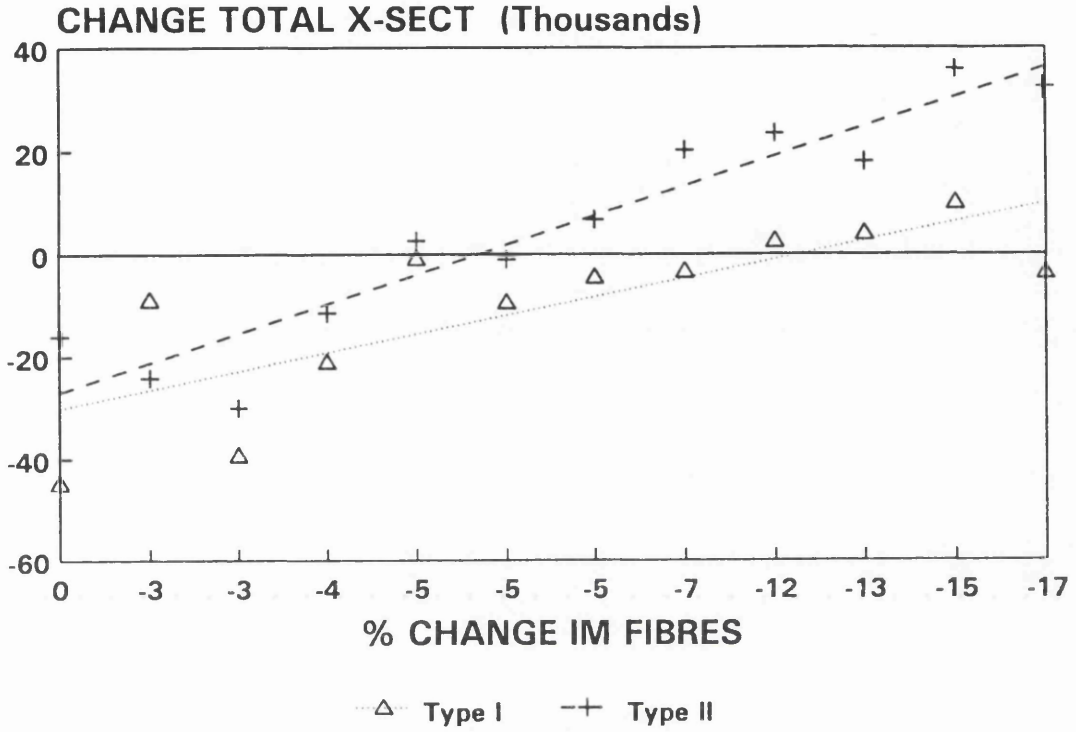


It is apparent from the results that the masseter muscles have adapted following surgical intervention but in a varied manner. In some instances the change in metabolic profile has been favourable with the muscles more closely resembling the pattern seen in subjects with more normal skeletal relationships, whereas in other cases the changes must be considered as undesirable. It is interesting to speculate why and how this variation might occur.

The exact role of Intermediate fibres has yet to be established. Ringqvist (1974b) observed a greater proportion of Intermediate fibres in individuals with abnormal jaw relationships and hypothesized that these fibres were associated with abnormal function of the masticatory muscles. Considering those variables established through the principal component analysis of the previous study as being important with regard to abnormal skeletal and dental relationships in the vertical dimension and giving the patients a weighted loading governed by the extent that those variables vary from 'normal' figures, then there appears to be little, if any, association between the severity of the skeletal abnormality and the incidence of Intermediate fibres (r = -0.07). It is unlikely, therefore, that the incidence of Intermediate fibres is necessarily associated with muscles that are functioning in an abnormal manner as a result of the relationship of the bony attachments, although this point will require further clarification through the muscle function studies.

A more recent view is that Intermediate fibres may represent immature fibres capable of adaptation into mature fibre types depending upon functional needs, and the evidence from this study goes some way towards supporting this concept. Figure 36 gives a plot of the percentage change in the incidence of Intermediate fibres compared with change in cross-sectional area of both the type I and II fibres over the review period. The individual correlation coefficients were -0.72 and -0.89 respectively for the type I and II fibres, both of which were highly significant ($p \leq 0.001$). It would appear, therefore, that the ability of the muscle to adapt may to some extent depend upon the presence of a proportion of Intermediate fibres initially.

Figure 36 - Plot of the change in percentage incidence of Intermediate fibres with the change in total X - sectional area of type I and type II fibres.



Both type I and type II fibres are involved in the adaptive process although in this sample the greater change was observed in the type II group. If, as has been suggested the type I fibres serve primarily a postural role then it is feasible that additional mature fibres are present to combat the atrophy which may occur through reduced mandibular movement so as to maintain the postural relationship. It would be expected that this should be far more important in situations where surgery produces an increase in muscle resting length but unfortunately such a sample was unavailable to test this hypothesis. Further information should help clarify this point following the studies of muscle function in the succeeding chapters.

The need for the type II fibres to increase in number and the increase in their contribution towards the total muscle fibre cross-sectional area may be as a result of improved masticatory function following surgery. Again, the non-

invasive muscle function studies which are to follow should throw further light on this hypothesis.

Further evidence as to the importance of Intermediate fibres in muscle adaptation was obtained from the data relating the incidence of these fibres to the stability of the surgical result. Table XX lists the response of the Intermediate fibres to the surgical change of total posterior facial height and its subsequent stability one year later. The correlation coefficient between the percentage surgical relapse and the incidence of Intermediate fibres prior to operation was −0.94, which was highly statistically significant ($p \leq 0.001$).

Figure 37 - A plot of the percentage relapse of TPFH against the incidence of Intermediate fibres pre-operatively.

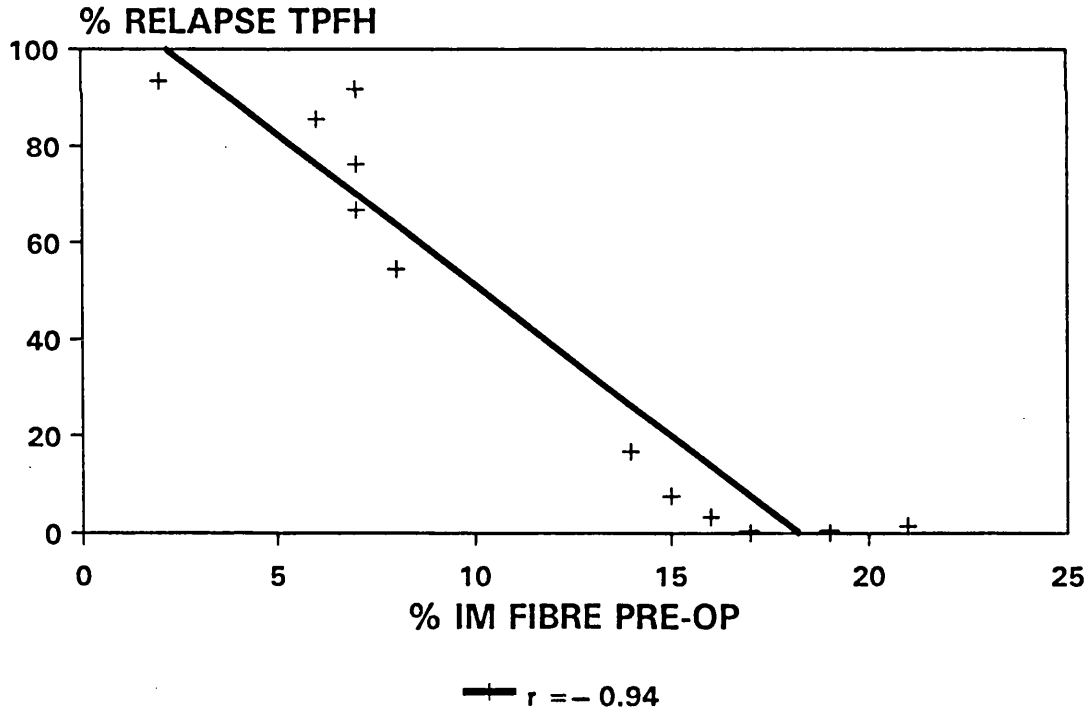


Table XX - The incidence of Intermediate fibres prior to surgery, the response to the surgical change of total posterior face height and the percentage skeletal relapse.

Patient no.	% Incidence IM fibres pre-op	Change in TPFH	Relapse of TPFH	% Relapse of TPFH
1	2	-1.5	1.4	93.3
2	17	-5.2	0	0
3	7	-6.3	4.8	76.2
4	19	-1.3	0	0
5	21	-7.2	0.1	1.4
6	8	-1.1	0.6	54.5
7	6	-6.2	5.3	85.5
8	16	-6.3	0.2	3.2
9	7	-0.9	0.6	66.7
10	14	-1.2	0.2	16.7
11	15	-4.0	0.3	7.5
12	7	-1.2	1.1	91.7

Correlation between the incidence of Intermediate fibres pre-operatively with the % surgical relapse =-0.94.

Discussion of the histochemistry studies

Prior to embarking upon the studies of the human masseter muscle fibre structure, it was essential to establish a reproducible and reliable histochemical staining technique which allowed morphometric analysis. Fibre typing using the myofibrillar ATPase staining reaction with subsequent measurement using the MOP-1 system proved both reproducible and reliable with a very acceptable overall method error. At the time the experimental protocol was being devised there was considerable uncertainty within the literature as to whether fibres with an intermediate staining intensity under alkaline conditions should be considered within their own right. In the initial studies such fibres were therefore included in the most closely allied fibre group in accordance with other workers. With greater experience it was possible to reliably classify Intermediate fibres as a distinct fibre group. The recent development of immunocytochemical techniques employing antibodies to fast, slow and neonatal myosins may help to further clarify the picture.

When describing the fibre profile of the human masseter muscle it is essential to be specific as to the anatomical source of the biopsy, since variations in both the size and incidence of fibre types occur between regions. Study 1 has shown that, for the muscle examined, the size of both the type I and type II fibres was reduced in the superficial aspect of the superficial bundle in comparison to the deeper regions. However, within the deeper regions themselves (the deep aspect of the superficial fibres and the deep fibre group) the results were remarkably consistent with no significant difference between the biopsy sites. A single biopsy from the deeper regions can therefore be considered as representative of the fibre profile of those regions which constitute by far the majority of the muscle mass.

The histochemical studies described have been based upon the largest sample of human masseter muscle biopsies reported to date. The results of study 2 would indicate that individuals with relatively normal cranio-facial form show a masseter muscle structure whereby type I and type II fibres are

approximately equal in size, at least in the deeper part of the superficial group of fibres. Although the need to be precise as to the anatomical region of the muscle has been stressed, these results contradict the often quoted view of Eriksson and Thornell (1983) that type II fibres are consistently smaller than type I in all parts of the muscle. These authors also reported that type I fibres predominated in masseter muscle but in the present investigation, type II fibres were present in a slightly greater proportion than type I fibres, and overall, the type II fibres accounted for 56.4 % of the total muscle fibre cross-sectional area.

The sub-divisions of the type II fibres showed IIa and IIb fibres to be present in almost equal proportions, although the range of individual variation has been noted. These findings contradict the view of Serratrice *et al.* (1976) that type IIa fibres are rare in human masticatory muscles.

It was impossible in study 2 to make reliable observations regarding Intermediate fibres, but it would appear likely that Intermediate fibres form part of the normal fibre profile of masseter muscle. Certainly they were demonstrated in patients who presented for surgery, but their presence does not appear to be related to the extent of skeletal discrepancy as postulated by Ringqvist (1974b).

In comparison to the control subjects, Study 3 demonstrated a consistent variation in the fibre profile of patients with facial characteristics of the long face syndrome. There was a highly significant reduction in the size of the type II fibres whilst variation in fibre size within a sample was common. Unlike Boyd *et al.* (1984), the type II fibre atrophy did not appear to be specific to one particular sub-type, with both IIa and IIb fibres affected. The incidence of type II fibres was also significantly less than for the control group, and as a consequence type I fibres accounted for 71% of the total fibre cross-sectional area.

Study 4 was designed to further investigate the possible relationship between muscle structure and facial form by attempting to identify specific

groups of cranio-facial measurements which correlated with the muscle fibre profile. The correlations between those groups of variables which represented vertical facial form and the individual measures of muscle fibre size and incidence were low, and in agreement with Shaughnessy (1986). However, when the percentage fibre total cross-sectional area was included, there were highly significant correlations such that the greater the contribution of type I fibres to muscle structure, the greater the tendency towards a long face form, confirming the results established in the previous study. The correlations relating to variables representing other aspects of facial morphology, including the antero-posterior and the posterior vertical jaw relationships, were low and of neither statistical nor clinical significance.

One important outcome of the canonical correlation analysis was that the muscle variables were reasonably good predictors of anterior vertical facial form, but the vertical form variables were relatively poor predictors of muscle structure. Although the question as to whether skeletal form affects muscle structure and function or whether form is secondary to structure and activity remains unanswered, these findings would tend to suggest that muscle structure and /or activity may be important in determining one specific aspect of facial shape. Certainly it would appear unlikely that the abnormal relationship of the muscle attachments directly affect the muscle structure.

It was mentioned in study 3 that one possible explanation as to why type II fibre atrophy occurred in the long face group, whereas the short face group failed to show any significant difference in fibre structure, was perhaps related to the efficiency of the occlusion through the mechanical relationship of the muscle to the occlusal planes. The correlation analysis between the orientation of the masseter muscles and their structure, reported in study 4, however, failed to demonstrate such a relationship.

The results of the correlation between the muscle orientation angles and facial form in many ways proved the obvious, in that if the origins and insertions of the muscles move as a result of abnormal facial form, then this

would inevitably affect the relationship of the muscle to the occlusal planes. It was interesting to note, however, that the orientation angles were reliable predictors of form in only the vertical, and no other dimension.

The metabolic properties of the different fibre types are such that type II fibres are capable of fast action but are relatively easily fatigued, whereas type I fibres are responsible for more sustained activity. If the hypothesis is true that an alteration in the shape of a bone, and possibly its relationship with other structures, is brought about through prolonged and continuous, rather than short, sharp intermittent forces acting upon it, then it is more likely to be the slow but less easily fatigued type I fibres which are of importance.

The results of these studies have indicated that the variations occurring within the muscle fibre structure are principally within the type II fibre population. Two conclusions can therefore be formed; either, that the above hypothesis is incorrect, or, that it is the relative contribution of the fibres to the total fibre cross-sectional area which may influence at least the anterior vertical form of the face.

Study 5 included the largest reported sample to date of patients willing to provide a follow-up biopsy subsequent to orthognathic surgery designed to reduce the vertical face height. It was evident that muscle adaptation occurred following surgery but in a varied manner.

One consistent finding was that type I fibre atrophy was evident one year following the operation, possibly due to the immobilization during the period of intermaxillary fixation and the subsequent muscle activity occurring at a length less than its pre-operative resting length. However, the correlation of the reduction in fibre area with the change in posterior face height was 0.57, indicating that the surgical change was only associated with 32% of the fibre atrophy.

The reduction in type I fibre size was, to a large extent, offset by the

increase in fibre incidence, such that there was no significant change in the total type I fibre cross-sectional area. Although the type II fibres showed a mean increase in both size and incidence, the results did not reach the level of statistical significance due to the large variation between patients from a relatively small sample size.

As discussed, the results could possibly implicate Intermediate fibres in the adaptive process, supporting the views of Butler-Browne *et al.* (1988). A relationship was certainly evident between the fall in incidence of Intermediate fibres and the increase in cross-sectional area of both type I and type II fibres. Further evidence as to their important role in the adaptive process resulted from the study of surgical relapse or stability and the incidence of Intermediate fibres. Although this aspect of the study should be repeated on a larger sample, it is interesting to speculate whether a pre-operative biopsy may be useful in predicting the likelihood of achieving a stable surgical correction depending upon the pre-operative incidence of Intermediate fibres.

Chapter 4

ELECTROMYOGRAPHY AND KINESIOGRAPHY STUDIES OF MASSETER AND TEMPORALIS MUSCLES

Electromyography

Literature review

i) Electrophysiology underlying electromyography.

When a motor unit is activated, the post-synaptic membrane of the neuro-muscular junction of each muscle fibre is depolarized. This depolarization starts in the middle of the muscle fibres at the motor end plate and spreads in both directions along the fibre. The associated movement of ions generates an electromagnetic field in the vicinity of the fibres and the potential or voltage can be detected by an electrode located in or near the field (Basmajian and De Luca, 1985). If a muscle is only very slightly active one may record the action potential of a single fibre. As muscle force increases the number of active motor units increases and the action potentials of individual fibres are no longer identifiable. Instead an interference pattern is produced that is the sum of all the action potentials (Gonyea *et al.* 1985). In human muscle the amplitude of the action potential recorded is dependent on several factors including the diameter of the muscle fibre, the distance between the active muscle fibre and the detection site, and the filtering properties of the electrode (Basmajian and De Luca, 1985).

ii) Methods of quantifying electromyography.

Møller (1966) lists seven methods of estimating the amplitude of the interference pattern but only three still merit consideration.

The first method employs graphic determination of the average peak-to-peak voltage from the interference pattern over a certain time interval. This method was suggested by Inman *et al.* (1944) and has been used by several authors including Moss and Greenfield (1965), Moss (1971, 1975a 1975b) and Pancherz (1977). The technique is only appropriate to those

activities where peak-to-peak amplitude remains constant for an adequate period of time.

The alternative methods are based upon the electronically integrated electromyogram which employs a full wave rectifier to convert all the negative voltage spikes to positive values. The signal is then passed through a filter (the integrator) so producing a smooth curve.

The second method involves continuous mean voltage recording through the average value per unit time of the area under the original wave form. Again the technique has found wide application (Ahlgren, 1966; Møller, 1966; and Zuniga and Simons, 1969).

The third method feeds the rectified wave into a capacitor which sums the total area under the original wave form and discharges automatically when its stored voltage reaches a pre-set value. Harradine (1980) claims this method to be the most accurate and comprehensive of the quantitative methods although there is no factual evidence to support this claim. Møller (1966) states that the time course of certain patterns of activity can be difficult to assess by this method but simultaneous recording of the raw interference pattern overcomes the problem. This technique has also been used in numerous studies (Ahlgren, 1966; Simpson and Richardson, 1975; and Hammond, 1984). It is this method which will be used in the present study.

iii) The relationship between quantified EMG and muscle activity

a) Isometric activity

Inman *et al.* (1952), Lippold (1952) and Angelone *et al.* (1960) have determined, amongst others, that in general the integrated EMG signal is linearly related to the amount of tension produced by the muscle during isometric contraction. Later, Møller (1966) and Ahlgren (1966) confirmed this relationship for masseter and temporalis muscles whilst loading the

mandible.

However, as Inman *et al.* (1952) pointed out the relationship is not present at extreme ranges of muscle length and Lippold (1967) drew attention to the fact that the relationship between tension and EMG activity will have a different slope at each differing initial length of the muscle.

Although the linear relationship still holds true when a muscle is fatigued (Edwards and Lippold, 1956), the relationship changes such that a given tension is associated with more electrical activity (Lippold *et al.*, 1960). Ideally therefore quantitative studies should be designed to avoid fatigue.

Visser and De Rijke (1974) studied the influence of sex and age on the contraction pattern of adductor pollicis muscle under isometric conditions. Although there was no difference in EMG activity at half maximum strength, generally women activate more motor units than men to produce the same contraction. Despite a slight decrease in EMG amplitude was observed with age, for the majority of parameters the decrease was not significant.

De Vries (1968) introduced the concept of "efficiency of electrical activity" (EEA) which was the slope coefficient between tension and mean EMG activity. In trained athletes the slope was flatter, that is less activity was required to produce a given tension. He suggested that EEA can be used as a measure of muscle quality.

Although structural changes in the muscle fibres are an important factor in the development of strength, a neuro-muscular adaptation leading to a more efficient use of the available motor units may be equally significant (Lenman, 1969).

b) Isotonic activity

The relationship between EMG activity and isotonic activity is of relevance when examining muscle activity during mandibular movements. Bigland and

Lippold (1954) found that a linear relationship between tension and EMG activity was maintained where the length of the muscle changed at a constant velocity. Ralston (1961) stated that unless the conditions of muscle behaviour were recorded quantitatively EMG was of little value as an accurate indication of tension since for the same tension the EMG amplitude was lower in lengthening than in shortening.

iv) Sources of variation in quantified EMG recordings

Variation in quantified EMG recordings can be related to factors concerning the electrodes and/or features of the recording system itself.

a) Type of electrode - surface or inserted.

There are various types of electrode available ranging from gold or silver disc or cup shaped surface electrodes, subcutaneous hook electrodes (Ahlgren, 1966) or platinum needle electrodes which may be either isolated or in a concentric arrangement (Adrian and Bronk, 1929).

The major advantages of surface electrodes are that they are readily available, they can be applied to the skin after very little training and they give relatively little discomfort to the subject. The disadvantages are that they may be used effectively only with superficial muscles and since they detect "cross-talk" signals from adjacent muscles, they cannot be used to detect signals selectively from small muscles.

The most common indwelling electrode is the needle electrode of which a wide variety is now available. Their main advantage is that the relatively small pick up area enables the electrode to detect individual motor unit action potentials, especially during relatively low force contractions. The major disadvantages of needle electrodes include; the pain and discomfort of insertion, problems of sterility, needle movement once in position (Ahlgren, 1966) and the phenomenon of "splinting" in which persistent or sustained involuntary contraction of the muscle may occur. Despite these

problems needle electrodes are the only ones appropriate to record deep muscle activity, for example the pterygoid muscles.

Subcutaneous hook electrodes have been advocated by Ahlgren (1966, 1970). These allow accurate and apparently painless placement, overcome skin resistance and have obvious advantages above the hairline.

Møller (1966) compared simultaneous recording using surface and needle electrodes of masseter and temporalis muscles. Similar voltages were recorded during isometric contraction.

Lenman (1969) has stressed that in integrated studies where it is important to sample as large a portion of the muscle as possible, surface electrodes prove satisfactory, whilst Basmajian and De Luca (1985) recommend surface electrodes in kinesiological and neurophysiological studies of surface muscles where characteristics of individual motor unit action potentials are unimportant.

b) Unipolar or Bipolar electrodes.

Unipolar recording techniques compare the electrical potential in or over the muscle under study with respect to a distant "reference" electrode located in an environment where electrical activity is either absent or slight but physiologically and anatomically unrelated.

The advantage of the unipolar technique is that a small number of electrodes is required which is obviously important when measuring either a large number of muscles or where access to the region of a muscle is limited, for example the region of hair-less skin overlying the anterior and posterior fibres of temporalis. The disadvantage of the technique is the diminished certainty of the origin of the recorded activity. Ahlgren (1966) noted that activity from masticatory muscles was supplemented by activity arising from the facial muscles.

The bipolar recording configuration overcomes this limitation as two electrodes are used to detect two potentials in the muscle, each with respect to a reference electrode. Any "common mode" components, for example "background noise", of the two signals are then eliminated by the recording apparatus.

The higher voltages noted by both Møller (1966) and Lenman (1969) for unipolar recordings as compared to simultaneous bipolar recordings are not surprising since not only may unipolar electrodes be supplemented by adjacent muscle activity but also there is less common mode rejection.

c) Electrode position

It is recognized that the siting of the electrode on the muscle has a significant effect on the level of activity recorded. Indeed, Liebman and Cosenza (1960) concluded that since small changes of $\pm$ 5 mm in the position of the electrodes produced such varying amplitudes of the recorded signal, quantitative recordings were of limited value.

The importance of accurate positioning of electrodes was emphasized by Buchtal *et al.* (1952) who noted that mean voltage could vary by a factor of two between sites 5mm apart. Furthermore Lippold (1967) observed a 60% change in recorded voltage with differences of 5mm in electrode position. The ability to accurately reproduce the position of electrodes relative to anatomically meaningful landmarks is an essential requirement for worthwhile quantitative electromyography.

Both Møller (1958, 1966) and Ahlgren (1966) studied the effect of bipolar electrode placement relative to the muscle fibre orientation. Whilst all three studies agree that in masseter muscle higher values are noted when the electrodes are placed parallel to the muscle fibre rather than at right angles to the fibre orientation, Ahlgren did not confirm this effect for temporalis. Unfortunately his results are only presented as raw traces with no figures but these could illustrate the greater difficulty in accurately ascertaining

fibre orientation in the temporalis muscle.

Møller (1966) investigated the effect of varying the inter-electrode distance when using the bipolar technique. His results, based upon the biceps muscle, showed an increase in the mean voltage recorded when increasing the separation up to 20 - 25 mm, with the mean voltage at 20 mm being almost double that recorded at 10 mm. Between 25 and 35 mm, the voltage increased slightly but there was almost no change detectable at greater separations. Although Ahlgren (1966) found a similar trend for masseter and temporalis he did comment that over such large distances (up to 45 mm) small variations of 1-2 mm in electrode separation were not significant and could be ignored.

d) Impedance

As stressed by Basmajianm and De Luca (1985) in order to obtain the highest quality recordings it is essential when using surface electrodes to have good electrical contact, a low skin impedance, a low electrode impedance and a high impedance amplifier. Similarly, as Møller (1966) pointed out, it is desirable to have as small a difference in impedance between a pair of bipolar electrodes as possible in order to maximize common voltage rejection.

Electrical contact is improved by the combined use of adhesive collars or discs to secure the electrodes in position and the use of a saline gel or paste retained between the skin and the electrode.

Various techniques have been suggested in order to reduce skin impedance through removing the dead surface layer of skin, along with its protective oils. Methods of skin preparation have included; rubbing the surface with alcohol and Bentonite paste (Baril and Moyers, 1960), swabbing the surface with ether (Møller, 1966) or through alcohol sponging and rubbing the skin with fine sandpaper (Harradine, 1980). With the use of high input impedance equipment, a maximum skin impedance of 10 KOhms is

considered adequate (Schanne and Chaffin, 1970). The same authors also stressed the importance of leaving electrodes in position for a few minutes prior to recording as the electrode resistance falls to a steady lower level. This phenomenon is termed "electrode ageing".

Most authors (for example, Ahlgren and Posselt, 1963; Harradine, 1980) would accept an inter-electrode impedance of 10 KOhms sufficient in view of the other sources of error in electromyography.

v) The Reproducibility of Quantitative Electromyography

The reproducibility of quantified electromyography has been exhaustively reviewed by Harradine (1980). Reproducibility can be influenced by factors which affect the recording of a given contraction and also by the ability to repeat exactly a given contraction. With regard to recording, a lack of accuracy of electrode replacement is by far the largest potential source of error. Furthermore, if the same muscle contraction is to be compared in different people, the electrodes must be placed in the same position relative to that muscle in each individual.

Other factors which are important in the standardization of EMG for recordings on different days include consistent body and head posture (Forsberg *et al.,* 1985), skin resistance and the maintenance of a constant bite force (Greenfield and Wyke, 1956).

Komi and Buskirk (1970) investigated reproducibility and reliability of using bipolar needle and surface electrode recordings for biceps brachii muscle. Average test-retest correlations of 0.88 for bipolar surface electrodes and 0.62 for bipolar needle electrodes were noted following 10 minute intervals on the same day. Following a three day interval these figures dropped to 0.69 and 0.22 respectively. The reliability of surface electrodes was also investigated at a 55 day interval and for maximal activity high reliability coefficients were maintained ($r = 0.95$). The authors concluded that surface electrodes could be utilized reliably in long term studies.

Reproducibility studies involving the oro-facial muscles have given mixed results. Liebman and Cosenza (1960) stated that the variation in electrode placement caused such alteration in the recorded voltage that quantitative EMG was of little value. Although Angelone *et al.* (1960) found good reproducibility within visits when measuring masseteric activity by bipolar surface electrodes, between-visit reproducibility was poor. Sources of error in the electrode positioning and recording technique are immediately evident in the study and unfortunately very few figures and no statistics are recorded.

Nouri *et al.* (1976) in a study of five patients using bipolar suction surface electrodes to record masseteric activity found good consistency between recordings made on the same day and on different occasions. Great attention was paid to standardization of procedure to the extent that an electrode positioning template was constructed for each subject. No significant variations in recordings were found.

In conclusion, the potential for error in EMG research is large and it is essential that the protocol be designed to minimize such error whenever possible. This is particularly important with regard to electrode positioning and recording technique and that the subject has a clear understanding of the task they are required to perform prior to recording.

vi) The relationship between EMG activity and facial form

A large number of investigators have studied EMG characteristics in relation to various categories of dental malocclusion. Ahlgren (1966), for example, studied normal and Angle class II occlusions, whilst Moss and Greenfield (1965) described patterns of activity of masseter and temporalis muscles in subjects with class III incisor relationships. As indicated by Ingervall and Thilander (1974), dental features may vary independently of skeletal morphology and therefore any possible relationship between muscle activity and form should be addressed from the point of view of skeletal rather than dental characteristics.

Møller (1966), in his classic study, reported several significant correlations between certain variables of muscle activity and facial morphology in an adult population. With regard to activity at rest, a significant correlation ($r = 0.35$, $p \leq 0.05$) was observed between the posterior temporalis activity and the degree of maxillary prognathism. During maximum bite, subjects with strong activity in masseter muscle were characterized by mandibular prognathism, ($r = 0.35$, $p \leq 0.05$) and "an anteriorly inclined mandible" with the correlation coefficients relating to activity and the SN-mandibular plane angle, the gonial angle and the anterior lower face height being -0.35, -0.34 and -0.34 respectively, all significant at the $p \leq 0.05$ level. Similarly strong activity in the anterior temporalis muscle correlated with the features representing an anterior inclination of the mandible (SN-mand. $r = -0.35$, gonial angle $r = -0.33$, both significant at the $p \leq 0.05$ level). There were no significant correlations with the skeletal variables for posterior temporalis muscle during maximal bite, although there was a positive and significant correlation with the depth of the incisor overbite ($r = 0.40$, $p \leq 0.05$).

Ingerval and Thilander (1974) in their study of the correlation of skeletal form with EMG activity in 52 children aged 9 to 11 years, found the clearest correlations during maximal bite and during chewing activity. As such the amplitudes of the temporalis and masseter muscles were large in those cases where there was a tendency towards parallelism of the horizontal facial planes, a rectangular shape of the face and a small lower face height. The correlation coefficients ranged from -0.27 to -0.43.

Finn *et al.* (1980a) reported an investigation of EMG activity in five short faced patients, eight long faced patients and four control individuals with "normal facial proportions". Unipolar wire electrodes were inserted into the anterior temporalis muscle and the deep masseter muscle. The short face group displayed the greatest activity for both masseter and temporalis during maximum incisor and molar biting, whilst the long face group displayed the least activity.

vii) The effect of orthognathic surgery on EMG activity.

Studies into the response of the masticatory muscles to orthognathic surgery, as measured through EMG activity, are few in number. Ingervall *et al.* (1979) suggested that changes in skeletal morphology following surgery may be associated with changes in muscle function, but the exact functional response was, and in fact remains, unknown.

In their study of patients undergoing surgery to the rami in order to correct mandibular prognathism, Ingervall *et al.* (1979) presented EMG data of 18 patients, aged 19 to 50 years, recorded prior to surgery, during and immediately following the removal of fixation and between 27 and 43 weeks after operation. Recordings from masseter and both anterior and posterior temporalis muscles were made using bipolar hook electrodes. The changes in recorded activity were related to the skeletal changes as observed from cephalometric data. The results showed that at rest, there was no significant change in masseter muscle activity throughout the study, and whilst there was a small increase in activity in both temporalis muscles during the period of fixation, this subsequently returned to a level below that recorded prior to operation.

With regard to the activity recorded during maximal bite, not surprisingly, all three muscles showed a significant decrease in activity whilst in fixation and although all three muscles displayed an increase in activity above the preoperative level at follow-up, the overall change was only significant ($p \leq 0.01$) for the anterior temporalis muscle.

In an attempt to understand the movement observed in the skeletal elements during the period of intermaxillary fixation, the authors correlated movement of the cephalometric points gnathion and gonion with the amplitude of the pre-operative EMG recordings. Despite rather weak correlation coefficients, the highest being 0.41, the authors felt confident to suggest that "special precautions" may be required to prevent movement of the mandible during fixation in patients with strong anterior temporalis

and weak masseter muscles.

Johnston *et al.* (1984) reported a pilot study, based on three patients designed to relate the changes occurring in the amplitude of recorded EMG activity with estimates of the change in mechanical advantage of the muscle system as a result of orthognathic surgery, The surgery involved the correction of vertical maxillary excess with associated mandibular deficiency. The study can be criticized on several counts. Firstly, the three patients (two females and one male, of mixed race) although principally undergoing a Le Fort I osteotomy, experienced a variety of operative procedures, and secondly, despite the extensive statistical description, there was no indication of the error of the method used to establish EMG activity or mechanical advantage of the muscles.

The EMG activity was recorded using bilateral unipolar surface electrodes at pre-established levels of bite force.The results were inconsistent with large variation both between and within individuals for the various muscles, and certainly the study requires to be repeated with a larger sample size before meaningful conclusions can be made.

Kinesiography

Introduction

Over the past sixty years numerous techniques have been described as a means of measuring mandibular movement. In many ways the improvement in techniques have reflected the advances in three-dimensional scientific measurement procedures, and these have been extensively reviewed by Howell (1985). In recent years, the most widely used approach employs electronic techniques by which a signal generated intra-orally is monitored or tracked by sensor systems placed extra-orally. Two instruments, the Sirognathograph (Lewin *et al.*, 1974) and the Kinesiograph (Jankleson *et al.*, 1975) rely on the detection of changes in strength of the magnetic field generated by a bar magnet cemented to the lower incisor teeth. It is the latter technique which will be employed in the present investigations of mandibular movement.

Literature review

i) Mandibular rest position

An appreciation of the concept of a resting position of the mandible has relevance to many fields of dentistry including orthodontics, restorative dentistry and oral surgery.

Thompson (1946) stressed that the mandible assumed its positional relationship to the maxilla in the first few months of life, a position which remained inviolate thereafter.

Ricketts (1952a) postulated that the rest position would only remain constant providing the proprioceptive mechanisms responsible for its control remained unchanged. Any alteration in those control systems could lead to a new stable rest position. This concept was later confirmed by

cephalometric examination of treated cases (Ricketts, 1952b).

Moyers (1956) suggested that the reflex was controlled by proprioceptors within the muscles and tendons. However, as the teeth erupt a new reflex develops in order to provide maximum masticatory and occlusal efficiency. This latter reflex is controlled not only by receptors in muscles, tendons and the temporomandibular joints but also by highly sensitive proprioceptors within the periodontal ligament. More recently the presence of these proprioceptors has been questioned (Willis and DiCosimo, 1979) with the result that it is now recognized that mechanoreceptors within the periodontal ligament serve to inhibit the jaw closing reflex so protecting the dentition.

Two distinct but reproducible rest positions are recognised. Firstly, the physiological rest position which is an inbred postural reflex primarily dependent on the physiological resting length of the mandibular elevator muscles, and secondly the clinical rest position which is learned, is dependent upon the dentition and is adaptive to such factors as age, stress and occlusal features (Wessberg *et al.,* 1983).

The clinical rest position is the position the mandible adopts following activities such as swallowing or phonetics, for example saying 'Mississippi' (Rugh and Drago, 1981).

The physiological rest position can be identified by eliminating the sensormotor feedback from the teeth so allowing the mandible to adopt a posture dependent upon the resting length of the elevator muscles. Such a position has been shown to occur following the application of repetitive physiological depolarization by transcutaneous electrical stimulation (TES) to the pre-auricular region of the face (Jankelson and Swain, 1972; Jankelson *et al.*, 1975).

Hickey *et al.* (1963) reported that the clinical rest position could be identified through electromyography studies suggesting that muscle activity

was minimal at the rest position. This view has been questioned by several authors including Garnick and Ramfjord (1962). More recently however, Wessberg *et al.* (1983) found no statistically significant difference between the rest position recorded following TES and the position of minimal EMG activity.

ii) Mandibular rest position in relation to facial morphology.

Very few studies have examined the possible relationship between mandibular resting position and the skeletal morphology of the face. Lindegard (1953) noted that the interocclusal distance was increased in individuals with a small maxillary-mandibular planes angle and with mandibular prognathism. Conversely, a reduced interocclusal distance was seen in conjunction with a high maxillary-mandibular angle and with facial retrognathia.

Wessberg *et al.* (1982b) compared three groups of subjects each comprising 10 individuals, described as exhibiting vertical maxillary excess (VME), normal vertical height (VMN) and vertical maxillary deficiency (VMD) respectively. Both the trans-cutaneous electrically stimulated rest position (TESP) and the clinical rest position (RVD) were recorded. The mean EMG activity occurring in the mandibular elevator muscles was also recorded for each of the three groups at both resting positions.

In all three groups the TESP showed on average a greater (+ 2.6 mm) interocclusal distance compared with the RVD and, as one would expect, the amount of EMG activity recorded at the TESP was less than that at the RVD.

The mean interocclusal distance for the vertical maxillary excess group was significantly reduced compared with the normal group at both the RVD (1.2 ± 0.7 mm) and the TESP (3.2 ± 1.7 mm). In contrast, the interocclusal distance at the RVD was not significantly different for the vertical maxillary deficiency group (3.4 ± 1.6 mm) when compared with the normal group

(3.5 ± 2.0 mm), but was highly significantly increased (8.3 ± 2.7 mm) at the TESP, the normal group values being 6.1 ± 3.1 mm.

Although a tendency was noted for EMG activity to be decreased in the VME group and increased in the VMD group at both rest positions when compared to the normal group, these differences were not statistically significant.

The authors concluded that the isometric muscle force at the rest position does not exert a significant influence on vertical facial morphology.

In a pilot study, Peterson *et al.* (1983) compared clinical rest position with the position of minimal recorded EMG activity in 10 patients with a high Frankfort- mandibular planes angle (>30 deg.) and 10 low angle cases (FMPA < 20 deg.). Minimal EMG rest position was recorded with the aid of a kinesiograph and a biofeedback system whereas clinical rest position was measured between soft tissue markings on the nose and chin.

Although the interocclusal distance at the clinical rest position was significantly greater in the low angle group (4.6 ± 1.42 mm) compared with the high angle results (3.15 ± 1.09 mm), there was no significant difference in the position of minimal EMG activity. It should be noted, however,that the range of interocclusal distances at minimal recorded EMG activity was wide for both groups being 7 to 14 mm for the low angle group and 4 to 15 mm for the high angle subjects.

The authors suggested that resting muscle length may be determined more by functional demands, for example the need to maintain an airway, rather than by facial morphology.

iii) The effect of vertical maxillary repositioning on mandibular rest position.

To date only one investigative team has studied the effect of surgical

repositioning of the maxilla on the rest position of the mandible. Wessberg *et al.* (1981, 1982a) aimed to resolve the controversy as to whether, following superior repositioning of the maxilla, the mandibular rest position remained constant with a consequent increase in the size of the interocclusal distance, or whether adaptation occurred with mandibular autorotation so maintaining a constant interocclusal distance.

Fifteen adult patients were evaluated before and three months after surgery by means of cephalometrics, kinesiography and electromyography (Wessberg *et al.,* 1981). Both clinical and physiological rest positions were noted. The vertical change induced by surgery resulted in a mean vertical movement of menton by 6.2 mm. with the teeth in occlusion. Although there was no significant difference between the interocclusal distance at the clinical rest position following surgery, the distance at the physiological rest position increased on average 1.6 mm, an increase significant at the $p \leq 0.05$ level. There was no significant change in EMG activity at either rest position as a result of surgery.

In a later study (Wessberg *et al.,* 1982a), five of the above patients were re-examined 24 months following surgery. The mean vertical surgical change was again 6.2 mm. There was no significant difference in the interocclusal distance at the clinical rest position, whereas the distance increased on average 5.1 mm at the physiological rest position ($p \leq 0.05$). As in the earlier study there was no significant change in EMG activity at either rest position.

The results of these studies suggest that following maxillary impaction surgery, whereas clinical autorotation of the mandible occurs almost immediately and is maintained long term, physiological autorotation occurs less readily despite being partially evident following immobilization. It is evident from the above that very few studies have examined the response of the mandibular resting positions to vertical skeletal change, and of those only maxillary impaction to reduce the vertical dimension has been investigated. The response to increasing the vertical dimension has not been

reported, neither has the possible variation in post-surgery adaptation in relation to the stability of the surgical result. It was therefore, considered appropriate to investigate these aspects further.

iv) The range of mandibular movement in response to orthognathic surgery

Over the past 30 years, several authors have examined the effect of orthognathic surgery on the range of movement of the mandible. In most cases these have concentrated on the extent of incisal opening, and in all cases the method of measurement has been extremely crude, usually involving a millimetre rule placed between the teeth. The observations have nevertheless been extremely variable and frequently contradictory, even for the same surgical procedure.

Pepersack and Chausse (1978), for example,in a five year follow-up of 67 patients who had undergone a sagittal split osteotomy to correct mandibular prognathism, concluded that surgery had little effect on mouth opening, whereas Edlund *et al.*(1978), in a study of 44 patients who had experienced similar surgery, reported significant reductions in the extent of inter-incisal opening and mandibular protrusion.

With regard to forward advancement of the mandible, Freihofer and Petresevic (1975) noted that 37 of 38 patients maintained or increased their inter-incisal opening, whereas Storum and Bell (1984) reported significant hypomobility of the mandible following surgery.

The same authors (Storum and Bell, 1984) noted a similar range of movement before and after surgery in patients who had undergone a horizontal maxillary, Le Fort I osteotomy, and this was supported by Aragon *et al.* (1985) who noted a small but not significant reduction in maximal inter-incisal opening. Unfortunately the last study did not differentiate those patients in whom the mandible autorotated in a clockwise manner from those with an anticlockwise mandibular rotation.

Aragon *et al.* (1985) also compared mandibular movement in patients who had experienced combined maxillary and mandibular surgical procedures. Six patients who had a Le Fort I osteotomy and mandibular set-back showed a significant reduction in both mean incisor opening and protrusion, but no change in the range of lateral excursions. The authors commented that the results for lateral movements were extremely variable in all the patient groups and this may, in part, reflect the method of assessment which was based on the relationship of the upper to lower dental midlines. Unfortunately the reproducibility of the assessment was not reported. The reduction in incisor opening correlated highly (r = 0.90) with the extent of the mandibular set-back. This was interesting as the results contradict : those patients who were treated by a mandibular set-back alone, the more the mandible was moved the less the reduction in incisor opening.

The study also reported significant reductions in all movements in a group of 11 patients who had experienced a Le Fort I osteotomy coupled with mandibular advancement, although again there was no separation according to whether the maxillary move produced an overall increase or decrease in facial height. There was no correlation between the reduction in incisor opening and the extent of the mandibular advancement.

It is apparent, therefore, that the literature contains conflicting reports as to the effects of corrective surgery on the range of mandibular movement. Further investigation of this aspect was considered desirable not only to clarify the issue but also to provide further information as to the muscular adaptation associated with orthognathic surgery.

The aims of the EMG and Kinesiography studies

The masseter muscle biopsy studies previously described have provided information as to the variations in structure of the muscle and how that structure varies in response to orthognathic surgery. Electromyography can be a non-invasive technique which provides information as to muscle function, whilst recent advances in instrumentation allow sensitive three-

dimensional assessment of the position of the mandible in space. By interfacing the electromyograph and kinesiograph it is possible to record the amount of activity occurring within the muscles of mastication at precise positions of the mandible.

The overall aims of this section of the study were to provide further information as to the function of the masticatory muscles in patients with abnormal vertical facial morphology and the ways in which that function is affected by corrective surgery.

Recording equipment and methodology - i) Electromyography

i) EMG Recording Apparatus

Grass[6] E5H 10 mm diameter cup shaped silver electrodes were connected to an eight channel Grass model 7D Polygraph incorporating a model 7DA Driver Amplifier and model 7P10 Summating Integrator. Channels 1-3 recorded the raw interference pattern from the muscle under study, whilst channels 5-7 recorded the integrated signal which had been passed through preset capacitors. Throughout the study each channel always received signals from the same muscle.

Channels 4 and 8 provided a means of duplicating the recordings of channels 1-3 and 5-7 in turn providing a means of checking for channel bias.

ii) Calibration of the EMG system

The Driver Amplifier was calibrated such that an internally generated signal of 100 microvolts gave a 20mm pen deflection. The AC preamplifiers (Grass model 7P3) were calibrated to give a 10mm pen deflection for an internally generated signal of 200 microvolts. Recordings of four patients, however, required the preamplification to be increased such that the 10mm pen deflection was achieved with a signal of 100 microvolts.

The integrator channels were calibrated in full wave rectification mode using an internally generated DC signal of 5 millivolts, such that the pen moved 15mm/sec and reset every 2.7 seconds. One full sweep or 'reset' of the integrator pen writer covered 40 divisions of the curvilinear paper.

The calibration of the apparatus was checked at the start of each recording session.

Although the recordings were not made in a Faraday cage, all equipment was earthed and all metal pipework within the room screened. The recording area was checked for electrical interference routinely using a "dummy patient" electrode with an impedance of 10K Ohms.

The paper speed was kept constant throughout the study at 5mm per second.

iii) Electrode Placement

The electrodes were attached to the skin using double sided adhesive discs. In order to reduce skin impedance the area of attachment was swabbed twice with acetone on cotton wool, allowing the area to dry between applications then rubbed with fine grain sandpaper. Electrode jelly was introduced into the discs using a syringe and blunted hypodermic needle. The interelectrode impedance was checked by means of a Grass EZM5 electrode impedance meter with 10K Ohms being the maximum impedance accepted.

iv) Electrode Positions (figure 38)

Bipolar electrodes were placed over the right masseter whilst unipolar recordings were taken of the right anterior and posterior temporalis. An earth electrode was placed on the back of the right hand and a reference electrode for the unipolar recordings was positioned on the dorsal surface of the neck level with the sixth cervical vertebra.

Right Masseter

The muscle was palpated whilst the subject was in maximal clench in order to delineate its anterior and inferior borders. The first electrode was positioned 15mm from the anterior border and 20mm from the inferior border. The second electrode was placed 20mm above the first orientated along an imaginary line passing through the first electrode and parallel with the anterior border of the muscle.

Anterior Temporalis

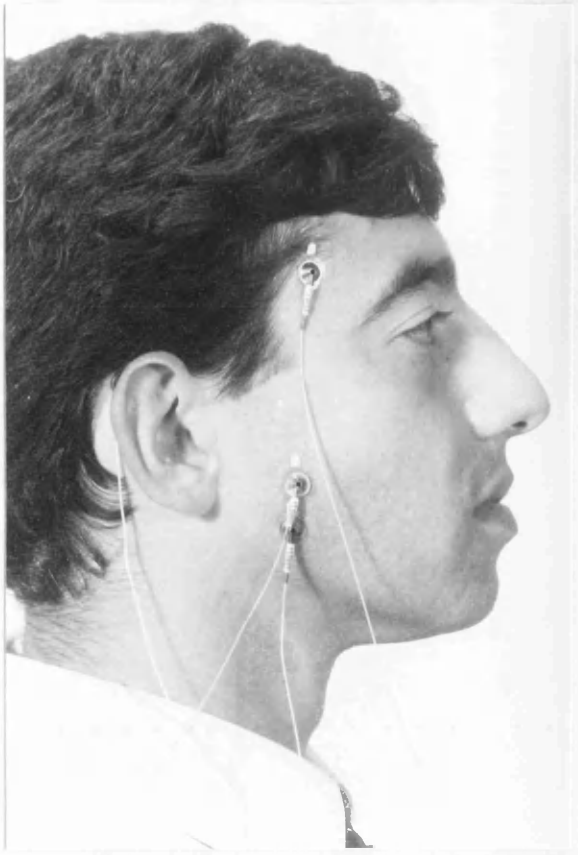
The unipolar electrode was placed in a hair-free zone over the area of maximum bulbosity of the clenched muscle. Because of the variations in hair line, the exact location of the electrode varied between individuals but was approximately 10-15mm from the anterior border of the palpated muscle and 30-40mm above the zygomatic arch.

Posterior Temporalis

The exact location of the electrode varied between individuals in relation to the hair-free zone behind the right ear overlying an area of muscle activity palpated during mandibular movement.

Once located, the positions of the anterior and posterior temporalis electrodes were recorded using callipers in relation to identifiable anatomical landmarks unlikely to be affected by surgery. The static landmarks were taken as the outer canthus of the eye and the antero-inferior point of the tragus of the ear. This procedure ensured accurate relocation of the electrodes on subsequent occasions.

Figure 38 - EMG electrode positions



v) Experimental protocol

Recordings were made with the patient seated upright in a dental chair with the head unsupported and in a subjectively determined natural head position. This was achieved by asking the patient to focus on an object at eye level set on the wall opposite. Three separate recordings, each of 7 seconds duration, were made at rest, during maximal bilateral clench and concentrated biting on the right and left sides.

From the three recordings of each position, the least activity occurring over a 5 second period within the 7 second activity represented the noted value for the rest position, whereas the maximum activity was taken for the various biting positions. Measurements were made to the nearest division on the curvilinear paper, where one full sweep of the pen covered 40 divisions prior to reset. Each division, therefore, represented 0.025 of a

reset.

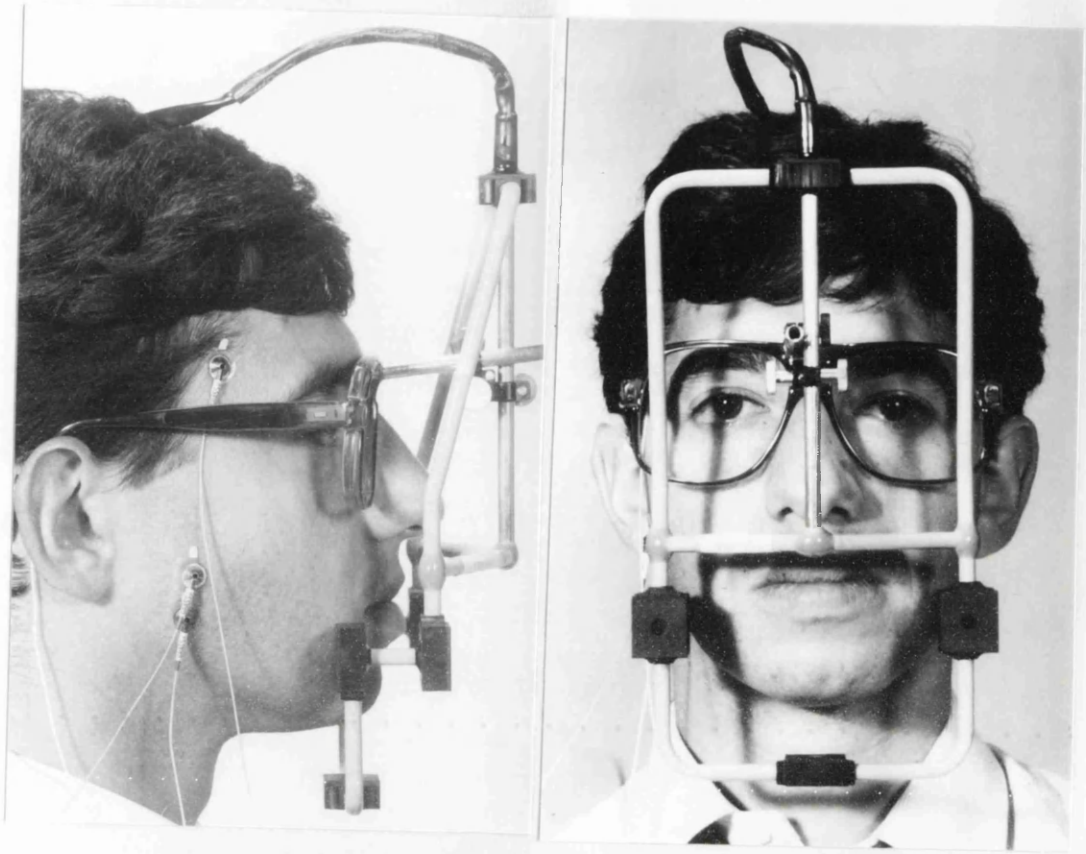
Recording equipment and methodology - ii) Kinesiography

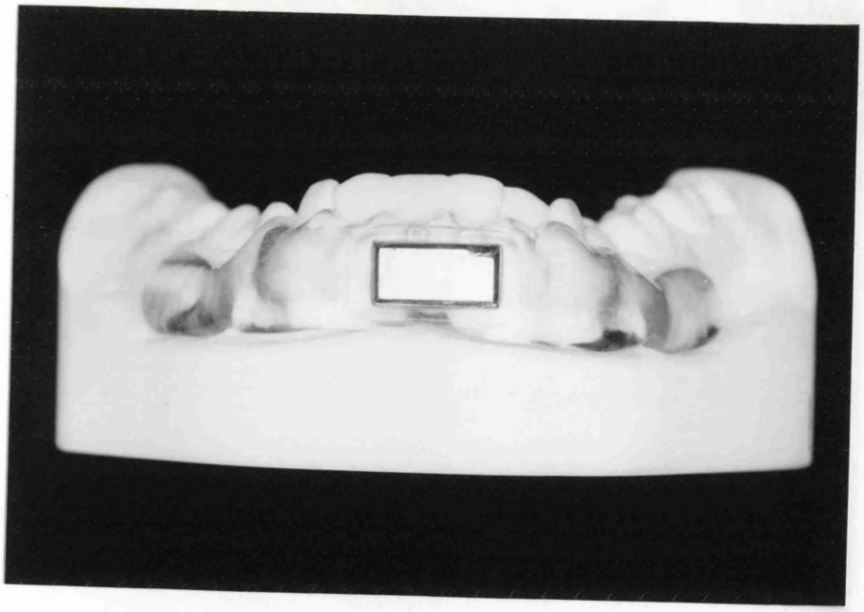
i) Kinesiograph recording equipment

The mandibular kinesiograph[7] is an electronic system designed to trace and record mandibular movement in three dimensions (Jankelson *et al.*, 1975). The system consists of a small bar magnet, measuring approximately 15mm x 6mm x 2mm (weight 2.8 gm) which is located in the lower labial sulcus where it acts as a transponder (figure 39). An aluminium frame is attached by way of a 3-way adjustable joint to a short length of aluminium tubing protruding from a pair of glassless spectacles, held in position on the patient by velcro tapes passing behind the head. The aluminium frame holds an array of five sensors or flux gate magnetometers which respond to the changing strength of magnetic field as the mandible and attached magnet are moved relative to the sensor array. Mandibular movement is, therefore, measured in three primary directions; antero-posteriorly, laterally and vertically. A sixth sensor mounted at the top of the frame detects and cancels the effects of any externally generated magnetic fields. The sensor output passes by way of a single cable to an oscilloscope where the measured mandibular movement is displayed, linearized and passed on to a microcomputer for data storage and analysis. The total weight of the sensor array and cable is approximately 100gm.

In order to provide the computer with a digital signal, the analogue signal produced by the kinesiograph is converted using an eight channel 12 bit analogue to digital converter (A to D converter)[8]. The software for the data storage and analysis and the printout of the results in millimeters was written by Dr P. Howell.

Figure 39 - The mandibular kinesiograph.





Movement of the bar magnet is detected by the five sensors with the sixth sensor mounted at the top of the frame cancelling the effects of any externally generated magnetic fields.

ii) Calibration of the kinesiograph.

Although the kinesiograph is linear at or near the intercuspal position, this is not the case at the extremes of mandibular position (Hannam *et al.*, 1980). It was therefore, necessary, to bench calibrate the system for each of the three planes of movement enabling a linearizing program to be written which automatically corrected the recorded data.

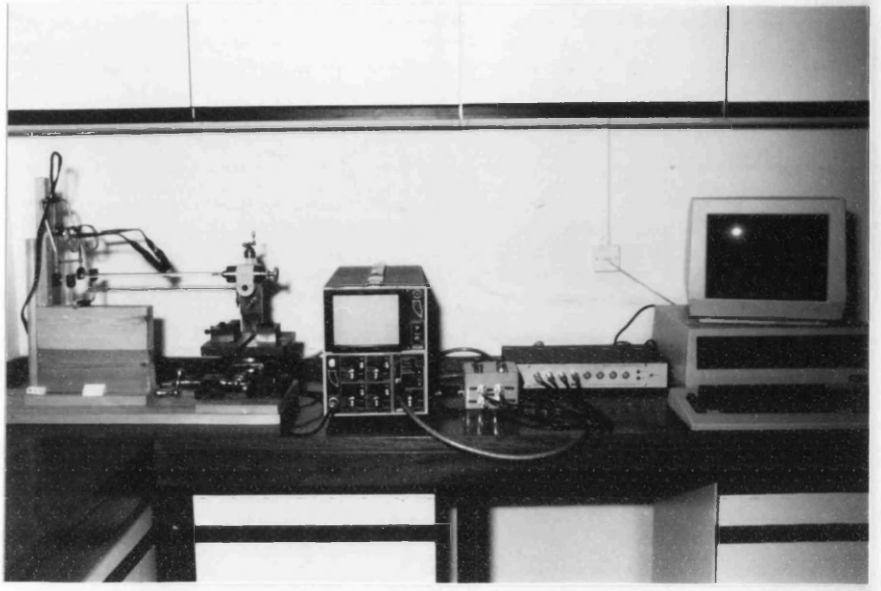
In order to do this the bar magnet of the kinesiograph was mounted at one end of a perspex rod measuring 300 mm long. The other end of the rod was fixed into the chuck of an adjustable Vernier scale which gave accurate vertical movement in 0.01 mm increments. The whole assembly was fixed into the platen of an X-Y slide capable of measurement to 0.025 mm. (figure 40).

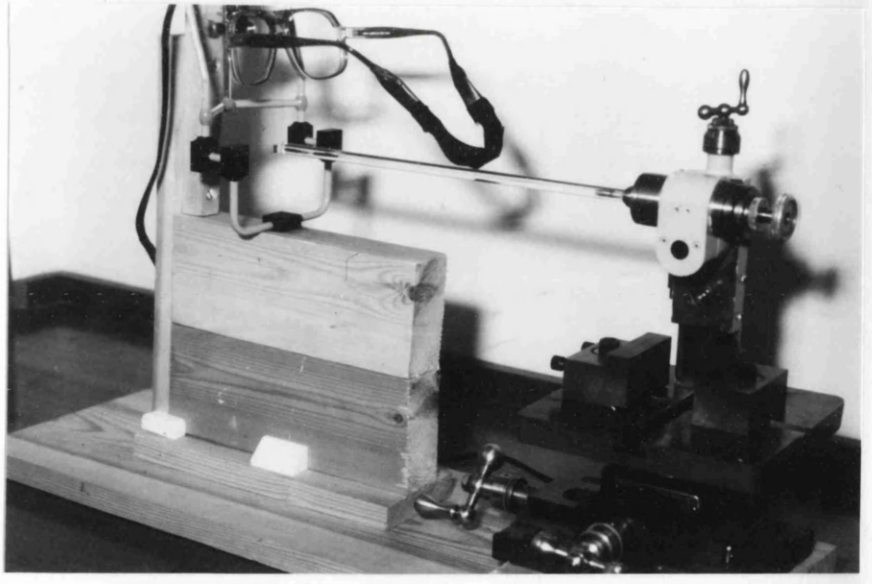
The magnet was positioned in turn at a total of 370 data points at the x2, x5 and x10 amplifications within an envelope of dimensions 42mm vertical movement, ± 12mm lateral movement and antero-posteriorly from 12 mm forwards to 16 mm backwards. The large range of movement was specifically chosen in anticipation of the need to accommodate patients with diverse cranio-facial morphologies.

A short computer program written by Dr. P. Howell instructed the A-D converter to sample the signal from the kinesiograph twenty times for each of the X, Y and Z coordinate channels, with the mean and standard deviation displayed on the computer screen. This information was then logged manually, together with the "true" coordinates of the magnet as noted on the Vernier scales of the calibration slide.

The conversion of the raw X, Y and Z data and the values from the A-D converter to the true coordinates (x, y, z) was made using a specially written least squares programme (Howell,1985).

Figure 40 - Calibration of the kinesiograph





Movement of the bar magnet could be monitored directly by the x-y-z slide and the results compared with the X,Y and Z coordinates recorded by the kinesiograph.

The correction coefficients are represented by the equation:

$$f(x, y, z) = a_0 + a_1X + a_2Y + a_3Z + a_4XY + a_5XZ + a_6YZ + a_7X^2 + a_8Y^2 + a_9Z^2$$

where $a_{0\text{-}9}$ are the calculated coordinates.

The coefficients when substituted back into the equations for the known data points yielded a regression coefficient of 0.998 indicating that all but 0.2% of the non-linearity of the kinesiograph had been taken into account.

The error of the method of the electromyography and kinesiography studies

a) Electromyography

In order to establish the error of the method involved in the study duplicate recordings were taken to determine both the within visit and between visit error.

For the within visit error, 15 patients were selected at random at various stages of their measurement sequence. The recording procedure was undertaken as reported in the method section and then repeated without removing the electrodes.

For the between visit error, 10 patients agreed to a second recording at a time interval of not less than three weeks after the first recording. Again the procedure followed that previously described.

Statistical analysis

The duplicate recordings were first checked to ensure the data met the requirements for parametric statistical analysis, that is, that the data were normally distributed and that the variances were approximately equal. The results were evaluated using the paired *t* test and the coefficients of

reliability and the overall error of the method as described by Dahlberg (1940) were calculated. The results for the muscles and their various activities are presented in table XXI.

Table XXI- The error of the method of the EMG studies.

	Within visit (n= 15)		Between visit (n= 10)	
	% Coeff. of reliab.	Dahlberg error	% Coeff. of reliab.	Dahlberg error
Masseter				
Rest	91.8	2.8	84.1	2.4
Clench	98.9	5.3	99.4	4.8
Bite Rt.	98.2	5.9	97.7	7.1
Ant.Temp.				
Rest	84.6	4.0	85.4	4.5
Clench	96.5	11.3	92.9	9.5
Bite Rt.	96.6	10.6	88.3	9.8
Post.Temp.				
Rest	86.8	4.4	80.8	5.8
Clench	91.4	6.4	94.1	7.9
Bite Rt.	97.2	6.5	93.8	7.7

Dahlberg error : units = 0.025 of a reset

There were no significant differences as noted by the *t* test.

i) EMG Results

The results for the error studies can be considered to be acceptable when compared to those of previous studies involving electromyography. The coefficients of reliability were generally high, although those for resting activity were less than 90 % and therefore the test results would need to be watched closely. The recorded level of resting activity is relatively more susceptible to minor variations in background noise or skin impedance compared to the recorded levels during function.

Perhaps not surprisingly, the between visit results were less well correlated than the within visit figures. Leaving the electrodes in position for the within visit recordings eliminated a major source of random error. Overall the results were more consistent than those recorded by Hammond (1984) and Coutts (1986) using the same recording apparatus.

The results for masseter muscle were also comparable with those reported by Garrett and Kapur (1986) who reported correlation coefficients greater than 0.90. The figures for masseter were consistently higher than for temporalis which was perhaps to be expected. Firstly, the temporalis recordings were made using unipolar electrodes which eliminate less background noise than the bipolar technique used for masseter, and secondly, as indicated by Burdette and Gale (1990) the temporal region, especially the anterior part, includes several muscles (for example, the ocular muscles) whose variable activity may influence the signal recorded by the surface electrodes. Whilst surface electrodes were similarly used for the masseter recordings the variability of the adjacent muscle activity is less marked.

b) Kinesiography

In order to ascertain the reproducibility of the kinesiograph system, recordings were taken on eight healthy postgraduate students and dental surgery assistants. Recordings were taken twice on the same day and

repeated after a two month time interval. Measurements were taken in the clinical rest position and at maximum intercuspation in order to establish the clinical freeway space. Mandibular position was also recorded at maximum opening, maximum right and left lateral movements without vertical opening, and protrusion, again without opening. The position of the mandible was also recorded following transcutaneous electrical stimulation but this was only feasible for the between visit analysis. As before the coefficients of reliability and the Dahlberg error were calculated in addition to the *t* test for paired data. The results are presented in table XXII.

Table XXII - The error of the method of the kinesiograph studies

	Within visit		Between visit	
	% Coeff. of reliab.	Dahlberg error (mm)	% Coeff. of reliab.	Dahlberg error (mm)
Clin. freeway space	98.6	0.10	95.4	0.21
TESP freeway space	-	-	91.8	0.30
Max. opening	96.5	0.64	94.5	0.89
Max. right	97.2	0.32	92.1	0.48
Max. left	96.6	0.37	87.3	0.63
Max protrusion	92.9	0.21	84.6	0.72

The paired *t* test was not significant for all measurements.

ii) Kinesiography Results

The kinesiograph proved to be extremely reproducible for all activities as assessed both on the same occasion and on a separate visit. The Dahlberg errors were very acceptable with all measurements having an overall error of less than one millimetre. It is impossible to compare the error of the method using the kinesiograph with previous studies as these have not previously been reported.

Study 6

Comparison of EMG activity for the long and short faced patients prior to treatment

i) Subjects

Although recordings of 52 patients were made initially, it was ultimately decided to limit the subjects included in this study to those who subsequently agreed to a muscle biopsy at the time of surgery. As a consequence, data for the 17 patients considered as having features of a short face and the 25 patients with long faces will be presented. The mean age of the patients was 23.3 years (95% CI 21.5 to 25.1 yrs).

ii) Results

Comparison of the EMG activity levels was limited to those recordings taken at rest, at maximum clench, and biting on the right and left side. Biting on the incisors was not included since very few of the long face group could actually achieve this position. The group mean findings, together with statistical comparisons are presented in table XXIII. The 95 % confidence intervals are presented separately in table XXIV.

Table XXIII - EMG levels in the long and short face groups prior to surgery.

	Long face group n=25			Short face group n=17			
	mean	SD	SE	mean	SD	SE	Sig
Masseter							
rest	5.5	4.7	0.9	14.3	7.1	1.7	***
max. bite	47.6	47.6	9.5	73.2	47.1	11.4	ns
right	46.2	45.2	9.0	78.8	52.6	12.8	*
left	35.7	30.7	6.1	43.4	43.1	10.5	ns
Ant. Temp							
rest	30.9	8.9	1.8	13.7	8.5	2.1	***
max. bite	60.6	55.0	11.0	97.0	57.3	13.9	*
right	56.4	52.4	10.5	85.7	56.9	13.8	ns
left	47.8	53.6	10.7	53.6	47.7	11.6	ns
Post. Temp							
rest	18.7	15.1	3.0	17.3	8.8	2.1	ns
max. bite	37.2	43.5	8.7	39.2	55.1	13.4	ns
right	26.0	28.3	5.7	32.2	51.0	12.4	ns
left	25.2	31.0	6.2	18.5	22.2	5.4	ns

Units : x 0.025 resets

Table XXIV - The 95 % confidence intervals for the pre-surgical EMG levels

	Long face group	Short face group
Masseter		
rest	3.5 - 7.5	10.6 - 17.9
max.bite	7.9 - 67.3	49.0 - 97.4
right	27.5 - 64.9	51.7 - 126.5
left	23.0 - 48.3	21.2 - 65.5
Ant.Temp.		
rest	27.2 - 34.6	9.3 - 18.1
max.bite	7.9 - 83.3	67.5 - 126.5
right	34.8 - 78.0	56.5 - 115.0
left	25.6 - 69.9	29.1 - 78.1
Post.Temp.		
rest	12.4 - 24.9	12.8 - 21.8
max.bite	9.2 - 55.2	10.8 - 67.5
right	14.3 - 37.7	6.0 - 58.4
left	12.3 - 38.0	7.0 - 29.9

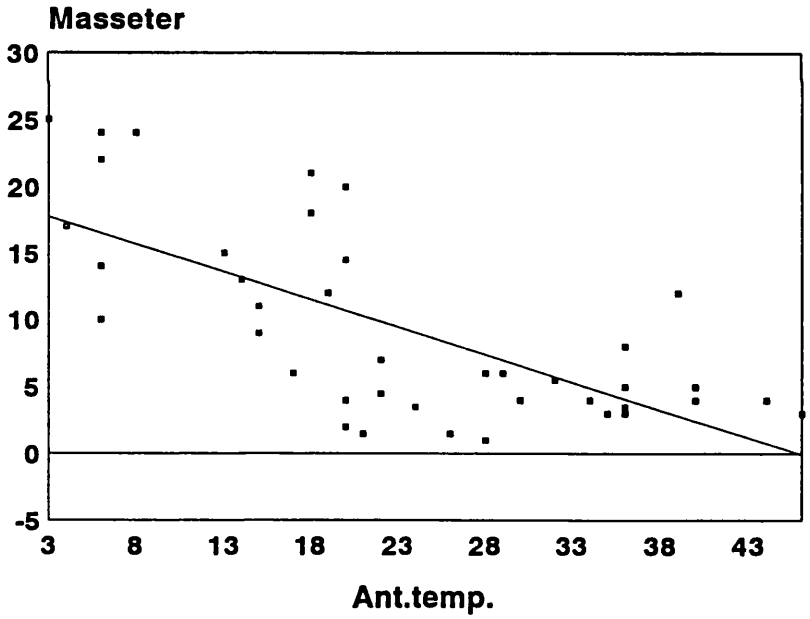
Units: x 0.025 resets

The most striking feature of the results is the extremely large variation between individuals of the same group, to the extent that statistical analysis is rather limited in value. It is apparent, however, that there is a trend towards increased levels of activity in the short face group as compared to the long face counterparts. The exceptions to this are the highly significantly reduced activity occurring in the anterior temporalis muscle at rest and the

somewhat equivocal results for the posterior temporalis at rest.

The differences between the resting activity in masseter and anterior temporalis between the two groups were highly significant for both muscles but in opposite directions. This would suggest the possibility of a reciprocal relationship and to a certain extent this is borne out by the plot shown in figure 41, in which the levels of activity for the two muscles are plotted against each other for the entire study population of 42 patients. The correlation coefficient was -0.70 ($p \leq 0.001$). It is perhaps not surprising that such a relationship should exist between two mandibular elevator muscles although the mechanism behind the relationship is unclear. Once again,however, it must be remembered that the error of the method for resting activity was relatively large.

Figure 41 - Plot of resting EMG activity in masseter and anterior temporalis muscles



r = -0.70

The level of activity recorded from the anterior temporalis muscle was unexpectedly high in the context of the overall levels of activity. As a consequence there was a highly significant difference in resting activity (

$p \leq 0.001$) between the anterior and posterior parts of the temporalis muscle in the long face group but this did not apply to the short face sample. These results complete the range of possibilities as Ingervall and Thilander (1974) noted greater activity in the posterior part of the muscle in their study of 9 - 11 year old children, whereas Moyers (1949) and Møller (1966) found no difference in the two parts of the muscle in their studies based on individuals with apparently normal skeletal relationships.

The two remaining activities which achieved significance between the long and short face groups related to right-sided biting for masseter and maximum biting for anterior temporalis. There were no significant differences in the EMG levels recorded for posterior temporalis muscle for any of the tasks.

With respect to the levels of activity during the biting exercises there was consistently higher activity recorded in the anterior temporalis when compared to the posterior part of the muscle but whilst the difference was statistically significant for all three tasks in the short face group, only biting on the right attained significance for the long face group. On the whole these results are in keeping with those of Greenfield and Wyke (1956) and Møller (1966) both of whom noted greater activity in the anterior part of the muscle.

Within group comparisons of the levels of activity recorded for the various tasks for each muscle were analyzed using the one-way analysis of variance or the Kruskal-Wallis test as appropriate. The results showed that the level of activity recorded at rest in masseter muscle was highly significantly different from that recorded for the other three tasks in both the long and short face groups but there was no significant difference between the levels of the three bites. This differed from the anterior temporalis muscle where although the results mirrored those of masseter in the short face group, there was no significant difference between any of the mean levels recorded (rest and bites) in the long face group. Finally, there were no significant differences at all, in either group with regard to temporalis muscle.

Overall the results were rather unexpected and were at variance in several respects to the findings of previous workers. It must be stressed however that it is difficult to make exact comparisons with previous results as data relating to a comparable group with a matched protocol and recording conditions does not exist.

Study 7 - The relationship between EMG activity and facial form

In order to study the relationship between specific aspects of facial form and the EMG activity recorded both at rest and during function, the group of 42 patients was considered as a whole.

i) Results

The individual linear correlations between the recorded levels of EMG activity and the principal components of facial form were very low, the highest being 0.57 between the first principal component and anterior temporalis activity at rest.

The first two canonical correlations exceeded the simple linear correlations being 0.78 and 0.71 respectively. However, neither of these were significant at an alpha level of 0.05. The standardized canonical coefficients showed the first canonical variable of the principal components received little effect from the fourth principal component but the greatest effects from the first, sixth and seventh components. With regard to the coefficients for the EMG variables, there was a fairly even weighting throughout the variables with the largest influence from posterior temporalis activity whilst biting on the right. In terms of prediction, the ability to predict either form from activity ,or activity from form was very poor.

Table XXV - Correlations between the principal components of facial form and the EMG measurements

MASSETER	REST	CLENCH	BITE RT.	BITE LT.
PRIN #1	-0.44	-0.27	-0.30	-0.12
PRIN #2	-0.11	0.04	-0.03	0.05
PRIN #3	0.30	0.26	0.29	-0.23
PRIN #4	0.12	0.16	0.18	0.07
PRIN #5	-0.01	0.23	0.23	0.11
PRIN #6	0.19	0.01	0.01	-0.24
PRIN #7	-0.01	-0.17	-0.20	0.08
ANT.TEMP.				
PRIN #1	0.57	-0.31	-0.33	-0.18
PRIM #2	-0.09	-0.03	-0.02	-0.08
PRIN #3	-0.21	0.11	0.01	-0.04
PRIN #4	0.04	0.29	0.18	0.17
PRIN #5	-0.04	0.16	0.18	0.12
PRIN #6	-0.17	-0.13	-0.08	-0.01
PRIN #7	0.01	-0.27	-0.24	-0.35
POST.TEMP.				
PRIN #1	-0.03	-0.05	-0.09	0.20
PRIN #2	0.22	0.22	0.12	0.05
PRIN #3	-0.18	0.01	0.10	0.10
PRIN #4	0.01	0.13	0.06	0.08
PRIN #5	0.01	0.11	0.05	0.09
PRIN #6	-0.10	-0.15	-0.30	-0.11
PRIN #7	-0.25	-0.32	-0.48	-0.43

Canonical correlations

	Canon. coeff.	Coeff.^{2}	Eigen.	Sig.	Prop^n. of var.of form expl^d.	Prop^n. of var of EMG expl^d.
1st	0.78	0.61	1.54	ns	0.09	0.11
2nd	0.71	0.50	1.01	ns	0.16	0.16

The correlations between the percentage lower anterior and posterior face heights and the EMG variables showed no significant correlations for posterior measurements, and significant anterior face height measurements as follows:

Masseter rest	-0.42 **
Masseter clench	-0.36 *
Masseter right	-0.40 **
Ant.temp. rest	0.55 ***
Ant temp. clench	-0.37 *
Ant temp. right	-0.36 *

These results are in keeping with those for the first principal component and although reaching statistical significance are of limited clinical significance, the highest correlation of 0.55 accounting for approximately 30 % of the variation in the relationship between the anterior temporalis activity at rest and the % LAFH.

Study 8 -

The rest position in long and short faced individuals and the response to surgery

i) Subjects

38 patients agreed to participate in this aspect of the study, 19 of whom (7 males, 12 females) were scheduled for surgery to increase their vertical facial dimensions, whilst 19 subjects (8 males, 11 females) were to undergo surgery to reduce their vertical facial heights. The surgical procedures involved either a down-fracture Le Fort I osteotomy with or without a bone graft, a mandibular sagittal split osteotomy or a combination of a Le Fort I and mandibular osteotomies. Only those patients where the pterygo-masseteric sling was not detached were included. The data were checked to ensure no significant difference between the sub-groups of patients based upon sex or the operative procedure received. As no significant difference was detected for any parameter the results were pooled in order to produce

groups of more meaningful size.

All patients were placed in intermaxillary fixation for between 6 and 8 weeks following operation.

ii) Method

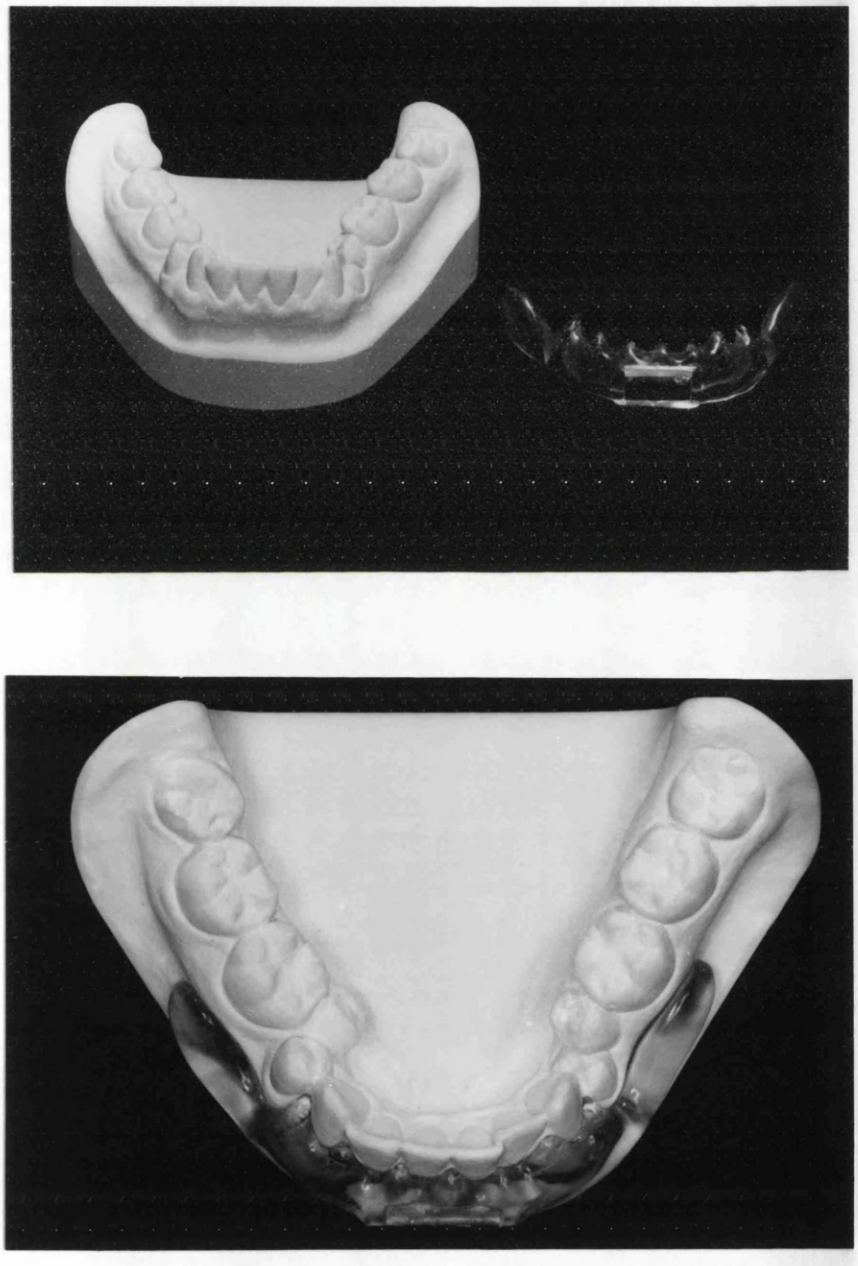
All recordings were made by the author with the patient sitting upright and the head unsupported. The patient was asked to focus on a distant object in order to attain the natural head position.

To facilitate the relocation of the bar magnet of the kinesiograph in a reproducible position, an acrylic slip was prepared on a study cast of the individuals lower dentition and labial sulcus (figure 42). This slip extended from first premolar to first premolar on the labial aspect and engaged the small but discernible undercuts below the alveolar margin in these areas. The slip was thickened in the region of the lower incisor teeth to accommodate the magnet. The magnet was positioned in the slip such that it lay across the midline in the labial sulcus with the labial face vertical. Care was taken to ensure the slip and magnet did not interfere with the occlusion.

The spectacles were placed on the subject and the velcro tape fastened to ensure the framework was firmly in place. The sensor array was placed on the aluminium protuberance and aligned with the aid of the MKG Electronic Alignment System[7] in accordance with the manufacturers instructions. Once in position the vertical sensors were perpendicular to the Frankfort plane and as near perpendicular to the magnet as possible when the teeth were in the inter-cuspal position. In the frontal view the vertical strut of the sensor frame was parallel to the vertical midline of the face and as such the lateral sensors were equidistant from the facial midline. In some instances, especially those cases of facial asymmetry, this resulted in the lateral sensors being closer to one cheek than the other. Another minor adjustment was made in those cases, especially the long faced individuals, where the

chin hit the vertical sensor on maximal opening. In such cases the vertical strut was tilted slightly forwards as instructed by the manufacturers. The system was then explained and demonstrated to the patient prior to recording.

Figure 42 - The kinesiograph magnet realignment slip



The acrylic gum slip ensured the magnet could be relocated in the labial sulcus for successive recordings.

The following sequence was adopted with recordings taken at :

Inter-cuspal position
Clinical rest position
Inter-cuspal position
Maximum vertical opening
Inter-cuspal position
Maximum right excursion without vertical opening
Inter-cuspal position
Maximum left excursion without vertical opening
Inter-cuspal position
Maximum protrusion without vertical opening
Inter-cuspal position
Clinical rest position

Clinical rest position was taken as the position of the mandible having instructed the patient to lick the lips, swallow and relax.

The gain on the oscilloscope of the kinesiograph system was set at x2 for the measurement of the freeway space, x5 for lateral and protrusive movements and x10 for maximum opening in order to visualize the movements on the oscilloscope screen.

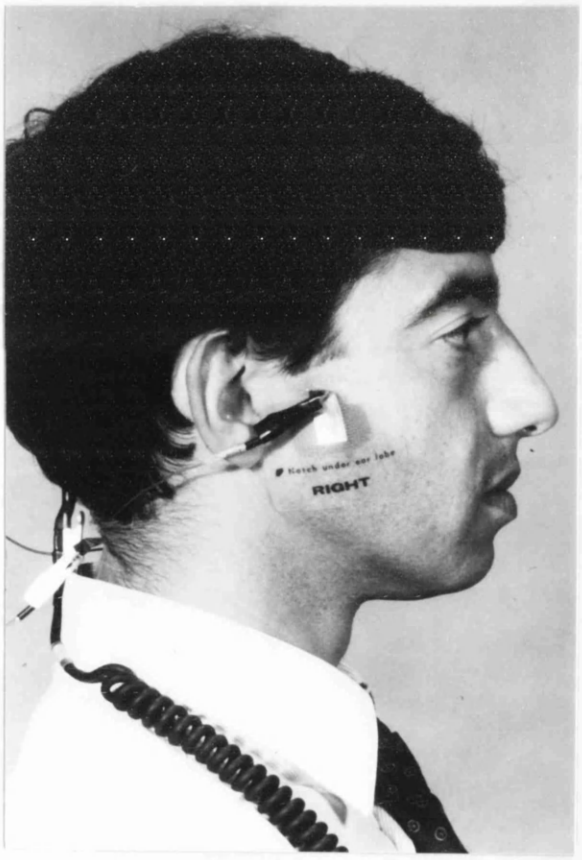
The above sequence was recorded twice with the average values taken for the rest position results and the maximum values taken for the various excursions.

A note was made of the baseline X,Y and Z coordinates at inter-cuspal position so as to ensure accurate relocation of the sensor array in relation to the magnet at subsequent recording sessions.

Following the recording of the above sequence a J4 myomonitor[7] was attached to the pre-auricular regions of the face according to the manufacturer's instructions. The myomonitor delivers a stimulus of approximately 500 microseconds duration repeated at 1.5 second intervals,

which has been shown to produce a reproducible rest position after approximately 30 minutes application (Wessberg *et al.* 1983). The resting position of the mandible was noted on the oscilloscope screen and the amplitude of the myomonitor adjusted so as to show a detectable vertical movement of the trace but without causing tooth contact. Stimulation was applied until a constant vertical position of the trace between pulses was noted. This position was taken as the physiological rest position (TESP). The EMG activity occurring at the TESP was recorded.

Figure 43 - The J4 myomonitor in position



Mandibular movement was analysed before surgery, between two and four months following the removal of fixation and approximately one year following operation.

iii) Results

The results of the mandibular rest positions study are shown in tables XXVI to XXVIII.

Table XXVI - Mandibular rest positions - Comparisons between the groups prior to surgery

	Long faces			Short faces			
	mean	SD	SE	mean	SD	SE	Sig
FMPA°	35.3	5.4	1.2	22.7	6.7	1.4	***
TAFH (mm)	121.9	11.3	2.6	107.5	5.4	1.3	**
TPFH (mm)	72.9	6.4	1.5	74.4	6.8	1.6	ns
RVD (mm)	2.8	1.0	0.2	3.4	1.8	0.4	ns
TESP (mm)	5.2	1.0	0.2	6.8	1.7	0.4	**
EMG -RVD (ccets)	6.3	5.0	1.1	11.9	5.9	1.4	**
EMG - TESP (ccets)	4.0	3.4	0.8	9.5	4.6	1.1	**

95 % Confidence intervals

	Long faces	Short faces
FMPA	32.7 to 37.9	19.7 to 25.7
TAFH	116.4 to 127.3	104.9 to 110.2
TPFH	69.8 to 76.0	71.1 to 77.6
RVD	2.3 to 3.2	2.6 to 4.3
TESP	4.7 to 5.7	6.0 to 7.6
EMG - RVD	3.9 to 8.7	9.1 to 14.8
EMG - TESP	2.4 to 5.7	7.3 to 11.7

Mandibular rest position

A comparison of the two groups prior to surgical correction showed that there was no significant difference in the size of the freeway space as measured at the clinical rest position. Those patients considered to exhibit a long face (LFG) gave a mean resting vertical dimension of 2.8 mm (SD 1.0 mm, 95% CI 2.3 to 3.2mm) whereas the short face group (SFG) were measured at 3.4 mm (SD 1.8mm, 95% CI 2.6 to 4.3 mm).

Following stimulation, however, the distance between the inter-cuspal position and the physiological rest position was measured at 5.2 mm (SD 1.0mm, 95% CI 4.7 to 5.7mm) for the LFG and 6.8 mm (SD 1.7mm, 95% CI 2.6 to 4.3 mm) for SFG. These figures were clinically and statistically different both between the groups and when compared to the clinical rest positions.

Although these values are within the ranges quoted by other workers using the kinesiograph, variations in results probably reflect the variations in relative severity of the underlying skeletal deformities of the samples under investigation. For example, Peterson *et al.* (1983) compared groups with high FMPAs (mean 32.4°) with a low angle group (mean 14.7°) and found the clinical freeway space to be 3.1 mm (SD 1.4 mm) and 4.6 mm (SD 1.1 mm) respectively, figures statistically different at the $p \leq 0.05$ level.

The mean FMPAs for the two groups in this study were 35.3° (SD 5.4°, 95% CI 32.7° to 37.9°) and 22.7° (SD 6.2°, 95% CI 19.7° to 25.7°).

Similarly, Wessberg *et al.* (1982b) noted an inter-cuspal position to TESP distance of 3.2 mm (SD 1.7mm) in the vertical excess group whose initial total anterior face height was 122.3 mm (SD 6.7mm) but a greater distance of 8.3 mm (SD 2.7mm) in the vertically deficient group with a total anterior face height of 112.6 mm (SD 7.4mm). The corresponding facial height measurements for the two groups in the present study were 121.9 mm (SD 11.3mm, 95%CI 116.4 to 127.3mm) and 107.5 mm (SD 5.4mm, 95% CI

104.9 to 110.2 mm) respectively.

The increased vertical dimension at the TESP compared to the clinical rest position is, however, a universal finding.

The amount of EMG activity at the TESP was consistently less ($p \leq 0.001$) than that measured at clinical rest for both groups, a finding similarly noted by Wessberg *et al.* (1982 b). Furthermore, there was a significant difference between the level of EMG activity measured between the two groups at each position.

The response to surgical intervention

a) Long face group

Surgical correction involved either a down - fracture Le Fort I impaction osteotomy of the maxilla alone, or a combination of a Le Fort I, and a sagittal split osteotomy of the mandible. The effect was a highly significant mean reduction in both anterior and posterior facial heights of 3.7 and 3.4 mm respectively.

In response, the clinical resting vertical dimension adapted totally to the change (2.7 mm as compared with 2.8 mm pre-operatively) whereas the TESP resting dimension increased by a mean of 0.9 mm. Although this increase was statistically significant ($p \leq 0.01$), the results do show that by far the majority of the reduction in facial proportions had been accommodated through physiological adaptation.

These results strongly support those of Wessberg *et al.* (1982a) who found only a 1.6 mm increase in physiological rest dimension despite a reduction in vertical dimension of 6.2 mm. As the authors suggested, the adaptation probably occurs through a shortening of the muscle-tendon system.

The change in the mean recorded EMG activity at the TESP was small and

Table XXVII - The effect of surgery on the vertical rest positions.

LONG FACE GROUP		Pre-op	Post-op	mean diff.	95 % CI	Sig.
TAFH	mean	121.9	118.2	- 3.7	-6.0 to -1.4	***
	SD	11.3	8.5			
	SE	2.6	1.9			
TPFH	mean	72.9	69.5	- 3.4	-4.8 to -2.0	***
	SD	6.4	7.5			
	SE	1.5	1.7			
RVD	mean	2.8	2.7	- 0.1	-0.9 to 0.7	ns
	SD	1.0	1.4			
	SE	0.2	0.3			
TESP	mean	5.2	6.1	0.9	0.4 to 1.4	***
	SD	1.0	1.4			
	SE	0.2	0.3			
EMG - RVD	mean	6.3	11.5	5.2	2.8 to 7.6	***
	SD	5.0	4.7			
	SE	1.1	1.1			
EMG - TESP	mean	4.0	4.1	0.1	-0.5 to 0.7	ns
	SD	3.4	3.7			
	SE	0.8	0.8			
SHORT FACE GROUP						
TAFH	mean	107.5	112.1	4.6	2.9 to 6.3	***
	SD	5.5	6.0			
	SE	1.3	1.4			
TPFH	mean	74.4	75.2	0.9	-0.3 to 1.9	ns
	SD	6.8	7.0			
	SE	1.6	1.6			
RVD	mean	3.4	2.7	-0.7	-1.2 to -0.2	**
	SD	1.8	1.8			
	SE	0.4	0.4			
TESP	mean	6.8	6.3	-0.5	-1.1 to 0.1	ns
	SD	1.7	1.2			
	SE	0.4	0.3			
EMG - RVD	mean	11.9	6.5	-5.4	-7.5 to -3.3	***
	SD	5.9	4.3			
	SE	1.4	1.0			
EMG - TESP	mean	9.5	6.3	-3.2	-4.5 to -1.9	***
	SD	4.6	4.0			
	SE	1.1	0.9			

not significant. However, at the clinical rest position the change was more dramatic increasing from a mean of 6.3 resets (SD 5.0, 95% CI 3.9 to 8.7)

prior to surgery, to a mean of 11.5 resets (SD 4.7, 95% CI 9.2 to 13.7) following operation - a highly significant difference ($p < 0.001$). Such a change almost certainly reflects the increased muscle fibre recruitment necessary in the elevator muscles to bring about mandibular closure, so maintaining a relatively constant clinical freeway space. As this process is mediated through the sensormotor system, the response is virtually immediate following the removal of fixation.

These observations are in total contrast to the findings of Wessberg *et al.* (1982a) who failed to reveal any significant change in EMG activity at either the clinical or physiological rest position. Consequently those authors considered that central nervous system adaptation to the new rest position occurred through changes in head posture. All recordings in this study were taken with the patient in a comfortable natural head position, both before and after surgery. Whilst postural changes cannot be excluded it is unlikely that such changes alone could account for the observed variation in EMG activity.

b) Short face group

All patients in this group underwent the same surgical procedure which consisted of a down-fracture Le Fort I osteotomy of the maxilla with an inter-positional bone graft, together with a sagittal split osteotomy of the mandible. Whilst surgery produced a highly significant mean increase in total anterior face height of 4.6 mm, the posterior face height showed a mean increase of only 0.8 mm (SD 2.1mm, 95% CI -0.1 to 1.9 mm), presumably in an attempt to avoid stretching the pterygo-masseteric sling. As a consequence the cant of the occlusal plane increased and this was reflected in the highly significant increase in the maxillary-mandibular planes angle. The occlusion was maintained, however, through the sagittal split procedure on the mandible.

The clinical freeway space showed a mean reduction of 0.7 mm (SD 1.0mm, 95% CI -0.3 to -1.2mm). Again, it would appear that there has

been adaptation or compensation for the surgical change as mediated through the sensormotor system bearing in mind the overall surgical change. Input to the proprioceptive system comes from several sources including the important mechanoreceptors in the periodontal ligaments of the posterior teeth. Despite the change in vertical dimension in the anterior part of the face, sensory input will to a certain extent be initiated once the posterior teeth come into occlusion. As such the change in posterior face height has been accommodated.

The change in the clinical resting vertical dimension was accompanied by a highly significant fall in EMG activity at that position, again presumably in response to sensormotor feedback.

The change in the stimulated resting vertical dimension also displayed a significant reduction in size but bearing in mind the magnitude of the changes involved,it is difficult to suggest whether or not full adaptation had occurred. This change in position was also accompanied by a highly significant fall in measured EMG activity.

The surgical change in vertical dimension increased the distance from origin to insertion of the mandibular elevator muscles. Obviously this would change the physiological resting length. Theoretically in order for the TESP dimension to be maintained post-operatively either the muscle fibres must increase in length or the muscle fibre attachment must migrate over the bone so preserving the resting muscle fibre length. Animal experiments (McNamara *et al.,* 1978) have shown that increasing the vertical dimension through the use of bite-blocks led to the migration of attachment of the elevator muscles but that this effect only occurred some time following insertion of the blocks. Similarly, Goldspink (1976) has shown that muscles can increase their length by addition of sarcomeres or rearrangement of fibre geometry. Although some or all of these physiological adaptations could undoubtedly occur in masseter muscle, the changes observed in the present study would indicate that a longer time span is necessary for complete adaptation.

Table XXVIII - The long term response of the vertical rest positions.

LONG FACE GROUP		Post -op	1 year	mean diff.	95 % CI	Sig.
TAFH	mean	118.2	119.0	0.8	0.0 to 1.6	ns
	SD	8.5	8.5			
	SE	1.9	2.0			
TPFH	mean	69.5	69.6	0.1	-0.8 to 1.0	ns
	SD	7.5	7.7			
	SE	1.7	1.8			
RVD	mean	2.7	2.7	0.0	-0.7 to 0.7	ns
	SD	1.4	0.7			
	SE	0.3	0.2			
TESP	mean	6.1	4.8	-1.3	-1.8 to -0.7	***
	SD	1.4	1.3			
	SE	0.3	0.3			
EMG - RVD	mean	11.5	10.4	-1.1	-4.6 to 2.6	ns
	SD	4.7	6.9			
	SE	1.1	1.6			
EMG - TESP	mean	4.1	3.5	-0.6	-1.6 to 0.4	ns
	SD	3.7	3.2			
	SE	0.8	0.7			
SHORT FACE GROUP						
TAFH	mean	112.1	111.3	-0.8	-2.0 to 0.2	ns
	SD	6.0	6.9			
	SE	1.4	1.6			
TPFH	mean	75.2	74.4	-0.8	-1.5 to -0.1	*
	SD	7.0	7.0			
	SE	1.6	1.6			
RVD	mean	2.7	3.1	0.4	0.0 to 0.8	*
	SD	1.8	1.5			
	SE	0.4	0.3			
TESP	mean	6.3	6.0	-0.3	-0.7 to 0.1	ns
	SD	1.2	1.1			
	SE	0.3	0.2			
EMG - RVD	mean	6.5	8.1	1.6	-1.2 to 4.2	ns
	SD	4.3	4.5			
	SE	1.0	1.0			
EMG - TESP	mean	6.3	6.5	0.2	-1.7 to 2.1	ns
	SD	4.0	3.4			
	SE	0.9	0.8			

Longer term effects

a) Long face group

Examination of the records one year following surgery showed that on average the results were surgically stable with no significant change in either anterior or posterior face heights. The clinical rest position was maintained but there was a highly significant reduction in the inter-occlusal clearance following stimulation. The TESP distance reduced from a mean of 6.1 mm (SD 1.2, 95% CI 5.5 to 6.7mm) to a mean of 4.8 mm (SD 1.3, 95% CI 4.2 to 5.5 mm, $p \leq 0.001$). This latter finding was contrary to the results of Wessberg *et al.* (1982 a) who reported that the partial adaptation in TESP noted following operation was not maintained at 24 months, the physiological freeway space increasing from 1.5 mm to 7.9 mm ($p < 0.05$).

It is difficult to explain why longterm physiological adaptation was noted in the present investigation but not in the study of Wessberg *et al.* (1982a) and obviously further studies are required before definite conclusions can be drawn. The reduction in muscle fibre resting length which, by definition, must have occurred, presumably was mediated through a reduction of sarcomeres in an attempt to maintain or improve muscle tension and efficiency during function. Such changes have been noted previously following a reduction in muscle length in the limb muscles of young rabbits by Alder *et al.* (1958) and in the lateral pterygoid muscle of growing rats in the mandibular displacing experiments of Petrovic *et al.* (1975) and Oudet and Petrovic (1978), all of which reinforced the findings of Goldspink (1976).

The differences in recorded EMG activity at both the RVD and TESP did not change significantly during the follow up period.

b) Short face group

There was relapse in the vertical skeletal relationships produced at the time

of operation and whilst this was not statistically significant for the anterior facial dimension, the posterior relapse was significant and, in essence, complete. It is important to reiterate that the magnitude of the changes were small, but nevertheless there was a consistent trend towards returning to the pre-operative figures.

There were also small but significant changes in the freeway space at both the clinical and physiological rest positions.

The clinical rest position showed a trend to revert back to the original dimension with a mean increase in freeway space of 0.4 mm ($p \leq 0.05$), whilst the physiological inter-occlusal distance continued to reduce. Although the mean change in TESP (0.3 mm) was statistically significant ($p \leq 0.05$) the clinical significance of the change should be considered in the light of the error of the method which was of similar magnitude. The result, however, supports the generally held view that it is impossible to permanently stretch muscle fibres beyond their resting length (McNamara, 1977) and muscular adaptation must take place otherwise surgical relapse will occur.

The differential increase in anterior and posterior face heights produced at surgery would not only stretch the muscle attachments but also change the orientation of the muscle fibres to the occlusal plane. Adaptation would be necessary not only with regard to the resting length but also in relation to altered functional activity. The results of this study would tend to indicate that such adaptation is still occurring up to 12 months following surgery. It will be interesting to relate the results of this aspect of the study to the investigations relating to bite force (see later).

There was no significant change in the level of EMG activity recorded at either the RVD or the TESP, presumably as a result of the large individual variation.

Study 9 - The effect of surgery on mandibular range of motion.

i) Subjects

The effect of surgery on the range of mandibular movement was studied in two ways. Firstly by examination of groups divided on the basis of initial vertical facial dimensions and the subsequent surgery to either increase or decrease those dimensions, and secondly by examination of groups formed on the basis of the actual surgical procedure undertaken. Consequently in the first part of the study (study a) the groups were divided into either short faces or long faces, whereas in the second part (study b) the two groups consisted of those patients who underwent either a mandibular sagittal split osteotomy only, or a combination of a sagittal split procedure of the mandible and a Le Fort I osteotomy of the maxilla. The number of patients who received a maxillary procedure alone was too small for meaningful evaluation.

Measurements were taken prior to surgery, within four to six weeks of the removal of inter-maxillary fixation and approximately one year following surgery. Although 19 long faced and 19 short faced individuals were originally included in the study, only 13 short faced patients and 14 long faced patients completed all three measurements. Statistical evaluation was therefore limited to these 27 patients, the details of which are presented in table XXIX.

Table XXIX - Subjects involved in the range of movement studies

	Number	Males	Females
Study a			
Total	27	11	16
Long face	14	7	7
Short face	13	4	9
Study b			
Total	24	10	14
Mand. surgery	10	3	7
Bimax. surgery	14	7	7

ii) Materials and method.

Measurements were made using the mandibular kinesiograph previously described, and the experimental protocol followed that described in study 8.

iii) Results

The results of the first part of the study with the comparisons both within and between the groups,prior to surgery,following the release of fixation and approximately one year following surgery are presented in tables XXX to XXXIV. The equivalent results for the groups formed according to the type of surgery received are presented in tables XXXV to XXXVII. In all cases the data was normally distributed with variances which satisfied the requirements for parametric statistical analysis.

Table XXX - Mandibular range of motion - Comparison of groups prior to surgery

		Short faces	Long faces	Sig
		(13)	(14)	
Opening	mean	38.5	42.2	ns
	SD	5.0	5.3	
	SE	1.4	1.4	
	95% CI	35.5 to 41.5	39.2 to 45.3	
Right	mean	6.6	4.6	ns
	SD	4.6	3.4	
	SE	1.3	1.0	
	95% CI	3.8 to 9.4	2.6 to 6.6	
Left	mean	6.7	5.7	ns
	SD	4.0	4.3	
	SE	1.1	1.1	
	95% CI	4.3 to 9.1	3.2 to 8.1	
Protr.	mean	4.1	2.2	*
	SD	2.7	1.5	
	SE	0.7	0.4	
	95% CI	2.5 to 5.7	1.3 to 3.1	
		Sagittal split osteotomy	Bimaxillary osteotomy	
		(10)	(14)	
Opening	mean	37.9	40.8	ns
	SD	4.7	5.2	
	SE	1.5	1.4	
	95% CI	34.5 to 41.2	37.8 to 43.8	
Right	mean	6.8	4.8	ns
	SD	3.7	3.3	
	SE	1.2	0.9	
	95% CI	4.1 to 9.5	2.9 to 6.7	
Left	mean	7.6	4.9	ns
	SD	3.7	3.3	
	SE	1.2	0.9	
	95% CI	4.9 to 10.2	3.0 to 6.8	
Protr.	mean	4.4	2.2	*
	SD	2.7	1.0	
	SE	0.8	0.3	
	95% CI	2.5 to 6.3	1.6 to 2.7	

Table XXXI - Mandibular range of motion - Response to surgery

Short face group (13)		Pre-op	Post-op	mean diff.	95% CI	Sig
Opening	mean	38.5	28.2	-10.3	-14.7 to -5.9	***
	SD	5.0	6.2			
	SE	1.4	1.7			
Right	mean	6.6	6.8	0.2	-2.3 to 2.6	ns
	SD	4.6	4.1			
	SE	1.3	1.1			
Left	mean	6.7	6.1	-0.6	-2.7 to 1.5	ns
	SD	4.0	2.7			
	SE	1.1	0.7			
Protr.	mean	4.1	2.7	-1.4	-3.3 to 0.5	ns
	SD	2.7	1.0			
	SE	0.7	0.3			
Long face group (14)						
Opening	mean	42.2	34.3	-7.9	-11.3 to -4.6	***
	SD	5.3	4.7			
	SE	1.4	1.3			
Right	mean	4.6	6.3	1.7	0 to 3.5	*
	SD	3.4	3.4			
	SE	1.0	0.9			
Left	mean	5.7	6.4	0.7	-1.9 to 3.4	ns
	SD	4.3	2.3			
	SE	1.1	0.6			
Protr.	mean	2.2	1.8	-0.4	-1.1 to 0.3	ns
	SD	1.5	1.2			
	SE	0.4	0.3			

Table XXXII - Mandibular range of motion - Change over review period

Short face group (13)		Post-op	Review	mean diff.	95% CI	Sig.
Opening	mean	28.2	35.8	7.6	4.4 to 10.8	***
	SD	6.2	4.8			
	SE	1.7	1.3			
Right	mean	6.8	7.9	1.1	0.4 to 1.9	**
	SD	4.1	3.8			
	SE	1.1	1.1			
Left	mean	6.1	6.8	0.7	-0.3 to 1.7	ns
	SD	2.7	2.7			
	SE	0.7	0.7			
Protr.	mean	2.7	3.2	0.5	-0.3 to 1.3	ns
	SD	1.0	1.0			
	SE	0.3	0.3			
Long face group (14)						
Opening	mean	34.3	36.2	1.9	-0.7 to 4.6	***
	SD	4.7	4.8			
	SE	1.3	1.3			
Right	mean	6.3	7.3	1.0	0.2 to 1.7	*
	SD	3.4	2.9			
	SE	0.9	0.8			
Left	mean	6.4	6.8	0.4	-0.2 to 1.0	ns
	SD	2.3	2.1			
	SE	0.6	0.6			
Protr.	mean	1.8	2.3	0.5	0 to 0.9	*
	SD	1.2	1.0			
	SE	0.3	0.3			

Table XXXIII - Mandibular range of motion - Overall change

Short face group (13)		Pre-op	Review	mean diff.	95% CI	Sig.
Opening	mean	38.5	35.8	-2.7	-6.1 to 0.8	ns
	SD	5.0	4.8			
	SE	1.4	1.3			
Right	mean	6.6	7.9	1.3	-1.2 to 3.9	ns
	SD	4.6	3.8			
	SE	1.3	1.1			
Left	mean	6.7	6.8	0.1	-1.8 to 2.0	ns
	SD	4.0	2.7			
	SE	1.1	0.7			
Protr.	mean	4.1	3.2	-0.9	-2.3 to 0.5	ns
	SD	2.7	1.0			
	SE	0.7	0.3			
Long face group (14)						
Opening	mean	42.2	36.2	-6.0	-9.9 to -2.2	**
	SD	5.3	4.8			
	SE	1.4	1.3			
Right	mean	4.6	7.3	2.7	1.1 to 4.3	**
	SD	3.4	2.9			
	SE	1.0	0.8			
Left	mean	5.7	6.8	1.1	-1.1 to 3.4	ns
	SD	4.3	2.1			
	SE	1.1	0.6			
Protr.	mean	2.2	2.3	0.1	-0.4 to 0.6	ns
	SD	1.5	1.0			
	SE	0.4	0.3			

Table XXXIV - Mandibular range of motion - Response to the surgical procedure

Sagittal split group (10)		Pre-op	Post-op	mean diff.	95% CI	Sig.
Opening	mean	37.9	28.9	-9.0	-14.1 to -3.8	**
	SD	4.7	6.1			
	SE	1.5	1.9			
Right	mean	6.8	5.9	-0.9	-2.0 to 0.2	ns
	SD	3.7	3.1			
	SE	1.2	1.0			
Left	mean	7.6	5.9	-1.7	-4.3 to 1.0	ns
	SD	3.7	2.8			
	SE	1.2	0.9			
Protr.	mean	4.4	2.7	-1.7	-4.0 to 0.5	ns
	SD	2.7	1.0			
	SE	0.7	0.3			
Bimaxillary group (14)						
Opening	mean	40.8	32.6	-8.2	-12.1 to -4.3	***
	SD	5.2	5.7			
	SE	1.4	1.5			
Right	mean	4.8	6.3	1.5	-1.0 to 4.0	ns
	SD	3.3	4.1			
	SE	0.9	1.1			
Left	mean	4.9	6.2	1.3	-0.9 to 3.5	ns
	SD	3.3	2.2			
	SE	0.9	0.6			
Protr.	mean	2.2	1.8	-0.4	-0.9 to 0.3	ns
	SD	1.0	1.2			
	SE	0.3	0.3			

Table XXXV - Mandibular range of motion - Surgical procedure groups

change over the review period

Sagittal split group (10)		Post-op	Review	mean diff.	95% CI	Sig.
Opening	mean	28.9	35.9	6.5	2.2 to 10.9	**
	SD	6.1	4.8			
	SE	1.9	1.3			
Right	mean	5.9	7.0	1.1	0.2 to 1.8	*
	SD	3.1	3.4			
	SE	1.0	1.1			
Left	mean	5.9	6.8	0.9	-0.4 to 2.2	ns
	SD	2.8	2.4			
	SE	0.9	0.8			
Protr.	mean	2.7	3.4	0.7	-0.4 to 1.8	ns
	SD	1.0	1.2			
	SE	0.3	0.4			
Bimaxillary group (14)						
Opening	mean	32.6	35.6	3.0	-0.2 to 6.3	ns
	SD	5.7	4.1			
	SE	1.5	1.1			
Right	mean	6.3	7.6	1.3	0.4 to 2.1	**
	SD	4.1	3.5			
	SE	1.1	0.9			
Left	mean	6.2	6.6	0.4	-0.3 to 1.0	ns
	SD	2.2	2.1			
	SE	0.6	0.6			
Protr.	mean	1.8	2.3	0.5	0 to 0.9	ns
	SD	1.2	0.9			
	SE	0.3	0.2			

Table XXXVI - Mandibular range of motion - Surgical procedure groups

overall change

Sagittal split group (10)		Pre-op	Review	mean diff.	95% CI	Sig.
Opening	mean	37.9	35.9	-2.0	-6.5 to 1.6	ns
	SD	4.7	4.8			
	SE	1.5	1.3			
Right	mean	6.8	7.0	0.2	-1.3 to 1.6	ns
	SD	3.7	3.4			
	SE	1.2	1.1			
Left	mean	7.6	6.8	-0.8	-2.9 to 1.3	ns
	SD	3.7	2.4			
	SE	1.2	0.8			
Protr.	mean	4.4	3.4	-1.0	-2.6 to 0.5	ns
	SD	2.7	1.2			
	SE	0.8	0.4			
Bimaxillary group (14)						
Opening	mean	40.8	35.6	-5.2	-9.4 to -0.9	*
	SD	5.2	4.1			
	SE	1.4	1.1			
Right	mean	4.8	7.6	2.8	0.5 to 4.9	*
	SD	3.3	3.5			
	SE	0.9	0.9			
Left	mean	4.9	6.6	1.7	-0.4 to 3.7	ns
	SD	3.3	2.1			
	SE	0.9	0.6			
Protr.	mean	2.2	2.3	0.1	-0.3 to 0.6	ns
	SD	1.0	0.9			
	SE	0.3	0.2			

Table XXXVII - Mandibular range of motion - Comparison of effects of the different surgical procedures.

		Sagittal split osteotomy (10)	Bimaxillary osteotomy (14)	Sig
Opening	mean	-9.0	-8.2	ns
	SD	7.2	6.7	
	SE	2.3	1.8	
	95% CI	-14.1 to -3.8	-12.1 to -4.3	
Right	mean	-0.9	1.5	ns
	SD	1.5	4.3	
	SE	0.5	1.1	
	95% CI	-2.0 to 0.2	-1.0 to 4.0	
Left	mean	-1.7	1.5	ns
	SD	3.7	3.8	
	SE	1.2	1.0	
	95% CI	-4.3 to 1.0	-0.9 to 3.5	
Protr.	mean	-1.7	-0.4	ns
	SD	3.2	1.0	
	SE	1.0	0.3	
	95% CI	-4.0 to 0.5	-0.9 to 0.3	

Maximum opening

Although the long faced group showed a slightly greater mean maximum opening prior to surgery (3.7 mm), the difference between the groups was not significant. Following surgery and the release of fixation, both groups showed a significant reduction in opening. Such a change was perhaps to be expected following a period of immobilization and an obvious unease on behalf of the patients to open too widely. The short face group reduced by a mean of 26.8% of the pre-operative value, whereas the long faced group showed an 18.8% reduction.This variation coupled with the slightly greater extent of opening in the long face group prior to surgery resulted in a significant difference ($p \leq 0.01$) in maximum opening between the between the two groups.

Considering the effect of the two surgical approaches, both operative procedures initially produced a significant reduction in maximal opening, but the difference between the types of surgery was not significant.

These results are in agreement with those of Aragon *et al.* (1985) in that they similarly noted a reduction in all surgical groups at six or more months following operation but that there was no significant difference between those patients who had experienced an isolated sagittal split osteotomy of the mandible and those who had undergone a bimaxillary procedure.

One year following operation, the short face group showed an increase in opening compared to the post-operative mean values, the average opening being 93% of the pre-operative measurement. This was at variance,however, to the results for the long face group which showed a minimal amd non-significant increase compared to the post-operative figures, with the maximal opening achievable being 86% of the mean figure prior to surgery.

Considering the groups on the basis of operative procedure, although

maximal opening increased in both groups over the review period, the mean figure observed for those patients who had experienced a mandibular procedure alone was more than double that exhibited for the bimaxillary group. As by far the majority of patients in the long face group underwent bimaxillary surgery the results are perhaps to be expected.

Left and right lateral movements

There was no significant difference in the range of lateral excursive movements between the groups at the start of treatment. Surgery had a variable effect both between groups and within groups with respect to side of movement. Overall there was a tendency for the range of movement to increase both following surgery and continuing over the review period, although this failed to reach a significant level in the majority of comparisons. There were ,however, significant increases in the extent of movement to the right in the long face group following surgery and again over the follow-up period. This group showed a low initial value for right lateral excursion which probably was a reflection of the greater incidence of buccal segment crossbites in this group compared to the short face group. Since lateral excursive movements were undertaken without vertical opening the presence of crossbites would limit the extent of lateral movement.

Although the mean values for the change in right and left lateral movement following surgery showed a slight hypomobility in the sagittal split group, these figures were not significantly different from the overall slight hypermobility seen in the bimaxillary surgery group. On the whole these results support the findings of Aragon *et al.*(1985) who similarly noted a small but not significant reduction in the lateral excursive movements following sagittal split osteotomies but they failed to observe any significant differences between the various types of osteotomy.

Protrusion

The extent of anterior protrusion was more or less maintained following

surgery and over the review period with the changes approximating the error of the method. Similarly there was no significant variation in response to the type of surgery undertaken. These results are in partial agreement with those of Aragon *et al.* (1985) who, despite noting a significant reduction ($p \leq 0.05$) in protrusion following surgery in their Le Fort I/ sagittal split group, failed to observe any significant differences when the different operative procedures were compared.

Discussion of the EMG and Kinesiograph studies

Overall the results of the study into the comparisons of EMG activity in the long and short face groups were rather disappointing and it was difficult to draw meaningful conclusions in view of the large variation between individuals of the same group. However, it was interesting to note that despite the large variation in the levels of resting activity of the anterior temporalis and masseter muscles, there was the suggestion that a reciprocal level of activity occurred between the muscles, although it was noted that the error of the method and the coefficient of reliability suggested that results for resting activity should be viewed with caution. The exact mechanism behind this possible relationship was unclear.

In view of the variation in results when EMG activity was assessed during the various tasks, it was not surprising that the overall correlation between EMG activity and the principal components of facial form failed to reach a level of statistical significance.

The use of the mandibular kinesiograph proved extremely reproducible and reliable in the assessment of mandibular movement. The results, once again, emphasized the need to be specific in terminology when discussing the rest position of the mandible with respect to the rest of the face, and in particular the maxilla. The two distinct rest positions were confirmed, namely the clinical and physiological rest positions. The increase in the freeway space having overridden the muscle proprioceptive feedback mechanism was, in accordance with previous workers, a universal finding.

Although the mean freeway space at both the clinical and physiological rest positions was larger in the short face group, compared to the long face group, this difference was statistically significant only at the physiological position. The amount of EMG activity recorded in masseter muscle was, however, significantly higher in the vertically deficient group at both rest positions.

Further information as to the mechanisms of muscular adaptation was gained from study 8. Surgical alteration of the vertical facial heights was accompanied by an immediate adaptation of the clinical freeway space, presumably mediated through the proprioceptive system, and accompanied by a significant alteration in the level of recorded EMG activity. The physiological rest position partially adapted to the skeletal change immediately following operation, but continued to adapt up to twelve months post-surgery, especially in the vertical excess group. Such change may have occurred as a result of an alteration in muscle fibre resting length, perhaps mediated through a reduction of sarcomeres although this was impossible to prove, in an attempt to maintain or improve muscle tension and efficiency during functional activities.

The results have demonstrated once again that any increase in posterior vertical facial dimension is prone to relapse in the long term. At least three possibilities exist as to how this may occur. Firstly, stretching of the pterygo-masseteric sling could lead to increased tension at the osteotomy site with bone resorption and loss of vertical dimension. Secondly, in an attempt to maintain an efficient muscular system, both at rest and during function, muscle adaptation could occur through migration of the attachments in preference to increasing the number of sarcomeres. As a consequence, the area of bone devoid of attachment could remodel or resorb thereby reducing the vertical height. Thirdly, a combination of these two hypotheses could exist. Unfortunately the cephalometric measurements recorded in the study did not allow determination as to which, if any, of the possibilities occurred.

The effect of surgery on the mandibular range of motion demonstrated a clinically and statistically significant reduction in the amount of mandibular opening in all groups, irrespective of the operative procedure performed. Whilst there was a tendency for the extent of opening to improve in patients who experienced mandibular surgery alone, the increase was significantly less in the bimaxillary group.

Aragon *et al.* (1985) concluded their study by saying that since orthognathic procedures produce reduced opening there was therefore a "critical need" to provide muscular rehabilitation programmes for patients following surgery. The results of the present study, which observed patients over a longer period following surgery, would indicate that mouth opening continues to improve spontaneously. A comparison of the extent of opening prior to surgery and that achieved at one year following operation showed no significant difference for the sagittal split group, but the difference remained significant ($p \leq 0.05$) for the bimaxillary surgery group. The question as to whether a return to the pre-surgical level of opening is desirable in those patients with a long face is debatable as it could be argued that a reduced opening is indicative of successful muscular adaptation.

Lateral and protrusive movements displayed little variation either in response to surgery or over the recovery period.

Chapter 5

OCCLUSAL FORCE STUDIES

i) The relationship between occlusal force and facial morphology

Although studies of bite or masticatory force levels date back to the 19th century, investigations into possible relationships between facial morphology and isometric bite forces have mainly been undertaken over the last two decades.

Sassouni (1969) reported that deep bite subjects had a maximum molar bite force of 150 - 200 lbs (approx. 68 - 91 kg) whereas comparative figures for open bite individuals were 50 - 80 lbs (23 - 36 kg).

Ringqvist (1973a) recorded maximum voluntary isometric bite force in 29 healthy females aged 19 - 23 years, using a dynamometer incorporating strain gauges previously described by Linderholm and Wennstrom (1970). This apparatus gave a 4 mm separation of the teeth in the molar region and 6 mm between the incisors. Maximum bite force was recorded as 29.9 kg (range 20.5 - 45.7 kg) in the incisor region and 47.7 kg (range 30.8 - 69.3 kg) in the molar area. The results showed a positive correlation between maximum bite and mandibular prognathism, parallel dental bases and a small gonial angle. The author considered the results to be an expression of a positive correlation between the size of a bone and the size of its muscles but emphasised that this expression was only valid when the dental and/or jaw relationships were within normal limits.

Ingervall and Helkimo (1978) compared molar bite force with facial dimensions in 50 female students with a mean age of 24.8 years. Those students with the greatest bite force were noted to have smaller anterior face heights and greater posterior face heights, smaller gonial angles and parallelism of the lower occlusal and mandibular planes when compared with the 25 students exhibiting the weakest maximum bite force.

Finn *et al.* (1980a) compared maximum incisor and molar bite forces in five

patients with the short face syndrome and eight patients with long face characteristics. The mean results showed that in the incisor region the short faced group produced 29.2 kg force, which was almost double the corresponding value for the long faced individuals (14.8 kg). The authors did comment that some of the long face group found it impossible to produce an incisor registration. In the molar region, the short face group showed a mean force of 72.0 kg whilst the long face group produced a mean force of 30.5 kg.

Proffit *et al.* (1983) studied occlusal forces in normal and long faced adults using piezo-foil force transducers, giving 2.5 mm molar separation, as well as using quartz transducers giving 6mm separation. The average maximum bite force recorded at 2.5 mm opening was 31.0 kg (SD 20.0 kg) for 21 patients in the normal group compared with 11.2 kg (SD 7.9 kg) for the 19 patients in the long faced adults. At 6.0 mm separation, the normal values were 35.6 kg (SD 18.7 kg) compared with 15.5 kg (SD 10.5 kg) for the long face group.

It is apparent from the literature that there are large variations between individuals and between studies as to the absolute values of bite force recorded. As mentioned by Proffit *et al.* (1983) these variations may be related to such factors as the degree of dental separation and hence muscle fibre length and efficiency, the type of transducers used, the exact location of the measuring equipment in the mouth and its relationship to the occlusal plane, as well as the quality of the dentition and periodontal status (Proffit *et al.*, 1989). Although Linderholm and Wennstrom (1970) failed to find a correlation between isometric bite force and general muscle force or body build, Proffit *et al.* (1983) further speculated that the large variations in bite force observed may be due partly to individual differences in muscle strength and partly due to the respective jaw muscle lever systems.

Saski *et al.* (1989) in a study of 11 healthy adults with normal cranio-facial morphology employed magnetic resonance imaging as well as lateral skull cephalograms and study casts to evaluate the role of muscle cross-sectional

size and lever arms in bite force production. Although no significant correlation was found between the muscle or bite-point lever arms, highly significant correlations occurred between the cross-sectional size of masseter and medial pterygoid muscles and the bite force recorded. Jaw muscle size would therefore appear to explain most of the variation in bite force reported.

ii) Changes in occlusal force in response to surgery

Orthognathic surgery has the potential to affect occlusal force in at least two ways: mechanically by altering jaw geometry so changing the mechanical advantage of the muscle lever system and physiologically by changing the sensory and proprioceptive inputs or other physiologic variables (Proffit *et al.*, 1989).

The effect of orthognathic surgery on occlusal force measured during chewing, swallowing and maximum effort was studied by Proffit *et al.* (1989). A total of 70 patients had surgery to correct a mandibular deficiency, mandibular prognathism or a long face condition by repositioning of the maxilla and/or mandible. Overall, larger changes than could simply be explained by geometric alterations were observed in all groups. Interestingly despite sizeable mean alterations in skeletal variables, the mechanical advantage changes were not significant.

b) Aims of the occlusal force studies.

Occlusal force measurement is a non-invasive technique which provides further information as to muscle function. The aims of these studies were: firstly, to provide further evidence as to whether or not a difference exists in force levels between long and short faced individuals. Secondly, to ascertain whether or not a relationship exists between measured force and patterns of variables representing cranio-facial morphology, and thirdly, to observe the effect of orthognathic surgery on occlusal force generation.

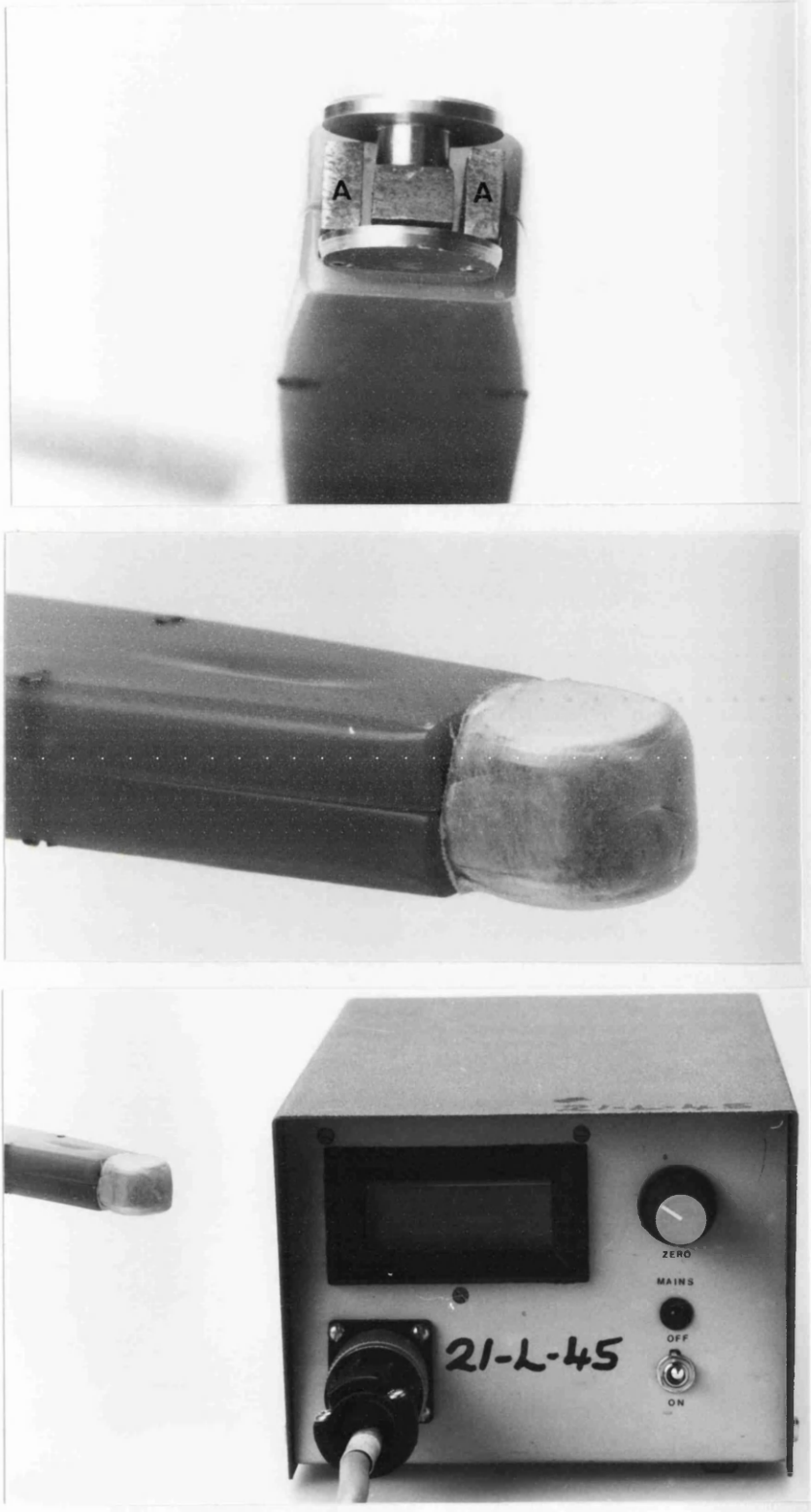
c) Equipment for measuring occlusal force

Maximum occlusal bite force was measured using a custom built bite force gauge. The transducer element was constructed from Nickel / Chrome alloy steel and consisted of two parts (Fig 44). The first was machined to form a rectangular bar (part A) with one end shaped into three horizontal prongs. The second element was machined into a U-shaped channel with the vertical parts of the U supporting the outer prongs of part A, leaving the central prong unsupported. A circular plate was attached to the central prong in order to direct the applied force vertically. In this way any glancing force was incorporated in the movement so enabling the effect of minor variations in localized occlusal plane angulation to be reduced. The resulting strain was monitored using a half bridge circuit from two strain gauges mounted on the upper and lower surfaces of the central prong of the transducer. The bridge was completed with two wire wound precision resistors. The power supply was constructed on a ready made printed circuit board employing a dual $\pm$ 15 volt regulator. A strain gauge amplifier chip driven from a $\pm$ 15 volt supply produced an overall circuit gain of approximately 1000.

The output from the strain amplifier was displayed on a digital voltmeter module (figure 44), calibrated to indicate kilogrammes force units. The instrument was designed to measure and detect forces between zero and 100 kg.

In order to provide increased hygiene and comfort when biting on to the steel bar, an alginate impression was taken of the transducer head, a stone cast poured and 3 mm thick thermoplastic disposable sheaths[9] prepared using a Drufomat drawing machine[10] and which easily slipped over the transducer elements. The overall opening produced by the strain gauge system was 9mms.

Figure 44 - The customized bite force gauge



Pressure on the circular plates is transmitted to the central unsupported bar with the resulting strain amplified prior to display on the digital voltmeter. The thermoplastic disposable sheaths provided improved comfort during the biting exercises.

d) Subjects and method

42 patients agreed to participate in the bite force investigations. Using the grouping scheme based upon weighted cephalometric variables, 17 and 25 patients were classified as belonging to the short and long face groups respectively. The details of the patients are shown in table XXXVIII.

Table XXXVIII - Subjects involved in the occlusal force studies

	Males	Females	Total
Short face group	7	10	17
Long face group	10	15	25
Combined group	**17**	**25**	**42**

The bite force measurements were taken with the transducer placed against the occlusal surface of the lower right first molar tooth with the patient asked to close onto the gauge in a natural closing arc.

The recordings were taken in the natural head position. The patient was asked to bite onto the gauge until the plastic sleeve "gave" then on the command of "bite hard" the highest recorded value on the screen was noted. Visual feed-back encouraged the subjects to generate the highest possible force levels. Between three and five measurements were taken with a 30 second interval between recordings to allow muscle recovery and to ensure that the digital read-out reset to zero between each measurement. The overall maximum values were recorded.

The recordings were taken prior to the start of any treatment, within three and six months of operation and again at approximately 12 months

following surgery.

e) Error of the method of the bite force system.

In order to assess the reproducibility of the system and the overall error of the method of bite force registration, measurements were taken of 8 healthy postgraduate students and dental surgery assistants on two occasions with a minimum time interval of two months. The Dahlberg error and percentage coefficient of reliability are presented in table XXXIX.

Table XXXIX - The error of the method of the bite force measurements

	Dahlberg error	% Coeff. of reliability
Within visit	0.65	99.6
Between visits	1.87	97.3

Units : Kg.

It is very difficult to draw meaningful comparisons between the method errors as shown in this study with those occurring in previous studies utilizing different measurement systems as many of the previous studies have failed to include such figures in their reports. The exceptions to this were Linderholm and Wennstrom (1970) and Ringqvist (1973a) both of whom recorded the method error as a coefficient of variation. Linderholm and Wennstrom reported a figure of 4.1 % for maximum molar bite whilst Ringqvist (1973a) gave figures of 5.8 % for the incisor bite and 5.3 % for the molar force. The results for the equipment and technique used in the present study would, therefore, appear favourable, particularly in relation to the size of force recorded.

Study 10 - Occlusal force in relation to facial morphology

i) A comparison of the long and short face groups prior to surgery

Table XXXX - Comparison of the bite force of the long and short face groups prior to surgery

		Males	Females	Sig	Combined		Sig SF vs LF
Short face group	mean	36.7	35.9	ns	mean	36.2	*
	SD	16.9	10.7		SD	13.1	
	SE	6.4	6.4		SE	3.2	
					95% CI	29.5 to 43.0	
Long face group	mean	32.8	23.3	ns	mean	27.1	
	SD	16.7	11.1		SD	14.1	
	SE	5.3	2.9		SE	2.8	
					95% CI	21.3 to 32.9	

Table XXXX shows the overall results for the maximum bite force recorded in the molar region for the long and short faced groups prior to surgery. The ratio of males to females was approximately equal in both groups and although the males recorded a larger mean bite force, the difference between the sexes was not statistically significant. This finding was also reported by Linderholm and Wennstrom (1970) who interestingly failed to find any correlation between bite force and general body build.

Analysis based on mean figures for the combined sexes showed that the difference between the groups was probably significant at the 5 % level. In accordance with the results of previous workers, the short face group demonstrated higher force levels than their long face counterparts but it is important to stress that the range of individual variation was large.

The average maximum bite force for the long face group was 27.1 kg (SD 14.1 kg, 95% CI 21.3 to 32.9) and these figures are in accordance with those reported by Finn *et al.* (1980a) in their sample of 8 patients which gave a mean force of 30.5 kg. Unfortunately the range was not reported. The measurement in the present study was taken with a molar separation of 9 mm whilst the study of Finn *et al.* (1980a) used a force gauge which separated the molar teeth by 10mm. Proffit *et al.*(1983) on the other hand used piezo-foil transducers with recordings taken at 2.5 mm and 6 mm. Their results showed much lower values for the long face group with forces of 11.2 kg (SD 7.9 kg) and 15.5 kg (SD 10.5 kg) respectively. The present results do tend to confirm the suggestion of Proffit *et al.* (1983) that bite force increases with greater molar separation.

The results for the short face group in the present study were considerably lower than those reported by Finn *et al.* (1980a) and indeed more closely approximated the force levels reported by Proffit *et al.* (1983) as occurring in normal individuals (35.6 kg SD 18.7 kg) at a molar separation of 6 mm. It is not clear why this should be although the underlying skeletal discrepancy may have been less marked in the short face group.

ii) The correlation of molar bite force with facial form

In order to study the possible relationships between the dimensions of the facial skeleton and the occlusal force, the total of 42 patients were considered as a whole.

Correlations of cephalometric variables with molar bite force were small with the two skeletal variables recording the highest correlations being the FMPA (r = -0.41) and the gonial angle (r = -0.40). The correlations with the principal components of the cranio-facial variables were low with only the correlation with the 1st principal component reaching statistical significance (r = -0.36, $p \leq .05$). The canonical correlation coefficient for the combined principal components was 0.55, which was not significant.

Table XXXXI - Correlations between molar bite force and facial form

	FMPA	Ar-Go-Me	LAFH	OJ	OB
BF	- 0.41	-0.40	-0.34	0.45	0.41
Sig.	**	**	*	**	**

	PRIN #1	PRIN #2	PRIN #3	PRIN #4	PRIN #5	PRIN #6	PRIN #7
BF	-0.36	-0.16	0.21	0.13	0.25	0.07	-0.15
Sig.	*	ns	ns	ns	ns	ns	ns

	Canon. Coeff.	Coeff^2	Eigen.	Sig.	Prop^n. of var. of form expl^d.	Prop^n. of var. of bite expl^d.
1st.	0.55	0.31	0.44	ns	0.04	0.31

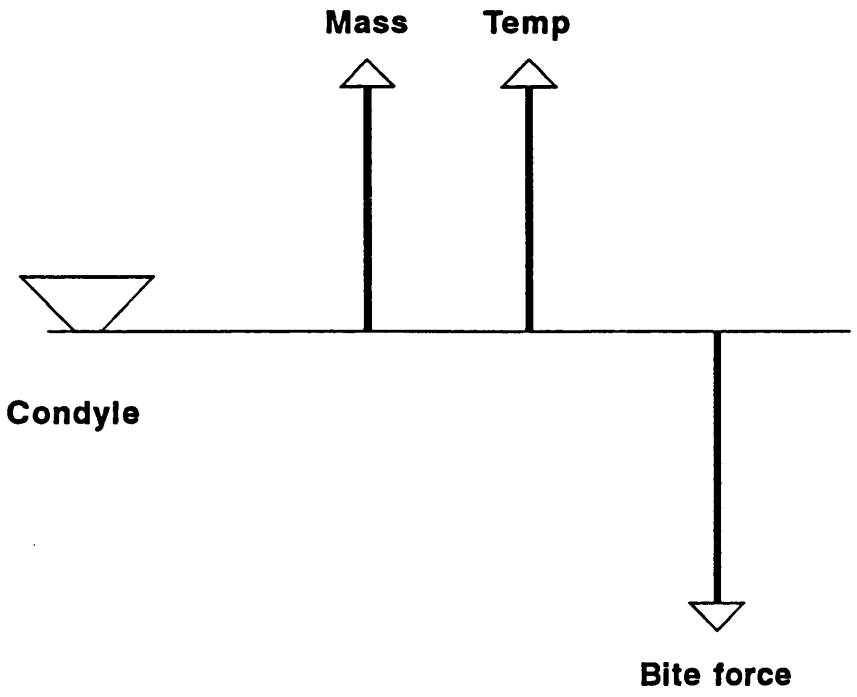
As was previously discussed in study 4, the first principal component represents a general index of the vertical relationship of the mandible to the skull and whilst not implying a cause and effect relationship there is a tendency for the maximum occlusal force to decrease with increasing vertical dimension. The second principal component reflects the antero-posterior jaw relationship but there was no significant association with the occlusal force. Interestingly, the highest correlation with bite force related to incisor overjet (r = 0.45, $p \leq 0.01$) illustrating the importance of differentiating between skeletal and dental variables.

These results support the findings of Ringqvist (1973a) with regard to the gonial angle and parallelism of the horizontal facial planes but they do not support her results regarding the antero-posterior jaw relationship.

The results also give some information as to the validity of the hypothesis that the measured occlusal force is simply a reflection of the geometric arrangement of the lever system of the jaw as proposed by Throckmorton *et al.* (1980).

When the patient bites on the gauge, a torque is produced which is equal and opposite in direction to the sum of the torque produced by the mandibular elevator muscles. This torque is the product of the perpendicular distance from the molar to the condyle (the moment arm) multiplied by the bite force. As there is no overall movement of the jaw during isometric measurement, the bite force torque must exactly equal the muscle forces. In these experiments the mechanical advantage of the muscles can be considered as the ratio of the moment arm of the muscle to the moment arm of the load at the bite force gauge (see figure 45).

Figure 45 - Stylized mandibular lever system
(Adapted from Throckmorton *et al.*, 1980)



As Throckmorton *et al.* (1980) demonstrated, moving the point of occlusal measurement away from the condyle reduces the mechanical advantage of the adductor muscles by increasing the moment arm of the load. Consequently class II patients would be expected to exhibit greater mechanical advantage than class III individuals. As mentioned, however, there was no significant correlation with the cephalometric parameters representing antero-posterior skeletal relationships.

Conversely, the mechanical advantage of the masseter and temporalis muscles can be increased by lengthening the muscle moment arm through anterior and/or inferior repositioning of gonion, as in the case of masseter, or anterior and/or superior repositioning of the coronoid process as in the case of temporalis muscle.

It would be expected, therefore, that long face patients with a small posterior face height and a posterior position of gonion, would exhibit a reduced mechanical advantage when compared to short faces and hence an equivalent effort by the muscle would produce less force at the level of the occlusion. The results of the present study support this aspect of the hypothesis.

The results of the theoretical analysis of mechanical advantage of 20 long faced patients, 27 short faced individuals and Bolton standards for 18 year-old males (Throckmorton *et al.*, 1980) confirmed that the short faced group had the significantly greater mechanical advantage for the masseter muscle when compared to the long faced group. Interestingly, although also larger than the Bolton standard this difference was not significant.

iii) Correlation of bite force with muscle orientation

Correlations between the muscle orientation angles relative to the lower occlusal plane and the maximum bite force levels were low (r = -0.37 and -0.33, $p \leq 0.05$). Furthermore, if the orientation angles as a group were correlated with the occlusal force measures, the canonical correlation

Table XXXXII - Correlation of molar bite force with muscle orientation

	UOPMASS	LOPMASS	UOPAT	LOPAT	UOPPT	LOPPT
BF	-0.17	-0.37	-0.13	-0.33	-0.11	-0.37
Sig.	ns	*	ns	*	ns	*

	Canon. Coeff.	Coeff^2.	Eigen.	Sig.	Prop^n. of var. of orient^n. expl^d.	Prop^n. of var. of bite expl^d.
1st	0.41	0.17	0.20	ns	0.07	0.17

coefficient was also low (r = 0.41) even though statistically significant at the $p \leq 0.05$ level. These figures are surprisingly low considering the correlations cited above.

Finally, the maximum biting force was correlated with the number of occlusal contacts present in the pre-operative dentition. This was assessed somewhat crudely by asking the patient to bite into a full arch pre-fornmed wax wafer and counting the number of perforations. The correlation was extremely low (r = 0.08).

Study 11 - The effect of orthognathic surgery on occlusal force.

i) Method.

The 42 patients were observed following surgery with molar bite force registrations taken at approximately three, six and twelve months after the operation. The measurement procedure followed that as described in the pre-operative study.

ii) Results.

Table XXXXIII - The effect of surgery on occlusal force

Short face group (17)	Pre-op (1)	3 mths post-op (2)	6 mths post-op (3)	12 mths post-op (4)
mean	36.2	20.5	27.8	33.4
SD	13.1	9.5	9.8	10.1
SE	3.2	2.3	2.4	2.5
95% CI	29.5 to 43.0	15.6 to 25.4	22.8 to 32.8	28.1 to 38.6
Sig.		(1) to (2) ***	(2) to (3) ***	(3) to (4) ** (1) to (4) ns
Long face group (25)				
mean	27.1	16.8	26.3	35.6
SD	14.1	9.1	12.6	16.8
SE	2.8	1.8	2.5	3.4
95% CI	21.3 to 32.9	13.1 to 20.6	21.1 to 31.5	29.7 to 42.5
Sig.		(1) to (2) ***	(2) to (3) ***	(3) to (4) *** (1) to (4) ***

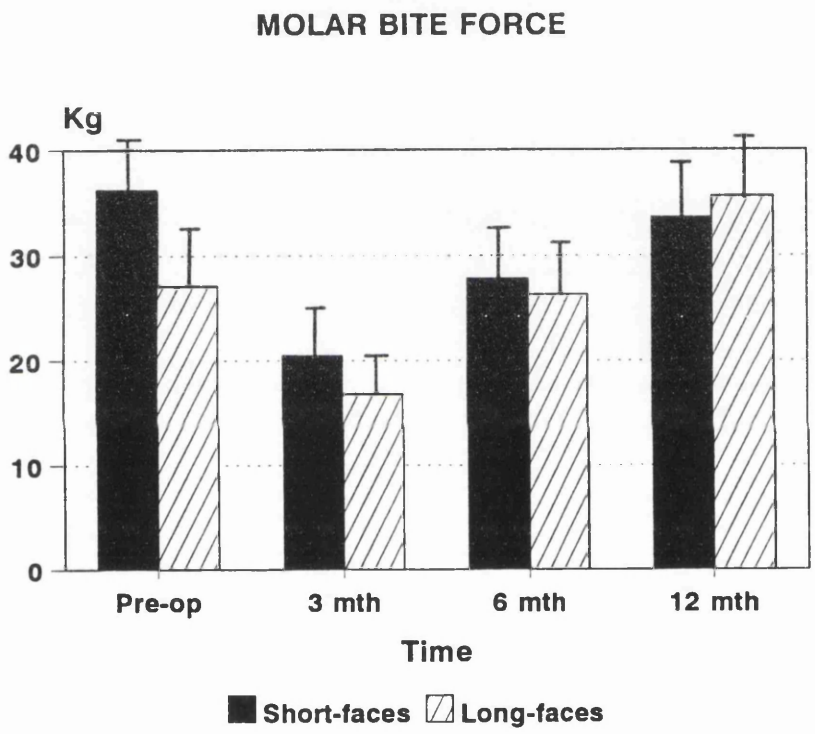
The mean results for the long and short faced groups are presented in table XXXXIII.

One of the most consistent findings was that at three months, 40 of the 42 patients showed a fall in the level of the maximum biting force. The two exceptions were from the long face group. In the short face group the fall was to almost 57 % of the pre-operative value, whilst the long face group showed a smaller reduction to 62 % of the original level. Both these changes were highly significant.

A fall in maximum occlusal force at this stage is to be expected. Firstly, all

patients were placed in intermaxillary fixation for between six and eight weeks. Full recovery of jaw movement and function would be unlikely to occur after a period of only four to six weeks. Secondly, it was readily apparent from a clinical point of view that the patients themselves were anxious and hesitant towards clenching too hard with a risk of disruption to the healing process.

Figure 46 - The change in maximum occlusal force following surgery



At six months the results were again fairly consistent in that 40 of the 42 patients demonstrated a "recovery" from their post-operative level. Again the two exceptions were from the long face group although they were not the same patients noted as exceptions at the three month stage. Whilst the increase in force between three and six months was highly significant within each group, the extent to which the "recovery" occurred was extremely variable both within and between groups. In the short face group, five of the

17 patients (29 %) generated a force in excess of the pre-operative value whilst the remainder stayed below that recorded initially. In the long face group, 13 patients (52 %) produced a force equal to or above that recorded prior to operation.

Between six months and one year all but four patients (one short face, three long face) continued to increase the force level generated. The difference in mean recordings was statistically significant in the short face group, and highly significant in the long face group. The mean figure for the short face group represented 92 % of the pre-operative value with the difference between the initial and final readings being non-significant, whereas the long face individuals increased to 131 % of the original recorded level, a change which was highly significant statistically.

iii) The comparative effects of the surgical procedures on occlusal force

Reclassification of the 42 patients involved in the occlusal force studies according to their definitive operative procedure, resulted in surgical groups of sufficient size to merit analysis.

The groups consisted of 10 patients who experienced a forward sliding sagittal split osteotomy of the mandibular ramus, 10 patients with a backward movement sagittal split osteotomy and 15 patients who underwent bimaxillary surgery involving a Le Fort I impaction osteotomy of the maxilla coupled with a sagittal split osteotomy of the mandible in order to produce a class I occlusion. The remaining seven patients were not included as they formed two small groups who either had a Le Fort I osteotomy alone or a combination of an inferior positioning Le Fort I and a mandibular sagittal split. The details of the patients are presented in table XXXXIV, and the results in table XXXXV.

Table XXXXIV - Subjects classified according to surgical procedure

Operation	Males	Females	Total
Forward sag. split	4	6	10
Backward sag. split	1	9	10
Bimax. osteotomy	11	9	15

A one-way analysis of variance showed a significant difference between the groups prior to surgery and unpaired *t* tests confirmed that the maximum occlusal force generated by the forward sliding sagittal split group was significantly higher ($p \leq 0.05$) than the bimaxillary group. This was not surprising as nine of the ten patients in the forward sliding sagittal split group were from the previously described short face group whilst all the patients who recieved bimaxilary surgery were from the long face group.

Surgery had the effect of reducing the level of maximum occlusal force in all groups with the effect being most marked in the forward sagittal split group. Consequently, at three months following operation, there was no significant difference between the three groups.

Occlusal force levels increased significantly in all three groups in both the periods three months to six months and six months to one year following operation. On average the bimaxillary group showed the largest and most significant increase up to six months but thereafter the increases were of similar magnitude across the groups. In all groups the range of individual variation was large.

Table XXXXV - The comparative effects of surgery on molar bite force

		mean	SD	SE	95% CI	Sig. (ANOVA)
PRE-OP	Fwd. sag.	40.0	15.2	4.8	29.1 to 50.9	*
	Back. sag.	31.3	14.2	4.5	21.1 to 41.1	
	Bimax.	24.3	9.9	2.6	18.9 to 29.8	
3 MONTHS POST-OP	Fwd. sag.	19.0	9.3	2.9	12.3 to 25.7	ns
	Back. sag.	23.3	11.4	3.6	15.1 to 31.4	
	Bimax.	14.5	6.8	1.8	10.7 to 18.3	
6 MONTHS POST-OP	Fwd. sag.	26.6	10.6	3.3	19.0 to 34.1	ns
	Back. sag.	29.8	13.9	4.4	19.9 to 39.8	
	Bimax.	25.0	10.1	2.6	19.4 to 30.6	
1 YEAR POST-OP	Fwd. sag.	32.8	9.3	2.7	26.1 to 39.5	ns
	Back. sag.	38.2	16.7	5.3	26.3 to 50.1	
	Bimax.	32.7	14.8	3.8	24.5 to 40.9	

Comparison between pre-op groups

Fwd. sag. vs Back. sag. - ns
Fwd. sag. vs Bimax. - *
Back. sag. vs Bimax. - ns

Comparisons between time intervals

		mean	SD	SE	95% CI	Sig.
PRE-OP to 3 MONTHS POST-OP	Fwd. sag.	- 21.0	11.6	3.7	-29.4 to -12.7	***
	Back. sag.	- 8.0	6.1	1.9	-12.3 to - 3.7	**
	Bimax.	- 9.8	9.7	2.5	-15.2 to - 4.4	***
3 MONTHS to 6 MONTHS POST-OP	Fwd. sag.	+ 7.6	7.6	2.4	2.1 to 13.0	*
	Back. sag.	+ 6.6	7.2	2.3	1.4 to 11.7	*
	Bimax.	+10.5	7.9	2.0	6.1 to 14.9	***
6 MONTHS to 1 YEAR POST-OP	Fwd. sag.	+ 6.2	7.6	2.4	0.8 to 11.7	*
	Back. sag.	+ 8.4	5.8	1.8	4.2 to 12.5	**
	Bimax.	+ 7.7	8.0	2.1	3.2 to 12.1	**
PRE-OP to 1 YEAR POST-OP	Fwd. sag.	- 7.2	15.8	5.0	-18.5 to 4.1	ns
	Back. sag.	+ 6.9	10.6	3.4	- 0.7 to 14.5	ns
	Bimax.	+ 8.4	10.5	2.7	2.5 to 14.1	**

Considering the overall change, as measured before surgery to the end of the review period, the mean change for the forward sliding group showed a net reduction in force of 7.2 Kg. (18%), whilst the backward sliding and bimaxillary groups displayed a net increase in force levels of 6.9 Kg. (31%) and 8.4 Kg.(35%) respectively. Again, individual variation within groups was noted and as a consequence the comparison of initial and final force levels was not statistically significant for the two sagittal split only groups. Variation was less marked in the bimaxillary group in whom all but one patient displayed a net increase in force.

Comparison of the results of this study with those of other workers must be restricted to the mandibular procedures alone as no one has previously reported findings in relation to a bimaxillary sample. Proffit *et al.* (1989) measured occlusal force in patients before and after mandibular advancement or set-back, at 2mm and 6mm jaw separation. Whilst marked individual variation was noted, the results recorded at the 6mm jaw separation,which most closely allies towards the present investigation, were at variance with those presented above. Those patients in whom the mandible was brought forward showed a mean increase in maximum occlusal force above the pre-operative level, at six months following operation but this subsequently reduced over the following six months period. Those patients in whom the mandible was posteriorly positioned showed a mean decrease in force of approximately 6% at six months but this subsequently increased after one year, such that there was an overall increase to a level 127% above that recorded initially. Attempts to relate the changes in occlusal force to those of mechanical advantage as predicted by the Throckmorton model (Throckmorton *et al.*, 1980) proved unsuccessful.

Discussion of the occlusal force studies

The results of the present study have once again confirmed the previously reported finding that the maximum occlusal force generated in short faced adults is significantly greater than that reported in long faced counterparts, although somewhat surprisingly facial form accounted for only 31% of the

variation in occlusal force. Similarly, although there were significant correlations between the orientation of the masseter and temporalis muscles relative to the lower occlusal plane and maximum occlusal force, these correlations were rather weak and collectively accounted for 17% of the variation in molar bite force.

The present study has shown that orthognathic surgery produces marked alterations in occlusal force levels with changes continuing to occur at least one year following operation. The changes associated with mandibular ramus procedures were extremely variable, but there is the possibility that surgery to advance the mandible may result in weaker long-term force levels. It would appear that bimaxillary surgery in patients with long faces brings about a steady increase in the rather deficient level of initial force towards a more 'normal' level.

It is difficult to conclude whether or not the results support the mechanical advantage hypothesis proposed by Throckmorton *et al.* (1980). Certainly the observations both before, and the changes occurring after surgery support the hypothesis with regard to the vertical aspects of facial form. With regard to the antero-posterior jaw relationships, however, the results appear contradictory. There was no significant correlation between occlusal force and the horizontal arch relationships prior to surgery and yet surgery to advance the mandible, so increasing the moment arm of the load, led to a reduced bite force as predicted by the lever theory. It should be reiterated, however, that the range of individual variation was large.

Chapter 6

COMPARATIVE STUDIES OF MASSETER MUSCLE STRUCTURE AND FUNCTION

Introduction

The material collected throughout the various studies has provided information on both muscle structure and function. The literature contains several references which have correlated different measures of function, notably electromyography and bite force investigations, but there have been very few comparisons of masticatory muscle structure with functional parameters. The aim of the final part of this thesis is to investigate the possible relationships between masseter muscle fibre structure and the functional activity as reflected through EMG and bite force evaluation.

a) Literature review

There have been several reports in scientific and medical journals which have shown a positive correlation between muscle cross-sectional area and muscle strength (for example, Thortensson *et al.*, 1976), as well as qualitative observations as to the relative predominance of type I and II fibres in endurance runners and sprinters. Furthermore, Maughan *et al.* (1983) demonstrated a positive correlation between type II fibre size and muscle strength in human limb muscles.

With regard to muscles of mastication there have been only two papers which have attempted to relate muscle structure and function.

Ringqvist (1973a), in her study based on ten patients with class III malocclusions and variable occlusal states observed a significant correlation (r = 0.88) between the size of type II fibres and occlusal force. Shaugnessy (1986),however, failed to observe any significant correlations between muscle fibre characteristics and occlusal force, in ten patients scheduled for orthognathic surgery.

The latter author, however, did observe several significant correlations at

the $p \leq 0.05$ level between masseter histochemical characteristics and EMG data. Spearman correlation coefficients were calculated between the slope of the muscles mean power frequency versus the linear regression equation of the percentage of maximum voluntary contraction, and the size and distribution of muscle fibre types. A coefficient of 0.63 was noted between the size of type I fibres and the EMG slope, although this increased to 0.90 having eliminated one outlier result. A significant correlation of 0.67 was also noted when the combined size of type IIa and IIb fibres was plotted against the EMG slope. With regard to the incidence of fibres, there was a positive correlation of 0.70 between the percentage of type I fibres and the slope of the EMG regression equation, but a negative correlation of -0.71 between the combined incidence of type IIa and IIb fibres and the slope of the line.

In view of the paucity of data relating non-invasive measures of muscle function with muscle structure, further studies need to be undertaken before drawing meaningful conclusions.

b) The relationship between occlusal force and muscle fibre profile.

All 42 patients who had occlusal force measurements prior to surgery agreed to a masseter muscle biopsy at the start of treatment. The biopsies were processed in the manner as described previously. Fibres were classified using ATPase typing techniques into type I and II, with sub-division of the type II fibres into either type IIa or IIb in 32 of the cases. Fibres with intermediate staining intensity were classified according to the most closely allied fibre group. The correlation coefficients between the maximum recorded molar bite force and the muscle fibre areas, distribution and total cross-sectional area are given in table XXXXVI.

i) Results

The results show that of the muscle variables considered, the size of the type II fibres, especially the IIb sub-group, had the closest association with

maximum bite force.

Table XXXXVI -

Correlation coefficients between the muscle fibre size, distribution and total cross-sectional area with occlusal force.

Muscle variable	Correl^{n}. coeff.	Sig.
Type I %	-0.31	*
Type I area	0.45	**
Type I total X-sect^{n}. area	0.19	ns
Type II %	0.31	*
Type II area	0.83	***
Type II total X-sect^{n}. area	0.80	***
Type IIa %	0.21	ns
Type IIa area	0.73	***
Type IIa total X-sect^{n}. area	0.69	***
Type IIb %	0.05	ns
Type IIb area	0.85	***
Type IIb total X-sect^{n}. area	0.71	***

Stepwise multiple regression analysis of bite force with the six variables related to type I and type II fibres indicated that the type II fibre area accounted for 69.6% of the variation in bite force with none of the other variables adding significantly to the prediction.

These results confirm those of Ringqvist (1973a) with regard to the type II fibres but whereas she failed to observe any significant correlations whatsoever for type I fibres, the present study did give a significant correlation of 0.45 ($p \leq 0.01$) for type I fibre area. Although not adding

significantly to the prediction of maximum occlusal force this could be considered to give some support to the suggestion quoted by Ringqvist that type I fibres are recruited in activities of up to 20% of maximum force with type II fibres activated above that level.

With regard to the type II fibre sub-groups there were highly significant correlations between maximum force and both the type IIa and and IIb fibres. Stepwise multiple regression analysis of the three type I and six type II sub-group variables indicated that the IIb fibre area accounted for 72.0% of the variation in force with the other variables failing to add significantly to the prediction.

Measurement of occlusal force in the present study recorded only the maximum force generated and did not require that level to be maintained for a specific time. As such it is extremely unlikely that muscle fatigue would have started to occur. In retrospect it would have proved extremely useful to have had information relating to that force level which could be maintained for a period of time. If type IIa fibres are important for the maintenance of sustained work activities at high force levels then they may have accounted for a relatively greater proportion of the variation in that force.

c) The relationship between EMG activity and muscle structure.

EMG data for the masseter muscle, with recordings taken at rest, during maximum bilateral clench and during biting on the right and left, were available for the 42 patients who subsequently had muscle biopsies at the time of corrective surgery. The correlation coefficients, together with their statistical significance, for the EMG recordings and the muscle profile variables are presented in table XXXXVII.

i) Results

Despite several highly significant correlations, particularly in relation to the

Table XXXXVII -

Correlation coefficients between muscle fibre size, percentage distribution and total cross-sectional area and EMG activity.

Muscle variable	Rest	Maximum clench	Right bite	Left bite
Type I %	-0.27	-0.30	-0.32 *	-0.06
Type I area	-0.28	0.39 *	0.33 *	0.06
Type I total X-sect". area	-0.43 **	0.16	0.09	0.04
Type II %	0.27	0.30	0.32 *	0.06
Type II area	0.38 *	0.73 ***	0.70 ***	0.10
Type II total X-sect". area	0.42 **	0.69 ***	0.69 ***	0.12
Type IIa %	0.12	0.23	0.24	0.21
Type IIa area	0.27	0.64 ***	0.60 ***	-0.05
Type IIa total X-sect". area	0.23	0.62 ***	0.60 ***	0.04
Type IIb %	0.28	0.14	0.15	-0.35 *
Type IIb area	0.37 *	0.76 ***	0.73 ***	-0.04
Type IIb total X-sect". area	0.47 **	0.65 ***	0.64 ***	-0.22

size of the type II fibres and the activity recorded during maximum clench and biting on the right, the overall relationship between the EMG activity and the fibre variables was low, especially from a predictive aspect. Using stepwise multiple regression techniques, the highest proportion of the variation in any of the EMG levels explained by fibre profiles was 57.5% and 53.0% for the size of type IIb fibres during clenching activity and biting on the right respectively. Stepwise regression failed to reveal any structure variable which could account for a significant proportion of the variance during biting on the left.

The results with respect to resting activity showed that both the size and percentage composition of type I fibres were negatively correlated with EMG activity, indicating that the smaller the cross-sectional area ascribed to type

I fibres, the greater the resting activity. It would therefore be apparent that in order to maintain a given rest position individuals with a relatively small proportion and number of type I fibres will elicit a greater number of action potentials. This therefore endorses the view as to the important role of type I fibres in the maintenance of the postural relationships of the mandible to the maxilla.

In conclusion these studies have served to highlight that although the measurement of certain muscle functions correlate to a highly statistical level with muscle structure, the use of non-invasive functional measurements as a means of predicting structure must be considered unsatisfactory.

Chapter 7

GENERAL DISCUSSION AND CONCLUSIONS

General Discussion

The various parts of this study were designed as a means of providing further information as to the relationship between cranio-facial form and muscle structure and function. Furthermore, the studies were designed to record the manner in which the masseter and temporalis muscles respond to surgical correction of vertical facial deformity. The results enable several comments to be made before drawing the final conclusions.

It is clear from the various results that important differences exist in both muscle structure and function between individuals with extremes of vertical facial form. The differences were far more dramatic for those patients who could be described as exhibiting features of a long face in comparison to their short face counterparts, but this may simply be a reflection of the relative severity of the discrepancy from a "normal" vertical facial form.

The long faced subjects displayed a reduction in the size and incidence of type II muscle fibres with both type II sub-types affected. As a result, the maximal occlusal force generated in the molar region was significantly reduced. Following surgery to reduce the vertical dimension, the muscles adapted in several ways with an immediate reduction in their resting length and an increase in recorded action potentials so as to maintain the clinical freeway space. Further adaptation continued over the 12 month post-operative period, presumably to facilitate maximum functional efficiency of the muscle. The gradual increase in the generated occlusal force to a level in excess of that recorded prior to operation, coupled with an increase in the contribution of the type II fibres to the total fibre cross-sectional area, provided evidence of such adaptation.

The results from those patients in whom surgery increased the vertical dimension gave some in-sight into the time scale involved for muscles to increase their resting length in non-growing individuals. The increased posterior face height was not maintained one year following surgery

indicating that either the immediate post-surgical demands of muscle function had exceeded the rate of muscle adaptation or that the muscle was inherently incapable of increasing its functioning length at a rate conducive to skeletal and functional stability.

Whilst the mechanism of muscle adaptation remains unclear, the possible role of Intermediate muscle fibres cannot be ignored. Surgery resulted in a significant reduction in the incidence of such fibres and there was a highly significant correlation between their pre-operative presence and surgical relapse.

Finally, as mentioned, one of the principal objectives of these studies was to provide information as to whether muscle structure and function, as environmental factors, influence facial morphology, or, whether the form and relationships of the components of the facial skeleton influence muscle structure and function. From the results described, one would conclude that the structure and function of the masseter muscle fibres are primarily independent of skeletal form. Masseter muscle structure, and hence function, may however be important in influencing the ultimate vertical morphology of the anterior part of the face, but no other aspect of facial form.

Conclusions

The results of this series of studies into the structure and function of the chosen masticatory muscles would allow the following list of conclusions to be made:

1. Although the fibre profile of masseter muscle varies according to anatomical region, a single biopsy can be considered representative of that region which represents the majority of the muscle structure.

2. There were no significant differences in the size of type I and II fibres in biopsies taken from the deep aspect of the superficial masseter muscle in individuals with 'normal' cranio-facial morphology.

3. The normal fibre profile of masseter muscle varies in association with abnormalities of vertical facial form, especially increased vertical form, principally through an alteration in the size of type II fibres.

4. Variation in the size or incidence of individual fibre types has no significant influence on facial form. The relative contribution of the fibre types may, however, be important.

5. The less the contribution of type II fibres to the total fibre profile of the muscle, the greater the tendency towards an anatomically long face.

6. Muscle structure, possibly through the relative fibre profile, has an apparent environmental influence on the ultimate vertical form of the anterior, but no other part of the face.

7. Although difficult to prove categorically, the evidence of this study would suggest that the variation in fibre profile is determined primarily rather than secondary to the variation in anatomical form of the face and jaws.

8. Intermediate fibres should now be considered as part of the normal fibre profile of masseter muscle and such fibres may well have a role in the mechanism of muscular adaptation.

9. Orthognathic surgery is associated with an alteration in the structure and function of the masseter muscle and the structure of the temporalis muscle.

10. Surgery is associated with an immediate adaptation in the clinical rest position of the mandible so as to maintain a normal freeway space. Physiological adaptation, however, is still evident up to one year following operation.

11. The structural changes which occur following surgery lead to a more 'normal' level of functional activity as measured through electromyography and maximum occlusal force generation.

12. The stability of the surgical correction of vertical facial imbalance appears to be related to the pre-operative incidence of Intermediate fibres.

13. Whilst non-invasive measures of muscle function give an overview of muscle structure, especially the type II fibre content, they do not provide a reliable method for prediction of other specific aspects of the fibre components.

Recommendations for further study

1. The enormous implications as to the presence and role of Intermediate fibres warrant further study. Ideally the investigation should be repeated by another investigating team on a different, and ideally a larger sample of individuals who are willing to undergo a repeat biopsy following surgery.

2. The development of monoclonal and polyclonal antibodies to the various myosin isoforms would provide a more detailed method of analyzing the muscle fibre composition. Again this would be especially appropriate with reference to Intermediate fibres.

3. This study has concentrated on the fibre aspects of skeletal muscle structure. It would be appropriate to quantify the connective tissue component and hence the ratio of fibres to connective tissue and its relationship to facial form.

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APPENDICES

Appendix A - Working solutions and buffers used in histochemical techniques.

ATPase at pH 9.4

Working solution

5 mg Adenosine 5' triphosphate dissolved in a few drops of water.
10 ml Buffered Calcium Chloride.
1 drop of Dithiothreiol.

Buffered Calcium Chloride

500 ml Glycine buffer
100 ml Calcium Chloride
Adjust the pH to 9.4 with 0.1N Sodium Hydroxide

Glycine Buffer

7.5 g Glycine
5.85 g Sodium Chloride
Made up to 1 litre with distilled water

1% Calcium Chloride

9.1 ml 1M Calcium Chloride in 100 ml of distilled water

2% Cobalt Chloride

2 g Cobalt Chloride in 100 ml of distilled water

Dithiothreiol

1.54 mg in 10 ml of distilled water

Acetate Buffer pH 4.3

Solution A 5.85 g Sodium Acetate
14.7 g Sodium Barbitone
Made up to 500 ml with distilled water

Solution B 0.1N Hydrochloric acid (8.4 ml/1 litre of distilled water)

Acetate buffer pH 4.6

100 ml Solution A
50 ml Solution B
80 ml distilled water

NADH Tetrazolium Reductase

Working solution

Thaw 1 ml Stock solution and add 5 mg of Sodium Hydroxide

Stock Nitro Blue Tetrazolium (NBT)

1 g NBT in 100 ml distilled water

Stock Buffered NBT Solution

6.25 ml NBT Stock
6.25 0.2M Tris Buffer pH 7.4
8.75 ml distilled water
Adjust pH to 7.4 and freeze into 1 ml aliquots

Tris Buffer pH 7.4

25 ml of 0.2M Tris (24.2 g Tris [hydroxymethyl] Methyl Amine /litre)
2.07 ml 0.2 ml 0.2N Hydrochloric acid
Made up to 100 ml with distilled water

Appendix B

Variations in muscle fibre area and percentage composition in relation to anatomical region

Superficial aspect of superficial fibres

	Type I			Type II		
	mean area	SD	%	mean area	SD	%
Section 1						
Site a	1111	410	50	881	488	50
b	1320	417	53	758	320	47
c	1272	652	49	1123	643	51
Section 2						
Site a	1250	350	46	758	370	54
b	1066	430	45	795	747	55
c	1549	857	45	1229	504	55
Overall mean	1261	171	48	924	203	52

Deep aspect of superficial fibres

Section 1						
Site a	1588	622	52	1619	711	48
b	1555	574	56	1612	667	44
c	1564	330	55	1546	369	45
Section 2						
Site a	1322	276	55	1475	488	45
b	1652	629	52	1660	701	44
c	1638	753	56	1469	578	44
Section 3						
Site a	1489	576	56	1334	655	46
b	1675	610	52	1649	341	48
c	1332	430	55	1306	487	45
Section 4						
Site a	1652	520	52	1457	665	48
b	1444	560	50	1650	460	50
c	1372	420	50	1360	740	50
Overall mean	1523	129	53.4	1511	130	46.4

Appendix B cont[d].

Deep fibres

	Type I			Type II		
	mean area	SD	%	mean area	SD	%
Section 1						
Site a	1685	788	54	1679	834	46
b	1417	601	55	1422	697	45
c	1532	630	54	1555	606	46
Section 2						
Site a	1627	775	54	1767	777	46
b	1610	690	56	1660	701	44
c	1444	728	56	1516	767	44
Overall mean	1552	106	54.8	1599	125	45.2

Appendix C

Control group biopsy results (Individual patient mean results)

Patient no	Sex	Type I area	Type I %	Type II area	Type IIa area	Type IIb area	Type IIa %	Type IIb %
1	F	1066	41	1486				
2	F	1441	51	2404				
3	F	1791	59	2347	1867	1960	20	21
4	F	1657	36	1688	1634	1631	31	33
5	F	1920	48	2555	2906	3044	26	26
6	F	1164	48	2003				
7	F	1656	44	1419				
8	F	1910	42	1476				
9	F	2773	51	2420				
10	F	1633	49	1763	1601	1909	24	27
11	M	1624	38	1949	1910	2046	35	27
12	M	2283	40	2281				
13	M	1725	46	1882	1964	1666	27	27
14	M	1869	36	1688				
15	M	1893	41	1658				
16	M	1934	57	1992	1716	2342	25	18
17	M	1842	46	2225				
18	M	1845	39	1334	1189	1464	40	21
19	M	1524	38	2039				
20	M	1865	59	1571				

Appendix C cont[d].

The histochemical fibre profile of the control group - females vs males

	Females				Males			
	mean	SD	SE	95% CI	mean	SD	SE	95% CI
Area I	1701	473	150	1362 to 2040	1956	444	140	1695 to 1985
Area II	1840	202	64	1638 to 2274	1862	298	94	1649 to 2075
Area IIa	2002	614	307	1025 to 2979	1694	353	176	1132 to 2257
Area IIb	2136	622	311	1145 to 3126	1879	391	195	1256 to 2502
% I	46.9	6.4	2.0	42.3 to 51.5	44.0	(median 40.5, inter ¼ -tile 38.0 to 48.7)		
% II	53.1	6.4	2.0	48.5 to 57.7	56.0	(median 59.5, inter ¼ -tile 51.2 to 62.0)		
% IIa	25.0	4.6	2.3	18.0 to 32.5	32.0	7.0	3.5	20.6 to 42.9
% IIb	27.0	4.9	2.5	18.9 to 34.6	23.0	4.5	2.2	16.1 to 30.4
% X-sect.I	43.3	7.6	2.4	37.8 to 48.8	43.9	9.7	3.1	37.0 to 50.8
% X-sect.II	56.7	7.6	2.4	51.2 to 62.1	56.1	9.7	3.1	49.1 to 63.0
% X-sect.IIa	26.1	5.4	2.7	17.4 to 34.8	30.0	6.0	3.0	20.4 to 39.5
% X-sect.IIb	29.4	4.8	2.4	21.7 to 37.1	24.4	4.3	2.1	17.5 to 31.2

Sample:	females	males
I vs II	10	10
I vs IIa vs IIb	4	4

No statistical significance recorded between the sexes for any parameter

Appendix D

Short face group biopsy results (Individual patient mean results)

Patient no	Sex	Type I area	Type I %	Type II area	Type IIa area	Type IIb area	Type IIa %	Type IIb %
1	M	1734	49	2161	2422	2190	21	30
2	F	1774	40	2081	1845	1827	52	8
3	F	1934	43	1992				
4	F	1791	38	1978				
5	M	1230	42	1884	1950	1695	25	33
6	M	1218	45	859	1180	551	27	28
7	M	1486	50	1066	878	1528	26	24
8	F	1607	46	1904				
9	F	2435	40	1804				
10	M	2267	48	1377	695	1511	16	36
11	F	1471	44	1423	1218	1146	40	16
12	M	1887	46	3023	2750	3318	29	25
13	M	1375	30	932	931	891	43	27
14	F	2299	55	1918	2346	1818	17	28
15	M	1232	64	1501	1914	1701	15	21
16	F	1886	42	1996				
17	F	1370	56	1383	659	1501	14	30

Appendix D cont[d].

The histochemical fibre profile of the short face group - females vs males

	Females				Males			
	mean	SD	SE	95% CI	mean	SD	SE	95% CI
Area I	1780	384	121	1505 to 2054	1559	385	145	1243 to 1956
Area II	1798	261	83	1610 to 1985	1604	786	297	876 to 1332
Area IIa	1596	661	295	775 to 2417	1543	823	311	782 to 2304
Area IIb	1598	285	127	1244 to 1952	1669	903	341	834 to 2504
% I	46.8	8.6	2.7	40.6 to 52.9	44.3	(median 46.0, inter ¼ -tile 42.0 to 49.0)		
% II	53.2	8.6	2.7	47.1 to 59.3	55.7	(median 54.0, inter ¼ -tile 51.0 to 58.0)		
% IIa	27.6	17.3	7.8	6.0 to 49.2	26.7	8.4	3.2	19.0 to 24.5
% IIb	20.6	9.0	4.0	9.4 to 31.8	29.0	4.3	1.6	25.0 to 33.0
% X-sect.I	46.3	8.9	2.8	39.9 to 52.7	46.0	11.3	4.3	35.5 to 56.5
% X-sect.II	53.7	8.9	2.8	47.3 to 60.0	54.0	11.3	4.6	43.5 to 64.5
% X-sect.IIa	27.0	17.9	8.0	4.7 to 49.3	25.9	10.8	4.1	15.9 to 35.8
% X-sect.IIb	20.9	10.2	4.6	8.2 to 33.6	28.3	7.2	2.7	21.6 to 35.0

Sample:	females	males
I vs II	10	7
I vs IIa vs IIb	5	7

No statistical significance recorded between the sexes for any parameter

Appendix D cont[d].

Long face group biopsy results (Individual patient mean results)

Patient no	Sex	Type I area	Type I %	Type II area	Type IIa area	Type IIb area	Type IIa %	Type IIb %
1	M	3392	52	2559	2695	2826	31	17
2	F	2553	48	1585				
3	M	1729	65	2902	2047	2265	20	15
4	F	1622	75	367	403	362	16	9
5	F	1120	73	414				
6	F	1726	55	1283				
7	M	2097	67	919	801	1100	25	8
8	F	1189	75	668	636	806	16	9
9	M	1928	40	551	428	639	38	22
10	F	1535	66	1397	622	610	13	21
11	M	2164	55	574				
12	M	1740	66	808	810	623	11	23
13	F	1667	34	689	525	685	40	26
14	F	1417	68	633	618	608	14	18
15	M	1526	53	657	512	724	25	22
16	F	2517	64	2180	2047	2265	20	16
17	M	2144	54	2582	3695	2862	30	16
18	F	1568	44	1073	1225	789	36	20
19	F	2355	47	550	302	1094	38	15
20	F	1092	67	691	376	932	13	20
21	F	1717	58	994	878	1528	22	20
22	M	2500	62	1779				
23	M	2159	61	789	622	937	20	19
24	F	2059	55	605	487	681	20	25
25	F	1480	52	1033	690	918	19	29

Appendix D cont[d].

The histochemical fibre profile of the long face group - females vs males

	Females				Males			
	mean	SD	SE	95% CI	mean	SD	SE	95% CI
Area I	1708	471	121	1447 to 1968	2137	(median 2120, inter - ¼ile 1737 to 2248)		
Area II	944	498	129	668 to 1219	1412	(median 863, inter - ¼ile 636 to 2564)		
Area IIa	734	(median 620, inter - ¼ile 424 to 831)			1451	1218	430	432 to 2470
Area IIb	939	(median 797, inter - ¼ile 627 to 1053)			1497	(median 1018, inter - ¼ile 660 to 2685)		
% I	58.7	12.3	3.2	51.9 to 65.5	57.5	8.3	2.6	51.5 to 63.4
% II	41.3	12.3	3.2	34.4 to 48.1	42.5	8.3	2.6	23.6 to 36.5
% IIa	22.2	(median 19.5, inter - ¼ile 14.5 to 32.5)			19.0	6.2	1.8	15.1 to 22.9
% IIb	25.0	8.2	2.9	18.1 to 31.9	17.7	4.9	1.7	13.6 to 21.9
% X-sect.I	72.6	11.7	3.0	66.2 to 79.1	69.9	12.4	3.9	61.0 to 78.8
% X-sect.II	27.4	11.7	3.0	20.9 to 33.8	30.1	12.4	3.9	21.2 to 39.0
% X-sect.IIa	12.2	(median 8.9, inter - ¼ile 6.7 to 16.1)			17.8	11.6	4.1	8.1 to 27.4
% X-sect.IIb	13.5	6.0	1.7	9.7 to 17.3	13.1	4.1	1.5	9.6 to 16.6

Sample:	females	males
I vs II	15	10
I vs IIa vs IIb	12	8

Type I area significant ($p \leq 0.05$), all other parameters not significant.

Appendix - E

List of Manufacturers

1. **Minitab Release 7**
   Minitab Statistical Software
   Minitab Inc.
   3081, Enterprise Drive
   State College
   Pennsylvania 16801
   USA

2. **SAS System for Statistical Analysis**
   SAS Institute Inc.
   SAS Campus Drive
   Cary
   N.Carolina 27513
   USA

3. **GTCO Digitizer**
   GTCO Corp.
   1055 First Street
   Rockville
   Maryland 20850
   USA

4. **OCT Mounting Compound**
   Lab-Tek Products, Inc.
   Miles Laboratories
   Napierville
   USA

5. **Reichert-Jung MOP-1 Measuring System**
   Reichert-Jung Ltd.
   Vicking Way
   Barhill
   Cambridge CB3 8EL

6. **Grass Electromyography Equipment**
   Grass Medical Instruments
   101 Old Colony Avenue
   Quincy
   Massechusettes
   USA

7. **Model K5-R Mandibular Kinesiograph**
   Myo-Tronics Research, Inc.
   Seattle
   USA

8. **A to D converter**
   3 D Digital Design and Development
   Warren Street
   London WI

9. **Drufosoft Thermoplastic Sheet**
   Panadent Ltd.
   15 Great Dover Street
   London SE1 4YW

10. **Drufomat Drawing Machine**
    Dreve-Dentamid-GmbH
    D-4750 Unna
    Germany