THE ANATOMY AND BIOMECHANICS OF THE MASTICATORY APPARATUS IN THE AUSTRALIAN MERINO SHEEP

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DECLARATION

This work contains no material which has been accepted for the award of any other degree or diploma in any university or tertiary institution and, to the best of my knowledge and belief, contains no material written or published by any other person, except where due reference has been made in the text.

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BRIAN P FINN
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DEDICATION AND ACKNOWLEDGEMENTS

This thesis is dedicated to Emm whose unfailing enthusiasm and support are responsible for the production of this thesis.

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CHAPTER I.

SUMMARY

The temporomandibular joint is a component of the masticatory apparatus [Williams 1982]. The masticatory apparatus can be defined as that system consisting of the teeth and gums, the temporomandibular joint and the symphyseal joints of the jaws, and the masticatory muscles [Dyce 1987]. The interactions between these components are extremely complex. The Australian Merino sheep has been developed as a suitable model for temporomandibular joint surgical research [Bosanquet and Goss 1987].

Biomechanics is that science which applies physical laws to biological systems. Biomechanical studies attempt to quantify biologic structures in terms of a number of physical parameters which include force, pressure, resistance and movement. Although the use of the sheep animal model has been extensive it is only recently that specific biomechanical studies have been undertaken [de Jongh 1989].

The most common pathologies of the temporomandibular joint requiring surgical correction are osteoarthritis and internal derangement [De Bont and Stegenga 1993]. A comprehensive analysis of the temporomandibular joint by various authors has resolved the once controversial issue of joint loading. It has now been shown that under a wide range of function the TMJ condyles must be loaded [Nickel et al 1988]. There is increasing speculation that a major factor in the degenerative changes found in the human temporomandibular joint is excessive joint force which exceeds the adaptive capabilities of the joint. To what extent the common pathologies that affect the joint are induced or their pathogenesis is modified by the application of load is unknown. The proposal that abnormal joint loading can lead to degenerative disease in the human TMJ [Roberts 1974] remains untested because it has not been possible to determine whether patients with joint disease have had abnormal joint loads.

The quantification of intracapsular force may have relevance to treatment of the diseased joint whether it be in the design of an occlusal splint or in the development of a total temporomandibular joint replacement. Replacement is sometimes indicated in those joints affected by trauma, ankylosis, osteoarthritis, surgery for tumor removal or developmental disorders [Falkenstrom 1993]. If such devices are to be successful they must be designed on sound engineering principles based on a thorough knowledge of the forces experienced within the joint itself [Hohl and Tucek 1982]. Catastrophic failure has already been documented in some commercially available TMJ implants [Lindqvist et al 1992]. The implantation of such devices in humans should only follow successful trials in a suitable animal model.

There is a small but growing amount of literature on the use of animal models for evaluation of surgical reconstruction of the temporomandibular joint [Ishimaru et al 1991]. The complete description of the promising sheep model awaits its further definition in both anatomical and biomechanical terms. The aims of this study were therefore to further develop the Australian Merino sheep as an animal model for TMJ research by:

1. Description, in detail, of the anatomy of the sheep masticatory system.

2. Development of a mathematical model to estimate forces within the temporomandibular joint.

Chapter two reviews the literature regarding the anatomy of the masticatory apparatus of the sheep and the general order *Ruminata*. A sequential examination of the anatomy includes osteological and dental information as well as a review of the masticatory muscles and the structure of the disc itself. A general comparison between the sheep as a typical herbivore, a typical carnivore and man as an omnivore are undertaken in order to highlight the specialised nature of both the sheep and carnivore masticatory apparatus. Although broadly similar differences between the sheep and human temporomandibular joint emerge and the implications of this dissimilarity in structure are examined.

Chapter 3 is a review of the literature on mandibular biomechanics which is a rapidly expanding but still poorly understood science. Its early development is characterised by controversy and disagreement crossing the disciplines of anthropology, dentistry, physiology and biomechanics. Both indirect and direct methods of study are dealt with. The correlation of mandibular function with the microscopic and gross anatomical changes seen to occur in the temporomandibular joint is also discussed.

The use of photoelastic models of the mandible employed to investigate stress distribution is reviewed. Numerous graphical and experimental models are presented in a chronological fashion. The review sees the development of an increasing sophistication and complexity in mathematical modelling in two dimensions. This sophistication requires that the elements which comprise the masticatory system are further defined. These are discussed in the section on the components of the mathematical model. The study of mandibular movement and the introduction of the third dimension in the modelling of the masticatory system is then described. There is also a review of the less frequent but critical attempts at the direct measurement of bite force and temporomandibular joint loads. The study of the masticatory mechanics of the ungulate is of direct relevance and this is also presented.

Chapter 4 presents a mathematical model which attempts to incorporate the direct measurement of anatomical and physiological variables wherever possible. These variables include muscle fibre size and direction, electromyographic recordings and measurement of the physiological cross sectional areas of the muscles. The accurate localisation of the joint, bite force and muscles has been emphasised in the protocol. Estimation of TMJ reaction force has not previously been attempted in the Australian Merino sheep.

Chapter 5 presents the results of an anatomical study in which fifteen adult merino sheep heads were macroscopically dissected. The osteology of the craniomandibular articulation, the dentition and the structure of the joint disc itself are examined. Each muscle was dissected to determine its precise origin, insertion and fibre direction.

Chapter 6 presents the subsequent biomechanical investigation. Radiographic examination of anatomical specimens was undertaken in order to construct a composite three dimensional analysis of force. A computer model simulation of these specimens allows the various effects of bite and joint reaction forces to be estimated in the position of maximal muscle recruitment. A value for temporomandibular joint reaction force is presented. This model shows that the powerful grinding forces developed in the occlusion result in significant joint reaction forces.

Chapter 7 is a discussion of both the anatomical and biomechanical implications of this study. The significant differences between the human and sheep joints revealed by the anatomical study are examined. The value for

TMJ reaction force obtained in the mathematical analysis is discussed. The many technical difficulties involved in making this prediction are explored.

It is felt that this study is the small first step in totally elucidating the biomechanics of mastication in the Australian Merino sheep. Suggestions are made for the direction of future studies and of the implications these might have on the development of the sheep as a model for temporomandibular joint research. The direct implications of this to the human condition are also explored.

CHAPTER TWO

ANATOMY OF THE AUSTRALIAN MERINO SHEEP - LITERATURE REVIEW

The Australian Merino sheep belongs to the Phylum Chordata, Subphylum Vertebrata, Class Mammalia, Sub-class Theria, Order Artiodactyla, Sub-order Ruminata, Infraorder Pecora, Family Bovidae, Genus Ovis [Parker 1982 and Bosanquet 1988]. Morphologic similarity between human and sheep temporomandibular joints suggests that functional comparisons of the masticatory systems may be made [Bosanquet and Goss 1987]. There are however dissimilarities in osteological, muscle, joint and dental features. These differences are identified and discussed.

The general anatomy of the Australian Merino sheep has been well characterised by May [1970]. Several features of its masticatory apparatus clearly identify it as a herbivore. Clear differences exist between the herbivore and carnivore groups. Man as an omnivore blends harmoniously the features of both groups [Iyde 1991]. The comparative anatomy of the masticatory musculature of different species has been dealt with by numerous authors [Schumacher 1961, Turnbull 1970, Noble 1973, Dyce et al 1987, Iyde 1991]. The most well defined differences in the anatomy of the masticatory apparatus are thought to relate to the differences in feeding requirements between animals [Dyce et al 1987].

2.1 OSTEOLOGY

Osteological examination of the size, shape and location of the condylar head and its cranial articulating surface reveals clear differences between the herbivore, carnivore and omnivore groups. These differences concern the height of the condyle above the occlusal plane, the size, shape and orientation of the condylar head, the corresponding form of the glenoid fossa and the structure of the disc itself. These structural differences affect condylar movements and have important biomechanical implications [Smith and Savage 1959].

Examination of the sheep mandible in norma lateralis shows its mandibular condyle to be located high above the tooth row. In contrast the condyle in the carnivore is situated low on the ramus and it is almost level with the tooth row. In man the temporomandibular joint is much higher than the occlusal plane. Animals whose joints are situated high above the occlusal plan gain some advantage in mastication as the lower teeth can be drawn forward over their upper fellows as they approach [Dyce et al 1987]. This contributes a grinding component that is absent when the joint and occlusal surfaces are more nearly level.

The condylar head of the sheep is broad and flat. Parsons [1899] commented on the ruminant condyle as being "perfectly flat" and that "all the mechanical arrangements of the joint were wholly subsidiary to the grinding movements of the back teeth". The long axis of the condyle is orientated antero-medially [Parsons 1899, Schumacher 1961]. The condyle is slightly convex in the antero-posterior direction and is slightly concave from side to side [Noble 1973]. Bermejo [1993] has described the structure as concavo-convex. Reciprocal articular facets have been described on the condyle of the Australian Merino sheep [Murphy 1959].

Murphy divides the sheep joint into anterior and posterior districts with reciprocal articular facets. These facets are widely separated on the cranial component and narrowly on the mandible. Anterior superior and posterior articular facet can be seen on the mandibular condyle. The anterior superior facet is only about one third the extent of its reciprocal cranial facet. The posterior facet is small and medially placed on the condyle in order to be reciprocal with the facet on the post glenoid tubercle [Murphy 1959].

In carnivorous species, such as the dog, the condylar head takes the form of a transverse cylinder to which the fossa provides a corresponding gutter [Dyce et al 1987]. The condylar head is relatively smooth and lacks the prominent facets of the sheep. The long axis linking the medial and lateral poles in the condyle in the carnivore do not cross each other [Iyde 1991]. This arrangement implies that only hinge movement is possible. The sheep and dog are typical examples of herbivores and carnivores exhibiting differences in the position of the joint in relation to the teeth. **Fig 2.1** indicates a clear difference in the relative position of the condylar articulation to the occlusal surfaces in the domestic dog and sheep .

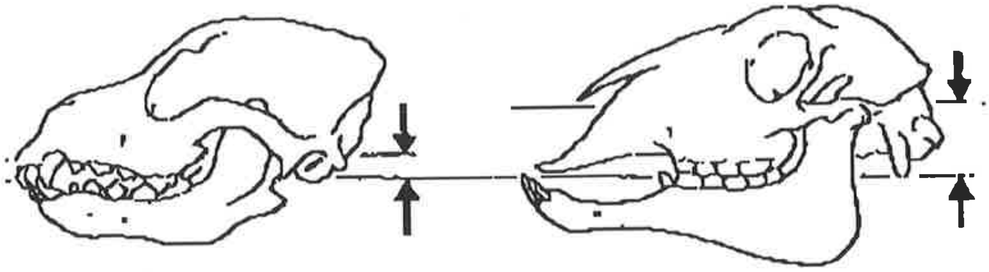


Fig 2.1 (modified after Dyce 1987)

In man the condyle is asymmetrical. The head is convex in the para-sagittal plane and twice as large in its medio-lateral than in its antero-posterior dimension [Mohl 1988]. A line drawn between the medial and lateral poles of each condyle forms long axes that intersect posterior to the mandible. The condylar head in the human thus has a posterior inclination that allows some components of lateral motion [Iyde et al 1991]. A similar situation exists in the sheep. There is considerable variability in the morphology of the human mandibular condyle both in its size and shape and in the angle at which the condyle is related to the mandible [Yale et al 1966].

The cranial cavity in the sheep is a medial relation to the temporomandibular joint [Bosanquet and Goss 1987]. The roof of the sheep glenoid fossa is the undersurface of a bony ledge which forms a broad articular plateau laterally related to the ungulate cranial vault. The upper surface of this ledge provides an area of insertion for some the inferiorly directed fibres of the temporalis muscle and does not include the cranial cavity [Scott 1955, Murphy 1965]. The glenoid fossa in the sheep is shallow and almost flattened horizontally with no eminence anteriorly. A slight convexity of the glenoid has been described by Bermejo et al [1993]. Two articular facets are visible on the glenoid of the sheep. The large anterior facet is a smooth plateau, which is described as being gently convex in all directions and facing downwards and slightly backwards. The postglenoid tubercle is placed on the medial side of the posterior limit of the articular fossa facing forwards and laterally. The postglenoid tubercle posseses the smaller posterior facet [Murphy 1959]. The reciprocal components of the temporomandibular joints in the sheep are shown in **Fig 2.2**

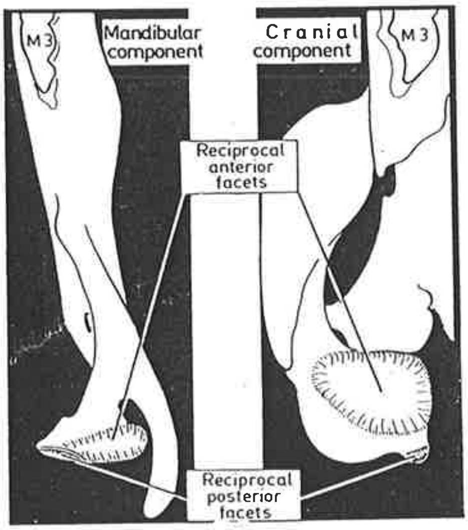


Fig 2.2 (After Murphy 1959)

Carnivores have a deep glenoid fossa and a prominent retro-articular tubercle. The prominent bony ridges seen in front and behind the mandibular condyle in the carnivore provide an arrangement that allows the prehension of struggling prey [Fox 1965]. This ensures that the condyle is not dislocated by the powerful forces so generated [Hylander 1978] but both lateral and anterior movements are severely limited [Iyde et al 1991]. The preservation of some degree of lateral movement is important as this allows the the animal to vary the closeness of the contact between the upper and lower teeth [Dyce et al 1987]. In some carnivores, such as the wolverine and badger, the condyle is so completely encircled by the glenoid fossa that the bone must be fractured to disarticulate the mandible from the skull [Smith 1985].

The morphology of the mandible associated with a carnivorian dentition is characteristic. The large lower canine is strongly supported by buttressing layers of compact bone. Forces are transmitted to the ascending ramus of the mandible by a stout mandibular body. The coronoid process is well developed and extends for some distance above the condyle to provide a very large area of insertion for the temporalis [Noble 1973]. Carnivora and Herbivora represent extremes in the size and shape of of the articular eminence and differences in the morphology of the cranial and mandibular articulating surfaces [Iyde et al 1991].

In man the cranium is superior to the joint with the middle cranial fossa being immediately superior relation to the thinly roofed glenoid fossa. Because of this the fossa can be broached by the mandibular condyle in fractures of that involve upwardly directed forces to the cranial base [Fonesca 1974]. Migration of the head of artificial condylar prosthesis into the middle cranial fossa has also been described [Lindqvist et al 1992]. The human glenoid fossa is a medio-lateral elongated depression corresponding to the shape of the condyle. In front of this fossa is the anterior eminence which together with the concave fossa makes a sigmoid curve in the lateral projection [Iyde et al 1991]. The articular surfaces of the temporomandibular joint consists of the mandibular condyle and the basal surface of the squamous part of the skull which forms the glenoid fossa. A distinct articular tubercle is present in both man and sheep [Williams and Warwick 1982]. Posterior to the fossa in humans is the bony wall of the external ear, and superior to it the petrotympanic fissure through which the chordae tympani of the facial nerve passes medio-laterally [Iyde et al 1991]. The post glenoid tubercle and its reciprocal condylar facet are laterally placed whereas in the sheep these structures are medial [Murphy 1965]. Boucher [1962] states ruminants have a comparatively insignificant postglenoid tubercle and that it is absent in some species. In contrast the mandibular fossa in the sheep is succeeded by a prominent retro-articular process [Murphy 1955].

Movements of the ungulate mandible have been examined by various authors [Smith and Savage 1959, Murphy 1959, Schumacher 1961, Turnbull 1970, Greaves 1978, Dyce et al 1987]. In some ungulates, such as sheep and cattle, it is impossible for the molar teeth to be in occlusion on both sides of the jaw simultaneously [Smith and Savage 1959]. In a study of the domestic sheep the distance between the left and right rows of premolars and molars was shown to exceed the distance in the lower jaw by the width of a tooth row [de Jongh et al 1989]. This horizontal discrepancy is called "anisognathy" [Ryder 1878]. Murphy [1959] traced a coronal section through the muzzle of an Australian Merino sheep. The discrepancy between the upper and lower jaws can be clearly seen **(Fig 2.3).** Murphy states that the degree of isognathism exhibited by the Australian Merino Sheep the sheep is greater than that implied by the coronal section of other ruminants. This contrasts with the "isognathism" or approximately equal width of the human tooth arches [Murphy 1959].

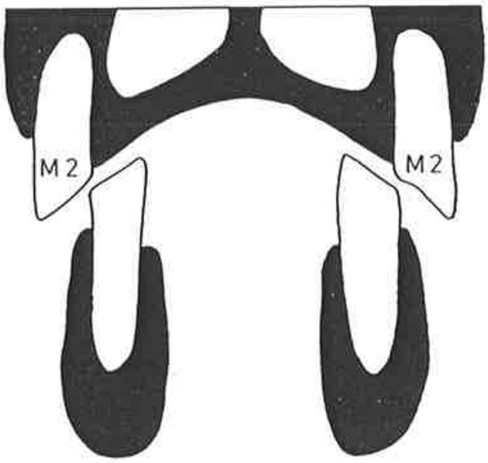


Fig 2.3

In centric occlusion the condyle is in its most posterior, superior and unstrained position [Mohl 1988]. In this position minimal tooth contact occurs in anisognathic animals. Murphy 1959 has described centric relation in the Australian Merino sheep by superimposing celluloid tracings of photographs of the occlusal surfaces of the maxillary and mandibular dentition. Murphy's diagram shows minimal tooth contact in centric occlusion **(Fig 2.4).**

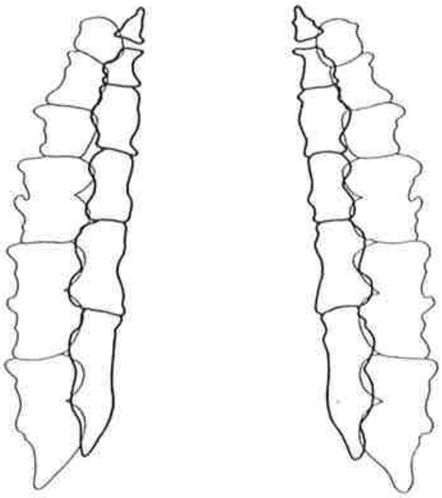


Fig 2.4

Centric occlusion is the position at which grass is cropped; a position at which the anterior mandibular dentition functions against the fleshy pad of the maxilla.

During chewing movements unilateral occlusion of maxillary and mandibular molar dental segments occurs on the working side. There is no occlusal contact on the non working or contralateral side.

Sheep grind their food with a predominantly lateral movement of the jaw. The joint translates laterally rather than anteriorly. Backward dislocation of the jaw is prevented by the post glenoid tubercle. This tubercle has probably has been developed to protect the auditory canal from a wide range of condylar movements during mastication [Bosanquet 1988]. Conversely the jaw action of the carnivores is a simple hinge movement. The cylindrical condyle rotates in the transversely extended glenoid cavity which forms a corresponding gutter. Movements of the canine mandible are predominantly vertical. Lateral grinding is prevented by the interfering carnassial blades [Scapino 1965]. Dogs chop or tear their food into lumps which are then swallowed [Ardan and Kemp 1960].

Omnivores exhibit a masticatory system that as far as mandibular dynamics are concerned is a combination of lateral and vertical movements [Dovitch and Herzberg 1968]. The shape of the articular eminence in man allows both hinge, glide and lateral movement. Thus the human jaw joint may be considered a universal type joint permitting excursions of the mandible in all three planes of space [Noble 1973]. The articular eminence acts both to prevent excessive anterior movement and to guide the sliding motion of the condyle following hinge movement. The mandibular ramus is high and the temporomandibular joint is well above the level of the occlusion and approximately level with the coronoid process. There is a large area of occlusal surface available for mastication and simultaneous occlusion is possible. Cutting, splitting and grinding movements are all possible in the versatile human articulation [Iyde et al 1991].

2.2 THE DENTITION

Tooth morphology reflects and dictates the principle masticatory movements. The molar pattern of sheep teeth have been described as typically selenodont because of the sickle shape of the worn occlusal surfaces ("Selene" means moon). These cresentic areas represent enamel invaginations together with the surrounding dentine. These areas can be seen on the occlusal surfaces of the molars and premolars. The wear patterns, ridges and furrows of these teeth are predominantly transverse indicating the lateral direction of mastication. The dental formulae is given as;

I: 0/3 C: 0/1 P: 3/3 M: 3/3 x 2 = 32

May [1970] considers the smallest laterally placed anterior tooth an incisor and gives the dental formulae as C: 0/0. This tooth differs markedly from its anterior neighbours in size shape and root length. Other authors give the commonly accepted general dental formulae for the ruminant dentition as above but describe the assimilation of the canines to the incisors [Dyce et al 1987].

The number of anterior teeth have been reduced as these are only used to pluck or crop vegetation and only a small degree of vertical movement is required to accomplish this action [Gilbe 1973]. The mandibular incisors present a broad spatulate crown with a pronounced labial curvature. In the domestic sheep the lower teeth are splayed to articulate with a fleshy pad and the upper incisors are absent. The gum of the anterior maxilla is flattened into a hard pad of fibrous tissue called the dental pad or plate which is moulded into the premaxilla on its deep surface [May 1970]. The lips of the sheep have only limited mobility but its tongue is long and rough. The tongue can be readily curved around herbage which is then drawn between the incisor teeth and dental pad. Sheep have a cleft upper lip which permits very close grazing with the incisor teeth and the tongue being the principle prehensile structures [Dukes 1955].

Only minimal occlusion can be demonstrated in centric position in the Australian Merino sheep [Murphy 1959]. This jaw position is thought to be used only briefly during cropping. For all functional masticatory movements the discrepancy between the dental arcades is such that it is impossible for molar teeth to be in occlusion on both sides of the jaw simultaneously [Smith and Savage 1959]. This means that when full occlusion occurs on one side no occlusion can occur on the contralateral side. When a sheep grinds its teeth mastication its therefore unilateral. Although both sides are used alternately the animal tends to favour a particular side [Dyce 1989]. When cropping the lower jaw is centred [de Jongh et al 1989]. Cropping and chewing movements are made at different times and in some species the geometry of the jaws is such that when the cropping teeth are in occlusion the molars are discluded.

The grinding surfaces of the mandibular molars face upward and outwards. The upper molars face downwards and inwards and are larger than their mandibular counterparts. The occlusal plane of ruminants is complicated by an anterior posterior curve similar to that described in man by Spee [1919] and by a lateral curve the reverse of that described by Monson [1920]. Smith and Savage [1959] have described the typical wear patterns of selenodont teeth using the example of *Strepsiceros*. Wearing of the dentition in the selenodont accentuates the development of ridges and valleys; the ridges of the upper teeth fitting into the valleys of the lower and vice-versa. The occlusal surfaces of the sheep molars are described as having a large infundibulum surrounded by a ridge of enamel. Between this layer of enamel and the external enamel covering are wide layers of dentine which occupy almost two thirds of the occlusal surface [May 1970]. **Fig 2.5** shows an occlusal view of the upper (above) and lower (below) teeth of

Strepsiceros . The black areas represent the enamel ridges. The lines *a-a* and b-b indicate the guiding ridges and valleys respectively. The sequential arrangement of across the tooth is enamel, dentine, enamel, cementum, enamel, dentine and enamel [Murphy 1959].

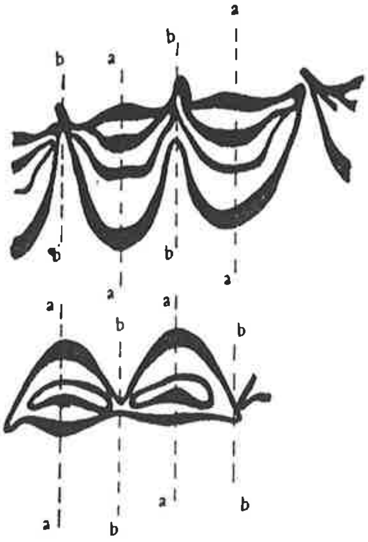


Fig 2.5 (After Smith and Savage 1959)

The occlusal relationships between the teeth in centric occlusion are variable, even in the same individual in different ages, since the teeth come together in an altered fashion as wear reduces the enamel projections. Both temporary and permanent premolars exist but the molars are permanent teeth. The relationship between the teeth is a dynamic one. A tooth deprived of normal support may drift under the influence of the masticatory forces, the processes exerted by the lips, cheeks and tongue are also important in maintaining normal contact and alignment.

The ridges and valleys formed with tooth wear act as guides to mandibular movement. The enamel ridges running along the length of the jaw are used for cutting. The ridges on the upper teeth fit into valleys in the lower. These ridges run at right angles to the guiding ridges formed by the progressively increasing or decreasing size of cusps in the bucco-lingual direction. In the upper third molar the ridge summits are transverse to the long axis of the tooth whereas in the maxillary premolar the ridge summit is obliquely placed to the long axis of the tooth. First and second molar tooth ridges show intermediate stages of obliquity so that their is a progressive difference in the orientation of the ridges relative to the to the tooth axis as one moves along the cheek teeth series **(Fig 2.6).**

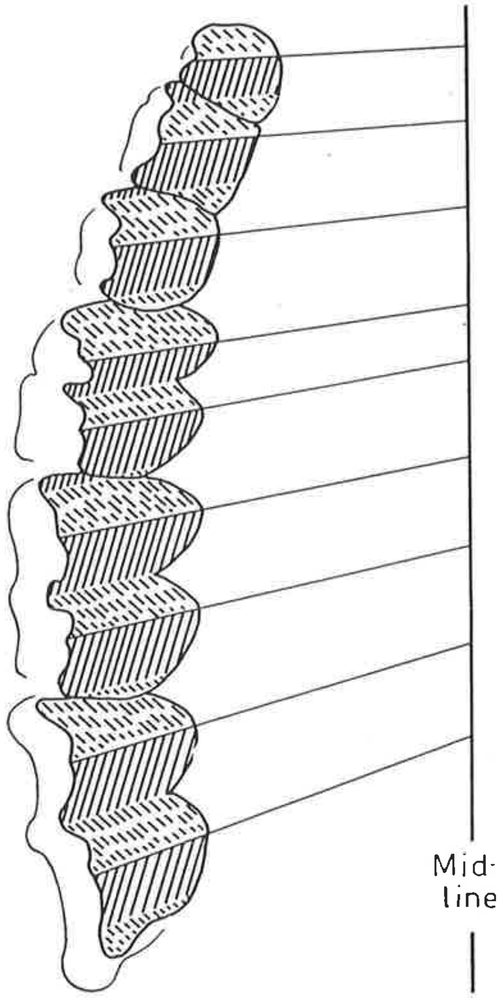


Fig 2.6 (After Murphy 1959)

The lower cheek teeth are narrower and are set in an almost straight line. A similar arrangement of progressively varying transverse ridge obliquity is seen. The ridges of both maxillary and mandibular dentitions therefore converge medially. The degree of convergence is sometimes obscured by the differential attrition of enamel dentine and cementum [Murphy 1959].

The morphology of the teeth allow the animal to grind in its predominantly lateral direction. The broad molars are used to chew and the inclined nature of the molar cusps mean that chewing is predominantly lateral. Wear patterns of teeth have been used to estimate the pattern of mastication in a number of fossilised and extant species [Smith and Savage 1959, Crompton 1970, and Crompton and Hiiemae 1970]. In the sheep the wear pattern of has been said to indicate its "uncomplicated lateral movement" [Murphy 1959].

Ungulates are hoofed mammals that feed on plants [Noble 1973]. Turnbull [1970] has classified the sheep along with most herbivores as having an ungulate grinding or mill type dentition. The cheek teeth of the sheep function like millstones, having flattened occlusal surfaces which rub across each other during horizontal excursions of the mandible, grinding the food. Grinding power is increased by roughening of the occlusal surface provided by complex folds of enamel which project as ridges above the softer dentine on the worn surface of the tooth. Grinding movement is transverse to the jaw. The mandible moving bucco-lingually whilst the teeth are in contact. The enamel ridges run perpendicular to the direction of movement, i.e. mesio distally in the sheep.

Not all herbivores have grinding teeth working on this principle. The rabbit, kangaroo and elephant grind antero-posteriorly the ridges working in grooves on the opposite teeth creating a shearing action between the distal surfaces of the lower ridges and the mesial surfaces of the upper ridges. Such teeth are more useful for cutting up leaves and other such vegetation than for grinding grass. In general the oblique occlusal surfaces of the herbivores form chisel like grinding surfaces which are efficient when used with lateral grinding movements. The molars have broad occlusal surfaces and the premolars have undergone a process of molarisation increasing the area available for grinding [Noble 1973]. The enamel and dentine of the occlusal surfaces have uneven wear characteristics which increases the efficiency of these grinding surfaces [Dukes 1955] exposed dentine enamel and cementum wear at different rates [Mohl 1988]. This provides a rasp like quality [Dyce et al 1987].

The sheep like the cow is a ruminant. The rumen is specialised part of the digestive tract where extensive microbiological fermentation of the vegetable diet occurs prior to digestion by alimentary enzymes [Dukes 1955]. These animals swallow their herbage quickly which travels to these specialised stomach parts where bacteria and other micro-organisms assist in softening the cell walls. The bolus is intermittently returned to the mouth and chewed as a cud. In this process the sheep's teeth are subject to continual grinding and suffer a great deal of abrasion. Data has been obtained via radiotelemetry from microphones placed on the heads of grazing sheep. These studies indicate that Australian Merino Sheep spend an average of 50% of their waking hours eating. In one 8.48 hour session one specimen recorded 32,277 eating and ruminating chews. Plant material, particularly grass, contains silica and a great deal of mastication is required to to break up this as well as the cellulose in its cell walls. In addition grass contains phyoliths which may contain up to 18% of its dry weight. The teeth of sheep in particular are subject to very rough wear. Tooth loss or "broken mouth" is a frequent reason for culling wasting older animals [Dyce et al 1987]. This has major commercial implications when it is the cause of death for stud rams.

The enamel coating of sheep teeth does not end abruptly at the gingivae as it in humans. What can be seen in the sheep's mouth is only a fraction of the total of the crown length. A large portion of the crown exists subgingivally which allows for the tooths gradual extrusion with wear. These crowns are described as elongated or hypsodont [Mohl 1988]. Hypselenodontal teeth are therefore high crowned sickle shaped teeth (hypselos = high). Those found in the dog or human are called brachyodont or short crowned teeth [Dyce et al 1987]. The hypseledont teeth of the sheep have relatively short roots. Pocket depth is approximately 2mm with most of the crown being buried in the alveolus. The teeth are thus very well supported with the buried part of the tooth essentially functioning as a root [Fox 1965].

Crown attrition is compensated for by crown growth. The crowns are erupted and in use long before the roots which form late in the development of the tooth or not at all [Noble 1973, Dyce et al 1987]. When this occurs the height of the exposed part of the tooth is maintained only by the extrusion of the of the embedded portion of the crown. The height of the crown is increased at the expense of the root. Some investigators suggest that the teeth do not continue to erupt but that as age increases the gums recede and expose more of the tooth which is gradually worn down [May 1970]. By either process the crowns may eventually be consumed in those animals that survive to an advanced age [Dyce et al 1987].

As the crown of the hypsodont increases in height, the valleys between the cusp and the ridges deepen to form vertical grooves or tubes passing down the length of the tooth. These grooves become filled with cementum. Thus in the elephant the tooth has a series of transverse ridges which when worn down appear as islands of dentine bordered by enamel, the whole series is set in a mass of cementum. Each incisor of the horse has a deep pit filled with cementum, known as the mark. As the teeth wear down the mark changes in size and may be used in determining the age of the horse.

In herbivorous species the anterior teeth do not form a continuous row with the canines and incisors. A prominent diastema is noted between the anterior mandibular teeth which articulate with fleshy part of the edentulous anterior maxilla and the posterior maxillary and molar segments. This diastema means the jaw is elongated so that the animal can reach the ground when grazing [Dyce 1987]. It also provides a space in which food can be manipulated by the tongue and cheeks into the right position for passing back between the grinding teeth. In rodents the same gap allows a fold of skin to close off the mouth behind the incisors which are used in gnawing. Ardan et al [1958] and Landry [1970] saw this separation as necessary for the independent function of these two dental units. In association with this elongation is a well developed nasal region which is of great importance to grazing animals in danger from predators [Mohl 1988].

The masticatory action of the sheep commences with a opening or depression of the lower jaw. This is achieved by slackening or cessation of activity of the masticatory muscles by contraction of their antagonists being assisted by gravity. At the beginning of the masticatory stroke the condyle is thought to be retracted in order for the posterior condylar facet to articulate with the cranial facet on the post glenoid tubercle [Murphy 1959]. As the jaw is lowered the mandibular head rolls forward upon the articular disc while the disc itself slides forward in the mandibular fossa assisted by the attached lateral pterygoid fibres. Closure of the mouth requires the reversal of these processes. The whole action must be vigorous enough to detach vegetation. The sheep employs its neck musculature in providing the tearing force required to detach vegetation lifting its head to pull clumps of grass from the ground. Herbivores then employ the cheek teeth for grinding food passed posteriorly in the mouth. Active closing or grinding motions are is proceeded by a marked lateral displacement [Dyce 1987].

The morphology of the teeth of a carnivore support the concept that the movement of the jaw is a simple hinge [Jenkins 1966]. The dental formulae of the domestic dog is;

$$I: 3/3 \quad C: 1/1 \quad P\,4/4 \quad M\,2/3 \quad \times\ 2 = 42$$

Examination of a dog's teeth reveals that the lower molars fit entirely inside the uppers. This arrangement allows for efficient tearing [Gilbe 1973]. There is no centric occlusion as such [Fox 1965]. Wear patterns seen on older specimens shows that only a small amount of lateral movement occurs but that the chewing pattern may be considered largely vertical [Gilbe 1973].

The chewing action of the carnivores is mechanically equivalent to that of a scissors [Fox 1965]. It is usual to find that each cheek tooth engages the two tooth of the opposite series. The lower teeth being slightly mesial to their upper counterparts. In the dog the largest teeth, the last upper premolar and the first lower molar bite together and constitute the sectorial teeth, the principal shear. The teeth in front of the sectorials do not meet but leave an opening carrying space whilst the last cheek teeth make more extensive contact [Dyce 1987]. The canine engages in front of the upper canine filling the space between this and the third incisor. The relatively soft food of the carnivore is thus divided into chunks leaving the bulk of digestion to the gastric juices [Fox 1965]

The teeth of man more closely resemble those of a carnivore than those of a herbivore in their morphology [Fox 1965]. Both dental and skeletal elements show the features of minimal specialisation. All of the teeth are of similar size. The incisors are not reduced and the canines not enlarged. The molars are of similar size and have rounded cusps. Man has a double row of cusps which except in cases of extreme wear have an outer enamel coating with minimal dentinal exposure. The human dental formulae is given by;

I: 2/2 C: 1/1 P: 2/2 M: 3/3 = 32

The mandible is of moderate length and the dentition is not interrupted by a diastema. Although lateral grinding movements are possible food is still taken and swallowed as large chunks [Fox 1965].

2.3 MUSCLES OF MASTICATION

The muscles that provide masticatory force are derived from the first branchial arch. These muscles are supplied by the fifth nerve [Williams 1982]. They comprise of temporalis, masseter, and medial and lateral pterygoids. Other muscles play some part in jaw movements, particularly in opening the mouth, but are not normally included under the term muscles of mastication [Dyce et al 1987]. Extensive myological studies have lead to the identification in mammals of a basic muscular prototype [Yoshikawa et al 1961]. A temporo-masseteric superficial plane and a pterygoid deep plane are described and these are present in the domestic sheep as well as man [May 1970].

The masseter muscle is found only in mammals [Mohl 1988]. The temporalis and masseter act to close the jaws and their attachments to the mandible are broadly similar [Dovitch and Herzberg 1968]. Distinct differences exist between the musculature of carnivores and herbivores particularly in respect to the relative bulk of temporalis and masseter. The bulk of these muscles in different species indicates which are the main jaw closing muscle.

The muscles of mastication of the general class of Ruminanta have been examined in detail by some authors [Schumaker 1960, Turnbull 1970, and Noble 1979]. The masseter in ruminants is a strong, broad and flat muscle lying lateral to the mandibular ramus. Its origin is from the malar region of the skull and zygomatic arch. In the sheep this is defined by a bony prominence called the facial tuber [May 1970]. The muscle has a wide insertion on the more caudal part of the mandible.

The masseter has a multi-pennate structure intersected by strong tendinous plates and tissue septa. The fibres in a different strata do not all run parallel and different parts may have contrasting functions [Dyce et al 1987]. Two layers have been described in the goat and ox [Noble 1973]. Three clearly defined layers have been identified in the Australian Merino Sheep [May 1970]. The masseter has also been described as consisting of two layers; a superficial layer called the pars superficialis and a deeper layer the pars profundus [Zey 1940, Turnbull 1970].

Turnbull's text and diagrams refer to the deepest layer of muscular tissue not as a third masseteric part but as a separate muscle; the zygomatico-mandibularis. This muscle thus lies on the lateral bony surface of the mandible and is the deepest of all of the facial muscles lateral to the mandible. May [1970] describes a third masseteric layer and does not mention the zygomatico-mandibularis. Other authors acknowledge the existence of all three masseteric layers together with an underlying zygomatico-mandibularis. Others see this muscle as but a third layer of the masseteric complex [Stocker 1967, Noble 1979].

The zygomatico-mandibularis muscle has also been considered as a fifth muscle of mastication and is sometimes seen as part of the masseter muscle and sometimes as part of the temporal muscle [Fox 1965]. This study has shown that in the sheep the thin fibres of the zygomaticus mandibularis are not clearly distinguishable from the deeper layers of the masseter. The fibres of zygomatico-mandibularis are directed more nearly vertical than the innermost masseteric fibres. A vestige of this muscle has been identified in humans as a fascia extending from the temporal surface of the tendon of the temporalis muscle [Fox 1965].

Independent function of the masseteric muscle layers has been described [Carlsoo 1956]. Some layers may serve to protrude the mandible, others to retract it, but the general effect is to raise the mandible and draw it towards the active side. The muscle is proportionally better developed in herbivorous species such as the sheep where chewing movements are predominantly lateral. The demand for power and control in the lateral dimension means that pterygoid group are similarly well developed in most ruminants [Noble 1979]. Despite the masseter being proportionately smaller in the carnivores it is nevertheless quite strong and serves an important role along with the medial pterygoid in jaw elevation.

The angle of the mandible is the masseteric insertion and the zygomatic arch provides its origin [Williams et al 1982]. These features are as well developed in both sheep and man emphasising their importance in function in these species. May [1970] highlights the muscles ability to raise and protrude the rostral end of the mandible. Though this action is clearly important in rumination the muscles greatest role is probably in effecting high powered lateral movement at the level of the dental occlusion. The independent function of each entire masseter can also produce lateral motion [Noble 1979].

The actions of the masseter and medial pterygoid are greater in the herbivorous species with the temporalis being less well developed [Iyde 1991]. The sheep temporalis is much smaller than that of the carnivores; it has a smaller area of origin and a thinner narrower insertion along the coronoid process [Iyde et al 1991]. The muscle arises from the lateral surface of the cranium the fibres then converge to insert on the coronoid process of the mandible. The small braincase of the sheep means that the origin of the posterior fibres of temporalis are medial to their insertion. The line of action therefore has a significant medial component [Murphy 1965].

The temporalis is well developed in the carnivores with the masseter muscle being proportionately smaller [Dyce et al 1987]. Becht's [1953] examination of the carnivore found the weight of the temporalis to be greater than that of all of the other masticatory muscles combined. Contraction of the temporalis muscle provides a resultant force that pulls the mandible upward as well as backward. The long fibres of the temporalis are responsible for the snapping action in the carnivore. The hinge like temporomandibular articulation ensures reproducibility in the path of closure in rapid jaw movements [Noble 1979].

This muscle is especially large in those species such as the dog or cat in which the chief jaw movement is scissor-like and is therefore proportionately smaller in the sheep [Noble 1979]. The degree of lateralization of the zygomatic arch in some species gives an indication of its relative importance in jaw closing. The well developed sagittal crests and the widely flared zygomatic arch of the dog emphasise the importance of the temporalis in this species [Dyce et al 1987]. The more lateral the location of this arch the more room is provided for this muscle, which is especially bulky in the carnivores.

The carnivorian temporalis arises from a wide area extending from the temporal bone to the parietal region. The parietal margins of these muscles are wide enough to touch each other at the sagittal crest of the skull. Posteriorly the muscle extends to the muscles of the neck in the occipital region [Iyde et al 1991]. The main action is to raise the mandible which is an action which must be performed quickly and efficiently in the predator. Other temporal fibres tend to draw the mandible forward whilst some pull the condyle against the retro articular processes stabilising the joint in function. The insertion of the temporalis to the coronoid process as well as the coronoid process itself is very well developed in the carnivore.

The large human braincase provides a laterally based anchorage for the posterior temporal fibres. Its line of action is therefore lateral as well as backwards [Murphy 1965]. In the Australian Merino sheep the action of the temporalis is to clench the teeth by elevating the body of the mandible from its attachment along the anterior border of the ascending ramus. At least some of its fibres tend to retract the mandible [May 1970].

The pterygoid muscles lie medial to the mandible. They have a general area of origin in the pterygopalatine region of the skull. In most species the mass is clearly divided into a small lateral and larger medial muscle [Dyce et al 1987]. The large medial pterygoid muscles when acting together elevate the mandible also drawing it inwards with some simultaneous protrusion. When functioning independently they move the ramus toward the median plane.

The distance of the point of origin of the medial pterygoid muscle from the median plane gives some indication of the degree of lateral motion possible. The role of the masseter and contra-lateral pterygoid muscles as a functional pair which is especially well developed in species in where transverse movements are important. The masseter and medial pterygoids contract on the bolus with a powerful crushing action whilst grinding.

In the sheep the medial pterygoid forms a large fan shaped muscle overlying the medial surface of the mandibular ramus. May [1970] describes a single layered muscle arising from the ventral and lateral parts of the pterygoid and palatine bones and from the pterygoid process of the sphenoid bone. The muscle continues to insert on the medial surface, the ventral and caudal borders of the ramus and angle of the mandible. Turnbull [1970] describes a single muscle mass into which four muscle bundles "can be only be artificially distinguished".

The lateral pterygoid is described as a muscle that is flattened transversely and which takes a broad area of origin in the pterygopalatine fossa and the pterygoid process of the sphenoid bone. The muscle is seen to partially overlie the medial pterygoid and insert on the medial surface of the ventral and caudal borders of the vertical ramus and to the angle of the mandible [May 1970].

A similar description is advanced by Getty [1973] in his description of ruminant myology. The origin of the lateral pterygoid is the pterygopalatine fossa and the pterygoid process of the basisphenoid bone. The muscle is described as having a broad insertion which is similar to that described by May [1970]. The muscle inserts on the medial surface of the mandible from the base of the coronoid process to the junction of the ramus and body of the mandible. Getty however includes the rostromedial border of the mandibular condyle as well as the adjacent part of the neck of the condyle as part of this insertion. May [1970] does not include a description of this part of the muscle.

The action of the two muscles when working together brings about mandibular protrusion and produces marked lateral movement when functioning independently. Unilateral activation of the lateral pterygoid is probably important in initiating lateral movements. The thrust provided by the contra-lateral lateral pterygoid is an essential prerequisite of the more powerful grinding stroke which is assisted by the masseters and medial pterygoids. The powerful masseter and medial pterygoid crush the food in lateral excursions. The activity of the contralateral temporalis is important in the grinding phase as it assists the mandible in returning to central occlusion [Noble 1979].

Examination of the masticatory musculature of the omnivore shows a balance in muscle size that allows this group a wide range of mandibular movements. The medial pterygoid and temporalis are well balanced both for closing and lateral movements of the jaw. Lateral pterygoid also supports a wide range of lateral mandibular movements [Iyde 1991].

Opening the mouth is assisted by gravity with certain other muscles being available for the performance of this movement. The digastricus muscle is considered by most not to be a masticatory muscle. The digastric arises from the jugular process of the skull caudal to the temporomandibular joint and descends to the angle of the mandible. The muscle consists of two parts arranged together in tandem. The rostral portion is supplied by the mandibular nerve, the caudal portion by the facial, an indication that the muscle has a composite origin in the mesoderm of the first two branchial arches. The digastric muscle is thought to be most important in depressing the mandible to open the mouth [Getty 1973].

2.4 THE ARTICULAR DISC

Gilbe [1973] attempted to correlate the morphological differences in the anatomy of the articular disc with the different types of masticatory pattern found in three different mammals. The animals chosen were the domestic sheep, the dog and the rat. Rodents have an extremely complex masticatory apparatus dedicated to propaline (back and forth) movements. The masticatory system of rodents has undergone a slightly divergent evolution [Fox 1965]. The structure of the rat disc is therefore not discussed in further detail here. Bermejo et al [1993] compared the discs of humans, pigs, dogs and cats, rabbits and rats, and cows, sheep and goats.

Gilbe describes the disc of the domestic sheep as a thick structure separating the bony structures of the temporal fossa and condyle. In order to fit the bony articulating surfaces of the glenoid fossa and condylar head the upper articular surface of the sheep meniscus is slightly concave and its undersurface concavo-convex [Bermejo et al 1993]. The disc was thickened peripherally especially posteriorly with a thin area laterally. The anterior limit of the disc was difficult to define due to the lack of an obvious capsule [Gilbe 1973].

Histologically the disc was shown to merge anteriorly with vascular sinusoids.

These blood sinusoids fill the space between the disc and the coronoid process and form the attachment of the disc to the mandible. The disc itself was shown to be composed of collagen fibres running predominantly in an antero-posterior direction but some fibres ran medio-laterally. There were no blood vessels in the disc and few blood vessels present posteriorly [Gilbe 1975]. These fibres were observed in the central and posterior parts of the disc while at the posterior extremity the fibres ran vertically to be attached to the condyle and skull.

The attachments of the disc to the skull were long and ran parallel to the bony components of the joint. Conversely the attachments between the disc and the mandible were short. Little movement between the mandible and disc was possible with most movement occurring between the disc and skull. This arrangement is appropriate to the lateral movement of the sheep joint during mastication with the disc moving freely over the skull.

The articular capsule is indistinct in the sheep [Gilbe 1973]. Its is composed of two layers an outer fibrous layer and an inner synovial layer. The capsule is thickened on its lateral surface by fibres of the lateral ligament. Noble [1979] describes the capsule as strong but moderately loose. Mohl [1988] similarly described the sheep capsule as strong but lax. The inner synovial layer is composed of thin connective tissue which lines all but the articulating surfaces of the joint.

Fibrocartilage as well as elastin has been demonstrated within the sheep disc [Barnett et al 1961]. Cartilage is found where it is necessary to have a certain amount of rigidity combined with a certain degree of elasticity [Williams et al 1982]. The presence of elastin is thought to confer a greater degree of resilience to the disc [Gilbe 1975]. Elastin was seen throughout the disc running in various directions amongst the collagen fibres. Elastin fibres are also present within in the vertically directed attachment fibres in the posterior part of the disc. Where identified fibrocartilage was always surrounded by fibrous tissue. This fibrocartilage was distributed through the central and posterior portions of the disc but was not located peripherally [Gilbe 1973]. As well as the presence of scattered amounts of fibrocartilage a cartilaginous nodule in the posterior region of the sheep disc has also been described [Barnett et al 1961].

The structure of the dog disc was thought to reflect the relatively simple rotational movements of the canine mandible [Dyce et al 1987]. This disc had short attachment fibres and a strong anchorage to restrict lateral movements. The dog disc is broad at its antero-posterior margin widening toward the centre of the joint and then narrowing medially [Gilbe 1973]. The disc is thickest at its periphery and is unusual in having powerful anchorage to the skull medially and the outer pole of the mandibular condyle laterally. The temporomandibular joint disc therefore acts as a ligament to arrest lateral movement when the carnassial teeth are aligned for cutting [Scapino 1965].

Compared to the dog the attachments of the sheep disc are loose and allow wide ranging lateral movements in the superior joint space. A marked anterior thickening found in the dog disc may be present to prevent forward dislocation of the disc when the mouth is opened wide. No such thickening could be found in the disc of the sheep as this is an animal that makes little use of hinge movement [Gilbe 1975]. The limitations to disc excursion the attachment fibres of the dog disc provide serve to augment the bony restrictions to antero-posterior or lateral movements. The attachment of the lateral pterygoid in the dog runs in a different direction to that of the sheep making it impossible for the canine jaw to produce a uni or bilateral anterior movements [Iyde et al 1991].

The human temporomandibular joint disc is located between the glenoid fossa and the condyle of the mandible thus dividing the joint cavity into superior and inferior joint spaces. The disc is biconcave in lateral projection corresponding to the sigmoid curve described by the glenoid fossa. The contour of the disc has been described as having a latero-medial convexity and an antero-posterior concavity [Bermejo et al 1993]. Tight connections to its medial and lateral poles anchor the disc to the condyle. Superiorly and inferiorly the disc is continuous with the joint capsule. The capacious joint cavities allow free translation of the disc condyle complex. The disc more closely resembles that of the sheep than the dog.

The joint capsule is attached to the lateral border of the fossa and the articular eminence and to the mandibular condyle at its neck. A reinforcement of the capsule at its lateral surface forms the temporomandibular ligament. The fibres of this ligament run from the zygomatic process of the temporal bone and insert into the lateral aspect of the condylar neck. The temporomandibular ligament strengthens the articular capsule, limits excessive lateral excursion and keeps the articular surfaces close together when the condyle moves.

The human temporomandibular joint is a true synovial joint but unlike most others it surfaces are not covered by hyaline cartilage. The articular surfaces as well as the central part of the disc are composed of fibrocartilage. Fibrocartilage is a nerve free, avascular dense fibrous connective tissue [Moffet 1964, Hylander 1979, Oberg and Carlsson 1979, DuBrul 1980]. Histologically the tissue can be seen to be composed of areas with few cartilage cells surrounded by a scanty cartilage matrix in dense fibrous connective tissue [Mohl 1988]. In man the fibrocartilage covered surfaces extend from the deepest part of the fossa to the frontal part of the articular eminence. This implies that the fossa itself is not a real articulating part of the joint [Falkenstrom 1993].

Gilbe [1973] felt that the presence of elastic tissue and cartilage in the centre of the disc made the sheep disc quite unlike that of the human. Griffin and Sharpe

[1962], Miles and Dawson [1962] and Keith [1979] suggested that elastin fibres add to the resilience of surfaces which are deformed in functional movement. Elastic tissue had been demonstrated in the posterior attachment tissues of the human disc as early as Rees [1954] and Dixon [1962]. Gilbe suggested that the presence of elastin within the sheep disc itself had not been reported in any other mammalian craniomandibular joint. A review of the literature however shows that several morphologic studies have indicated the presence, and in some cases the general distribution of elastin fibres throughout the TMJ [O' Dell et al 1990].

Elastin fibres have been found in the articular discs of the mouse [Frommer and Monroe 1966], the bull [Keith 1979], the rabbit and the hamster [O' Dell 1990] and in man [Miles and Dawson 1962]. Although elastic tissue now seems ubiquitous it's amount and distribution may vary. Elastic tissue is plentiful in the upper and lower stratum as well as the being loosely distributed throughout the central part of the retrodiscal tissues [Wilkinson and Crowley 1994]. Correspondingly less elastic tissue is found in the disc itself. These observations support the concept that if the elastic content of the sheep disc is high it may be better able to withstand force than the disc of dogs or humans [Gilbe 1975].

Elastic tissue in the posterior attachments of the human joint has been ascribed the function of retracting the disc after it has been drawn forward during protrusive movements of the mandible [Dixon 1962]. The elastic tissue is present in the posterior part of the sheep disc may have a similar function. The vascular sinusoids or blood spaces present in the sheep are located anteriorly rather than posteriorly. The role of elastin present in the central part of the temporomandibular joint disc and its function in the anterior vascular sinusoids is unknown.

Fibrocartilage is distributed more widely in the sheep than in human, dog or rat discs examined by Gilbe. The combination of greater amounts of this material as well as the presence of elastin within the disc itself may increase the stress bearing capabilities of the sheep temporomandibular disc [Gilbe 1973].

It is the opinion of some authors that the measured thickness of the disc reflects the variation in transarticular pressure in different parts of the joint in function. The areas of thickening corresponding to areas of greater pressure within the joint and the overall thickness of the meniscus in a particular animal relating to the degree of stress encountered in function. Measurements in the sheep were 100, 40, and 60 microns respectively. In the human specimen however measurements were 370 microns over the the articular eminence, 75 microns over the roof of the glenoid fossa, 150 microns over the post glenoid tubercle [Murphy 1965].

The sturdy articular disc in sheep and humans may allow the complex combination of rotation and translation seen in mandibular movements in these species. The strong but relatively loose capsule in the sheep allowing a wide range of particularly lateral condylar translation in the upper joint space. The human disc is tightly attached to the medial and lateral poles of the condyle with its capsule being strongly reinforced laterally by the temporomandibular joint ligament, most of the movement occurring in the lower joint space. By contrast the disc in dogs is thin and underdeveloped with movement being predominantly rotational. One author reported that there was no disc but rather a thick membrane [Fox 1965], Parsons [1899], Sisson and Grossman [1961] commented only on the thin nature of the canine meniscus.

2.5 THE MANDIBULAR SYMPHYSIS

In common with most mammals the mandibular symphysis of the Australian Merino Sheep is unfused [May 1970]. In essence the mandible can then be considered as consisting of two halves with three joints; two temporomandibular joints and one symphyseal joint. All members of the family Bovidae (Artiodactyla) to which the the Australian Merino sheep belongs have an unfused mandibular symphysis. This fact may be considered surprising in that these are uniformly grass and leaf eating animals as these foods are known for the large forces required for their trituration [Beecher 1977].

The mandibular symphysis may also be seen as a variably moving functional joint. This synarthrosis has its own neurovascular supply and special connective tissue arrangement. The posterior, ligamentous portion of the symphysis is laced with a profuse network of nerves [Scapino 1965]. A small unpaired intermandibular muscle has been demonstrated slightly distal to the unfused symphysis in the muskrat [Van Vendeloo 1953]. In all species third joint is thought to have a strong influence on the structure and function of the temporomandibular joint [Noble 1979].

The presence of an unfused symphysis in the sheep means that the bones are connected relatively loosely to allow for lateral sliding movements during mastication [Iyde et al 1991]. The symphyseal joint may allow small movements that are important in securing a more precise adjustment of the upper and lower tooth rows, and therefore a more effective cutting mechanism [Dyce et al 1987].
The amount of movement available at this joint varies between animals. The sheep symphysis is quite mobile. When the right lateral pterygoid is activated the right condyle and mandible are pushed forward. Most of the thrust of this muscle is probably transferred via the symphysis to the contralateral mandible. In this way the left mandible is pushed laterally so as to permit the cheek teeth to occlude in their normally unilateral fashion. Two types of movement at the mandibular symphysis appear to be possible. A spreading movement altering the angle between the two halves of the mandible and a movement in which one in which

each half rotates about its own long axis so that the tooth cusp alter their inclination to the vertical [Dyce et al 1987].

Ewer [1973] noted that not all carnivores possess this third joint. The presence of an unfused symphysis has however been described in the domestic dog [Scapino 1965]. The dog symphysis has a strip of fibrocartilage which runs antero-superiorly between its bony articulating plates. Strong cruciate ligaments bind and stabilise the joint in function. The fibrocartilaginous portion of the joint is thought to cushion symphyseal movements and mediate rotational movements of the mandible about its long axis. In this way the dog temporomandibular and symphyseal joints collaborate to align the canine teeth for shearing motion.

Although the dog has a unfused symphysis its mobility is much less than that seen in the domestic sheep [Gilbe 1973]. The dog appears to use both types of symphyseal movement when adjusting the position of a bone between its teeth when attempting to crack it [Dyce et al 1987]. Shearing movements require small independent movements of the two hemi-mandibles which is possible with a non united symphysis.

The presence of an unfused symphysis is considered a primitive morphological feature. This is an adaptation which does not reflect the general evolutionary trend toward a reduction in the number of facial bones. Reduction in the number of facial bones is an adaptation which affords greater mechanical stability [Scapino 1981]. Great mechanical stability is required for the rigid prehension of food. In this way independent movement of the two halves of the mandible can also be seen as a reflection of the feeding requirements of the animal.

The added stress of chewing leaves and grass is though to have induced at least partial fusion in most species of primate [Hylander 1979] and in man the two halves of the mandible are firmly fused together. Symphyseal fusion is thought to be a consequence of diets which require large occlusally directed forces in mastication [Beecher 1977]. The presence of considerable shear stress in the fused symphysis of primates has been described [Hylander 1979].

In man the presence of a fused symphysis has lead some authors thus consider the two temporomandibular joints as widely separated halves of a single condylar joint. Movement of one joint being accompanied by a movement not necessarily identical on the contra lateral side [Dyce et al 1989]. Precise control of the dentition on one side by the contralateral pterygoid group can be demonstrated in human mastication, presumably without marked reduction in the magnitude of muscle force [Noble 1979]. In this way it has been suggested that symphyseal fusion in man allows for a more efficient transfer of the force generated from the balancing side musculature to the biting side [Hylander 1975].

CHAPTER THREE

BIOMECHANICAL INVESTIGATION

3.1 ANATOMICAL EVIDENCE FOR JOINT LOADING

Numerous authors have sought to deduce the biomechanic activity of the masticatory apparatus via functional anatomical comparisons. Traditionally biomechanical function was based on the classification of animals into various feeding types. The size and shape of the mandible, maxilla and the spatial relationships between teeth, muscles and jaw joint were described in terms of these feeding requirements [Weijs 1980]. The functional advantages of differences in the relative sizes of muscles and variance in the shape of their jaw bones have been compared by various authors [Davis 1955, Turnbull 1970, Greaves 1978]. Interestingly Ostrom [1964] deduced the jaw mechanics of the prehistoric dinosaur Triceratops from a study of its fossilised remains indicating the degree of information concerning muscle size and fibre orientation that can be obtained purely from skeletal material.

The design of the facial skeleton itself is intended to withstand and distribute masticatory forces in a way that does not endanger facial structures [Oyen et al 1991]. Benninghoff [1925] and Sicher and Tandler [1928] presented a beam hypothesis that proposed the transmission of masticatory forces through several routes along the facial skeleton. Roberts [1974] in a review of skull form and the mechanics of mandibular elevation in mammals describes how bone structure correlates with the resolution of masticatory force generated at the dentition. Roberts considers that the size and morphology of the facial skeleton are determined largely, if not entirely, by the feeding requirements of a particular animal.

Typical primate facial architecture is described as a bilateral tripodal structure [Roberts and Tattersall 1974]. The central member of this tripod consists of the median septa of the nasal cavity and the frontal sinus. Anteriorly biting stresses are conducted through the the canine root and the nasal process of the maxilla to the frontal bone. Laterally stress conduction occurs through the antero-inferior root of the zygomatic arch through the postorbital bar again to the frontal bone. The anterior portion of the pterygoid laminae forms the inferior part of the posterior buttress with stresses passing through the floor of the anterior cranial fossa to the frontal bone. Consideration of this structure leads Roberts to conclude that occlusal forces are orientated so that stresses are directed to the apex of this pyramid; the dome shaped, bulky, frontal bone which is ideally suited to stress distribution.

With regard to the teeth it has been argued that the roots of the molars are inclined in the frontal plane in such a way as to minimise the torques developed during mastication [Osborn 1982]. Jaw muscles receive feedback from periodontal receptors and combine in function to produce a bite force directed along the long axis of the molar roots with the object of minimising the torque on the teeth [Osborn and Baragar 1985].

Although the bony architecture of the human mandible was described in antiquity the biomechanical significance of its form has received much less attention. Walkoff [1900, 1902] described the trabecular pattern of bone in the human mandible and Winkler [1921] and Benninghoff [1925] described a method of revealing the lamellar structure of its cortical plates. Seipel [1948] added the techniques of low power microdissection and histological examination to describe more completely the internal organisation of the bone matrix. Seipel [1948] proposed a system of trajectories to describe the mechanical function of the jaw. These lines of skeletal reinforcement connect the masticatory muscles to the dentition and are of functional significance in conducting the stresses of mastication through the mandible. Seipel's lines were 1. the inferior basal 2. external and internal oblique trajectories 3. the temporal trajectory 4. connecting trajectory and 5. the alveolar arcade system (**Fig 3.1**).

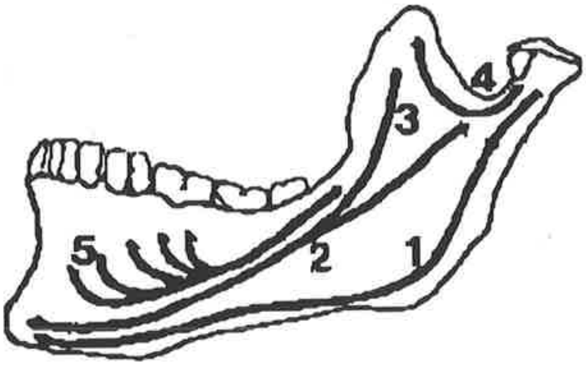


Fig 3.1 (After Ralph 1974)

Seipel stated that the inferior basal was a compressive trajectory and that the external and internal oblique trajectories were tensile. These observations formed a basis for future studies that predicted the optimal placement of bone plates in the repair of fracures of the mandible. The pulling trajectory being located on the oral side and the pressure trajectory on the basal surface of the mandible [Spiessel 1976].

The structure of the condylar head and its slender neck has also been examined in regard to its stress bearing capabilities [Tattersall 1973, Hylander 1975]. In reviewing the anatomy of the condylar neck of the primate lemur *Archaeolemurine* Tattersall suggests that "it is sufficiently weak for it to be said categorically that it could not have withstood the forces that were imposed on it in a lever system" [Tattersall 1973]. This statement lead to an extensive investigation of the structure of the human condylar neck by Hylander [1975].

Hylander's investigation of condylar structure found that its cortical structure was appropriate to bear the anticipated tensile and compressive stresses engendered by normal mastication. A critical stress analysis showed it to be capable of withstanding a shearing reactive force of 610 N [Hylander 1975]. Later investigators found the largest predicted joint reaction force in normal function to be 513 N [Koolstra et al 1988].

Comprehensive radiographic examination of the temporomandibular joint has been undertaken by Frank [1950]. Individuals were asked to bite on 20 mm objects in the incisor and left and right premolar regions. Frank noted when the mandible dropped open to engage a food bolus the condyle moved downward out of the deep area of the fossa to a point near or under the eminentia. If the mandible moved in this way it seemed that pressure exerted by the mandible on the bolus did not require the condyle to act as a fulcrum. Frank saw the bolus itself as the temporary fulcrum, dissolving when its function was completed. No contact was seen between the condyle and the temporal bone during biting. Examination of maximal biting in three progressively posterior positions showed no change in condyle position relative to the eminence. These observations were interpreted by Frank as evidence that no matter which side is under pressure the muscles of the opposing side offset this pressure keeping the mandible in balance. Hylander has critically reviewed Frank's work, and stated that although no contact is visible radiographically between these structures the observed space would no doubt be occupied by radiolucent fibrocartilagenous tissues which could provide a fulcrum point [Hylander 1975].

Roberts [1974] used phylogenetic evidence to support the conclusion that the temporomandibular joint is not a stress bearing joint. Primitive reptilian masticatory function was observed to involve simple grasping movements. These animals have an articular quadrate craniomandibular articulation which is suitable for load bearing. This arrangement no longer exists and a more complex masticatory pattern has evolved in modern mammals. This is seen as evidence that evolution has determined a non stress bearing role for the joint and that it has been retained simply to maintain the integrity and alignment of the osseous components. The loss of a specific load bearing articulation has been paralleled by the differentiation and refinement of the masticatory musculature so that the forces produced remain in mechanical equilibrium with the bite forces generated at the tooth row [Roberts 1974].

Microscopic and gross anatomical changes are observed to occur throughout the life of the temporomandibular joint [Smith 1978]. Correlation of these changes with increased mechanical stress have been attempted by various authors [Wright 1968; Moffet 1964]. The degree of remodelling and the new shape imposed on the condyles has been related to changes in the dentition [Mongini 1972, 1975 and Mongini et al 1978]. The fact the condyles are never static and undergo extensive remodelling is seen by some authors as proof of its lever action and load bearing function [Mansour, Reynik and Larson 1973]. A clinical and radiographic examination of 400 temporomandibular joints in patients who chewed on one side only because of lost molars found deformities in the joint especially on the chewing side [Boering 1979]. A morphological study on cadavers [Oberg et al 1971] showed an increased incidence of joint deformities in older individuals or those that had defective teeth. Articular remodeling is sometimes however seen in asymptomatic joints. Although an increase in the frequency of radiologic morphologic changes occurs in patients with TMJ pain, these changes are neither exclusive or pathognomonic. On these grounds caution must be emphasised in overestimating the significance of radiographically discernable change in patients with joint pain [Muir and Goss 1990]. Ishimaru et al [1991] examined the effect of unilateral loss of teeth in the Australian Merino Sheep. Although the animals lost weight there was no discernable radiographic change within the temporomandibular joint.

Some authors consider that anatomical examination of joint structure provides compelling evidence as to its function. Robinson [1946], Scott [1955], Steinhardt [1958] provided individual reviews of joint structure that suggested the joint was not load bearing. These investigators argued that the temporomandibular joint is one morphologically incapable of bearing stress. Some arguments have used histological evidence to support the non loading concept of the TMJ and in doing so discuss the dissimilarities between the TMJ and other stress bearing articulations. Robinson [1946] stated, "The tissue found in the TMJ is not of the type found elsewhere in the body" and that "Therefore, it is reasonable that there should be no appreciable stress in the TMJ".

Unlike the articular surfaces of joints between long bones the articular surfaces of the TMJ are covered by a layer of dense collagenous tissue. There is no articular cartilage and this joint lacks the stout cap of bone or epiphysis beneath this layer. Epiphyseal cartilage is not seen at any stage in the development of the temporomandibular joint. Steinhardt [1958] states that when joints are affected by pressure they have a protective epiphyseal cartilage so that the lack of this in the temporomandibular joint means; "masticatory pressure is not inflicted on this joint". Barbenel accounts for these morphologic dissimilarities by discussing the quite distinct embryological origins of the mandible. Whereas the mandible develops from membrane bone, long bones develop from cartilage precursors and epiphyses are typical of this form of development [Barbenel 1972].

Robinson discusses other anatomical observations to support the non loading concept of the TMJ. The paper thin roof of the glenoid fossa and the presence of a synovial layer between it and the mandibular condyle are described. The roof is composed of laminar and not haversian bone and is not supported above by cancellous bone [Walker 1978]. The fibrocartilagenous nature of the articular disc the presence of blood vessels, nerves and lymphatics within the disc itself seem to suggest that this joint is unsuited to compressive stress. Synovial tissues are not found in stress bearing joints elsewhere in the body and these joints have hyaline coverings. The thin nature of the lamina seen in the fossa was also alluded to by Taylor [1986] who saw the fossa as having no provision to meet significant stress.

The notion that the thinly roofed glenoid fossa is unsuited to stress bearing seems plausible. The main force bearing region in most primates is however thought to be confined to the articular eminence. The eminence is composed of thick cancellous bone with a dense cancellous plate [Hylander 1975, 1979]. Both the condyle and the eminence develop reconstructive haversian systems during life [Walker 1978]. The location of the synovial layer immediately beneath the fossa roof is thus appropriate as this region is merely the receptacle for the glenoid fossa when the jaws are closed [Moss 1960]. Remodelling of the bony surfaces around the temporomandibular joint has been studied and some reconstructive features that are associated with load bearing have been found. When remodelling occurred in the superior aspect of the joint it occurred in the articular eminence rather than in the thin plate of the roof of the fossa [Moffet et al 1964].

The pattern of bony trabeculations within the mandible has also been examined. Observation of the buttressing of bony trabeculi within the mandibular condyle and the articular eminence have been used to estimate the directions of compressive force in this region [O'Ryan and Epker 1984, Faulkner Hatcher and Hay 1987]. Studies of the radiographs and tracings of the bony trabeculae in the sheep have been performed [Dovitch and Herzberg 1968]. These authors describe a "N" shaped pattern in the mandibular ramus and a horizontally directed pattern of trabeculations in the coronoid process of herbivores which is not seen in other animals **(Fig 3.2)**.

Fig 3.2 (after Dovitch and Herzberg 1968)

These patterns reflect the direction of significant forces from condyle to angle of jaw and condyle and coronoid to retromolar area. Although broadly similar the differences in trabecular pattern between species are thought to relate to different direction of force which results from the slightly different actions of the masticatory muscles in animals with dissimilar dentitions [Dovitch and Herzberg 1968].

On closer examination the presence of blood vessels nerves and lymphatics of concern to Robinson are noted to occur only at the peripheries or in the posterior aspects of the articular disc; areas which are less likely to bear the brunt of reactive forces [Hylander 1975]. The region of the articular disc situated between the articular eminence and the mandibular condyle however contains an avascular portion that lacking blood vessels, nerves, lymphatics and a synovial layer [Rees 1954, Sicher and Bhasker, 1972].

The descriptions of fibrocartilage advanced by some authors suggest that its stress bearing capabilities may be at least as good and in some situations better than hyaline cartilage [Hylander 1975]. Inkster [1964] describes it as containing strong bundles of fibrous tissue that make it less cellular and more flexible than fibrocartilage. Leeson and Leeson [1970], and Ham [1969] conclude that its properties may make it better able to cope with tensile forces than hyaline cartilage. Fibrous connective tissue has been described as having greater shear resistant qualities than hyaline cartilage [Moss 1959, 1960]. Hyaline cartilage is more resistant to compressive forces and the presence of islands of hyaline cartilage in the fibrous layers and very occasionally in the disc itself is seen by some authors as a response of the tissue to increased functional loads [Boucher 1962, Sicher 1970]. Boucher felt that the joint was designed both histologically and morphologically to withstand pressure remarking on the toughness and flexibility of the fibrous connective tissue that lines its surfaces. The absence of blood vessels in the firm central area of the joint and the direction of the fibre bundles are also described as evidence of the pressure-bearing adaptation of the joint.

Anatomical investigation of the issue of joint loading has been carried out to ultrastructural levels. Bacon et al [1980] continued the theme that the structure and texture of bone are related to its function by experimentally measuring the mineral structure of the bone itself. Bacon concludes that the anisotropy of individual crystal orientation in bones provides an index to muscular activity and presumably to the whole macroscopic stress environment to which they are subject. Currey [1979] suggested that the superior bending strength of the femur over the antler may be related to the relatively high degree of orientation of its microscopic constituents. Studies of the ultrastructure of the scapula have shown greater detail in muscle pull and bone structure relationships than more conventional modelling studies [Bacon et al 1979].

The *c* -axis of apatite crystals can be measured by neutron diffraction techniques [Bacon et al 1979]. In these studies crystals are found to be orientated along the long axis of shaft bones and are directed along the length of individual trabeculae. Crystallite orientation over bone can be correlated with the directions of pull of the attached muscles. In Bacon's study neutron beams were directed at 90' to the surface of the mandible. The resultant alignment of crystals reveals that highly directional forces and muscle pull induced loads operate over the surface of the mandible.

A simple force resultant is described by the highly orientated crystals along the posterior margin of the ascending ramus of the mandible and this is directed towards the temporomandibular joint. Superiorly the lateral pterygoid produces a considerable widening of the crystal orientation pattern. The angular pull of the temporalis relative to the main component of force along the posterior margin indicates that this muscle produces shear force on the coronoid and on the anterior part of the ramus. The pull of the medial pterygoid is not directed toward the temporomandibular joint although most of the apatite crystals point in this direction. This observation perhaps indicates that the major importance of the masseter is in jaw closure.

At the juncture of the mandibular body and ascending ramus horizontally arranged crystals can be found. Such an arrangement is suggestive of the resolution of tensile and compressive forces at the outer surface of the structure and accounts for the relative density of the cortical compared with cancellous bone. A similar pattern is duplicated in the ascending ramus. There are two distinct concentrations of stress; one directed along the upper surface of the body of the mandible which curves up toward the coronoid. A second trajectory follows the lower margin of the body and ramus and ends at the temporomandibular joint. The conclusions of Bacon's ultrastructural studies suggest the human mandible can be modelled as a hollow tubular beam. This is especially true in its horizontal body [Bacon et al 1979].

Anatomical evidence of the pressure bearing nature of the temporomandibular articulation is occasionally provided by "experiments of nature". Humans and several other animals that have bilateral condylar fractures develop an anterior open bite. The mandible rotates about the last molar on each side until the fractured condylar neck contacts the temporal bone. Poswillo [1972] removed the condyles in the Rhesus monkeys and found that the monkeys could then only bite by using the molars as a hinge.

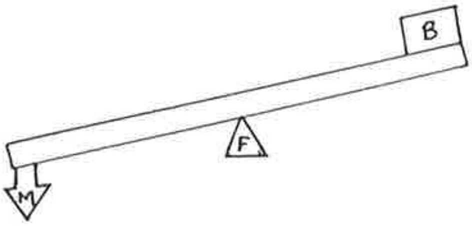
3.2. LEVER MECHANICS; 2-D MATHEMATICAL MODELLING

The first major issue to evolve in the study of joint biomechanics was whether the joint was stress bearing or not. Most of the early attempts at mathematical modelling were also designed to answer this question. The issue of joint loading has been the source of much controversy and remains central to the study of mandibular biomechanics. Investigators commonly use graphical or numerical models to support or refute the concept of joint loading.

In 1921, Alfred Gysi contended that the mandible acted as a lever with the TMJ as the fulcrum. Gysi's suggestion was that the two craniomandibular joints acted together to support the jaw reaction forces. Wilson as early as 1920 purported to show "with true physical demonstration" that the muscle force on the mandible was "expended on the bolus of food and not a portion of it upon the condyle". Wilson [1920] had argued that because the resultant force of the temporalis, masseter, and medial pterygoid acted perpendicular to the occlusal plane that there was no resultant force at the mandibular condyle. This would make a lever concept of mandibular action impossible and this would mean there was no force at the mandibular condyle. Wilson used the earlier work of Prentiss [1918] to explain the increased TMJ pathology noted in people who had lost their molar teeth as evidence that the joint was normally not loaded but became so as teeth were lost. This same work is given a different interpretation by later workers.

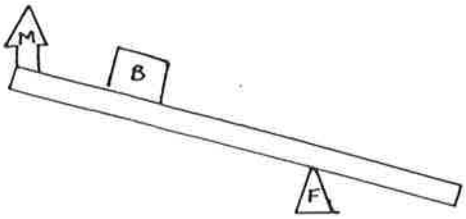
Gysi [1910] explained the concept of condylar loading in terms of lever mechanics. Wilson's [1920] suggestion that there was little or no reactive force at either mandibular condyle. This theory explained mandibular function as non lever mechanics. A lever is defined as; "a bar pivoted on a fixed point" [Oxford dictionary]. The bar equates to the mandibular corpus and the condyle is described as the fixed point or fulcrum. Three forces are involved in the lever model of he mammalian masticatory system [Gingerich 1979]. These forces are the applied force supplied by the muscles of mastication, a bite force along the tooth row, and a reaction force at the TMJ. Levers can be classified into three types;

FIRST CLASS LEVERS. In this system the fulcrum (joint) always lies between the effort (muscle) and the resistance (weight). This is the most efficient class of lever. For a constant weight the longer the distance F-M, relative to the distance F-B, the less muscle effort is required **(Fig 3.3)**. An example of this lever system is the human head as it rests on the spinal cord. The fulcrum is the axis of the cervical spine, the power the post cervical musculature and the work performed is energy necessary to prevent the head from tilting forward. This lever approximates the classical situation of a see-saw with a central fulcrum providing a good deal of mechanical advantage.



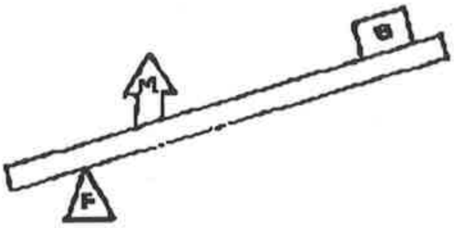
(Fig 3.3)

SECOND CLASS LEVERS. In this system the resistance always lies between the fulcrum [joint] and the effort [muscle], such as when pushing a wheelbarrow. In this case, the longer F-M distance relative to the shorter F-B distance provides a good mechanical advantage for the muscle **(Fig 3.4)**. When a person stands on his toes the fulcrum lies at the toe, the power arm at the gastrocnemius insertion at the heel and the work performed is the elevation of the body weight resting on the bones of the leg [Nagle and Sears 1958].



(Fig 3.4)

THIRD CLASS LEVERS These are the least efficient of the lever systems. The muscular effort is placed between the weight and the joint, providing a poor mechanical advantage **(Fig 3.5)**. As an example lifting a 50-lb box with your arms (third class lever) takes significantly more effort than lifting your 150-lb body by standing on the tips of your metatarsals [Kapit and Elson 1977]. Third class levers are inefficient [Nagle and Sears 1958].



(Fig 3.5)

Divergent opinions exist as to whether the mandible functions as a different type of lever in different situations. Gysi 1921 contended that the mandible acted as a class 2 or class 3 lever depending on the placement of the food. Later researchers have supported this concept adding that the mandible functions as a class 2 or 3 lever or in some positions or can be in equilibrium depending on the position of the bolus [Tradowsky 1981]. A purely class 2 lever action has been described in certain functional or occlusal positions [Schweitzer 1951, and Kallenbach 1931].

Though some investigators describe lever mechanics as an oversimplification of mandibular movement [Wheeler 1974] this is the most commonly used biomechanical analogy for the mandible [Roydhouse 1955]. In this instance the condyle acts as the fulcrum, the resultant force of vectors of the masticatory muscles as the applied force, and the bite force as the resistance or load [Smith 1978]. The spatial relationship of these components determines which type of lever system is operating [Tradowsky 1981]. Seitlin [1968], convinced of the lever action of the mandible, used lever mechanics to describe the role of teeth in the dental occlusion. Seitlin described "load determining teeth" on the basis of the span between them and the muscle force. The role of the temporomandibular joint as the fulcrum was emphasised. In this system the cuspids were ideally placed to be the principle dental load determinants. The ability of the supporting tissues to tolerate muscle force, and the effects of occlusal interferences, were explained on the basis their position from the fulcrum. The concept of the class 3 lever system persists [Kornfield 1974, Kraus et al 1969, Garliner 1976 and Dawson 1974, Mohl 1988]. **Fig 3.6** illustrates the concept of the mandible as a class three lever [Nagle and Sears 1978].

Fig 3.6 (After Nagle and Sears 1978)

Roydhouse [1955], reviewed Gysi's [1921] earlier work reflecting on the then current disfavour of the non lever concept of the mandible. Many of the concepts of the load bearing nature of the joint suggested by Gysi had been undermined by the work of Wilson [1920] and Robinson [1946]. The wide acceptance of these theories may have led Moyers [1950] to interpret his electromyographic results in support of a non lever, non pressure bearing articulation. These authors concentrated on the functional and anatomical aspects of the joint and provided only simple mathematical models to support their conclusions.

Davis [1955] provides an elegant and comprehensive account of the masticatory apparatus in the spectacled bear *Tremarctos ornatus*. The masseter and temporalis were described as a force couple that conferred mechanical efficiency. The concept of class three lever mechanics was disregarded as inefficient and improbable. Later workers have criticised this account on the basis of its assumption that the couple enabled the forces at the fulcrum to be eliminated. Muscle forces are divided into horizontal and vertical axes with only the horizontal muscles being considered relevant to jaw closure. The large vertical components are ignored. A couple is produced by equal and opposite, non colinear parallel forces in the same plane. Forces that produce a couple cannot be combined into a single force since there sum in every direction is zero [Smith 1978].

Hylander [1975] has reviewed the work of earlier investigators and suggested that the association of tooth loss and TMJ pathology does not imply that the joint is unloaded. Increased pathology in the joint can be also be explained in terms of 3rd class lever mechanics. Because posterior support is lost with the molars incisor biting is used and greater joint reaction forces occur as a consequence of an increase in the length of the lever arm [Hylander 1975]. Hylander discounted Wilson's [1920] mathematical model. If TMJ reaction force is to be eliminated the resultant force of the masticatory muscles must pass through the bite point. In Wilson's construction this is not possible as the resultant is orientated perpendicular to the occlusal plane [Hylander 1975].

Robinson [1946] was another early advocate of the non lever concept of the mandible stating there was, "no provision for the development of heavy stresses in an upward direction on the joint". The observation was also made that; "On the other hand the dental arches are so formed as to receive the heavy stresses of the masticatory muscles". Robinson produced a model with springs to simulate the elevator muscles. The glenoid fossa could be removed from this model without disturbing the equilibrium of the system. A simple geometric figure was also supplied in which the teeth were shown to receive all of the stress **(Fig 3.7)**.

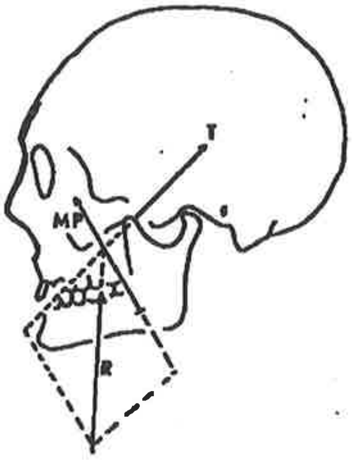


Fig 3.7 (after Robinson 1946)

Barbenel criticised the placement of the muscle force vectors in Robinson's model and questioned the validity of using springs to simulate masticatory muscle [Barbenel 1969]. Hylander similarly rejects Robinson's conclusions both on the grounds of the validity of the determination of the lines of muscle action and on the basis of a critical analysis of the model itself [Hylander 1975]. Whilst the model is valid when resultant forces are directed through the first molar this is the single position in which this is so. Biting forces anterior or posterior to this position result in a lever action. Later authors attribute different lines of action to the temporalis, pterygoids and masseter than are described by Robinson [Gingerich 1971, Hylander 1975]. Hylander further argues that Robinson's diagram is incorrect with inaccurate placement of critical anatomical structures including the dental arch itself.

The conclusion that the joint is load bearing during function was demonstrated separately by Craddock [1951]. A simple geometric analysis was used (**Fig 3.8**).

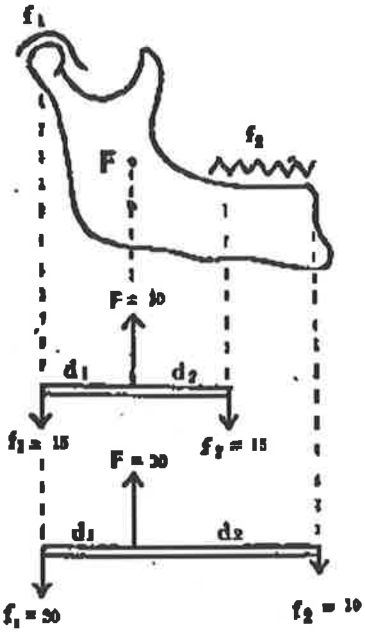


Fig 3.8 (after Craddock 1951)

Craddock then provides an equation to determine the force on the disc;

$$f_1 = \frac{F.d_2}{d_1 + d_2}$$

In this relation;

f_1 = upward force on the articular disc

f_2 = upward muscular force

d_1 = distance of condyle to presumed muscle insertion

d_2 = distance from muscle insertion to food morsel

A number of assumptions where made in this construction. Firstly the mandible was seen as a class three lever system. The upward forces of all of the elevator muscles of the mandible were seen to be concentrated at a point midway between the molar teeth and condyles. The antero-posterior distances between the condyle muscle insertion, molars and incisors were assumed to be equal. The use of this simple mathematical model allowed Craddock to demonstrate that for a given force expended on food crushed between the molars a similar amount of force would be delivered to the temporomandibular joint. If this same force were applied to incisor biting then less would be delivered to the bolus and correspondingly more would be delivered to the joint. In broad terms a decrease in crushing force and an increase in force borne by the joint was seen as the food bolus is shifted forward. Although Craddock saw little chance of overload in a normal occlusion the loss of posterior teeth was seem as a predisposing factor in Costen's syndrome as it functionally duplicated the constant anterior positioning of chewed food [Craddock 1951].

Further support to the renewed confidence in lever concept of mandibular mechanics was supplied by Roydhouse [1955]. Roydhouse described the directions of the muscles of mastication as; "the backward and upward pull of the temporalis muscle and the forward and upward pull of the masseter and medial pterygoid". He determined that the resultant of these "like forces" could only be directed to a point between the application of their components. This force therefore could never be anterior to the anterior border of the ramus. Roydhouse supplies a mathematical analysis that yields a vertical muscle resultant that passes upward in the vicinity of the coronoid processes of the mandible; a "muscular zone". Opposing this force was the food resistance with a downward vertical resultant in a zone bounded by and including the teeth. In Roydhouse's diagram the upward component of the temporal muscle is represented by T, the upward component of the masseter and internal pterygoid by MP which yielded R the the vertical resultant of the muscular force on each side. M' represents the muscle zone and T' the tooth zone **(Fig 3.9)**.

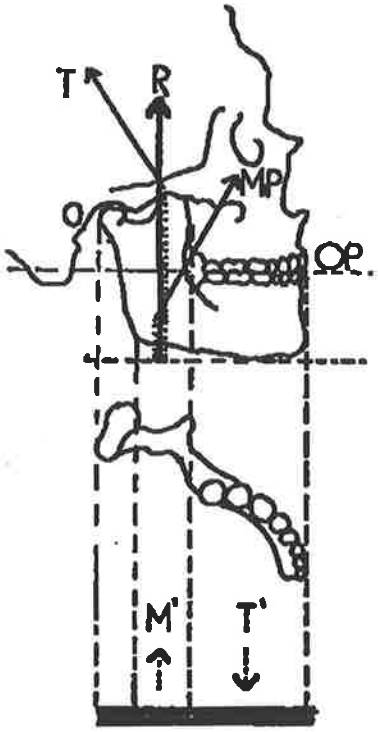


Fig 3.9. (after Roydhouse 1955)

Roydhouse felt that the total muscular force must exceed the resistance of the bolus to allow the food to be triturated and that this created an additional force outside the mandibular system. This force was directed posterior to the muscular zone and caused one or both condyles to move vertically during mastication. A coronal analysis was also performed and consideration was given to electromyographic data that showed an inequality of muscle activation between the mandibular halves [Moyers 1950, Carlsoo 1952]. The proposition was advanced that during mastication both condyles tended to move upward. A restraining influence was provided by the passive resistance to upward movement supplied by the cranium and the pressure bearing capabilities of the temporomandibular joint [Roydhouse 1955].

Both Craddock and Roydhouse concluded a vertical force occurred at the temporomandibular joint. The analyses provided by these authors was critically examined by Barbenel [1969, 1972]. Barbenel, though an advocate of lever mechanics and joint loading, criticised these early analyses for their assumption of the lines of muscle action and their lack of consideration of horizontal force components. Barbenel's concern was that these authors had considered only; "half of the problem" and that while the vertical component of the muscle force may lie within the muscle zone the horizontal forces need not. The muscles considered in Barbenel's analysis were the masseter (M), temporal (T) and pterygoids (I) and (E) **(Fig 3.10)**.

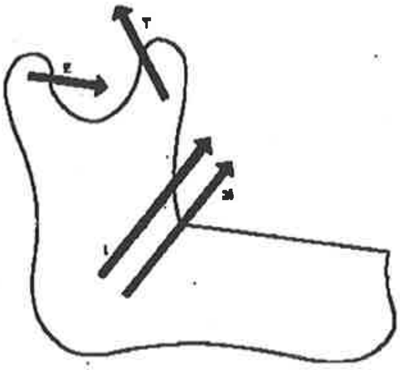


Fig 3.10. (After Barbenel 1969)

To establish the lines of muscle action Barbenel made measurements from both superficial and deep cadaveric dissections. The distance between the centroids of the origin and insertion of each muscle was used as its line of action. Barbenel's data for force components were derived initially from his own dissections, these were then compared with those of Mainland and Hiltz [1934], and the results were pooled. The results thus obtained were placed on three orthogonal axes; the X axis was directed along the intercondylar axis, the Y axis parallel to the to the Frankfort plane, and the Z axis directed at right angles to the other two. From this construction the muscle forces produced by the masseter, medial pterygoid, lateral pterygoid and temporalis were considered in the lateral projection. These were designated F_M, F_I, F_E and F_T respectively [Barbenel 1969, 1972, 1983].

Barbenel examined the mandible during the stationary stage of biting. In this position force was considered in three categories. The first of these was the force due to muscle action and the assumption was made that the muscles acted equally on both sides. Another force considered was that due to occlusal load and this was also assumed to act on the equally on both sides of the mandible. The occlusal load also had a moment about the intercondylar axis which was assumed to act at an angle θ to the Y axis. If the magnitude of the load was assumed to be L then the moment of the load about the intercondylar axis can be derived from the formulae;

$$L \,.\, (Y \cos\theta + Z \sin\theta)$$

where X and Y were the coordinates of the point at which the line of action of the load intersects the occlusal plane. The force at the temporomandibular joint, of magnitude R and acting at an angle $\varnothing$ to the Z axis was also considered. All forces were assumed to be symmetrical with respect to the mid-line and to have an equal magnitude on both sides of the mandible [Barbenel 1983]. **Fig 3.11** shows the variables describing temporomandibular joint and occlusal forces superimposed on a diagram of the mandible.

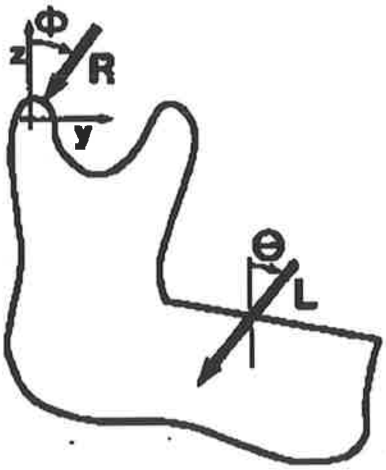


Fig 3.11. (After Barbenel 1969)

Three equations of equilibrium are described for this system when the mandible is at rest under the action of these forces. These are that the sum of the force components in the X and in the Y direction are equal to zero and that the sum of the moments of forces about any axis is equal to zero. The first of these relations, that the sum of the vertical (Z) components should be equal to zero, may be expressed numerically (using Barbenel's values for force components) as;

$$0.84F_M + 0.84F_T + 0.78F_I - 0.17F_E - R\cos\phi - L\cos\theta = 0$$

similarly the other two equations of equilibrium may be constructed,

That the sum of all horizontal (Y) forces should be equal to zero;

$$0.55F_M - 0.46F_T + 0.50F_I + 0.91F_E - R\sin\phi - L\sin\theta = 0$$

That the sum of the moments of the forces is equal to zero. Taking the moments about the intercondylar axis yields;

$$2.7F_M + 2.6F_T + 2.3F_I - L\,(Y \cos\theta + Z \sin\theta) = 0$$

Barbenel noted that their were six unknown quantities in these three equations which were therefore incalculable by their direct solution. The introduction of four further inequalities; that the sum of each of the muscle forces must be zero or positive, simplified the matter. Barbenel recognised that these equations were in the form of the zero sum, two person game described by Grass [1964] and that this game could be converted into a simple linear programming problem. Linear programming is a method of minimising (or maximising) a linear function, known as the objective function (for method see appendix). This method is based on the hypothesis that normal functioning is in some way optimal. Numerical optimisation gives a solution which optimises the objective function [Falkenstrom 1993]. An optimality constraint must therefore be determined if a unique solution is to be found. Barbenel chose two objective functions; one minimising force at the temporomandibular joint and the other minimising the total muscular force [Barbenel 1972]. Barbenel was the first investigator to use optimisation criteria to determine TMJ reaction force.

Barbenel further examined the effect of variation of the angle between the occlusal load and the occlusal plane. His results indicated that increasing the occlusal load angle increased the magnitude of the joint reaction force. The solution for minimum joint force also found that the magnitude of the joint force increased the greater the distance the occlusal load was placed from the intercondylar axis. The solution for minimum muscle force yielded higher values for joint loading. It was found that the load increased with increasing load angle over small distances but fell over longer distances. As for the solution for minimal joint force reduced values were calculated for loads placed closest to the intercondylar axis [Barbenel 1972]. The analysis thus showed that the magnitude of the joint forces increases with the occlusal load angle θ, which is the angle between the occlusal load and the normal to the occlusal plane. Increasing the distance D from the condylar axis also increased the joint reaction force. Regardless of the values of θ and D the joint force was larger than zero.

The minimum muscle force theory states that that no more muscle force is used than is necessary to perform a specific task [MacConnaill 1967]. According to Barbenel his investigation did not support the concept. His analysis showed that only the masseter was expected to function. The method selected the masseter as this was the muscle with the longest moment arm about the intercondylar axis. The idea that only the masseter functioned was at odds with the available electromyographic data which showed activity in at least three of the masticatory muscles [Moller 1966]. The solution for minimal joint force predicted that only the lateral pterygoid and the temporalis would be active; a condition which again could not be substantiated by electromyographic data.

Osborn and Baragar [1985] criticised several aspects of Barbenel's study and suggest that their own model which minimises the sum of muscle forces more closely corresponds with observations in human subjects. The discrepancies noted between the predicted behaviour and that recorded with EMG invalidate the model and therefore Barbenel's calculated joint reaction force. Barbenel's use of linear programming cannot be considered quantitative as the technique cannot predict an upper limit to joint force. The study is useful however in indicating that the joint was loaded in function and in its prediction of a minimum joint load.

Frankel and Burstein [1970] have suggested that the mandible cannot function as a lever and that no reaction force acted on the mandibular condyle. In a sketch of the lateral aspect of the skull the forces of the masseter, temporalis and the resultant tooth load were considered **(Fig 3.12)**.

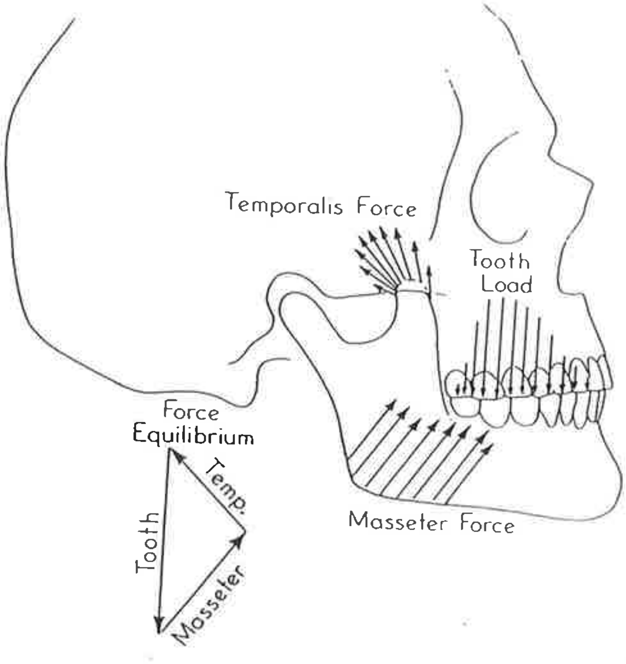


Fig 3.12. (After Frankel and Burstein 1970)

As these forces could be arranged to form a closed triangle they were therefore in equilibrium. Hylander [1975] questioned these assumptions on the grounds that the constructed vectors were incorrectly determined. Hylander further cites Moller [1966] who states that in powerful molar biting the mandibular elevators are all activated to a similar degree. When the true distribution of the fibres of the mandibular elevators are reconstructed and the contribution of the medial pterygoid considered, the resultant force is found to be located posteriorly to the tooth row [Hylander 1975].

Gingerich [1971] noted the large support for the lever model of mandibular biomechanics. Part of this author's concern for the validity of this system was its inefficiency in delivering energy to the food bolus. The long length of the bite lever arm and the energy wasted as reaction force at the jaw joint seemed to make this model improbable. Gingerich's solution was provided by his own analysis of the masticatory system. In this model the temporalis is considered as the primary generator of bite force. This muscle is chosen because its fan shaped anatomy allows a variety of lines of muscle action. The mechanics of the temporalis as proposed by Gingerich are illustrated below **(Fig 3.13)**. In this Fig **A** shows how the envelope of temporalis fibers is aligned with the entire tooth row. The origin and insertion of the temporalis described is by the stipled areas in diagram **B**. The force of the temporalis Ft and bite force Ft' at the bite point B are equivalent. This allowed Gingerich to diagramatically represent the mandible as a link between these forces in **D**.

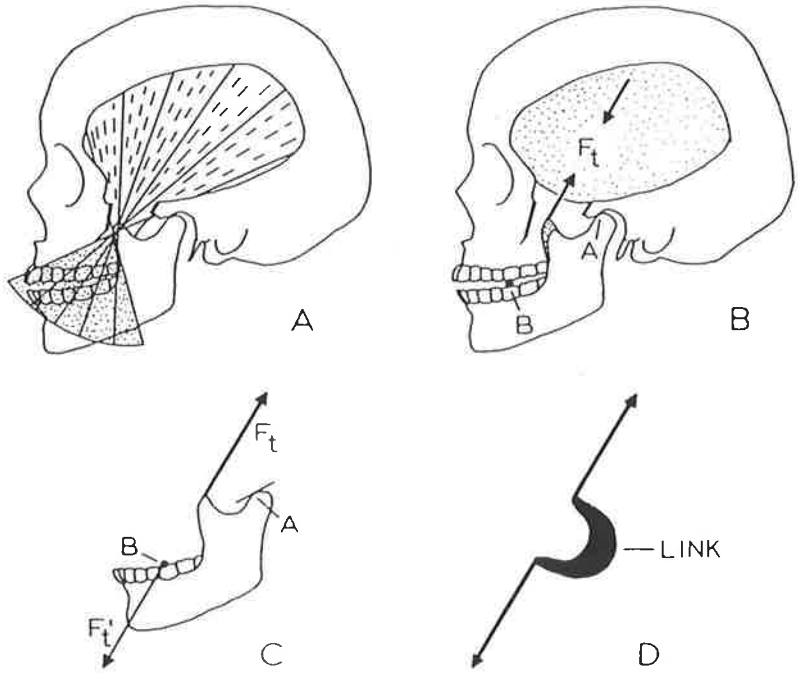


Fig 3.13 (after Gingerich 1971)

Gingerich's diagram illustrates how these lines of action may act along any of the potential bite points in the dental arch. In this system the mandible is seen as providing a functional link between the power generating temporalis and the resultant force at the bite point. Although the masseter medial pterygoid complex is omitted from the analysis its mechanical inefficiency in the production if bite force is described; some energy being converted into useful bite force and some being wasted as temporomandibular joint reaction force [Gingerich 1971]. The primary role of the temporalis in Gingerich's analysis provides a highly efficient system for the delivery of muscular energy to the food bolus. Energy in this system is directed through the food eliminating force couples in the lever arm. Such force couples could only be equilibrated by additional muscle force or dissipation of energy through the jaw joint [Gingerich 1971].

Hylander disputes Gingerich's "link" theory on the grounds of a review of the available electromyographic data [Hylander 1975]. Data provided by Latif [1957] and Woelful et al [1960] suggests that the activation of certain parts of the temporalis does not occur in the pattern expected by the link theory. Incisal biting should activate posterior temporalis as these fibres are those most efficiently aligned for the production of incisive force. The electromyographic data recorded in such positions however shows a general reduction in temporalis activity or greater activity of the anterior portion of the muscle. Conversely high levels of activity are recorded in the medial pterygoid, a muscle largely ignored in Gingerich's analysis.

Gingerich's link theory incorporated the concept of "orthol retraction". The author developed this concept through the analysis of striated wear facets detected on the molar occlusal surfaces of the Eocene primate adaptis [Gingerich 1972] and later on the Jurrasic mammal Docodon [Gingerich 1973].

These striated facets were seen to be evidence of an upward and backward mandibular movement during biting. Hylander contends that orthol retraction is not a feature of human jaw mechanics. Studies of human mandibular motion and the investigation of mastication in several other mammals had also confirmed the absence of orthol retraction in humans [Gibbs 1969, Crompton and Hiiemae 1970]. If this is the case then Gingerich's conclusions of the direction of bite force may be in question [Hylander 1975]. The theory of orthol retraction is further undermined by the work of other authors who contend that the tooth striations noted by Gingerich may have been created in a different phase of mandibular motion [Kay and Hiiemae 1974].

Gingerich revisited the question of lever mechanics in a later publication [Gingerich 1979]. In this paper he acknowledged the criticisms of Hylander. Gingerich subsequently modified his description of mandibular biomechanics describing its function as a simultaneous lever and link. The link model of mandibular function is a special case of the lever hypothesis that occurs when the applied muscle and bite forces are aligned. In this sense the lever model clearly predominates but there may be a significant link component in mandibular function during incisal biting [Gingerich 1979].

Tattersall published an analysis of the masticatory apparatus in the extinct Malagasy lemur Archaeolemurinae, this was followed by a review of the mechanics of mandibular elevation in mammals [Tattersall 1973, Roberts and Tattersall 1974]. These papers are underscored by two basic assumptions considered, at least to these authors, to be "not greatly open to question". This is an interesting perspective given the contrary opinions of their then contemporary workers [Roydhouse 1955, Ostrom 1964, Badoux 1972, Barbenel 1972, 1974]. The assumptions were that no significant force was expended at the temporomandibular joint and that structure of the orofacial skeleton reflected the demands of the resultant forces of mastication.

The lever system described by other authors was discounted on the basis of its gross inefficiency with only 50% of the available muscular energy being expended at the dentition [Roberts and Tattersall 1974]. Such an inefficient arrangement seemed improbable in its development and conservation in the face of natural selection [Tattersall 1973]. The importance of the role of efficiency in the preservation of physiological systems has not however gone unchallenged with Hylander [1975] highlighting some even more inefficient, but well preserved, processes in the human musculo-skeletal system. Smith [1978] on this same matter remarks "the process of evolution probably results in species that are just a little better than their competitors rather than optimal design".

Tattersall presents a biomechanical analysis of mastication which includes the temporalis, the masseter and medial pterygoid, the latter two being grouped together as a single unit. The mandible is seen to rotate around the attachment of the sphenomandibular ligament with a couple action being formed by the anterior and posterior adductor muscle groups. This system permits the generation of an occlusal force, variable in orientation according to the position of the bite point. In this system anterior bite points require increased activation of the posterior fibres of the temporalis. The pinnate morphology of the temporalis affords this variability in its line of action [Roberts and Tattersall 1974].

A mechanically simplistic model is thus presented in which the interactions of muscles and resultant forces are depicted. According to this scheme an arbitrary magnitude and line of action is assigned to the masseter medial pterygoid complex and this remains constant. Different resultant forces R1, R2, and R3 equal in magnitude but variable in direction, according to the position of the bite point, can be constructed. The system is equilibrated and the joint freed from pressure by the action of the temporalis which provides a vector, variable in both magnitude and direction to close and balance the triangle of forces. Provided that the temporalis is able to exert the required force in the required direction in all phases of mastication then the system will always be in equilibrium. These authors provide a second analysis in which the masseter is divided into superficial and deep portions of different orientations this subdivision assumes the independent activation of these portions but greatly reduces the effort required of the Temporalis [Roberts and Tattersall 1974].

Smith [1978] has reviewed the analyses of Roberts and Tattersall and disputes its validity. Smith includes this approach with a number of others which describe the temporalis and masseter-internal pterygoid complex as acting as a couple [Davis 1955, Scapino 1965]. In an identical manner to his rebuttal of Davis' paper Smith states that since a couple is produced by equal and opposite, non co-linear parallel forces in the same plane they cannot be combined into a single force because their sum in every direction should equal zero [Smith 1978].

The ability of the bite force vectors generated in Roberts and Tattersall's model like those of the Frankel and Burstein model [1970] to form a closed triangle and therefore an equilibrium of forces is questioned. The direction of the muscle forces has not been accurately determined and more importantly no attempt has been made to determine the magnitude of the muscle force and therefore the length of the balancing muscle vector. Smith contends "a vector of arbitrary length is simply not a vector" and that "a triangle of these forces in equilibrium is entirely hypothetical" [Smith 1978].

The description of mandibular function in terms of a class three lever system means that anterior teeth receive less occlusal load than the posteriors. Theoretical investigation of the variance of these load have been performed by Gosen [1974]. Gosen assumed the centre of mandibular rotation to exist in the area of the condyle. He also resolved the various vectors of masticatory muscle force into a single component of a fixed magnitude which was arbitrarily assumed to act perpendicular to the radius of closure of the mandible. Cephalometric radiographs were taken and measurements made on dry skulls. An attempt to quantitatively evaluate the relative forces applied to the anterior and posterior teeth was made but these results were not subject to experimental verification [Gosen 1974].

Hekneby [1974] also attempted to demonstrate an increase in temporomandibular joint loading when forces are applied to teeth at different positions in the dental arch. An analysis was performed when pressure was applied to the first premolar and then the second molar on the same side. The calculations showed that greater joint forces could be anticipated when vertical pressure was applied to the first premolar rather than the second molar. Although the pressure applied to these two teeth was the same the torque arm of the first premolar was much longer and these was the explanation for the increased load at the TMJ.

Hekneby used twenty-five cadaver mandibles which were measured with a mechanical device called a symmetrograph. The device was used to measure the distance from the joint to each of four attack points. These attack points described the resultant force of the muscles of mastication on the left (K_1) and the right (K_1') side. The resultant force on the load for each of the joints was denoted (K_3) and (K_3'). The point at which the occlusal load was applied was designated (K_2). **Fig 3.14** demonstrates a horizontal plane parallel to the occlusal plane which passes through the attack point at K_2. The forces K_1, K_1', K_2, K_3, andK_3' are at right angles to the plane.

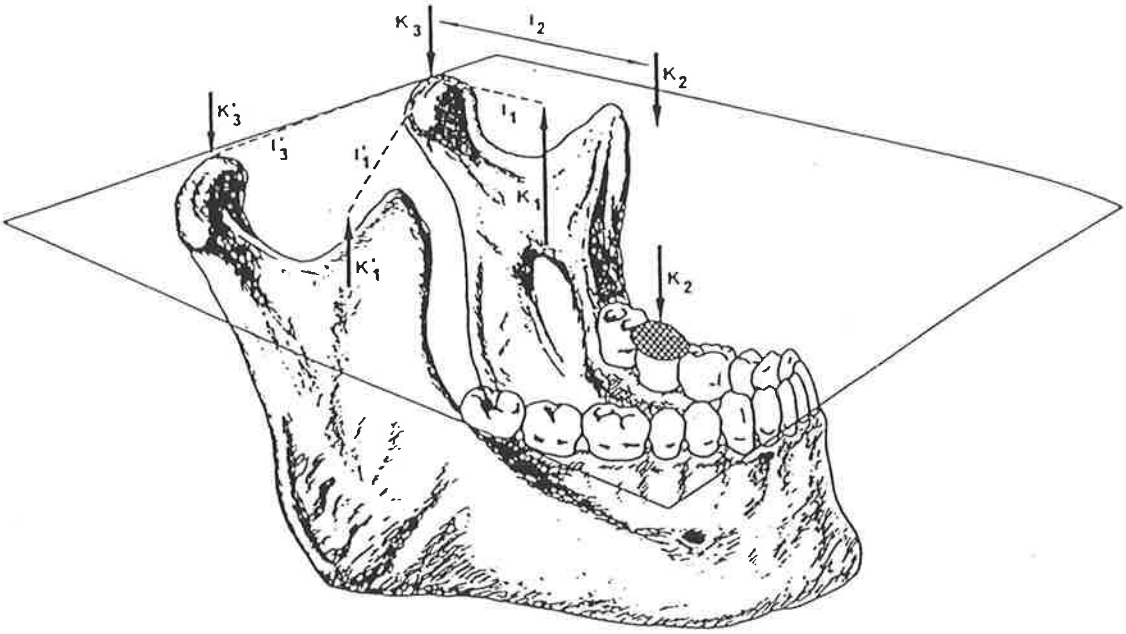


Fig 3.14. (After Hekneby 1974)

The following equation of equilibrium was then applied;

$$K_1 + K_1' = K_2 + K_3 + K_3'$$

Expressions for the equilibrium of the torques of the forces described by the attack points were derived (where l is length of the lever arm). This yielded two equations which could only be solved when the pressure side only was considered

$$K1 = K2 + K3$$

and: $$K_1.l_1 = K_2.l_2$$

The calculations used in Heknebys analysis were simplified. The load on the pressure side of the mandible was considered independently of the other side and all forces were assumed to act in a vertical sense. The attack point was arbitrarily assigned as the highest point on the condyle when the occlusal plane was horizontal rather than the exact point where load was instantaneously transmitted to the fossa. The point of application of the resultant force of the mandibular elevators was assumed from the work of Carlsoo [1952] and a averaged torque arm was used [Hekneby 1974].

Tradowsky [1981] defined a physiologic equilibrium point. This is a point on the occlusal plane where the resultant force of the vectors of the jaw closing muscles intersect during maximal contraction. At this point there would be no pressure on the temporomandibular joints. Biting at a position anterior or posterior to this physiological equilibrium point would result in tilting of the mandible and either compression or tension at the mandibular joint. Tradowsky's method for determining this position was to place a support between the dental arches during maximal clenching about which rotation did not occur. The position so determined was thought to coincide with the location of the resultant force of the mandibular elevators. The use of this concept helped these authors explain the lever action of the mandible. If the resultant force intersects the mandible at the physiologic equilibrium point the mandible can act as a class 2 or class 3 lever or be in equilibrium depending on the placement of the bolus [Tradowsky and Kubicek 1981].

As is evident from a review of the literature regarding the development of lever and non-lever, loaded and non loaded concepts of mandibular biomechanics consensus has been difficult to achieve. Most now believe the mandible functions as a class 3 lever system. The major force for the lever is provided by the medial pterygoid and masseter with the lateral pterygoid acting to keep the the condyle in contact with the posterior surface of the articular eminence. It is now generally accepted that the joint is load bearing under most normal conditions. In the class three lever system muscular force is always shared between the the joint and the dentition. The division of load depends on the relative distance from the force so that more force can be expended at the first molar region relative to the condyles and the central incisors.

It is also thought that in asymmetric occlusal positions that the mandible functions as a loaded beam. The axis of this beam running obliquely between the occlusal bite points on the working side and the non working side condyle. Both of these areas are therefore loaded. Some agreement has also been reached regarding differential loading with the balancing condyle being thought to be more heavily loaded during a unilateral bite [Hylander 1975, Throckmorton and Throckmorton 1985]. More importantly the pursuit of the answer to the question of joint loading has provided the stimulus which has allowed the development of the science of mandibular biomechanics. It is against this background that modern mathematical models have been developed. Attempts to model mandibular function as a class three lever have been described as overly simplistic [Wheeler 1974]. The major criticism is the implication that the various external forces acting on the mandible all act in the same plane and furthermore that the analysis of moment does not depend on determining what lever type prevails [Hylander 1985].

As recently as 1986 Taylor presented a paper that disputed the validity of the lever model of mandibular biomechanics. Taylor's conclusion again suggested that the neither the disc nor the condyle was subject to compression. As suggested by Picq et al [1987] Taylor's omission was not to discuss the fairly large body of evidence to the contrary [Hylander 1975, 1978,1979, Smith 1978, Walker 1978, Brehnan et al 1981, Picq 1983]. The quick and effective rebuttal this paper received on the grounds of both anatomical and biomechanical evidence has largely laid the issue of non loading of the joint to rest.

In response to Taylor's publication Picq [1987] has emphasised the importance of three dimensional analyses to explain what might otherwise appear as contradictory data. Evidence produced by the direct measurement of subcondylar bone strain in monkeys [Hylander 1979] can demonstrate a particular condyle to be unloaded or even loaded in tension. Such data appears to contradict the lever hypothesis if the analysis of muscle and reaction forces is carried out solely in a two dimensional lateral view of the mandible. Two dimensional analysis fail to take into account both the working and non working side joint reaction forces and the position of the food bolus with unilateral bites. If however a three dimensional analysis is performed the lever hypothesis is supported [Picq 1987].

3.3 THREE DIMENSIONAL MATHEMATICAL MODELLING.

The modelling of mandibular biomechanics began as two dimensional analysis of forces and movements. The possible actions of the masticatory being projected in the sagittal plane. The intent of these early theoretical studies was to prove whether or not the joint was loaded in clenching [Robinson 1946, Roydhouse 1955, Gingerich 1971, Barbenel 1972]. Predictions from these models can be incomplete because forces and moments operate in three dimensions. Projection of three dimensional information onto a plane may suppress what may be important biomechanical aspects of the system [Baragar and Osborn 1984]. The various forms of mathematical modelling of jaw mechanics have values and limitations influenced by the complexity of biomechanical elements added to these artificially created models. In some models the balance between completeness and simplification has been shifted towards simplification in their development [dos Santos 1991].

The projection of forces and reactions onto a sagittal plane can be justified when bite forces are kept symmetrical and this has been attempted by some authors [Prium et al 1980]. Measurements can be taken whilst subjects are clenching or biting on a bar placed symmetrically between the molar segments. A bite force centred between left and right teeth reproduces the situation described by a sagittal analysis but is probably less relevant to the more common situation of unilateral biting. Clearly projection of forces onto the sagittal plane reduces the problem into a two dimensional one but asymmetric three dimensional mathematical modelling can provides a more valuable insight. Walker [1978] states simply; "the human mandible acts asymmetrically during chewing and a two dimensional biomechanical analysis will therefore be inadequate".

Most of the analyses of mammalian jaws have used a lateral projection [Davis 1955, Smith and Savage 1959, Hiiemae 1969, Barbenel 1972,1983]. The first authors to include a frontal analysis were Nagle and Sears [1958]. Both a sagittal and frontal projection are provided by these authors. The lateral view depicted a third class lever and in the frontal projection a lever of the second class. Although the contralateral condyle is considered a fulcrum the muscles of this side are not incorporated in this analysis. Hylander [1975] points out this discrepancy citing this as an important omission especially given the electromyographic data of Moller [1966] which shows greater muscle activity on the contralateral side.

Hylander presents an analysis that includes a frontal projection. As Hylander points out a sagittal analysis is only relevant where the resultant force can be located in the mid sagittal plane. Though such a situation may exist in the cases of incisor or bilateral molar biting this is not so in the more common situation of unilateral bites [Hylander 1975, 1985]. Hylander considered the muscles of both sides as this had not been done in the earlier work of Nagle and Sears [1958]. This approach took into account the available EMG data which described the presence of bilateral muscle activity during unilateral bites [Moller 1966].

Hylander's diagram shows a powerful unilateral bite in the frontal projection during powerful unilateral biting **(Fig 3.15).** FM, FB and FR represent the adductor muscle force respectively.

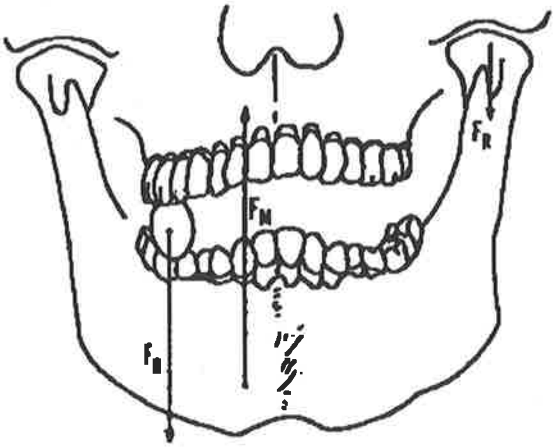


Fig 3.15. (After Hylander 1985)

If the muscles on the working side are slightly more active than the other then the resultant force shifts closer to the mid-sagittal plane. This is true even if the resultant muscle force of the mandibular elevators passes through the bite point in the lateral projection. Hylander used Moller's [1966] earlier electromyographic evidence of greater muscle force being generated on the working side to place a resultant between the bite point and the mid-sagittal plane. Such a placement meant there must be a compressive reaction force at the balancing condyle to maintain equilibrium. Although the working side condyle need not necessarily be loaded both joints could only be unloaded if the working side musculature maintained an activity three times greater than the non working or balancing side. Moller's data lends no support to this latter theory [Hylander 1975].

Hylander's [1975] conclusion that the contralateral condyle was subject to the greatest loading in unilateral biting was in agreement with the earliest investigations of Gysi [1921] despite a different analysis being used. Roydhouse [1955] had felt the condyles were loaded equally. Some of the other authors reviewed thus far, though in agreement that the joint was loaded, did not specify which condyle was subject to the greatest force [Sicher 1970, Smith and Savage 1959, Davis 1964 Crompton and Hiiemae 1969, Turnbull 1970, Barbenel 1972, Bramble 1978].

In later experiments [Hylander 1978,1979] used subcondylar strain gauges to demonstrate greater loading of the contralateral joint. This information has served to refute several previously advanced concepts of joint loading. In 1954 Page had suggested only the ipsilateral side was loaded. Hekneby [1974] described loading of both joints but felt that the ipsilateral joint had the heaviest load. The suggestion that only the contralateral is loaded had also been made [Walker 1978, Greaves 1978].

The conclusion of Hylander's study is that heavier loading may occur on the contralateral condyle. Hylander alludes to the observations of Ramfjord and

Ash [1983] that individuals with a painful joint prefer to chew on that same side as evidence for there being less reactive force on the working side condyle. As previously mentioned however caution should be exercised in attributing too much significance to radiographic changes. Some studies have not shown a significant association between the degree of morphologic change and the presence of symptoms. Greater degrees of joint remodelling have been observed on the pain free side in patients with TMJ dysfunction [Muir and Goss 1990]. Incisor biting evokes more pain because the joint is more heavily loaded in this condition. Differential loading of the condyles may occur just as much as differential activations of the masticatory muscles on either side of the mandible are possible. Because of these factors the mandible must be analysed in more than just the lateral projection [Hylander 1978].

Mansour and Reynik [1975] measured the maximal biting forces in one subject using microducers. Modified cephalometric roentgenogram techniques were used to obtain maxillary and mandibular profile mapping and to record cephalometric landmarks. Mandibular moment was calculated around the condylar axis using the simple formulae;

$$\text{Moment} = \text{force} \cdot \text{moment arm}$$

A tracing of the mandible and maxilla with the transducer was made **(Fig 3.16).** The direction and line of action of the average maximum biting force P, the average moment arm I and the average distance D between the center of the occlusal surface of the mandibular second premolar and the center of the condyle was made.

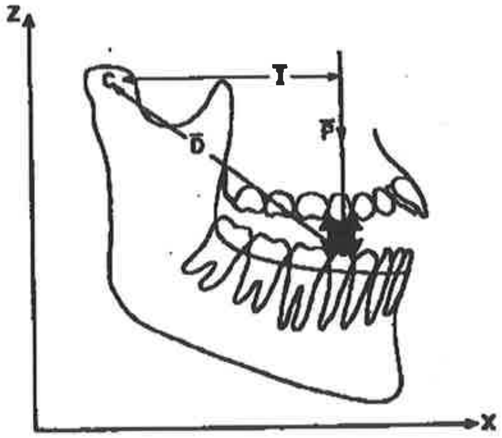


Fig 3.16 (After Mansour and Reynik 1973)

These studies showed that the force at the second molar was 10% greater than at the first molar and the moment of force was 15% less at the second molar than the first. The mandible could be seen to act as a class three lever anterior to the second molar and a class two lever at the second molar.

In a later study the maximum occlusal force and moment data of the original experiment were expressed in mathematical terms. The investigators determined that the maximum occlusal force was a linearly decreasing function of the increasing distance from the condylar centre. The function proved to be symmetrical on both mandibular right and left sides. The average maximum occlusal force produced a moment at the condylar centre that was a linearly increasing function as the maximum biting force of individual tooth positions increased. This function was similarly symmetrical for both mandibular right and left sides [Mansour and Reynik 1973].

The mandible has been modelled as an asymmetric beam [Walker 1976]. This beam is loaded by the muscles of mastication and accepts the bite force on one side and the condylar reaction force on the other forming two opposing couples. Walker felt that the muscles would work in such a way as to increase the bite force and reduce the condylar reaction force. For the purposes of determining forces in incisal biting and symmetric bites the mandible can be considered a bent lever with aligned fulcra at the condyles with each bearing some of the resultant forces. In the last phase of the chewing stroke the mandible functions as an asymmetric beam loaded by the balancing condylar and working side muscular forces as well as the elevating muscle forces [Walker 1978].

Walker depicted the lines of action of the masticatory muscles on the mandible in a unique way. Rather than using the standard orthogonal axes the mandible was aligned so that the axis of the loaded beam was in one of the three reference planes at right angles to each other. Bite force BF, condylar reaction force CR were represented as well as vector projections of the muscles of mastication. The lines of action of the muscles are thus visualised in terms of what action a particular muscle might have on the beam. The axis of this beam was constructed between the balancing side condyle and a bite point on the working side **(Fig 3.17).**

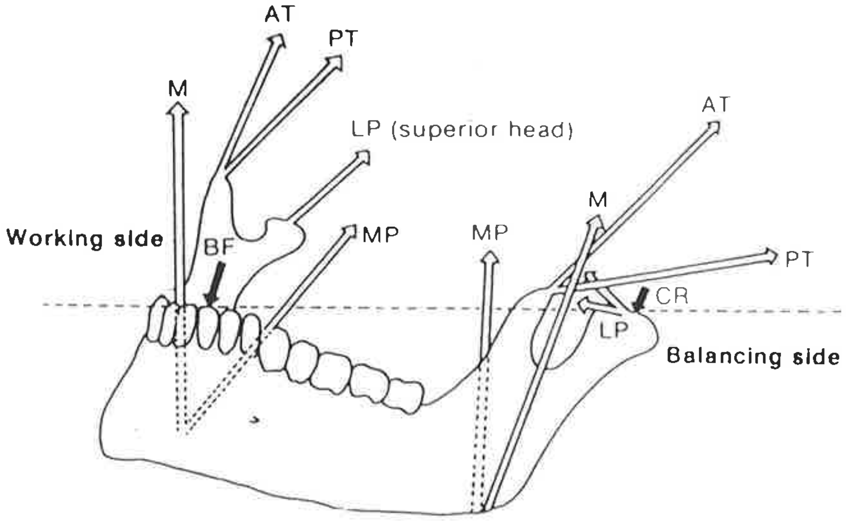


Fig 3.17. (After Walker 1978)

Walker's diagram allowed the mandible to be orientated so that the loading of the mandibular beam was evident in the plane of the diagram. The fact that the mandible's shape between these two points is far from that of a straight beam is not of any immediate biomechanical significance. This is because the only points where forces can be transmitted between the mandible and the cranium are at the bite point and the condyle. Walker demonstrated that the mandible acts as a lever for the opening movement and during the first part of the closing stroke, then as a loaded beam after the bite force has been applied [Walker 1978].

Smith [1978] described the mandible as a class three lever. The direction of the bite force and the line of action of the temporalis, and masseter were represented in a sagittal projection **(Fig 3.18)**. Smith's diagram shows that the combined muscle force vector (M + T) is closer to the fulcrum than the bite force B. Equilibrium is reached when the moments produced by these forces namely M + T x the distance X and B x the distance y are equal. If this is the case then the bite force is less than the muscle force and a third force or condylar reaction force must be present at the condyle for vertical equilibrium [Smith 1978].

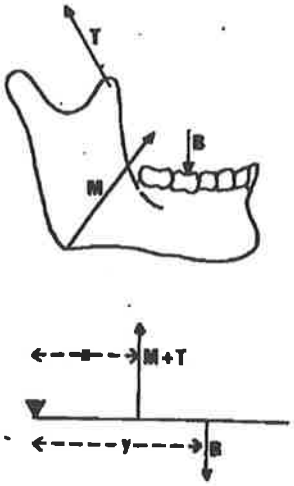


Fig 3.18. (after Smith 1978)

Smith [1978] like Hylander also used a frontal analysis in his mathematical model. By the use of these orthogonal frontal and sagittal projections Smith proposed that the mandible functioned as a class three lever but as soon as the resistance of the food is met the mandible "changed states" to function as the beam this was a similar conclusion to Walker [1978]. Ahlgren and Owall [1970], Gibbs [1975], and Hannam et al [1977] had demonstrated maximum occlusal force is generated for about 100 msec when the upper and lower teeth are in contact so this period was used in Smith's analysis. Given that the total combined condylar reaction force was known Smith's method enabled the estimation of both balancing and working side condylar forces. These working and balancing side reaction forces were demonstrated to be a function of differential muscle force recruitment patterns.

The analysis began in a traditional manner with the sagittal view being considered (**Fig 3.19** part **A**). A line from the incisal edge (bite point) to the mandibular condyle (reaction point) has been constructed. The numbers 1-6 denote individual muscle forces acting on the beam. These forces have both vertical and horizontal components but only the vertical are considered to contribute to the bite force.

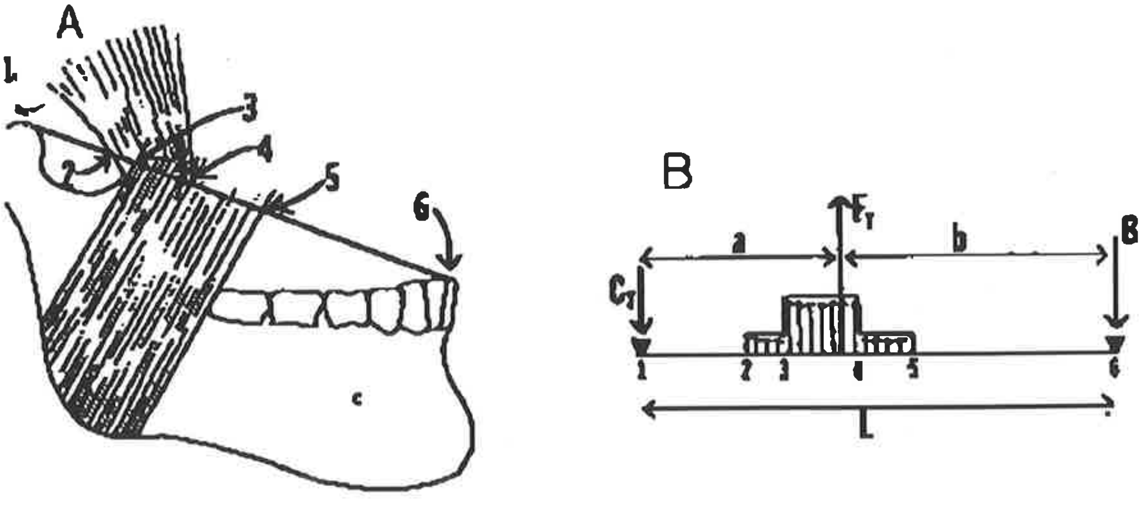


Fig 3.19 (After Smith (1978)

In the second diagram **(Fig 3.19 part B)** B represents the bite force and F_T the muscle force as a vector replacing the distributed muscle forces between points 2-5. Between points 2 and 3 only the temporalis muscle overlaps the beam, from 3 and 4 all muscles overlap the beam, and from 4 and 5 only the masseter and medial pterygoid overlap the beam.

Unknown muscular forces are assumed to act uniformly along their length of overlap with the beam forming a single distributed load. Given the bite force B a relative value is assigned to the total muscle force applied F_T ;

$$F_T = \frac{BL}{a}$$

moments were calculated in the sagittal projection to solve for total condylar reaction force (C_T)

$$C_T = \frac{Bb}{a}$$

The muscle and condylar forces are the sum of left and right sides during biting at a single point. At this point the frontal analysis is introduced. The total condylar reaction force (C_T) derived from the previous equation is divided into left (C_l) and right (C_r) components

$$C_T = C_l + C_r$$

and similarly for left and right muscle forces;

$$F_T = F_l + F_r$$

Moments are taken about the working side condyle in the frontal projection to solve for the amount of force along the balancing side condyle.

Although the total bite and muscle force are already known from the sagittal analysis assumptions must be made about the ratio of muscle forces on both sides of the mandible. The position of the resultant muscle force vector depends on which of these forces are greater; if the working side force exceeds that of the balancing side the resultant will lie to working side of the mandible, if both sides exert an equal force then the resultant will occur in the mid-sagittal plane. Once this relationship is known calculation of each condylar reaction force can be derived from simple subtraction from the total condylar reaction force [Smith 1978]. Smith's analysis was therefore three dimensional. The combination of the analysis of moments in both the frontal and lateral projections allowing a calculation of both working and balancing side condylar reaction forces [Hylander 1985].

Significantly Smith presented a summary of the calculated muscle force thought to be experienced at the temporomandibular joint of humans as well as that of three primate species. The estimated magnitude of each force was expressed as a percentage of the useful bite force. The weight and angular position of the masticatory muscles was assessed by dissection and measurement. Mean values of skeletal dimension were obtained from comparison with specimens of the same species wherever possible. These results showed large condylar forces during both molar and incisal biting. For example a 50kg bite force in the region of the first molars results in a condylar reaction force of about 39kg. An incisal bite of 10kg results in a condylar load of approximately 14kg. Man was shown to exhibit a lower condylar reaction force for a given bite force when compared with the other primates [Smith 1978].

Hylander [1975] has examined the balance of forces between the condyles. In these studies the balancing side condyle is thought to be subject to greater loading in unilateral molar bites. Asymmetric muscle activity was thought to compensate for excessive load on a particular condyle. Smith also demonstrated that given bilaterally equivalent muscle forces the contralateral condyle would bear up to 80% of the total condylar load. If the working side musculature were to contribute twice as much force then the force on the non working side would be reduced by approximately 40%. Smith postulated that normal working to non working side ratio would approximate a 1 : 1 ratio [Smith 1978].

The concept of the mandible changing state from lever to beam [Walker 1978, Smith 1978] has been criticised by Hylander [1979, 1985] who suggests every loaded lever functions as a beam. The different interpretations of mandibular mechanics according to whether the jaw is in a moving or stationary phase [Smith 1978] has also come under scrutiny. Any analysis of mandibular biomechanics should attempt to determine if lever mechanics are operating irrespective of whether the mandible is moving or stationary [Hylander 1985].

Hylander [1978] published an analysis of human mandibular bite force using a rosette strain gauges attached to the sides of a plastic block. The block could be varied in size to allow recordings in the different phases of mandibular opening. When the stress of biting was applied the deformation of the block was measured by variations detected in the strain gauge elements. In a sample of ten subjects the maxillary incisal bite force was shown to be vertically and anteriorly directed. This occurred during static biting and during biting associated with simultaneous mandibular translation and rotation. On the basis of electromyographic data as well as the anatomical constraints of muscle fibre direction a resultant jaw muscle force simply cannot be generated in an equal and opposite direction to the vertical and anterior incisal bite force. These results are consistent with a lever action of the mandible as the force generated by the mandibular elevators must be divided between incisal bite force and the joints. Once again these authors have demonstrated that in function the joints must bear some load [Hylander 1978].

Baron and Debussy [1979] attempted to determine the functional potential of the muscles of mastication in humans by the use of a three dimensional graphing technique. This biomechanical analysis used anatomical knowledge about the architecture of the masticatory muscles to plot the points of origin and insertion of twelve fasicles which form parts of these muscles. The points were precisely defined and situated with reference to three perpendicular spatial planes having an origin O. The origin was placed at the bisection of the line linking the two condylar vertices. **Fig 3.20** shows the orientation of the mandible to the median sagittal, horizontal and frontal planes [Baron and DeBussy 1979].

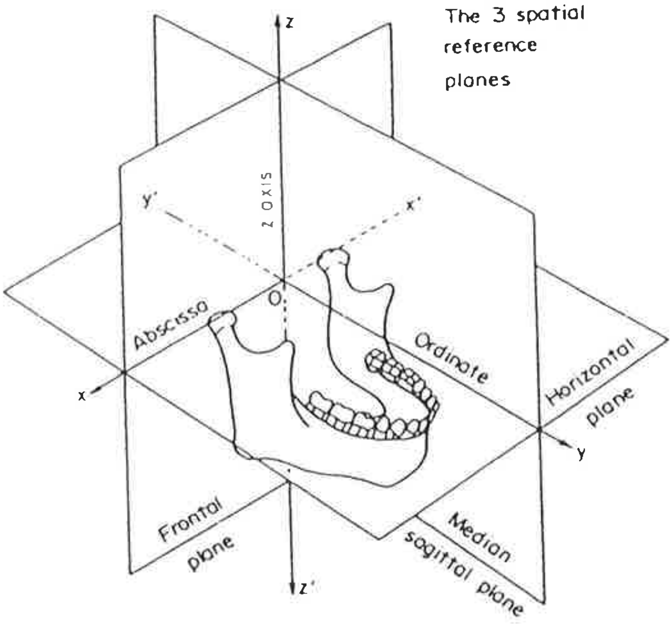


Fig 3.20 (After Baron and DeBussy 1979)

Average values for the different coordinates of muscle origin and insertion were determined the data presented by the three diagrams. Each diagram represented projections of each of the muscular bundles on graphs of the three reference planes **(Figs 3.21, 3.22, 3.23)**. The vectors were simply anatomical as the length of the vector did not represent the intensity of the force.

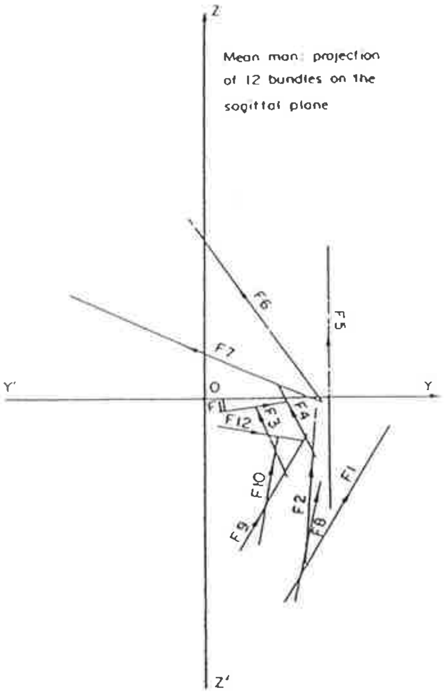
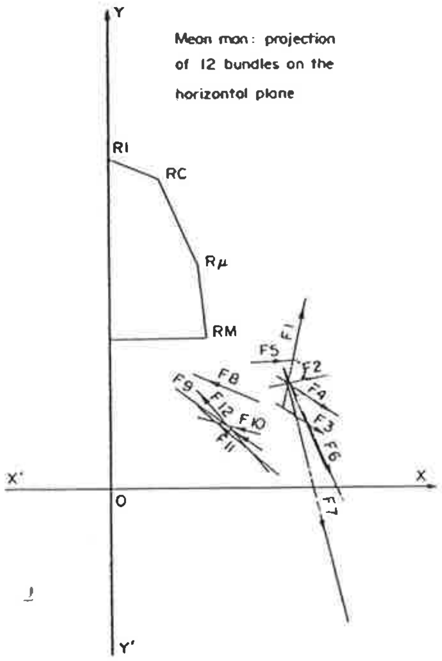
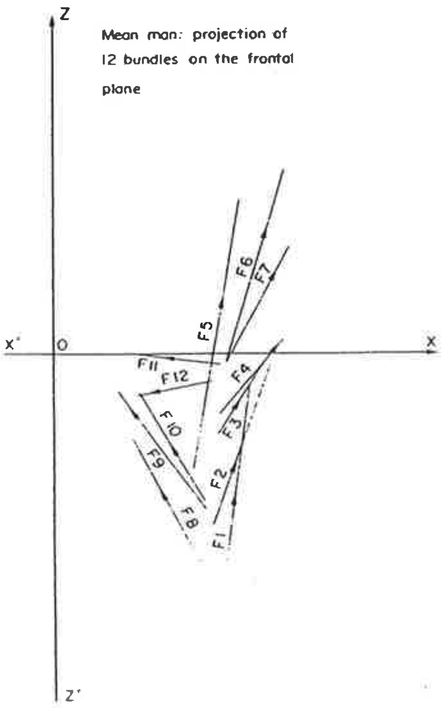


Fig 3.21 (After Baron and Debussy 1979).





Figs 3.22 and 3.23 (After Baron and DeBussy 1979)

These same authors thought it more useful to study the rotational component of each of the twelve muscular bundles rather than the vectors themselves. The rotational component of a vector describes the ability of any force to pivot around an axis. Each vector has a rotational component with respect to the rotational axis during a given movement. The rotational component of a vector αa with respect to the origin O to a rotation axis Δ corresponds in magnitude to the projection of this vector α a on the tangent to the trajectory at α (**Fig 3.24**).

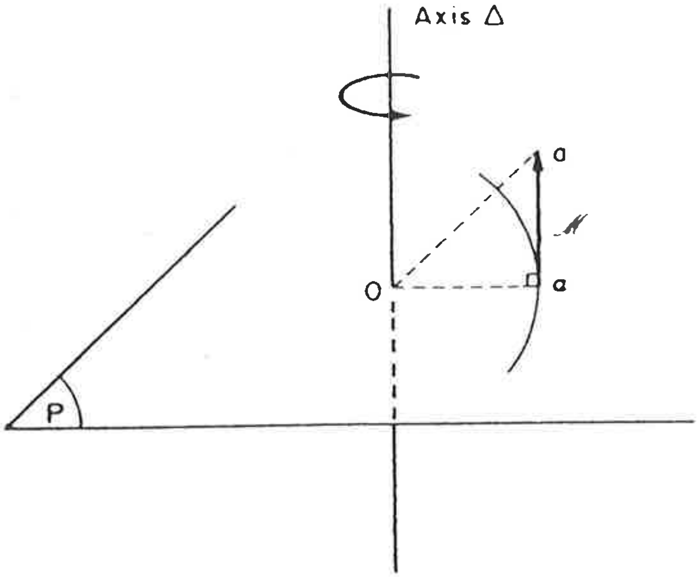


Fig 3.24 (After Baron and DeBussy 1979)

This method allowed at least some determination of the functional potential of the twelve muscle fasicles described. The use of rotational components gave a rudimentary idea of the functional potential of each fasicle. As a result Baron and Debussy described possible actions for each of the components of the masticatory musculature. These descriptions were in keeping with the conventionally described actions of the masticatory musculature including medial pterygoid after McNamara [1973].

Two dimensional mathematical models can be modified to include a third dimension. The physiologic equilibrium point of Tradowsky [1981, 1982] described earlier was modified for this purpose. Tradowsky's earlier investigation was an analysis in the sagittal projection. The analysis of Smith [1978] was used to describe a third dimension. Consideration of the resilience of the dental tissues was also incorporated. The location of the equilibrium point was expressed mathematically using the model of the mandible as a beam on rigid supports.

The physiologic equilibrium point (where the resultant force of the vectors of the jaw closing muscles intersect during maximal contraction) had been positioned at the level of the premolars. The results of the 3-D experiment noted that positioning the bolus anteriorly or posteriorly to the equilibrium point again resulted in mandibular tilt and had repercussions in the coronal plane with medial or lateral shift of the equilibrium point. The location of the point was found to vary with the Angle classification of the subject [Tradowsky and Dworkin 1982].

3.4 EMG DATA IN MATHEMATICAL MODELLING

The contribution of electromyography (EMG) to the study of mandibular biomechanics has been valuable. EMG is essentially a qualitative indicator of of the duration and sequence of muscular activation. These studies have shown with few exceptions that mastication is unilateral. EMG can define the working and non working sides of the jaw during mastication. Both regular and irregular shifts of this side can be demonstrated during mastication. Investigations are currently underway to characterise the electromyography of mastication in the Australian Merino Sheep [Hirakawa Finn unpublished work].

The suggestion that there is a quantitative relationship between integrated electromyography and muscle force was advanced by Lippold [1952]. A linear increase in EMG with an increase in bite force between 50 N and maximal voluntary force has been described [Van Eijden et al 1989]. EMG activity is considered an indicator of the degree of neural input into a muscle with increasing amounts of input leading to the recruitment of further motor units and an increase in their firing rate [De Luca 1982]. How accurately EMG reflects true relative force magnitude however is contentious and the concept has not gone unchallenged [Chapman and Calvert 1979, Hof and van den burg 1977]. The use of EMG data in early studies has been criticised for its rather qualitative nature [van Eijden 1989].

Prium et al [1978] suggested there was no reason to doubt that a linear relationship existed between integrated EMG activity and the force exerted by individual muscles in isometric conditions. Although an alinearity of individual muscle EMG activity with respect to the bite force had been described in this paper this alinearity was interpreted as being due to the increased action of antagonists at higher bite force levels and did not effect the assumed linear relationship between EMG and muscle force [Prium 1978]. In a later publication [Prium 1980] described a mathematical model to calculate forces within the temporomandibular joint based on this relationship.

Prium's mechanical approach enabled the calculation of all of the muscle forces as well as the forces in both of the temporomandibular joints during bilateral biting at three different positions in the human dentition. Muscle force vectors defined by the points of origin and insertion of the individual muscle were constructed. An X - Y co-ordinate axis system superimposed on frontal and lateral cephalograms allowed this quantitative geometrical data to be graphically represented. **Fig 3.25** illustrates the sagittal projection of this data. The centroids of the condyles have been chosen as the origins for this analysis. The forces exerted by the contracting muscles are defined by vectors whose direction had been anatomically determined and whose magnitude was assumed to be directly proportional to its integrated EMG recording. In this diagram force vectors are presented in direction and quantity. 1cm according to the scale represents a force of 20 N. The muscles of mastication are m + pt.m; masseter, medial pterygoid; t.a, anterior temporal; t.p, posterior temporal and pt.l the lateral pterygoid. The jaw depressors are represented by o. Both bite force B and joint force j are considered. M_2, M_1 and P_1 denote different bite points along the dental arch form molars to premolar.

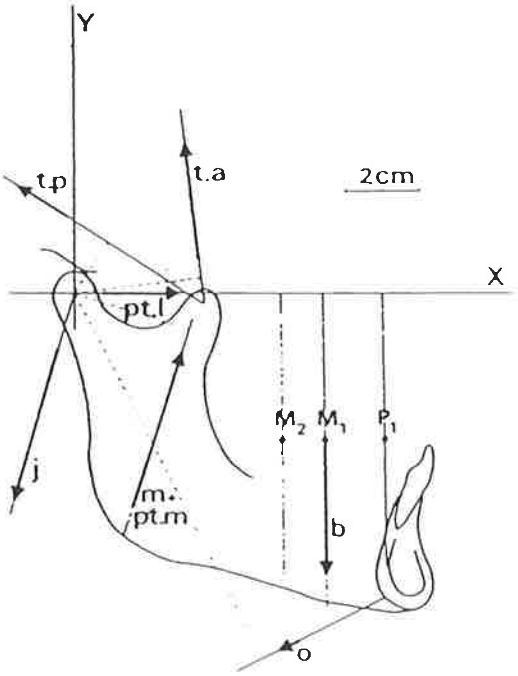


Fig 3.25 (After Prium 1980)

In Prium's experiment the integrated electromyographic activity of the main masticatory muscles was recorded from surface electrodes as well as data from bilateral bite force transducers, five muscle vectors were included in the model. Prium made use of Schumaker's [1961] measurements of the physiological cross sectional area for the muscles of mastication except the lateral pterygoid. This anatomical information was used in conjunction with EMG data to calculate maximum muscle force. The unknown variables were the magnitude of the joint force, maximum muscle tension and the magnitude of the force of the lateral pterygoid.

The laws of static equilibrium were used and calculations of the moment arms obtained from the cephalograms. These studies found the joint to be loaded during biting. Joint forces increased as a constant bite force was moved anteriorly. The bite force was seen to increase as the bite point was moved posteriorly from the incisors to the first molar. If the bite force was placed more posteriorly all forces decreased in magnitude. Maximum bite and muscle forces are encountered in biting in the region of the first molar. TMJ loading was highest in biting at the first premolars. The maximum joint forces were larger than those previously reported in the literature varying from 399 to 1118 newton per condyle. In the region of the first premolar the maximum joint force was nearly equal to the overall maximum bite force.

Prium assumed the calculated muscle force exerted during isometric contraction, denoted F_m was directly proportional to its integrated EMG or EMGI (integrated electromyogram). A further quality $\neg$, a muscle independent value (in N/m^2) was described, $\neg$ relates to the maximum force exerted by a muscle ($F_{m(max)}$) to its physiological cross section $\o_m$ (in m^2).

$$Fm(max) = \neg \, . \, \o_m$$

where

$\neg$ =the intrinsic strength of the muscle

$\o_m$ = the cross sectional area of the muscle

Prium used the values of physiological cross-section as determined by Schumaker [1961] for males according to Buchners [1877] method. Given $\mathrm{EMGI}_{m(max)}$ as the maximum value of EMGI_m of a single muscle ever recorded from an electrode pair, he expressed the relationship between muscle force and EMG as;

$$\mathrm{Fm} = \frac{\mathrm{EMGI}_{m(actual)}}{\mathrm{EMGI}_{m(max)}} \cdot F_{m(max)}$$

$$= \frac{\mathrm{EMGI}_{m(actual)}}{\mathrm{EMGI}_{m(max)}} \cdot \neg \cdot \o_m$$

Prium felt the results obtained from incorporating EMG data reconfirmed the validity of this method to study bite force patterns [Prium 1980]. The use of electromyography however is seen by some authors as a means of crudely describing how actively a muscle is working rather than a means of quantifying how much force it is producing [Latif 1957, Moller 1966, McNamara 1973, Osborn and Baragar 1985].

Although Prium's model [1980] was three dimensional the full potential of the model is not realised. This is because the technique of equal bilateral loading is used. All data is presented as the sums of values from both the left and right sides thereby leaving the problems of asymmetry aside. Osborn and Baragar [1985] developed a three dimensional model again using forces symmetric to the sagittal plane. The justification for this was that the primary aim of the study was to firstly validate the model with available absolute measurements. The technique of projecting forces onto the sagittal plane is used in order to simplify the mathematics reducing the problem to a two dimensional one. As aforementioned such simplifications are only valid when the experimental subjects produce symmetrical bite forces.

In 1985 Osborn and Baragar developed a computerised model based on the principle of linear programming. Barbenel [1972] had used linear programming and the principle of static equilibrium in his analysis and these are presented in greatly modified form in the Osborn and Baragar model. The mandible is considered to be in a state of static equilibrium. The conditions of static equilibrium in a rigid body require that the vector sums of the forces on the body be zero and the vector sum of the torques about a point in space be zero. These assumptions in a similar manner to Barbenel's model create six linear equations. If one considers the large number of variables (such as the tension each of the masticatory muscles and the two joint reaction forces) it is clear that the equations of equilibrium will not yield a unique solution. This is because there are an infinite number of of combinations of tensions and joint reactions that will produce a given bite force. The use of linear programming techniques (see appendix for method) allows the solution of this otherwise intractable problem [Osborn and Baragar 1985].

A cartesian co-ordinate system was introduced with the mid-point of a line joining the two condyles selected as the origin all other anatomical points were expressed in terms of their relative X Y and Z values. This analysis like those of Baron and Debussy [1979] and Prium [1980] divided muscles into functional subunits. The masseter was divided into four subunits and the temporalis into three separate parts. The upper and lower attachments of the muscles of mastication were measured on a single human skull and divided into thirteen independent units on each side. The values obtained by Schumacher [1961] for physiological cross-sectional area were again referred to as in Prium's [1980] study. The figures used by Osborn and Baragar were therefore a combination of the work of two earlier investigators. The maximum force values thus obtained were subsequently divided between the different parts of the muscle according to the approximate size of the elements. Although no two pairs of left and right measurements were exactly the same the measurements of one side were chosen and duplicated for the other side. **Fig 3.26** shows the muscle elements used in the study. Msa and Msp are the masseter superficial anterior and posterior. Mda and Mdp the masseter deep anterior and deep posterior. Tv, Toa, and Top are temporalis vertical oblique, anterior and oblique posterior. Di is digastric. Pma and Pmp are pterygoid medial anterior and posterior. Pls is pterygoid lateral superior. Plu and Pli are the upper and inferior head of the lateral pterygoid **(Fig 3.26).**

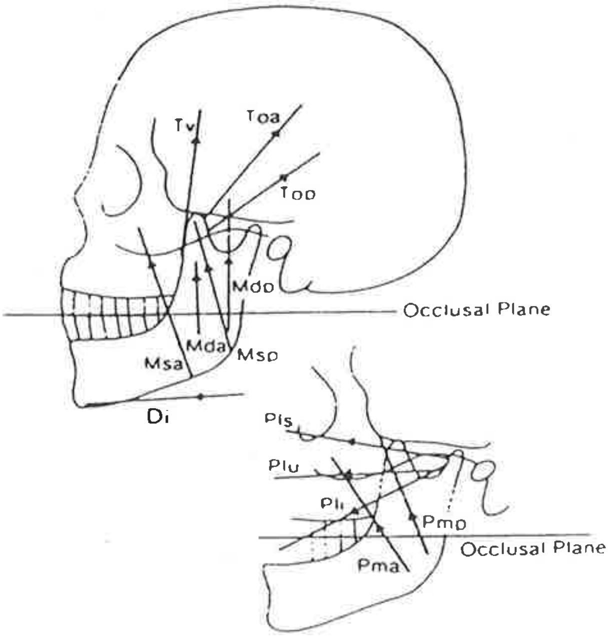


Fig 3.26 (After Osborn and Baragar 1985)

In a similar fashion to Barbenel [1972] analysis is performed when the linear functions of muscle and bite force are independently minimised. This analysis is performed with computer assistance. The objective function of the sum of the joint forces may be constant over a range of bite forces. In each case the computer recognises each of the infinite number of solutions for the equations of equilibrium as being equivalent. These solutions can be asymmetric. In general this study showed the activity of certain muscles to be predominant, the action of part of the temporalis in particular seemed to serve to off-load the joint. Under some conditions however balancing muscular action could not prevent condylar loading.

Osborn and Baragar critically examined the pattern of activity predicted by the model minimising joint reaction force. This system predicted that pairs of muscles with antiparallel lines of action could be saturated with activity in an attempt to reduce joint loads. This proposal seemed unlikely and did not coincide with observed muscular activity. Furthermore the general patterns of activation predicted could not be observed in Prium's or any other study. The authors concluded that this pattern of activation does not occur in biological systems and subsequently rejected this model.

The alternate proposal that the sum of muscle forces is minimised was also examined. In this instance quite different patterns of muscular activation are generated. The patterns of activation predicted in the latter proposal correspond well with previous observations in human subjects. A comparison of the data with the bite and joint force data generated by the computer analysis corresponded with the results of Prium et al [1980]. Prium predicted that for maximum bite force the maximum joint force would be in the range of 40-110 kgs whereas Osborn and Baragar put this value at ~ 50kgs [Osborn and Baragar 1985].

A numerical model of temporomandibular joint loading is described by Smith et al [1986]. Smith's model proposed the null hypothesis that under normal conditions the temporomandibular joint remained free of load. An integrated program was designed using several mathematical and engineering models. This program generated combinations of bite force magnitude, direction, and points of application that minimised the root mean square of the condylar load. Minimising the root mean square means that the magnitude of the resultant condylar force is minimised independent of its direction. This process was repeated using a number of different bite forces thought to be representative of normal masticatory function [Smith et al 1986].

The model was three dimensional and included the mandible and its articulating surfaces constructed from measurements made on a dry skull. The muscle forces exerted by the temporalis, lateral pterygoid, and the medial pterygoid masseter complex were included. Individual masticatory muscles were described as vectors using the centroids of their origin and insertion for their alignment. Muscle forces were then described in terms their mutually perpendicular components projected onto an orthogonal axis system. The bite force was described in terms of both magnitude and direction. Bite force direction was defined in relation to both the horizontal and vertical directions. The bite force in the coronal (X-Z) plane being $\theta_{X\text{-}Z}$ as measured from the X axis and θ_Y defining the bite force direction in relation to the Y axis. **Fig 3.27** show's the orthogonal planes and the vector notation used in this model. The inset depicts the description of bite force in terms of the magnitude of the two angles, θ_Y and $\theta_{X\text{-}Z}$. The bite force in this example is applied to the mesial fossa of the mandibular second bicuspid and is directed medio-inferiorly [Smith et al 1986].

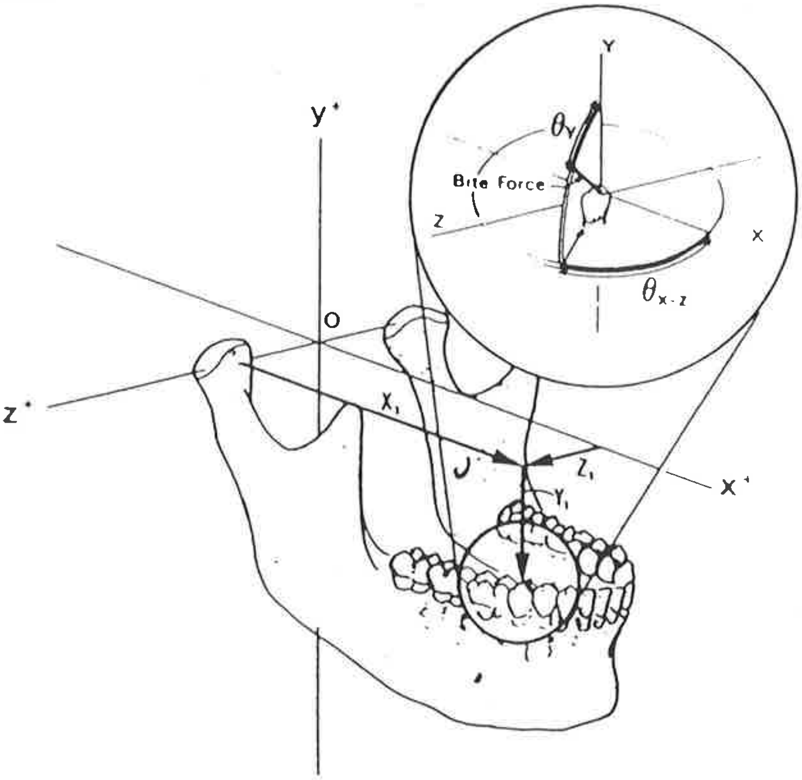


Fig 3.27 (After Smith et al 1986)

The commonly used method of superimposing muscles in the sagittal plane was again used. The combination of muscle pairs in the sagittal plane was followed by satisfying the requirements for static equilibrium in the other two planes. The three dimensional solution of static equilibrium includes both bite forces and moments of force about the intercondylar axis. Computation involved varying the muscular force and checking whether the root mean square of the condylar force was being reduced. As condylar force was increased muscle forces were altered in the opposite direction and the iterative cycle repeated until no further reduction in condylar force could be achieved. A second stage maintained the equilibrium obtained in the sagittal plane and derived the solution of static equilibrium for moments about the X and Y axis.

Smiths data was represented as a series of radial plots **(Fig 3.28)**. Radial plotting allows a large amount of information to be visualised. Groupings of favourable and unfavourable load conditions are most easily recognised using this method.

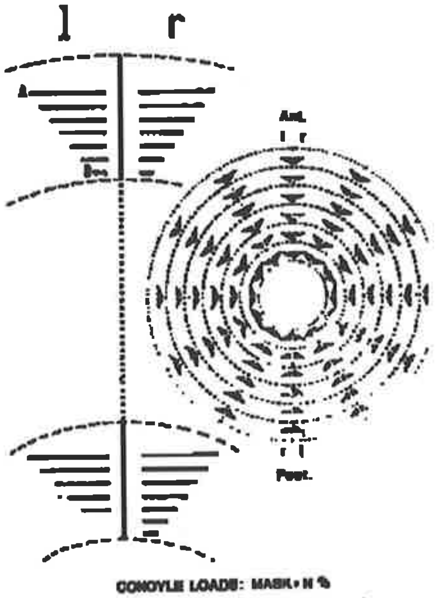


Fig 3.28 [After Smith et al 1986]

These plots consist of twelve radiating lines composed of six annuli which arranged along the length of each radial arm. The radiating lines indicate the direction of bite forces in the horizontal plane; the twelve O'clock position is 0° and the six O'clock line 180°, the other lines occur radially to the left and right sides at increments of 30°. The annuli represent vertical bite force directions from the innermost line representing 0° to the outermost representing 50° in steps of 10°. The length of the the side arms represents the position of the bite force along the tooth row. The use of a single annular diagram allows the visualisation of a large number (~427) of biting conditions.

The results of Smiths investigation lead to the rejection of the proposed null hypothesis finding that, apart from a point of cross over from apposition to distraction, the joint was found to be loaded either in tension or compression. In order to satisfy static equilibrium, the condyle must be load bearing over the normal range of bite force positions and angles. The magnitude of the load varied from a maximal appositional force of 60% of the bite force when the force was applied to the incisors, to a distracting force of 5% of the bite force when the load was applied to the distal surfaces of the third molars. Joint loads were large with vertically directed bite forces on the second molars and reached a maximum with mediolaterally directed loads.

Conditions of stability within the joint were engendered by forces directed parallel to or within about 20° of the mid-sagittal plane. Part of this stability occurred as a result of symmetry in the magnitude and direction of the condylar loads as well as the presence of small forces that tended to appose the condyle and articular eminence. For sagittal loads force directions were limited to a direction nearly perpendicular to the articular eminence.

Smith's results suggest a role for the masticatory muscles in protecting the TMJ from excess load within the the full extent of their geometric capability and force range. This observation is consistent with the known orientation of the masticatory muscles whose fibres run predominantly in an antero-posterior direction [Smith 1986]. Conversely large asymmetrical joint forces were encountered in response to mediolaterally directed bite forces. Smith postulated that the TMJ was unsuited to and incapable of resisting significantly mediolaterally directed forces.

Hatcher, Faulkner and Hay [1986] developed two models to study temporomandibular joint loading. One comprised an in-vitro mechanical model fashioned from a human skull and the other a mathematical model using vector analysis combined with measurements taken from the in-vitro model. Faulkner et al [1987] describes the parallel development of these models as being designed to verify the accuracy of the mathematical model to justify its exclusive use in the future. The dried skull of the in-vitro model was loaded by synthetic muscle forces provided by kevlar strands bonded to the mandible. The kevlar strands were attached to a turnbuckle by which means they were tightened and also to muscle force transducers which measured the forces supplied. Due its small size and inaccessibility mechanical difficulties prevented the lateral pterygoid muscle from being incorporated in the in vitro model. The aim of this experiment was to directly measure the load at this artificial temporomandibular joint.

Two pieces of aluminium instrumented with strain gauges were bonded to the superior surface of each articular fossa. After the attachment of the gauges the skull was sectioned. **Fig 3.29** shows the transducers fitted to the dried skull.

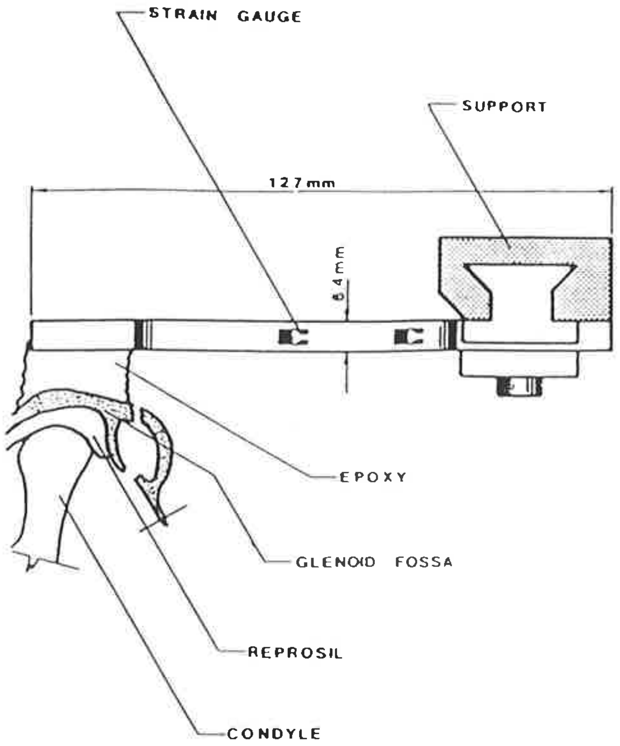


Fig 3.29 (After Hatcher et al 1986)

The fossa and eminence were cut in such a way that force supplied to either condyle would be supported by the beam alone. These beams were fitted with eight strain gauges with individually measurable outputs. A bite force transducer was also fitted between the occlusally modified molar surfaces of the skull.

A mathematic representation of the model for unilateral bite situations was subsequently developed. In this model the positions of the twelve muscles were described by a cartesian coordinate system centred at the apex of the left condylar process. The relative magnitude of muscle forces considered both cross sectional area from the data supplied by Schumacher [1961] and its combination with EMG data from Carlsoo [1952]. These measurements were combined with those taken from the dry skull. The angles of occlusal contact were specified and the system made symmetric with respect to the mid-sagittal plane. The conditions of static equilibrium (where the sum of moments and muscle forces about the three axis were zero) was again used. A three dimensional vectorial analysis was then performed to determine temporomandibular reaction force.

The results of this investigation supported the concept of the temporomandibular joint as a stress bearing articulation. The two different models were thought to behave in a complimentary rather than an antagonistic manner. What discrepancies were noted between the models were accounted for by errors in the measurement of the muscle forces or in the difficulty in determining the effective point of application and direction of their action in the in-vitro model. The inclusion of the lateral pterygoid muscle in the mathematical model (omitted from the in-vitro model because of technical difficulties) showed that it tended to alter the direction of the joint load rather than its magnitude. This was interpreted by the authors as being further evidence for the role of this muscle as a stabilising controlling muscle rather than a force generating one [Hatcher et al 1986].

In this model both EMG and cross-sectional area were used. Mathematical models which combine EMG data and muscle cross sectional area are thought to be more accurate than those based on muscle cross sectional area alone [Throckmorton and Throckmorton 1985]. **Fig 3.30** is a schematic representation of the mathematical model with the muscle occlusal and condylar forces represented as three dimensional vectors.

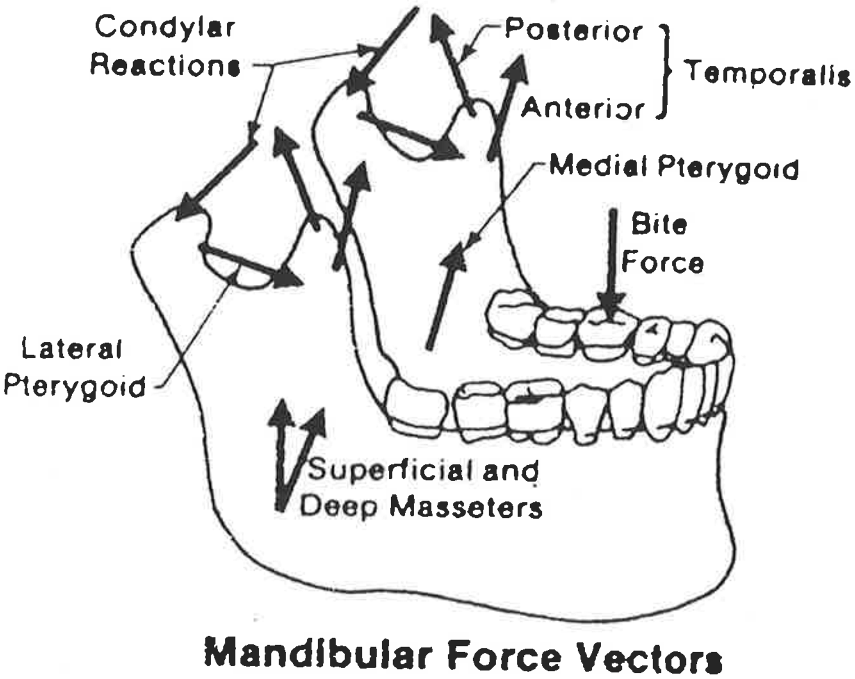


Fig 3.30 (After Faulkner et al 1987)

Vectorial analysis was performed under the conditions of static equilibrium. The indeterminant solution obtained required simplification by the application of a supplementary condition. The assumption made in this case was that the reaction of the left and right condyles was equal in magnitude in a direction perpendicular to the sagittal plane. Although there was no reason to make this assumption it was considered that its inclusion was not critical as the largest components of condylar reaction force are generated in the sagittal plane.

Each occlusal load generates a specific moment about the mandibular condyle to balance the moment created by the musculature. If this moment is to remain constant the magnitude of occlusal force must increase as loads are moved distally in the dental arch. In this mathematical model occlusal loads were simulated for the first, second and third molar positions. Data generated from this showed an increase of 50% in occlusal load as the point of occlusal contact moves from the more anterior to the more posterior molar.

The results of Faulkner's investigations are in general agreement with those of other authors [Mansour and Reynik 1975, Prium et al 1980] who describe an increase in the magnitude of the maximum bite force as the as the bite point is moved posteriorly. This pattern however assumes the muscles maintain the same amount of activity in all three molar positions. It is more likely that the muscles vary their activity whilst maintaining a constant bite force. This would mean that muscle activity would be reduced as the bite point is moved posteriorly. The consequence at the temporomandibular joint is that condylar loading would reduce at posterior bite points but that the relative magnitude between the two condyles would be unchanged [Faulkner et al 1987].

For all three occlusal positions the balancing side condyle carries approximately twice as much load. Total condylar load is divided into one third on the working side and two thirds on the balancing side. This result coincides with one of the earliest investigations by Gysi [1921] who derived his result with a less sophisticated mathematical analysis. Faulkner et al assign the total force generated by the masticatory muscles a value of 100% of which the occlusal load receives between 45 and 65% and the condyle 25% on the balancing side and 10-15% on the working side. The load at the balancing side condyle is therefore ~ 60% of the bite force at the first molar. Using the data of Mansour and Reynik a maximum joint reaction force of 540N would be experienced at the balancing condyle when biting at the first molar. A condylar reaction force force of 400N would be anticipated when biting at the second molar. The balancing condyle/working side condyle experiences force in a 2:1 ratio [Falkenstrom 1993].

Importantly, the direction of the occlusal load also received some attention in this study. The common assumption that bite forces act principally in a direction parallel to the occlusal plane limits the study of the masticatory system to a narrow part of its functional range [Koolstra et al 1988]. When this force is varied in the parasagittal plane both anterior and posterior force components modify its direction and affect the overall magnitude of the generated bite force. This is because the moment arms of the occlusal load to the condyle change. More bite force is generated for a positive load direction than for a negative one [Faulkner et al 1987].

Changing the occlusal load direction also affects the direction of condylar loads. The direction of the ipsilateral condylar force varies considerably as the direction of occlusal load changes in the parasagittal plane. Changes in the direction of about 80' could be seen at the ipsilateral condyle. The magnitude of force on the contralateral condyle remains relatively constant in magnitude and direction varying only about 20' [Faulkner et al 1987]. These observations were explained by the fact that the ipsilateral condyle is well centred in the glenoid fossa and able to apply the relatively low forces at various angles.

Further information on the direction of the condylar load was provided by Osborn and Baragar [1985] who used their mathematical model to restrict joint reaction force to a direction perpendicular to the 30' slope of the articular eminence. This was done under the assumption that the low coefficient of friction that exists in all synovial joints [Charnley 1959] meant that when the mandible was in equilibrium joint reaction force could only be perpendicular to the articular surface of the condyle. Their study showed that for incisal bites the most efficient bite angles were for protrusive bites. These protrusive bites occurred at condyle angles from 0 to 30'. Function between these condylar angles also yielded the smallest joint reaction forces. Joint reaction force is relatively small if directed perpendicular to the articular surface of the condyle and the anterior slope of the articular eminence. The angle of the eminence and articulating part of the condyle in the human is about 20-30' serving to reduce Fj the joint reaction force **(Fig 3.31)**.

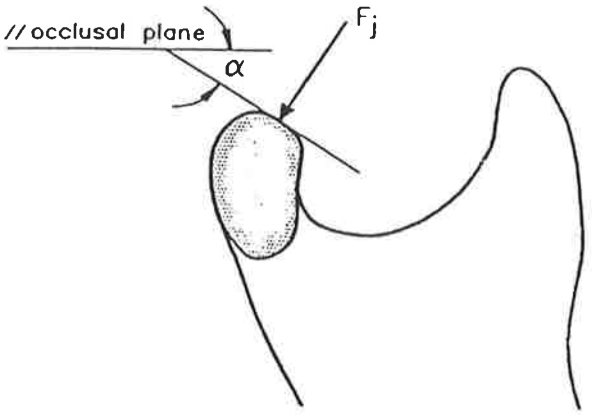


Fig 3.31 (After Falkenstrom 1993)

Working side loads are more sensitive to shifts in the parasagittal plane because their moment arm lengths alter more whilst the moment arm to the contralateral condyle is essentially unchanged. The magnitude of the condylar reaction force at the first molar increases rapidly as the bite force moves posteriorly because a 10° variation in load direction at the third molar will have a much larger percentage change in moment arm length than it would at the first molar. The predicted direction for the contralateral side load directions are at right angles to the slope of the articular eminence [Faulkner et al 1987]. This direction corresponds with the predominant direction of the trabeculi in both mandibular and cranial components of the joint [Osborn and Baragar 1985].

The contralateral side condyle is more heavily loaded as it has to balance both the unilateral occlusal load as well as any imbalance between the muscle force magnitudes on the right and left hand sides. The condyle must also be further from the point of application of force than the working side condyle and can therefore create a relatively larger moment. The working side condyle may be more centrally positioned in the fossa acting as a lightly loaded stabilising pivot with the contralateral side bearing the greatest load. During balancing function the contralateral condyle is positioned antero-inferiorly within its fossa opposed by the posterior slope of the articular eminence [Faulkner et al 1987].

Koolstra et al [1988] described a mathematical model in which bite force was considered as a three dimensional variable. An embalmed male cadaver was use to obtain geometric data. Under the assumption of symmetry only one side was measured. Cross sectional areas of the masticatory muscles were obtained from CT scans taken perpendicular to the fibre direction of each muscle. A value for the intrinsic strength of each muscle was obtained from the earlier work of Weijs and Hillen [1984] and each muscle was divided on anatomical grounds into different functional parts. The action lines of the muscles were determined by the analysis of X-rays taken from sagittal and frontal projections after radiopaque markers had been placed on the muscles. These are illustrated in **Fig 3.32**.

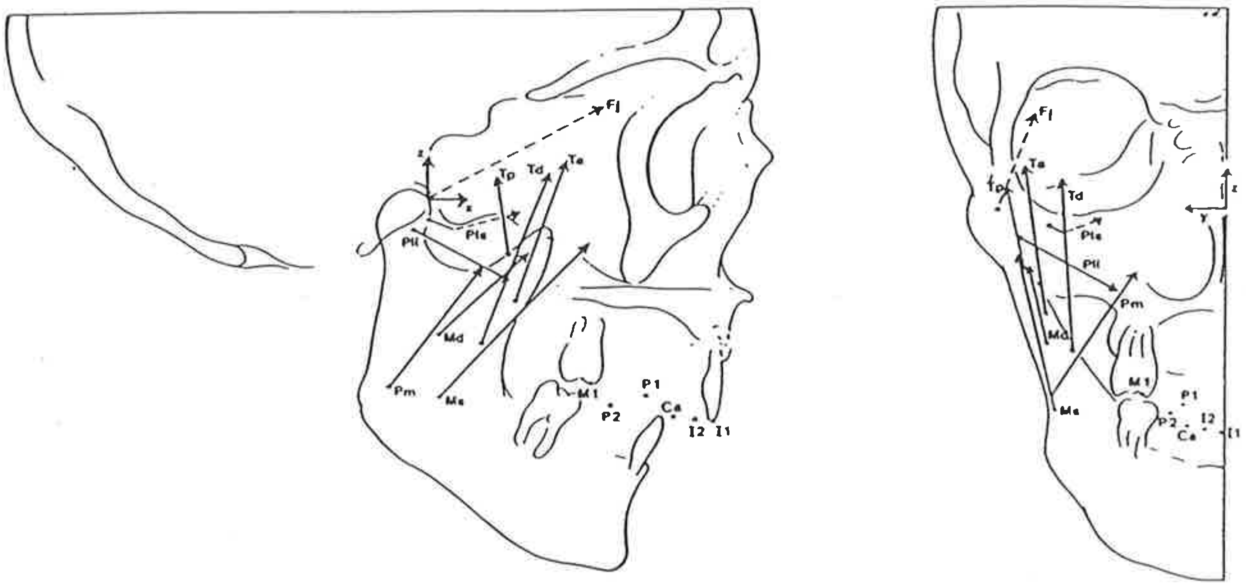


Fig 3.32 (After Koolstra 1988)

The point of application of the joint reaction force was determined by gluing a fine lead wire to both the condyle and the articular eminence. A lateral X-ray was then taken parallel to the condylar axis. The point of contact was defined as the point where the distance between the two sites was shortest. The joint reaction force was then assumed to act perpendicular to the direction of both wires at the site of contact in the plane of the radiograph. Lead markers were also added to the occlusal surfaces of some of the teeth to determine the location of the points of application of bite force [Koolstra et al 1988].

With reference to a cartesian coordinate system muscle and joint reaction forces were examined under the conditions of static equilibrium. Under these conditions six linear equations are generated. These equations may be solved via the use of linear optimisation methods. These complex problems require an objective function (expressing a constraint on how the masticatory muscles are recruited) to allow the mathematics to be simplified. In a manner similar to that of Faulkner et al [1987] the unknown variables are represented by 16 muscle force vectors and two unknown joint reaction forces these are illustrated in **Fig 3.33**.

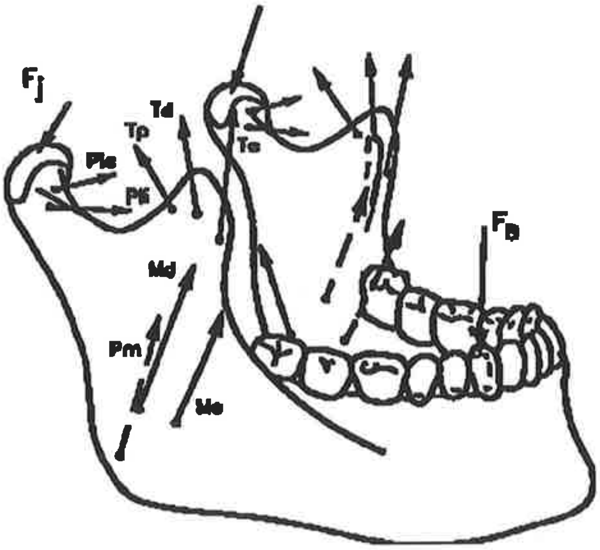


Fig 3.33 [After Koolstra et al 1988]

The optimisation selected by Koolstra et al was that the relative activity of the most active muscle should be as small as possible. With this objective function and the constraints used for optimisation the problem was solved using the simplex method for linear programming. These authors used a computer system driven by a *FORTRAN* ® programme to implement their solution

The results of these investigations are represented in bite and joint force envelopes. Bite force envelopes are three dimensional shapes constructed by connecting the far ends of the of the obtained bite force vectors. Joint force vectors were also constructed. The length of a joint force vector represents the magnitude of the joint reaction force. These vectors are further orientated with respect to the concomitant bite force vectors. Joint force envelopes are constructed by combining these joint force vectors. Both lateral and frontal projections of these envelopes are presented. **Fig 3.34** shows some bite force envelopes the bite force vector with the largest magnitude is marked with a dot and the maximum bite force perpendicular to the occlusal plane with an asterisk.

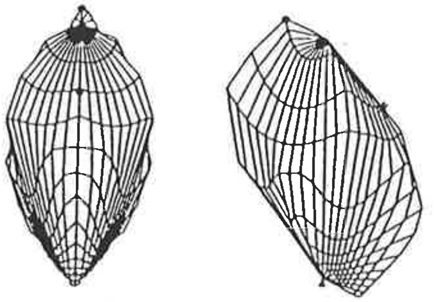


Fig 3.34 (After Koolstra 1988)

Bite and joint force envelopes were generated for various bite point locations and mandibular positions. Examination of these envelopes suggests that for each specific bite point a wide range of direction of forces can be produced. The magnitude of the maximum bite force depends on its direction. The relationship between bite force direction and its maximum magnitude depends on the bite force location and on mandibular position. The largest possible bite force does not always coincide with the direction perpendicular to the occlusal plane. In the molar region the largest possible bite force is directed upward, backward and mesially. In incisor bites bite force is directed posteriorly [Koolstra et al 1988].

The pattern of muscle recruitment necessary to generate large bite forces involves the maximal activation of most muscle elements with the exception of the two heads of lateral pterygoid [Koolstra 1988]. This recruitment pattern differs slightly from that predicted by Moller [1966]. Later investigators suggest that whilst nearly all muscles are recruited maximally in vertical bites, this is not the case for oblique directions [van Eijden 1989]. Incisal bites resulted in only partial activity of the anterior temporalis a difference which has been suggested to be due to an underestimation of the the maximum masseter force [Falkenstrom 1993]. In the incisal region, and for small deviations of bite force direction from that which will generate maximum force, unilateral bite forces can be almost as efficient as bilateral bite forces [Koolstra 1988]. On average homonymous right and left sided muscles behaved similarly in this and other studies [van Eijden 1989].

Koolstra's mathematical model showed that a variety of different recruitment patterns can lead to similar values for bite force but may cause vastly differing joint loading patterns. Joint loading is symmetrical when the direction of maximum bite force is parallel to the sagittal plane. This symmetry is progressively decreased as the bite point is located more posteriorly. Balancing side joint force envelopes were considerably larger than those of the working side in unilateral molar biting. Laterally directed bite forces tended to load the condyles more than medially directed forces in a manner that was independent of bite point location. Joint loading in incisor bites was large and could exceed the bite force itself. These findings were in agreement with the earlier work of Smith et al [1986]. The maximum calculated joint force was 500N [Koolstra et al 1988].

3.5 COMPONENTS OF A MATHEMATICAL MODEL

The difficulties encountered in modelling the biomechanics of the masticatory apparatus are evident in the volume of literature devoted to this purpose. This complex system demands an ever increasing sophistication in measurement of its parameters. A complete model of all the forces involved in mastication is complex. In the human subject muscle vectors representing at least sixteen or more muscles that can act on the mandible at any one time must be considered. This sixteen components include all of the muscles of mastication, their subunits, as well as the depressor musculature acting on the mandible. The bite force vector and the forces contributed by the connective tissues, ligaments, teeth and bones need to be determined in three dimensions.

The acquisition of all of the data required to properly construct a mathematical model of the masticatory system is extremely difficult. The minimal criteria required should include; an understanding of the range of possible mandibular movements, knowledge of the direction and strength of the masticatory muscles as well as their pattern and degree of activation.

Due to the complexity of the system complete models have not yet been developed, nor is it known which of these forces are required for a reliable calculation of the TMJ reaction force [Throckmorton and Throckmorton 1985]. Despite these difficulties several authors have provided useful insight into the nature of TMJ reaction force through the use of mathematical models. The system is further compounded by the complexity of its driving neural network and the changing of muscle length and tension with mandibular movement [Osborn and Baragar 1985]. For this reason biomechanical studies studies are restricted to static bite situations. It is further felt that as muscles in isometric contraction can develop higher muscle force the condylar reaction force will be correspondingly higher in this condition [Falkenstrom 1993].

The use of optimisation techniques by applying constraints to the system is one method that has seen extensive use in simplifying the complexity of mandibular biomechanics. Examples have been provided by Barbenel [1972, 1974, 1983] and McConnail [1967] who minimised joint forces or alternately total muscle force. Faulkner [1987] suggested that the reaction of right and left condyles was equal in magnitude and in a direction perpendicular to the sagittal plane. Koolstra [1988] suggested the relative activity of the most active muscle should be as small as possible. Once optimisation criteria have been applied the problem may be solved with the use of linear programming [Barbenel 1972, 1974, 1983, Osborn and Baragar 1985].

Another means of simplifying the system has been to reduce the number of unknown variables by describing the way in which certain muscles are recruited. This has been achieved through the use of EMG data. Koolstra [1988] based his optimisation criteria on such information. EMG data had showed that showed that once bite force had been initiated in a certain direction the pattern of activity did not change much. The assumption could be made that once a pattern of recruitment appropriate to a maximal bite force had been established the muscles would maintain there proportionate level of activity. The relative activity of the most active muscle would therefore be minimal.

EMG data also allows one to eliminate certain muscle forces. Although this method may be mathematically valid it does not represent the complete biological system [Falkenstrom 1993]. This technique has been used for the finger [Chao et al 1976] and for the knee [Nissan 1981]. The number of of unknown muscle and joint forces can also be reduced by grouping the muscles on anatomical and functional grounds [Falkenstrom 1993]. This method has been used on the hip [Paul 1967] knee [Morrison 1968], elbow [Nicol et al 1977] and ankle [Proctor and Paul 1982]. Similarly the grouping of the masseter and medial pterygoid into a single vector is an attempt to simplify masticatory biomechanics [Prium et al 1980 and Smith et al 1986]

The models of Hylander [1978], Prium [1978, 1980] and Faulkner Hatcher and Hay [1986,1987] attempt to describe the system by the use of anatomical data such as muscle length and cross sectional area. This information can be used to construct muscle vectors. The activity of each vector can be then determined by recourse to electromyographic data [Falkenstrom 1993].

The major difficulty encountered in calculating joint reaction force has been the determination of muscle forces [Faulkner, Hatcher, and Hay 1987, Falkenstrom 1993]. Masticatory muscles produce considerable force during biting and chewing. These forces are transmitted by the teeth to the object being chewed and strong resultant forces are conveyed to the mandible itself [Barbenel 72]. Although the maxillae are fixed the mandible is freely mobile through a large range of movements afforded by its articulation at the temporomandibular joint [Boering 1981]. Each muscle can generate a force vector with a specific orientation [Koolstra et al 1988]. Nearly all of the theoretical and experimental force studies give only crude descriptions of the line of action, moment arm and muscle force [Falkenstrom 1993]. Mathematical modelling requires very precise determination of muscle force directions to reliably calculate temporomandibular joint reaction force [Throckmorton 1985].

3.5.1. MASTICATORY MUSCLE: FIBRE DIRECTION

The muscles of mastication are the masseter, the medial and lateral pterygoid and the temporalis [Williams et al 1982]. Clearly other muscles are attached to the mandible and influence its movement but these are not included in this classical description. That other muscles are involved in the generation of masticatory force has been denied by the earliest investigators; "all other muscles are either horizontally inclined or contribute only small forces during mastication" [Roydhouse 1955]. However individual inspection of the masticatory muscles shows that most are capable of generating compressive load at the temporomandibular joint. Even the oblique or horizontally directed fibres of the middle and posterior fibres of the temporalis curve down around the root of the zygomatic arch to produce forces on the coronoid that are mainly superior [Mohl 1988].

There has been little argument as to the principal muscles which lead to the development of occlusal force. Indeed some authors have considered only the contributions of masseter and temporalis as relevant to the generation of occlusal force and therefore to the analysis of temporomandibular joint reaction force. These are used exclusively in some early studies [Carlsoo 1952, Schumaker 1961, Roberts and Tattersall 1974]. Although acknowledging the existence of the other masticatory muscles Gingerich [1971] saw the temporalis as the key muscle in the generation of bite force and did not include the others in his mathematical analysis. Some authors have suggested the role of the lateral pterygoid is principally as a depressor muscle [Barbenel 1983] but it is still included in mathematical analysis because of electromyographic evidence of its activity in biting [Moller 1966].

Some authors have sought to include the digastric muscle in the study of the development of occlusal force. Described as a jaw opening muscle [Williams et al 1982] recent investigators have noted that the digastric can make small contributions to jaw closing bite forces especially when they are directed backward [Koolstra et al 1988]. Prium [1978] contends that this muscle plays an important role as an antagonist in modifying bite force. For directions perpendicular to the occlusal plane however the role of this muscle in developing maximum bite force can be ignored [Osborn and Baragar 1985, Koolstra et al 1988].

Smith's [1978] model of mandibular biomechanics in incisal biting attempted to incorporate the forces contributed by the masseter, temporalis, and medial pterygoid. The mandible was modelled on a beam drawn from the incisal bite point to the mandibular condyle. Masticatory muscles were assumed to apply a single uniformly distributed load over their length of overlap with this beam. Individual muscle forces were divided into components horizontal and vertical to the beam. Only the vertical components were considered to contribute to bite force.

In mastication the the direction and magnitude of the force applied to the food will constantly change [van Eijden 1989]. At the same time it has been shown the magnitude and orientation of the masticatory muscles in space is a critical factor in modelling bite and joint force generation [Throckmorton 1985]. Even a slight change of bite force direction may have a profound effect on the magnitude of the bite force and the recruitment pattern of the muscles [van Eijden et al 1988].

Koolstra [1988] showed that when the mandible moves with respect to the skull the orientation of the lines of muscle action also change and this fact is overlooked in some mechanical models. With slightly more divergent lines of muscular action bite forces can be generated in a wider range of directions and a larger bite force may be generated [Koolstra et al 1988]. Increase in maximum bite force when the mouth is opened slightly has been observed by other investigators [Manns et al 1979]. A shift in the working lines of muscle with mechanical displacement of the mandible in function is also described by Weijs [1980]. Angulation in masticatory muscle vectors in the rat have been shown to shift 10' in the superficial masseter and up to 32' in the medial pterygoid between chewing and maximal gape [Weijs and Dantuma 1975].

Muscle forces are usually represented as a single vector with a fixed direction under the assumption that the muscle acts as a whole. These assumptions disregard the complex multipennate nature of these muscles. In his examination of the temporalis Tattersall [1973] warned of the oversimplification of using the "average lines of pull" to generate a force vector in a muscle that had such wide variation in the orientation of its muscle fibres. Broad attachment areas and differing lines of muscle action within individual muscles mean a number of possible vector combinations are possible within a single muscle [van Eijden 1988]. The averaging of muscle vectors for a particular specimen may be more relevant were the muscle is a prime mover than when it is an antagonist or synergist of other muscles Tattersall [1973].

The separation of muscle mass by tendons is called pennation. Pennation increases the complexity of a given muscle and is believed to convey several advantages. These include the ability of the muscle to apply force over a wide range of mandibular positions [Gans and de Vree 1987, Herring 1976]. The multipennate nature of masticatory muscles is well described [Schumaker and Rehmer, 1960; Yoshikawa et al 1961]. Gaspard 1974 describes each muscle as an aggregation of muscular fascicles rather than a homogeneous mass. Muscles that have a complex internal architecture can consist of more efficient packages of individual fibres and have a shorter distance between their origin and insertion [Gans and Bock 1965]. Any muscle mass may be divided into two or more parts if independent function of these parts is possible [Matthews 1972]. It has been demonstrated by anatomicomechanical analysis using anthropologic measurements and radiographs of living persons that all portions of the muscles of elevation have the ability to cooperate in mandibular closure [Carlsoo 1952].

Thus the broad fan shape of the masticatory muscles means that a single vector representation is unreliable [Falkenstrom 1993]. This has lead to the subdivision of individual masticatory muscles into separate subunits which make the model biologically more realistic. Faulkner [1986] in describing his own mathematical model includes the following bilateral muscle groups; superficial and deep masseter, medial and lateral pterygoid, and the temporalis which is divided into anterior and posterior portions. Other authors have made their description more complex and have divided the four masticatory muscles in man into 24 subunits. Such analysis assumes that each muscle has its own area of insertion, its own fibre direction and its own independent action [Baron and Debussy 1979].

Early investigators arbitrarily selected directions for jaw elevators which were consistent with unproven biomechanical theories [Wilson 1920, Robinson 1946, Page 1954, Gingerich 71, Roberts 1974, Smith 1978]. The most common method used to determine direction of muscle force has been to simply draw a straight line between the point of origin and insertion of each muscle [Prium et al 1980, Weijs and Dantuma 1981, Faulkner 1987] often only taking measurements on a dried skull. The areas of origin and insertion of muscles are determined on a dry skull by using the deformations of bony relief produced by the traction of the muscular bundles [Baron and Debussy 1979]. Mainland and Hiltz [1934] assessed the lines of action from the direction of the superficial fibres of the muscle. Carlsoo [1952] measured the projected area of the muscles in three orthogonal planes by the use of a cephalostat. Another method has been to take lateral cephalograms after radiodense markers, such as tiny steel balls, had been attached to the specimen and to take measurements from the radiograph [van Eijden 1988].

That a muscle produces a force along a straight line connecting its point of origin and insertion is an approximation that will generally hold true for straight parallel-fibered muscles with small areas of attachment. The presence of tendons and aponeuroses in pinnate muscles which act to concentrate and dissipate forces over a wider area further complicates analysis. Muscles that have a broad area of attachment over an irregular bony surface show marked deviations in the line of action as the muscle performs different functions These deviations may be in part determind by the tendons and aponeurosis that divide its strucure [Weijs 1980].

The possible actions of isolated muscles or muscle components should be understood in the context of the whole muscle. To maintain static equilibrium some muscle activity may be wasted in balancing unwanted components of muscle force. If the masseter is considered as an example the action of its principle fibres do not produce a purely vertical force. Some anteriorly directed forces may need to be counter balanced by posteriorly directed ones such as those generated by the posterior temporalis. This process may reduce the amount of muscular energy devoted purely to bite force production.

In order to minimise the inaccuracies produced by variable recruitment patterns uniform activation of the fibres of each muscle elements must occur. In turn this assumes that each muscle is capable of producing a single bite force direction. If a heterogeneous pattern of muscle activation occurs then each muscle can generate a unique variety of bite force directions. Barbenel [1983] determind the lines of action of the masticatory muscles by locating their centroids of origin and insertion and drawing a line between them. This technique makes no provision for less than the whole of the muscle being active. Division of the masseter into subunits has been used to demonstrate functional heterogeneity in the pig [Herring et al 1979].

The degree of variability in a given muscle is a consequence of its geometry and attachment area which in the masticatory muscles are complex and broad [van Eijden et al 1988]. It has been demonstrated however that when a muscle produces its maximum force this line of action is unique and is related to the muscles shape. Calculation of masticatory muscle vector directions may thus be valid for maximal forces given that the muscle architecture and its subunits have been properly defined. Falkenstrom [1993] states that perhaps only when all fibres are maximally activated is it acceptable to represent a muscle by a single force vector. Calculations made at submaximal forces rely on the activated fibres being evenly distributed throughout the muscle [Koolstra et al 1990].

Patterns of recruitment within individual muscles are also under question and several factors may be important in determining the relative recruitment of muscles in motor tasks [van Eijden 1988]. Electrical activity may not be uniform and different levels of activation may exist throughout different portions of the same muscle [Moller 1966]. Independent contraction of muscle parts has been observed in muscles with broad attachments such as gluteus medius [Soderburg and Dostal 1978] and some shoulder muscles [Yoshikawa et al 1975]. The independent action of fibres of different orientations may occur within the masticatory muscle mass but it is generally agreed that for significant bite force production adjacent fibres must cooperate.

Electromyography has been used to explore the recruitment patterns of muscles but information regarding heterogeneity in function of the human jaw muscles is sparse [van Eijden et al 1988]. Limited electrode studies have been performed in non human mammals but with the exception of the temporalis, recordings in human subjects have often been taken from a single electrode pair [Carlsoo 1952, Moller 1966, Vitti and Basmajian 1977, Hannam and Wood 1981]. The activation of different portions of a single muscle have been shown to produce different bite force magnitudes [van Eijden et al 1988].

The level of activation of each muscle determines how much it will contribute to the generation of a particular bite force in relation to other masticatory muscles. The way the load is shared between muscles is potentially infinite [van Eijden 1988]. Osborn and Baragar [1985] described two theories to describe the way the different muscles cooperate to produce a given bite force. They proposed combination of muscle groups to minimise the total muscle force used to produce a given bite force or alternately that muscle action was combined in such a way as to minimise the total joint reaction force. A further proposition by these same authors was that muscle activation occurred in a "ripple" effect. Independently functioning muscle elements were activated sequentially as bite force increased, those with long moment arms becoming active before those with shorter moment arms.

A specific bite force can be generated by a variety of combinations of muscles or by the action of certain muscles in isolation [Prium et al 1980, Koolstra et al 1988]. A single bite force can be generated by an infinite number of combinations of muscle force and an infinite number of number of activation patterns are theoretically possible. The criteria that that is used by the central nervous system to determine the the pattern of activation are unknown [van Eijden 1989]. Prium had noted that different subjects used a similar combinations of muscles to produce a given bite force and this was suggestive of the existence of control mechanisms in muscle recruitment. Biomechanically based criteria to determine appropriate muscle combinations are used to limit the possible actions of the masticatory muscles. These have already been described in the discussion of some of the mathematical models [Barbenel 1972, 1974, 1984, Osborn and Baragar 1985, Koolstra et al 1988]. Some of these were shown to have no biological validity when compared with EMG data [Barbenel 1972]. Whatever the proposal the application of each of these different constraints will lead to differences in predicted recruitment order and describe different contributions from each masticatory muscle [van Eijden 1989].

The masticatory muscles may be divided in their mode of action into power muscles and control muscles [Osborn and Baragar 1985]. Power muscles produce a bite force but tend to displace the condyle up or down the articular eminence. This displacement is prevented by the control muscles which have very poor moment arms for generating the usual bite forces but which are efficient for preventing condylar slide. These conclusions are supported by the examination of the electromyographic recordings of these separate groups [Osborn and Baragar 1985].

The subunits which comprise masseter and medial pterygoid show a strict linear increase in tension until saturation occurs. No other muscle analysed always performed in this way suggesting that these muscles share a common function in the production of symmetric vertical bite forces. The most efficient generators of muscle force in the class three model of lever mechanics are those which have a long moment arms about the fulcrum or joint. The relative lengths of the moment arms of certain components of masseter and medial pterygoid exceed those of the other jaw elevators. The superficial part of masseter being the most efficient power muscle for vertical bite forces [Osborn and Baragar 1985].

The role of the lateral pterygoid in mandibular biomechanics has historically been one of the most difficult to determine. The location of the muscle deep within the infratemporal fossa makes it relatively inaccessible. Attempts at placement of electrodes to measure its electromyographic activity are difficult and the recorded function may well be altered by the associated pain and haematoma formation. The discovery of two reproducible patterns of electromyographic activity from electrodes placed in the lateral pterygoid muscle lead McNamara [1973] to describe an independent function for the two heads of the lateral pterygoid. The superior head was thought to position and stabilize the condylar head and disc against the articular eminence during closing movements of the mandible. The inferior head assisted in the translation of the condylar head downward, anteriorly and contralaterally during opening movements [McNamara 1973].

A role for the lateral pterygoid has been suggested by Osborn and Baragar [1985]. These authors note that a component of the bite force will always act perpendicular to the joint reaction force tending to displace the condyle along the articular eminence. Although the orientation of the lateral pterygoid makes it a remarkably inefficient power muscle its major action may be to prevent the condyle from sliding up and down the eminence. The two oblique parts of the temporalis assist the lateral pterygoid in neutralising these displacing forces. Vectors of lateral pterygoid pass below the condyle and those of the oblique temporalis above. The combination of fan shaped architecture and opposing lines of action means that any unwanted power activity, whether it be tending to displace the condyle up or down the eminence, could be compensated for by these muscles.

Osborn and Baragar felt that all of the jaw muscles could have both power and control functions but that the superficial masseter and the medial pterygoid exemplified the power type of muscles whilst the lateral pterygoid and oblique parts of the temporalis were control type muscles. If this theory were to be strictly applied then the controlling muscles would be attached in front and immediately behind the condylar neck. The disposition of a muscle immediately behind the condyle however would mean that some part of its force vector would tend to open the jaw thereby reducing the bite force. The attachment of temporalis in front of the condyle with a backward and upward vector allows this muscle both control and power functions. Osborn and Baragar thus include power and control muscle theories together with electromyographic data to describe the sequence of activation of the masticatory muscles.

The concept of controlling muscles is consistent with the earlier work of Carlsoo [1956] who proposed that as the bite force increased there is an increase in the activity of the lateral pterygoid and the oblique temporalis. Carlsoo concluded that the lateral pterygoid acted to prevent the condyle from being driven upwards and backwards into the thin floor of the articular fossa. McNamara [1973] similarly presumed that activity in the superior head of lateral pterygoid positioned or stabilised the condylar head and disc against the closing movements of the mandible.

As the determination of the lines of muscle action have been achieved mainly through dissection, these techniques are not applicable to in-vivo human studies [An, Takahashi and Chao 1984]. The recent development of sophisticated imaging techniques such as computer assisted tomography and magnetic resonance imaging provide a different method of providing an in-vivo estimation of the lines of muscle action. The results for the determination of the lines of action obtained by both dissection and imaging techniques vary but fall within reasonable range.

3.5.2 THE STRENGTH OF MASTICATORY MUSCLE.

One of the most challenging aspects of biomechanics has been to determine the force produced by an individual muscle. Muscular force probably represents the complex interaction between weight, cross-sectional area, actin to myosin ratio, vascularization, muscle architecture and innervation [Smith 1978]. One of the earliest investigators in the search for a means of quantifying muscular force was Weber [1846]. Weber's attempts at estimation of the combined cross sectional area of all fibres in a pennate muscle were later duplicated by others trying to define absolute muscle force [Franke 1920, Morris 1948]. Cross sectional area has been used by other authors to estimate muscle force in the masticatory system [Gysi 1921, Mainland and Hiltz 1934, Carlsoo 1952].

Weber [1851] defined the physiological cross section (PCS) of a muscle as the ratio between total muscle weight and the mean fibre length. Before weighing the muscle Weber removed all vessels, fat and tendinous material. PCS was then calculated from wet muscle mass, tissue density and fibre length. The relative wet weight of each muscle was assumed to be proportional to its contribution to force. Another method was described by Buchner [1877]. Buchner's method involves careful dissection, detachment and measurement of the muscle. Individual muscle fibres are gently teased apart until the small parallel fibres are reached. These fibres are then inserted under slight pressure into a U-shaped calibrated vessel. Schumacher [1961] refined the concept of physiological cross-section [PCS] in the analysis of the jaw muscles defining it as the total cross section of all muscle fibres at a specified length this includes the summed cross sections of its individual fibres.

Schumacher's application of the PCS method to the levator muscles of the jaw made use of both the Weber and Buchner techniques. Other authors have preferred one method over the other; Carlsoo [1952] used Weber's method exclusively and Prium et al [1980] used data obtained from both techniques. The PCS concept is now commonly used in modelling of the masticatory system [Prium et al 1980, Hatcher et al 1986, Koolstra et al 1988]. Though these techniques are suited to post mortem studies results have been obtained in-vivo. Measurement of limb circumference and calculation of muscle cross section in humans has been achieved by assuming the same ratio between the circumference in living subjects as cadavers [Franke 1920, Haxton 1944].

Various medical imaging methods have been used in the measurement of cross sectional areas of the limbs. Ikai and Fukunaga [1968] used ultrasonic scanning. Computer assisted tomography was used by Nygaard et al [1983] and Schantz et al [1983]. Muscular tissue can be readily identified on CT and patches of fat beneath the fascia, large vessels and nerves can be excluded from the measured areas on the basis of density. Although these non invasive methods have made possible individual assesement of of muscular cross section in vivo some authors have criticised these techniques for their neglect of muscle architecture [Weijs and Hillen 1985].

Electromyographic recording [EMG] has been used in conjunction with cross sectional area in mathematical models in an attempt to determine muscular force and the way the masticatory load is shared more accurately [Barbenel 1974, Prium et al 1978,1980, Faulkner et al 1987]. Since it is unlikely that each muscle functions maximally in mastication the relative activity and therefore contribution of each muscle to a given biting force should be considered [Throckmorton and Throckmorton 1985]. More quantitative information has been obtained from experiments which include the use of bite force transducers and a consideration of the three dimensional nature of the bite force [Wanatabe and Hannam 1986, van Eijden et al 1988].

Other physiological mechanisms besides muscle morphology may act to determine muscular performance. The internal arrangement of fibres is seen as a critical factor [van Eijden et al 1988] and their length tension relationship has been investigated [Manns et al 1979]. The contractile and metabolic capacity of individual muscle fibres can be expressed in terms of muscle fibre types [Burke et al 1973].

Fibre types can be identified by an ATP-ase method [Pierobon-Bormioli et al 1981]. Although the exact method responsible for the staining modality is not known it has been verified by immunological techniques [Butler Browne et al 1988]. The ATP-ase method has been combined with physiological methods and remains in common use today [Strom 1990]. Measurement of whole muscle as well as individual motor units has been performed [Wells 1965, Close 1972, Burke 1973]. Although investigations have shown that the intrinsic strength and the mechanical properties of muscle are related to the fibre type involved [Weijs 1980, van Eijden et al 1989] the effect of fibre type on intrinsic strength is still a matter of controversy [Weijs 1985].

The number of fibre types identified in masticatory muscle tissue has been reviewed by Strom [1990]. These fibres are grouped as;

Type 1: slow twitch motor units characterised by a long contraction time.
Type 2A: rapidly contracting motor units resistant to fatigue.
Type 2B: rapidly contracting fast twitch motor units
and
Intermediate fibres: type 2C and 1B.

Different values of intrinsic strength have been recorded for these fibre types. There is little distinction between some groups such as between type 2 subtypes. Slow units have the lowest strength. Intermediate types are between types 1 and 2 and contain both fast and slow units [Burke et al 1973].

Information of the fibre composition of mammalian masticatory muscles is scarce. Studies have been performed in the human [Ringqvist 1974, Eriksson 1982]. Animal studies have been performed in the cat [Taylor et al 1973], rhesus monkeys [Maxwell et al 1980] and the pig [Strom 1990] these show some important differences. An inverse fibre diameter relationship between jaw and limb muscles has been noted [Eriksson 1982]. Rindqvist 1973 found a positive correlation between the size of fast twitch fibres and biting force in man. The predominance of fast twitch fibres in the masticatory muscles was noted in most mammals studied [Weijs 1980]. Specialised superfast myosin has been identified in cat jaw closing muscles [Taylor et al 1973]. In cattle and sheep however all fibres contain alkaline unstable myosin ATP-ase and are probably of the slow twitch type [Suzuki 1977].

3.5.3 MANDIBULAR MOVEMENT & THE INSTANTANEOUS CENTRE OF ROTATION

The temporomandibular articulation between the mandibular condyle and the glenoid fossa of the temporal bone together with its meniscus and ligamentous attachments allows a wide variety of movements to occur at the joint. Opening and closing, protrusion, retrusion, and lateral movements are possible [Moss 1960]. The mandible rotates and translates about the three condylar axes and chewing is achieved by a complex combination of alternate contraction and relaxation of the powerful muscles of mastication [Hohl and Tucek 1982]. Rotation and translation about almost any point in free space is possible [Falkenstrom 1993].

Among the earliest attempts at the study of mandibular motion were those of Chissin in 1906. Chissin described three centres of rotation using graphical drawings of marker points on the mandible this work was reviewed later by Hall [1929]. The opening movement of the human mandible has been variously described [Koski 1962]. Description has varied from a simple hinge with its axis passing through the mandibular foramen [Last 1954], an undefined hinge axis [Terry 1953], or a moving axis [Scott 1955]. In contrast to the carnivorian less restrictive bony anatomy surrounds the joint in human and herbivorous species. This affords both condylar translation and rotation [Hylander 1978]. Although a purely rotational movement is supposed to be possible [Posselt 1950], it is likely that all functional movements of the human jaw joint involve both rotation and antero-inferior translation [Smith 1985].

The mandibular opening movement has been seen by some authors as particularly relevant to an understanding of mandibular biomechanics [Grant 1973, Roberts and Tattersall 1974]. This is because class three lever mechanics involve the calculation of mandibular moment about a centre of rotation. The centre is usually placed at the mandibular condyle but such rotation would only occur if the mandible opened as a simple hinge [Hylander 1975]. The analyses of Davis [1955], Crompton and Hiiemae [1969], and Turnbull [1970] have also used this technique.

The ability of a condyle to both slide and rotate however means that the arc of mandibular closure may vary continuously [Posselt 1968]. The mandible can therefore be described as having a moving instantaneous centre of rotation [Grant 1973]. The instantaneous centre of rotation [ICR] of two objects undergoing relative planar motion is described as the location of a point on the plane of one object, about which the other object is being instantaneously rotated [Falkenstrom 1993]. In simple terms the centre of rotation varies as the mandible is opened and closed.

Moss [1960] described the basic principles of diathrodial movement. All motion must occur about an axis but it also must be considered that this axis may alter during motion. Kinematically the mandible can be considered as a free body that may rotate in three dimensions of space. Each of several degrees of freedom of movement are possible within the joint but each of these has its own axis of rotation. The individual axis of rotation is significant because the work or torque which a muscle will produce at a given point is a function of its cross sectional area and the vertical distance from the axis of motion to the line of action of the muscle [Moss 1960]. Moss [1960] and Grant [1973] have suggested that mandibular moment should be calculated about the instantaneous centre of rotation.

Moss located the ICR about the region of the mandibular foramen and Grant at a variable position depending on the position of the mandible at any one time. Gibbs et al [1969] showed that the instantaneous centre of rotation in the lateral projection was dependent on individual variation as well as which condyle was functioning at that time and on the texture of the food. The use of the ICR in calculations makes the analysis complex because none of the muscle or reaction forces can be ignored [Hylander 1975].

Grant [1973] used a projection of the skull in norma lateralis from Schumacher [1961] and illustrated the instantaneous centre of rotation (ICR) as interpolated from Chissin [1906] and Hall [1929]. From these diagrams Grant indicated that the centre of rotation is never at or near the mandibular condyle and that large displacements of the axis occur from rest to opening. The path of the instantaneous center of rotation as proposed by Grant is illustrated in **Fig 3.34**. CC represents the axis of rotation as located at the center of the condyle. R, O and W represent the center of rotation at rest, open and wide locations. The path described by the moving ICR is called the centrode.

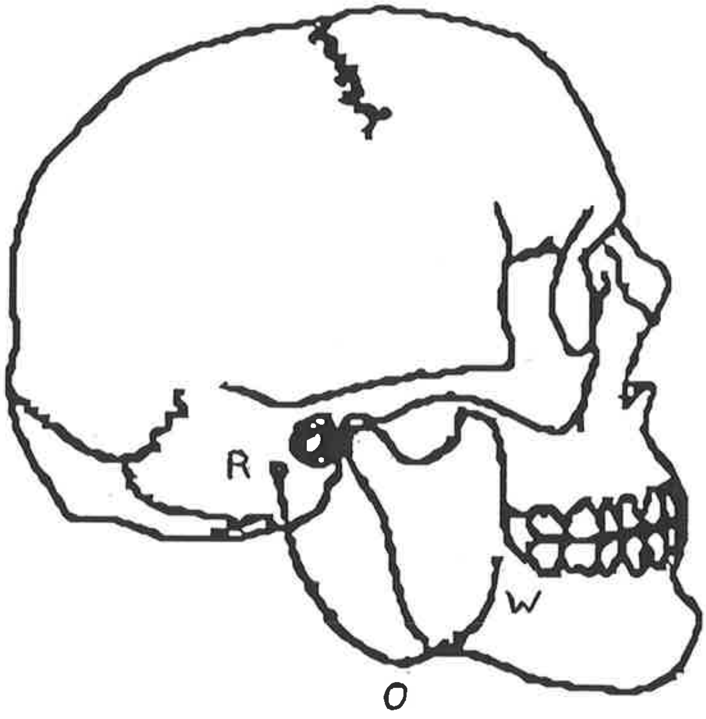


Fig 3.34 (After Hylander 1975)

Grant used Schumacher's data for the origins and insertions as well as the physiological cross sectional area of the masticatory muscles. This data was used to calculate the moments of muscle force comparing the results obtained by using the centre of the condyle as well as the instantaneous centre of rotation. Grant found wide variation between the results obtained by using the different centres for calculation. In the nearly closed jaw a 175% increase in the torque of the mandibular adductors occurred about the ICR than about the mandibular condyle. In the open position the potential moments were again found to be larger using the ICR. Grant argued a fixed axis of rotation at the condyle was much less efficient than a variable one. Grant went further to suggest that muscles were in their most efficient functional positions when orientated about an ICR and this was further evidence of its biological significance [Grant 1973].

Grants concepts were rebutted by Stern [1974] who pointed out the equation of rotary equilibrium had not been satisfied in Grant's analysis. When the jaws exert a force on an object between them conditions of static equilibrium occur such that the moments about any point equal zero. Thus the relative contribution of each of the muscles of mastication is not affected by the location of the axis of rotation. If the moments are to be measured about the ICR then the moments for bite and reaction forces must be taken into account. The joint reaction force exerts a torque counter to that of the jaw adductors resulting in the same calculated bite force. This bite force is independent of the point about which the torques are taken [Stern 1974]. The use of the condyle for the axis of rotation simplifies calculations by eliminating the need to account for joint reaction in the analysis of rotatory equilibrium [Carlson 1977].

Hylander [1975] similarly disputes the supposed significance of the ICR to the calculation of mandibular moment quoting Stern and adding a criticism of Grant's later paper [1973b]. In this paper Grant calculated the different orientations and relations of the two heads of the lateral pterygoid to the ICR in the Rhesus monkey. Hylander disputes Grant's claim that knowledge of the ICR might allow one to determine the action of a given muscle. Applied strictly the moment of the masseter and medial pterygoid about the ICR would have lead to the conclusion that during opening these mandibular elevator muscles would have an opening or clockwise moment indicating a depressor action [Hylander 1975]. Hylander [1985] has suggested it is usually more convenient to calculate moments about the bite, muscle or condylar reaction forces.

Some authors consider the mandibular foramen the centre of rotation [Moss 1960]. This centre of rotation was thought to minimise the potential for trauma to the inferior alveolar nerve [Ricketts 1975]. Moss further explained the relative size of the masseter as being due to the fact it had a small moment arm compared with the digastric which although thin had a large moment arm. Hylander disputes that the relative size of these muscles is related to the centre of mandibular rotation. This author explained that the masseter required bulk to perform its functions as a powerful adductor of the jaw whilst the slender digastric could easily supply the relatively small amounts of force required to retract and open the jaw [Hylander 1975].

The ICR has been shown to be useful in the analysis of function apart from the delivery of masticatory force [Smith 1978]. Greaves [1972] has demonstrated its usefulness in allowing for an adequate gape. Carlson [1977] has stressed that although the ICR may not be useful to a consideration of muscle torque that this is not the only parameter of muscle function that should be considered. The path of mandibular opening described by the ICR may allow for the most efficient use of the masticatory muscles in terms of a reduction in muscle excursion which in turn allows the maintenance of relative torque and optimum length tension relationship for a given muscle [Carlson 1977]. Although there has been debate as to the theoretical and clinical significance of the ICR [Stern 1974] its importance in attempts to simulate the natural movement of the mandible with mechanical devices cannot be understated [Koski 1962, Grant 1973, Falkenstrom 1993].

Mathematical models have been constructed in an attempt to quantify mandibular movement [Osborn and Baragar 1984]. These authors consider the articular eminence, upper and lower tooth contacts, ligaments, and the patterns of muscular activity as constraints to mandibular movement. These constraints were analysed mathematically in three dimensions in order to determine possible condylar movements during jaw opening. The movements described by this model predicted an ICR which is first located behind and below the condyle which the moved downward and then forward and upward to to end in front of the condyle at the position of maximum gape [Osborn and Baragar 1985].

Falkenstrom used a movement analysis system incorporating a TV camera to register mandibular movements. The system was based on the detection of infra red light which was reflected by landmarks on a moving object. This technique allowed the path of the centre of the condyle to be traced and the ICR to be determined. Condylar translation and its relation to mandibular rotation are constantly variable. In general both mandibular translation and rotation occurred simultaneously. In these experiments the path of the ICR began at the mastoid then passed downwards and forward to end in the last phase of movement in the region of the condyle [Falkenstrom1993].

Falkenstrom's study demonstrated that condylar translation forms a major part of mandibular movement. That purely rotational movements of the mandible cannot be demonstrated and a continually shifting axis of rotation is required supports the concept of the ICR in human mastication. Polycentric movement characterises jaw movement. Falkenstrom [1993] concluded that the accurate reproduction of the centrode or the path of the ICR was an essential consideration in the design of any temporomandibular joint prosthesis. Duplication of such movement is essential from a biomechanical point of view in order to allow for the changing mechanical and biological conditions during mastication.

3.6 THE DIRECT MEASUREMENT OF PHYSIOLOGICAL PARAMETERS.

3.6.1 BITE FORCE MEASUREMENT

The lower jaw in mammals can freely develop forces greater than are required to produce unrestrained jaw movement. The excess created is available to generate bite force [Osborn and Baragar 1985]. The first known measurements of bite force date back to the 17th century and up to 1950 at least 50 different devices for this purpose have been described [Carlsson 1974]. The type in most common usage has been the gnathodynamometer in which the bite force is recorded by placing the apparatus between the upper and lower teeth. Over the last twenty years measurements have been made with various types of pressure gauges usually strain gauge transducers which have been shown to give reasonably reliable results [Carlsson 1974]. More recently technological advances have enabled small transducers to be incorporated into the design of dentures, bridges and crowns to enable the recording of bite pressures during function such as chewing. The advantage with these types is that they can function without opening of the bite and interfering with the occlusion of the teeth [Anderson 1956].

3.6.2. THE DIRECT MEASUREMENT OF TMJ LOADING.

The difficulty in performing direct measurements of condylar loading is perhaps reflected in the fact few reports of such work can be found in the literature [Brehnan et al 1979, 1981, Hohl and Tucek 1982, Boyd et al 1990]. Implantation of strain gauges on the surfaces of bones near joints has been successfully performed [Cochran 1972]. Strain gauges are electrically resistive transducers which can measure the deformation at the surface of the skeletal element to which they are applied [de Jongh 1989]. Pressure transmitting elements have been inserted into the hip joint [Rydell 1966]. The use of subcondylar implants to indirectly measure temporomandibular joint force has been attempted.

Surface strain in the mandible was first measured in rabbit alveolar bone directly in front of the masseter [Weijs and de Jongh 1977]. These experiments demonstrated a positive correlation between strain magnitude and muscular activity. Hylander and Bays [1979] measured the strains in the subcondylar regions of *Macaca* monkeys without breaching the articular surfaces of the joint. These authors showed that the temporomandibular joint in *Macaca* is loaded during incisal biting and that it is loaded to varying degrees during mastication depending on the position of the bite point.

Hylander and Bays [1978, 1979] surgically implanted strain gauges on the necks of condyles in monkeys in order to avoid direct intracapsular measurement. It was felt that violation of the joint would alter its functional anatomy in a manner that would make any result questionable. The technical difficulty of this procedure and of the problems of constructing a transducer that would sense external reaction force during various condylar positions following condylar rotation was self evident. Although the absolute amount of reactive force or its direction could not be determined a qualitative estimation of the presence of joint loading could be attempted. The insertion of a strain gauge in the subcondylar region avoided damage to the internal structures of the joint although the surgical approach to the subcondylar region meant the subject would not be free of pain in the area overlying the joint [Hylander 1979].

An area of cortical bone immediately below the joint capsule was surgically exposed and rossete and single element strain gauges were bonded to the subcondylar region. Rosette strain gauges consist of three strain gauge elements aligned in known orientation. These gauges can detect the magnitude and direction of the principle strains along the bony surface to which they are bonded. Single element strain gauges detect only the amount of strain parallel to their long axis. Single element gauges were used once Rosette gauges had determined the principle direction of strain. The smaller size of the single element allowed easier insertion and bonding to the subcondylar region. Thirteen experiments were performed to characterize the condylar reaction forces in nine macaque monkeys of the genus *Macaca Fasicularis* and *Macaca Mulatta.* Incisal biting, isometric biting and mastication on a force transducer were trialed. The mandibular movements of the monkeys were recorded on videotape which was later replayed slowly in an attempt to coordinate the subcondylar bone strain recordings with different phases of mastication.

All of the recorded bone strain patterns showed the mandibular condyle of the monkeys to be compressively loaded during the power stroke of mastication and incision as well as in isometric molar and incisor biting. Data for forces generated by asymmetric biting showed the force at the contralateral condyle was on average greater than that recorded for the working side. The force on the working side condyle was shown to be more sensitive to the position of the bitepoint during isometric molar biting. A point M2 was determined to exist at the second mandibular molar, biting at a point anterior to this saw the joint loaded in compression. Beyond M2 strain reversal occurred and the working side was demonstrated to be either unloaded or loaded in tension [Hylander 1979].

Roe [1977] implanted an instrumented prosthesis which replaced the entire head and neck of the condyle in an attempt to measure the force borne by the condyle in mastication. Great difficulty was encountered in in satisfactorily duplicating the morphology and function of the excised condyle. With the normal joint structure lost, the resultant disturbance in function made measurement of force at the joint unreliable [Hohl and Tucek 1982].

The work of Brehnan and Boyd represents one of the first attempts to directly measure the intra-articular forces of the temporomandibular joint. Brehnan performed his direct in-vivo measurement by implanting a 20 um teflon coated piezoelectric foil into the inferior joint space of the TMJ of two stumptail monkeys. The foil transducer system is limited to recording total compressive loads at the head of the condyle. The system cannot measure tensile forces or the direction of force. As a load is applied to the foil a charge builds up on its surface, which is in effect pumped into the amplifier input to give the positive deflection and positive reading. When the load is released it returns to its original shape and draws current into itself. The charge amplifier was used to convert the charge on the piezoelectric film into a voltage that was proportional to the force at the joint. Recordings were made on a strip chart recorder [Brehnan et al 1981].

These experiments necessitated the exposure of the joint. A horizontal incision was carried along the zygomatic arch anterior to the external auditory meatus. The incision was continued from one to one and a half inches further forward. The attachment of the TMJ capsule was cut from the zygomatic arch. The capsule was lifted from the zygomatic arch and retracted inferiorly, exposing the superior capsule of the TMJ. In order to enter the inferior cavity of the TMJ, the lateral attachments of the meniscus on the neck of the condyle were cut, exposing the head of the condyle. In order to create enough space to place and cement the piezoelectric film to the condylar heads, the condyle was slightly subluxated. Subluxation was achieved by placing a small block in the posterior region of the dentition and applying an upward force at the anterior region of the mandible. Once the joint was dislocated a piezoelectric film was cemented to the head of the condyle with cyanoacrylate cement [Brehnan et al 1981].

The first experiments [Brehnan and Boyd 1979] used a 20 µm thick foil which was inserted into the joint capsule of two monkeys. Wires from the foil were buried under the skin and exposed when the recordings were taken. The results of the initial investigations indicated that the temporomandibular joint was a non stress bearing joint. Later experiments were carried out using a 9um piezoelectric foil [Brehnan et al 1981]. Wires from the transducer were inserted into a socket on the monkeys head. Problems were encountered due to fluid leakage into the fluid transducer system. Leakage problems were countered by sealing the foil with teflon tape which further increased the transducer thickness. Although these experiments were carried out on several animals recordings were successfully taken from only one monkey. The data obtained in this investigation indicated the presence of condyle loading during chewing and incisal biting. The values recoded were fairly low but greater for incisal biting (3-4 lbs) than for molar mastication (1-3 lbs) [Brehnan et al 1981].

The same group of co-workers produced a third report [Boyd et al 1982]. In this case a 15µm thick teflon tape sealed foil was used. Connecting wires from this foil passed beneath the skin to an FM transmitter which was then implanted into the monkey's back. This greatly reduced the earlier problems of fluid leakage, the monkeys interfering with the recording wires and the need for restraint. Recordings could be taken from anywhere within a 15 foot radius. Data was obtained over approximately one week period in three experiments using two male monkeys. This experiment also demonstrated condylar reaction forces. These measured forces were much larger than had previously been recorded. Larger reaction forces were recorded in the bigger of the two monkeys. The recorded levels of force were 34 lbs during chewing and 39 lbs during aggression and 7lbs during drinking. Forces were greater on the working side than on the balancing side [Boyd et al 1982].

Boyd and his group of co-workers have performed a fourth investigation which represents the most recent experiment in direct measurement of condylar loads [Boyd et al 1990]. The recording system has been further refined by the subcutaneous installation of a telemetry unit into the monkey's back. In this system the FM radio transmitter can be located outside the animal's body. Data was collected over an 8 day period from two unrestrained stumptailed monkeys. There was no recording of jaw movement so it was not possible to distinguish whether forces had been measured during an opening or a closing phase. The study found the joint to be load bearing during incisal biting, mastication and aggressive behaviours. The lower values for temporomandibular joint reaction force found in the earlier studies were not duplicated. The working side condyle was again found to be more heavily loaded than the balancing side condyle. The higest value recorded was 39lbs recorded in vocal aggression and 34.5 lbs in chewing. There was a ratio of forces on the balancing side compared with the working side of 1.4 to 2.6. A unilateral occlusal interference placed on the most distal molar reduced reaction force by 50% or more, the monkey refusing to chew on the side opposite the interference.

Analysis of the data of Brehnan and Boyd has been insufficient to establish a relationship between incisal force and temporomandibular joint reaction force. Broadly the condylar head was seen to be loaded by electrically induced incisal biting. Bite loads of up to 8lbs corresponded to increasing axial loads of comparable magnitude. Although the major advantage of this method is to allow direct measurement of compressive force there are several disadvantages with this technique. The author's state care is taken to replace and suture structures in their normal presurgical position but the joint cannot be considered normal as a surgical exposure is necessary. The temporomandibular ligament and the lateral supports of the disc are cut from the condyle. The capsule is ruptured to implant the foil and the loss of synovial fluid occurs. Post operative pain, intra and extra capsular swelling, as well as modification of the joint surface interferes with normal masticatory movements.

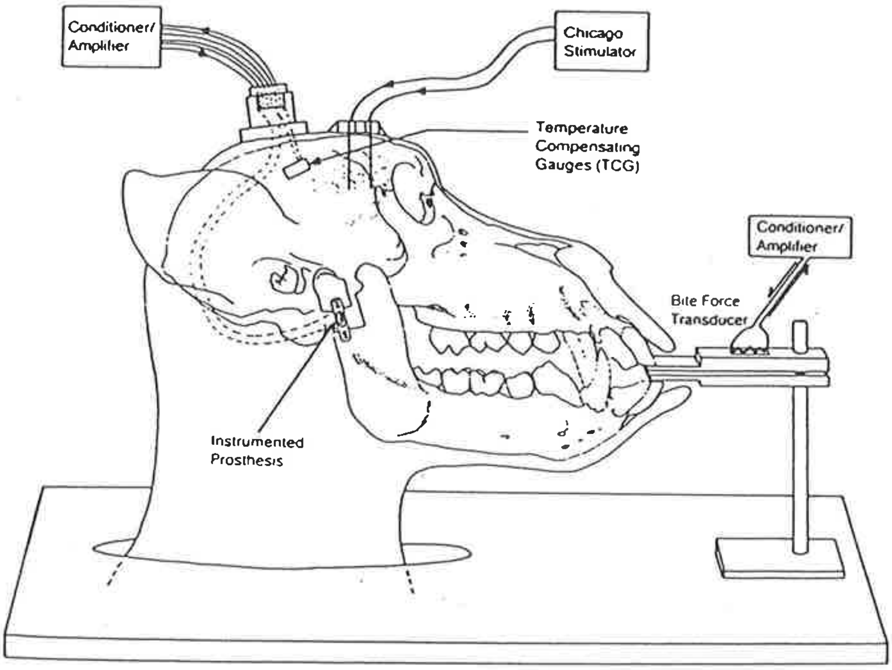
The dental occlusion was also disturbed in these experiments. The combined thickness of the foil, the teflon tape insulation and cyanoacrylate glue slightly increase the height of the mandibular condyle reducing the contact of the posterior aspects of the tooth row on the operated side. Boyd noted however that the placement of a dental occlusal interference affected the monkey much more than the presence of the transducer, as the monkey refused to chew on the side opposite the occlusal interference but regained full masticatory activities a short time after the implantation of the transducer [Boyd et al 1990]. As aforementioned the transducer system does not measure tensile forces or the direction of the force. Because it is in a single position it cannot record in-vivo reaction force through the full range of mandibular movements [Hylander 1985]. Brehnan et al [1981] suggested that loads as large as those produced by incisal biting occurred as the condyle translated forward. Hylander [1985] commented on the fact it is unclear from these studies as to whether recordings were made in the opening or the power stroke of mastication and advocates the use of indicators of jaw position in such experiments.

The recorded results indicate heavier loading on the working side condyle in

Brehnan and Boyd et al series of studies [1979, 1982, 1982, 1990]. Such results are in disagreement with those of Hylander and others who have suggested heavier loads occur at balancing condyle [Greaves 1978, Smith 1978, Walker 1978]. Boyd explains these differences by suggesting that a wide range of values have been found in all of the studies on temporomandibular joint reaction force. These differences may represent different patterns muscle recruitment depending on the animal species and food type [Boyd 1990].

The only other attempt to measure temporomandibular joint reaction force directly was performed by Hohl and Tucek in 1982. In this case an instrumented prosthesis was implanted into the mandibular ramus of a baboon. Roe [1977] had shown the feasibility of implanting an instrumented prosthesis. Hohl and Tucek however did not attempt the complete replacement of the condyle. In this experiment only the neck was operated so that the condylar head, joint capsule and glenoid fossa were undisturbed. Skin incision and elevation of the tissues from the lateral aspect of the mandibular ramus was performed with care taken to preserve the masseteric attachment to the mandible. A section of bone was excised from the posterior border of the ramus and the calibrated prosthesis screwed firmly in place before the remaining anterior bridge of bone was removed. Temperature sensing gauges were implanted on the parietal bone and the leads from the prosthesis were run subcutaneously to a connector on the animal's head.

A specially designed bite force transducer was used in conjunction with the instrumented prosthesis and this was placed between the monkey's anterior teeth. The masticatory muscles were stimulated by the application of electric current to the motor tract of the trigeminal nerve via long term implanted bilateral intracranial bipolar electrodes. Such stimulation was assumed to excite all four masticatory muscles. Recording sessions were performed on a restrained lightly anaestheized baboon **(Fig 3.35)**.



(Fig 3.35)

Two experiments were performed on one animal. The first resulted in the failure of the prosthesis 48 hours after its placement. On removal of the prosthesis six weeks later it was found to have sustained a right angled bend in a direction perpendicular to the sagittal plane. A second implant was placed at the time of the removal of the original and recordings were performed on the same day.

Hohl and Tucek showed that data on the magnitude and components of the force can be collected via this method and the implant proved responsive to any load applied to the condyle. Problems were encountered with the failure of the prosthesis as well as leakage and loosening of the electrical connections. The manner of induction of muscular contraction is also open to question as to how closely stimulation of the trigeminal ganglion represents normal masticatory muscle function. No rest periods were allowed and muscle fatigue may have intervened prior to the death of the subject by respiratory failure [Hohl and Tucek 1982].

3.7 PHOTOELASTIC MANDIBULAR MODELS.

The use of photoelastic models in stress analysis is a familiar technique in engineering [Dixon 1959]. The technique involves the construction in photoelastic materials of replicas of a given structure. The material is then loaded in a similar pattern as the parent object. A series of isochromatic fringes appear in birefringent material under load. The fringes are visible under plane and circularly polarised light. The proximity of fringes indicates stress concentration and their number stress intensity [Standlee et al 1981]. Lehman [1972] used photoelastic models of the maxilla and mandible to demonstrate the stress concentrations in the common sites of fracture of the facial bones.

One of the earliest attempts to model mandibular biomechanics using photoelastic materials was described by Ralph and Caputo [1975]. Replicas of a dentate human mandible were constructed out of photoelastic resin material. This model was supported by mechanical struts representing the principle muscles of mastication. Loading was simulated by the action of suspended weights on the occlusal surfaces of the tooth bearing areas of the model. A "stress freezing" technique was used to preserve the loading patterns generated in the birefringent material. "Stress freezing"occurs when the loads are applied to the model at the elevated temperature of 230' F the model is then slowly cooled whilst the load is maintained [Ralph and Caputo 1975].

Ralph and Caputo showed that stress was concentrated in those areas suspected of being structurally reinforced by the earlier anatomical studies of Seipel [1948] and Sicher and De Brul [1970]. The accuracy to which these expected trajectories of force were described were surprising given the dissimilarity between the homogeneous resin and the structurally diverse components of the mandible. An attempt to address this problem was made by using different birefringent materials to simulate bone, periodontium and teeth [Standlee and Caputo 1978] and in a later study only the external surface of the mandible was coated with photoelastic material [Mongini et al 1978]. The latter method allowed the study of the stress field on the surface of real bone by means of reflection photoelasticity.

These models predict a load at the mandibular condyle considering it the ultimate destination of all of the major stress trajectories in the mandible [Standlee 1977]. High stress intensities were recorded in the condylar neck which diminished in the condyle. The elliptical shape of the condyle is thought to be and adaptation to stress bearing which allows a broad distribution of forces [Standlee, Caputo and Ralph 1981]. The condylar neck is thickened and reinforced against unidirectional forces. Examination of the bony architecture of the condyle reveals it to be composed of uniform trabeculations and extremely thin cortex [Hylander 1975, Standlee, Caputo and Ralph 1981]. These structural differences may be due to to the requirements of the condyle to provide stress distribution for light and varied forces over a wide range of mandibular positions. Temporomandibular joint derangement and condylar erosion can the be interpreted as a breakdown of balanced mandibular biomechanics when subject to heavy cyclic forces [Standlee, Caputo and Ralph 1981].

A consistent relationship between the experimental strain induced and the shape and orientation of the condylar head has also demonstrated. Stress trajectories communicate with the condyle in both centric and excursive movements and are increased in unilateral loading of the occlusion. The pronounced degree of remodelling that occurs in the condylar head may be accounted for by the observation that most of the stress lines evident in the ramus are directed toward the condyle [Ralph and Caputo 1975, Mongini, Caulderdale, and Barberi 1978].

Stress lines revealed by photoelastic examination broadly conform to the cortical or trabecular reinforcements described by anatomical or radiographic examination [Dovitch and Herzberg 1968]. High stress concentrations generated in occlusion are distributed through individual teeth to the cushioning periodontal membrane. Force is then directed through dense trabecular struts to cortical bone. Once through the boundaries of mandibular bone stresses are concentrated posteriorly through the ramus via the trabecular and cortical reinforcements to the condyle [Standlee, Caputo and Ralph 1977, 1981].

3.8 FINITE ELEMENT ANALYSIS.

Three-dimensional finite element analysis (FE), like photoelastic modelling, is a well known technique in stress analysis in mechanical engineering. This type of modelling allows the prediction of regional stresses and strains in inaccessible locations. The technique involves subdividing objects with a relatively complex shape into a number of regularly shaped elements. Each element is divided into isotropic or anisotropic categories and assigned an individual elastic constraint. After the application of load a study of the deformation of individual elements and the effect of their deformation on adjacent elements is performed. The consecutive calculation and summation of these deformations facilitates the prediction of stress and strain for the entire object.

This technique was first applied to the human mandible by Knoell in 1977. The bone of the mandible was idealised as a homogeneous, isotropic and linearly elastic solid. The finite elements consisted of hexagonal, tetrahedral and wedge type shapes applied geometrically to the surface of the mandible and teeth **(Fig 3.36)**.

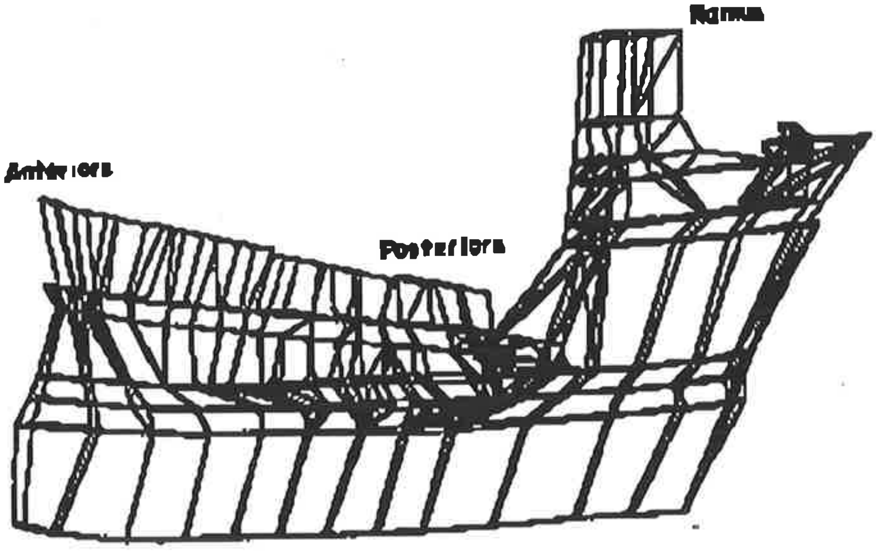


Fig 3.36 (After Knoell 1977)

Calculations were performed for several loads applied in both the horizontal and vertical directions to the molar and premolar regions. The recorded strains approximated those obtained from strain gauge analysis conferring some validity to this modelling method [Knoell 1977].

Three dimensional FE models have also been constructed by Korioth et al [1992]. In this study models of a human mandible were constructed from tomograms of a dried human jaw. Groups of parallel multiple vectors simulating individual masticatory loads were applied. The muscle force vectors applied simulated muscles with wide areas of attachment. The model was subsequently solved for displacements, stresses, strains and forces. These studies showed the highest principle strains occurred at the bite point, anterior aspects of the coronoid processes, symphyseal region, and the right and left sides of the mandibular corpus. The increasing degree of complexity and refinement in FE modelling is illustrated in **Fig 3.37** note the large number of sectional profiles required to give an accurate representation of the complex osseous and dental elements of the mandible.

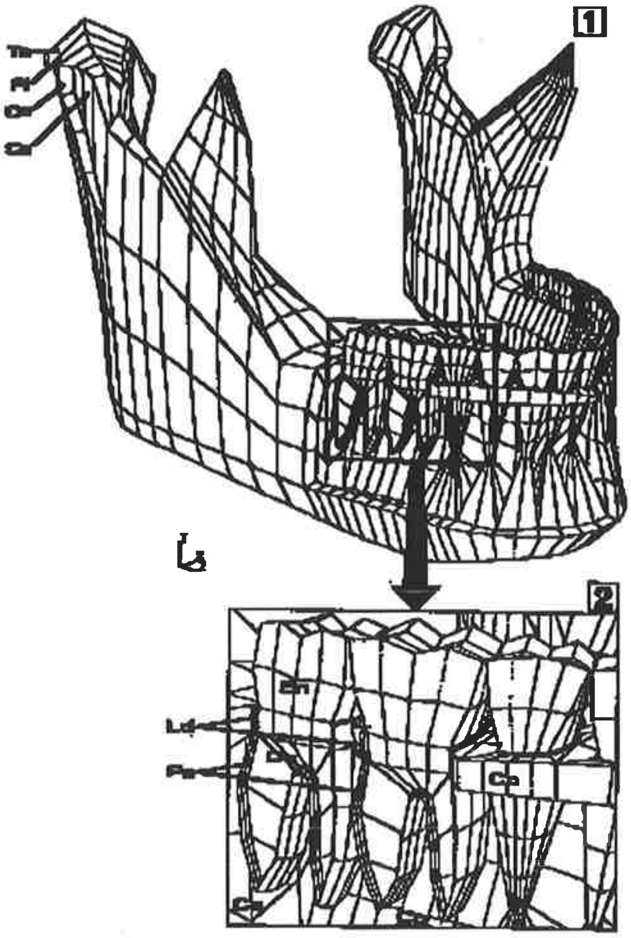


Fig 3.37(After Korioth et al 1992)

This model also predicted a condylar reaction force. A greater magnitude of force was transmitted to the balancing side TMJ during unilateral isometric molar biting. This was found to be concentrated on the antero-medial aspect of the working side condyle and on the central and lateral aspects of the balancing side. These FE based predictions were found to be consistent with the current notions of mandibular mechanics derived from experimental recordings in man and non human primates [Koroith et al 1992].

The development of FE modelling of the mandible has seen an ever increasing degree of grid refinement. Hart et al [1992] used convergence tests to establish that the level of mesh refinement required for accurate analysis accuracy was a model that had over 30,000 degrees of freedom. Hart criticised earlier attempts at FE modelling for their gross simplification of mandibular geometry and material description. Hart's model of functional loading cases was based on an algorithm that assigned muscle force in accordance with muscle cross sectional area while maintaining the conditions of static equilibrium.

The results of these, the most sophisticated form of mandibular modelling yet devised, have yielded results similar to those of earlier studies. In agreement with the results of Picq [1983] and Hylander [1984] during unilateral mastication the balancing condyle was subject to a force magnitude of 57.7 N. This force was twice as high as the the force of 27.8 N experienced at the working condyle. These results approximate the 2:1 ratio of non-working to working side condylar reaction forces predicted by the earlier less sophisticated analyses. In accordance with the earliest of anatomical studies [Seipel 1948] substantial bending was predicted in the molar region of the corpus and high tensile strains were seen to occur in the anterior portion of the ramus.

Finite element modelling represents an increasing sophistication in mathematical modelling. The inclusion of large amounts of geometric data, materials study, and loading complexity may be what is required to fully characterise the biomechanics of the human mandible. Even so a number of limiting assumptions are made in order to analyse and generate FE models. Further comparison of the computed results with the measurements obtained from in vivo measurements are required to establish full confidence in this promising experimental technique.

BIOMECHANICS IN THE SHEEP

The Australian Merino sheep has already been presented as a suitable model for temporomandibular joint research [Bosanquet and Goss 1987]. The size and anatomy of the sheep TMJ, its wide availability, relatively cheap cost and its high ethical acceptability have contributed to the success of this model [Ishimaru and Goss 1992]. Some of the anatomical features of the sheep joint may in fact facilitate experimentation. Such features would include the ease of surgical access to the joint. The lateral location of the joint to the cranial base affords access to both the glenoid fossa and its bony roof. Other features such as the medial and anteriorly located vascular sinusoids and the profuse bleeds of which they are capable make surgery more difficult.

The use of this model has already stimulated areas of research. These include the effect of silastic replacement following discectomy [Bosanquet, Ishimaru and Goss 1991], the effect of fascial repair on the joint disc [Bosanquet et al 1991], temporal fascia repair [Thyne et al 1992], the effect of marrow perforation, and a model for osteoarthritis [Ishimaru et al 1992]. The study of various treatment modalities in this model are able to be undertaken not only in healthy joints but in joints which have been preconditioned with experimentally induced degenerative joint disease. This is despite the fact their is still some doubt that the degenerative changes observed in the disc of humans have been observed in other animals [Gilbe 1973].

An important omission in the studies thus far has been the consideration of biomechanics. The sheep as an ungulate has a distinct musculo-skeletal morphology. The nature of its diet, the large forces required for its trituration together with a constant intake of food means that its masticatory system is subject to intensive wear. If significant morphological differences exist between the sheep and human masticatory systems then these should be fully described so that the biomechanic implications of these differences can be defined.

Comparatively little is known of the masticatory movements of the Australian Merino sheep although the masticatory movements of man have been studied intensively. A number of investigations into the grazing behaviour of the Australian Merino Sheep are currently being undertaken in Australia. Investigations characterising the frequency of chewing and rumination using the sheep's head as a sound box for radiotelemetry have been performed [Klein et al 1994, Wang et al 1994]. The energy required to masticate certain feed types is also being studied [Baker 1994]. These studies emphasise the commercial importance of understanding sheep grazing habits. A study of the kinematics of the sheep masticatory system has however not yet been undertaken. Human studies have focused on the rotation translation mechanism of the TMJ. Little rotational movement is thought to occur in sheep mastication apart from that which would be required to complete small hinging movements in opening. The sheep condyle has a broad flat articulating surface with the glenoid fossa. There are few bony restraints to hinder lateral movements which characterise its mastication [May 1970, de Jongh 1989].

Masticatory movements of the ungulate are best examined in the planiform projection. **Fig 3.38** shows such a projection with the teeth in unilateral occlusion and the jaw being moved from the left to the right. CL is the centre line of the skull. D is the direction of the chewing movement. M, Pt, T are the lines of action of the masseter, pterygoid and temporal muscles.

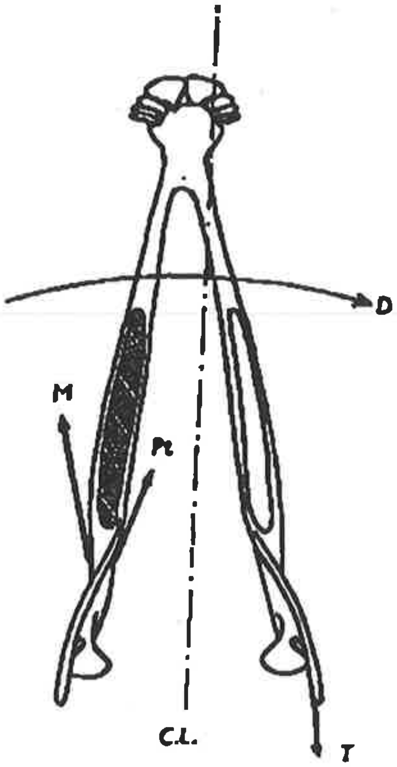


Fig 3.38 (After Smith and Savage 1959)

It is evident that the horizontal rotation of the whole jaw occurs in this movement. The working side condyle would be expected to translate forward with the balancing side condyle moving backwards [Radinsky 1985]. Rotation is produced by the contraction of the masseter and medial pterygoid muscles of the left side which have an anterior component to their line of action or by the temporal muscle of the right side which has a posterior line of action. Smith and Savage [1959] suggest that the temporal muscle can only produce the required movement if it contracts on the opposite side to the occluding teeth. If the temporal muscle were to be used alone, the load applied to the teeth on the contralateral mandible would need to be balanced by a force from a muscle on the right mandible. This situation would lead to the generation of large stresses on both sides of the mandible and through the mandibular symphysis. In contrast the use of the masseter and medial pterygoid alone will lead to only a small section between the roots of the molar teeth and the insertion of the muscles on the working side being subject to stress [Smith and Savage 1959].

Weijs and Dantuma [1981] concluded that horizontal rotation of the mandible provided the medial power stroke in mastication. This movement was said to occur as the result of the masseter and medial pterygoid on the working side and the temporalis on the balancing side just as Smith and Savage [1959] had proposed. The advantage of this type of movement was that it allowed a large degree of translation at the molar teeth but for only a small amount of translatory movement at the condyles. Further to this these small movements mean that the masticatory muscles are able to work close to their normal resting lengths under almost isometric conditions thus generating maximal amounts of force [Weijs and Dantuma 1981].

The morphology of the skull in the herbivore is characteristic. The angular process of ungulates is expanded to accommodate the large masseter with the temporal fossa being correspondingly reduced in comparison to the carnivore [Radinsky 1985]. Several authorities have suggested that the geometry of the herbivorian mandible increases its mechanical advantage [Noble 1973]. Elongation of the mandible affects jaw mechanics by extending the lever arm. Some attach great importance to the height of the condyle above the occlusal plane [Storch 1968]. The increase in the height of the perpendicular from the articular surface of the condyle to the line of action of the masseter muscle is thought to improve that muscles mechanical advantage [Smith and Savage 1959]. Muscle development in the herbivore has occurred so that lateral and propanal (front and back) movements are emphasised [Noble 1973]. A large medial orientation to the fibres of the masseter and medial pterygoid muscle in the ungulate has been described [Radinsky 1985]. This development serves to increase the force on the tooth row although wide gape is no longer possible [Mohl 1988].

Smith and Savage [1959] critically analysed the mechanical advantage of ungulate masticatory muscles by contrasting them with those of a typical carnivore. Taking the condyle as the centre of rotation the moments generated by the masseter and the temporalis in these species were compared. Muscles whose lines of action pass close to a joint or pivot are considered to have a small mechanical advantage. Such an arrangement allows the animal to produce rapid but relatively weak movements. If the line of muscular action is distant from the point a large mechanical advantage is conferred allowing slow but strong movements. Striking differences can be observed between the temporal and masseter muscles of the two types chosen for their analysis. The carnivore jaw apparatus is characterised by the strongly developed temporalis whereas in ungulates the masseter and medial pterygoid muscles are the largest [Weijs 1980]. Differences in jaw morphology convey mechanical advantage to the masseter in herbivores and the temporalis in carnivores. The relative bulk of these muscles in each case indicates which is the main jaw closing muscle.

The different jaw mechanics of carnivore and herbivore are evident in sagittal projection. The large masseter of the herbivore has a long moment arm around the dentition. The size of the moment arm of the masseter exceeds that of the temporalis which has a different orientation. The larger size of the masseter and pterygoids relative to the temporalis is evident in the lateral and medial projections of the herbivore skull. The condyle articulates with the cranium at the glenoid which is both broad and flat. Large lateral and antero-posterior movements are possible. The condyle is located high above the level of the teeth. These features are illustrated in **Fig 3.39,** T represents the temporalis and m_1 its moment arm around the point of articulation. M is the masseter and m_2 its relevant moment arm.

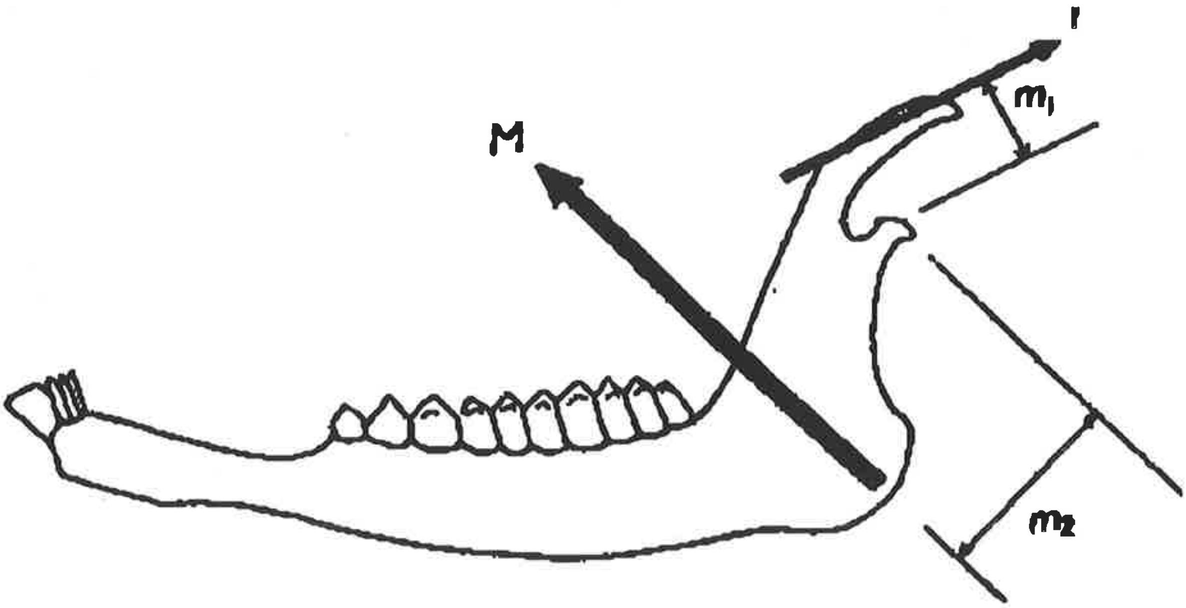


Fig 3.39 Herbivore jaw (After Smith and Savage 1959)

The relatively small size of the temporal muscle in the sheep has been described as a mechanism which allows lower reaction forces at the TMJ [Greaves 1972]. The sheep has the ability to apply large forces at the dental occlusion via its robust masseter and medial pterygoid muscles. The line of action of these muscles passes close to the dental batteries and away from the craniomandibular articulation. The temporalis whose principle action is to apply strong posterior forces, which may be directed through the joint, is correspondingly smaller. In an analysis of horse jaws Scapino [1972] suggested that development of the protrusive adductors (masseter and medial pterygoid over the retrusive adductors (temporalis) served to lessen temporomandibular reaction force and that this was an important factor in ungulates which do so much more chewing than carnivores.

The location of the condyle well above the tooth row is a functional adaptation that allows an increase in mechanical advantage. The moment arm of the masseter is extended in the herbivore. Chewing forces are vertical and thought to be more evenly distributed over the cheek teeth than in carnivores

[Weijs 1980]. Unilateral and transverse chewing movements are made by a jaw joint that allows broad ranging translatory movements. Mechanical advantage could also be conferred by positioning of the masseter insertions further anteriorly but this would compromise the forward pull of the muscle necessary to rotate the jaw [Smith and Savage 1959].

As for loading whilst cropping vegetation the jaws need only sufficient force to maintain their grasp of the herbage whilst the neck muscles provide the force. Little tendency towards condylar dislocation is generated in this system as the sharp incisal edges of the mandibular molars are arranged at 90' to the tearing action. Further strain is though to be absorbed by the jaw closing muscles [Noble 1973]. Radinsky [1985] has suggested that the lack of development in the temporalis in ungulates presumably represents a lack of heavy loading on their anterior teeth. The absence of anterior maxillary teeth in the Australian Merino sheep would tend to support this conclusion.

In contrast the bulky temporalis provides the major force vector in the carnivore this muscle is considerably larger than its masseter. The moment arm for the carnivorian temporalis is similarly larger than that of the masseter. The condyle is situated low on the ramus level with the tooth row [Smith and Savage 1959]. The principle vector of the temporalis resists the main component of force generated by the prey. As this vector acts in an equal and opposite direction a relatively small compressive force is required to secure prey. These features are illustrated in **Fig 3.40**.

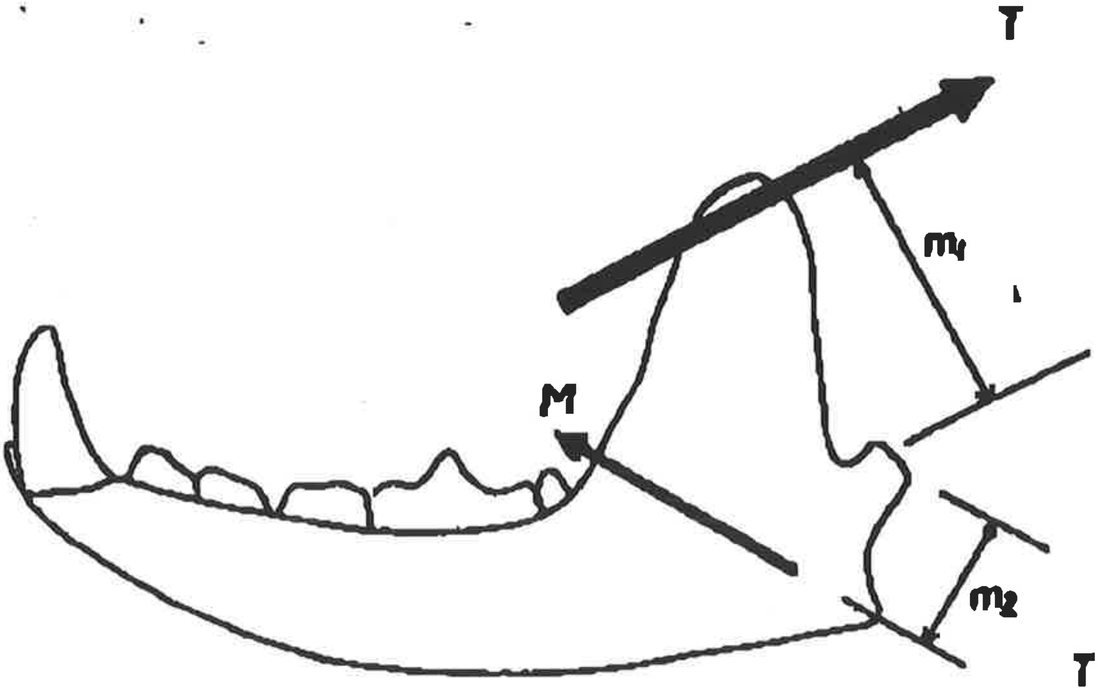


Fig 3.40 Carnivore jaw (After Smith and Savage 1959)

The low position of the condyle and the high coronoid process allow the generation of large moment. Large forces are involved in jaw adduction and increase the leverage of the temporalis. The much smaller masseter and medial pterygoid muscles are though to be functionally related to molar or canine biting [Weijs 1980]. The small moment arm of the masseter close to its point of action is also appropriate and assists in preventing mandibular dislocation [Smith and Savage 1959].

In this analyses the functional importance of muscle orientation is emphasised. A carnivore that captures its prey using the masseters alone runs the risk of dislocating its jaw. The use of the temporal muscle affords fast jaw closing with a retrusive component resisting forward forces. The temporal muscle inserts onto a larger coronoid process. The bony structure of the carnivorian glenoid limits mandibular translation. Limitation to anterior and posterior translation means that there is a predominantly rotational arc to mandibular closure. The carnivorian mandible simply rotates around the centre of the mandibular condyle during closure [Davis 1964].

Scott [1955] reviewed the anatomy of the temporomandibular joint from a dissection of human and comparative animal material which included the domestic sheep. A pressure-regulating mechanism designed to reduce the conduction of the stresses of mastication through the joint was described. The prominent backward curve of the coronoid process was noted to continue high above the zygomatic arch until it curves backward to lie in the same vertical plane as the mandibular condyle. The condyle itself is invested throughout its length by the temporalis. The superficial fibres of this muscle run forward and upward from the back part of the zygomatic arch to the coronoid process. This bony and muscular arrangement allows the condyle to be depressed from the roof of the glenoid fossa at the same time as the masseter and medial pterygoid are drawing the mandible upward and forward in closing the mouth. This arrangement affords the sheep a special muscular mechanism for reducing pressures directed through the temporomandibular joint. The mechanism appears to involve the temporalis alone. A similar arrangement is seen in the domestic dog and is thought to be duplicated by the temporal muscle acting with the lateral pterygoid in man and primates [Scott 1955].

Steinhardt [1958] reviewed Scott's earlier work and included that of Rees [1954] stating that in the human the lateral pterygoid acts as a brake and that further masticatory pressure is taken by the teeth and ligaments. The disappointing results noted with total temporomandibular joint replacement may be due, at least in part, to the loss of attachment of this muscle and the protective function this provides [Falkenstrom 1993].

It has been suggested that in anisognathic animals the jaw joint on the balancing side serves as a fulcrum. Similarly the observation in ungulates that the distance from the jaw joint to the last molar tooth is approximately the same as that that of the grinding tooth length is thought to have biomechanical implications. This equality allows the tooth row to be positioned in such a way that relatively simple muscle action can supply occlusal pressure as well as produce equal forces to balance the fulcrum [Greaves 1978]. One of the explanations advanced to explain the expansion of the masseter and internal pterygoid muscle group is that they are on the same side of the jaw as the joint (or fulcrum) as the cheek teeth (or resistance) joint. If this is the case then they are better positioned than the temporalis to exert fine control over the magnitude and direction of the forces between the opposing teeth during chewing [Radinsky 1985].

Greaves [1978] has proposed that only the balancing side serves as a fulcrum in ungulates and anisognathic (one dental arcade being narrower than the other) mammals. Greaves' model treats the mandible as a class three lever. The functioning mandible is seen as having contact with the upper jaw in three places. These contact points are the two condyles and the bite point the three points forming a triangle of support. If vertical muscle force components are considered alone they may be resolved into a single vertical vector. This resultant force vector is presumed to lie within the triangle formed by the joints and the occluding teeth.

Greaves showed that for a fixed point on the tooth row maximum bite force can be developed if the bilateral muscle resultant intersects the connecting line between the balancing side joint and the bite point that is if the balancing joint functions as a fulcrum. This proposal is supported by the work of Weijs and Dantuma [1981] and later studies by Hylander [1975]. Hylander [1975] has modified the work of Greaves by superimposing the linear predictions of the previous author onto a planiform projection of the *Macaque* mandible (**Fig**

3.41). The point M (1:1) in this diagram denotes the position of the resultant muscle force when equal amounts of force are contributed from the musculature of each side. The direction of this force is perpendicular to the page. The position of the resultant changes depending on the relative contribution of the working and non working side musculature. If the working side musculature exceeds that of the balancing side the resultant muscle force is located at point M(2:1) or M(3:1), respectively. An outwardly directed force is experienced at all three positions.

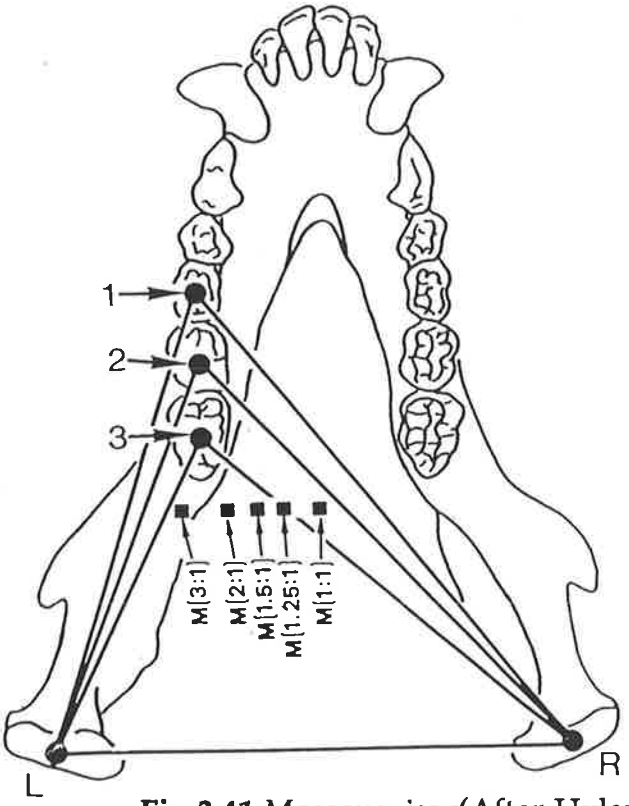


Fig 3.41 *Macaque* jaw(After Hylander 1985)

A situation also exists where the working side condyle may be unloaded. Only the third molar and the balancing side condyle are loaded when biting occurs at M3 and the resultant is shifted to M (1.25: 1). The working side condyle lifts away from the eminence as the mandible attempts to rotate around the axis defined by the line R3 [Greaves 1978, Hylander 1985].

Badoux [1965] gives a vector diagram of the masticatory forces and their components in a typical herbivore. The alternating but only one sided masticatory contact in the anisognathic ruminants has been described by several authors [Becht 1953, Smith and Savage 1959, Turnbull 1970]. Badoux contends that, not withstanding the discrepancy in the width of the jaws, bilateral contact between upper and lower molars occurs in the terminal phase of every masticatory movement. Only a limited amount of occlusal contact occurs and only when the jaw is in the midline. Smith and Savage [1959] contend however that in some species the dental arcade of the upper jaw exceeds that of the lower, so that it is impossible for molar teeth to be in occlusion on both sides of the jaw simultaneously.

Whatever situation exists in a particular herbivore it is tooth morphology often dictates the principle masticatory movements. The inclined nature of the molar cusps means that chewing is predominantly lateral. Badoux's study is perhaps most useful in suggesting a direction for the vector of masticatory force. The author's diagram shows the steep medio-dorsal to latero-ventral inclination of that characterises herbivorous molars. The geometric analysis is as follows. R1 is the normal of the masticatory pressure exerted on the maxillary tooth. R1 meets the reaction in R2 which is equal and opposite to R1. K1 and K4 are the components of R1, K3 and K2 are those of R2. The moments of the contralateral forces K4 about the midpoint A1 of the interconnecting line XY are + (K4. A1) for the left and - (K4. a1) for the right maxillary element. The line XY is represented by the hard palate and alveolus of the animal. The inferior line X' Y' line describes the distance between the contralateral halves of the mandible **(Fig 3.42)**.

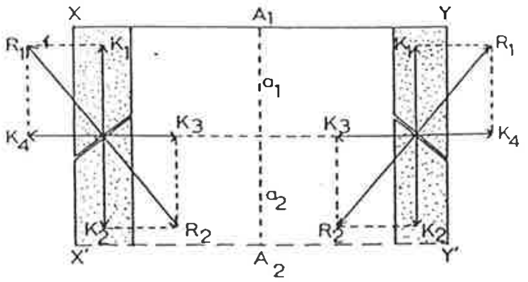


Fig 3.42. (after Badoux 1965)

The hard palate of the ruminant is a stout structure whereas the mandibular symphysis is unfused and flexible. Much of the considerable strain evoked by mastication is therefore directed through the mandibular symphysis. A torsion or twist is generated due to the positive moment for the left and negative for the right ramus mandibularis. Such a condition is distinctly different to that described by omnivorous animals where as well as torsion or twist the lower jaw is subject to bending strain imparted by the vertical components of masticatory force acting on the medio-ventral to latero-dorsal directed occlusal surfaces of the molars [Badoux 1965].

Badoux considered the structure of the body of the mandible as a appropriate adaptation to the mechanical demands placed on it by the forces of mastication. The structure of the horizontal part of the mandible is not unlike that of a hollow bar. As such the mandibular corpus of the sheep is a structure suited to withstand torsional or twisting forces as well as the bending strain imposed by the vertical forces of mastication [Badoux 1966]. Other studies have shown that the masseter could be expected to exert a lateral component of force during contraction and the medial pterygoid a medial component. The antagonist action of these muscles may serve to act as an opposing couple about the long axis of the mandible. Such an action would help orientate the dentition to the most effective cutting angle.

Although the mandible can then be considered as having three joints, two temporomandibular joints and one symphyseal, in most studies of the jaw and its mechanics only the temporomandibular joints are considered [Scapino 1981]. The unfused nature of the symphysis of the Australian Merino Sheep may have an influence on its mandibular biomechanics. Examination of the mandibular symphysis shows it is movable in a wet preparation and considerable rotation of the mandibular halves relative to each other can occur [de Jongh et al 1989]. Crompton and Hiiemae [1969] suggest the mobility an unfused symphysis allows may indicate a totally different pattern of mastication from those with synostosed dentaries.

Gilbe [1973] contends that although great mobility can occur around a mobile syndesmoses that this is of little functional importance when considering movements at the craniomandibular joint. Scapino however feels the morphology of the temporomandibular joint is intimately related to the function of the symphysis. Hylander [1979] demonstrates that the ability of the dentaries of some mammals to rotate will have an effect on the pattern of joint loading. The presence of a fused symphysis is considered an adaptation for stability. Superior and inferior transverse tauri are seen on the fused symphysis of some primates and these are considered to provide extra bony reinforcements to allow a greater transference and utilisation of the forces generated by the contralateral musculature [Hylander 1975]. The unfused mandibular symphysis may serve as a stress breaker and to increase the amount of rotational movement possible.

The power stroke of mastication in the prosimian primate *galagos* has been demonstrated cinefluorographically to rotate about its long axis [Hiiemae and Kay 1973]. In such a movement the lower border of the mandible everts as the alveolus and coronoid process invert and the joint load shifts from the medial to the lateral aspect of the mandibular condyle. The twisting of the mandible may have some significance to the pattern of joint loading in that individual joints are likely to be differentially loaded. The lateral aspect of the joint is thought to be exposed to more stress than the medial aspect. The asymmetric patterns of remodelling within joints observed by some authors [Moffet et al 1964, Oberg et al 1971] although not indicating the exact pattern of loading suggest it may occur differentially [Hylander 1985]. Hylander [1979] proposed the twisting of the mandibular corpus may be greater on the ipsilateral side. Although the contralateral side has been demonstrated to bear the largest overall reaction force this twisting may mean that some spots within the ipsilateral joint may be stressed more than the contralateral side.

To what extent the greater flexibility afforded by a mobile syndesmoses affects the transmission of forces between the two mandibular halves and to the temporomandibular joints is unknown. That the compact bone of the fused mandibular symphysis is an adaption to counter the bending movements of the mandible was advanced by De Brul and Sicher [1954]. These authors used brittle lacquer applied to the either side of the symphysis which when loaded demonstrated clear lines of stress. The mandibular symphysis may function in transferring muscle force from the balancing to the working side [Hylander 1975]. Although the symphysis of the human mandible is fused rotational movements about the long axis of the mandibular corpus do occur. Via a mechanical analysis Beecher shows that shear in the mandibular symphysis of the long snouted Ariodactyla may be decreased by lengthening the horizontal ramus of the mandible. Noble [1973] states that the presence of a flexible symphysis may slightly reduce the influence of the contralateral pterygoid in control of mandibular movement. Tattersall [1973] in a study of the primate *sifaka* states that its mobile symphyseal syndesmosis makes it unlikely that the contralateral temporalis can provide internal movement of the ipsilateral dentary.

Scapino [1965] suggests that the character of the articulating surfaces is not inconsistent with stress transmission. Movement at the symphysis allows the molars to splay out laterally. The balancing side can rotate along its long axis. These movements confer some stability to the occluding working side teeth [Greaves 1978]. The lines of action of some of the masticatory muscle may be altered by rotation of the mandibular halves. Because the rotation of the mandibular corpi alters the slope of the occlusal plane the lines of muscular section do not meet this plane at right angles. The medial pterygoid and the masseter may therefore have medial components of force. The orientation of the medial pterygoid on the balancing side in particular may be affected by symphyseal movement. **Fig 3.43** is a frontal section through the mandibles of a generalised selenodont artiodactyl. The arrow on the line representing the occlusal plane indicates the direction of mandibular movement. N is a line normal to the occlusal plane. L is the lower tooth and U the upper. M and Pt are the masseter and medial pterygoid muscles respectively.

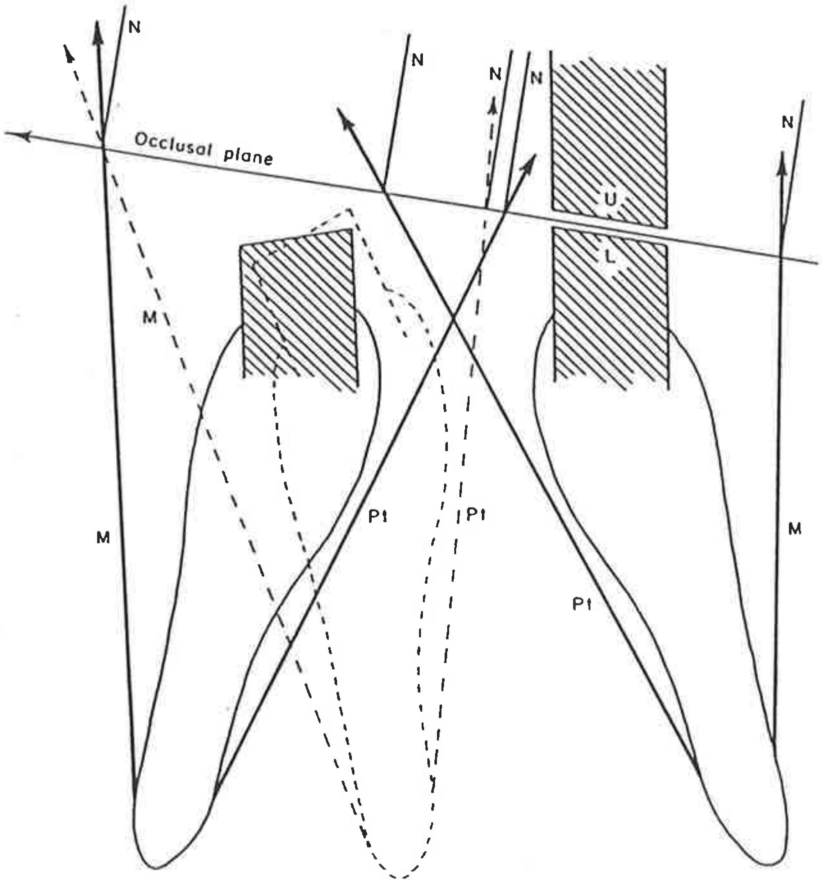


Fig 3.43 (After Greaves 1978)

The medial pterygoid muscle muscle can move the mandible into a rotated position (dashed outline) even though this is an action resisted by the balancing side masseter muscle. This rotation effectively changes the insertion of the balancing side medial pterygoid improving its orientation. A small medial component of muscle action can therefore be introduced while maintaining a medial component for all other muscles.

There have been few studies which use electromyography (EMG) to characterise ungulate mastication. Those that have been performed show a complexity of activation not seen in carnivorian systems [Radinsky 1985]. Weijs and Dantuma [1981] studied jaw muscle activity in the domestic rabbit. The rabbit is a lagomorph an animal whose masticatory apparatus is intermediate between that of rodents and ungulates which are both herbivorous species. These studies showed that virtually all of the jaw musculature was active during the closing stroke. Little separation in the activity of the various portions of the adductor musculature could be determined. Slight shifts in the levels of muscle firing in various portions of the musculature brought about a change in the direction of jaw movement. The amplitude and orientation of the force developed between the dental elements could similarly be altered by fairly subtle changes in muscle activity.

A biomechanical analysis of the sheep mandible has been undertaken [de Jongh 1989]. This study is extremely relevant as it incorporated a number of principles that have been useful in the succesful construction of mathematical models in the human. Finite element modelling (FE) was used, the physiological cross sectional areas of the masticatory muscles (PCS) were determined and elecctromyographic (EMG) values recorded. de Jongh's intention was not however to construct a mathematical model but to determine how mechanical loading provides an explanation for mandibular shape and aims to describe how the jaw is designed to accommodate the stresses of mastication. Central to this study was the construction of a finite element model of the sheep jaw. A major assumption was that skeletal elements are constructed in such a way that deformations (strains) resulting from mechanical stress will not exceed certain limits and that stresses will be evenly distributed.

Using the techniques used in the rabbit [Weijs and Dantuma1981] bipolar fine wire 14 electrode pairs were implanted into the masticatory muscles. The wires were then passed subcutaneously to the shoulder to an insulated connector attached to the skin. Recordings differentially amplified and displayed on an oscilliscope. Simultaneously a high speed cinecamera coupled to two stroboscopic flash units were recorded with the electromyograms for the purpose of synchronization [de Jongh 1989].

The EMG values obtained in the de Jongh study were used by expressing the activity of a muscle during a given interval as a percentage of the highest activity recorded for the muscle in question. When this data was used in combination with the PCS values estimates were made of the maximal forces which could be exerted by these muscles. These estimates were based on the principle that during submaximal isometric contractions the integrated EMG is linearly related to the force exerted by that muscle [Hof and van den Burg 1977]. Although no absolute forces can be measured by this method EMG can be used to determine the relative muscle forces acting on the mandible during various phases of the masticatory cycle. Since the maximum gape of the sheep is small the assumption was made that changes in muscle fibre length would be small and that no corrections for the non-linearity of the EMG force relationships are necessary [de Jongh et al 1989].

The two dimensional finite element model was constructed using the predictions of stress and strain resulting from muscular loading. Calculations were based on the highest loads that occured during the power stroke of mastication. Only cortical bone was modelled underr the assumption that the trabecular bone played a less important role. As in other finite element models the bone of the mandible was assumed to be isotropic and homogeneous and that its behaviour was linearly elastic. A modulus of elasticity of $E = 2^* 10^4$ N/mm^2 was chosen. Calculations were made for the power stroke and all muscles were assumed to be firing at their maximal intensity. Vector directions were derived from the measurements of the centroids of the areas of muscle attachments and values for PCS were used as estimates of relative muscle force. **Fig 3.44** shows the two dimensional finite element model. The isoprametric triangular element chosen can be seen superimposed on the profile view of the mandibular half of an adult ewe. This model was susequently used to calculate the stress distribution for premolar biting.

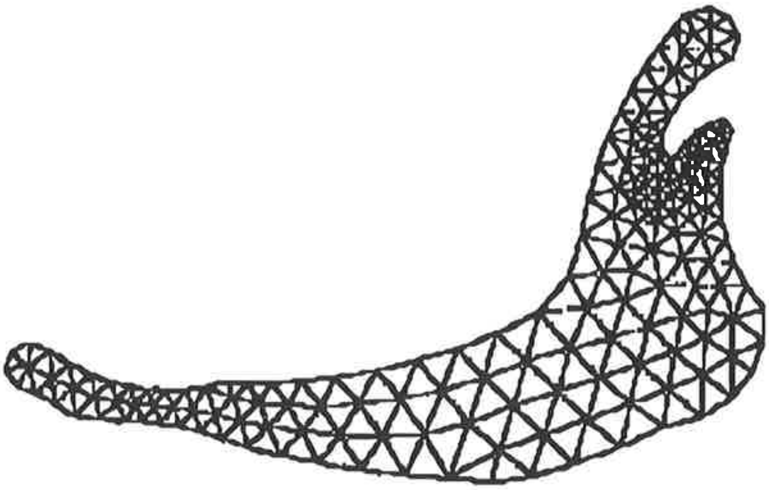


Fig 3.44

Although de Jongh made use of both the Weber and Buchner techniques his calculated values for PCS seem high both in comparision to the values obtained in this study and those values established for the human masticatory muscles [Koolstra et al 1988]. Koolstra tabulates the PCS of the human masseter as 9cms^2 whereas de Jongh lists values for the sheep of between 12.5 and 17.5 cms^2. These results are questionable as the human temporalis is clearly larger than that of the sheep. De Jongh records values of up to 55 cm^2 for the masseter in the sheep whereas Koolstra puts the combined PCS of the human masseteric layers at 8cms^2. Similar values for the lateral pterygioid muscle are quoted in both studies. The only other recording of PCS in the sheep was performed by Schumacher [1961]. Noting that his own results were so much higher than those obtained by Schumacher led de Jongh to state that; "the values given by this author are so low they were probably based on a juvenile specimen".

The motion analysis performed by de Jongh is incomplete but a number of useful observations were made. The vertical component of jaw dispacement is small. Large lateral movements occur in masticationand in every cycle the symphysis describes a triangular path. During the closing phase the symphysis passes far laterally toward the working side. This is followed by a long and almost horizontal power stroke directed to the opposite side. The animals did not show a preferential chewing side but during chewing sequences which comprised several hundered cycles they regularly shift sides at intervals of 10-20 cycles. In all cases gape did not exceed 15 degrees of opening.

De Jongh's EMG studies show activity in all masticatory muscles during the closing phase and in the power stroke of rumination and mastication. Both ipsilateral and contralateral sides were activated. There was no evidence of a fixed sequence of activation of muscles or muscle portions on either side. The jaw elevator muscles showed higher peaks of activity either in ipsilateral or contralateral firing. The temporalis showed little or no difference in firing between the ipsilateral and contralateral sides. Recorded firing patterns were more regular in rumination than in mastication. Higher firing amplitudes were recorded during rumination than in mastication. Some of the recordings indicate that grinding forces in rumination may be as much as twice those generated in mastication.

CHAPTER FOUR

MATERIALS AND METHODS

4.1 ANATOMICAL INVESTIGATION.

The heads used in this study were obtained from the bodies of Australian Merino sheep which had been sacrificed after orthopaedic spinal experimentation. The sheep were all wethers (desexed males) and weighed approximately 60-70 kg. They had been killed by an intravenous injection of Lethabarb® which contains 20ml of pentobarbitone sodium @ 325 mcg per ml.

Anatomical investigations were performed immediately post-mortem with all specimens then being preserved in formalin. The results were recorded by photographs taken with a Nikon FA camera using FP4 film. To study osseous components one specimen was grossly denuded of soft tissue and then prepared according to the protocol for the preparation of skeletal materials of the Adelaide Forensic Odontology Unit (see appendix). Radiographic examination of four specimens was undertaken using a Phillips Pendo diagnost 1 machine at 100cm focal film distance with Fuji Mi-NH film.

After decapitation a mid sagittal incision was made through skin and superficial fascia of the sheep head. Once this layer was peeled away the underlying muscles were immediately evident. Dissection of the masseter is best achieved from a posterior approach. In this manner the different levels of musculature can be more accurately defined. If an anterior approach is used this is more difficult as at the muscles anterior edge the fibres are strongly united in a single tendon. Both sharp and blunt dissection were continued until the size and shape of the underlying muscles could be clearly defined.

Once each superficial muscle belly could be identified it was transected and dissection continued until the deeper layers were revealed. Every effort was made in identifying each muscle to demonstrate its own nerve supply and fascial coverings as assist its description as a single entity with the possibility of independent function.

To allow examination of the muscles on the medial aspect of the mandible each sheep head was transected in the mid sagittal plane with the teeth in centric occlusion. Dissection was continued until the cranial base was reached. The lateral pterygoid muscle was traced from its pterygoid plate insertion to the lateral aspect of the mandible and the superficial layer incised to reveal its deeper level. In the case of the lateral pterygoid the mandible was disarticulated to reveal its insertion onto the lateral pole of the mandibular condyle. To better visualise the insertion of the temporalis the zygomatic arch was sectioned at its temporal and zygomatic roots.

4.2 BIOMECHANICAL INVESTIGATION

A COMPUTER GENERATED MATHEMATICAL MODEL.

A computer program was employed to calculate the muscle forces in the sheep masticatory system and the resultant temporomandibular reaction force during maximal bite force application. TMJ reaction force was calculated for three different bite points using three sheep skull specimens

4.2.1. CREATION OF SPATIAL REFERENCE PLAINS; THE USE OF PLAIN FILM RADIOGRAPHY

The anatomical dissections defined each of the muscles of mastication and revealed that some were composed of subunits. 26 gauge stainless steel wires [Zimmer® Warsaw, Indiana] were inserted unilaterally into each muscle layer along the principle fibre direction of each muscle or segment of muscle. Each part of each muscle had its point of origin and insertion located by inspection and each wire had been measured and was of a known length. The muscles were divided into subunits as follows;

1- Temporalis posterior fibres
2- Temporalis anterior fibres
3- Masseter superior fibres
4- Masseter middle fibres
5- Masseter deep anterior fibres
6- Masseter deep posterior fibres
7- Lateral pterygoid (not divided into upper and lower heads)
8- Medial pterygoid deep fibres (lateral)
9- Medial pterygoid superficial fibres (medial)

A metal grid was constructed from three stout wires of 22mm in length. This grid represented the three axes X, Y and Z in space. When this grid was attached to the internal aspect of the sheep skull it served as a reference frame. This point was as close to the intra muscular wires as possible and corresponded to the posterior naso pharynx at the level of the base of skull.

As in the anatomical study radiographic examination of the wired specimens was undertaken using a Phillips Pendo diagnost 1 machine at 100cm focal film distance with Fuji Mi-NH film. Three plane X-Ray films of each head were taken at 90 degrees to each other representing lateral, antero-posterior and superior-inferior projections of each specimen. The radiographs thus obtained were individually traced [Orthotrace Rocky Mountain]. Skeletal outline, and the origin and end point of each wire were recorded. The beginning and end of each wire thus represented the origin and insertion of each muscle or subunit of muscle and the direction of its principle line of action. Values representing these points were recorded electronically on a digitiser [Hewlett Packard 9874A]. In addition the position of the TMJ and each of three bite points were digitised. The bite points 1 through 3 ranged from closest to the TMJ to the furthest away. A reproducible reference point was arbitrarily assigned to the junction of the three metal axes. Individual values obtained from the digitiser were then subtracted from this reference point adjusting them to this common point.

The origin and insertion of each muscle subunit described by the wires could be visualised in each radiograph and each point in space has 6 values. Two points were thus obtained for the X plane, two for the Y plane, and two for the Z plane. These two values were averaged [mean] to give a more accurate estimation of the point in space.

The length of the individual muscle fibre wires was calculated from the

$$L=\{ [x_1-x_2]^2 +[y_1-y_2]^2+[z_1-z_2]^2\}.5$$

This equation considers the beginning and end point of each wire in the three planes of space as recorded on the digitiser. The answer was expressed in the number of digitiser points. This result was converted into mm, the number of digitiser points to the mm was calculated using the known length of one of the metal axes.

Once the axis was measured the length was calculated using the equation:

$$\frac{\text{length in mm}}{\text{Number of digitiser points}} = 0.025$$

$$\text{length in mm is therefore} = L \times 0.025$$

(where L is the length of the individual muscle fibre from the coordinate points)

The digitised coordinates for each of specimen 1, 2 and 3 are tabulated in Chapter 6. The use of the implant wires and orthogonal X-rays thus allowed an X-Y and a X-Z coordinate frame to be constructed. The insertion points of each muscle or muscle segment in the skull and mandible as well as the bite points and TMJ reaction force could be described in terms of this coordinate system.

4.2.2 PHYSIOLOGICAL CROSS SECTIONAL AREA; A VALUE FOR THE INTRINSIC STRENGTH OF THE JAW MUSCLES;.

The total cross sectional fibre area of a muscle is is an indication of its maximal strength [Weijs and Hillen 1985]. The quantity PCS was first described by Weber [1846] and Buchner [1877]. The method involves the careful dissection and detachment of muscle fibres which are then weighed after all vessels, fat and tendinous material have been removed. The length of fibres is measured by placing the fibres in a U shaped calibrating vessel. A value for PCS is then obtained by dividing the muscle weight by mean fibre length. A wide variation in results obtained for PCS by this method has been described in both human and animal studies [Weijs and Hillen 1984, Schumacher 1961, de Jongh 1989].

A statistically significant correlation between PCS and the measured cross section of the muscle at its widest point obtained by computer assisted tomography has been demonstrated [Weijs and Hillen 1985]. The CT generated quantity is known as the scan cross section (SCS). SCS has also been shown to be more highly correlated with maximal tension developed per unit of muscle than per cent muscle type [Schantz et al 1983]. By comparison with the earlier methods of obtaining a measure of the intrinsic strength of a muscle SCS can be quickly and easily obtained and can be used to predict PCS with an error of 0.3-1.0cms^2 [Weijs and Hillen 1984]. For these reasons CT determined SCS was the method chosen in this study.

CT scans were obtained from a decapitated sheep head on a Siemens "Hi-Q"® CT scanner. Serial scans at 5mm intervals were performed at right angles to the principle fibre direction of each of the individual masticatory muscles until the widest portion of the muscle was located. Manual tracing of the outline of area at this point. These results are listed in Table 6. in Chapter 6.

The scans chosen to represent the largest cross-section of each masticatory muscle were laser printed on Agfa film and are shown in photos **4.1-4.4.** Photo **4.1** shows a coronal section of the sheep head at the point where the lateral pterygoid is widest. After the manual tracing of the outline of the muscle the area is highlighted in white. The left and right sides are labeled 1 and 2 respectively.

Photo 4.1 (Cross sectional area; Lateral pterygoid)

Once the area has been so defined the computer determines the area of the highlighted portion yielding a value for the cross sectional area of that muscle. Photo **4.2** shows the area highlighted for the temporalis and **4.3** and **4.4** the medial pterygoid and masseter respectively. The results obtained by this

Photo **4.2** shows the area highlighted for the temporalis and **4.3** and **4.4** the medial pterygoid and masseter respectively. The results obtained by this method are very similar to those obtained in Schumacher's 1961 study of *Ovis Musimon* by the Weber technique. Schumacher also measured the PCS of the various human masticatory muscles. These results have been used in several studies as standard values in calculations of human masticatory muscle force [Baron and Debussy 1979, Prium et al 1980, Hatcher Faulkner and Hay 1986, Baragar and Osborn 1987, Koolstra 1988].

Photo 4.2 (Cross sectional area temporalis)

Photo 4.3 (Medial pterygoid)

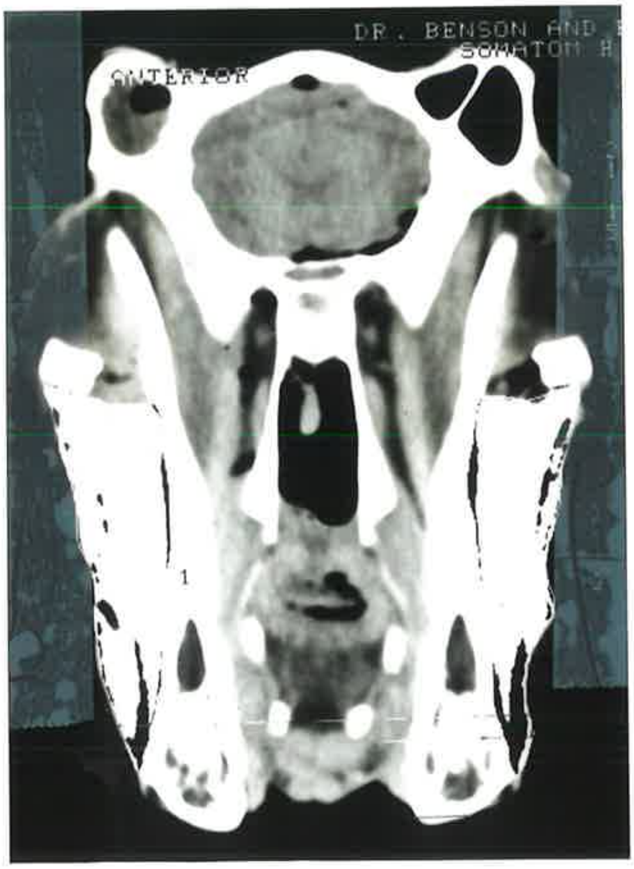


Photo 4.3 (Masseter)

4.2.3. THE COMPUTER VECTOR ANALYSIS PROGRAM

In order to examine the masticatory muscle force of the sheep a computer program was designed. This program was developed to receive data concerning the 3 dimensional position of muscle insertion points from the digitised X-rays. These were then combined with the experimentally derived PCS values for each of the nine components of the muscles associated with the sheep masticatory system.

A number of assumptions were used in constructing the computer model. The direction of TMJ reaction force was assumed to be opposing the temporalis anterior fibres. This assumption is based on the anatomy of the sheep mandible and published results in human studies. A unilateral bite model was assumed and the joint reaction force on the same bite side was assumed to be maximal. An intrinsic muscle strength constant was assumed to be similar to that of humans and was taken from published data.

The intrinsic muscle strength constant used was;

Intrinsic # = 0.39 * 10^6 N/m^2

The program initially inputs the digitised coordinates in a cartesian system (i.e x, y, z).

The coordinate sytstem is changed from digitiser units to centimetres by dividing by 400. This is neccesary as the digitiser runs on the units of 1 thou per point (0.025*mm).

The muscle force vectors are calculated using the difference in distance between the skull insertion point and the mandibular insertion point.

MFV = Skull insertion point - Mandibular insertion point

(1)

The unit vectors are then calculated for each of the muscle force vectors in the x, y and z directions. The x, y or z component is divided by the magnitude of the vector. This describes the component of the muscle force vector in each direction.

Unit V = MFV(x,y,z)/(SQR(MFV(x)^2 + MFV(y)^2 + MFV (z)^2)

(2)

The resultant muscle force vector is then calculated using a sum of the unit vectors multiplied by the PCSA for each muscle and the intrinsic muscle force constant. The magnitude of this vector is also calculated.

RMFV = ∑(Unit V)*PCSA*Intrinsic #

(3)

Mag MF = SQR(RMF(X)^2 + RMFV(Y)^2 + RMFV(Z)^2)

(4)

The moments created by each muscle force is then calculate for each of the three bite points around the x, y and z axes. The sample equation for the moments around the x axis is shown in equation 5.

Mmntx = Unit V(Y)*PCSA*INTRINSIC# *MMNTARM(Z) -
Unit V(Z)*PCSA*INTRINSIC# *MMNTARM(Y)

(5)

The sum of the moments is taken around the x, y and z axes.

SumMnt = Σ(Mmnt(x, y, z))

(6)

The moment arm for the TMJ to each of the bite points is taken and the TMJ reaction force is calculated using the sum of the moments in static equilibrium for each of the x, y, and z directions.

TMJRF = Summnt(x,y,z)/TMJ moment arm

(7)

The resultant TMJ reaction force has a magnitude calculated as shown in equation 8.

RF = SQR (TMJRF(X)^2 + TMJRF(Z)^2)

(8)

The presumed reaction of this force is opposing the temporalis anterior fibres. The results of the calculated TMJ reaction force are shown in Chapter 6. Appendix 3 contains the main calculation subroutine of the computer program used to calculate TMJ reaction force.

CHAPTER FIVE

RESULTS: ANATOMY

OSTEOLOGY

The sheep skull consists of a relatively small neurocranium with a large proboscis or beak attached anteriorly. A tendency towards elongation is reflected in the small width of the skull. The skull is broadest at the posterior margin of the globe superiorly and at the anterior root of the zygomatic arch inferiorly. The skull then tapers anteriorly to form a narrow beak. **Fig 1** shows the sheep skull in lateral projection note the long jaws and well developed nasal complex.

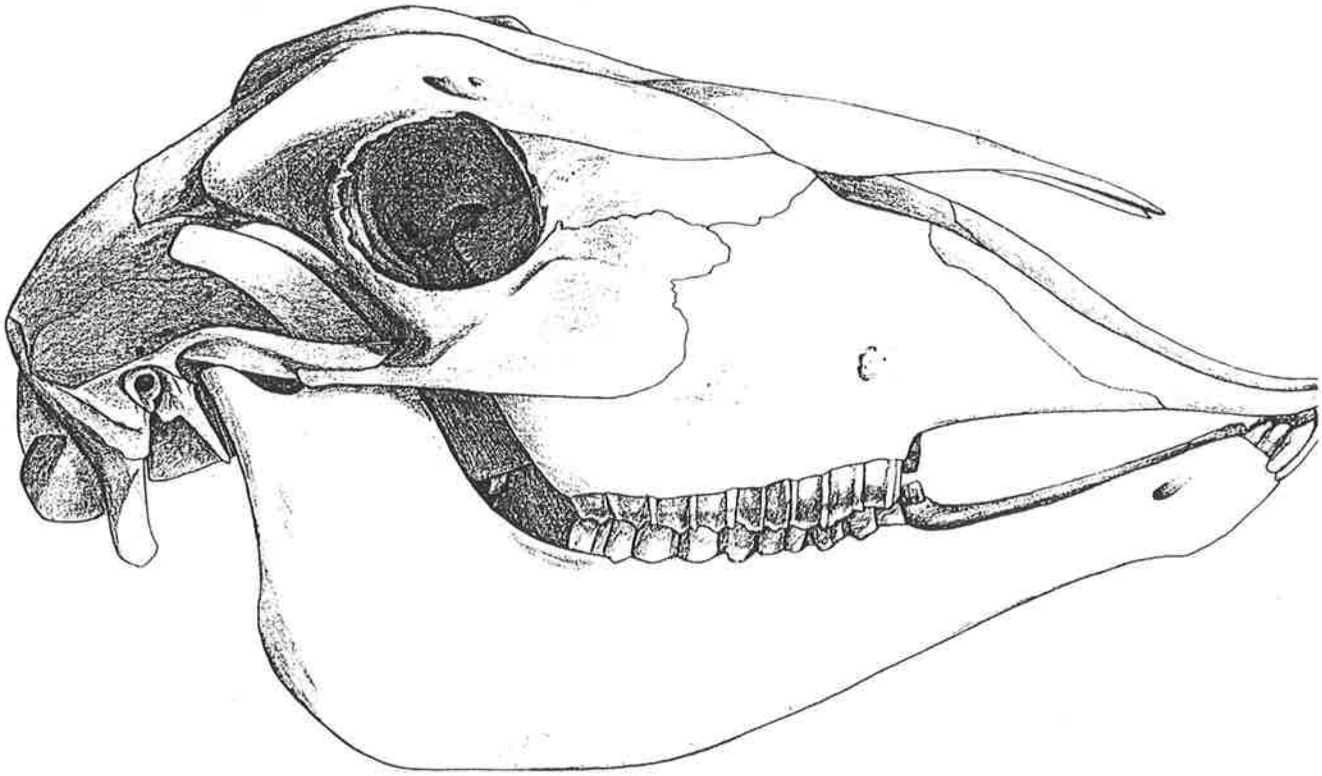


Fig 1

The neurocranium consists of strong thick bone whilst the snout is generally thin. The orbit lacks a postero-lateral wall with soft tissue and fat being the only separation between it and the anterior border of the coronoid process. A bony prominence called the facial tuber arises from the lateral aspect of the skull at the end of a lateral buttress of bone that begins at the zygomatic arch. The root of the zygomatic arch and thus the glenoid fossa is lateral to rather than beneath the middle cranial fossa.

The sheep's mandible consists of two bony bodies or corpi and two vertical rami each complete with a condylar and coronoid process. The two mandibular halves articulate with each other anteriorly at the mandibular symphysis and posteriorly with the skull at the glenoid fossae. The symphyseal surfaces are very rough and are marked by reciprocal projections and cavities. The mandible is longer in the rostro-caudal direction than it is high. The average mandibular length was 20 cms whilst mandibular height was 10 cms. A short condylar process and a long curved coronoid arise from a stout ramus mandibulae. These features are evident in **Fig 2.**

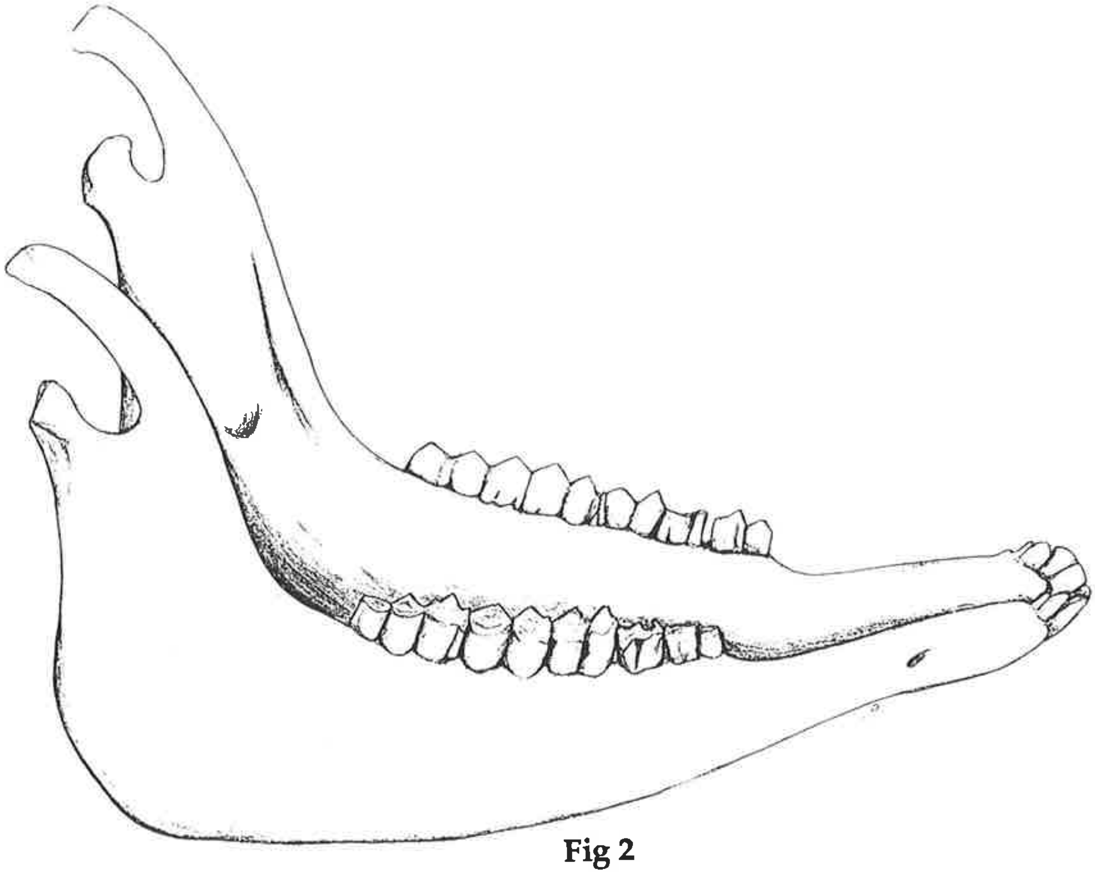


Fig 2

The mandibular condyle arises from an extremely short condylar process widening rapidly to form a broad flat articular surface. The anterior edge of this surface arises from the coronoid notch. This then rises steeply posteriorly progressively widening to form a broad slightly concave surface. This surface is defined posteriorly by a sharp ridge which drops precipitously away to form the posterior border of the mandible. The condyle thus forms a medio laterally elongated cylindrical structure about 25 mm in width. The long axis of this structure situated at almost 90' to the sagittal plane. The condyles fit snugly into the closely applied cranial articular surface.

The coronoid process is sickle shaped and arises from the anterior border of the ascending ramus. The process is well developed and curves progressively backwards to pass behind and then rise well above the zygomatic arch. This prominent curve continues until the process is located centrally in the temporal fossa superior and medial to the zygomatic arch (**Fig 3**). The curve of the coronoid allows it to eventually lie in the same vertical plane as the mandibular joint.

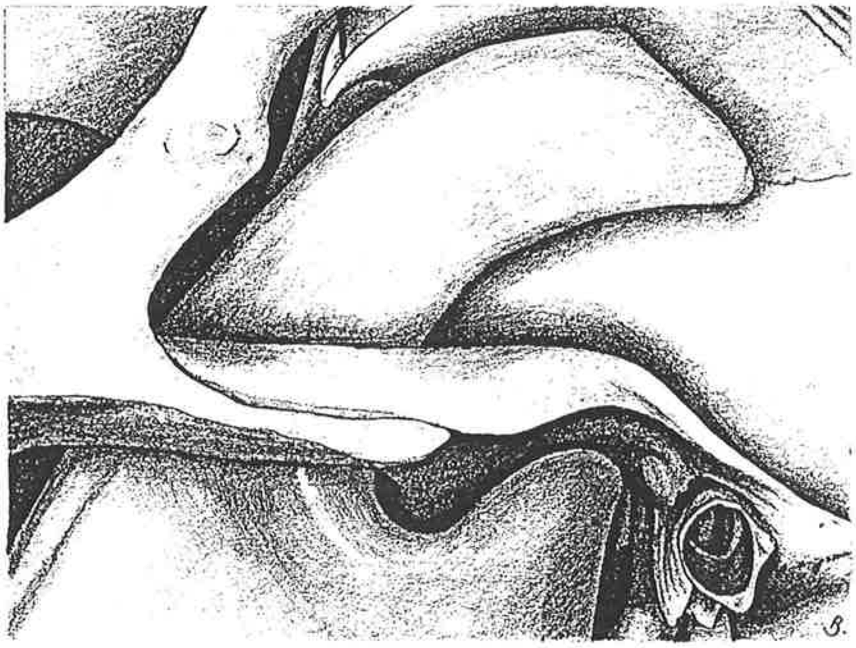


Fig 3.

The cranial component of the temporomandibular articulation is provided by the postero-inferior aspect of the temporal root of the zygomatic arch. The glenoid fossa is elongated medio-laterally and is convex in both the antero-posterior and medio-lateral directions. A convexity is noted at the medial edge of the articulating surface adjacent to the foramen ovale. A prominent ridge of bone arises from the inferior aspect of the temporal root of the zygomatic arch. This ridge is high medially and slopes gently away to form part of the lateral aspect of the zygomatic arch. This ridge provides the posterior border to the cranial articular surface and protects the external auditory meatus and the trunk of the facial nerve as they arise immediately behind it. There is no bony flange to limit lateral condylar movements. The foramen ovate and the mandibular nerve are immediate and medial relations of the articular fossa.

The temporal fossa is deep and is surrounded by crests of bone. The fossa is provided mainly by the squamous part of the temporal bone and extends slightly beyond it. The posterior aspect of anterior fossa is separated from the tympanic plate by the squamotympanic fissure and a foramen which communicates with both the cranial cavity and the temporal fossa above the root of the zygoma.

THE DENTITION

At rest between feeds in the living animal the mandible is supported by the tonic activity of the masticatory muscles possibly assisted by the hermetic seal created by the application by the dorsum of the tongue to the palate. When not feeding the jaws are symmetrically placed in relation to the median plane with the upper and lower tooth rows are slightly separated.

The maxillary incisors and canines are absent. In their place the anterior maxilla is covered with a thick pad of fibrous tissue. There are six lower incisors which have a broad shovel shaped appearance with sharp incisal edges. The incisor roots are narrow and peg like. The incisors are somewhat splayed and erupt at an acute angle to the long axis of the mandibular corpus forming a narrow but strongly curved arch. The canines are somewhat underdeveloped being smaller than the incisors and peg shaped. The teeth are relatively loosely attached. The anterior segment of teeth is well separated from the posterior segments by an edentulous segment or diastema. There are three premolars and three molars in the posterior part of each of the mandibular corpi which are widened and sturdy to accommodate them **(Fig 4).**

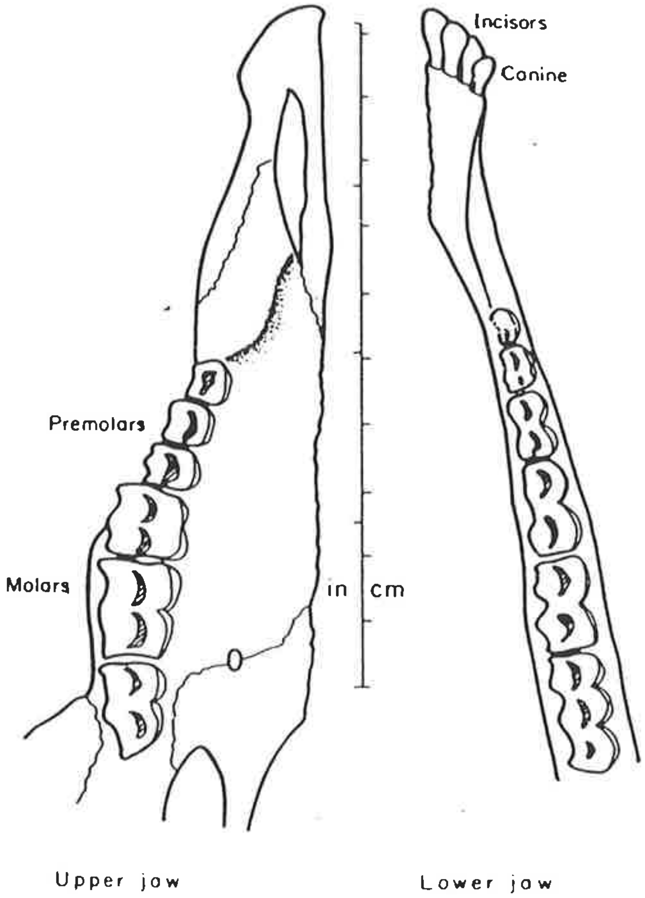


Fig 4. (After Ryder 1969)

outwards. Those of the maxillary dentition face downwards and inwards. A marked bucco-lingual incline is therefore seen on the occlusal surfaces of the mandibular molars and this corresponds to a palato-buccal slope to the maxillary dentition. The heavy wear facets of each specimen approximated exactly when the molar segments were held in unilateral occlusion.

Examination of the occlusal surfaces shows prominent succedinous ridges of enamel. Between the enamel ridges are wider layers of dentine which occupy almost two thirds of the occlusal surface. Prominent buccal cusps are noted on the maxillary molars whilst the lingual cusps are larger on the mandible. These prominent cusps are formed by ridges of enamel. In the mandible there are 4 ridges which increase in size from the buccal to the lingual surface. The buccal cusp is the largest in the maxilla and this similarly decreases in size toward the palate. The hard enamel ridges are separated by soft dentine. These features are evident in **photo 1** which shows an occlusal view of the maxillary dentition. The gentle lateral curve of the maxillary dentition as well as heavy dentine wear is evident. The teeth are blackened by food deposits. **Photo 2** shows a profile view of the maxillary molar segments. The "selenodont" or sickle shaped curve to the occlusal surfaces of individual teeth as well as the prominent curve of Spee in the dental arch can be seen.

The lingual surfaces of the mandibular molars present broad corrugations whilst their buccal surfaces have rounded surfaces contributing to larger corrugations. The palatal surface of the maxillary molars present similar corrugations whilst a sharp ridge defines the buccal surfaces of these teeth Each maxillary premolar possess a buccal ridge whilst two buccal ridges are present on the molars. The smaller size and straight alignment of the mandibular molars can be seen in **Photo 3** and **4** on page 192.

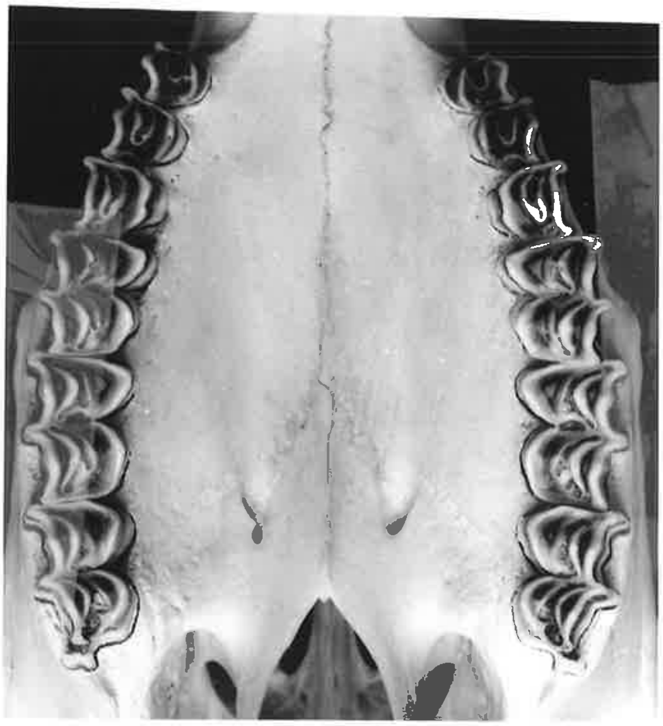


Photo 1

Photo 2

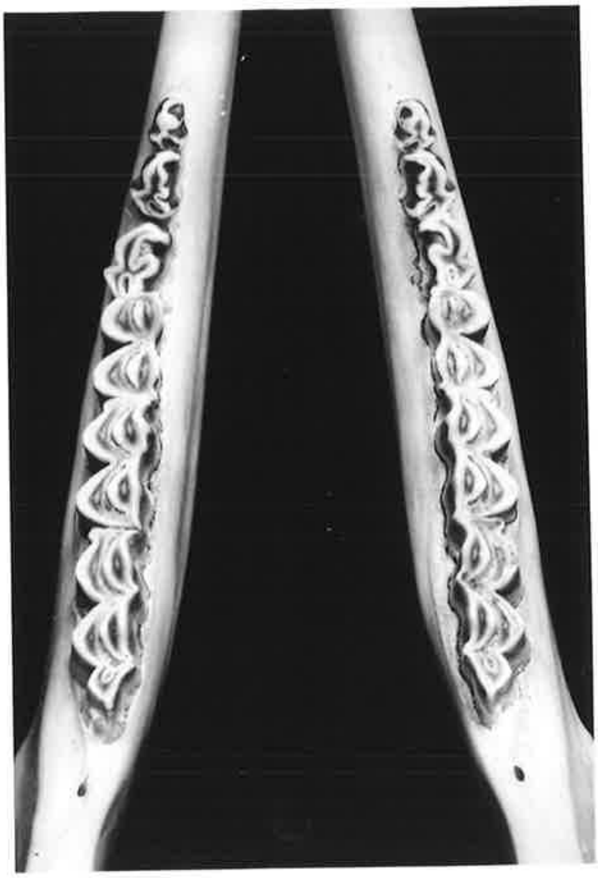


Photo 3

Photo 4

The roots of the anterior teeth curved gently backward within the mandibular symphysis. The length of the crowns of the incisors approached their root length in an approximate ratio of 1:1. Some degree of periodontal loss was present in all specimens. The single canine on each side had a similar crown/root ratio. The premolars had two roots which were only slightly longer than their small crowns. By contrast the molars were substantial with double cusps more than twice the size of the premolars. These teeth had short roots and a high crown/root ratio of approximately 1: 4 with the average length of a molar approaching 4cms. The long crowns of the upper molars extended high into the maxillary buttress and in the lower jaw almost to the lower border of the mandible. These crowns functioned essentially as roots being buried subgingivally for most of their length.

There is a marked curve to the occlusal plane. The width of the maxillary dental arcade exceeds that of the mandible by at least one tooth row. It is impossible for the molar teeth to be in occlusion on both sides of the jaw simultaneously. In centric occlusion minimal tooth contact occurs. During simulated chewing movements unilateral occlusion occurred on the working side only. There was no occlusion on the non working or contralateral side.

MUSCLES OF MASTICATION

THE MASSETER

This is the largest muscle of mastication and it consists of three layers. These layers are the superficial, middle and deep layers which are separated by thick fibrous septa. The first two of these are quite distinct although blending of fibres can occur at any level. The first photo **5** shows a lateral projection of a sheep skull with the overlying soft tissues removed. The superficial layers of muscle are evident. The glistening tendon of the superficial masseter is also visible in this view. The photo **6** shows a coronal section of the mandibular ramus at its mid point. The overlapping layers of muscle and their division by fibrous septa are visible in this view.

Photo 5

Photo 6

The masseter takes extensive origin over the zygomatic arch, malar, maxilla and forward to the facial tuber. It is also inserted broadly into the lateral aspect of the mandibular ramus. The different layers are bounded and covered by fascia which is continuous with the tendon of the superficial masseter. **Fig 5** shows the overlapping layers of the masseter on the medial aspect of the sheep skull. The large tendon can be seen to insert in the region of the facial tuber.

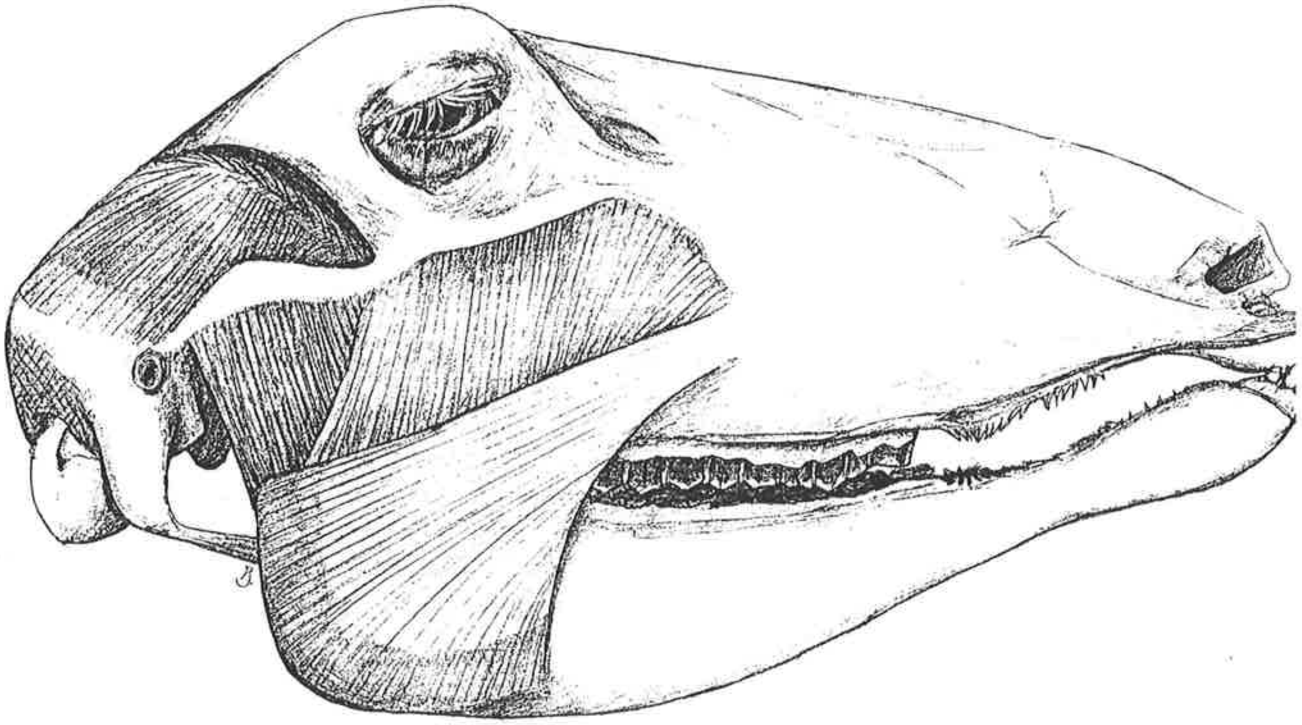


Fig 5.

1. The superficial layer

After the skin is removed the thick fascia covering the lateral aspect of the masseter is evident. At the anterior portion of this covering the prominent bony landmark of the facial tuber of the maxilla can be seen. The masseter arises from the tuber and for a short distance caudal to this point by a thick tendon. A further origin is via a fine tendinous sheath arising from the crest of the infra orbital rim. The rostral tendon widens rapidly and for a short distance encloses the rostral border of the deeper layers. The two tendons unite and continue as muscle fibres over the underlying middle layer. The fibres of the most superficial layer diverge as they pass posteriorly forming a fan shaped mass which is tilted obliquely on the lateral side of the underlying muscle mass. The fibres end at their insertion on the lower surface of the caudal and ventral borders as well as at the angle of the mandible. Many of the fibres are fused at this point with the underlying middle layer of masseter.

2. The middle layer

This layer takes its origin from a bony crest extending along the infra orbital rim and from the crest of the maxilla and malar bones in a long arc from the facial tuber to the zygomatic arch. This layer is covered in its anterior and inferior portions by the overlying superficial layer. On lateral inspection of the skull only the superior portion of this muscle is visible unless the superficial layer is completely removed. The fibres of this layer course obliquely backward and are for the most part uniformly parallel **(Fig 6)**.

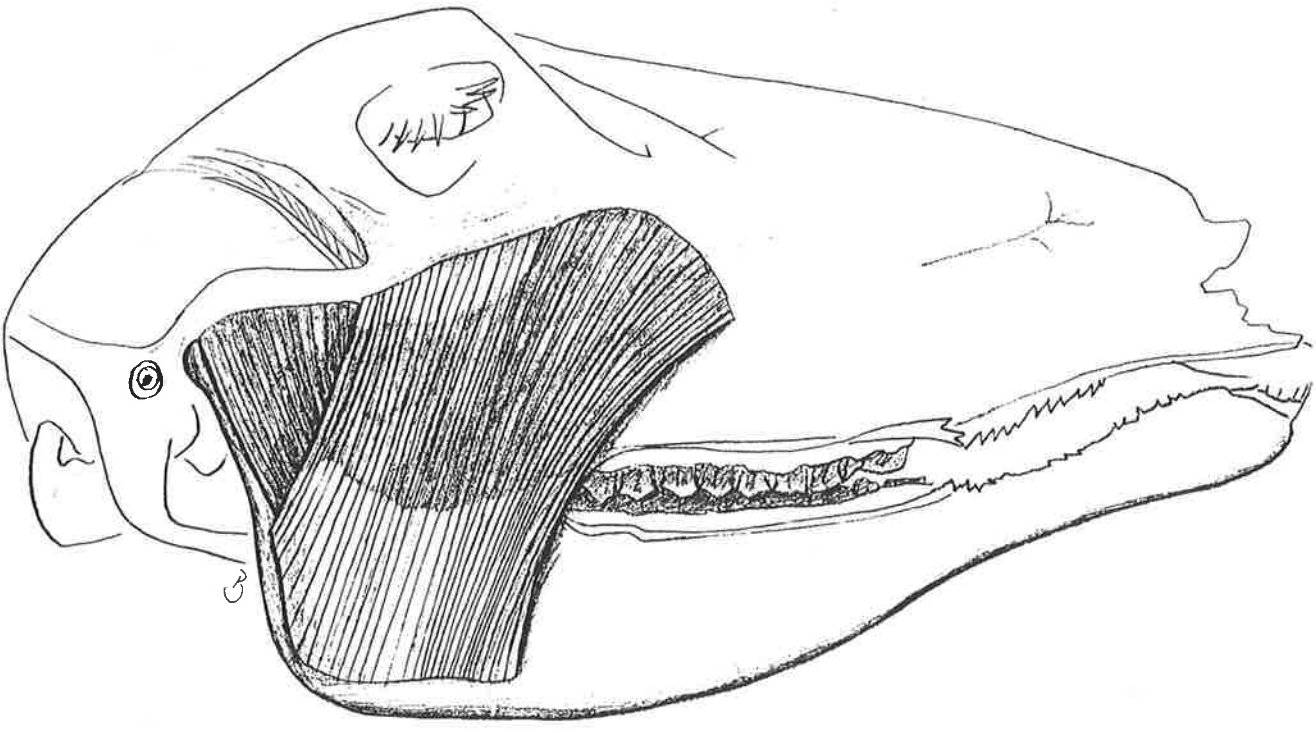


Fig 6

The middle layer ends in a strong flattened tendon attached to the caudal and ventral borders and to the angle and ramus of the mandible. Beyond the caudal border of the specimen illustrated in **Fig 6** a portion of the deep layer can be seen.

3. The deeper layer

Only a small portion of the postero-superior aspect of this muscle is seen on examination of the lateral aspect of the sheep skull. Complete visualisation of this layer demands removal of both superficial and middle layers. This layer arises from the crest of the infra orbital rim and the zygomatic arch. These fibres descend vertically to insert into the neck of the condylar process of the mandible. Some fibres continue in an oblique line traversing the lateral aspect of the vertical ramus of the mandible. The fibres arise from a point immediately ventral to the sigmoid notch and continue down to the region of the gonial notch of the mandible. At this point they are close to the rostral border of the superficial layer of the masseter. The blending of fibres both with overlying masseteric fibres as well as with those of the temporalis was most marked in this layer.

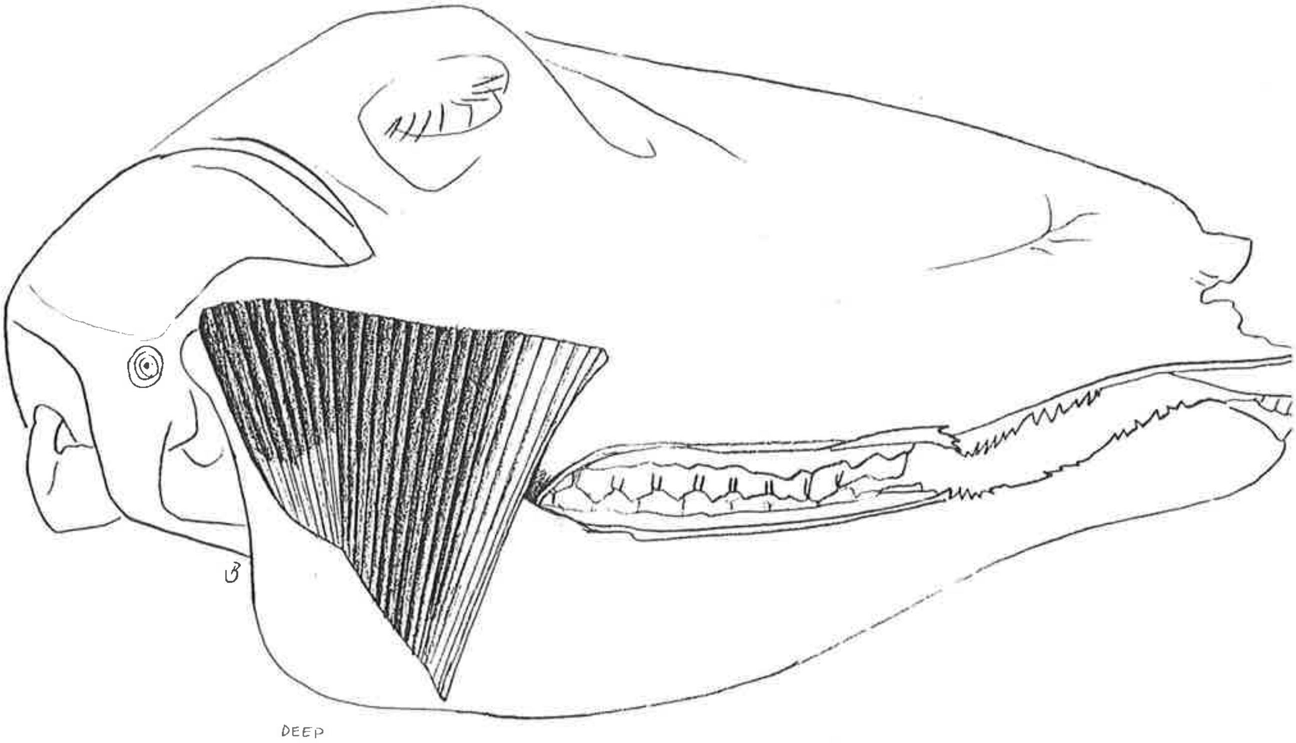


Fig 7

In two specimens the central portion of the deep layer was quite thin leading to the suggestion of there being two separate parts to this muscle. In most specimens the deep part of the masseter formed a clearly defined continuous layer. Some of the fibres of this layer were fleshy and others were tendinous for half of their length. All of the the individual layers were arranged so that the tendon fibres overlaid the muscled ones. Fibre direction was near vertical in the central part of the muscle whilst the anterior and posterior portions tended to diverge slightly as the fibres coursed superiorly. These slightly differing fibre directions are evident in **Fig 7**.

TEMPORALIS

The bulk of this muscle can be seen completely filling the temporal fossa on the lateral aspect of the sheep skull. To visualise the descending course of the fibres it was necessary to remove the zygomatic arch after sectioning its malar and temporal origins. It is covered by a thick sheet of fascia attached to the bony landmarks of the frontal and temporal crests of the skull. The broad origin of this muscle includes the temporal bone in the fossa down to the level of the muscular process and continuing on to the frontal and temporal crests to the extension of this crest out along the zygomatic arch. These fibres follow a rostral caudal direction and pass between the zygomatic arch and the skull in a strongly arched curve. The descending fibres insert into the medial and lateral aspects of the coronoid process, essentially enveloping it over its entire length. The fibres on the medial surface continue in an oblique direction close to the rostral border of the coronoid process. The fibres insert at the junction of the horizontal and vertical rami at the level of the mandibular foramen in the region of the lingula of the mandible.

A separate group of short fibres could be identified arising from the superior aspect of a bony ledge at the temporal root of the zygomatic arch. These fibres course vertically to invest the lateral surface and anterior border of the mandibular coronoid. This arrangement allows some temporal fibres to be diametrically opposed to parts of the masseter whose fibres are inserted on the undersurface of the bony ledge formed by the temporal root of the zygomatic arch **(Fig 8)**.

Fig 8.

Photo 7 shows an oblique view of the temporal muscle. In this photo the posterior orbital rim has been removed. The removal of this section of bone allows the course of the anterior fibres of temporalis along the anterior border of the coronoid process to be visualised. These fibre directions are schematically represented in **Fig 8.** The manner in which the posterior fibres completely occupy the temporal fossa can also be seen in this view.

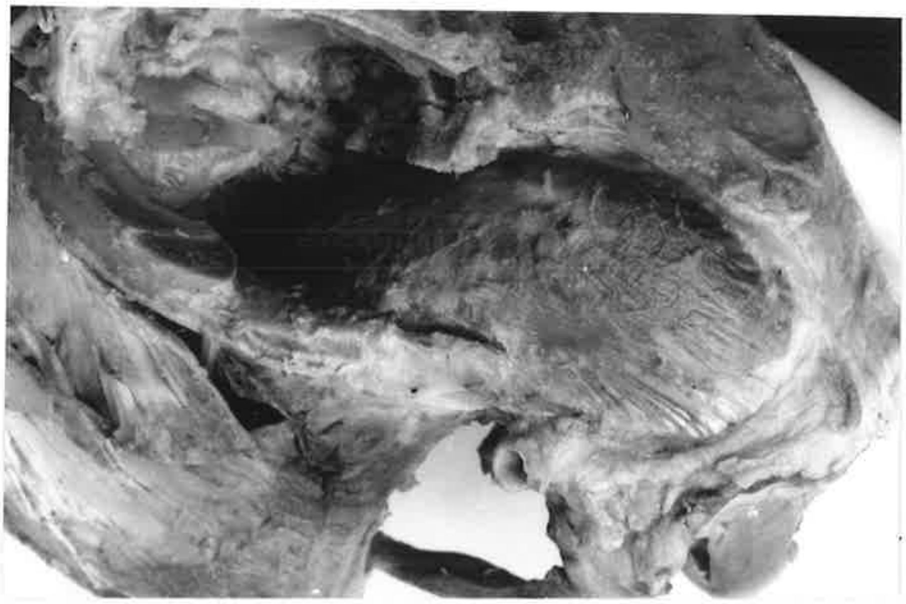


Photo 7

Photo 8 shows a lateral view of the temporal muscle. In this view a section of the zygomatic arch has been removed and the muscles occupying the lateral aspect of the mandible have been stripped away. An almost 90 degree change in direction from the posterior to the anterior fibres of temporalis can be seen. The anterior temporal fibres invest the anterior border of the ramus of the mandible. The fibres descend to become thin slips of muscle fibre which blend with the overlying masseter fibres (**Fig 7 and photos 7** and **8**)

Photo 8

THE MEDIAL PTERYGOID

Proper visualisation of the pterygoid muscles demands that the sheep skull be sectioned in the sagittal plane. The muscle consists of two broad layers divided by well defined tendinous tissue septa which are attached to and occupy the medial side of the mandibular ramus. It is partly covered on its medial aspect by a glistening tendinous sheath. The deep layer of medial pterygoid can be seen overlying the superficial layer which is immediately subjacent to the mandible. The deep layer forms a fan-shape which covers and obscures most of the superficial layer **(Photo 9)**. This muscle arises as a thick tendon from the medial lamina of the pterygoid process of the sphenoid bone caudal to the hard palate and extending for a short distance behind to reach the pterygoid hamulus. The fibres course obliquely downward to insert into the ventral and caudal borders as well as the angle of the mandible.

Photo 9

The superficial layer becomes evident on removal of the overlying deep layer. This layer arises from the fossa between the lateral and medial lamina of the pterygoid process. The origin of this layer extends further posteriorly than the deep layer and again courses down to insert dorsally into the broad insertion of the deep layer of the medial surface of the vertical and horizontal rami of the mandible **(Fig 8)**.

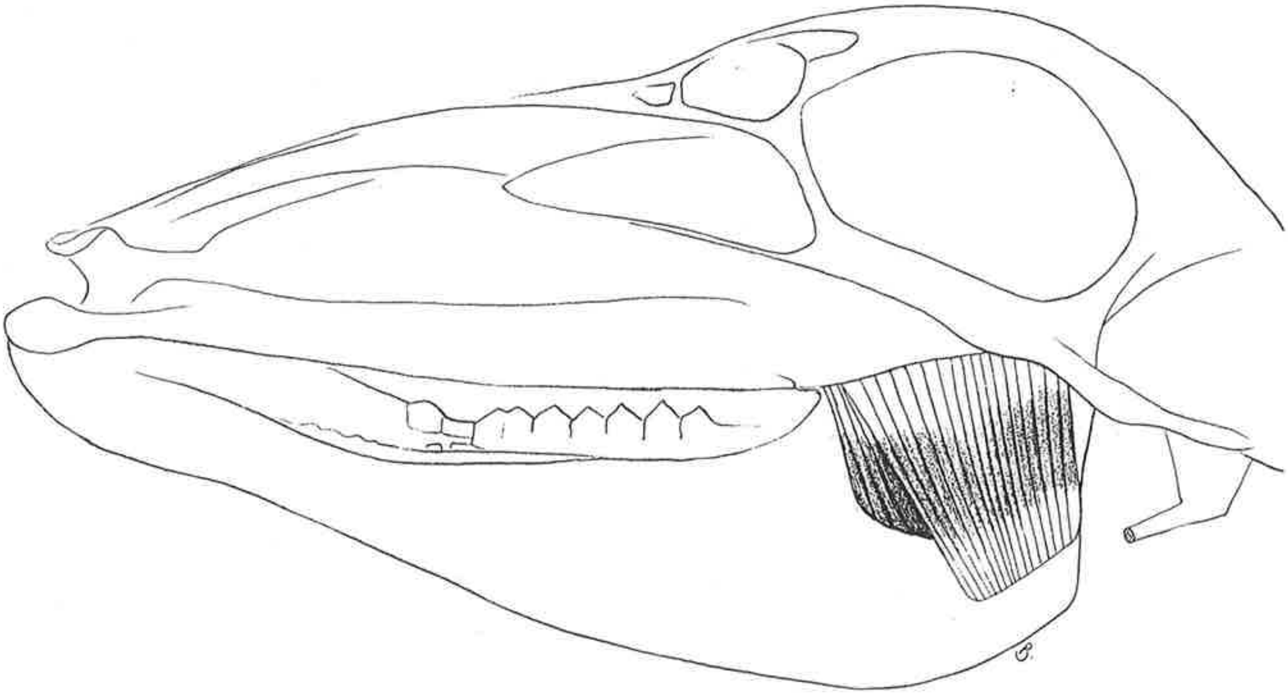


Fig 8

THE LATERAL PTERYGOID

This triangular shaped muscle is the smallest of the muscles of mastication. The lateral pterygoid cannot be seen until both layers of medial pterygoid have been detached along with parts of the pterygoid lamina. The lateral pterygoid arises from the lateral aspect of the lateral lamina of the pterygoid process of the sphenoid bone. Its fibres course posteriorly to insert into the medial pole of the mandibular condyle **(Figs 10** and **11)** Further fine attachment can be seen to parts of the joint capsule and to the medial edge of the articular disc via a thin tendon. **Fig 9** shows a schematic diagram of an inferior view of the sheep skull. The origin of the lateral pterygoid is clearly larger than its mandibular insertion. Muscle fibres convergence to a narrow insertion on the medial pole of the condyle. **Fig 10**, a lateral view of the same muscle, shows again the broad insertion on the pterygoid plates and the convergence of the fibres to their mandibular insertion.

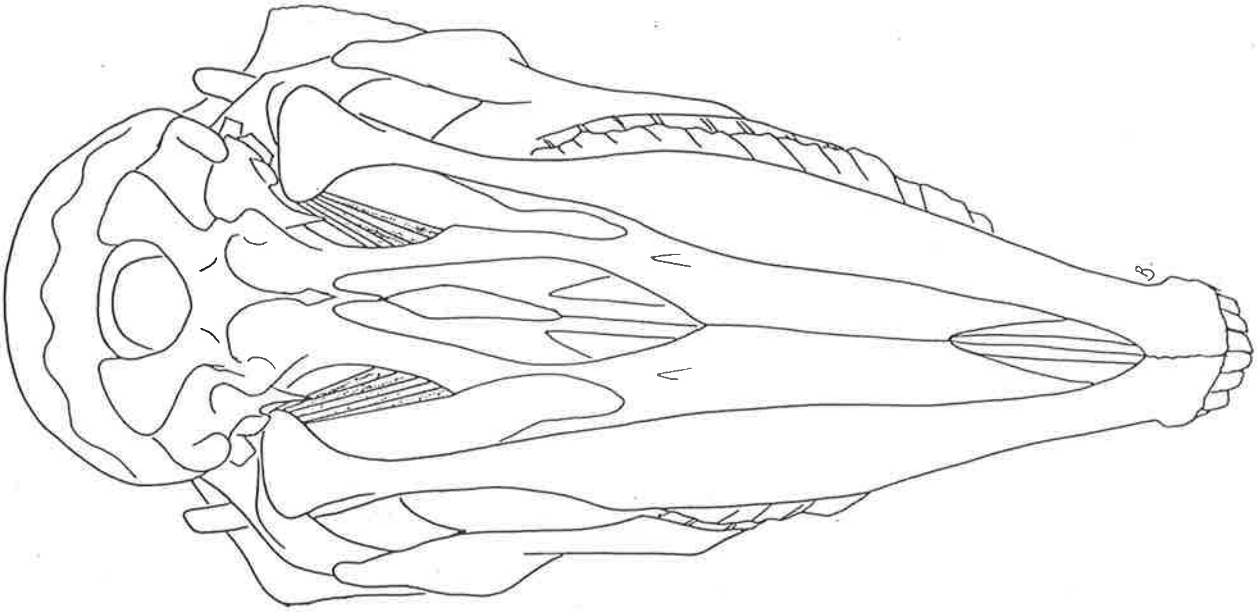


Fig 9

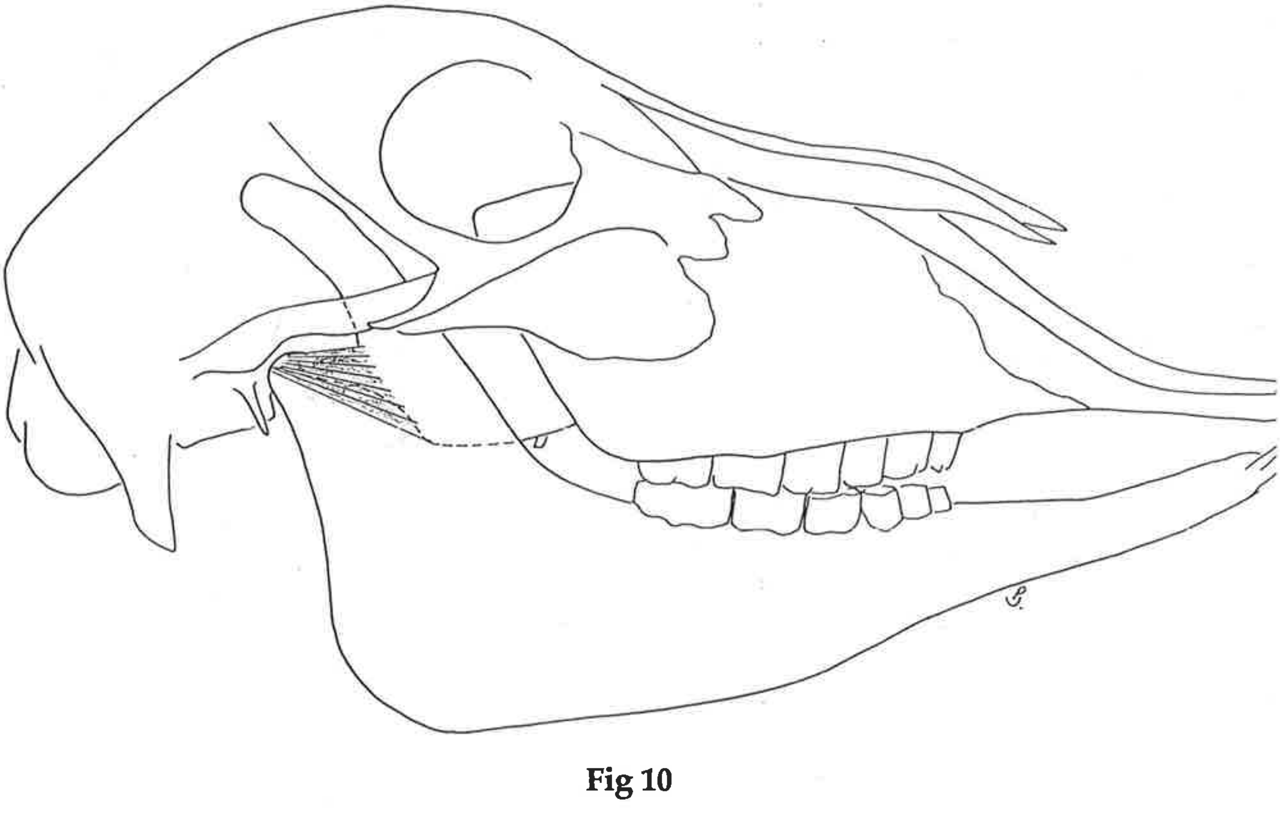


Fig 10

Photo 10 shows an inferior view of the lateral pterygoid with the condyle located in its fossa. The caudal direction of the fibres from the pterygoid plates seen in this view.

Photo 10

Photo 11 shows a view of a disarticulated mandible. The lateral pterygoid muscle has been separated from the skull from its origin at the pterygoid plates. The distinct insertion of the muscle onto the medial pole of the mandibular condyle can be seen in this view.

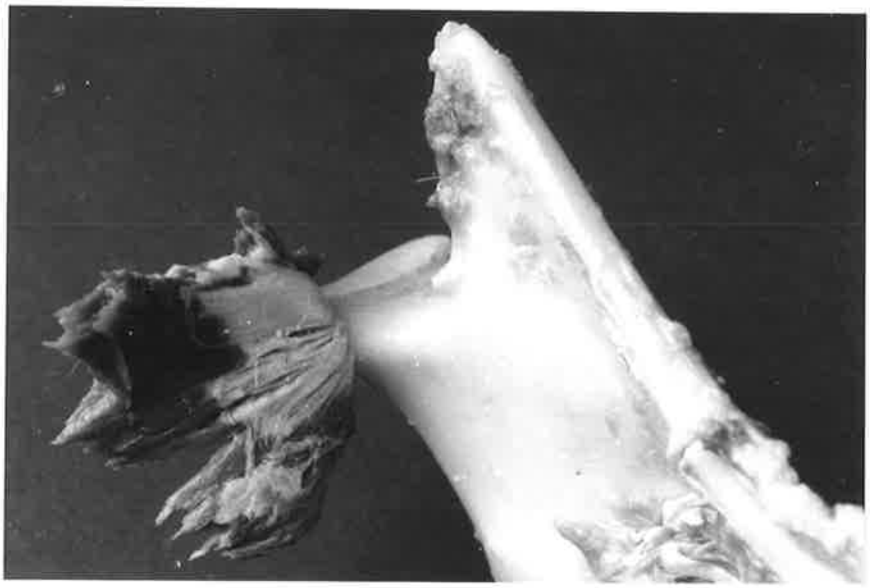


Photo 11

DIGASTRIC

The digastric has a tendinous origin from the prominent jugular process of the occipital bone. Arising behind the angle of the mandible, and caudal to the temporomandibular joint the muscle courses anteriorly to form a round, narrow intermediate tendon. The intermediate tendon widens to form its anterior belly. The direction of the muscle fibres and their origin from the jugular process is seen in **Fig 11.**

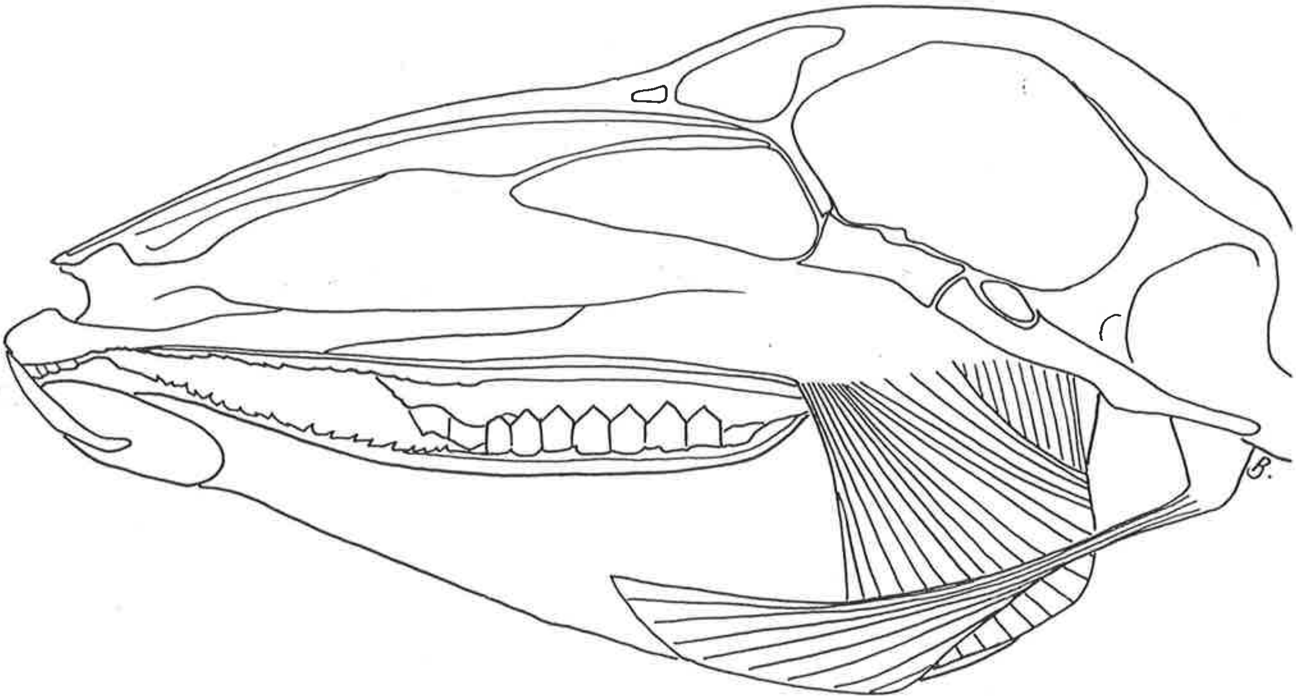


Fig 11

The anterior belly is largely fleshy with some tendinous fibres at its insertion **(Photo 12)**. The anterior belly is inserted on the medial surface on the body of the mandible. The area of insertion corresponded with a roughened area on the medial aspect of the mandible on the dried skull.

Photo 12

3. THE JOINT AND ARTICULAR DISC

The temporomandibular joint is broadly considered to consist of condyle, disc and temporal component. The joint is located high above the tooth row. The joint is surrounded by a fibrous capsule attached at the periphery by a strong but lax joint capsule that permits a wide range of condylar movements. The joint cavity is occupied by the meniscus which is essentially a connective tissue plate dividing the articular space into two synovial cavities.

The disarticulated disc is a broad flat piece of tissue composed of fibrocartilage. The disc is concave on its inferior surface and conforms to the head of the mandibular condyle. Superiorly it is convex in its articulation with the glenoid fossa. This biconcavity results in anterior and posterior thickenings with the disc being thinnest in its central portion. The disc is thickest posteriorly and has a well defined attachment to the posterior ridge. Anteriorly the limit of the disc is difficult to define as it merges into vascular sinusoids. Vascular tissue replaces the capsule anteriorly filling the space above the coronoid notch.

above the coronoid notch.

The disc is attached more tightly and by shorter fibres to the mandible than compared with the cranium. Cranial articulation was in general looser and had longer attachment fibres. In simulated chewing movements wide ranges of mandibular motion could be demonstrated. Most of the movement was seen to occur in the superior joint space between the disc and the glenoid rather than between the mandible and disc.

CHAPTER SIX; RESULTS BIOMECHANICS

6.1 VECTOR CONSTRUCTION

Figures 1 to 3 show tracings of the radiographs of a sheep skull with the implant wires in place (specimen A). **Fig 6.1** is the lateral view of the sheep skull.

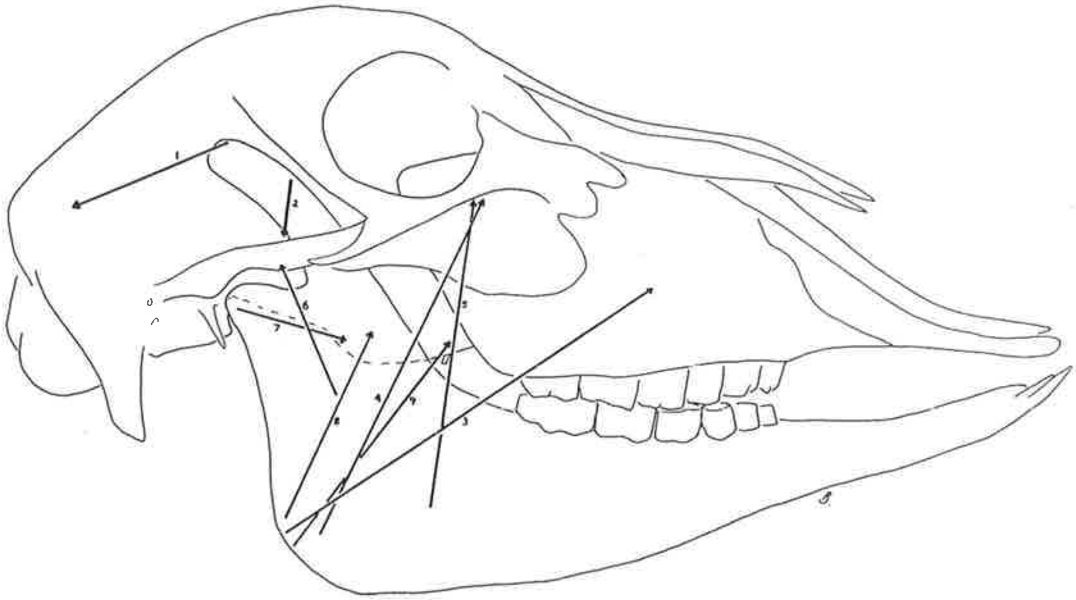


Fig 6.1

Fig 6.2 below shows an antero-posterior projection. The beginning and end of each line represents the origin and insertion of each masticatory muscle.

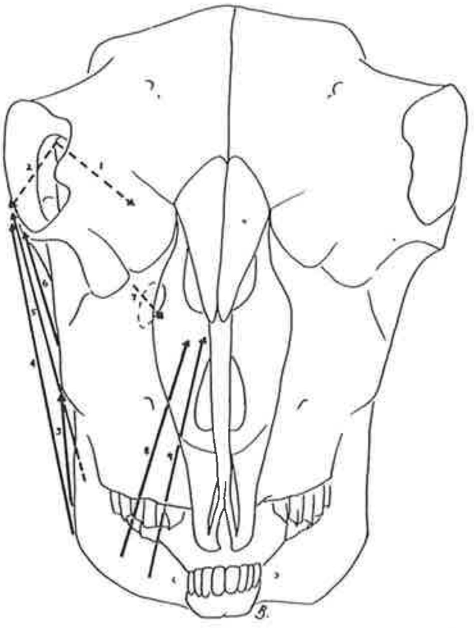


Fig 6.2

The numbers adjacent to each line correspond with the tabulated muscle elements listed below.

1- Temporalis posterior fibres
2- Temporalis anterior fibres
3- Masseter superior fibres
4- Masseter middle fibres
5- Masseter deep anterior fibres
6- Masseter deep posterior fibres
7- Lateral pterygoid (not divided into upper and lower heads)
8- Medial pterygoid deep fibres (lateral)
9- Medial pterygoid superficial fibres (medial)

The coordinate axis via which three planes of space are constructed is illustrated in **Fig. 6.3**.

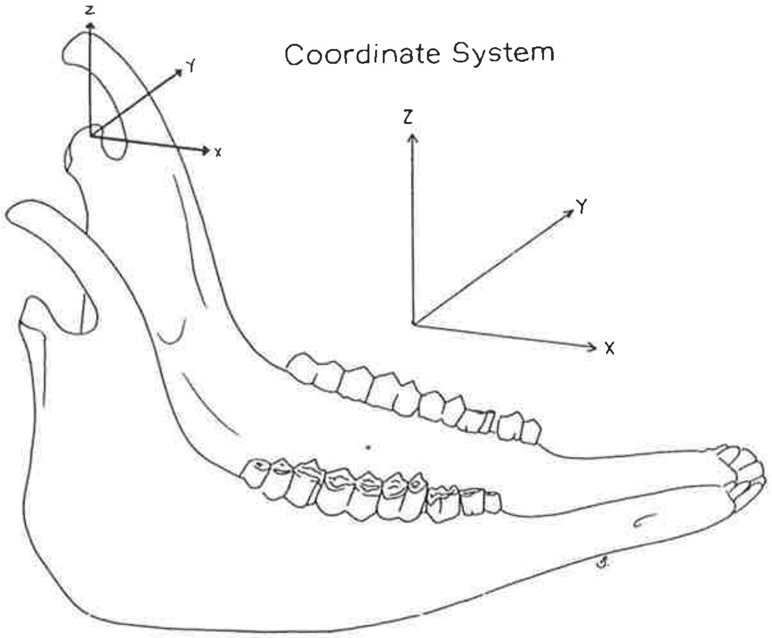


Fig. 6.3

Data concerning the origin and insertion of each muscle is recorded for each of the three specimens in the tables for sheep A,B and C in the pages to follow.

SHEEP A

	X	Y	Z	WIRE PTS	LENGTH mm
TEMPORALIS POSTERIOR FIBRES	-1049.0 -1065.0	2364.5 1769.5	1520.0 1536.0	595.43	14.89
TEMPORALIS ANTERIOR FIBRES	511.0 542.0	2106.5 1617.5	1978.5 2318.5	596.39	14.91
MASSETER SUPERIOR FIBRES	969.5 4878.0	-1512.5 1018.5	1905.0 1836.5	4656.77	116.42
MASSETER MIDDLE FIBRES	1458.0 2577.0	-1831.0 1848.0	1519.0 2476.5	3962.83	99.07
MASSETER DEEP ANTERIOR FIBRES	2617.5 2895.5	-1491.0 2073.0	1416.0 2243.5	3669.35	91.73
MASSETER DEEP.POSTERIOR FIBRES	1557.5 873.0	-193.0 1078.0	1368.0 2361.5	1752.43	43.81
LATERAL PTERYGOID FIBRES	255.0 1407.5	482.5 454.5	768.5 764.0	1152.85	28.82
MEDIAL PTERYGOID DEEP FIBRES (lateral)	1103.0 1802.0	-1697.0 321.0	972.5 466.0	2194.87	54.87
MEDIAL PTERYGOID SUPERFICAL FIBRES (medial)	1085.0 2678.5	-2245.5 340.0	621.5 256.5	3058.97	76.47

SHEEP B

	X	Y	Z	WIRE PTS	LENGTH mm
TEMPORALIS POSTERIOR FIBRES	863.5 796.0	2431.0 1729.5	-2118.0 -1493.5	941.63	23.5
TEMPORALIS ANTERIOR FIBRES	1429.5 1379.0	2077.5 1413.5	-1967.0 -2163.5	694.3	17.4
MASSETER SUPERIOR FIBRES	1724.0 5537.5	-1817.5 806.5	-2276.5 -1848.5	4648.8	116.2
MASSETER MIDDLE FIBRES	2029.0 3705.0	-1904.5 1850.0	-1460.0 -2310.5	4196.64	104.9
MASSETER DEEP ANTERIOR FIBRES	3199.0 3613.0	-1676.5 1811.0	-1383.0 -21548.5	3691.55	92.3
MASSETER DEEP.POSTERIOR FIBRES	2183.5 1518.0	-350.5 1080.0	-1508.5 -2411.0	1817.62	45.4
LATERAL PTERYGOID FIBRES	1031.5 2192.0	555.5 575.5	-845.0 -825.0	1161.36	29.0
MEDIAL PTERYGOID DEEP FIBRES (lateral)	1650.5 2451.5	-1845.5 327.0	-1042.5 -377.0	2409.2	60.2
MEDIAL PTERYGOID SUPERFICAL FIBRES (medial)	1786.5 3320.5	2110.5 295.5	-669.5 -270.5	2409.69	60.2

using = n for length

$= [(x^1 - x^2 =)^2 = (y^1 - y^2)^2 = (z^1 - z^1)^2]^{.5}$ = wire length

SHEEP C

	X	Y	Z	WIRE PTS	LENGTH mm
TEMPORALIS POSTERIOR FIBRES	-596.5 -2652.0	2203.5 1496.0	2086.0 1072	1909.77	47.74
TEMPORALIS ANTERIOR FIBRES	312.0 343.0	2054.5 1542.0	2000.5 2360.0	626.78	15.67
MASSETER SUPERIOR FIBRES	689.0 4733.0	-1656.5 620.0	2432.0 2051.5	4656.3	116.4
MASSETER MIDDLE FIBRES	1298.5 2749.0	-1984.0 1894.5	1913.5 2520.0	4185.0	104.63
MASSETER DEEP ANTERIOR FIBRES	2271.5 2291.0	-1238.5 1416.5	1608.0 2295.5	2742.64	68.57
MASSETER DEEP.POSTERIOR FIBRES	1477.5 829.0	-439.0 920.5	1598.5 2580.5	1798.09	44.95
LATERAL PTERYGOID FIBRES	21.5 1378.5	425.0 406.0	825.5 848.0	1357.33	33.93
MEDIAL PTERYGOID DEEP FIBRES (lateral)	980.0 1668.0	-1696.5 254.5	1177.5 469.5	2186.55	54.60
MEDIAL PTERYGOID SUPERFICAL FIBRES (medial)	1031.5 2591.0	-2183.0 245.5	788.5 349.5	2919.31	72.98

In an earlier study an attempt was made to quantify the amount of distortion or magnification inherent in the X-ray images (for method see Ch 4). This involved digitising the wires in the three specimens. In the tables on pages 210-212 the first three columns give the corrected digitised coordinates for origin and insertion of each wire. The top figure is origin and the lower insertion. The coordinates in each plane are given in the three columns marked X, Y and Z. Columns 4 and 5 give the length of the individual muscle fibre wires calculated as outlined in chapter 4 from the equation:

$$L=([x_1-x_2]^2 +[y_1-y_2]^2+[z_1-z_2]^2)^{.5}$$

The answer is expressed in the number of digitiser points in column 4. This result was converted into mm the number of digitiser points to the mm being calculated using the known length of one of the metal axes. The use of this method showed the digitised length of each muscle fibre approximated that obtained by the direct measurement of each wire upon its removal from the muscle element confirming the accuracy of the procedure. As a result the same film object distance of was used in the final study.

6.2 RESULTS; PHYSIOLOGICAL CROSS-SECTIONAL AREA

The physiological cross-sectional areas of the masticatory muscles of the Australian Merino sheep are tabulated below. These results were obtained as outlined in Chapter 4 via the use of Computer assisted tomography (CT) studies. These results closely correspond with those of Schumacher [1961] and compare favourably with those of the human masticatory muscles given the relative differences in size between the two species. These values are further discussed in Chapter 7.

Muscle group	left	right	mean
Temporalis posterior fibres	2.30	2.25	2.28
Temporalis anterior fibres	1.39	1.36	1.38
Masseter superior fibres	3.12	2.90	3.01
Masseter middle fibres	4.50	4.26	4.38
Masseter deep anterior fibres	0.95	0.92	0.94
Masseter deep posterior fibres	1.73	1.64	1.69
Lateral pterygoid	0.90	0.92	0.91
Medial pterygoid deep fibres (lateral)	2.49	2.13	2.31
Medial pterygoid superficial fibres (medial)	3.11	2.67	2.89

6.3 TEMPOROMANDIBULAR JOINT REACTION FORCE (TMJRF); THE COMPUTER CALCULATION.

The required input data for the computer program is;

a.) The digitised coordinates for each of the specimens. These include the origin and insertion of each of the muscle groups as well as the position of the bite points 1, 2 and 3 and the presumed location of the TMJ reaction force in each specimen.

b.)Values for PCS of each of the masticatory muscle or subunits.

c.) An intrinsic muscle strength constant; 0.39*10^6 N/m^2.

Once inputted the program can construct mandibular force vectors schematically illustrated in fig 6.

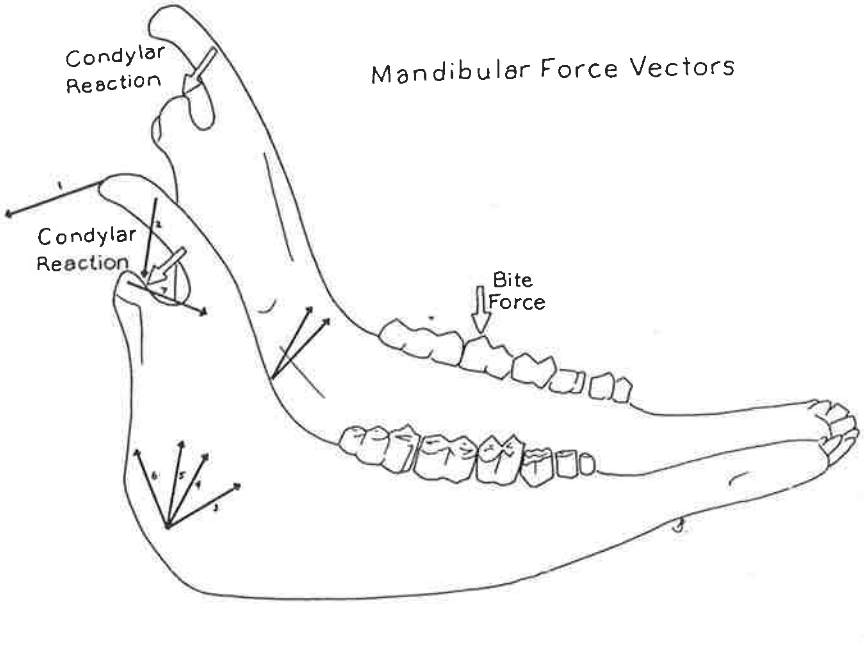


Fig 6.

The computer is thus able to calculate a value for TMJ reaction force for each of the specimens. These were;

Sheep A	At bite point 1	134.47
	At bite point 2	292.32
	At bite point 3	584.00
Sheep B	At bite point 1	140.16
	At bite point 2	315.00
	At bite point 3	673.32
Sheep C	At bite point 1	266.45
	At bite point 2	762.70
	At bite point 3	1485.14

Details of the functions involved in the computation are given in detail in Chapter 4. These results compare favourably with the maximum predicted value of 500N obtained in the human [Koolstra et al 1988]. For further discussion see Chapter 7.

CHAPTER SEVEN

DISCUSSION

DISCUSSION ANATOMY

A comparison of the masticatory apparatus of the human and sheep reveals broad similarities as well as significant morphological and functional differences. The sheep is an ungulate; a hoofed mammal that feeds on plants. Sheep digestion includes the process of rumination and regurgitation of the food bolus. The continual grinding and regrinding of tough plant material in the ruminant places high stresses on the teeth. Large masticatory forces are required to assist in the breakdown of plant cell walls.

By contrast carnivores slice and cut meat into portions that are quickly swallowed. The teeth and jaws are more specialised for the prehension and crushing of prey than for its comminution. There is a correspondingly greater emphasis on digestion for the breakdown of food. Man as an omnivore occupies a somewhat intermediate position combining features of both types of masticatory system harmoniously. Human teeth are adapted so as to be able to chew every type of food.

This study has highlighted some functional morphological similarities in osteological, muscle and the articular disc features of sheep and man. The following observations have been made. The sheep condyle is located high above the occlusal plane; a situation duplicated in man. Condylar orientation is similar in that they both have a perpendicular relation to the mid sagittal plane. There is some conformity in condylar morphology in that both species the condyle forms a broad flat articular surface to the glenoid fossa. Its surface is oval and convex antero-posteriorly and larger in its medio-lateral dimension.

Although the glenoid fossa in both sheep and man is shallow the sheep lacks the sigmoidal shape of the human articular surface. There is no articular eminence and the post glenoid structures are medially rather than laterally placed. The shape of the fossa in both species allows lateral movements but these are much larger in the sheep.

Little hinge movement is necessary for plucking food. The arrangement of the masticatory musculature reflects the predominance of lateral movements in the sheep and gape is severely limited. The functional muscular pair of the medial pterygoid and particularly the masseter are more well developed in the ungulate. The masseter is multipennate with well defined tissue septa dividing it into three distinct layers. The human masseter has two layers and the medial pterygoid two. The human temporalis is considerably more well developed than it is in sheep. Differences in the bulk of the temporalis relate to the conformity of some human masticatory structures to the carnivorian scheme. These differences reflect a balance of features between the two groups which is absent in the sheep.

This study has identified some discrepancies in the English language literature concerning the morphology of some of the sheep masticatory muscles. May [1970] describes a muscle occupying the medial surface of the mandible as the lateral pterygoid. This muscle arose from the ptyergopalatine fossa and from the base of the coronoid process of the sphenoid bone. The muscle inserted onto the medial surface of the mandible from the base of the coronoid process to the junction of the horizontal and vertical rami of the mandible. Whether the muscle arose from the medial or lateral aspect of the medial or lateral pterygoid plates was not discussed. A distinct insertion onto the medial pole of the mandibular condyle was not described. These descriptions are incomplete in that important morphological features have escaped description.

A more extensive insertion to the rostromedial border of the condyle rather than to the medial pole has been described. The results of this present study however suggest that the medial pterygoid consists of two distinct layers. The muscle described by previous authors may have been that of the superficial medial pterygoid. This muscle is closest to the mandibular ramus and is partially covered by the deep layer of the medial pterygoid. That this muscle should consist of two layers is conceivable given the multilayered structure of the masseter and the predominantly lateral directions of masticatory movement. Although the muscle described seems to be a part of the medial pterygoid the normal functions of the lateral pterygoid have been ascribed to it [May 1970].

In this study the lateral pterygoid is identified as a separate muscle arising from the lateral aspect of the lateral lamina of the pterygoid process of the sphenoid bone. The muscle has a distinct point of attachment on the medial pole of the mandibular condyle. As such this is a muscle that has escaped description by some authors. This modified description makes the description of the masticatory muscles somewhat more analogous to that found in the human. Both the human and sheep medial pterygoid muscles have two parts. The longer fibres of the masseter and its division into three separate parts remain significant differences between human and sheep masticatory musculature.

Significant differences exist between the human and sheep dentition. These differences relate to tooth and root morphology. The feature of continual eruption has much less significance in the human as does the ungulate dentition which experiences intensive wear. The human dental arch lacks the large diastema between anterior and posterior segments as well as the functional integrity of these separate dental units. Even more significance can be attached to the anisognathic state of the ungulates which precludes simultaneous bilateral occlusion. This has an effect on the possible masticatory patterns. Simultaneous occlusion of both anterior and posterior segments as well as bilateral occlusion is an important identifying feature of the human dentition but is a situation that is unlikely to occur in ungulate mastication.

Direct comparison of the sheep and human temporomandibular joint disc shows substantial differences. In many respects the structure of the sheep articular disc can be considered unusual. Both the human and sheep have a biconcave structure with the sheep disc being a somewhat thinner structure [Gilbe 1973]. The structure of the disc in the joint in the sheep is determined by the forces occurring in the joint and the overall thickness of the meniscus in a particular animal may relate to the degree of stress encountered in function [Gilbe 1975]. Measurements in the human specimen are 370 microns over the the articular eminence, 75 microns over the roof of the glenoid fossa, 150 microns over the post glenoid tubercle. Corresponding measurements in the sheep were 100, 40, and 60 microns respectively [Murphy 1965]. These measurements indicate that the sheep disc is substantially thinner than human one. The measurements however do not consider the histological structure of these two joints. Elastic tissue and cartilage can be found in the centre of the sheep disc. Although this is not a feature unique to the sheep it is readily apparent and its presence may confer additional resilience to the disc in function [Gilbe 1973].

The human joint is known to contain retrodiscal tissue comprising a thick layer of loose and vascularised connective tissue. This tissue is fused to the posterior wall of the anterior capsule and is known to contain some elastic tissue. This tissue has been ascribed the function of retracting the disc after it has been drawn forward in protrusive movements of the mandible. In the Australian Merino sheep the meniscus is thickened anteriorly but narrows as it merges into vascular sinusoids. The "retrodiscal tissues" are therefore anterior rather than posterior. Although anteriorly located sinusoids have been described in relation to the disc of the Rhesus monkey these are not as numerous as in the sheep [Ramfjord et al 1971].

As in humans most of the movement of the TMJ disc occurs in the superior joint cavity. The fibrous attachment of the temporomandibular joint to the cranium in the sheep and its strong but lax capsule permits a wider range of condylar movements than that which is provided by the human attachment tissues.

The unfused symphysis effectively functions as a third joint to the jaw. This joint has its own connective tissue and nerve supply and is capable of compensatory movements during mastication [Scapino 1965]. The anisognathic state of the sheep mandible means only one side of the jaw can be in occlusion at any particular time [Schumacher 1961]. The joint allows a degree of rotation of each hemi-mandible about its long axis [Beecher 1977]. Small degrees of rotation allow the dentition to be more precisely aligned affording greater masticatory efficiency.

Between species the shape of the symphysis and its pattern of interdigitation will determine the range of movement possible at the joint. Movement at the symphysis affects the range of condylar rotation and translation. In this way the bony morphology of the condyle itself can be related to the shape of the mandibular symphysis [Scapino 1965]. Shearing stresses have been demonstrated at the mandibular symphysis in man [Hylander 1986]. By contrast however the human mandibular symphysis is fused. Although twisting movements about the mandibular corpus can occur this is limited by the solid and indeed buttressed structure of the symphysis. Similarly the dental arches cannot be independently rotated along the long axis of the mandible. These adaptions are less important in the isognathic human whose mandible functions as a single unit in mastication.

DISCUSSION BIOMECHANICS

A review of the biomechanical literature relevant to the TMJ shows that it is now generally accepted that the joint is loaded during biting and chewing. Although this issue was at one time controversial there is now a large body of evidence in support of this conclusion. The aim of this study is to demonstrate that the sheep temporomandibular joint is also loaded.

A biomechanical analysis of the sheep skull suggests that, unlike the human, the transmission of force through the facial skeleton is not canine but molar based. The structure of the maxilla is weak anteriorly and exceedingly sturdy posteriorly. Powerful bony buttresses support the maxillary molar dentition. The mandible is long and slender again being reinforced for medio-lateral movement.

Detailed investigation of the strength of the sheep mandibular condyle that might suggest its load bearing capabilities have not yet been undertaken. Hylander [1975] showed that despite its slender structure the human condylar neck was capable of enduring a shearing reactive force of 610 N. Ultrastructural studies of the crystalline axes of the appatite of the sheep mandible have not been performed. However examination of the trabecular patterns have shown that they are highly orientated to the proposed directions of the stresses of mastication. This suggests significant forces are directed through these trabeculations from the condyle to the angle of the mandible [Dovitch and Herzberg 1968].

Without doubt the determination of stress and load at the human joint has proved extremely difficult. The difficulties encountered in determining the magnitude and direction of the muscle forces calculation of TMJ reaction force has been thought to be too imprecise for a quantitative analysis of joint load [Throckmorton and Throckmorton 1985]. The invasive nature of the direct determination of temporomandibular loads has meant that these techniques are only applicable to animal models. As a result mathematical models of the human masticatory system have been used as the mainstay of research. These models have not been subject to experimental verification. Due to technical difficulties the in-vivo measurement of TMJ reaction force in animals has met with only limited success. It is hoped that in the future the sheep may provide a suitable animal in which to verify the conclusions of the mathematical model described by this thesis.

In order to construct a model of biomechanical function in the sheep one could imagine that one could simply select the most substantiated human model and apply the values for muscle cross sectional area and length etc. in the sheep to obtain a result. This study, in highlighting the morphologic and functional differences between the species, shows that this is not possible. Studies of mandibular biomechanics in the sheep also face the same difficulties encountered in the human. Although there are problems in the direct extrapolation of human data to the sheep the broad principles determining the direction and magnitude of the joint reaction force have been usefully applied in this study.

The generation of a spatial reference plane and orthogonal axis with which to represent muscle vectors has been performed in a number of human studies [Baron and Debussy 1979, Osborn and Baragar 1985, Smith et al 1986, Koolstra et al 1988, Falkenstrom 1990]. Error is induced in recording the origins and insertions both in the radiographic determination of these points and in their electronic recording on a digitiser. A single operator was used to digitise all of the X-rays and all of the X-rays were digitised twice. It is felt that the main source of error induced is probably related to X-ray malalignment problems. This can be seen in the mismatch displayed between the digitised X- ray results for sheep B and sheep C (see chapter 6 results). The size of the error in measurement of the length of the unit vectors however was small (see Chapter 4 Materials and methods).

A major problem encountered in modelling of the masticatory system is the determination of the lines of muscular action. Perhaps even more so than the human the sheep has broad multipennate muscles, large areas of attachment and in some cases widely varying fibre directions. This variability necessitated the anatomical studies that were undertaken in this thesis.

The careful dissection and implantation of wires in the muscle bellies in the predominant fibre direction of each of the masticatory muscles is at best a crude estimation of a muscle's line of action. Similar techniques have been used in human studies. This method may provide a more accurate measure than the use of steel balls and pooled linear measurements that have been used in other studies as the wires position is recorded in three dimensions throughout it's length in the subsequent radiographs.

The radiographic image of the wire implanted into the muscle gave an indication of the origin and insertion as well as the line of action of each muscle. As part of the construction of the mandibular force vectors the length of the muscle fibres were determined mathematically from the digitised X- ray films as described in chapter 4. The length of the wires had been measured with a rule directly before implantation and after their removal before the muscles weight and volume was determined. A comparison of these direct measurements with those derived mathematically showed a maximum error of +/- 1mm for all of the wires and as such the error in measurement was thought to be small.

As often as possible the muscles were divided into functional subunits. This study has shown a degree of complexity in all of the sheep masticatory muscles. Three masseteric layers have been defined and some have suggested a that a fourth layer the zygomaticomandibularis exists. At least some of this complexity is due to the blending of fibres which may occur at any level. It is difficult to account for this complex morphology in a single line of muscle action. Dynamic variability in the line of muscle action and the question of uniform activation of a given muscle cannot be accounted for by this method.

Further information on the pattern of dynamic muscle recruitment during function could be obtained from EMG studies. All of the muscles of mastication have been considered in this study. The lateral pterygoid muscle muscle of the sheep is less easily divided into the superior and inferior heads described in human studies. A few small slips of muscle can be identified inserting into the disc. These fibres have essentially the same direction as the main part of that muscle but are felt to play more of a role in stabilising the disc condyle complex than in the generation of occlusal force.

In this study all muscles were assumed to contribute to biomechanical function so all were included in the calculation of TMJRF. Whether all muscles contribute to the production of maximum TMJ reaction force in the sheep is not known. In the past many researchers in human biomechanics have chosen to omit certain muscles from their calculations. Koolstra [1988] suggested that the pattern of muscle recruitment necessary to generate large bite forces involves the maximal activation of most muscle elements with the exception of the lateral pterygoid. Later investigators have suggested that whilst nearly all muscles are recruited maximally in vertical bites this is not the case for oblique directions [van Eijden 1989].

An ideal experiment would involve the recording of the relative level of EMG activity in as many muscles and subunits of muscles as possible. Investigations to characterise the EMG activity of the muscles in mastication is in progress [Hirakawa and Finn unpublished data] but measurement of EMG activity in maximal static bite conditions has not been undertaken. Koolstra et al [1988] have suggested that the pattern of recruitment of masticatory muscle does not vary as bite force is increased. This observation has been used as an optimisation criteria as means of simplifying the variables involved in his calculation of TMJRF. This model has not applied additional criteria to define a unique solution of muscle recruitment. Such criteria are used in some human models in order to assume optimum function. These methods then allow solution by linear programming techniques. These methods might equally be applied to the sheep if detailed information could be obtained through further EMG studies during maximal bites.

A major assumption is that physiological cross sections can be used to predict the maximum forces that can be exerted by muscles in spite of differences in fibre types and other muscle characteristics. No attempt to classify fibre type has been undertaken in this thesis. A number of animal studies have been undertaken in the cat and pig. Suzuki [1977] has undertaken a comparative histochemical study of the masseter of cattle, sheep, swine, dog, guinea pig and rat. Suzuki's results suggest that these fibres may be of the slow twitch type. The actual implication fibre type will have on the generation of TMJRF has not been quantified.

The non invasive nature of human studies have demanded established average estimates for the PCS of the various masticatory muscles be used in mathematical modelling [Schumacher 1961]. More recently CT generated information has allowed in-vivo estimates of PCS for individual subjects [Nygaard 1983 and Schantz 1983]. These values are thought to be more accurate than the averaged values which had often been derived from the relatively atrophied muscles of cadavers.

The method chosen to determine PCS in this study was the use of CT imaging. It was initially felt that the use of an animal model would allow direct dissection and hence a more accurate measure of such parameters such as muscle weight and cross sectional area. A review of the values obtained in the literature for human PCS of various skeletal muscles by both the Weber [1851] and Buchner [1877] techniques however showed wide variation. Similarly the values obtained by de Jongh et al [1989] by the Weber technique showed great variation from those obtained via the Buchner technique. De Jongh's results also showed a ten fold increase to those obtained by Schumacher [1961] which is the only other report in the literature on the PCS of the masticatory muscles in the sheep.

CT imaging was used to assess the PCS of sheep masticatory muscles was used in this study. The results obtained via this method closely conform to those obtained by Schumacher [1961] for *Ovis Musimon;* an animal that bears a distinct resemblance to the Australian Merino sheep. The results obtained compared favourably with the established values for man considering the various differences in their morphology. The lateral pterygoid of the sheep for example, a similar size to that of the human, had a similar value for PCS whereas the sheep masseter, correspondingly larger, had a larger PCS value. The temporalis of the sheep has a smaller PCS value than that of the larger human muscle. The table below shows the pooled results obtained in this study compared with the averaged values for man [Koolstra et al 1988] and those obtained for the sheep from the Schumacher [1961] and de Jongh [1989] studies. Various muscles were subdivided differently by different authors. For the purposes of comparison table **(7.1)** uses the sum of the PCS values for each of the muscular components to yield a total PCS for each masticatory muscle.

	SHEEP VALUES			HUMAN VALUES
	Schumacher [1961]	de Jongh [1989]	Finn [1994]	Koolstra [1988]
Temporalis	3.9	17.7	3.66	9.1
Masseter	9.8	55.0	10.03	8.0
Lateral pterygoid	0.8	1.90	0.91	0.8
Medial pterygoid	5.8	11.4	5.20	7.9

Table 7.1

Measurements of bite force in the Australian Merino sheep were not made in this study. Some of the anatomical features of the sheep skull make the use of conventional bite force transducers extremely difficult. The problem of access to the posteriorly located molar platform is obvious. The animal has a small gape and there are buccal tissues which would impede all but a specially designed transducer or measurement of bite force via a surgically created transbuccal access. A transducer would need to be appropriate to the steep medio-lateral inclined cusps of the sheep dentition. Osborn and Baragar [1987] suggest that the human condyle is most stable against forces produced in the sagittal plane and least stable against medio-laterally directed forces. Given the predominantly medio-lateral direction of the movement of the sheep jaw in mastication one might expect that the condyle is in the position of greatest stability in this plane. As a consequence maximal bite forces in the sheep may be laterally directed. Any bite force transducer must be sensitive to forces generated in this direction.

Problems could be anticipated in making the sheep achieve maximal bite force. Similar problems have been recorded in human subjects where variation in bite force can occur because of differences in the motivation of subjects. Motivation affects the individual's ability to activate the muscle completely and ignore discomfort or pain [Weijs and Hillen 1984]. The grazing habits of the Australian Merino sheep have been described as being "energy conscious" [Baker 1994]. The animal seeks out those foodstuffs that are easy to chew. Sheep loose weight rapidly when grazed on dry pasture preferring to eat less of those pastures that prove difficult eating. Hohl and Tucek [1982] applied electric current to the motor tract of the trigeminal nerve via intracranial implants but this method has been questioned as to how realistically this represents normal masticatory function or the generation of maximal bite force.

In this study it has been assumed that the calculated bite force vector is perpendicular to the occlusal plane. Koolstra [1988] has noted that bite force depends on bite force direction. It has been suggested that the coefficient of synovial fluid is such that it directs condylar reaction force obliquely laterally in a shearing rather than a upwardly directed force. Bite force direction is also dependent on cusp morphology. As aforementioned bite force direction in the sheep may well be perpendicular to the sharply sloped occlusal surface of the sheep molars as suggested by Badoux [1965]. The exact direction of the bite force vector may continually vary as the orientation of the occlusal surfaces to the long axis of the mandible changes along the curved dental arch. This problem is further compounded by the ability of the dentaries to individually rotate along their long axis [Scapino 1965]. Rotation of the mandibular halves would alter the slope of the occlusal surfaces to the perpendicular. This rotation is thought to convey masticatory efficiency [Greaves 1978] but in doing so it may continually vary the bite force direction and therefore TMJRF. Barbenel [1972] demonstrated that increasing the angle between the occlusal load and the occlusal plane increased TMJRF. Small adjustments in the symphysis may serve to limit the occlusal load angle and may be a mechanism by which the sheep keeps joint loads to a minimum.

The maximum magnitude of bite force and thus TMJRF depends on the location of the bite point and on mandibular position [Osborn and Baragar 1985]. As the sheep is capable of minimal gape variation due to changes in the vertical position of the mandible were assumed to be minimal. Three simulations for bite force were undertaken from the premolar to molar region. It is this area that provides the dental element dedicated to mastication. Relatively low bite forces could be expected anteriorly and high bite forces posteriorly. Despite the more anterior position of the mandibular incisors and the longer lever arm to the joint these teeth are not considered. The anterior dental element and its fleshy maxillary articulation is used in the cropping of vegetation. The measurement of bite force against the pliable maxillary bite pad might present even further technical difficulties in the measurement of bite force. Little gape is required in this process and it is assumed that less force will be manifest as joint reaction force compared with the grinding of cellulose on the molar platform. Greater joint reaction forces are experienced as the bite point shifts away from the condylar axis. The molar platform thus efficiently occupies a posterior position close to the joint. In this position the torque arm is smallest and large occlusal forces may be generated for a correspondingly low TMJRF. Conversely the anterior maxilla where large TMJRF could be generated is edentulous and generates minimal occlusal load in the cropping of grass.

All mathematical models have indicated that the joint force is greatest for incisive bites. Some indicate that this can be 60% of the bite force. The absence of upper incisors and its replacement with fleshy pad on the anterior maxilla in the sheep precludes the generation of large incisal bite forces and spare the joint from the maximum reaction force the ovine masticatory muscles could generate. This may be further mechanism that shields the sheep joint from excessive force. A logical extrapolation from these studies is that joint reaction force rarely exceeds bite force and is in most cases is considerably less than its value. A measurement of maximum bite force therefore provides a generous upper limit to maximum TMJ reaction force. The observation that, at least in human subjects, bite forces has been shown to have a wide range of individual variability may make this concept less useful. In normal function however one could anticipate that condylar reaction force would be low as bite forces during chewing are low.

Errors in this model and the calculations made may also stem from the presumed direction of the TMJ force and the assumption of unilateral bite force. One of the principle questions that must be asked is what is the direction of the joint reaction force? Most of the models reviewed have positioned this force perpendicular to the slope of the articular eminence. This assumption has been made on the basis of the anatomical structure and reinforcements of the eminence and based on the assumption that any frictional force in the TMJ can be neglected. This assumption is supported by the results of mathematical modelling which shows a low resultant joint reaction force if the forces of mastication are directed at right angles to the eminence.

The same principles have been applied to the sheep model in this study. After careful consideration of the relatively flat glenoid and the predominantly medio-lateral direction of condylar movement in the sheep a line perpendicular to the gradual slope of the eminence was constructed. We have been encouraged that the direction shown is the exact reciprocal to some of the predominant fibres of the anterior temporalis. These fibres originates from the long curved coronoid high above the joint and may provide a stress relieving method as first suggested by Scott [1955]. This situation may be analogous to the human where Osborn and Baragar [1985] have found evidence to suggest that part of the temporalis serves to off-load the joint.

Even though it seems likely that a wide range of temporomandibular joint reaction force exists there has been great variability in prediction of an upper limit to this force. Falkenstrom [1993] has tabulated the maximum TMJ reaction forces predicted by the mathematical models of Prium [1980], Osborn [1985] and Koolstra [1988]. An overview of these figures suggest a maximum human TMJ reaction force of 500N as a reasonable estimate. Even higher forces have been predicted by some models, such as 1100 N [Prium 1980] but in this and even the smaller figures the effect of biological inhibition has not been taken into account. An average maximum value of 914 N of sheep TMJRF at the M3 bite point has been recorded in this study. A comparison of the results obtained by the various mathematical models and the results of this study are presented in **table 7.2**

Author	I1	C1	P1	M1	M2	M3
Prium *et al*						400-1100
Osborn *et al*					500	
Koolstra *et al*	470					310
Finn (Sheep data)				180	457	914

Tab 7.2 (modified after Falkenstrom 1993)

The TMJRF results obtained for the sheep are proportionately larger with those obtained for the human. The result is consistent with lever mechanics and the greater forces expected in the sheep given the sheep's special morphology and diet. Although studies in the overall incidence of degenerative osteoarthritis in the sheep population have not been undertaken the continuous nature of masticatory activity in the sheep and the lack of pathology in normal controls suggest that adequate compensatory mechanisms exist to cope with these levels of TMJRF. Despite these compensatory mechanisms osteoarthritis may be experimentally induced [Ishimaru and Goss 1992].

Prium et al [1980] showed that TMJRF increased nearly linearly with increasing bite forces. Theoretically determined bite forces are larger than those determined experimentally as these calculations do not take into account biological restraints such as centrally mediated inhibition [Falkenstrom 1990]. This inhibition may represent the increased activation of antagonists at higher bite forces and would cause a similar reduction in TMJRF [Prium et al 1980]. Activation of the antagonist groups would be detectable by EMG. This factor may account for differences between the estimated TMJ reaction force and that which could be verified experimentally.

In the human two basic static bite situations can be distinguished. These are bilateral and unilateral bites. In order to reduce the complexity of the system most mathematical models assume symmetry in the sagittal plane and the problem becomes a two dimensional one. In the sheep the state of anisognathy may means that all bites are unilateral. The effect of the freely mobile symphysis on the transmission of force from one side of the mandible to the other has not been established. For these reasons this model has considered each side of the mandible as an independently functioning unit. The muscles on one side of the mandible and the TMJRF for that side only are considered. To what extent this is true and to what extent the symphysis affords the independent function of the mandibular halves and affects TMJRF is not known.

It is usual to divide the total condylar load between working and non working sides. Hylander [1987] suggests that the balancing and working side condyles experience force in a 2 : 1 ratio. Similar estimates have established the total force generated by the masticatory system occlusal load makes up about 45-65% and the condyle 25% on the balancing side and 10-15% on the working side. In humans during a maximal unilateral bite the recruitment pattern for the working and non balancing sides shows different patterns. Muscles on the balancing side are less active while the joint reaction force on the balancing side is considerably larger than on the working side [Hatcher et al 1986, Hylander 1983, Smith et al 1986, Faulkner et al 1987, Koolstra et al 1988]. In these situations Hylander [1985] describes an approximate division of load between working and non working sides in a 2:3 ratio.

As can be seen from the limited EMG studies that have been undertaken in the sheep the concept of the division of condylar load between the working and non working sides deserves extra consideration in the sheep model. The maxima for elevator muscle firing on the working side often shows a larger spread in time then when the the same muscles fire in a balancing position. Higher peaks of activity can recorded on both working and balancing sides, with the temporal muscle showing little difference in firing between the working and balancing sides [de Jongh et al 1989]. Determining the division of the load between the condyles, if this occurs in the sheep, awaits further experimentation to establish the effect of the mobile symphysis and the performance of quantitative EMG recordings during maximal bite force situations. The observation that working side EMG is greater than balancing side activity [Hirakawa Finn unpublished data] supports the concept of individual function of the mandibular halves and the assumption of unilateral bite force.

A future investigation could be directed to measuring the bite force and incorporating this information in the calculation of TMJRF. The parallel use of integrated EMG during maximum clenching in various functional and pathologic states would assist in defining the patterns of muscle recruitment and establish the division of condylar load. Direct intracapsular measurement with its considerable technical difficulties would also serve to experimentally verify the results of this model. The fusion of the mandibular symphysis via the application of a mandibular bone plate could easily be performed. If this modification were to induce degenerative arthritis at the TMJ a role for the symphysis in stress distribution or in balance of the mandibular components in wide lateral excursion could be demonstrated. Loss of lateral pterygoid function is an inevitable consequence of condylar resection. The effect of the loss of lateral pterygoid function by its detachment either with or without condylar resection could be investigated. Such loss would be likely to affect the patterns of muscle recruitment and alter the load on the contralateral joint. These changes might lead to degenerative processes in the opposite joint and may suggest a reason for the uniformly poor results of total TMJ replacements which do not replace lateral pterygoid function.

Anatomical and biomechanical variation between species will always prevent the direct extrapolation of the findings of sheep TMJ experimentation to humans. A thorough investigation and definition of these differences however helps us understand the sheep model and increases its validity as a model of temporomandibular joint pathogenesis. Treatment of TMJ pathosis in a fully defined model allows the development of treatment modalities which in some circumstances may be used in humans.

The larger forces and continual activity of the sheep masticatory apparatus would equate to several years of function in the human masticatory system. Wear particle production from biomaterials could be expected to be high and potential foreign body reactions would be quickly produced [Bosanquet 1988]. The harsh conditions present in the sheep jaw joint may in fact be an ideal test bed for treatments being contemplated in the human. A treatment modality that was successful in the sheep would be very likely to survive the less extreme conditions of the human joint. The model can be considered appropriate for any study that requires a highly stressed masticatory system.

In conclusion this study has attempted to investigate the anatomy and biomechanics of the Australian Merino sheep. The anatomy is fully described and several important anatomical and functional differences between the sheep and human masticatory system have been defined. The mathematical model described here estimates condylar reaction force to be in the order of 200-900 N depending on the position of the bite point. These results compare favourably with the estimate of TMJRF in the human of 513N [Koolstra 1988]. This value is consistent with lever mechanics and with the greater forces expected due to sheep morphology and diet. Further experimentation to better characterise each of the variables described in this study is required. If possible the values obtained for maximal TMJRF should be experimentally verified. Complete characterisation of these variables enhances the sheep model and increases its usefulness in understanding and modelling human temporomandibular joint pathogenesis.

Appendix I

THE PREPARATION OF SKELETAL MATERIAL

All skeletal material used in this study was prepared using the following protocol which was designed by the Forensic Odontology Unit, Faculty of Dentistry, The University of Adelaide.

Soft Tissue Digestion;

5 grams Papain
100 milligrams EDTA*
20 milligrams L Cysteine Hydrochloride
10 litres water

Add Papain, ETDA and Cysteine to warm water and mix well. Bring to boil slowly. Simmer for two hours. Cool. Remove residual soft tissue.

CAUTION: Avoid inhaling fumes - it is advisable to wear protective mask and rubber gloves.

Removal of fats from bone: Boil in Chloroform for one hour.

Bleach: Hydrogen peroxide (50 vols.) + 0.5ml ammonia per litre H2O2. Wash with running water for 1 hour. Dry.

CAUTION: Avoid skin contact with H_2O_2.

*EDTA: Diaminoethane tetra acetic acid (disodium salt).

Appendix II

LINEAR PROGRAMMING ANALYSIS

Barbenel [1972, 1974] provided a theoretical study of the biomechanics of the temporomandibular joint. A mathematical model of the forces to which the mandible was subject in the stationary phase of mandibular loading was presented.

The following abbreviations were used;

F_M = masseter muscle force
F_I = internal (medial) pterygoid muscle force
F_E = external (lateral) pterygoid muscle force
F_T = temporalis muscle force
L = the magnitude of the occlusal load
R = the temporomandibular joint force

The moment of the load about the intercondylar axis was derived from the formulae;

$$L\,.(Y\cos ¢ + Z\sin ¢)$$

where X and Y were the coordinates of the point at which the line of action of the occlusal load intersected the occlusal plane.

The angle ¢ was the angle at which the line of action of the occlusal load intersects the occlusal plane.

R, the force at the temporomandibular joint, was considered to act at an angle ø to the Y axis.

Three equations of equilibrium are described for Barbenels force system. These can be described and represented numerically as;

1. The sum of the vertical components should be equal to zero:

$$0.84F_M + 0.84F_T + 0.78F_I - 0.17F_E - R \cos ø - L \cos ¢ = 0$$

2. That the sum of all horizontal forces should be equal to zero:

$$0.55F_M - 0.46F_T + 0.50F_I + 0.91F_E - R \sin ø - L \sin ¢ = 0$$

3. That the sum of the moments of the forces is equal to zero (moments were calculated around the intercondylar axis):

$$2.7F_M + 2.6F_T + 2.3F_I - L (Y \cos ¢ + Z \sin ¢) = 0$$

Four additional inequalities were introduced; that is that each of the the muscle forces must be equal or positive. After the method of Grass [1964] a linear programming problem was created.

Linear programming is a method of maximising or minimising a linear function, known as the objective function. This function is subject to constraints in the form of linear equations or inequalities, within the overall limitation that the independent variables cannot be negative

Barbenel chose to investigate two objective functions one where the force at the temporomandibular joint was minimised and another were total muscle force was minimised.

1. Calculation for minimum joint force

$$\frac{1}{\cos \o} (0.84F_M + 0.84F_T + 0.77F_I - 0.17F_E - L \cos ¢)$$

Subject to:

$$2.7F_M + 2.6F_T + 2.3F_T + 2.3F_I - L (X \cos ¢ - Y \sin ¢) = 0$$

2. Calculation for minimum muscle force

The objective function to be minimized is;

$$FM + FT + FI + FE$$

The constraints being the three equations of equilibrium

LINEAR PROGRAMMING TECHNIQUE II

[OSBORN AND BARAGAR 1985]

Because of the great number of variables created in the construction of a model of the masticatory system the mathematical equations of equilibrium are insoluble even under the conditions of static equilibrium. This insolubility is a result of the infinite number of values for muscle tensions and joint reacton forces that can produce the same bite force value. If a function which is linear can be minimized the problem may be solvable using conventional linear programming techniques. Linear functions may be expressed as the sum of the first power of their variables even if each variable needs to be multiplied by some other factor.

Two functions to be minimised were selected. Muscle activity was restricted in such a way that the muscles either combined to

1. Minimize the total muscle force used or,

2. Minimize the joint reaction force

As the conditions for static equilibrium require the sum of vector forces be zero and the vector sums of the torques about a point in space thus the conditions for equilibrium are

$$\sum_{n=1}^{N} M_n + \sum_{k=1}^{K} T_k + \sum_{q=1}^{Q} J_q = 0 \qquad (1)$$

and

$$\sum_{n=1}^{N} r'_n \cdot M_n \quad + \quad \sum_{k=1}^{K} t'_k \cdot T_k \quad + \quad \sum_{q=1}^{Q} s'_q \cdot J_q \quad = \quad 0 \qquad (2)$$

given

M_n = the force of the n th muscle applied at r'_n

T_k = the k th tooth force applied at t'_k

J_q = the q th joint force applied at s'_q

N = the number of muscles

K = the number of bite forces

Q = the number of joint forces

Torques are computed around the mid-point of a line segment joining the centers of the condyles when the jaw is in centric occlusion

The n th muscle exerts a force

$$M_n = m_n \frac{(r_n - r'_n)}{|r_n - r'_n|} \qquad (3)$$

where

M_n = | M_n | as the magnitude of the force

r_n = the point of attachment of the muscle to the skull

M_n = a non-negative variable, bounded above by its saturation value m_n

The combination of equations (1) (2) and (3) yield six equations in $2(N + Q)$ variables. If one joint reaction force for each side of the skull is assumed $Q = 1$ and as 13 muscle elements are described $N = 13$ for a total of 28 variables there is no unique solution. Solutions are obtained by minimization.

Osborn and Baragar next assumed that tension sensors either in the temporomandibular joint or in the muscles themselves had an output f (MJ)

equivalent to $$f = (M J) = \sum_{n=1}^{N} A_n \cdot M_n + \sum_{q=1}^{Q} B_q \cdot J_q \qquad (4)$$

1. Minimize the joint reaction force (J_R)

This is accomplished by choosing $A_n = 0$ for all n in f (M, J) equation (4).

The two B_q are expected to be equal by symmetry to the sagittal plane and can be chosen to be one since the values of M_n and J_q that minimise f (M,J) depend only on the ratios of the coeffecients and not on their magnitudes.

Appendix 3

```
SUB Length


REM: This routine calculates the muscle force vectors, moments around
REM: each of the bite points and the TMJ reaction force



 WIDTH 80
 PALETTE 6,54: COLOR 8,3


CLOSE

REM: Declare shared arrays

SHARED MVEC(),BITE(),TMJ(),MLEN()
SHARED UVEC(),MAG(),PCSA(),TMJM()
SHARED MMNTX(),MMNTY(),MMNTZ()
SHARED SUMX(),SUMY(),SUMZ(),TMJRF()
SHARED RES#,RF(),TMJARM,FIL$

Rdy:

REM: Input and save data into an Edit File to omit muscle
REM: groups"MFORCE.DAT"

    CLS
     COLOR 2,8
     LOCATE 1,1: PRINT "  SAVE DATA INTO EDIT FILE       "
     COLOR 15,12 : LOCATE 4,1: INPUT " FILENAME :- ",FINAM$
     FIL$ = "C:\VEC\" + FINAM$

    PRINT FIL$
    DELAY(1)

    OPEN FIL$ FOR INPUT AS #6

    INPUT #6, FIL$
    INPUT #6,
TMJ(1),TMJ(2),TMJ(3),BITE(1,1),BITE(1,2),BITE(1,3),BITE(2,1),BITE(2,2),BITE(2,3)
,BITE(3,1),BITE(3,2),BITE(3,3)
    INPUT #6,
MVEC(1,1,1),MVEC(1,1,2),MVEC(1,2,1),MVEC(1,2,2),MVEC(1,3,1),MVEC(1,3,2)
    INPUT #6,
MVEC(2,1,1),MVEC(2,1,2),MVEC(2,2,1),MVEC(2,2,2),MVEC(2,3,1),MVEC(2,3,2)
    INPUT #6,
MVEC(3,1,1),MVEC(3,1,2),MVEC(3,2,1),MVEC(3,2,2),MVEC(3,3,1),MVEC(3,3,2)
```

```
          INPUT #6,
MVEC(4,1,1),MVEC(4,1,2),MVEC(4,2,1),MVEC(4,2,2),MVEC(4,3,1),MVEC(4,3,2)
          INPUT #6,
MVEC(5,1,1),MVEC(5,1,2),MVEC(5,2,1),MVEC(5,2,2),MVEC(5,3,1),MVEC(5,3,2)
          INPUT #6,
MVEC(6,1,1),MVEC(6,1,2),MVEC(6,2,1),MVEC(6,2,2),MVEC(6,3,1),MVEC(6,3,2)
          INPUT #6,
MVEC(7,1,1),MVEC(7,1,2),MVEC(7,2,1),MVEC(7,2,2),MVEC(7,3,1),MVEC(7,3,2)
          INPUT #6,
MVEC(8,1,1),MVEC(8,1,2),MVEC(8,2,1),MVEC(8,2,2),MVEC(8,3,1),MVEC(8,3,2)
          INPUT #6,
MVEC(9,1,1),MVEC(9,1,2),MVEC(9,2,1),MVEC(9,2,2),MVEC(9,3,1),MVEC(9,3,2)
          INPUT #6,
PCSA(1),PCSA(2),PCSA(3),PCSA(4),PCSA(5),PCSA(6),PCSA(7),PCSA(8),PCSA(9
)

          OPEN "C:\VEC\MFORCE.DAT" FOR OUTPUT AS #7

          WRITE #7, FIL$
          WRITE #7,
TMJ(1),TMJ(2),TMJ(3),BITE(1,1),BITE(1,2),BITE(1,3),BITE(2,1),BITE(2,2),BITE(2,3)
,BITE(3,1),BITE(3,2),BITE(3,3)
          WRITE #7,
MVEC(1,1,1),MVEC(1,1,2),MVEC(1,2,1),MVEC(1,2,2),MVEC(1,3,1),MVEC(1,3,2)
          WRITE #7,
MVEC(2,1,1),MVEC(2,1,2),MVEC(2,2,1),MVEC(2,2,2),MVEC(2,3,1),MVEC(2,3,2)
          WRITE #7,
MVEC(3,1,1),MVEC(3,1,2),MVEC(3,2,1),MVEC(3,2,2),MVEC(3,3,1),MVEC(3,3,2)
          WRITE #7,
MVEC(4,1,1),MVEC(4,1,2),MVEC(4,2,1),MVEC(4,2,2),MVEC(4,3,1),MVEC(4,3,2)
          WRITE #7,
MVEC(5,1,1),MVEC(5,1,2),MVEC(5,2,1),MVEC(5,2,2),MVEC(5,3,1),MVEC(5,3,2)
          WRITE #7,
MVEC(6,1,1),MVEC(6,1,2),MVEC(6,2,1),MVEC(6,2,2),MVEC(6,3,1),MVEC(6,3,2)
          WRITE #7,
MVEC(7,1,1),MVEC(7,1,2),MVEC(7,2,1),MVEC(7,2,2),MVEC(7,3,1),MVEC(7,3,2)
          WRITE #7,
MVEC(8,1,1),MVEC(8,1,2),MVEC(8,2,1),MVEC(8,2,2),MVEC(8,3,1),MVEC(8,3,2)
          WRITE #7,
MVEC(9,1,1),MVEC(9,1,2),MVEC(9,2,1),MVEC(9,2,2),MVEC(9,3,1),MVEC(9,3,2)
          WRITE #7,
PCSA(1),PCSA(2),PCSA(3),PCSA(4),PCSA(5),PCSA(6),PCSA(7),PCSA(8),PCSA(9
)

          CLOSE #6
          CLOSE #7

       REM:  Convert digitiser points to cm (ie. divide by 400)
```

```
VECLEN:
    FOR A = 1 TO 3
    FOR B = 1 TO 3
     TMJ(A) = TMJ(A)/400
     BITE(B,A) = BITE(B,A)/400
    NEXT B,A

    FOR A = 1 TO 9
     FOR B = 1 TO 3
     FOR C = 1 TO 2
     MVEC(A,B,C) = MVEC(A,B,C)/400
    NEXT C,B,A

REM: Declare intrinsic muscle force constant and PCSA

FORCE:

    INTRINS# = 37

REM: Intrinsic muscle force is expressed in N/cm^2
REM: PCSA is already expressed in cm^2


REM: Calculate muscle force vectors


    FOR A = 1 TO 9
     MLEN(A,1) = (MVEC(A,1,1) - MVEC(A,1,2))
     MLEN(A,2) = (MVEC(A,2,1) - MVEC(A,2,2))
     MLEN(A,3) = (MVEC(A,3,1) - MVEC(A,3,2))
    NEXT A


REM: Calculate unit vectors in x,y,z directions

UVECS:

    FOR C = 1 TO 9
     FOR Z = 1 TO 3
     UVEC(C,Z) = MLEN(C,Z)/SQR(MLEN(C,1)^2 + MLEN(C,2)^2 +
MLEN(C,3)^2)
    NEXT Z,C

REM: Calculate magnitude of resultant muscle force

MAGN:

    FOR Y = 1 TO 3
     MAG(Y) = 0
```

```
     NEXT Y

     FOR Y = 1 TO 3
      FOR D = 1 TO 9
      MAG(Y)= MAG(Y) + UVEC(D,Y)*PCSA(D)*INTRINS#
     NEXT D,Y

     RES# = SQR(MAG(1)^2 + MAG(2)^2 + MAG(3)^2)


   REM: Sum of moments in X,Y,Z planes in static equilibrium

      FOR E = 1 TO 9
       MMNTX(E,1) = UVEC(E,2)*PCSA(E)*INTRINS#*ABS(MVEC(E,3,1) -
BITE(1,3)) + UVEC(E,3)*PCSA(E)*INTRINS#*ABS(MVEC(E,2,1) - BITE(1,2))
       MMNTX(E,2) = UVEC(E,2)*PCSA(E)*INTRINS#*ABS(MVEC(E,3,1) -
BITE(2,3)) + UVEC(E,3)*PCSA(E)*INTRINS#*ABS(MVEC(E,2,1) - BITE(2,2))
       MMNTX(E,3) = UVEC(E,2)*PCSA(E)*INTRINS#*ABS(MVEC(E,3,1) -
BITE(3,3)) + UVEC(E,3)*PCSA(E)*INTRINS#*ABS(MVEC(E,2,1) - BITE(3,2))
       MMNTY(E,1) = UVEC(E,3)*PCSA(E)*INTRINS#*ABS(MVEC(E,1,1) -
BITE(1,1)) + UVEC(E,1)*PCSA(E)*INTRINS#*ABS(MVEC(E,3,1) - BITE(1,3))
       MMNTY(E,2) = UVEC(E,3)*PCSA(E)*INTRINS#*ABS(MVEC(E,1,1) -
BITE(2,1)) + UVEC(E,1)*PCSA(E)*INTRINS#*ABS(MVEC(E,3,1) - BITE(2,3))
       MMNTY(E,3) = UVEC(E,3)*PCSA(E)*INTRINS#*ABS(MVEC(E,1,1) -
BITE(3,1)) + UVEC(E,1)*PCSA(E)*INTRINS#*ABS(MVEC(E,3,1) - BITE(3,3))
       MMNTZ(E,1) = UVEC(E,1)*PCSA(E)*INTRINS#*ABS(MVEC(E,2,1) -
BITE(1,2)) + UVEC(E,2)*PCSA(E)*INTRINS#*ABS(MVEC(E,1,1) - BITE(1,1))
       MMNTZ(E,2) = UVEC(E,1)*PCSA(E)*INTRINS#*ABS(MVEC(E,2,1) -
BITE(2,2)) + UVEC(E,2)*PCSA(E)*INTRINS#*ABS(MVEC(E,1,1) - BITE(2,1))
       MMNTZ(E,3) = UVEC(E,1)*PCSA(E)*INTRINS#*ABS(MVEC(E,2,1) -
BITE(3,2)) + UVEC(E,2)*PCSA(E)*INTRINS#*ABS(MVEC(E,1,1) - BITE(3,1))
      NEXT E


   REM: Sum moments in x,y,z directions

     MMNTX# = 0
     MMNTY# = 0
     MMNTZ# = 0

     FOR G = 1 TO 3
      FOR H = 1 TO 9
      SUMX(G) = MMNTX# + MMNTX(H,G)
      SUMY(G) = MMNTY# + MMNTY(H,G)
      SUMZ(G) = MMNTZ# + MMNTZ(H,G)
     NEXT H,G
```

```
    FOR I = 1 TO 3
     TMJM(I) = SQR(SUMX(I)^2 + SUMY(I)^2 + SUMZ(I)^2)
    NEXT I

MARMTMJ:

REM: Calculate moment arm for TMJ to each bite point

    FOR J = 1 TO 3
     FOR K = 1 TO 3
     TMJARM(J,K)=  ABS(TMJ(K) - BITE(J,K))
    NEXT K,J

REM: Calculate TMJ reaction force using sum of moments in static equilibrium
REM: for each of x,y,z directions.

    FOR L = 1 TO 3
     TMJRF(L,1) = SUMX(L)/TMJARM(L,1)
     TMJRF(L,2) = SUMY(L)/TMJARM(L,2)
     TMJRF(L,3) = SUMZ(L)/TMJARM(L,3)
    NEXT L

    FOR P = 1 TO 3
     RF(P) = SQR(TMJRF(P,1)^2 + TMJRF(P,2)^2 + TMJRF(P,3)^2)
    NEXT P

REM: The presumed direction of this force is acting in
REM: the opposite direction to muscle force 2

COLOR 31,12
CLS
     LOCATE 10,5: PRINT "CALCULATIONS COMPLETE"

DELAY(1)
GOTO START

END SUB
```

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