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THE RELATIONSHIP BETWEEN WHIPLASH AND TEMPOROMANDIBULAR JOINT DYSFUNCTION

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SUMMARY

"Whiplash" describes the mechanism of retroflexion followed by flexion of the neck that occurs when the occupant of a motor vehicle is impacted from behind by another vehicle with the occupant of the impacted vehicle being unaware of the impending impact.

This thesis describes work carried out to investigate the possibility that injury can occur to the jaw joint (i.e. the temporomandibular joint) during a "whiplash" event.

A review of the literature showed that there is a body of clinical evidence pointing to an aetiological relationship between "whiplash" and injuries to the TMJ. However much as in an earlier debate regarding injury to the cervical region, these claims have led to dispute regarding the viability of such injuries occurring particularly as the jaw is not subjected to direct trauma in the classical "whiplash" event.

The anatomy of the TMJ and the surrounding region was studied, with particular reference made to the individual variations in the superior and inferior heads of the lateral pterygoid muscle, especially the attachments of the superior head to the TMJ disc and condyle of the mandible respectively. This revealed a considerable variation in the size and attachment of the two heads of the muscle between one individual and another and also variations in the attachments of the superior head to the disc and condyle respectively.

Based on these findings a theoretical analysis was performed, which showed that the claims made by some authors maintaining that the superior head of the lateral pterygoid plays a role in the displacement of the disc may be valid.

It was concluded that some people may be more susceptible to TMJ injury depending on the proportion of the fibres of the superior head which insert into the disc and condyle respectively. It was also concluded that the variations of these attachments may have an important role in the displacement of the disc, which may occur due to complete displacement at the time of the accident or more gradual displacement due to normal activity of the muscle on a partially ruptured attachment.

A theoretical model was developed in order to predict the motions and forces arising in the TMJ region during the "whiplash" event. This showed that the inertial properties of the mandible resulted in mouth opening during retroflexion and mouth closing during flexion. The model also showed that forces of approximately 180 Newtons were sustained by the lateral TMJ ligament and the attachment of the TMJ disc to the lateral pole of the mandible.

Experimental tests were carried out on cadaveric specimens. In these tests the lateral ligament failed with a load of approximately 94N. However the attachment of the disc to the lateral

pole failed at much smaller loads of the order of 5N. This showed that the lateral ligament of the TMJ and particularly the attachment of the disc to the lateral pole of the condyle are vulnerable to forces that may be sustained in a "whiplash" event.

The above investigations showed that the predicted forces acting on the joint were well in excess of those needed to cause failure in the TMJ ligament and particularly in the attachment of the disc to the lateral pole of the condyle. This indicates that the concept of injury to the TMJ during "whiplash" is a sound one.

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Chapter 1 Introduction

1.1 Background to "whiplash" concept

The term "whiplash" has been used for many years to describe the mechanism of retroflexion followed by flexion of the neck which occurs to the occupant of a motor vehicle, which is struck from behind by another vehicle with the occupant of the impacted vehicle being unaware of the impending impact.
Other types of vehicular (and non-vehicular) impacts can result in "whiplash" with different combinations and sequences of retroflexion, flexion and lateral neck movements. However the most common cause of "whiplash" is the low velocity rear impact automobile accident.

Although the term "whiplash" is imprecise there are valid comparisons between the oscillating movements of the head and neck which occur in such events and those which occur when a whip is cracked. Thus the handle of the whip can be considered analogous to the human torso and the tip of the whip analogous to the human head.
Other terms which have been used to describe this phenomenon include the inapt "coup de lapin" (rabbit's blow) in French and the more appropriate "schleudertrauma" (slinging trauma) in German.

Over 100 years ago neck injuries due to "whiplash" were reported in railway accidents. These occurred to individuals who were sitting with their backs to the engine when the train came to a sudden halt. At that time they were referred to as "railway spine injuries (Evans 1996).
This type of injury became a clinically significant problem in the U.S.A., in the 1940's when "whiplash" type injuries were reported by pilots of fighter aircraft, which were rapidly accelerated at take off by a catapult mechanism from the decks of aircraft carriers (MacNab1964). These injuries were eliminated by constructing the seat and head rest to the individual pilots' needs so that the head was supported adequately and was thus accelerated at the same time and rate as the rest of the body.

Unfortunately the automobile industry was slow to put this preventive information into use. To the present day although the legislation making headrests mandatory is adhered to, the "design" of many makes the headrests incapable of preventing the movements which occur in a whiplash event. Furthermore some headrests actually aggravate the problem.

The first use of the term "whiplash" may have been by Crowe in 1928 in a symposium at which he delivered a report on 8 cases of neck injury due to traffic accidents (Evans1996). The contents of this symposium were not published but a number of years later Crowe (1964) stated:

"In 1928 presenting a report on 8 cases of neck injury resulting from traffic accidents before the Western Orthopedic Association in San Francisco, I used the term "whiplash". This expression was intended to be a description of motion but has been accepted by patients and attorneys as the name of a disease; and the misunderstanding has led to it's misapplication by many physicians and others over the years" (Evans 1996).

For many years the medical profession found it difficult to accept the concept that injury to the tissues of the cervical region could occur in the absence of direct trauma.

Furthermore in the climate of legal claims which prevailed arising from whiplash events many articles were published making claim and counter claim regarding the genuineness of these injuries.

Gotten (1956), a neurosurgeon carried out a survey on 100 patients who had suffered whiplash injury after settlement of litigation and concluded that "we were forced by the survey to draw definite conclusions with regard to psychosomatic symptoms that had developed in a considerable number of these patients".

Miller (1961) following a review of 50 whiplash patients stated that the majority of symptoms subside after court proceedings ended and concluded that 'a compensation neurosis is a state of mind born out of fear, kept alive by avarice, stimulated by lawyers and cured by a verdict'.

Berry (1976) stated regarding "whiplash" that 'the symptoms largely subside once the financial issue is settled'. Berry made a number of points, which attempted to refute the existence of whiplash injuries. Basing his conclusions on his experience of the Toronto Demolition Derby, he stated that the "whiplash syndrome" did not occur in the context of sport where the motivation to recover is high, although the nature of the trauma may be identical".

However although there were antagonists to the concept of injuries due to "whiplash" it was accompanied by an ever increasing amount of work claiming that both the concept and the extent of the injuries were genuine.

MacNab (1964) evaluated 266 patients who had suffered hyperextension injuries to the neck, at least 2 years after legal settlement. He found that approximately 50% of the patients were still exhibiting symptoms.

Thompson (1965) reported on 500 patients with "post-traumatic psychoneurosis". Of these, 190 had claims, which had been settled. Of this 190, 15% reported that their symptoms had improved after litigation had been concluded. He states "the effects of the financial settlement on the course of the illness had negligible benefit".

Mendelson (1985) stated that "the concept of compensation neurosis has been invoked for many years in discussing the emotional sequelae of accidental injury, when litigants present with symptoms and disability, which are disproportionate to the original injury or to any demonstrable continuing physical abnormality". Mendelson concluded that the possibility of financial compensation after injury should be regarded as only one of several factors from an hysterical conversion reaction, and that multiple dynamics need to be considered in the medical assessment and treatment of litigants who complain of continuing symptoms after recovery from physical injury.

The stance taken by those refuting the existence of injuries resulting from "whiplash" was in some ways understandable as it was largely based on negative radiographic findings and a lack of understanding of the laws of physics by some of the medical fraternity.
It was in fact recognised by some medics prior to the advent of the whiplash controversy that conventional radiography will not show soft tissue damage and will therefore invariably give negative results.
As far back as 1919 Marshall recognised this when he stated:
"Negative x-rays with (cases of) severe ligamentous strain do not necessarily signify a favourable prognosis" (Marshall 1919).
Furthermore the property of inertia, which all bodies possess and is based on Newtons' first law of motion, adequately explains how injury can occur in the absence of direct trauma.
Inertia can be defined as "the tendency of an object to remain in a state of rest or uniform motion until an external force is applied to it". Thus the greater the mass of a body the greater will be its tendency to resist movement.
Thus if two or more components of a system are joined by non rigid substances such as ligaments and cervical vertebrae, a force sustained by one part of the system will be transmitted to the other parts via the non-rigid substances. The damage sustained by the non rigid substances will depend on the initial force and the masses (inertia) of the other body parts. This

is the essential principle of the injury mechanism which occurs in "whiplash". Therefore as the head has a mass of approximately 4.5 kg., it possesses considerable inertia.

Further work by clinicians and researchers added weight to the growing body of opinion supporting the concept that injury due to a "whiplash" event was a viable proposition.

Gay and Abbott (1953) stated "In our experience most of the accidents that followed a "whiplash" injury of the neck were caused by a collision in which one vehicle was rammed from behind by another vehicle". Interestingly Gay and Abbott inaccurately described the sequence of neck movements as flexion followed by extension (retroflexion) rather than the other way round. This was an understandable error from clinicians who were working in the relatively early days of the condition.

Severy et al. (1955) were able to correct this error in the interpretation of the sequence of neck movements following a series of pioneering experimental rear impact collisions using humans and crash dummies in combination with high speed photography and accelerometers. Following this work they stated:
"The low speed rear end collision is one of the more common types of urban automobile accidents and it is probably the most misleading. Unlike most collisions the rear-end collision frequently results in minor car damage with major bodily injury. Also unlike most injury producing accidents there is generally no visible sign of injury for the rear-end collision victim".
Many subsequent workers confirmed the above findings. These included:
Martinez et al (1965), Mertz and Patrick (1967), McKenzie and Williams (1971), Clemens and Burrow (1972), MacNab (1977), Norris and Watt (1983), Mc Connell et al (1995).
As a result of this soft tissue injuries to the head and neck region resulting from "whiplash" have been accepted as a clinical entity by the medical profession.

More recently a sizable body of clinical evidence over approximately a 40 year period has indicated an aetiological relationship between "whiplash" and injuries to the TMJ (See chapter 3).
This gave rise to a similar pattern of controversy as that which initially existed regarding injuries to the cervical region resulting from "whiplash".

Thus a number of authors stated that the concept of TMJ injuries in such circumstances was not possible in the absence of direct trauma to the jaw. Individuals making claims of such

injuries were labelled by some as suffering from "litigation neurosis syndrome" and similar terms.

However in spite of the clinical evidence indicating TMJ injuries in such events, to date there is no scientific evidence to explain the means whereby these injuries occur.
This void in knowledge has created an obvious need for research in this area. This thesis provides some initial insight into this complex subject.

1.2 Objectives and outline of the thesis

- To make an initial evaluation of the movements (if any) of the TMJ in a 15Mph rear impact collision.

- To make an estimate of the magnitude of the forces on the TMJ arising from such movements

- To assess the TMJ tissues, which were most vulnerable to forces arising from the jaw movements.

- To evaluate the strength of these vulnerable TMJ tissues and relate this information to the forces acting on them.

Chapter 1 consists of an outline of the background to the "whiplash" concept and the objectives and outline of the thesis.
A survey of the literature in chapter 2 reviews the epidemiological and clinical evidence supporting the belief that TMJ injury is caused by "whiplash" and also those taking the opposing view.
Chapter 3 reviews the normal anatomy of the joint and the surrounding craniofacial structures. It also examines the variations which were present in the different specimens looked at.
In this regard particular attention was made to the lateral pterygoid muscle with respect to the variations in size of the muscle in different individuals and the relative sizes of the two heads in the same individual. A histological evaluation of the lateral pterygoid muscle was also carried out in order to shed some light on the attachments of this muscle into the disc and condyle of the mandible. These attachments have been implicated by some workers to play a role in the type of damage, which occurs as a result of "whiplash".

On the basis of these findings a theoretical model was used to test whether or not variations in the attachments of the superior head of the lateral pterygoid into the disc and condyle respectively could be factors in the displacement of the disc from the lateral pole of the condyle.

Chapter 4 evaluates the jaw movements which occur due to retroflexion and flexion using a theoretical model and based on known data of the head movements which took place in experimental rear impact crashes on cadaver specimens.
An estimate of the forces affecting the TMJ tissues in retroflexion and flexion was also carried out.

Chapter 5 reports on the results of tests on the strength on the lateral ligament of the joint and of the attachment of the disc to the condyle of the mandible in order to evaluate whether the forces involved in the "whiplash" event were of sufficient magnitude to cause damage to these joint tissues.

Chapter 6 reviews the results of the research carried out and chapter 7 draws conclusions regarding these results and the bearing that "whiplash" may have on injuries to the TMJ.

Chapter 2 Review of the Literature

2.1 Introduction

In 1991, nine thousand eight hundred and seventy four people were injured in motor vehicle accidents (MVAs) in the Irish Republic according to official Garda figures. This constitutes approximately 0.4% of the total population (Environmental Research Unit 1992). In 1985 in the USA 1.3 million people were injured as a result of MVAs (Schneider et al 1989). In the United States 167,000 rear collisions were recorded by the police as a result of which, 269,000 individuals received emergency treatment (Schneider et al 1989). Rear collisions constitute more than one third of urban MVAs, and nearly 40% of these result in "whiplash" induced injuries (Balla 1982).

Furthermore approximately 70% of MVA fatalities are reportedly due to injury to the head and neck region (Nusholtz et al 1984).

For the purposes of this study, whiplash is defined as "an event in which the lower part of an unprepared individuals' body is impacted from behind, resulting in various body parts being accelerated at different times, and different rates, with particular reference to the head and neck region".

Whiplash is one of the most controversial medical issues of the day. There are wide differences of opinion concerning the nature of the injuries, which result and in some cases whether any injuries have been sustained. The debate whether cervical spine and related soft tissue injuries occur in such accidents has been taking place for many years.

Experimental evidence has shown that rear impact collisions can cause excessive acceleration of the head and neck and clinical evidence has shown that injuries to the soft tissues of the cervical spine can result from this. These injuries can occur as a result of inertial forces, without direct trauma to the head and neck region (Marshall 1919, Gay and Abbott 1953, Severy et al 1955, Martinez et al 1965, Crowe 1964, Mertz and Patrick 1967, Martinez and Garcia 1968, States et al 1970, McKenzie and Williams 1971, Mertz and Patrick 1971, Clemens and Burrow 1972, Ewing et al 1977, Hohl 1975, King and Chou 1976, MacNab 1977, Norris and Watt 1983, Bogduk 1986, Maimaris et al 1988, Hohl 1990, Davis et al 1991, Bogduk and Yoganadan 2001, Cusik et al 2001, Kasch et al 2001).

More recently it has become evident that a number of these cases present with the signs and symptoms of temporomandibular dysfunction (TMD). Clinical evidence indicates that there is

a causal relationship between whiplash and TMD (Pringle 1918, Wakeley 1948, Frankel 1965, Roydhouse 1973, Brooke et al 1977, Brooke and Stenn 1978, Ernest 1979, Lader 1983, Mahan 1980, Harkins and Martenay 1985, Weinberg and Lapointe 1987, Mannheimer et al 1989, Schneider et al 1989, Bring and Westman 1991, Burgess 1991, Pullinger and Seligman 1991, Epstein 1992, Heise et al 1992, Pressman et al 1992, Magnussen 1994, Garcia and Arrington 1996, Huang 1999).

Whilst inertial forces can be implicated in excessive mouth opening, the mechanism whereby TMJ damage may occur is not understood, particularly the disruption of the attachment of the disc to the condyle of the mandible.

The most common symptoms of whiplash are neck, shoulder, and head pain. These symptoms may be severe enough to initially mask any damage to the soft tissues of the TMJ. TMJ damage may therefore not become evident until some time after the accident, when some of the other symptoms have subsided or when an expert in the diagnosis of TMJ dysfunction examines the patient.

2.2 Anecdotal Evidence

Historically there is anecdotal evidence indicating a relationship between TMJ damage and indirect trauma. Pringle (1918) an oral surgeon stated that anterior displacement of the disc "is the consequence in almost every instance of a sudden and generally excessive closing of the mouth such as occurs in the free gratification of an inclination to yawn or sneeze". The head movements, which occur in a sneeze, are in fact similar to those which take place in a typical rear- end whiplash event (retroflexion /flexion).

Wakely (1948), an oral surgeon endorsed Pringle's statement, maintaining that anterior displacement of the temporomandibular disc could occur without a direct blow being sustained, and was due to the sudden and irregular contraction of the lateral pterygoid muscle during mouth closure.
Wakely (1948) stated that "displacement of the cartilage (disc) may be caused by a violent cough, sneeze or yawn, the external (lateral) pterygoid muscle contracting during rapid closing of the mouth, drawing the articular disc forwards and inwards" (antero-medially).

In the act of sneezing the head is thrown initially into retroflexion resulting in mouth opening and air inhalation. The sneeze is completed by the head being thrown into flexion and is accompanied by mouth closure and the expulsion of air.

Wakely (1948) contended that in the second stage of sneezing the rapidity of mouth closure resulted in the condyle being returned to the fossa while the disc is held in a forward position by the superior head of the lateral pterygoid muscle (which has been shown to be electromyographically active during mouth closing (Lipke et al 1977, Mahan et al 1983).
Both of the above references are of particular interest, as they were made long before "whiplash" became associated with large personal injury claims. Furthermore it is an indication that acute displacement of the disc may occur in the absence of direct trauma.
Many years after this Weinberg and Lapointe (1987) revisited the subject in relation to the rear MVA accident and proposed that the inertia of the mandible led to mouth opening during retroflexion and disc displacement due to its Lateral Pterygoid attachments during flexion*.

Roydhouse (1973) offered anecdotal evidence based on his clinical observations of fourteen patients and also suggested that there was a link between whiplash and TMJ damage. He did not however specify his method of evaluation, or list the presenting signs and symptoms.

2.3 Clinical Evidence

Two types of onset have been established as causative factors in the onset of damage to the TMJ. These are due to either a gradual breakdown associated with occlusion and hyperactive jaw function or due to a sudden instantaneous injury (Moffett & Westesson1984).

Over the past 30 years there has been a mounting volume of clinical evidence claiming a relationship between whiplash and TMD. There is little argument that trauma is accepted as a causative factor in TMJ damage. However debate continues as to whether injury can occur in the absence of direct trauma.

Frankel (1965) published the first recorded clinical study on this subject. He evaluated a consecutive series of forty patients who had sustained whiplash injuries as result of MVAs. A history was obtained that each patient was seated in a parked car, which had been struck from behind by another automobile. Frankels' evaluation was carried out by history and standard TMJ clinical examination. His results showed that 15 (38 %) of the patients had symptoms and signs indicating TMJ derangement. The patients with a positive diagnosis exhibited a variety of complaints including, tenderness of facial muscles, and tenderness in the soft tissues around the T.M.J, limitation of mouth opening and deviation of the jaw to one side on mouth opening. In all of the cases there was some evidence of mal-occlusion.

*See Chapter 4 for further discussion on the inertial theory

Brooke, et al (1977) evaluated the response to conservative treatment of 194 patients diagnosed as suffering from TMD out of a total of 274 patients referred to the Department of Oral Medicine in the University of Western Ontario for TMD evaluation. Patient evaluation was carried out by, history, clinical examination, and radiographs. One hundred and sixty four patients (85%) were women, and sixty-four were men (15%), a ratio of 5.5 to 1.
Most of the patients diagnosed were between the ages of 15 and 35 years. All of the patients diagnosed with TMD had no clinical or radiographic evidence of ongoing disease of the TMJ. One hundred and eighty two patients (93%) had two or more symptoms of the disorder. Only twelve of the patients had a single symptom (pain). Twenty-three patients were treated with occlusal appliance therapy. Forty-nine were treated with a mild tranquilliser as it was felt that a minor stress component existed. The remaining 122 patients were treated with physiotherapy, consisting of ice applications and ultra sound.

The patients were re-assessed from 16 to 44 months following their first visit, and categorised under three headings:

- Those with symptoms still needing treatment.
- Those with occasional symptoms not needing treatment.
- Those completely free of symptoms.

Thirty-six patients (19%) still had symptoms needing treatment. Seventy-six patients (39%) had no symptoms, and eighty-one patients (42%) had occasional symptoms, which did not require treatment. When the data were examined in more detail it was found that twenty (10%) of the diagnosed patients had been involved in a MVA, which had resulted in direct or indirect injury to the TMJ. Furthermore, twelve of these patients (60%) were still experiencing symptoms requiring treatment and only 2 patients (10%), were completely free from symptoms. Because of the significant difference in response to therapy, the authors concluded that TMD cases where macro trauma is involved have a much less favourable prognosis.

Brooke & Stenn (1978) carried out a further study on the response to conservative treatment of 37 TMD patients resulting from trauma.
The patients were evaluated as in the previous study by Brooke et al (1977). Thirty-five patients (98%) had pain as a symptom. Thirty patients (81%) had abnormal jaw sounds. Twenty-four patients (65%) had restricted jaw opening, eighteen patients (49%) had all three of the above symptoms, nineteen (51%) had two symptoms, and two patients (5%) had pain as the only

symptom. The patients were again assessed according to their response to conservative treatment. The results showed five patients (14%) who were completely free from symptoms. Eight patients (22%) were sufficiently free from symptoms to need no further treatment. Twenty-three patients (62%) showed no permanent improvement following treatment. One patient could not be traced after follow up. Sixteen (43%) of the patients had been involved in whiplash MVAs. Only two of these patients were symptom free after treatment and eleven (69%) had no relief whatsoever.

Truelove et al (1985) carried out a retrospective study on 224 patients presenting with facial pain. 67 patients (30%) reported a history of trauma. Twenty-four (11%) of these stated that trauma was the precipitating factor to their facial pain. Thirty patients (13%) reported a previous traumatic event, 13 patients (6%) reported both previous trauma, and precipitating trauma, and 157 patients (70%) had no history of trauma.

Females outnumbered males by a ratio of 3:1 in the trauma group, and by an 8:1 ratio in the non-trauma group. Of the patients with precipitating trauma 52% were involved in a MVA. A history of traumatic dental treatment was recorded for 29% of the patients and 11% had suffered physical abuse.

Harkins and Martenay (1985) studied 727 symptomatic patients who sought treatment for TMD over a one-year period. The object of their study was to evaluate the role of extrinsic trauma as a precipitating factor in TMJ dysfunction in a large heterogeneous population. The data were collected by history, interview, clinical examination, self-administered questionnaire, and radiographs. Iatrogenic mal-occlusion was not included as a possible form of extrinsic trauma. Sixty-six patients were ruled out because of lack of objective signs of TMD.

The study was therefore based on the 661 patients, diagnosed as suffering from TMD. Five hundred and seventy (86%) patients were female. Their results showed that some form of macro trauma had occurred to the body of a large number of the patients (84%). Acute trauma had occurred to the head or neck in the life of 198 patients (30%), 83% of which were female. 284 patients (43%), reported extrinsic trauma to the head and neck as the factor, which had precipitated their TMD symptoms. One hundred and seventy patients (26%), reported a single head or neck trauma resulting from a MVA. One hundred and twenty eight (19%) of the patients reported whiplash injury as the precipitating factor to their TMD symptoms.

Weinberg and Lapointe (1987) evaluated 28 patients (17F, 11M) who had suffered medically diagnosed whiplash injuries as a result of MVAs. The average time elapsing between the injury and presentation for treatment was 126 days. The age range was 17 to 56 years. 18 of the accidents were rear impacts, 6 were front, and 4 side.

The patients were evaluated by history, clinical examination, and arthrographic evaluation. The clinical findings consisted of facial pain, localised to the TMJ, earaches, headaches, painful and tender craniomandibular and cervical muscles, clicking TMJs, painful limitation of mouth opening, mandibular deviation in mouth opening, vertigo, tinnitus, and retro-orbital pain.

Arthrographic evaluation was carried out on 25 of the patients, which revealed anterior disc displacement with reduction (ADDR) in 12 patients and anterior disc displacement without reduction (ADD) in 8 patients. Ten of the patients elected to have TMJ surgery and the arthrographic findings were confirmed in each case. Weinberg and Lapointe (1987) concluded from these findings that there appeared to be a relationship between the whiplash MVA event and internal derangement of the TMJ.

Pullinger and Seligman (1987) reviewed 219 consecutive patients evaluated for TMD. One hundred and twenty two of these patients were diagnosed as suffering from TMD or TMJ arthritis. In the diagnosed groups, females numbered 106 (87%) and males 16 (13%). Evaluation consisted of, history, clinical examination, and serial tomography in the sagittal and frontal planes. The patients were subdivided into 5 diagnostic sub-groups, each of which was assessed for associated macro trauma.

The sub-groups were as follows:

- Disc displacement with reduction, and no signs of arthritis
- TMJ locking with a history of clicking, and no history of arthritis.
- TMJ locking without a history of clicking, and no history of arthritis.
- TMJ arthritis with a prior history of locking.
- TMJ arthritis without a prior history of locking.

In summary Pullinger and Seligmans' (1987) results showed the following:

- 45 patients (37%) had disc displacement with reduction. Thirty-five of these (78%) were female. Twenty-one (47%) of this group had suffered MVA trauma and eleven (24%) had suffered other trauma.

- 14 patients (11%) had TMJ locking with a history of clicking. All the patients were female. Five patients (36%) were MVA associated, and six (43%) had suffered other trauma.
- 2 patients (2%) had TMJ locking with no history of clicking or arthritis. One of these was MVA related, and both were female.
- 29 patients (24%) had signs of TMJ arthritis and a prior history of locking. 27 patients (93%) were female. Seven patients (24%) were MVA associated, and six patients (21%) had suffered other trauma.
- 32 patients (26%) had TMJ arthritis without a history of locking. 28 of these (88%) were female. Nine of these patients (28%) were MVA associated and ten patients (31%) had suffered other trauma.

It can be seen from the above study that more patients with disc derangement had a MVA association than an arthritis association. When all forms of macro trauma were considered the incidence for patients with TMD without arthritis ranged from 50% to 71% while those in the arthritis groups had a 38% to 53% frequency of trauma.

As the disc displacement without reduction group was younger than the disc displacement with reduction group, Pullinger and Seligman (1987) concluded that the previously held opinion that disc displacement without reduction was the result of a dysfunction progression starting with derangement and clicking and developing over a period of years, did not hold in every instance. They also concluded that macro trauma, especially MVA trauma was associated with a significant percentage of derangements.

While the types of MVA were not divided into frontal, rear, and side impacts, the authors stated that most of the MVA associated cases had "contained a large measure of jaw whiplash".

Pullinger and Monteiro (1988) carried out another study in which they compared the prevalence of head and neck trauma, to the prevalence of orthodontic treatment, and molar oral surgery procedures in TMD. The TMD patient group consisted of a consecutive series of 50 male and 102 female patients in the age range of 18 to 35 years selected from patients attending the UCLA, TMJ and Facial pain clinic.

Two control groups were chosen from 2 complete freshman classes of Dental Students, and Dental Hygienist students (139 Males and 192 Females, age range 18 to 35 years).

The control groups were divided into Asymptomatic (N =116) and Symptomatic (N= 215) Subjects. A history was taken by questionnaire from all the groups, which included the following questions:

- Have you ever had an injury to your face, jaws or neck?
- Have you had orthodontic treatment?
- Have you had any wisdom teeth extracted or any difficult molar extraction?

The prevalence of the above 3 history factors was compared in the TMD patients as opposed to the control groups. The symptoms were categorised under pain intensity, derangement frequency, jaw function disability, dental or occlusal discomfort, and head or neck pain.

Their results showed:

- A prior record of trauma was the strongest association in the symptomatic groups.
- The prevalence of head or neck trauma was 1.7% in the asymptomatic control group. 13.1% in the symptomatic control group and 30.4% in the TMD group.

Pullinger and Seligman (1991) carried out yet a further separate study on a group of 230 patients, with a view to evaluating the role of trauma in different diagnostic sub-groups. Twenty-seven patients were classified as non-TMD and were thus excluded from the study. Patient evaluation was carried out by history and clinical examination. Trauma history was obtained through personal interview. Any mention of a past traumatic event in the patients' history was labelled as trauma positive.

The TMD patients were divided into the following diagnostic sub-groups:

- Anterior Disc displacement with reduction (ADDR)(Clicking)
- Anterior Disc displacement without reduction (ADD) (Locking)
- Myalgia only.
- Osteoarthritis with derangement history.
- Osteoarthritis with no derangement history.
- Subluxation. (Anterior dislocation of entire disc/ condyle assembly)

The above patients were compared to figures taken from three control groups:

- A symptomatic group of young adult non-patient dental and dental hygiene students N=161.

- An asymptomatic group of non-patient dental and dental hygiene students N = 61.
- A group of 150 general dental patients taken from every third chart in the files until 75 men and 75 women were collected.

The percentages of trauma in the diagnostic sub-groups were as follows:

- Disc displacement with reduction 63%
- Disc displacement without reduction 79%
- Osteoarthritis with derangement history 44%
- Primary Osteoarthritis 53%
- Myalgia only 43%
- Subluxation 29%

The trauma percentages for the control groups were as follows:

- Asymptomatic normal 13%
- Symptomatic normal 18%
- Dental patients 11%

It can be seen from the above that the incidence of trauma was considerably higher in the diagnostic groups as opposed to the control groups. It was also seen that the frequency of trauma was considerably higher in the TMD derangement groups than in the other diagnostic sub-groups. When the patients reporting trauma were looked at separately, MVA trauma and multiple trauma including MVA represented 91% of the ADDR group, 72% of the ADD group and 70% of the myalgia only group.

Goss and Bosanquet (1990) carried out arthroscopic evaluation on the TMJs of 20 patients who had sustained mandibular fractures. They found that 38 of 40 joints showed evidence of intra-articular damage. Hemarthrosis with shredding of the disc and joint surfaces was the most common finding. They found that the least damage occurred to the joint when there was an ipsilateral condylar fracture, and if TMJ damage did occur it tended to be in the joint on the contra lateral side.

Bring and Westman (1991) carried out a study of twenty-two patients suffering from "chronic posttraumatic syndrome after whiplash injury". They found that amongst many other problems, approximately half of the patients were suffering from pain in the jaws, difficulty in chewing and mouth opening, clicking of the temporomandibular joints, or all three of the above.

Burgess (1991) evaluated 100 consecutive patients (mean age 32 years; 82% female) who reported facial pain resulting from three types of trauma:

- Overt facial / head trauma. (0T)
- Whiplash injury without direct facial / head trauma. (W)
- Whiplash together with direct facial / head trauma. (WOT)

The patients were evaluated by questionnaire, history, and clinical examination. The questionnaire included anamnastic data and a visual analogue scale anchored by "no pain" and "worst pain possible". Other methods used were the McGill pain questionnaire, pain drawing, and an abbreviated version of the Hopkins symptom checklist, designed to measure psychological symptom patterns including anxiety, depression, and somatization. Clinical examination included a standardized head and neck examination, measurement of range of jaw movement, TMJ noise evaluation, palpation of craniomandibular muscles and palpation of the lateral pole of the mandibular condyles.

In summary:

- Thirty one per cent of the patients stated that overt trauma (OT) was the precipitating factor of their facial pain/TMD.
- TMJ clicking was found in 25% of the overt trauma (OT) cases (8 of 31).
- Sixty-nine patients of the total sample reported a whiplash event, which typically followed a MVA rear collision. Thirty-four (49%) of these reported facial or head contact with the steering wheel or other hard surface.
- All cases of non-reducing disc displacement (locking) were in the whiplash category (2 in W and 3 in WOT).

The majority of W (76%) and WOT (82%) patients reported the onset of facial and head pain within 48 hours of the accident. Only seven W or WOT patients reported onset of pain after one week. Most W and WOT patients with TMJ clicking reported onset within 1 month of the trauma (N=15). One patient noted onset at 6 months, one at 6 years, and one at 8 years after the accident. Of the patients with non-reducing disc displacement, one patient stated that it developed two years post accident and another stated that it occurred 8 years after MVA trauma. Two of the WOT patients with non-reducing disc displacement stated that it developed within 2 months of initial examination. One patient was unaware of the date of onset.

Heise et al, (1992) evaluated 155 patients diagnosed as suffering from cervical damage as a result of whiplash. All of the patients were seen initially in the acute trauma emergency

department at the Medical College of Virginia Hospitals, Richmond, Virginia, and were examined by the same examiner. The purpose of this study was to assess whether there was any associated TMJ damage. The patients were evaluated by history, interview, clinical examination, and radiology of the cervical spine. The key questions in the interview were related to the pre and post accident status regarding neck, ear, facial pain/headaches and TMJ pain and/or clicking. The clinical examination included palpation of the temporomandibular joints, evaluation of joint noises, and palpation of the craniomandibular and neck muscles.

The patients were divided into two groups:

- Those with radiological evidence of cervical injury.
- Those without radiological evidence of cervical injury.

The prevalence of the various TMJ signs and symptoms was compared within both groups.

The results were as follows:

Group I: Radiological evidence of cervical injury (63 patients)

At initial examination eight (13%) patients complained of masticatory muscle and temporomandibular joint pain. No patients had clicking or popping of the temporomandibular joints. Treatment consisted of analgesic or non-steroidal anti-inflammatory drug therapy, heat application, and soft diet. At 1 month 51 of the patients (81%) were contacted by telephone. At this stage the 8 patients above reported diminished symptoms. Two extra patients reported TMJ clicking. At 1 year 70% of the initial group were contacted by telephone. No additional patients reported TMJ or muscle problems. At this stage the original eight patients reported no myofascial pain.

Group II: No Radiological evidence of cervical injury (92 patients)

At initial examination fourteen patients (15%) complained of masticatory muscle and temporomandibular joint pain. One patient reported a click not present prior to the accident. Treatment was again "usually" similar to group I above. At 1 month 85% of the group were contacted by telephone. There were no additional cases of pain or clicking. A decrease in symptoms of the original 14 was reported. At 1 year 65% of the original group were contacted. There were no new cases and no complaints of <u>persistent</u> myofascial pain. In the above study the authors concluded that there was "no clinical evidence of a significant relationship between cervical musculoskeletal injury and the development of temporomandibular joint dysfunction".

Pressman et al (1992) using magnetic resonance imaging evaluated thirty-three patients (66 joints, 14 men, 19 women, age range 21-44 years) who had symptoms of TMJ dysfunction (headaches, clicking, crepitus, jaw locking, ear pain, and facial pain). All the patients had been involved in a rear MVA, and none had suffered direct trauma to the cranio-facial region or had a previous history of TMJ dysfunction. The length of time from the accident to the TMJ imaging ranged from 1 to 14 months (mean 4 weeks).

Pressmans' results showed the following:

- Disc displacement was seen in twenty-four patients (73%) (37 joints).
- 21 joints (32%) had anterior displacement of the disc with reduction.
- Nine joints (14%) had anterior displacement without reduction.
- Six joints (9%) had lateral or medial displacement of the disc.
- One joint (2%) had posterior displacement of the disc.
- Forty-three (65%) joints had joint fluid and / or soft tissue oedema.
- Ten joints (15%) had joint fluid and / or soft tissue oedema without disc displacement.

Magnussen (1994) reported on one hundred consecutive patients suffering from "Late whiplash syndrome". Sixty-two patients were excluded from the study because of previous whiplash, and head injury. The remaining thirty-eight patients had sustained a whiplash injury without direct head trauma and had no signs of radiculopathy* or myelopathy**.
All of the above patients had been involved in a MVA. Twenty-six (68%) were rear impacts, 9 (24%) were front impacts, and 4 (11%) were side impacts.

Twenty-five patients (66%) were female and 13 (34%) were male. The age range was 17 to 52 years. All the patients had been healthy prior to the accident and the time lapse from accident to investigation was 6 to 44 months (mean 17 months).

The method of investigation was by history and clinical examination. Magnussens' results showed that 11 patients (29%) had TMJ pain and tenderness (5 unilateral and 6 bilateral).
Of these, 4 patients (11%) had signs of TMD with crepitus, pain on jaw function and in one case jaw locking. Six patients (16%) had symptoms, which warranted referral to a TMJ

* Disease of the roots of spinal nerves

** Spinal cord disease

specialist for further evaluation and treatment. In no case was there any evidence that direct trauma was responsible for the TMJ symptoms.

These patients also suffered from a variety of other conditions including, headaches (97%), thoracic outlet syndrome (32%), and low back pain (47%). All of the patients had localised muscle tenderness in the neck, and 74% had restricted neck movements.

Probert et al (1994) carried out an analysis on 20,672 patients (10,533 male 51% and 10,139 female 49%) claiming health care from the Transport Accident Commission (TAC) of Victoria, Australia. The data were based on clinical reports sent to TAC by a number of dentists from the state of Victoria, after the injuries had been diagnosed and treated.

No standardised examination protocol or treatment philosophy was specified. The results of this study showed that whiplash injuries had occurred in 2198 patients (1430 female 65%) (Ratio of female to male 2: 1).

Of the above whiplash group 28 patients (1.3 %) were diagnosed as suffering from TMD. Twenty of these (71.5%) were female. Seventy five per cent of the TMD patients complained of symptoms immediately post accident and 96% of the patients complained of symptoms within 2 months of the accident.

The authors stated that only a small proportion of patients with TMD symptoms presented for treatment, and therefore their figures may be an underestimate of those who continued to have some symptoms.

Only one of the 237 patients with mandibular fracture sought treatment for TMD. This indicates as would be expected that the TMJ is subjected to less trauma when mandibular fracture occurs, in which circumstance stress concentrations would be at the fracture site and not at the joint. Probert et al (1994) concluded from their survey that although TMD did occur as a result of MVAs particularly in "whiplash" accidents, it was an infrequent occurrence.

Garcia and Arrington (1996) carried out a magnetic resonance imaging (MRI) evaluation on 164 consecutive MVA whiplash patients who presented with TMJ symptoms, and had sustained no direct trauma to the craniofacial region. The above group of patients had no history of previous TMJ complaints.

Their results showed the following:

- 118 (72%) patients had disc displacement with reduction.
- 25(15%) patients had disc displacement without reduction (locking).
- 113(69%) patients had joint effusion.

- 84(51%) patients had inflammation or oedema.
- The total TMJ abnormalities were found in 156 (95%) of the patients.

Bergman et al (1998) carried out a MRI study on 60 consecutive patients with neck symptoms after rear collisions within 3 to 14 days of the accidents. The symptomatic group was compared with a control group of 53 healthy volunteers.

Their results showed:

- 53% of the patient group and 45% of the control group had a displaced disc in one or both TMJs.
- Effusion was seen in 8% of joints in the control group, and 6% of joints in the patient group.
- No signs of bleeding or oedema in the soft tissues were observed in either group.

Bergman et al (1998) concluded that their study did not show any significantly increased incidence of TMJ injury after whiplash trauma, under MRI investigation.

2.4 Discussion

2.4.1 "Whiplash" resulting in TMD

Figure 2.1 shows the studies which looked at the incidence of TMD occurring as a result of "whiplash".

Most of the studies were based on tertiary referrals, which by definition would show an inflated estimate of the incidence of TMD resulting from "whiplash".

Most of the studies did not use control groups to compare the incidence and prevalence of "whiplash" in TMD to that in the general population

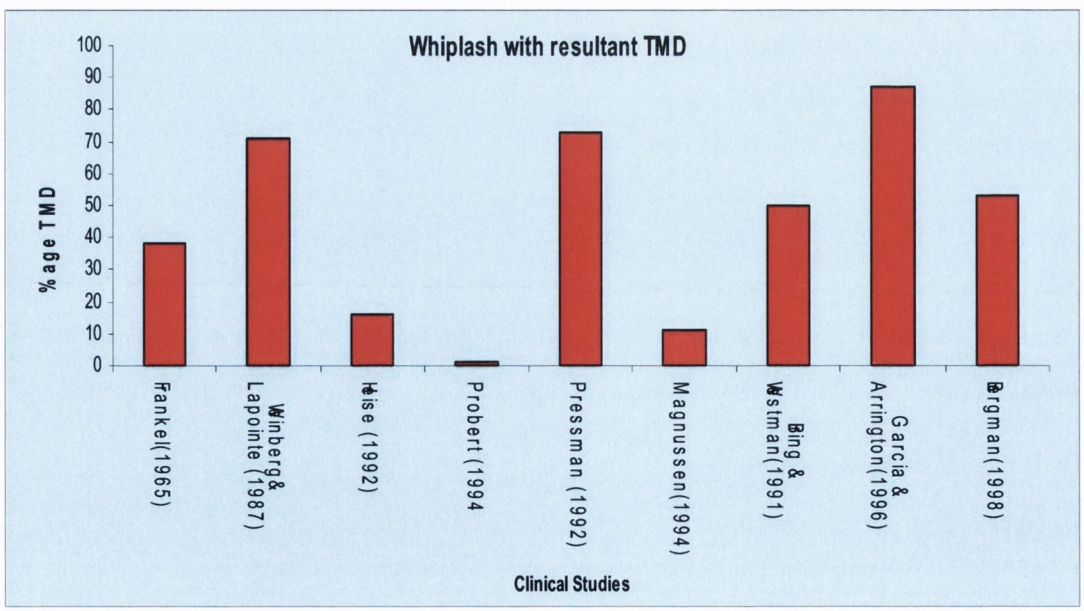


Figure 2:1 Studies on percentage of TMD resulting from "whiplash"

In addition many of the studies were based on relatively small samples of patients with the range being from 22 patients Bring & Westman (1991) to 155 patients (Heise et al 1992).
It was noted also that not all of the studies claimed to have been evaluating a consecutive series of patients and the methods of evaluation varied from study to study.

The studies not based on tertiary referrals (Heise et al 1992 & Probert et al 1994) showed a much lower incidence of TMD resulting from "whiplash".
The Heise et al (1992) study was based on patients attending a hospital emergency department. Therefore their figure should be a more accurate representation of the percentage incidence of TMD resulting from "whiplash" events. Their claim that there was "no clinical evidence of a significant relationship between cervical musculoskeletal injury and the development of temporomandibular joint dysfunction" would seem to be contradicted by their results which showed that 16% of the sample developed TMD symptoms post accident.
Their strategy of dividing patients into two groups based on conventional radiographic status of the cervical region is of doubtful diagnostic value as it has been shown that there is an inverse relationship between hard and soft tissue damage (Goss & Bosanquet 1990), and also the most frequent result of "whiplash" injury is soft tissue damage which would not be evident using conventional radiography.
The Probert et al (1994) study shows a very low incidence of TMD (1.3%) resulting from "whiplash". However the authors conducted their study on road traffic accidents (RTAs), which they defined as "any accident on a public road involving motorised or non-motorised vehicles, including pedestrians when struck by a road-using vehicle". This by definition would include a number of relatively minor traumas involving bicycles, pedestrians etc., whereas the other studies reviewed were based exclusively on rear impact MVAs. This may have given a lower figure to that which would have been obtained from a study on rear impacts alone.

Three MRI studies on the incidence of TMD in "whiplash" were reviewed.
Both Pressman et al (1992) and Garcia & Arrington (1996) using MRI evaluation found anterior disc displacement in 73% and 85% respectively of "whiplash" patients who presented with TMJ symptoms having sustained no direct trauma to the craniofacial region. In both of these studies no control groups were used. Bergman et al (1998) in another MRI study found that there was relatively little difference in the incidence of disc displacement between a patient group with neck symptoms following a "whiplash" event and that in a healthy control group.

Although the use of a control group in this study adheres to an important epidemiological criterion it falls short in the selection of the patient group, as 15% had mild clinical symptoms, which in normal clinical circumstances would not warrant MRI scanning.
Furthermore this study shows an unusually high % of patients in the control group with disc displacement
It should be pointed out that MRI evaluation of the TMJ is usually carried out after referral from a TMJ specialist who requires confirmation of a clinical diagnosis. Therefore MRI studies would often be based on samples of patients which had undergone further filtering and could be regarded as quaternary referrals.
While the MRI evaluation of the TMJ for the confirmation of disc displacement is a useful adjunct to clinical diagnosis the identification of effusions (Pressman et al 1992, Garcia & Arrington 1996) in the joint is of doubtful validity.
McKay& Christensen (1998) maintain that TMJ effusions detected by means of MRI evaluation can often be an expression of normal synovial fluid as well as displaced saliva from the parotid gland within the upper joint cavity and can be an expression of inflammatory exudate or non-inflammatory transudate in one or more component parts of the joint.
In effect they claim that as effusions can occur in both symptomatic as well as asymptomatic joints with and without disc displacement the true nature of the effusion cannot be determined by MRI and conclusions regarding its true nature can only be determined on the basis of laboratory analysis of aspirates.

2.4.2 TMD with history of "Whiplash"

Figure 2.2 shows the results of studies on the incidence of "whiplash" in TMD patients.
The study conducted by Brooke & Stenn (1978) was based on a relatively small sample of patients (37), of which 43% had a history of "whiplash".

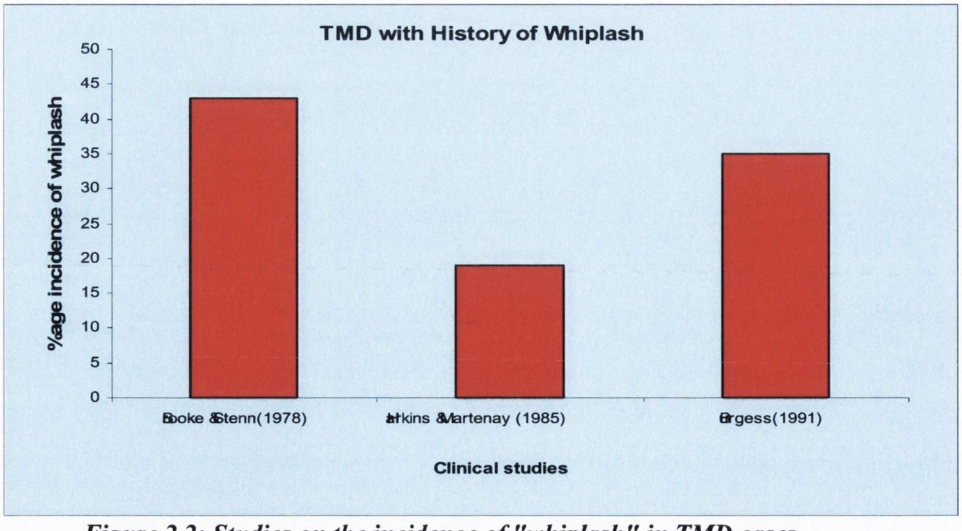


Figure 2.2: Studies on the incidence of "whiplash" in TMD cases

The Harkins & Martenay (1985) study found that in a relatively large sample of patients (661), 19% had experienced "whiplash" as a precipitating factor to their TMD.

The Burgess (1991) study showed that 35% of a group of TMD/facial pain patients had a history of "whiplash". However this study was carried out on a selected group of 100 trauma patients who were complaining of a combination of facial pain, neck injuries and TMD. The patients were subjected to cervical and TMJ evaluation. Objective signs of TMD were found but the patients were not divided into categories of facial pain due to TMD, facial pain of cervical origin, and a combination of both.

No control groups were used in the above three studies but given that approximately 0.1% of the population as a whole suffer "whiplash" accidents in one year, it can be estimated that during an average lifetime of 70 years an individual would have a 7% chance of experiencing a "whiplash" event. This would indicate a significantly higher prevalence of "whiplash" in TMD sufferers than in the population as a whole*.

The studies carried out by Pullinger and Seligman (1987), Pullinger and Monteiro (1988) and Pullinger and Seligman (1991) found that macro trauma, particularly MVA macro trauma was associated with a significant percentage of TMD derangements. They state that most of the MVA trauma cases had involved a large measure of "whiplash".
However no figures are given for this and the MVA trauma cases were not divided into frontal, rear, and side impacts.
Therefore conclusions cannot be drawn regarding the relationship of "whiplash" (rear collisions) to TMJ dysfunction. However it is worth noting that MVA rear collisions have been reported to account for over one third of urban accidents, and 40% of these produce "whiplash" injuries (Balla 1982).
The authors maintain that these "whiplash" events in their experience "often result in a chronically unstable disc producing persistent clicking but do not always progress to locking unless there are other pre-existing conditions". Notwithstanding this statement they challenge the concept that displacement of the disc can occur due to indirect trauma when its attachment to the condyle is healthy. They suggest that the more likely circumstance in the sudden displacement of the disc is that it results from trauma on an already compromised discal attachment to the condyle. This claim is based on conjecture with no evidence offered regarding the strength of the attachment of the disc to the condyle or the forces that it is likely to be subjected to.

*Estimate based on figures from Balla (1982)

2.4.3 Response to treatment

Brooke et al (1977) found that the response to conservative treatment in a group of TMD patients was considerably less favourable for patients who had suffered macro trauma in a MVA.

In a further study Brooke and Stenn (1978) found that the response to conservative treatment for TMD patients was much less favourable for those who had experienced "whiplash". Sixty-nine percent of the "whiplash" sample had no relief whatsoever and two of these patients had pain only as a symptom. As pain only is not diagnostic of TMJ dysfunction it is not unreasonable to assume that the poor response to treatment in the "whiplash" patients may not have been due to the severity of the injury but to faulty diagnosis. This may have been due to the fact that the authors called the condition myofascial pain dysfunction syndrome (MPDS), which they defined as "a condition in which painful spasm of the muscles of mastication occurs, often in association with difficulty in opening the jaw and clicking or popping sounds in the joints". These types of cases may have a TMD component but the definition overlooks the fact that pain in the muscles controlling jaw movement and pain in the joint itself can be referred from the cervical region. Indeed the use of the word syndrome implies a lack of specificity in the diagnosis.

It is now recognised that in cases of "TMD" resulting from MVA trauma many patients have suffered damage to other tissues (e.g. Brain or neck) which may either mask or mimic the TMD component. A more appropriate strategy with some patients who have TMJ pain together with soft tissue cervical injury in the absence of conclusive signs of TMD, is to deal with the cervical problems initially and then re-assess the TMJ.

It is difficult to arrive at accurate estimates of the prevalence or incidence of "whiplash" in TMD for a number of reasons.

Although clinical studies can supply detailed information about patients with TMD, in the absence of controls they cannot be compared to those members of the population who are free of the condition.

It might seem that if a large population of subjects was being evaluated in an epidemiological survey a more valid incidence/prevalence of a condition would be arrived at.

However large epidemiological surveys yield less accurate results based on evidence which is not ideal, as the evaluation of a large number of patients implies that a greater number of examiners would be required for the data collection. This applies to circumstances where the collection of objective data regarding TMJ dysfunction is needed.

Furthermore larger and more complex epidemiological surveys are usually carried out for problems which merit high priority. (TMD would not seem to fall into this category).

There was also a variation in the methods used to evaluate the patient samples, which precludes an accurate comparison between the different studies.

The Probert et al (1994) study for example fulfils one requirement of an epidemiological study but the number of examiners required for data collection implies that it would be difficult to maintain a high degree of accuracy in the results. Furthermore their inclusion criteria were too broad, as a portion of their sample consisted of minor traffic incidents, highly unlikely to cause damage to the temporomandibular system. A further source of bias in this study may have been that it was carried out on behalf of an insurance company.
In contrast to this clinical studies have the advantage of usually being carried out by one or two clinicians so that the patients in that particular study are evaluated in the same manner. However the clinical study has the disadvantage of often being carried out on a small group of patients who are sometimes selected and often filtered to a lesser or greater degree by the referral system.
Comparison between the different clinical studies is unfortunately not a viable proposition due to the lack of a standardised assessment protocol. The lack of control groups in most of the studies also precluded comparison to the general population.

The protocol used by Pullinger & Seligman (1991) with some minor modifications could act as a template for future studies, for example by dividing the MVA trauma category into frontal, rear, and side impacts, noting the type of vehicle the subject was occupying, in order to evaluate the potential for injury relative to the head restraint and seat design of the particular vehicle, and by adding the measurement of mandibular range of movement to their clinical examination procedure.

In order for valid comparisons to be made between different studies it is fundamental that a standardized evaluation protocol, consistent with accepted medical principles should be adhered to, using the traditional method of detailed history taking, clinical examination and special tests. In this manner a valid comparison can be made from study to study.

However before an evaluation for any condition is carried out it is essential that there is agreement on a definition of that condition.
Costen in 1934 was the first to attempt to define temporomandibular dysfunction when he described a condition, which consisted of a number of diverse symptoms including facial neuralgia, a variety of otological symptoms, altered taste sensation and damage to the TMJ muscles and joint . Costen claimed that these symptoms were due to backward displacement of the condyle, compression of the Eustachian tube and pressure on the Chorda tympani and Auriculo-temporal nerves. He claimed that these symptoms could be cured by occlusal equilibration (Balancing the bite).

The term "Costens' Syndrome" became common currency in the dental profession for some time until it was displaced by the term "TMJ syndrome".

The use of the term syndrome was unsatisfactory in that it was an excuse for a lack of a specific diagnosis to explain the variety of non-TMD symptoms which were found in many of these cases.

More recently through the use of greater diagnostic skills and knowledge regarding both the physical and the psychological aspects of pain it has become possible to make a differential diagnosis of craniofacial pain. This in turn has led to treatment based on a specific diagnosis rather than on an empirical basis.

Thus to determine a diagnosis by treating in order to exclude the possibility that the patient may have a TMD component (as is often the case) is not good practice.

The term TMD is now used to cover all dysfunctions of the temporomandibular system and can now be described as "a condition in which the normal neuromuscular pattern is disturbed or the working parts of the joint are damaged or deranged" (Ogus & Toller 1981).

2.4.4 Referred pain from the cervical region

As the cervical region is subjected to a considerable degree of stress in the "whiplash" event and is one of the most common sources of pain referral to the craniofacial region, special attention should be paid to the possibility that pain which is ostensibly TMD in origin may be coming from that area. Although acute trauma and primary pathological processes of the neck are not the realm of the dentist to diagnose and treat, many chronic dysfunctions of the cervical region appear first in the Dental practice for the reason that they manifest initially as facial pain. Therefore it is important for the dentist to acquire the basic skills needed to differentiate between TMD pain and cranio-facial pain being referred from the cervical region as well as other causes of cranio-facial pain.*

Many "whiplash" cases consist of both cervical and TMJ damage and it is important to decide which region should take precedence in terms of treatment. Often when the cervical region has been treated, seemingly severe cases of TMD prove to be of minimal consequence.

*See appendix A for further details on TMJ dysfunction and differential diagnosis

2.5 Conclusions

It can be stated from the above review that although there are some shortcomings in the protocols used, there is an indication of an aetiological relationship between "whiplash" and TMD, although the figures derived from these studies should be viewed with caution.

Moreover the evidence should not as yet be considered as conclusive. Much more epidemiological research and investigation of the mechanism whereby TMJ damage may occur in a "whiplash" event is required before there is universal acceptance of the concept of "whiplash" as a causative factor of TMD.

Therefore it is the objective of this research to make an evaluation of the mechanism(s) whereby disc displacement may occur by reviewing the anatomy of the joint with particular emphasis on the tissues considered to be most vulnerable, by estimating the forces sustained by the joint in a low velocity rear impact collision and relating these forces to the integrity of the soft tissues which are being challenged.

Chapter 3 Temporomandibular Joint Anatomy

3.1 Introduction

This description of temporomandibular joint (TMJ) anatomy is based on the following: -

1. Classical descriptions from recognised textbooks.
2. Contemporary literature.
3. Personal observations from cadaver dissection.
4. Histological Investigation of Lateral Pterygoid.

Whenever appropriate, references are cited. Diagrams are used selectively to illustrate the salient anatomical features of the TMJ. It should be stressed that the descriptions given in the classical anatomy books do not take into account the variations in individual anatomy. For example, a wide variation exists in the shape of the head of the mandibular condyle, and in the size and distribution of the Lateral Pterygoid muscle (see text later). These variations may play a significant role in the susceptibility of some individuals to TMJ injury.

3.2 Anatomy of the TMJ

The Temporomandibular Joint (T.M.J) is a synovial diarthrodial joint between the glenoid fossa in the base of the skull and the condyle of the mandible.

3.2.1 The bony elements of the TMJ

3.2.1.1 The Glenoid fossa

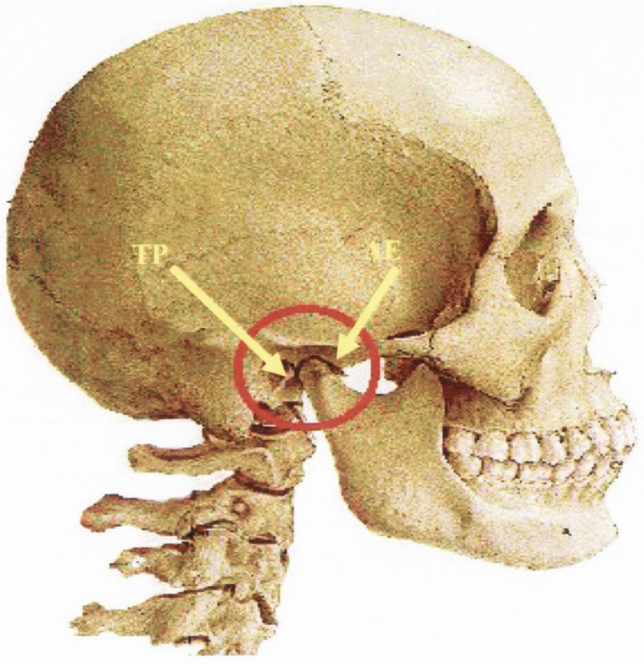


Figure 3.1: lateral View of bony elements of TMJ.
TP= Tympanic plate, AE=Articular eminence

The glenoid fossa is an oval shaped depression in the squamous part of the temporal bone, and lies just anterior to the external auditory meatus.

The fossa is bounded anteriorly by the articular eminence, laterally by the zygomatic process of the temporal bone, medially by a small projection of the tegmen tympani, and posteriorly by the tympanic plate of the temporal bone (Figures 3.1 and 3.2). The tympanic plate and squamous parts of the temporal bone meet at a fissure running transversely from medial to lateral across the deepest part of the glenoid fossa. This fissure is called the squamo-tympanic fissure (Figure 3.2).

It is divided towards its medial aspect into a petro-squamous part in front and a petro-tympanic part behind by a projecting margin of the temporal bone called the tegmen tympani.

Through the petro-tympanic fissure passes the chorda tympani nerve, which traverses the superior compartment of the joint, to join the lingual nerve about an inch below the base of the skull. It is then distributed to the anterior two thirds of the tongue (taste fibres), and also carries parasympathetic secretomotor fibres to the sublingual and submandibular salivary glands.

Other structures pass through the joint via the squamo-tympanic fissure. The anterior tympanic artery a branch of the maxillary artery passes up through the squamo-tympanic fissure to join the circular anastamosis around the tympanic membrane. The anterior malleolar ligament, which is attached below to the supero-medial aspect of the disc and capsule and to the sphenomandiblular ligament, passes up through the squamo-tympanic fissure to the middle ear where it becomes attached to the anterior process of the malleus (Pinto 1962). Both the sphenomandibular and the malleolar ligaments are remnants of the sheath around the Meckels' Cartilage.

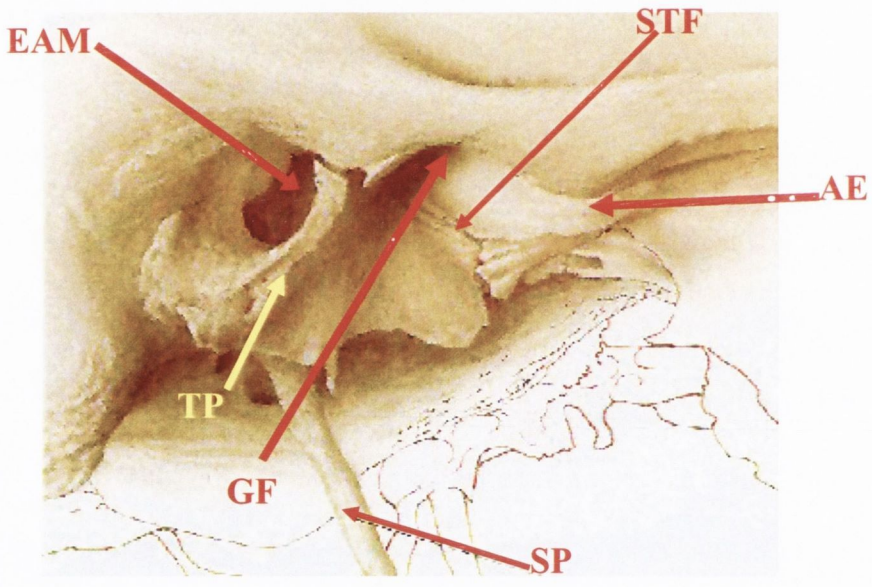


Figure 3.2: Infero-Lateral view of Glenoid fossa.
Tympanic Plate (TP), articular eminence (AE), glenoid fossa (GF), squamo-tympanic fissure (STF), and external auditory meatus (EAM)

The articular eminence arising anteriorly from the fossa is convex antero-posteriorly and slightly concave medio-laterally. This conforms to the shape of the disc/condyle assembly with which it articulates during mandibular movement. The articular surface of the fossa extends from the slope of the articular eminence past the crest of the articular eminence on to the upward anterior sloping surface of the infratemporal surface of the skull (the pre-glenoid plane). The articular surfaces are covered by tough white fibrocartilage, unlike other synovial joints, where hyaline cartilage covers the articular surfaces. Fibrocartilage does not cover the

most superior part of the glenoid fossa, as articulation does not take place in this area. A thin layer of periosteum covers this region.

3.2.1.2 Condylar process of the mandible

The Condylar process of the mandible (condyle) forms the inferior articular element. This is an upward projection from the posterior aspect of the ramus of the mandible (Figure 3.3). The condyle consists of a neck, which is flattened antero-posteriorly, and a head, which is approximately 2cm wide (from lateral to medial pole) and 1cm from anterior to posterior.

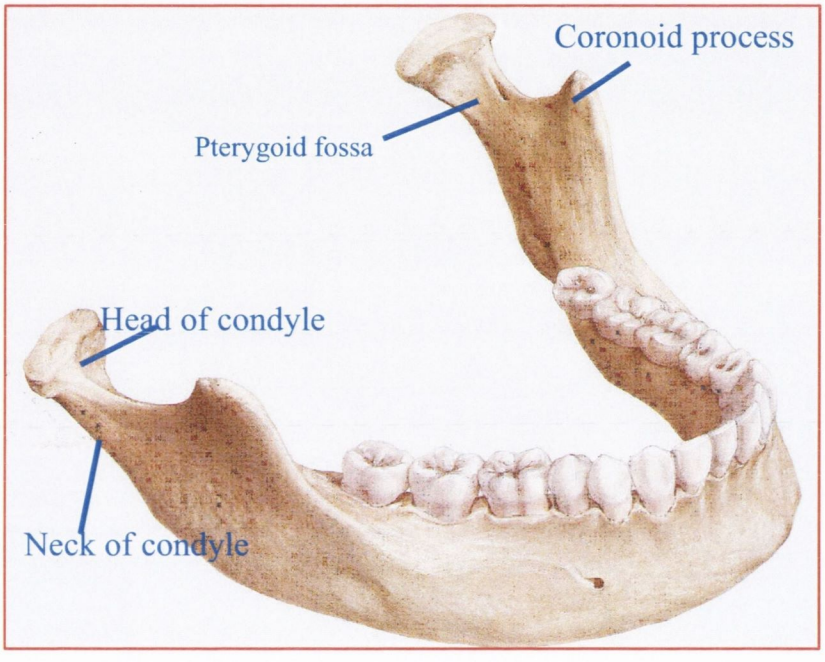


Figure 3.3: Dried mandible, showing head / neck of condyle, pterygoid fossa and coronoid process

The long axis of the condyle is rotated medially approximately at right angles to the plane of the ramus. The posterior surface of the head of the condyle is convex in shape and meets the anterior surface to form the antero-superior surface of the condyle (articulating surface), which is convex antero-posteriorly and convex or flat medio-laterally. The antero-superior surface of the condyle is the articular surface, and is covered by a tough layer of fibro-cartilage. The condylar head antero-posteriorly is approximately half of its medio-lateral dimension. However the dimensions of the condyle vary greatly (Berkovitz, et al., 1992).

There is also considerable variation in the shape of the head of the condyle. Baldioceda, et al., (1990), in a study on 53 subjects, categorised condylar profiles into four different types. They found that 39.6% of the condyles were rounded in sagittal profile, 32% were angular, 16% were rounded blunted, and 11.3% were rounded pointed (Figure 3.4).

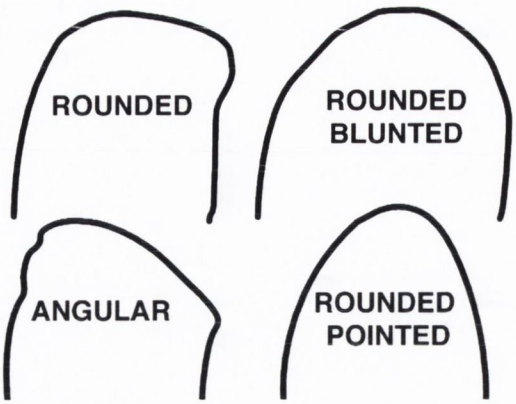


Figure 3.4: Diagram showing profile variations in condyles of young adults (Baldioceda et al 1990)

This variation in shape of condylar head particularly anteriorly may be of significance in determining the stress concentrations imposed on the tissues anterior to the condyle when excessive mouth opening occurs.

3.2.2 Soft Tissue Elements of the TMJ

3.2.2.1 The Disc

A fibro-cartilaginous disc is interposed between the condyle and fossa, and divides the joint into upper and lower compartments (Figure 3.5). When viewed from above the disc is roughly rectangular in shape from lateral to medial. At the lateral and medial side the disc tapers downward to be attached to the two poles of the condyle.

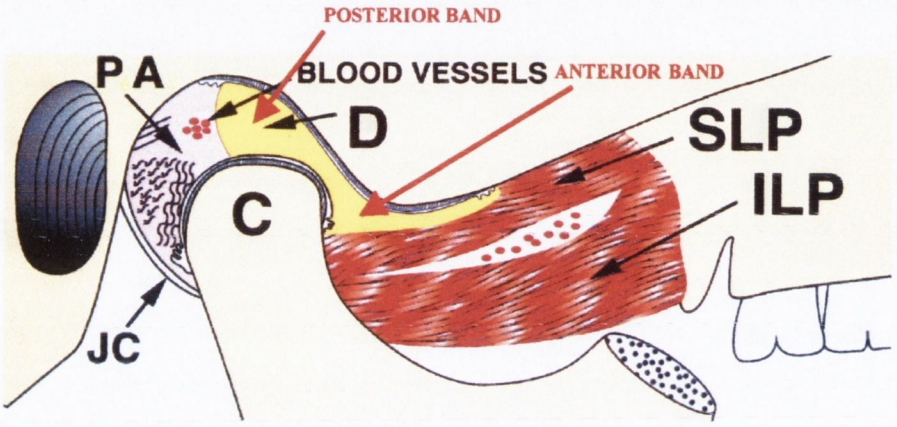


Figure 3.5: Diagram of sagittal section of temporomandibular Joint. Condyle(C), Disc (D), Posterior attachment (PA), Superior Lateral Pterygoid (SLP), Inferior Lateral Pterygoid (ILP) Joint capsule (JC)

In the sagittal view and at rest the disc is mainly concave on its inferior surface, whereas the superior surface is convex posteriorly and concave anteriorly. The shape of the disc changes during movement of the joint. The disc varies in thickness and accordingly Rees (1954) described it in three parts (Figure 3.5).

The Anterior Band: This is a thickening of the anterior part of the disc. The condyle moves onto this area in the final stages of mouth opening.

The Intermediate Zone: This is the central portion of the disc and lies between the anterior and posterior bands. The disc is very thin in this area and consists of collagen fibres arranged in sheets on the superior and inferior surfaces and aligned antero-posteriorly.

The Posterior Band: This is the thickest part of the disc, and is situated behind the intermediate zone.

Chondroid cells (resembling cartilage) have been identified in the discs of subjects over the age of 30 years, but no parallel rows of chondrocytes in a cartilaginous matrix as in hyaline

cartilage have been found (Mahan 1980). The disc is thus pliable and able to negotiate the undulating surfaces of the fossa and articulating eminence during the variety of mandibular movements, which occur during jaw function.

Anterior Attachments of the Disc: A fibrous extension of the anterior band is attached to part of the superior head of the Lateral Pterygoid. It is also attached to the anterior part of the pre-glenoid plane and to the anterior lip of the condylar process.

Posterior Attachment of the Disc or Bilaminar Zone: Attached to the posterior aspect of the disc is an area of soft tissue called the posterior attachment. It is sometimes referred to as the Bilaminar zone as it consists of two layers, called the superior and inferior strata.

The Superior Stratum: This is attached to the posterior aspect of the disc in front and the tympanic plate behind. It consists mainly of elastin tissue as it needs to stretch when the disc moves forward during condylar translation. Elastin is the only fibrous protein in the body with a true modulus of elasticity (Mahan 1980). The elastin tissue has two functions, viz. it permits forward movement, whilst maintaining stability of the disc on the head of the condyle. The disc is thus restricted slightly from moving forward during translation, and therefore assumes a more posterior position relative to the condyle during this movement.

Vascular Knee: This is a highly vascular area, which lies just in front of the bi-laminar zone and behind the posterior band of the disc. The superior and inferior strata are separated by loose areolar connective tissue.

The Inferior Stratum: This tissue is attached anteriorly to the lower part of the posterior band of the disc above and the posterior surface of the neck of the condyle below. It consists mainly of collagen fibres. It does not contain elastin as during mouth opening, the condyle is rotating backwards and upwards. This movement serves to counter any tension, which builds up in the inferior stratum as result of anterior translation.

3.2.2.2 The Joint Capsule

The inferior attachments of the capsule are to the lateral, medial, posterior and anterior surfaces of the neck of the mandibular condyle.

There is broad agreement in the literature regarding the lateral and medial portions of the superior attachments of the capsule. Laterally it is attached around the periphery of the joint in a line extending from the articular tubercle to the postglenoid tubercle, and medially around

the medial border of the glenoid fossa, from the entoglenoid process to the preglenoid plane (Gardner et al 1969, Dixon 1986, McDevitt 1989, Du Brul 1980).

There are however differences of opinion regarding the posterior and anterior attachments of the capsule.

- **Sicher (1960)** claims that the capsule is attached posteriorly to the tympanic plate in an area extending from the postglenoid process to the spine of the sphenoid, and anteriorly to the anterior rim of the preglenoid plane.
- **Gardner et al. (1969)** claims that the capsule is attached posteriorly to the squamotympanic fissure, and anteriorly to the margin of the fossa.
- **Mahan (1980)** states that there is no capsule present on the medial half of the anterior aspect of the joint, and that the synovial membrane lining the superior joint cavity is supported by loose areolar connective tissue. He also states that the lateral half anteriorly is poorly organised, and is in the main loose areolar connective tissue.
- **Williams and Warwick (1980)** state that the posterior attachments of the capsule are to the lips of the squamotympanic fissure
- **Last (1984)** states that the capsule is attached posteriorly to the squamo-tympanic fissure, and anteriorally just in front of the transverse prominence of the articular eminence.
- **Dixon (1986)** maintains that the capsule is weak in the anterior region and is attached posteriorly to the anterior margin of the squamotympanic fissure, so that structures passing through the fissure are outside the joint cavity.
- **McDevitt (1989)** maintains that the posterior attachments are to the postglenoid process, and the whole of the anterior surface of the tympanic plate. He further claims that there is no clearly defined joint capsule in the anterior region.
- **Gardener M. (1992)** states that the posterior attachments are from the spine on the post glenoid lip to the entoglenoid process and that the anterior attachments are around the anterior margin of the preglenoid plane.

The claims made that the capsular attachment posteriorly is to the squamotympanic fissure are difficult to sustain. When it is considered that the posterior attachment (bilaminar zone) extends from the posterior aspect of the disc to the posterior aspect of the condyle, and to the anterior surface of the tympanic plate, the capsule would need to pass through the posterior attachment to gain access to the squamotympanic fissure.

With regard to the anterior attachments of the capsule it should be pointed out that both heads of the Lateral Pterygoid muscle would need to pierce the capsule in this area, in order to gain access to the disc and condyle. This would require a window in the capsule or an absence of capsular tissue entirely. Thus the presence of a properly constituted capsule in this region is unlikely.

3.2.2.3 Ligaments Of The TMJ

The Temporomandibular Ligament

This is the principal temporomandibular ligament and is also known as the lateral ligament of the joint. It consists of a thickening of the capsular tissue on the lateral side (Figures 3.6, 3.7, 3.8 & 3.9), and extends from the lateral aspect of the tubercle of the zygomatic process, to the posterior aspect of the neck of the condyle. It is stated to be well developed (McDevitt 1989), but can vary in its dimensions from individual to individual, which may be of significance when considering its ability to withstand trauma. The dimensions of the ligament as measured on one joint by the author were found to be 3mm wide, 15mm in length. The distance of the ligament to the centre of rotation of the condyle was measured as 2.5mm.

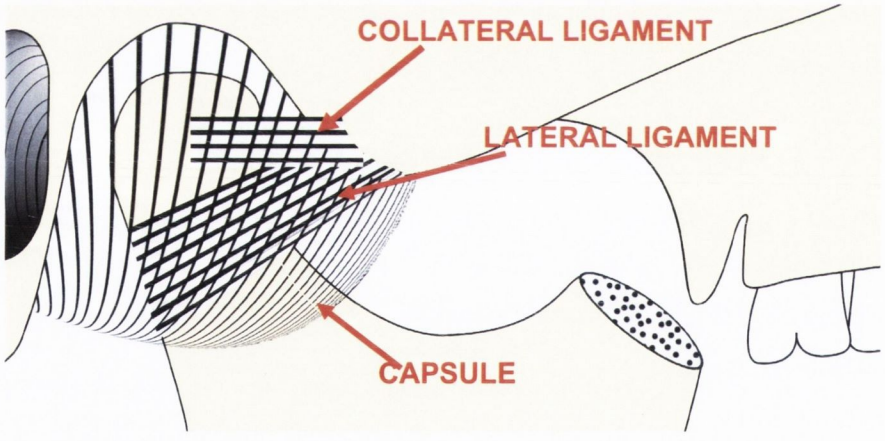


Figure 3.6: Lateral view of right TMJ, showing the ligaments within the capsule

However the ligament and capsule are not separable by blunt dissection. The whole structure is contiguous, the ligament being represented by a thickening of the capsular structure. Du Brul (1980) showed the lateral and collateral ligaments dissected out from the capsule (Figure 3.7). However this work was carried out by sharp dissection, which tends to give a false impression of the true nature of the structure.

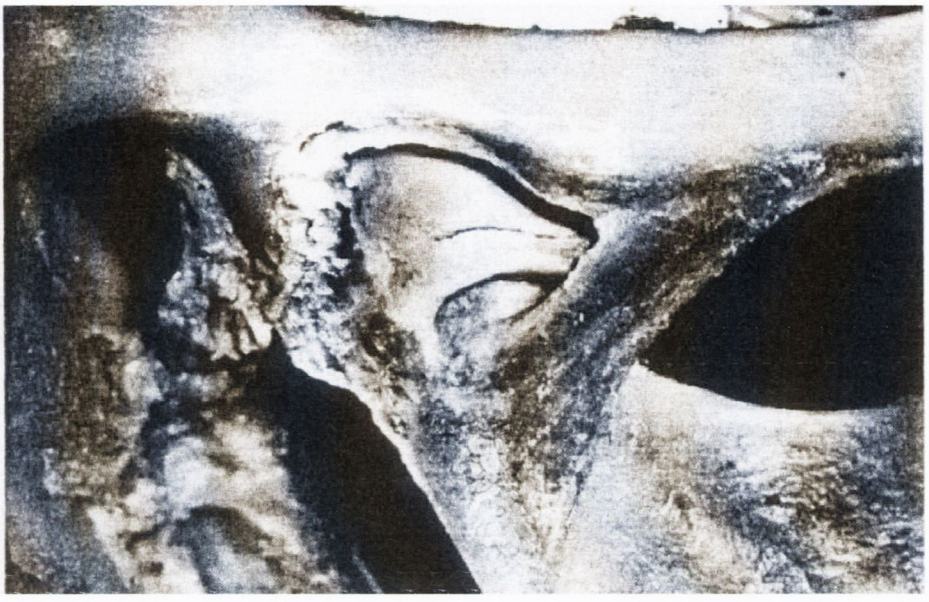


Figure 3.7: Lateral aspect of right TMJ showing lateral and collateral ligaments. (Du Brul 1980)

The lateral wall of the capsule and the ligament are rich in neural receptor end organs (Kraus et al 1969). The ligament is usually wider at its temporal attachment than at its condylar attachment.

The Collateral Ligaments

These are two narrow bands on the lateral and medial sides of the joint (Figure 3.8). DuBrul (1980) described the ligaments as an inner horizontal layer of the temporomandibular ligaments. Laterally the band arises from the crest of the articular tubercle where it is continuous with the attachment of the main ligaments. The band runs back horizontally to the lateral pole of the condyle. An upper part runs further back to be attached to the back of the disc.

On the medial side of the joint a less well-defined ligament runs from the medial pole to the crest of the articular eminence but there is no major ligament corresponding to that on the lateral aspect (Kraus et al 1969).

Functions of the Temporomandibular Ligaments

Suspensory Function: The temporomandibular ligaments (right and left joints) acting together are the main suspensory ligaments of the joint (McDevitt 1989). They resist displacement in an inferior and posterior direction.

Translatory Function: When the mandible is depressed in the initial stage of mouth opening the temporomandibular ligament tightens. The resultant build up of tension in the ligament forces the mandible to translate forward into the second phase of mouth opening, which consists of a combination of rotation and translation.

The ligament thus plays an important biomechanical role in mouth opening. (Osborn 1985, McDevitt 1989). The lateral and collateral ligaments act as restraining ligaments against posterior displacement of the condyles.

The total ligamentous unit functions optimally in response to a symmetrical force, such as a blow on the point of the chin (Figure 3.8). The ligaments on the contralateral side resist a lateral blow to the chin, while the ligaments on the ipsilateral side may offer resistance to lateral displacement of the condyle.

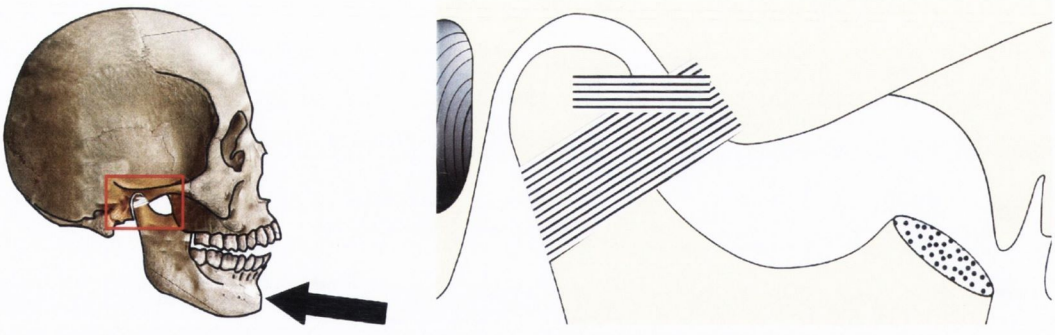


Figure 3.8: Skull and diagram showing Lateral Ligament resistance to direct trauma

However there is no ligamentous structure offering resistance to excessive anterior displacement of the disc/ condyle assembly, which might occur from a downward blow on the chin or from opening of the mouth due to indirect trauma (Figure 3.9).

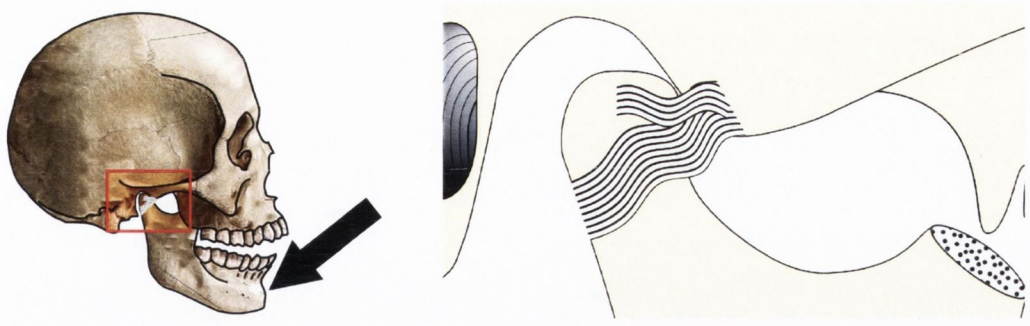


Figure 3.9: Skull and diagram showing lack of ligament resistance to anterior displacement of condyle

The medial and lateral collateral ligaments also act in conjunction with the lateral ligaments to maintain mechanical stability of the disc/condyle assembly at rest.

3.2.2.4 The Accessory Ligaments of the TMJ

There are two additional bands of fibrous tissue, which are described as accessory ligaments:

Sphenomandibular ligament: This is a remnant of Meckel's cartilage, and is continuous with the anterior malleolar ligament. It arises from the spine of the Sphenoid bone and petro-tympanic fissure, and runs inferiorly and laterally to insert into the lingula of the mandible spreading out into a fan shape at its mandibular attachment (Figure 3.10).

Stylomandibular ligament: DuBrul (1980) describes this ligament as a dense concentration of the deep investing layer of cervical fascia. It extends from the styloid process to the medial surface of the angle of the mandible (Figure 3.10).

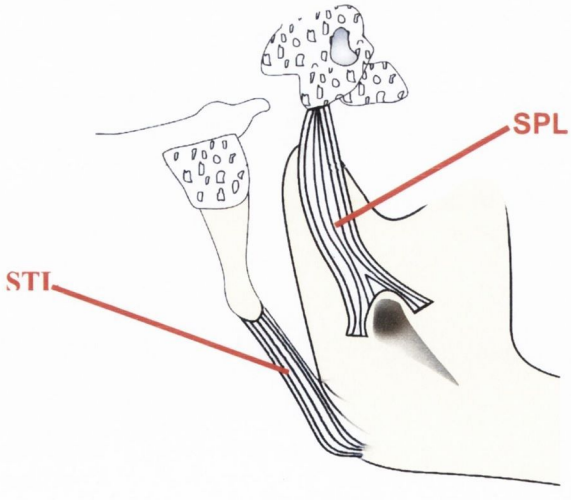


Figure 3.10: Medial view of Accessory TMJ Ligaments
Stylomandibular ligament (STL) and sphenomandibular ligament. (SPL)

Function of the Accessory Ligaments

The function of these ligaments is not known. The sphenomandibular ligament is passive during jaw movements (McDevitt 1989). When the direction of the ligament is examined, it would seem to be designed to prevent downward and slightly forward displacement of the condyle from the rest position. However, this could only occur from a blow delivered from behind the centre of rotation of the condyle, which is a highly unlikely event.

The anterior malleolar ligament, which according to Burch (1966) is an upward extension of the sphenomandibular ligament, may however have clinical and surgical significance. Burch showed that in the majority of cases the upper attachment of this ligament was to the petro-tympanic fissure, and through this fissure to the malleus of the middle ear. Other workers (MacAlister 1955, Richany, et al. 1954, Pinto 1962 and Mahan 1980) have also noted the presence of this ligament.

We confirmed the presence of an extension from the postero-superior aspect of the disc into the squamo-tympanic fissure in one specimen (Figure 3.42 page 89). This ligament may have significance in situations where auditory problems arise as a result of excessive inferior displacement of the condyle resulting from severe trauma either surgically or accidentally (Mahan 1980).

The stylomandibular ligament is stated to be lax when the jaws are closed or at rest. It slackens noticeably when the mouth is opened (DuBrul 1980). This occurs because the jaw is moving around an instantaneous axis of rotation during mouth opening. The ligament becomes tense only in extreme protrusive movements. The direction of the fibres of this ligament could act to resist downward and forward displacement of the mandible as a result of trauma delivered from *behind* the axis of rotation of the condyle. However a blow delivered from this direction would be a highly unusual event.

The T.M.J. of primitive man was designed to withstand forces delivered directly to the jaw, protection being given against posterior, superior and inferior displacement of the disc/condyle assembly by the arrangement of the ligaments described. However protection against excessive anterior movement is not afforded by the ligamentous arrangement. This is dependent upon neuromuscular defence mechanisms.

3.2.2.5 The Synovial Membrane

This is a smooth membrane, which lines the joint capsule and any other non-articular intracapsular surface of the joint (McDevitt 1989). The membrane does not extend on to any articular surfaces. The synovial tissues, which line the periphery of the joint spaces, are folded into villi-like structures. These folds permit movement to take place without tearing the membrane (Figure 3.11).

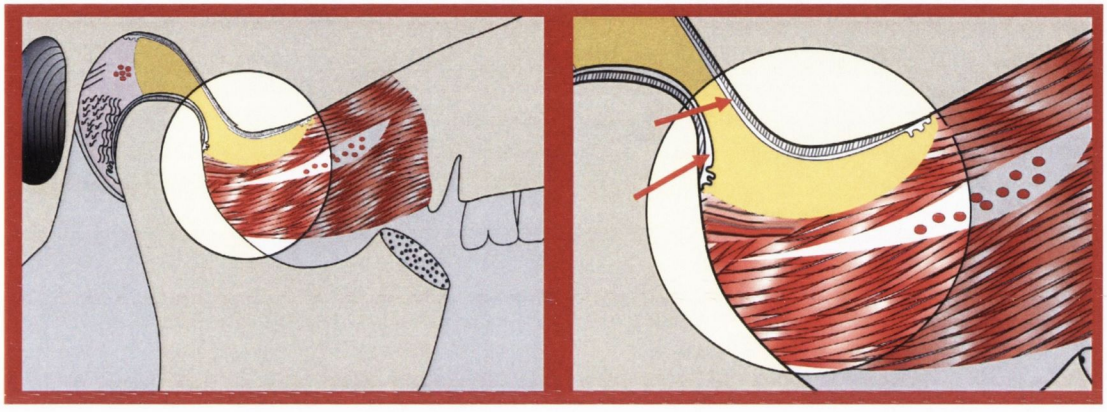


Figure 3.11: Diagram of normal and enlarged view of anterior band of disc and superior Lateral Pterygoid.
Also shown are superior and inferior joint spaces, lined by synovial membrane on non-articular surfaces (arrowed).

3.2.2.6 Lubrication of the TMJ

A thin film of synovial fluid, which contains a muco-polysaccharide (Hyaluronic acid), lubricates both the upper and lower joint spaces. This fluid is secreted by the synovial membrane, which lines the non-articular surfaces of the joint spaces. Lymphatic capillaries in the synovial membrane lining the non-articular surfaces of the joint spaces secrete a serum for the manufacture of the synovial fluid, which is needed for joint lubrication.

The amount of synovial fluid occupying the joint spaces is very small (approximately 1ml in each space). Fluid cannot therefore be aspirated from a healthy joint (Mahan 1980).

The slippiness of the joint surfaces insures that there is minimal resistance to movement of the articulating parts. Osborn (1985) stated that the relationship of the disc/condyle assembly to the fossa is akin to an individual stationary on roller-skates, delicately balanced, and susceptible to the slightest pressure. He further maintained that when the disc/condyle assembly is at rest against the posterior incline of the articular eminence (close-packed

position), it is in an unstable rather than a stable condition. Osborn stated that this position is held delicately by fine muscle balance, the slightest change in which will result in rapid movement.

3.2.2.7 Blood and nerve supply to the TMJ

According to Williams and Warwick (1980), every named artery within 30mm gives branches to the joint.

The articular branches are from:

- The superficial temporal artery.
- Maxillary artery
- Masseteric artery
- The vascular bed of arteries around the two heads of the Lateral Pterygoid muscle
- Periosteal vessels around the joint

The nerve supply is from:

- The auriculotemporal nerve posteriorly
- Articular branches of the Masseteric nerve
- Articular branches of the deep temporal nerve

Pain referral may occur to the ear via the auriculotemporal nerve in temporomandibular joint dysfunction (TMD) cases, or in cases of cervicogenic involvement (the sensory trigeminal nucleus extends into the upper two or three spinal segments (Last 1984).

The capsule and ligaments of the joint are rich in neural elements, which play a role in proprioception by monitoring mandibular position and act in conjunction with the craniomandibular muscles (Kawamura et al 1967). Damage to the capsule or ligaments may therefore cause disruption of the above feed back mechanism and interfere with functional jaw movement.

3.2.2.8 Clinical Considerations of TMJ Anatomy

Compression on the superior compartment of the joint may damage the anterior tympanic artery thus interfering with the blood supply to the tympanic membrane. Stretching of the malleolar ligament may affect the delicate relationship between the ossicles of the middle ear and thus contribute to hearing problems (Mahan 1980).

Surgery to the Temporomandibular Joint has been implicated in tearing of the postero-superior part of the tympanic membrane and an 80% reduction of hearing (Mahan, 1980). Similar hearing disturbances have also been recorded as a result of non-surgical trauma to the Joint.

The posterior deep temporal nerves are located on the temporal bone just anterior to the articular eminence. Thus in cases where excessive translation of the condyle occurs due to trauma these nerves could be traumatised.

The chorda tympani nerve passes out of the front of the middle ear and emerges through the petro-tympanic fissure, grooves the spine of the sphenoid, and passes through the superior compartment of the temporomandibular joint. It joins the lingual nerve an inch below the base of the skull, and is distributed with the lingual nerve to the anterior two thirds of the tongue (taste fibres). It also carries all the parasympathetic secreto motor fibres to the sublingual and the submandibular salivary glands. Damage to the chorda tympani as a result of trauma to the joint may thus cause excess salivary secretion, and /or changes in taste perception.

3.2.3 Muscles controlling mandibular movement

The muscles controlling mandibular movement are derived from the first branchial arch and are thus supplied by the mandibular nerve, with the exception of the posterior belly of the Digastric, which is derived from the second arch, and is therefore supplied by the facial nerve. These muscles are often referred to as the muscles of mastication. This term is imprecise as the muscles are involved in many other functions, such as talking, yawning, et cetera. They will therefore be referred to here as the craniomandibular muscles. They can broadly be considered under two headings viz, muscles primarily concerned with mouth opening and those primarily concerned with mouth closing. Muscles, which play an accessory role in jaw movements, will also be discussed.

3.2.3.1 Jaw Closing Muscles (Mandibular Elevators)

The muscles primarily concerned with mouth closing are:

- Masseter
- Medial Pterygoid
- Temporalis

Masseter Muscle

This is a rectangular muscle on the side of the face and jaw. For descriptive purposes it is usually described in two parts:

- Superficial head
- Deep head

Superficial Head - Origin and Insertion: This arises from the lower border of the zygomatic arch as far forward as the zygomatico-maxillary suture. The muscle runs downward and posteriorly to be inserted into the lateral surface and lower one half of the ramus and body of the mandible (Figure 3.12).

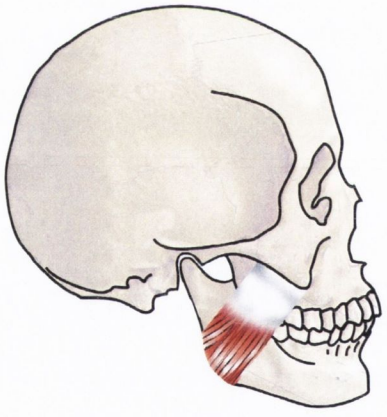


Figure 3.12: Origin and insertion of Superficial Head of Masseter Muscle

Deep Head - Origin and Insertion: This head arises from the medial surface and lower border of the zygomatic arch approximately 20mm in front of and 20mm behind the Temporo-zygomatic suture. The muscle passes down almost vertically to be inserted into a small-roughened area on the lateral aspect of the ramus of the mandible (Figure 3.13).

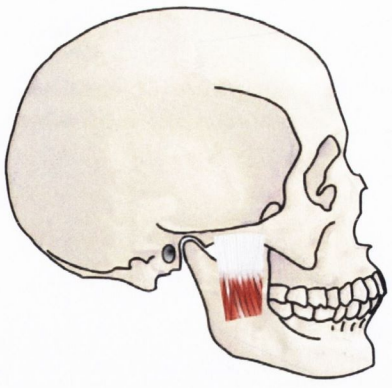


Figure 3.13: Origin and insertion of deep head of Masseter muscle

The main function of the Masseter is mandibular elevation. However, it can also exert a range of anterior vectors as the mandible is elevated from a depressed position into the position of maximum intercuspation. This is accomplished by contraction of first the anterior fibres and then the posterior fibres. The deep head has a slightly retrusive component, and the superficial head has a slightly protrusive component. The nerve supply is the Masseteric nerve, a branch from the anterior division of the mandibular nerve.

Medial Pterygoid muscle

This is a rectangular muscle on the medial aspect of the ramus of the mandible, approximately opposite the Masseter. It is not as wide or as thick as the Masseter.

Origin & Insertion: The main part of the muscle arises from the medial surface of the Lateral Pterygoid plate, the pterygoid fossa and the pyramidal process of the palatine bone (Figure 3.14).

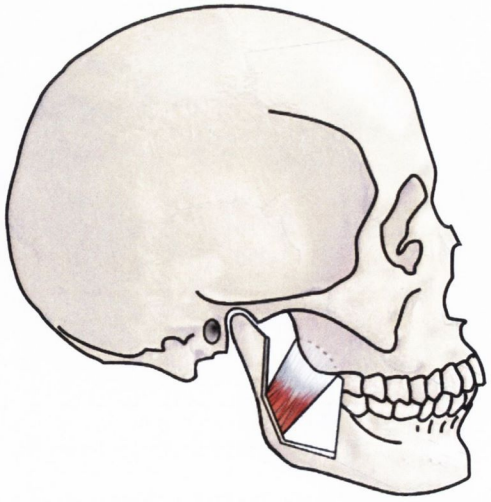


Figure 3.14: Origin and insertion of Medial Pterygoid muscle

A smaller head arises from the posterior surface of the tuberosity of the maxilla above the level of the buccinator muscle. The fibres from both heads run downward and laterally to insert into the medial aspect of the ramus and angle of the mandible.

The primary function is mandibular elevation. It may also have an anterior component near to the maximum intercusping position. Bi-lateral action of these muscles will seat the condyles antero-superiorly in the close-pack position in the glenoid fossa. Unilateral action of one muscle has an anterior, medial and superior effect.
This muscle is important in the function of mastication, acting in conjunction with the Lateral Pterygoid in side-to-side chewing movements.

Nerve supply
The nerve supply is the nerve to the Medial Pterygoid, a branch from the main trunk of the mandibular nerve.

Accessory Medial Pterygoid Muscle

This is a flat inverted triangular sheet of muscle, which lies on the medial aspect of the Medial Pterygoid (Koritzer and Suarez 1980). It is present in approximately 80% of cases.

Origin and Insertion: It arises from a line on the base of the skull, which extends from the pterygoid plates back along the medial side of the foramen ovale and foramen spinosum nearly as far as the carotid canal. The fibres converge inferiorly to be inserted into the Medial Pterygoid approximately 25mm below the base of skull.

It is thought to have a biofeedback function, which delivers proprioceptive information regarding the degree of activity in the muscle to the C.N.S. The nerve supply is a separate branch from the mandibular division of the trigeminal nerve (main trunk) (McDevitt 1989).

Temporalis Muscle

This is a large fan shaped muscle, which tapers down into a thick tendon of insertion (Figure 3.15).

Origin and Insertion: The main bulk of the muscle arises from the temporal fossa over the whole area between the inferior temporal line and the infratemporal crest (Last 1984).

A number of fibres also arise from an aponeurosis fused to the inner surface of the temporal fascia.

As it passes down to its insertion around the coronoid process, the fascial sheath of the muscle is intimately associated with the superior and lateral aspect of the infraorbital fissure and groove (Sicher1960). It is usually described in three parts according to the direction of the fibres:

- Anterior
- Middle
- Posterior

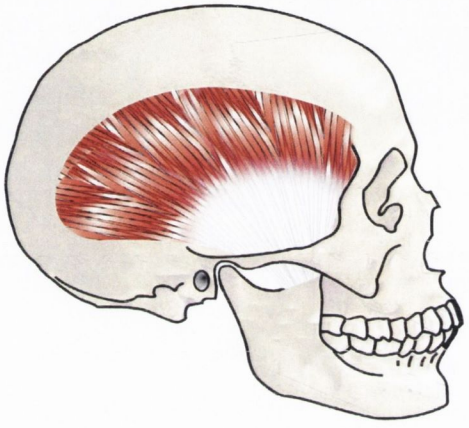


Figure 3.15: Temporalis Muscle Origin and Insertion

Anterior Fibres: These fibres arise from the temporal fossa anterior to the craniomandibular joint. The fibres are mainly vertical but some of the most anterior may have a slightly posterior inclination (Figure 3.16). Some fibres also arise laterally from the deep surface of the temporal fascia and medially from the surface of the temporal fossa lateral to the infratemporal crest.

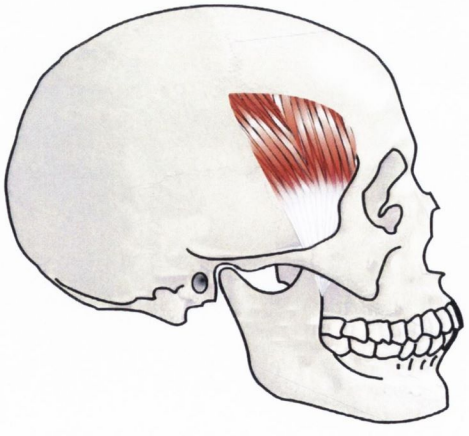


Figure 3.16: Origin and insertion of anterior fibres of Temporalis muscle

Middle Fibres: These fibres arise from the area of the temporal fossa directly above the craniomandibular joint. The fibres pass down to their insertion with a slightly anterior inclination (Figure 3.17).

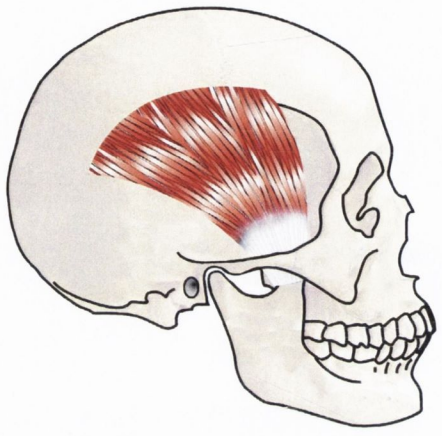


Figure 3.17: Middle fibres of Temporalis muscle

Posterior fibres: These fibres arise from the temporal fossa posterior to the craniomandibular joint. They run obliquely forward to their insertion, the more posterior ones being close to the horizontal (Figure 3.18).

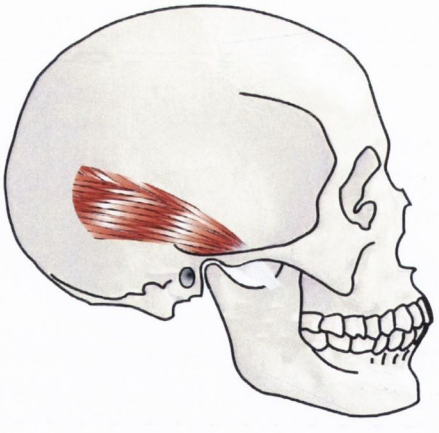


Figure 3.18: Origin and Insertion of the Posterior Fibres of the Temporalis Muscle

Insertion of Temporalis: The main insertion is into the bevelled surface on the inner plate of the coronoid process, and down the anterior ramus of the mandible, and at the anterior border down the ascending ramus, as far as the attachment of the buccinator muscle in the retromolar fossa (Last 1984). Sometimes this attachment reaches as far down as the last molar tooth (Brash & Jameson 1940).

In many cases there is a separate tendon running down the deep 'temporal crest' giving insertion for the deep, medial, and anterior part of the muscle (McDevitt 1989).

A very small portion of the tendon is inserted into the outer plate of the mandible. Some of the muscle fibres insert into the capsule of the temporomandibular joint (Rees 1954).

Where the Temporalis muscle arises on the inferior temporal surface of the skull lateral to the temporal crest it is closely associated with the superior head of the Lateral Pterygoid muscle. Some muscle fibres arising from this area insert into the disc/capsule complex over the articular eminence.

Rees (1954) also claimed that posteriorly fibres insert into the capsule and disc of the joint. The main function of this muscle is elevation and retrusion of the mandible. The tendon from the posterior almost horizontal fibres passes downwards around the root of the zygomatic arch at an acute angle. This angle becomes even more acute when the mandible is depressed during mouth opening. Contraction of these fibres pulls the condyle upward against the posterior incline of the eminence when the disc/condyle assembly is close to its fully seated position in the glenoid fossa.

The middle fibres pass downward and forwards and therefore have a more elevating and retrusive function.

The anterior fibres pass vertically downward and the most anterior fibres have a slightly posterior inclination. Therefore this part of the muscle has a vertical and slightly protrusive function.

Electromyographic studies carried out by Möller in 1966 showed the muscle to be active during the following movements:

- All elevation movements.
- Retrusion (particularly posterior fibres).
- During final seating of mandible into maximum intercuspation
- Maintaining elevation of the mandible during gliding tooth contact movements, particularly when the posterior teeth are separated during these movements. (Williamson & Brandt 1983)

Nerve supply: Temporal branches of the mandibular division of the trigeminal nerve (ant division)

Mandibular Capsular Muscle

This is a very slim muscle, which lies on the medial aspect of the Masseteric notch (McDevitt 1989).

Origin and Insertion: It arises from the medial edge of the posterior half of the Masseteric notch (Figure 3.19). The fibres pass upwards and backwards to be inserted into the lateral and anterior parts of the capsule and disc. Thus both the origin and insertion are moving parts.

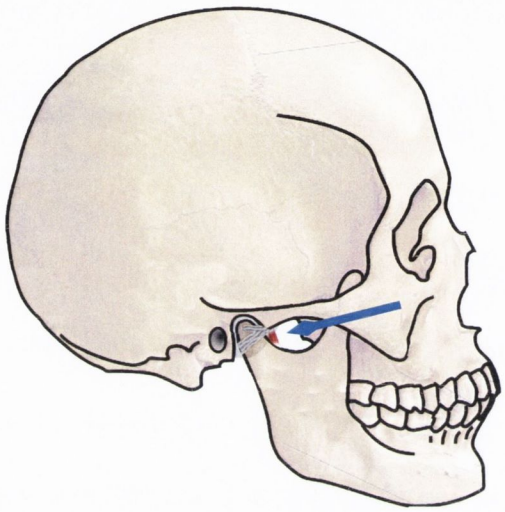


Figure 3.19: Mandibular Capsular Muscle (arrowed)

The function of this muscle is not clear. However a number of suggestions have been made in relation to this (McDevitt 1989).

These are as follows:

- To balance the action of the superior Lateral Pterygoid, which approaches the disc from an antero-medial direction whereas, this muscle approaches the disc from an infero-lateral direction.
- It may help to reduce torsion on the disc by contracting i.e., the disc is being helped during translation instead of merely being mechanically pushed by the condyle.
- It may help to control disc stability on the condyle during retrusion.

Nerve supply:
Branch from Masseteric nerve.

The Zygomatico-Mandibular Muscle

The Masseter and Temporalis muscles can only be separated where the buccal pad of fat lies between them. The deep surface of the deep head of the Masseter muscle which lies in front of the tubercle of the zygomatic arch and the Temporalis muscle which lies over it, intermingle and cannot be separated by blunt dissection. This section of muscle has been named the zygomatico-mandibular muscle (Figure 3.20). Some of the fibres from this muscle mass insert into the capsule and disc of the TMJ (Rees 1954, Koritzer and Suarez 1980, Widmalm, et al. 1987). This muscle mass acts as a supplementary mandibular elevator.

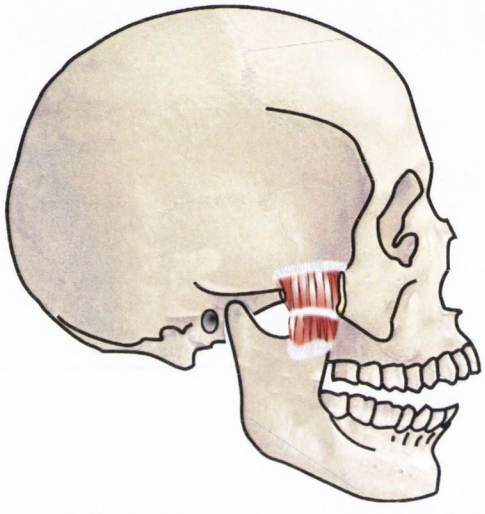


Figure 3.20: Origin and insertion of mandibular muscle mass. (Zygomatic arch removed).

3.2.3.2 Mandibular depressors (Jaw Opening Muscles)

The two principle mouth opening muscles are:

- The Lateral Pterygoid
- The Digastric muscle.

The Lateral Pterygoid Muscle

The Lateral Pterygoid lies in the infratemporal fossa just below the base of the skull, posterior to the maxilla and anterior to the posterior border of the mandibular ramus (Figure 3.21).

The muscle is described as having two parts:

- Superior Lateral Pterygoid.
- Inferior Lateral Pterygoid

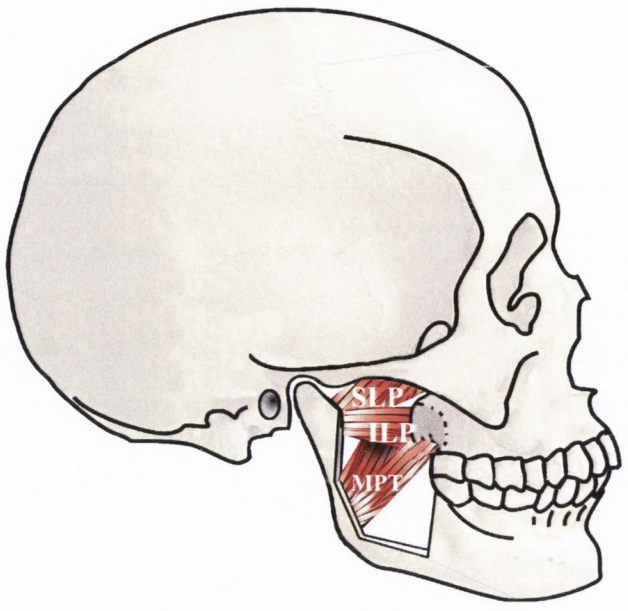


Figure 3.21: Lateral View of Pterygoid Muscles. Superior Lateral Pterygoid (SLP), inferior Lateral Pterygoid (ILP), Medial Pterygoid (MPT)

Superior head of Lateral Pterygoid: This muscle arises from the infratemporal surface of the greater wing of the sphenoid, as far forward as the inferior orbital fissure. The muscle may be continuous throughout the orbital fissure with the orbitalis muscle (McDevitt, 1989) laterally the muscle origin extends to the infratemporal crest where it blends with the Temporalis muscle (Christensen 1969). The superior head also arises from the superior third of the lateral surface of the Lateral Pterygoid plate. From its broad origin the muscle tapers as it passes backwards and laterally to be inserted into the capsule, disc, head and sometimes neck of the condyle. This muscle head was at one time thought to be involved in mouth opening, by acting to pull the disc anteriorly during translatory movements. Recent electromyographic evidence however indicates otherwise. The muscle is active during retrusion of the mandibular condyle. It thus acts to stabilise the disc on the head of the condyle during posterior translation (retrusion) in mouth closing (Lipke et al 1977 Mahan et al 1983). The muscle is thus lengthening, and at the same time maintaining muscle tone (eccentric action). It may also act to stabilise the disc while the disc/condyle assembly is in the rest position (Juniper 1981). The superior Lateral Pterygoid has also been shown to be active during tooth clenching (Widmalm et al., 1987, Mahan et al 1983). The superior head of the Lateral Pterygoid has been shown to be electromyographically inactive during protrusion of the mandible (Lipke et al 1977, Juniper 1981, Mahan et al 1983)

The Inferior head of Lateral Pterygoid: This head of the muscle arises from a fan shaped origin on the lateral surface of the Lateral Pterygoid plate and from the posterior wall of the maxilla up to the infra-orbital fissure. The muscle passes posteriorly and laterally to be inserted into the fovea on the antero-medial surface of the neck of the mandible.

This muscle has a number of functions according to different workers:

- The basic function is protrusion of the condyle.
- It may assist in rotation of the condyle (Grant 1973). The lower fibres of the muscle do approach the fovea from an inferior position, but mechanically the whole of the muscle would seem compromised in this function.
- Stabilization of the condyle on the articular eminence in the postural position (Dawson 1974, Sicher 1960).
- Protection against posterior and superior displacement of the condyle (Kawamura 1968).
- Lateral movement of the mandible to the contra-lateral side.

Nerve Supply:
Lateral Pterygoid branches from the anterior division of the mandibular nerve.

Various claims have been made regarding the posterior attachments of the superior head of Lateral Pterygoid. Honee (1972) dissected 10 muscles in 5 cadavers and Porter (1970) dissected the muscle in 42 cadavers. Both of these workers claim that in all their dissections, the superior head of the Lateral Pterygoid was inserted posteriorly into the capsular ligament and articular disc, and not into the neck of the condyle. Perry and Marsh (1977) illustrated vertical sections of each muscle attachment at the joint and reached the same conclusion. Mahan (1980) claims that many fibres of this muscle insert into the neck of the condyle serving to stabilize the anterior border of the disc just anterior to the condylar attachment. Wilkinson (1988) found that the superior head of the Lateral Pterygoid inserted mainly into the neck of the condyle and that only 20% of the fibres inserted directly into the disc.
Wilkinson and Chan (1989) examined 5 human cadaver joints under the dissecting microscope and found that in all 5 joints the major insertion of the superior head of the Lateral Pterygoid was into the condyle.

They subdivided the fibres into three groups:

- Fibres inserting into the condyle via the central tendon.
- Fibres inserting directly into fovea of the neck of the condyle.
- Fibres passing under the disc, blending with the fibres of the anterior joint capsule and then inserting into the condyle.

Based on these findings Wilkinson and Chan (1989) claimed, that it was highly unlikely that the contraction of the superior Lateral Pterygoid could cause displacement of the disc, thus refuting the claims of other authors (Pringle 1918), (Wakely 1948),(Weinberg and La Pointe 1987). Carpentier et al (1988) dissected the TMJs of 10 cadavers and found that the main posterior insertions of the superior Lateral Pterygoid were into the neck of the condyle. They found that only the medial one third of the disc had fibres of the superior head inserting into it. The middle one third of the disc had muscle fibres running under the anterior band and attaching into the upper part of the fovea. The lateral one third of the disc on the other hand had no muscle fibres inserting into it.

Digastric Muscle

This is the principal muscle involved in rotation/depression of the mandible. It consists of two bellies, which are connected by an intermediate tendon.

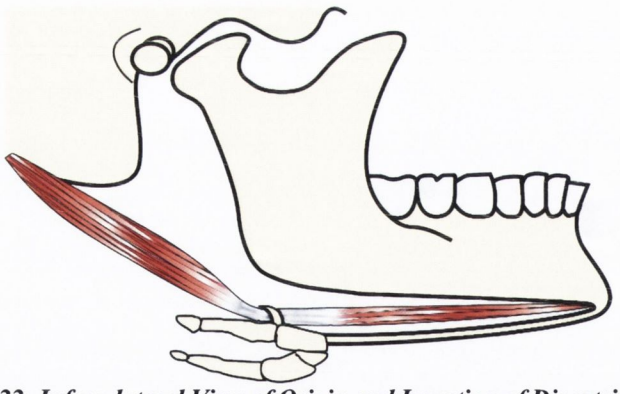


Figure 3.22: Infero-lateral View of Origin and Insertion of Digastric Muscle. The intermediate tendon is shown passing through a fibrous loop on the hyoid bone.

Origin and Insertion: The posterior belly arises from the mastoid notch medial to the mastoid process. The fibres run downward anteriorly and medially to the lesser cornu of the hyoid bone. The anterior belly arises from the Digastric fossa of the mandible, lateral to the mental symphysis. Its' fibres run backward laterally and almost horizontally to the lesser cornu of the hyoid bone. At the hyoid bone the two bellies are connected by an intermediate tendon, which is held down to the lesser cornu by a fibrous loop (Figure 3.22).

The fibrous loop permits sliding of the intermediate tendon. The muscle can therefore exert posterior, inferior and lateral forces on the mental symphysis. It should be noted that the Digastric muscles are often considered only in sagittal view. If they are looked at coronally it will be seen that the attachments of the muscle to the mastoid notch and hyoid bone are placed more laterally than the attachment to the Digastric fossa. As a result of this the muscle can also function medio-laterally. The jaw can be moved from side to side by one muscle contracting while the other is relaxing.

It should be stressed that the action of the Digastric muscle with regard to mandibular movement is dependent on a stable hyoid bone. Thus in situations where the anterior muscles of the neck have been strained, traumatised and torn especially the infrahyoid muscles, the hyoid bone may become elevated due to a loss of equilibrium between the suprahyoid and infrahyoid muscles. This can pose mechanical problems, which place an inordinate amount of stress on the Digastric muscle (Figure 3.23).

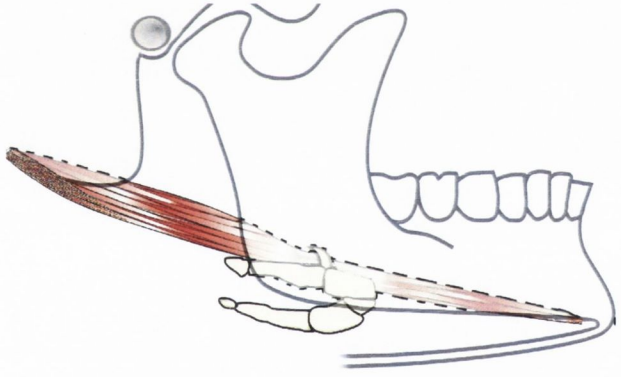


Figure 3.23: Diagram Showing the Digastric Muscle with Hyoid Bone Elevation.

The greatest electromyographic activity of the Digastric muscles takes place during depression of the mandible, both muscles (right and left) acting in unison (McDevitt 1989). During mouth closure, activity in the muscle is still present but reduced, as the muscle acts with controlled antagonism during mouth closure. The Digastric muscles are also active during all jaw movements including tooth grinding. They are however inactive during tooth clenching (McDevitt 1989). With the mandible stabilised in occlusion the Digastrics assist in the elevation of the hyoid bone, which takes place during swallowing.

Variations in this muscle are reported, which are mostly confined to the anterior belly. The most frequent deviation from the norm consists of oblique connections between the two anterior bellies. These connections sometimes occupy the entire space between the two muscle bellies (Sicher 1960).

Nerve Supply: The posterior belly is derived from the second branchial arch and is thus supplied by a branch from the Digastric branch of the facial nerve. The anterior belly is derived from the first arch and is supplied by a branch from the nerve to the mylohyoid (from the posterior division of the mandibular nerve).

Suprahyoid Muscles: The Digastric muscles are in fact best regarded as suprahyoid muscles. The other suprahyoid muscles are the genio-glossis, genio-hyoid and the mylo-hyoid. These muscles may contribute to mandibular depression at times but are probably not very important in this role. [Note that the lowest fibres of the genio-glossus are attached to the body of the hyoid bone].

3.2.4 Movements of the jaw joint

The movements that can occur at the TMJ are either rotation or translation or combinations of both. Posselt (1969) divided TMJ movements into the following categories:

- Border movements - Movements that take place on the boundaries of the movement space. These can be either anterior or posterior e.g. opening or closing of the mandible in the most anterior or posterior position.
- Intra-border movements - Movements that take place inside the boundaries of the movement space.

All of the normal functional movements of the mandible are intra-border movements and take place well inside the boundaries of the movement space.

3.2.4.1 Basic jaw Movements

Mouth Opening

In mouth opening, the condyles rotate against the discs around a moving axis as they travel downwards and forwards along the posterior incline of the articular eminence. This movement is facilitated initially by the action of the inferior head of the Lateral Pterygoid muscles, which brace the condyles firmly against the posterior slope of the articular eminence. This state of readiness is followed by contraction of the Digastric muscles, which causes downward rotation of the mandible. Then by the continuing action of the two pairs of muscles (the pterygoids acting to protrude the mandible, and the Digastrics acting to rotate it), mouth opening takes place around an anteriorly moving axis of rotation. In order to accommodate mouth opening, the elevators of the jaw must lengthen to act as balancers (eccentric contraction), and thus ensure smooth movement. Simultaneously the muscles of the cranium and hyoid bone act as stabilisers to ensure secure bases from which action can take place (DuBrul 1980).

Mouth Closing

Mouth closing consists of a combination of rotation of the mandible by elevation and retrusion by posterior linear movement (posterior translation). Elevation of the mandible by rotation is effected by the bilateral activity of the Masseter, Medial Pterygoid, and Temporalis muscles while the suprahyoids insure a smooth co-ordinated movement by eccentric contraction. The posterior and middle fibres of the Temporalis act to retrude the mandible in mouth closing.

Protrusion

Protrusion of the mandible is effected by the contraction of the inferior head of the Lateral Pterygoid muscle, which pulls the condyle downwards and forwards along the articular eminence. The superior head of the Lateral Pterygoid has been shown to be electromyographically inactive during mouth opening (Mahan et al 1983). The Digastric and posterior Temporalis muscles act antagonistically, to ensure smooth movement.

Retrusion

Retrusion is carried out by bilateral, activity of the posterior and middle fibres of the Temporalis together with the suprahyoids (including the Digastrics). The stability of the disc on the condylar head is controlled during this movement by eccentric action of the superior head of the Lateral Pterygoid. The inferior head of the Lateral Pterygoid also provides antagonistic action on the condyle.

Lateral Jaw Movement

This movement is carried out by contraction of the contralateral inferior head of the Lateral Pterygoid and Medial Pterygoid (both muscles approaching the mandible from an antero-medial aspect). These muscles act in co-ordination with the posterior fibres of the Temporalis muscle of the ipsilateral side, which holds the condyle firmly in the glenoid fossa while rotation takes place to that side. During this movement the condyle and disc on the contra-lateral slide downwards and medially along the posterior slope of the eminence, while the condyle on the side to which the movement is taking place rotates laterally around a vertical axis.

Mastication

There are two main movements involved in the mastication of food:

- Cutting which is carried out by the incisors and canines.
- Grinding or chewing of food, which is carried out by the molars and premolars.

Cutting

Cutting starts with opening of the mouth as described above, the amount of which is dependent on the dimensions of the particular portion of food. This is followed by a protrusive movement, which moves the lower incisors horizontally to the level of the upper incisors. The jaw is now raised to bring the incisors into an edge-to-edge contact. This movement is achieved by upward rotation of the condyles while the mandible is in a protruded position. The incising of the food is achieved by the gliding of the incisal edges of the lower teeth upwards and backwards against the palatal surfaces of the upper incisors. The

movement of the condyle during this movement is thus rotation and posterior translation. After each cutting stroke the teeth return to the edge-to-edge position by a combination of rotation and anterior translation.

Grinding

The grinding of food also begins with an opening movement as described above. The jaw is then rotated horizontally to the chewing side. Some lateral bodily movement of the mandible to the chewing side also takes place. This movement is called the Bennett movement (Posselt 1969). During these movements the condyle on the non-chewing side is sliding downwards and medially and also slightly towards the chewing side. The jaw is now elevated to bring the buccal and lingual cusps of the lower teeth into contact with their upper antagonists. The final part of this sequence consists of the movement of the lower teeth into full interdigitation, the condyles in the process reversing their movement. In close collaboration with the above movements the muscles of the neck act to steady the cranium and the hyoid bone, so that stable bases are established from which the opening and closing muscles can act. In mouth opening the hyoid bone moves up and down in co-ordination with the jaw when chewing is taking place. The tongue is thus able to move in conjunction with jaw opening and closing, and also acts as a manipulator of the food bolus. The above is a description of masticatory function in a class 1 jaw relationship when the lower incisor teeth rest against the palatal surfaces of the upper incisor teeth. This is the situation, which prevails in the majority of cases. In situations where the anterior teeth do not make contact in the resting position the individual must adapt to the anatomical circumstances. For example in angle class 3 jaw relationships the lower incisor teeth are situated anterior to the upper incisors, and in angle class 1 division 1 jaw relationships, the upper incisor teeth are situated a considerable distance anterior to the lower incisors. In both of these classes of occlusion the incising phase of mastication takes place on the canine and premolar teeth.

Swallowing

Before swallowing can take place, the air passage through the mouth must be sealed off. This is usually achieved by the closure of the lips, but can also be accomplished by pressure of the tongue against the hard palate.

- The first stage of swallowing is voluntary and consists of the food bolus being passed through the oro-pharyngeal isthmus. This is accomplished by contraction of the vertical intrinsic muscle of the tongue, which creates a longitudinal groove in the dorsum. The tip and sides of the tongue are kept in contact with the hard palate and teeth by the contraction of the mylohyoid muscle, which raises the floor of the mouth.
- The vertical intrinsic fibres of the tongue now relax from anterior to posterior, and at the same time upward pressure obliterates the groove thus forcing the food bolus backwards. The posterior aspect of the tongue is pushed back by compression of the contracting mylohyoid muscle, and it is pulled up and back by the stylo-glossus after the bolus has passed.
- The second stage of swallowing is involuntary, as the food bolus enters the oro-pharynx. The inlet to the larynx is elevated under the back of the tongue and is thus protected, and is closed by the contraction of the ary-epiglottis. The glottis is sealed off by the contraction of the adductors of the true vocal folds and respiration is temporarily halted. The epiglottis is inverted by the passing bolus and closes like a lid over the larynx.
- The soft palate is elevated against the overhanging shelf of passavant's ridge*, thus sealing off the naso-pharynx. The food bolus has now only one path to take, as the passages to the nose and larynx have been blocked off.
- The third stage of swallowing is oesophageal and is also involuntary, during which the food is carried to the stomach by reflex peristaltic movement.

Phonation

Phonation or the production of speech is achieved by the production of a stream of air through the larynx as a series of discrete jets in the much the same way as the production of a siren (Last 1984). Articulation in the context of phonetics is defined as the control of the organs of speech during the production of speech. At rest the vocal folds are separated and have sharp edges. During phonation the folds are held together, and the crico-vocal membrane is pulled up by the vocalis muscle, bringing the folds into contact over a vertical extent of about 3mm inferior to their free edges. The opposed parts of the folds are blown apart at irregular intervals by the pressure of expired air from below.

*Passavants' ridge is created by the contraction of the horizontal fibres of the palato–pharyngeus (sometimes referred to as Passavants' muscle, (Last1984)).

The function of the vocal folds is to produce sound, which varies only in pitch and intensity. The quality or resonance of the voice is dependent on the alteration of the position of the tongue and soft palate, which will change the volume of the naso-pharynx and oropharynx. The tongue, teeth and lips carry out the breaking up of sound into recognisable articulate speech.

In whispering the vocal folds are kept separated and vibrations are imposed on a constant, as opposed to an intermittent stream of air. Minimal movement of the jaws takes place during phonation, as the tongue lips and palate require stability of the jaws in order to function optimally.

Coughing and Sneezing

A cough or sneeze is an explosion of compressed air. The vocal folds are firmly adducted and a strong expiratory contraction is made to build up the intrathoracic pressure. The vocal folds are then suddenly abducted and a blast of compressed air is forced through the larynx. Narrowing of the trachea augments the affect of this blast. It is important to note that during the build up of intrathoracic pressure the head is thrown into retroflexion and the mouth is opened. As the pressure is released and the sneeze or cough takes place, the head is thrown into flexion, and the mouth is suddenly closed. This movement is similar to that which takes place in the whiplash event, and there are reports in the literature of disc displacement in the TMJ resulting from a violent sneeze or cough (Pringle 1918 Wakely 1948).

Intense Muscular Effort

Straining of the abdominal muscles such as takes place in evacuation of the bowels or the lifting of heavy weights is made more effective by the adduction of the vocal folds. The diaphragm is weaker than the muscles of the anterior abdominal wall. Therefore in order to prevent loss of intra-abdominal pressure, the folds are closed after a deep breath, and the diaphragm is forced upward against a cushion of compressd air. During the above functions, extreme contraction of the mandibular elevators often results in clenching of the teeth.

3.2.4.2 Parafunctional Habits (Abnormal Jaw Movements)

Bruxism

This is defined as persistent clenching, grinding or tapping of teeth. It is a habit, which is more common nocturnally than diurnally and often takes place without the knowledge of the individual who is indulging in the habit. Bruxism takes the form of three types of habit, viz. tooth clenching, tooth grinding, and tooth tapping.

Tooth Clenching

This consists of the static forcible bringing together of the upper and lower teeth, and maintaining this position by the forcible contraction of the mandibular elevators over varying periods of time. This habit can lead to pain in the Temporalis, Masseter, and Medial Pterygoid muscles, and can also be associated with tension type headache.

Tooth Grinding

This habit consists of the forcible horizontal movement of the mandibular teeth against the maxillary teeth. This movement can take place close to the maximum intercuspal position or it can occur at an extreme border position, commonly with the mandibular canine being repetitively moved from side to side over the maxillary canine in an edge-to-edge position. These habits principally involve the mandibular elevators on the ipsilateral side, and the lateral and Medial Pterygoids on the contra-lateral side and can thus lead to pain in these muscles. Again persistent indulgence in this habit can lead to pain in the muscles involved or to a gradual breakdown of the attachment of the disc to the condyle of the mandible.

Tooth Tapping

This habit involves the repetitive tapping of the lower teeth on the upper teeth for varying and sometimes protracted periods of time. The muscles involved are the elevators and excessive indulgence in the habit can lead to pain in these muscles.

All of the above habits may be associated with tongue thrusting and are usually associated with periods of stress in the subjects' life.

3.2.4.3 The Terminal Hinge position

Posselt (1969) stated that theoretically a purely hinge movement can be carried out at every degree of mandibular protrusion. When this occurs in the terminal (most retruded) position, it is termed the terminal hinge movement. The terminal position hinge movement can take place over a range, which separates the upper and lower incisors by 20-25mm (approx. 15°).

- The terminal hinge movement can be made actively by powerful contraction of the middle and posterior fibres of the Temporalis muscles. This maintains the condyles in the terminal position while the mandibular elevators and depressors perform the hinge movement.
- The terminal hinge movement can also be carried out passively by the operator rotating the mandible while the patient keeps the jaw muscles relaxed.

Rees (1954) studied jaw movement in cadaver specimens, and concluded that they could be divided in to the following phases:

- **Retruded opening phase:** In this phase the condyles commence to rotate around the bicondylar axis, while the axis remains more or less stationary. During this phase the condylar ridge moves forward 5 to 6 mm on to the intermediate zone of the meniscus. At the same time the disc moves slightly on the temporal bone.

- **Protrusive opening phase:** In this phase the intercondylar axis moves downwards and forward as the condyles continue to rotate around the axis. Simultaneously the condylar ridge moves further forwards on the inferior surface of the intermediate zone. The intermediate zone of the disc remains between the anterior, articular slope of the condyle, and the posterior slope of the articular eminence. The posterior attachment stretches some 6-9mm to allow for this movement.

- **Extreme opening phase:** During this phase the intercondylar axis continues to move downward and forward and the condylar poles move further forward relative to the posterior band of the disc. At the same time the condyle is still rotating, and close to the full extent of mouth opening the condylar ridge slips forward over the anterior band. In the extreme open position the transverse ridge of the condyle lies in front of the anterior band and fully occupies the anterior portion of the inferior joint space.

Rees (1954) made some measurements of joint movement in mouth opening, which showed the following:

- The total movement of the condyle relative to the disc was 8mm.
- The total movement of the condyle relative to the temporal bone was at least 15mm.
- The total movement of the disc relative to the temporal bone was approximately 7mm.

The above findings showed that the disc moves at about half the velocity of the condyle during mouth opening. The build up of tension in the temporomandibular ligament is one of the main factors causing the transition from rotation to a combination of rotation and translation, when the mandible is depressed during mouth opening. McDevitt (1989) stated that the mandible could hinge up and down over a range of (20-25mm). He further stated that after this amount of depression, tautness of the mandibular ligaments and compression on the structures dorsal to the mandible compel anterior translation of the condyle if further depression is to be achieved. Merlini and Palla (1989) carried out an investigation on the relationship between translation and rotation in healthy joints as opposed to clicking joints. They found that in both groups of subjects, translation and rotation occur almost simultaneously during active mouth opening. They did not however carry out a study on the relationship between rotation and translation during passive mouth opening, which as will be seen later is a critical factor when considering jaw behaviour resulting from whiplash.

3.3 Macroscopic and Histological Investigation of the TMJ

It was decided to carry out an investigation of the soft tissues of the TMJ with particular reference to the lateral Pterygoid muscle, as there is much debate regarding the role that this muscle plays in anterior displacement of the disc from the head of the condyle.

3.3.1 Materials and Methods

A total of twenty-three joints were chosen randomly to be evaluated in the study (13 males, and 10 females, average age 76 years). The specimens were chosen on the basis of availability of those which had not been dissected by the medical students prior to the commencement of this study. This ensured that there was no bias in the sample. The choice of specimens for histological evaluation was also made randomly.

The cadavers were fixed by slow perfusion through the femoral artery using a solution of formalin, glycerine, alcohol, phenol crystals, and salicylic acid).

- Macroscopic examination was carried out on thirteen specimens.
- Histological evaluation of the lateral Pterygoid was carried out on six of these thirteen specimens
- Four joints were used for tissue strength testing (see chapter 5).
- Six joints were discarded due to the soft tissue being excessively damaged.

Prior to dissection, the joints were removed from the cranium in the following manner. (The cranial vaults had already been removed from each specimen):

Initially the cranium of each specimen was hemi-sectioned with an electric saw by making a saggittal cut in the median plane from anterior to posterior through the median palatine suture.

Two vertical cuts in the coronal plane were now made in the cranium, one posterior to the external auditory meatus, and one through the maxilla anterior to the maxillary tuberosity. Both of these cuts extended superiorly above the inferior temporal line. Where possible a complete hemi-section of the mandible was retained. However in most cases this was not possible, due to previous dissections, which left only a small portion of the ramus and head/ neck of the mandible. All of the specimens used had an intact temporomandibular joint. Thus the specimens removed from the cadaver included the entire ipsilateral cranial fossa, and a small portion of the anterior cranial fossa.

The sections were now prepared for dissection by filling the middle and anterior cranial fossae with plaster of Paris, which was allowed to extend beyond the section, anteriorly, posteriorly, medially, and superiorly. This facilitated ease of handling.

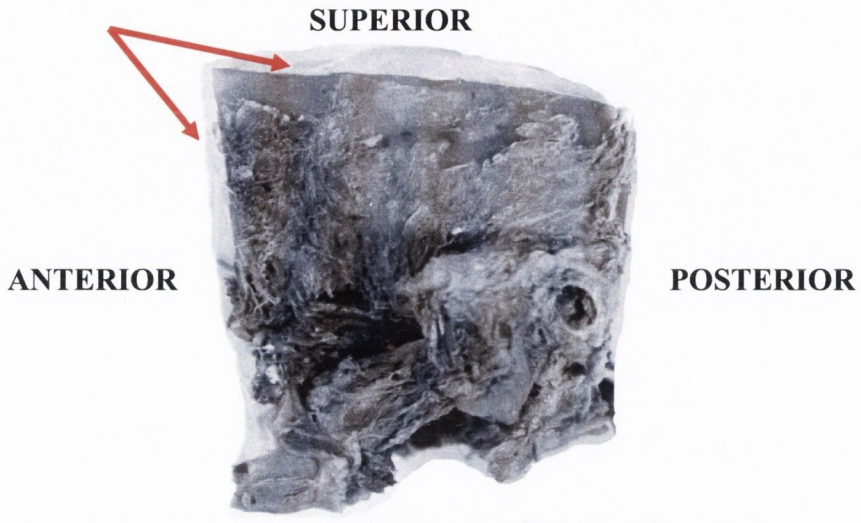


Figure 3.24: Specimen no.1.Left TMJ, mounted in plaster of Paris. The arrows indicate the plaster of Paris.

The elements of the joint were thus mounted in a stable fashion facilitating dissection without unwanted movement of the specimen (Figure 3.24). Initially the soft tissue covering the temporal bone and the mandible was removed down to the level of the joint capsule. This included the removal of the Temporalis and Masseter muscles, the parotid gland and the zygomatic arch. The attachment of the joint capsule was carefully examined and the capsule was then removed.

The joint elements deep to the capsule were now examined. The tissues examined were as follows:

- The integrity, condition and attachments of the joint capsule.
- The integrity and bulk of the temporomandibular ligament.
- The nature of the posterior attachment tissues.
- The integrity and the attachments of the disc.
- The attachments of the two heads of the lateral Pterygoid muscle, the relative sizes of the two heads and any other variations which were identified.

In this regard measurements were made of the two heads of the muscle in order to ascertain their comparative size in each specimen and also to compare the sizes of each head in all specimens.

The calculations of the volume of the two heads of the muscle were carried out in the following manner:

As the two heads of the muscle are tapered from origin to insertion, each was regarded as a fustrum* (Figure 3.25), with the widest part of the muscle origin being the base of the cone and the narrowest part at the muscle insertion being at the narrow end of the cone. Their volume could thus be calculated in the following manner. The formula for the volume of a Frustum is as follows:

$$V_f = \frac{1}{3}\pi\, h\, (R^2 + r^2 + Rr)$$

Where **h** is the height of the cone (length of the muscle), **R** is the radius of the base (widest point of the muscle), and **r** is the radius at the tip (narrowest point of the muscle,(Figure 3.25)).

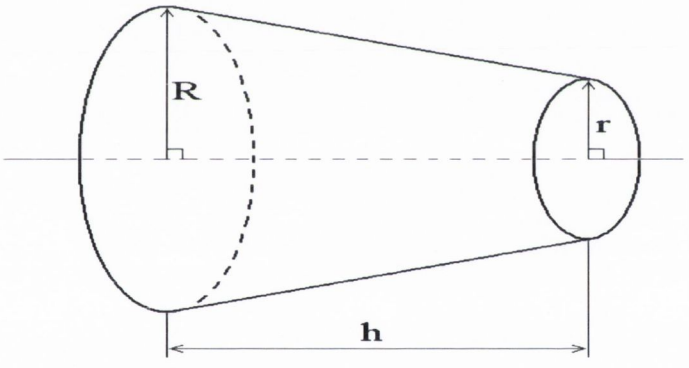
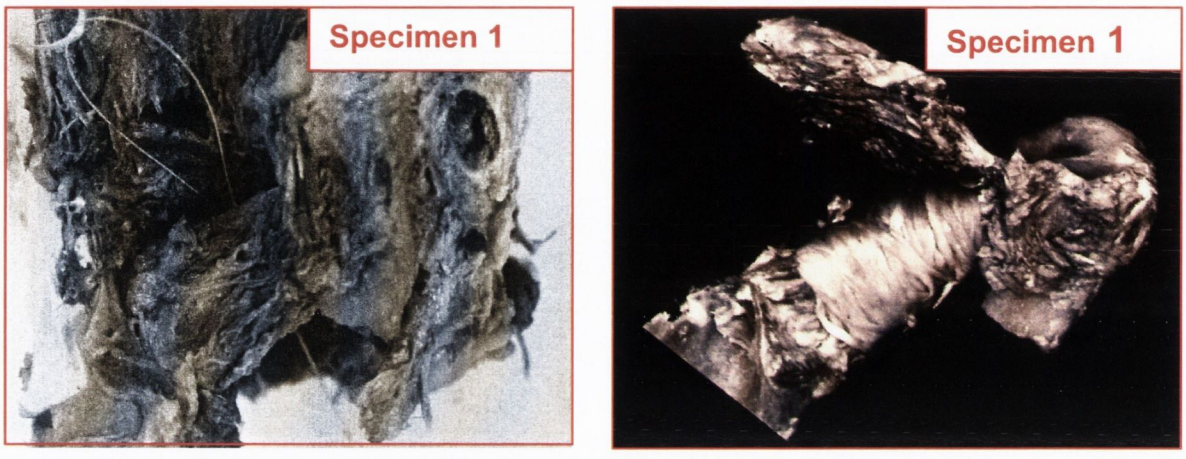


Figure 3.25: Illustration of fustrum
r= radius at the narrowest part, R=the radius at the widest part and h= height (length) of the cone (Thomas & Finney1996)

The calculations were thus carried out in the following manner. The circumference of the muscle heads were measured by wrapping dental floss around the muscle at the widest and narrowest point, and then measuring the length of floss (Figure 3.26). The length of the muscle head was measured by using a Mitutoyo digital caliper (Figure 3.27).

* Fustrum=truncated cone



(a) *(b)*

Figures 3.26 (a): Dental floss being threaded around the inferior head of the lateral Pterygoid to measure circumference, & 3.26 (b) the inferior head being moulded into the shape of a truncated cone (fustrum)



Figure 3.27: The length of the inferior head of the lateral Pterygoid being measured using a Mitutoyo digital calliper.

3.3.2 Macroscopic Findings

3.3.2.1 Specimen 1 (Male)

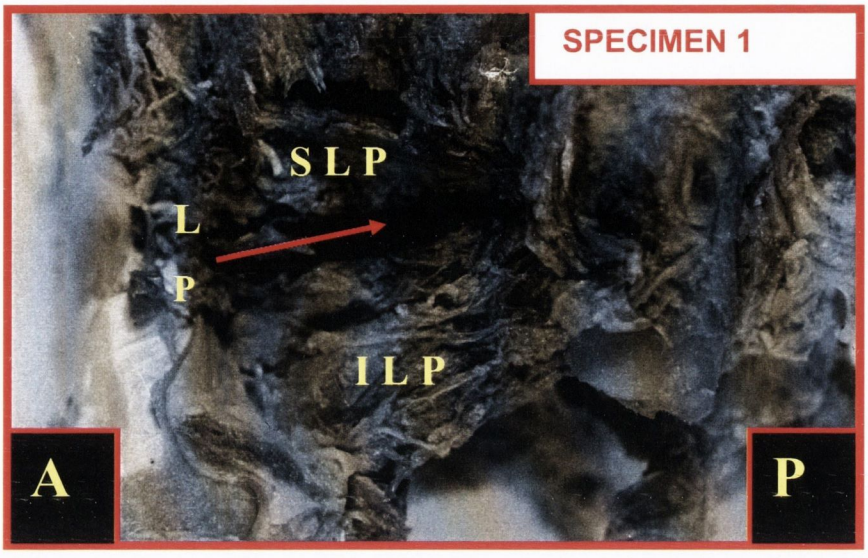


Figure 3.28: Specimen 1 showing both heads of Lateral Pterygoid muscle (SLP and ILP), attaching to the lateral Pterygoid plate (LP)
The space between the two heads was occupied by the pterygoid plexus of veins (arrowed)

The Capsule

Superior attachments:

- Posteriorly - To the tympanic plate and post glenoid process.
- Laterally - To the ridge of bone lateral to the glenoid fossa, lying between the glenoid processes posteriorly and the articular tubercle anteriorly.
- Medially - To the medial glenoid plane from the entoglenoid process to the crest of bone on the medial aspect of the articular eminence posteriorly.
- Anteriorly - The capsule was present in the lateral aspect, but toward the medial the tissue became very thin with no tough collagenous material being evident.
- Fibres of the Temporalis muscle were found inserting into the joint capsule.

Inferior attachments:

Around all the surfaces of the neck of the condyle and to the inferior aspect of the bi-laminar zone.

The Temporomandibular Ligament

The ligament was not clearly defined in this specimen.

The Disc

- The disc was well formed with no perforations, deformation or degenerative changes (Figure 3.29).
- The attachment of the disc to the medial wall of the fossa was very firm. It required sharp dissection to remove the disc / condyle assembly from the fossa.

The Posterior Attachment

- This tissue was well defined as two separate strata separated by loose connective tissue.
- The superior stratum was generously vascularized in the area just posterior and inferior to the posterior band of the disc.

The Lateral Pterygoid Muscle

- The inferior head was observed to be considerably larger than the superior head.(Fig 3.28)
- The medial fibres of the superior head had a tendinous attachment to the medial aspect of the articular eminence.
- The fascia covering the superior surface of the superior head was contiguous with the fascia surrounding the vessels and nerves emerging from the foramen ovale. Pulling on the muscle created tension on these tissues (Figure 3.29).
- Fibres of the Temporalis were found inserting into the myofascia of the superior head close to the anterior part of the of the infratemporal fossa.
- The superior head arose from the infratemporal fossa as far forward as the inferior orbital fissure, and from the superior aspect of the lateral surface of the lateral Pterygoid plate.
- The inferior head arose from most of the lateral surface of the lateral Pterygoid plate.
- The two heads of the muscle were distinct and separate until they approached their areas of insertion into the disc and condyle, where they fused. Fascial planes between the two heads were not present in this area and it was not possible to separate them by blunt dissection.

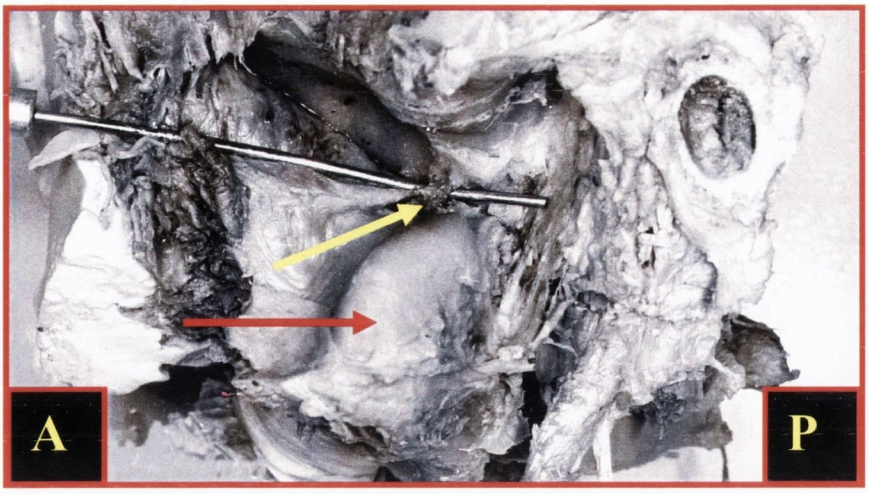


Figure 3.29: Specimen 1,attachment of Disc to Foramen Spinosum.
The red arrow shows the disc and yellow arrow the attachment to foramen spinosum.

Measurements of the lateral Pterygoid muscle

Superior head:

Anterior circumference = 51mm.

Posterior circumference = 48mm.

Length = 20mm.

Volume = 3.9 cc.

Inferior head:

Anterior circumference = 58mm.

Posterior circumference = 48mm.

Length = 24 mm.

Volume = 5.4 cc.

A further twelve specimens were evaluated in the same manner as described above (Figures 3.30&3.31).

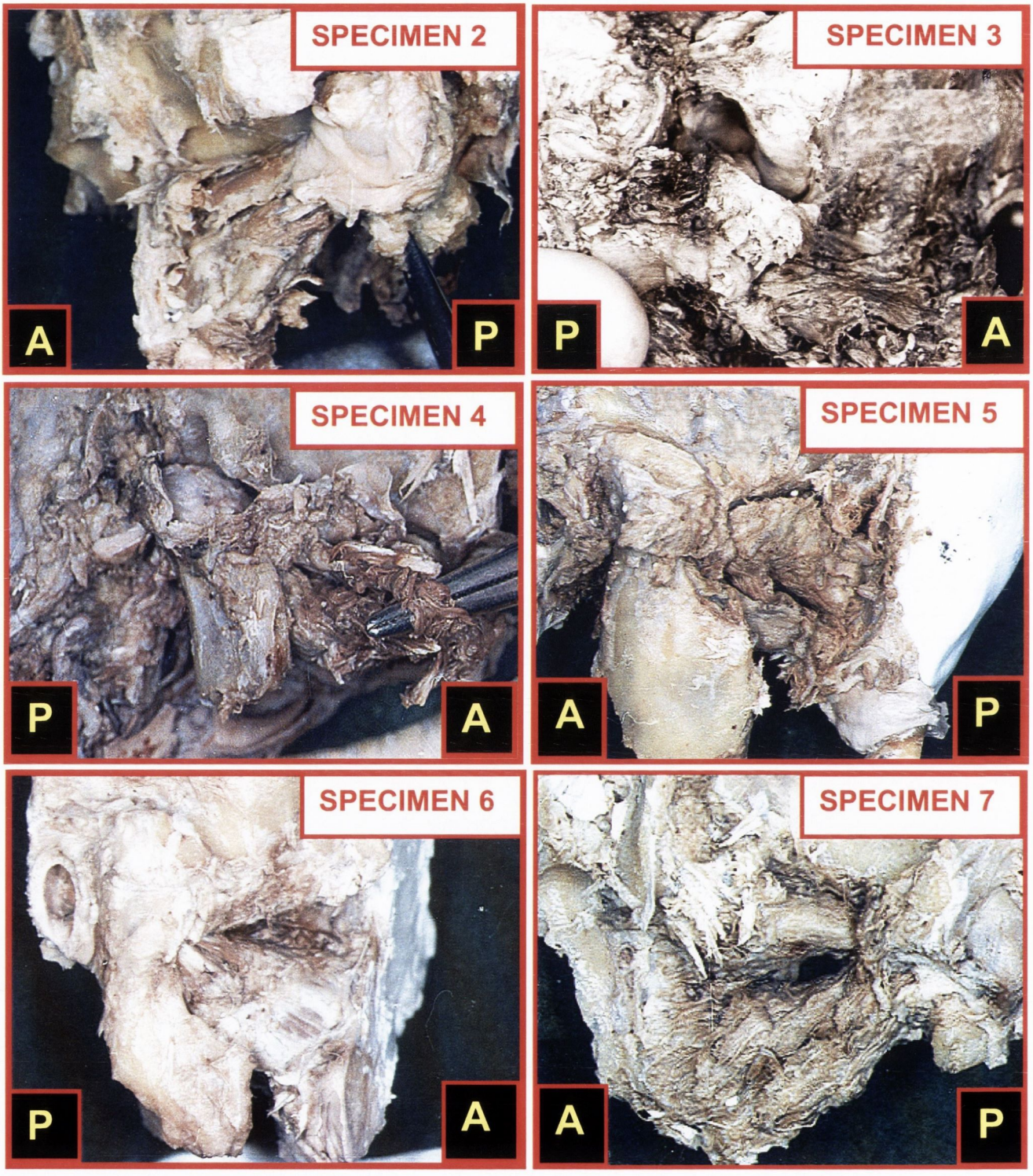


Figure 3.30: Specimens 2 to 7 in various stages of dissection, A= anterior and P=Posterior

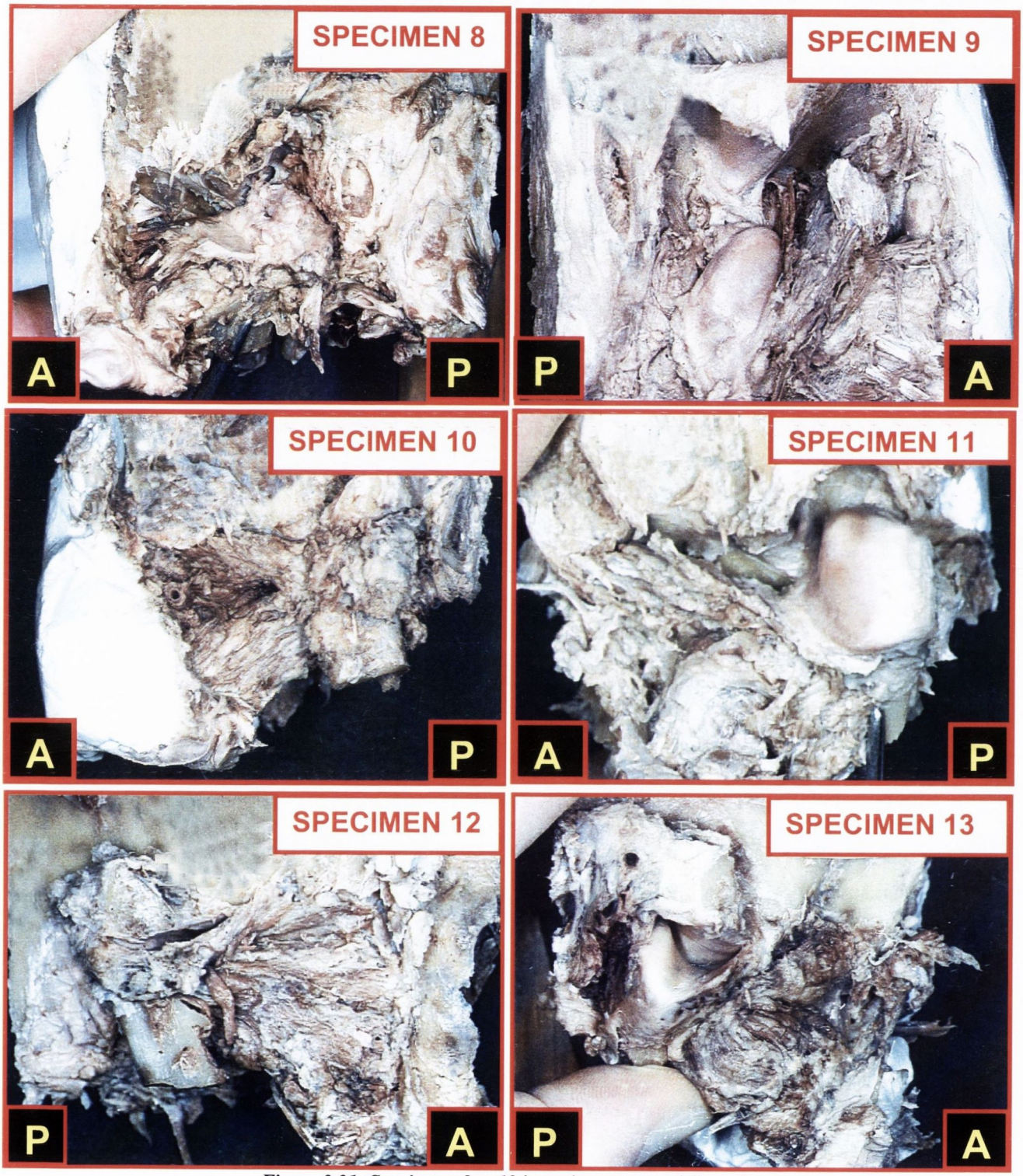


Figure 3.31: Specimens 8 to 13 in various stages of dissection

3.3.2.2 Specimen 2 (Female)

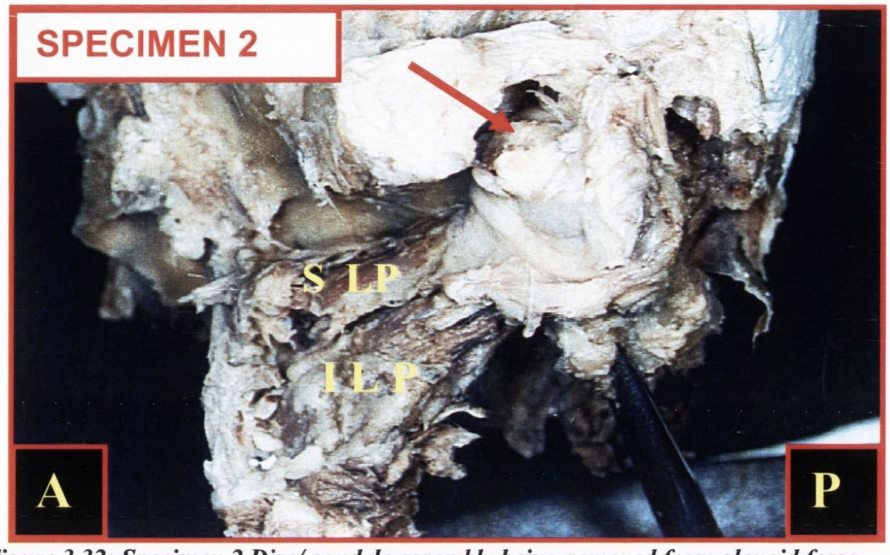


Figure 3.32: Specimen 2.Disc/ condyle assembly being removed from glenoid fossa. The disc was grossly degenerated (arrowed)

The Capsule

Superior Attachments:

- The capsular attachments were poorly defined in this specimen, only a limited amount of capsular tissue being observed
- Anteriorly some capsular tissue was present on the lateral aspect, but toward the medial no tough collagenous tissue was observed.
- Fibres of the Temporalis were found inserting into the joint capsule antero-laterally.

Inferior Attachments:

Around all the surfaces of the neck of the condyle, and to the inferior aspect of the bi-laminar zone.

The Temporomandibular Ligament

The Temporomandibular ligament was not clearly defined in this specimen.

The Disc

The disc was grossly degenerated and perforated in the intermediate zone (Figure 3.32).

The Posterior Attachment

- The posterior attachment was clearly defined into two layers separated by loose areolar tissue. The area just posterior and inferior to the posterior band of the disc was rich in vascular elements.

Lateral Pterygoid Muscle

- The superior head was considerably smaller than the inferior head (Figure 3.32)
- The two heads were distinct and separated at their areas of origin, but were fused together close to their areas of insertion.
- The superior head arose from the infratemporal fossa as far forward as the inferior orbital fissure.
- The inferior head arose from the entire length of the lateral surface of the lateral pyterygoid plate.
- Muscle fibres from the Temporalis were found inserting into the superior head of the lateral Pterygoid.
- The pterygoid plexus was identified between and around the two heads of the muscle.

Measurements of the pterygoid muscle

Superior Head:

Anterior circumference = 36mm

Posterior circumference= 32mm

Length = 26mm

Volume = 2.4 cc.

Inferior head:

Anterior circumference = 52mm

Posterior circumference =46mm

Length = 26mm

Volume = 4.9cc.

3.3.2.3 Specimen 3 (Male)

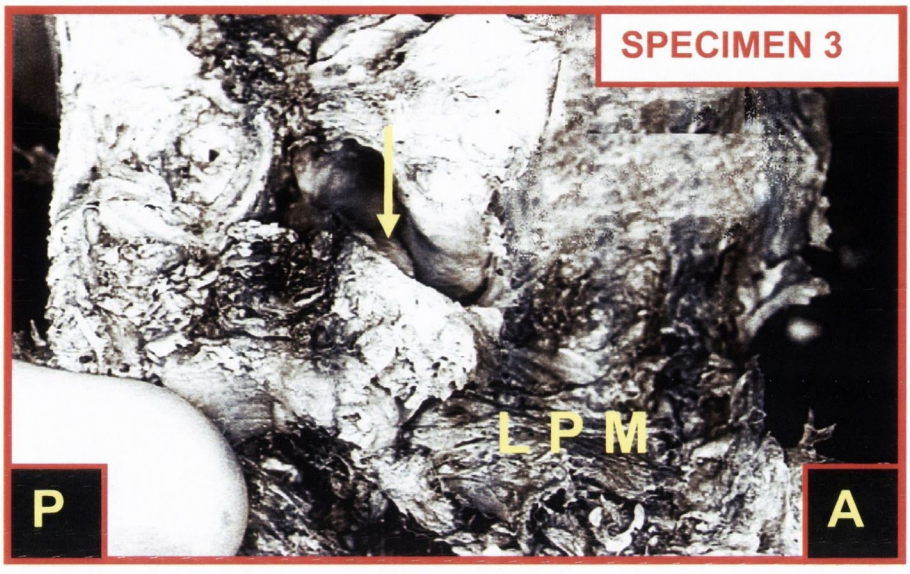


Figure 3.33: Specimen 3, articulation of disc/condyle on posterior slope of articular eminence. The two heads of the lateral Pterygoid are seen to be fused together as one muscle (LPM)

The Capsule

Superior Attachments:

- The capsule was well defined with attachments as seen in specimen 1.
- Anteriorly the capsule was present in the lateral aspect, but toward the medially the capsular tissue became increasingly thin, until no collagenous tissue could be identified.
- Fibres of the Temporalis were found inserting into the joint capsule.

Inferior Attachments:

To all surfaces of the neck of the condyle, and to inferior surface of the bilaminar zone.

The Temporomandibular Ligament

The lateral ligament was not clearly distinguishable from the capsular tissue.

The Disc

- The disc was intact with no degeneration or perforations.
- Fibres of the Temporalis muscle were found inserting into the disc on the anteromedial aspect. This is consistent with the claims of Berkovitz et al (1992)

The Posterior Attachment

- This tissue was clearly defined into two separate strata separated by a layer of loose connective tissue.
- The superior stratum was rich in blood vessels just posterior to the posterior band of the disc.

The Lateral Pterygoid Muscle

- The superior and inferior heads of the muscle were fused together (Figure 3.33).
- The superior fibres arose from the infratemporal fossa as far forward as the inferior orbital fissure.
- The tendon of the superior portion was firmly attached to the area of bone just anterior to the crest of the articular eminence.
- Fibres from the Temporalis were found inserting into the superior portion of the muscle.
- The pterygoid plexus was not identified in this specimen

Measurements of lateral Pterygoid

As the two heads were fused in the specimen the tissue was considered as a single muscle. Measurements were therefore made of the total muscle mass.

Total muscle measurements:

Anterior circumference = 85mm.
Posterior circumference = 60mm.
Length = 25mm.

Volume = 10.6cc

3.3.2.4 Specimen 4 (Female)

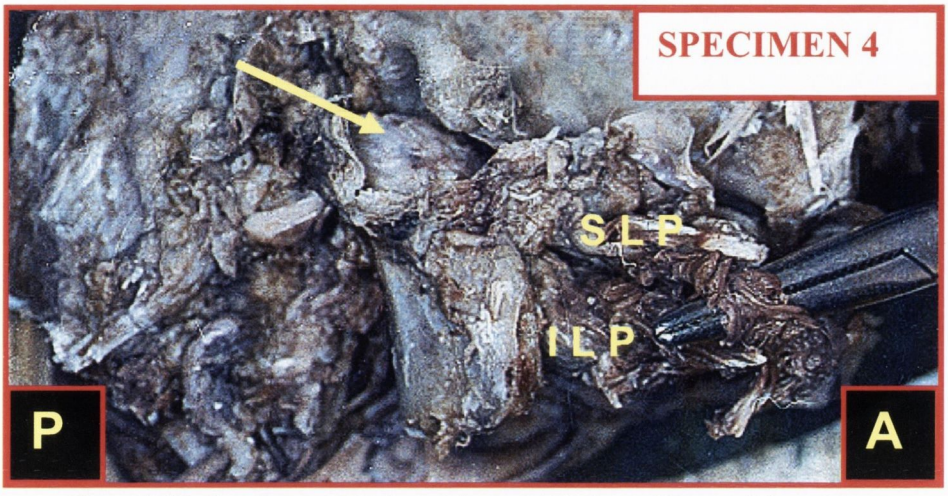


Figure 3.34: Specimen 4,Disc/ condyle assembly being distracted from fossa. The two heads of the lateral Pterygoid (SLP and ILP) are seen to be contiguous anteriorly. Some degeneration is seen in the disc (arrowed).

The Capsule

- The capsule was well defined in this specimen, with attachments as seen in the other specimens where the capsule was intact.
- A strong fibrous attachment of the capsule to the supero-medial wall of the fossa was found.
- Anteriorly the capsule was present in the lateral aspect but anteromedially the tissue became increasingly thin until no tough collagenous tissue could be identified

The Temporomandibular Ligament

The ligament was not clearly distinguishable from the capsular tissue.

The Disc

Thinning and degeneration of the disc was observed particularly in the central portion of the intermediate zone of the disc, although there was no perforation (Figure 3.34).

The Posterior Attachment

The posterior attachment tissues were poorly defined and damaged. Some chronic fibrous reparative tissue was observed.

The Lateral Pterygoid Muscle

- The two heads of the muscle were fused together at their origin to the lateral Pterygoid plate. The fibres were contiguous with each other in this area in a loop type arrangement (Figure 3.35).

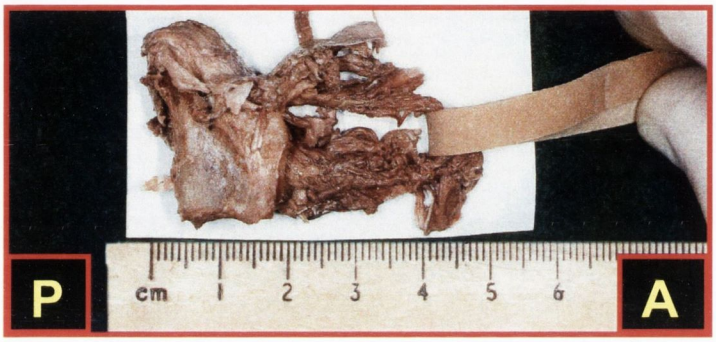


Figure 3.35: Specimen 4, fusion of two heads of lateral Pterygoid at their origin from lateral Pterygoid plate.

- The inferior head was considerably larger than the superior head.
- The two heads were distinct and separate throughout except close to their areas of insertion where they fused.
- The superior fibres of the superior head arose from the infratemporal fossa as far forward as the inferior orbital fissure.
- The more inferior fibres of the superior head arose from the superior surface of the lateral surface of the lateral plate.
- The inferior head arose from most of the lateral surface of the lateral Pterygoid plate

Measurements of the lateral Pterygoid:

Superior head:

Anterior circumference = 29.5mm

Posterior circumference = 36.mm

Length = 29 mm

Volume = 2.5 cc

Inferior head:

Anterior circumference = 37.5mm

Posterior circumference = 47.1mm

Length = 25.76mm

Volume = 3.7 cc.

3.3.2.5 Specimen 5 (Male)

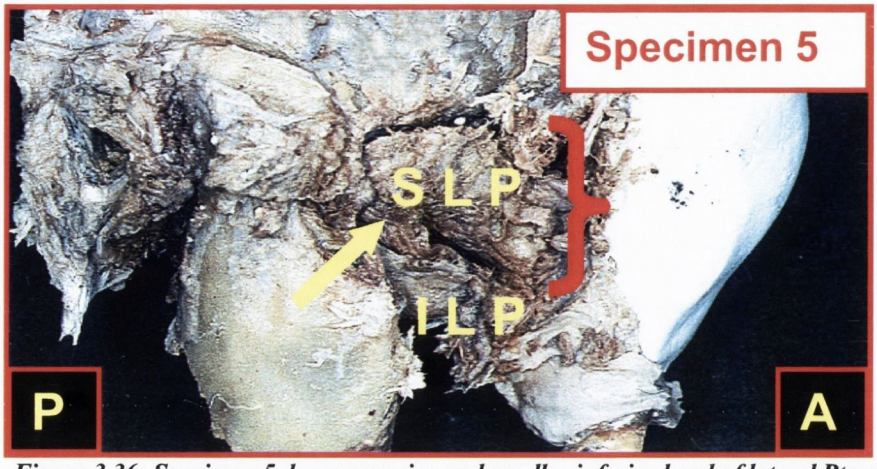


Figure 3.36: Specimen 5, large superior and smaller inferior head of lateral Pterygoid. Note the "third" head (arrowed) attaching the superior and inferior heads. The red bracket indicates the amount of the lateral Pterygoid plate taken up by the superior head of the muscle.

The Capsule

- The capsular attachments were the same as those found in the specimens where the capsule was intact.
- Capsular tissue was absent in the antero-medial region.
- Fibres from the Temporalis were found inserting into the capsule.

The Temporomandibular Ligament:

The lateral ligament was well defined as a thickening of capsular tissue.

The Disc

The disc was intact with no perforations or deformations.

The Posterior Attachment

The posterior attachment was well defined into superior and inferior strata separated by loose connective tissue. The superior stratum was rich in blood vessels postero-inferiorly to the posterior band of the disc.

The Lateral Pterygoid Muscle

- The superior head was considerably larger than the inferior head, this being the opposite of the normal situation.
- The origin of the superior head was from the infratemporal fossa as far forward as the inferior orbital fissure, but also most unusually from the superior two thirds of the lateral surface of the lateral Pterygoid plate.

- The origin of the inferior head came from only a small area of the inferior part of the lateral Pterygoid plate. This was a reversal of the usual arrangement where the inferior head arises from most of the pterygoid plate.
- The two heads were fused posteriorly and anteriorly, but were separable by blunt dissection approximately half way between their origins and insertions.
- A supplementary "third" muscle belly was identified "arising" from the superior surface of the inferior belly, and inserting into the inferior surface of the superior head (Figure 3.36).

Measurement of the lateral Pterygoid muscle:

The measurement of the two bellies was more difficult due to the presence of the third belly. It was decided to include the third belly as part of the muscle mass of the inferior head since the "origin" was from the inferior head. (The muscle tissue posterior to the point where the two heads fused was measured separately). As the fusion of the muscle heads occurred at some distance from the areas of insertion, the muscle lengths were measured to the point of fusion. It was decided therefore to also calculate the total volume of muscle mass.

Superior Head:

Anterior circumference = 60mm

Posterior circumference = 55mm

Length = 14 mm

Volume = 3.7cc.

Inferior Head:

Anterior circumference = 35mm $\therefore$ radius = 5.9 mm.

Posterior circumference = 33mm $\therefore$ radius = 5.1mm.

Length = 14mm

Volume = 1.3 cc

Total Muscle Mass

Anterior circumference = 95mm

Posterior circumference = 50mm

Length = 26mm

Volume = 11.2 cc.

3.3.2.6 Specimen 6 (Male)

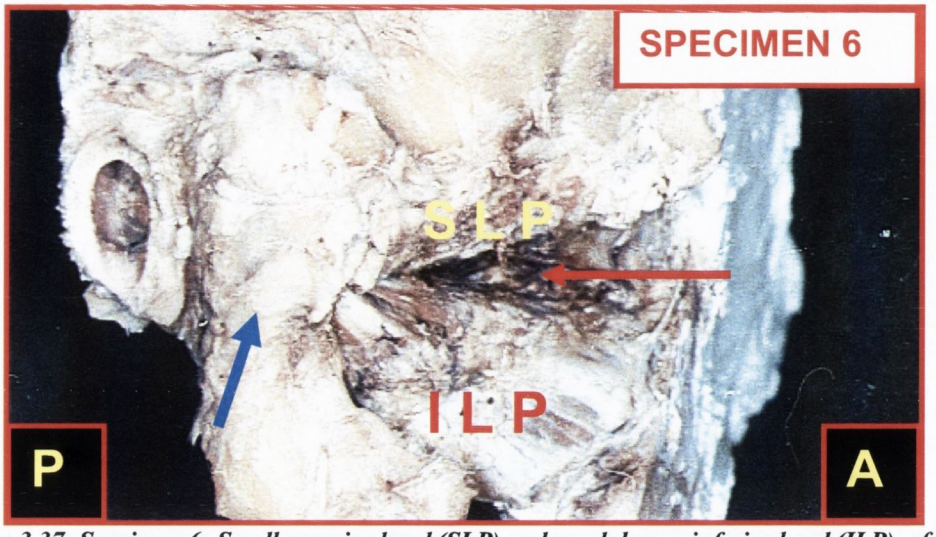


Figure 3.37: Specimen 6; Small superior head (SLP) and much larger inferior head (ILP), of lateral Pterygoid
Both heads are clearly separated in their anterior portions. The pterygoid plexus (red arrow) occupied the space between the two heads. The blue arrow indicates the TMJ ligament

The Capsule

The capsule was particularly strong in this specimen, with attachments as seen in the other specimens where the capsule was intact.

The Temporomandibular ligament

The lateral ligament was clearly defined as a thickening of the capsular tissue (Figures 3.37 and 3.38).



Figure 3.38: Specimen 6. TMJ ligament as thickening of capsule

The Disc

The disc was normal in this specimen, with no degeneration, deformation or perforations.

The Posterior Attachment

- The posterior attachment was clearly defined as two distinct strata separated by loose connective tissue.
- The area of the posterior attachment just postero-inferior to the posterior band was rich in vascular elements.

The Lateral Pterygoid Muscle

- The inferior head was considerably larger than the superior head (Figure 3.37).
- The origin of the superior head was from the infratemporal fossa as far forward as the inferior orbital fissure.
- The origin of the inferior head was from the entire length of the lateral surface of the lateral plate.
- The two heads were completely separate until close to their areas of insertion where they fused together.
- The pterygoid plexus of veins was identified lying between the two muscle heads.

Measurements of the lateral, pterygoid muscle

Superior head:

Anterior circumference = 45mm
Posterior circumference = 39mm
Length = 25mm.

Volume = 3.5 cc.

Inferior head:

Anterior circumference = 72mm
Posterior circumference = 55mm
Length =28mm.

Volume = 9.0cc.

3.3.2.7 Specimen 7 (Male)

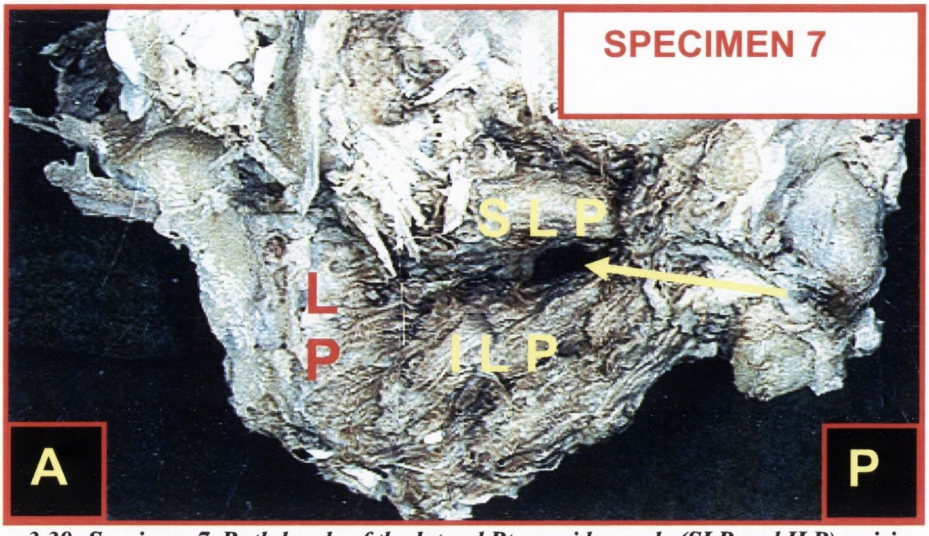


Figure 3.39: Specimen 7, Both heads of the lateral Pterygoid muscle (SLP and ILP), arising from lateral plate (LP).
The space between the two heads (arrowed) was occupied by the pterygoid plexus of veins

The Capsule

- The attachments of the capsule were consistent with those of the specimens where the capsule was intact.
- Anteriorly the capsule was present in the lateral aspect but toward the medial aspect the capsular tissue became increasingly thin until no collagenous tissue could be identified.
- Fibres of the Temporalis muscle were found inserting into the joint capsule.

The Temporomandibular Ligament:

The lateral ligament was not clearly defined in this specimen.

The Disc

The disc was thinned out towards its' attachment to the lateral pole of the condyle, but was otherwise in good condition.

The Posterior Attachment

- The posterior attachment was clearly defined as two distinct layers separated by loose connective tissue.
- The attachment was rich in blood vessels just posterior to the posterior band of the disc.

The Lateral Pterygoid Muscle

- The inferior head was considerably larger than the superior head (Figure 3.39).
- Fibres of the Temporalis muscle were found merging with those of the superior head.
- The pterygoid plexus of veins was identified lying between the two heads of the muscle.
- The two heads were distinct and separate except close to their areas of insertion where they fused together.

Measurements of the lateral Pterygoid muscle:

Superior Head:

Anterior circumference = 41mm
Posterior circumference = 35mm
Length = 21mm.

Volume = 2.4 cc.

Inferior Head:

Anterior circumference = 66mm
Posterior circumference = 58mm
Length = 24mm.

Volume = 7.4 cc.

3.3.2.8 Specimen 8 (Female)

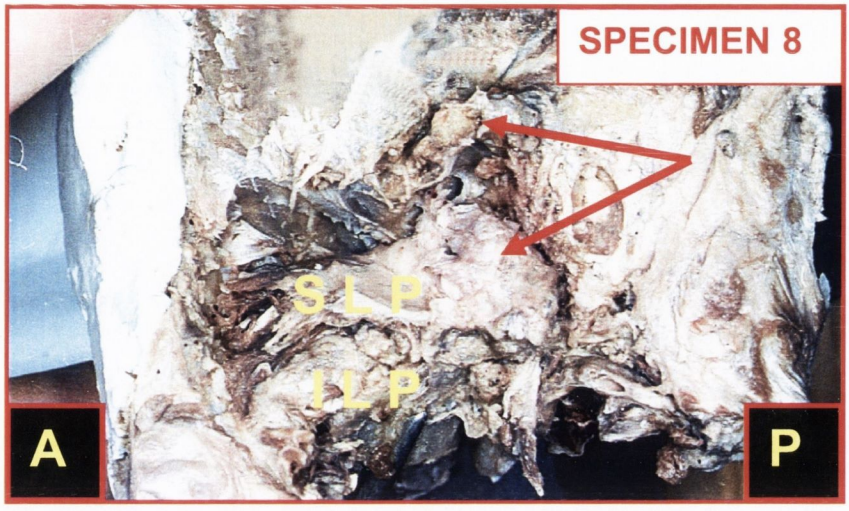


Figure 3.40: Specimen 8. Gross degeneration and perforation of disc, and fossa (arrowed), The two heads of the lateral Pterygoid muscle (SLP and ILP) are also shown.

The Capsule

Superior attachments:

- The capsule was badly damaged on its' lateral aspect and was therefore poorly defined
- Posteriorly some capsular tissue was observed attached to the tympanic plate
- Anteriorly no capsule was identifiable

Inferior Attachments:

Some remnants of the capsular tissue were found attached to the condylar neck and to the inferior surface of the posterior attachment.

Temporomandibular Ligament

The lateral ligament was not identifiable in this specimen.

The Disc

The disc was grossly degenerated with chronic hypertrophied tissue present on all surfaces with the exception of its' most anterior extension. Degenerative changes had also taken place in the articular cartilage of the glenoid fossa (Figure 3.40).

The Posterior Attachment

- The tissue was poorly defined and not identifiable as two zones.
- Blood vessels were present in the area just posterior and inferior to the posterior portion of the disc.

The Lateral Pterygoid Muscle

- The inferior head was larger than the superior head
- The superior head area of origin was from the infratemporal fossa, as far forward as the inferior orbital fissure.
- The origin of the inferior head was from the whole of the lateral surface of the lateral Pterygoid plate.
- The pterygoid plexus was not identified in this specimen
- The two heads were separate at their origins and remained so until close to their insertions

Measurements of the lateral Pterygoid

Superior head:

Anterior circumference = 39 mm

Posterior circumference = 31 mm

Length = 21mm.

Volume = 2.1cc.

Inferior head:

Anterior circumference = 49mm.

Posterior circumference = 45mm.

Length = 22mm.

Volume = 3.8 cc.

3.3.2.9 Specimen 9 (Male)

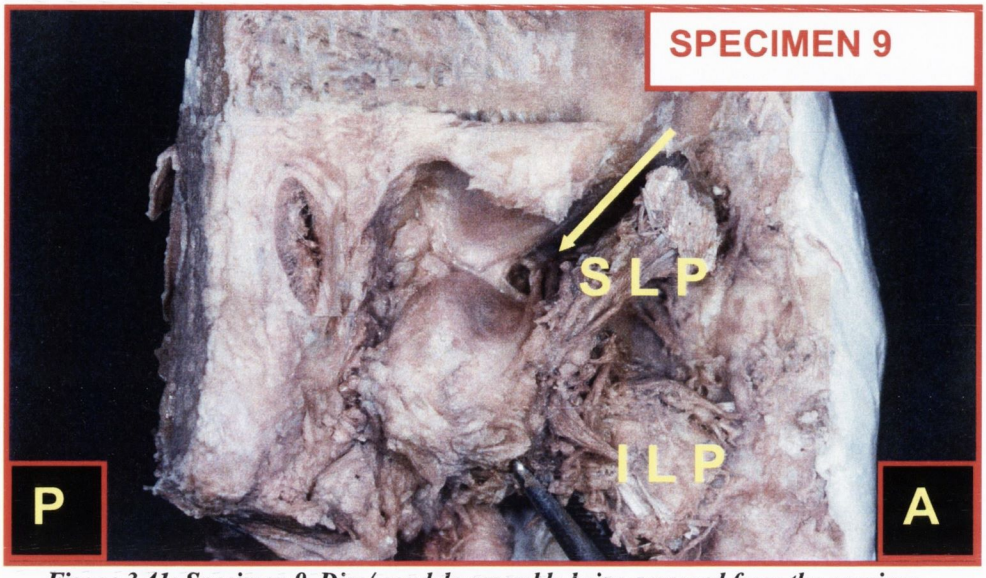


Figure 3.41: Specimen 9, Disc/ condyle assembly being removed from the cranium. Fibres of superior head of lateral Pterygoid are arrowed inserting into medial rim of foramen ovale.

The Capsule

Superior attachments:

- The capsule was in good condition, with attachments as seen in the other specimens where the capsule was intact.
- Antero-medially no capsular tissue was identified.
- Fibres from the Temporalis muscle were observed inserting into the capsule.

Inferior attachments:

The inferior attachments were to all surfaces of the neck of the condyle and to the inferior surface of the posterior attachment.

Temporomandibular Ligament

The ligament was well defined in this specimen.

The Disc

- The disc was intact without any deformation or perforation (Figure 3.41).
- There was an extremely strong ligamentous type of attachment of the disc from the supero-medial aspect of the fossa, and passing up to the roof of the glenoid fossa. (Figure 3.42).

This tissue may represent the anterior malleolar ligament referred to by Pinto (1962) and Burch (1966).

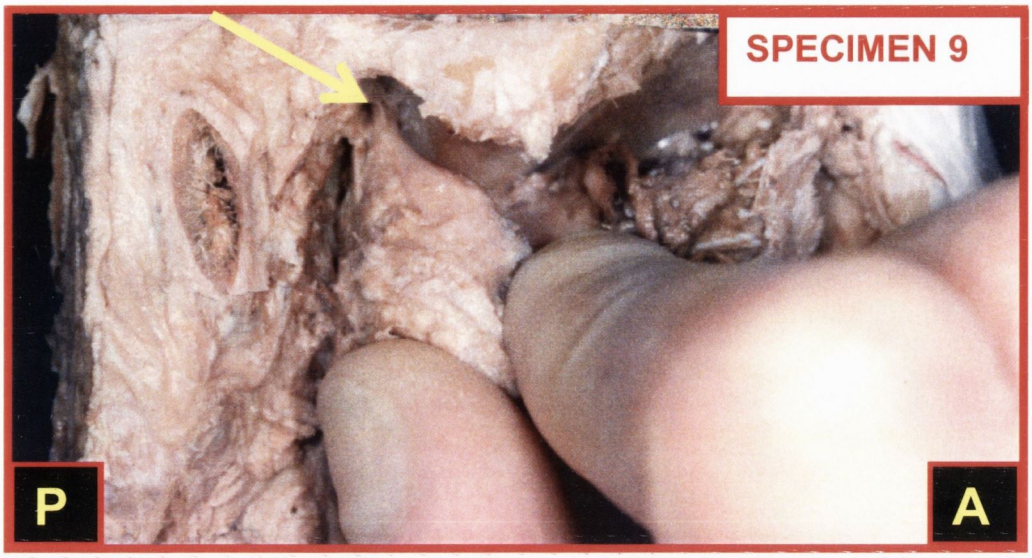


Figure 3.42: Specimen 9. Strong fibrous attachment from postero-superior aspect of disc to roof of glenoid fossa. (arrowed).

The Posterior Attachment

- This tissue was well defined into two distinct strata with connective tissue separating the two layers.
- The superior stratum was generously vascularised in the region just posterior and inferior to the posterior band of the disc.

The Lateral Pterygoid Muscle

- The two heads of the muscle were clearly separated at their sites of origin, and remained separate until close to their sites of insertion where they shared a common tendon.
- The inferior head was considerably larger than the superior head
- The pterygoid plexus was identified and occupied the space between the two heads.
- Fibres from the Temporalis were seen inserting into the superior head
- The two deep temporal nerves were found within the fascia overlying the superior head.
- The posterior branch was also attached to the antero-lateral part of the disc.
- Fibres of the Lateral Pterygoid were inserting into the inferior head of the lateral Pterygoid close to its origin at the antero-inferior border.
- Fibres of the superior head were inserting into the foramen ovale (Figure 3.41).

Measurements of the lateral Pterygoid

Superior head:

Anterior circumference = 44mm

Posterior circumference = 40mm

Length = 20mm

Volume = 2.8 cc.

Inferior head:

Anterior circumference = 62mm

Posterior circumference = 50mm

Length = 30mm

Volume = 7.5 cc.

3.3.2.10 Specimen 10 (Male)

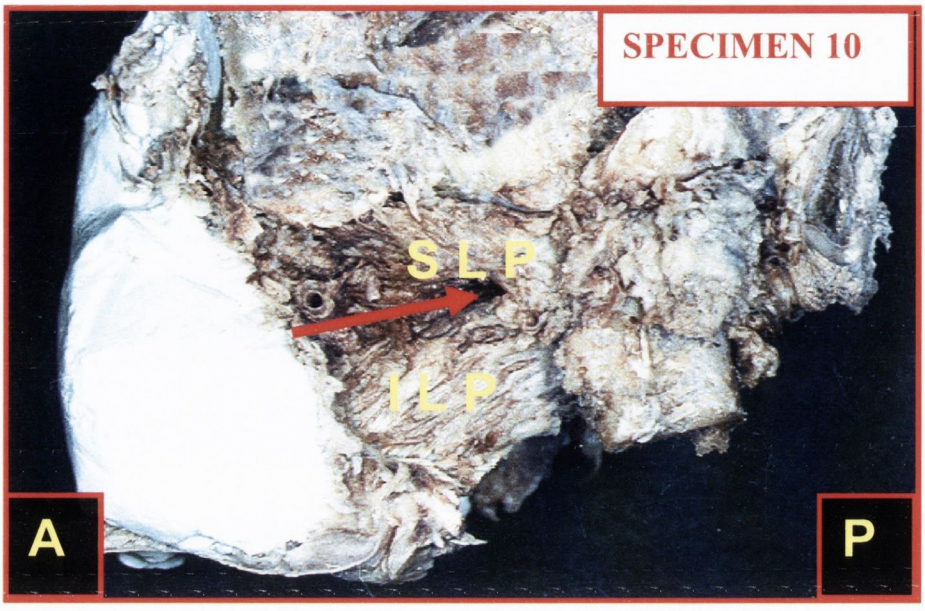


Figure 3.43: Specimen 10. Fusion of two heads of lateral Pterygoid anteriorly and posteriorly. The space between the two heads for the pterygoid plexus is indicated by the arrow.

The Capsule

- The capsule was in good condition with attachments as found in the other specimens where the capsule was intact.
- Fibres of Temporalis were inserting into the capsule.

Temporomandibular Ligament

The lateral ligament was well defined in this specimen.

The Disc

The disc was intact with no perforations or deformations or adhesions.

The Posterior Attachment

- Poorly defined in this specimen, with no obvious lamination.
- Blood vessels were observed just posterior and inferior to the posterior band of the disc (Figure 3.43).

The Lateral Pterygoid Muscle

- The two heads were fused anteriorly and posteriorly, and thus the tissue could be regarded as one muscle.
- On the lateral side there was a space between the two heads, which was occupied by the pterygoid plexus (Figure 3.43).
- However this space was not present on the medial side where the two heads were fused along their entire length.
- The origin of the superior fibres was from the infratemporal fossa as far forward as the inferior orbital fissure, and from the upper portion of the lateral surface of the lateral Pterygoid plate.
- A tendinous attachment was found joining the superior fibres to the bone approximately 4-5mm anterior to the medial one third of the articular eminence.
- Some fibres inserted into the antero- lateral aspect of foramen ovale.
- The origin of the superior fibres extended laterally beyond the infratemporal crest.
- The origin of the inferior fibres was from the lower two thirds of the lateral Pterygoid plate.
- Some fibres were attached to the posterior aspect of the maxilla adjoining the lateral Pterygoid plate.
- The superior fibres were inserting into the entire width of the disc from lateral to medial.

The disc / condyle assembly together with the pterygoid muscle complex was now dissected out of the cranium, and a mid-polar sagittal section was made through the disc and condyle, which sectioned the whole into medial and lateral portions (Figures 3.44, 3.45, 3.46).

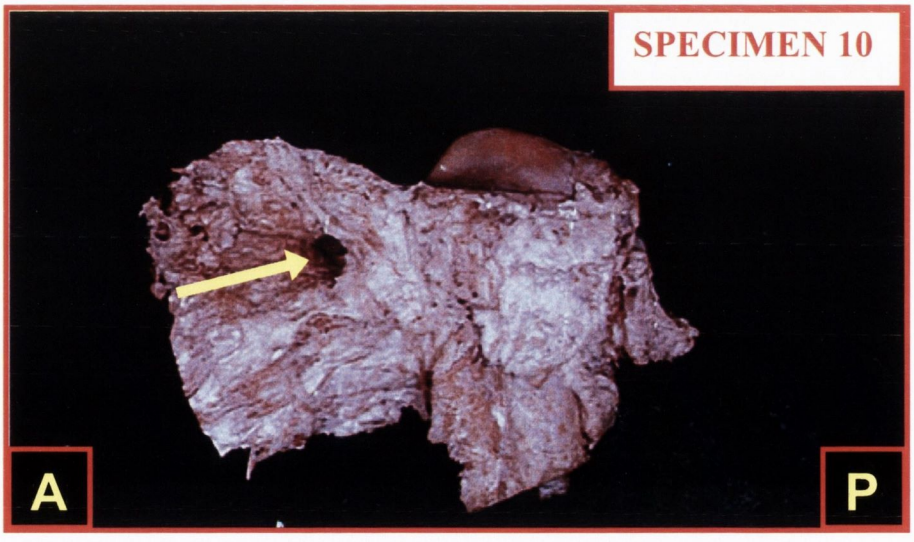


Figure 3.44: Lateral aspect of specimen 10 after removal from the cranium. The space, which was occupied by the Pterygoid plexus, is arrowed.

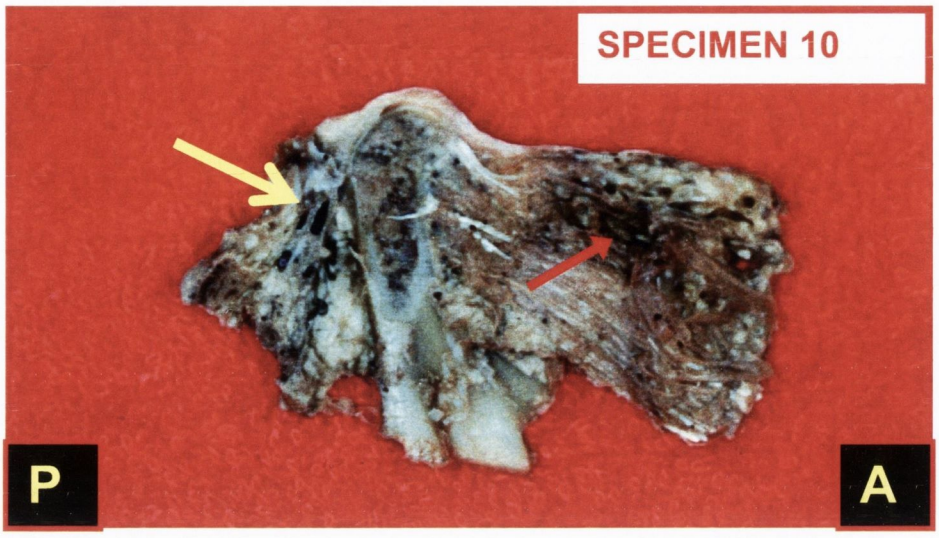


Figure 3.45: Lateral part of specimen 10 seen from the medial aspect after midpolar sagittal sectioning. The vascular tissue in the posterior attachment is indicated by yellow arrow. The red arrow shows space occupied by the Pterygoid plexus, which is much smaller than on lateral aspect.

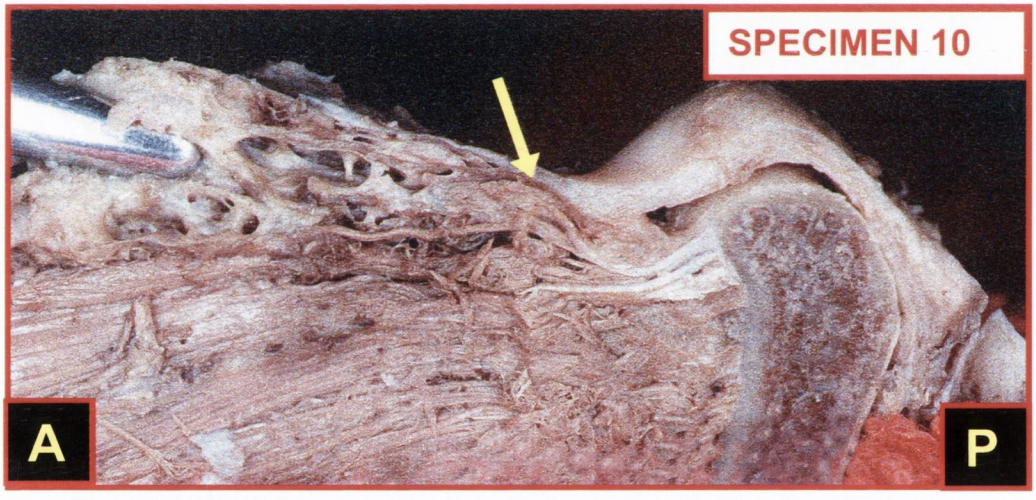


Figure 3.46: Medial portion of specimen 10 showing both heads as one muscle mass.. The upper most fibres are inserting into the disc (arrowed). Note that the space occupied by the Pterygoid plexus is not present in the medial portion of the muscle.

As the lateral Pterygoid muscle in the specimen was in effect one muscle mass it was not possible to make a comparison of the superior and inferior muscle masses. The value of the total muscle mass is given below.

Measurement of the total muscle mass of the lateral Pterygoid

Anterior circumference = 77mm

Posterior circumference = 69mm

Length = 29mm.

Volume = 12.3 cc.

3.3.2.11 Specimen 11 (Female)

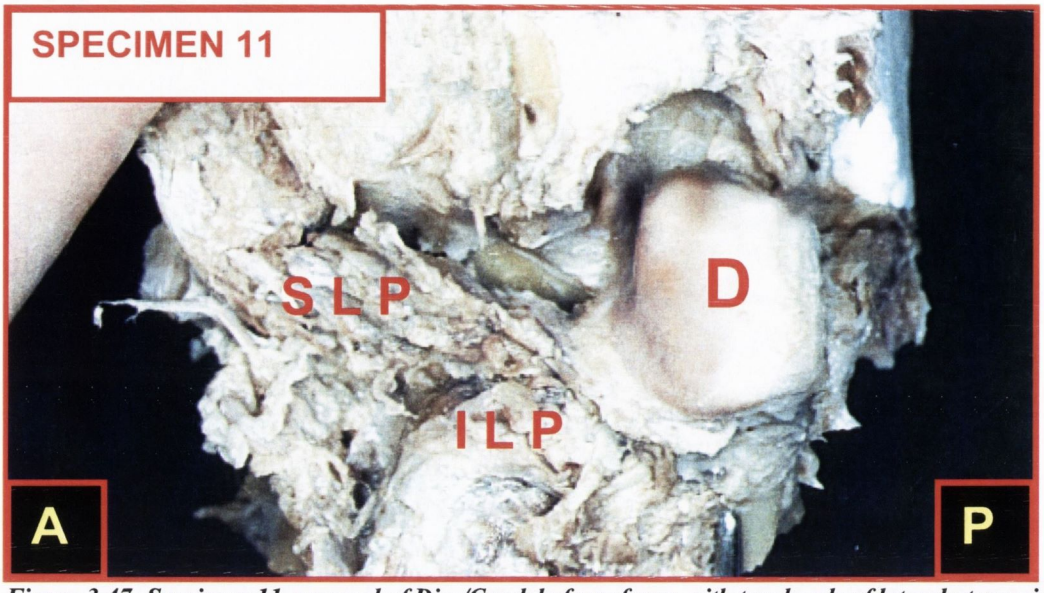


Figure 3.47: Specimen 11, removal of Disc/Condyle from fossa, with two heads of lateral pterygoid

The Capsule and Lateral Ligament

- The capsule was intact but thinner and less well defined than in the other specimens.
- The capsular attachments were consistent with the specimens where the capsule was intact.
- No capsular tissue was identified antero-medially.

Temporomandibular Ligament

The lateral ligament was identified, but was only a moderate thickening of the capsular tissue.

The Disc

The disc was in good condition with no perforation, deformation or degeneration (Figures 3.47& 3.48).

The Posterior Attachment

- The posterior attachment was not clearly defined as separate strata, and contained a considerable amount of tough collagenous tissue. (Figure 3.49).
- The area postero-inferior to the posterior band was vascularised.

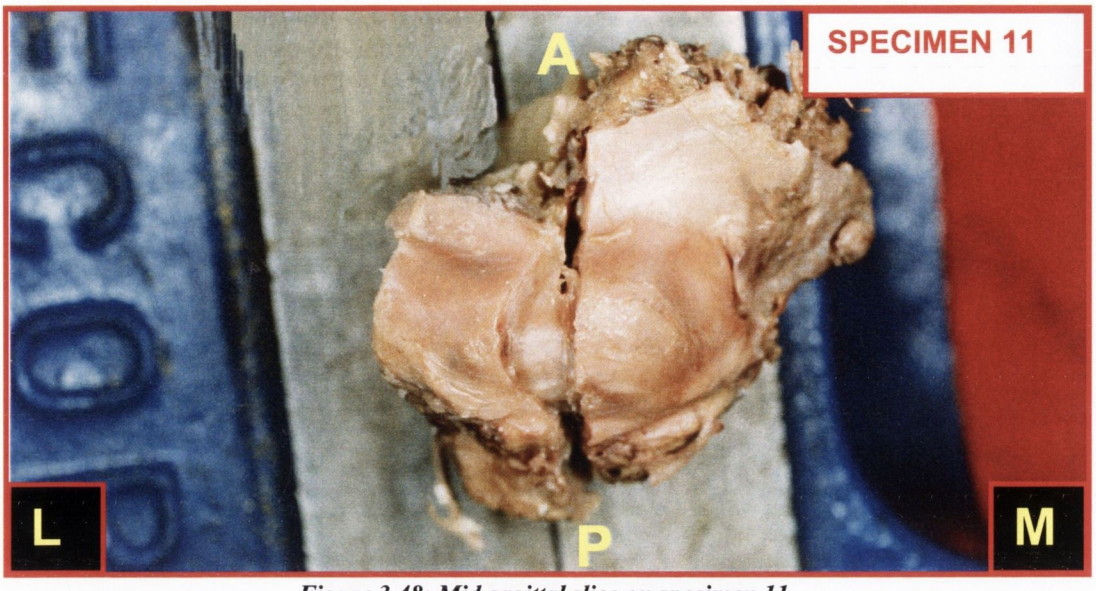


Figure 3.48: Mid-sagittal slice on specimen 11.
M=Medial,L=Lateral,A= anterior,P=posterior

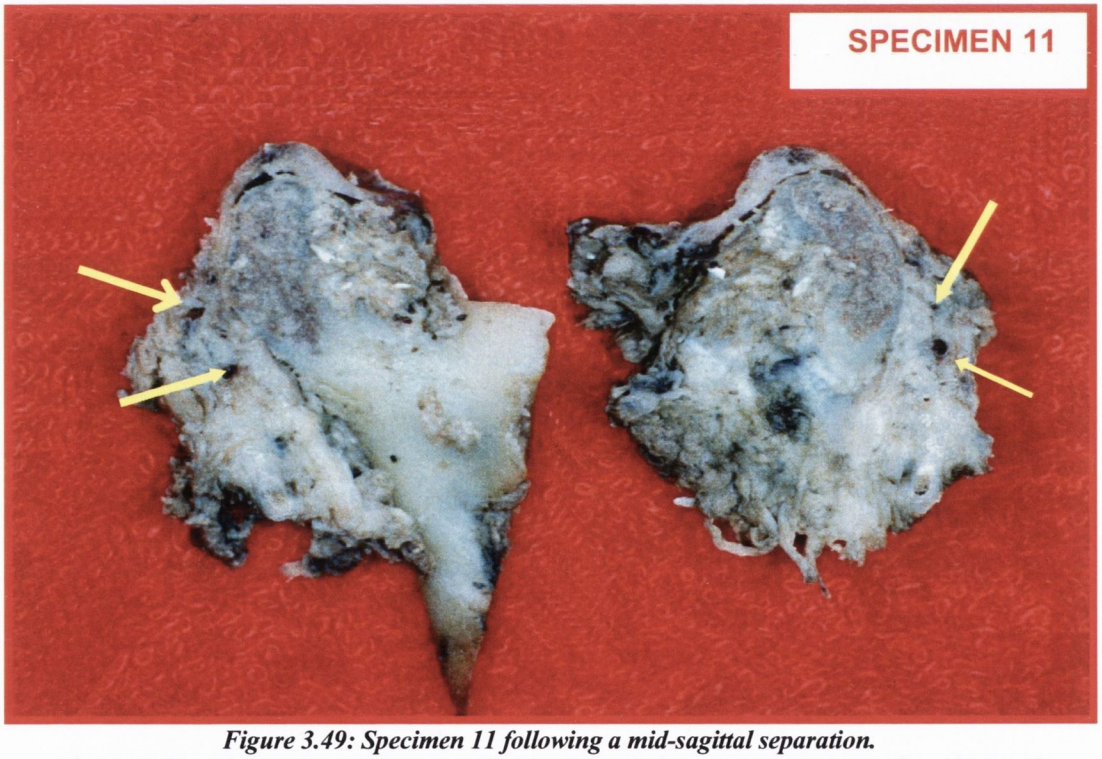


Figure 3.49: Specimen 11 following a mid-sagittal separation.
The posterior attachment, can be seen with blood vessels in antero -superior region (Arrowed)
The lateral section is on the left

The Lateral Pterygoid Muscle

- The two heads of the muscle were approximately equal in size.
- The two heads were separate until close to their areas of insertion.

- The superior head arose from the infratemporal fossa as far forward as the inferior orbital fissure and from a small area of the superior aspect of the lateral pterygoid plate.
- The inferior head arose from nearly the whole length of the lateral pterygoid plate.
- The pterygoid plexus was not identified in this specimen.

Measurements of the Lateral Pterygoid

Superior head:

Anterior circumference = 39mm
Posterior circumference =36mm
Length = 19mm

Volume = 2.1cc.

Inferior head:

Anterior circumference = 41mm
Posterior circumference = 38mm
Length = 21mm.

Volume = 2.6cc.

3.3.2.12 Specimen 12 (Female)

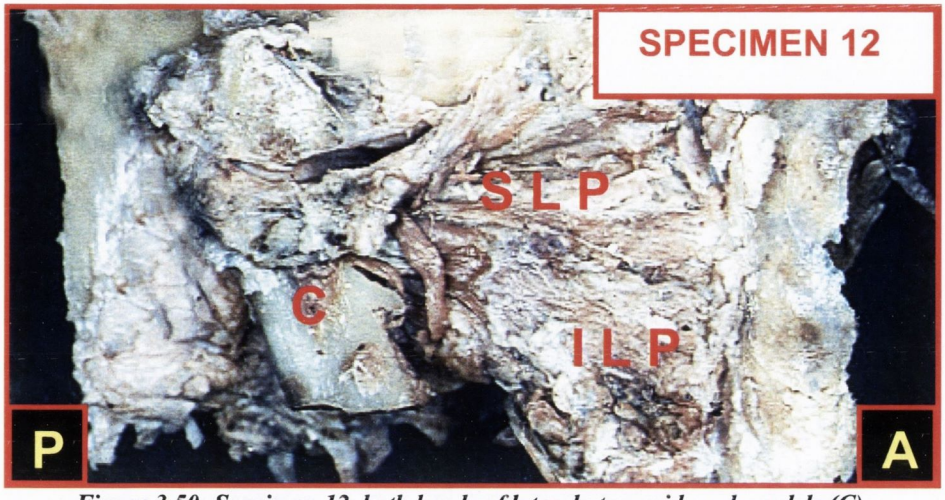


Figure 3.50: Specimen 12, both heads of lateral pterygoid, and condyle (C)

Capsule and Lateral Ligament

- The capsule was damaged on its lateral aspect making it difficult to examine in this region.
- Capsular tissue was not identified on the antero-medial aspect as in the other specimens.

Temporomandibular ligament

The lateral ligament was unidentifiable in this specimen.

The Disc

The disc showed degeneration and was perforated in the intermediate zone (Figure 3.51).

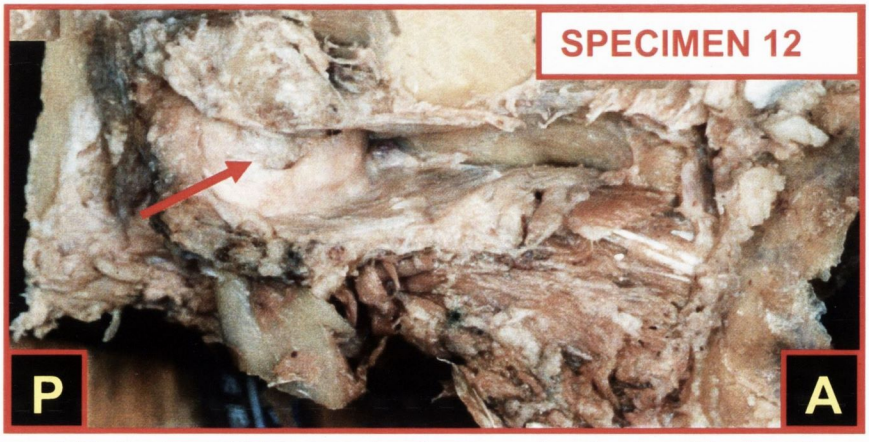


Figure 3.51: Specimen 12, Degenerative changes and perforation of the disc (Arrowed)

The Posterior Attachment

The posterior attachment showed degenerative changes and was poorly defined.

The Lateral Pterygoid Muscle

The superior head was considerably smaller than the inferior head (Figure 3.50). The tendon of the superior head was continuous with the disc. However the disc was not attached firmly to the area in front of the crest of the eminence, as in the other specimens. The superior head arose from the infratemporal fossa as far forward as the inferior orbital fissure. The inferior head arose from the entire surface of the lateral plate. The two heads of the muscle were distinct and separate until close to their areas of insertion.

Measurements of the Lateral Pterygoid

Superior head:

Anterior circumference = 28mm
Posterior circumference = 25mm
Length = 21mm

Volume = 1.2 cc.

Inferior head:

Anterior circumference = 40mm
Posterior circumference = 35mm
Length = 23mm

Volume = 2.6 cc.

3.3.2.13 Specimen 13 (Male)

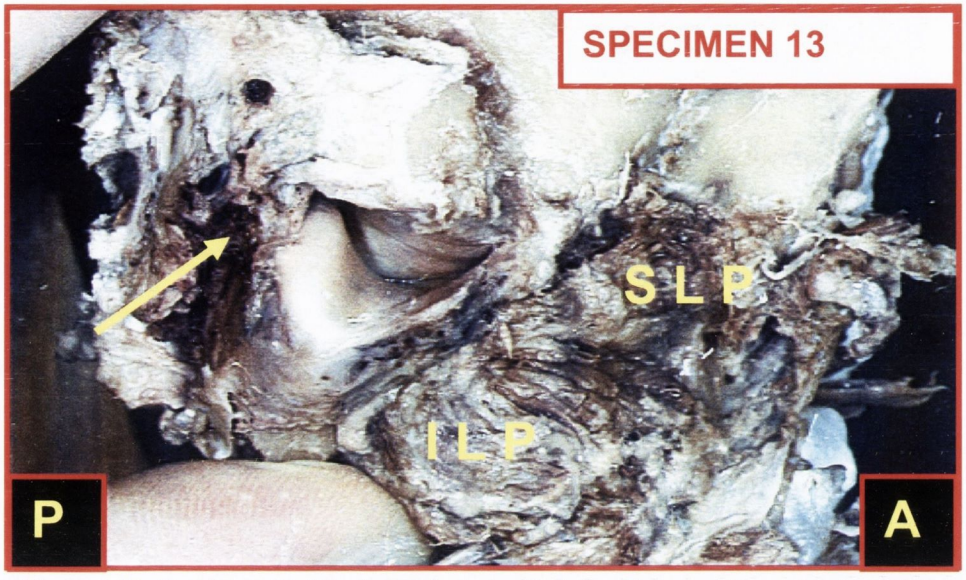


Figure 3.52: Specimen 13, Disc /condyle assembly being distracted from the glenoid fossa. The posterior attachment is arrowed.

The Capsule

Superior Attachments:

- The capsule was well defined, with attachments as described in the other intact specimens
- No capsular tissue could be identified on the anteromedial aspect of the joint.
- Fibres from the posterior belly of the digastric were inserting into the posterior aspect of the capsule.

Inferior Attachments:

To all surfaces of the neck of the condyle and to the inferior surface of the posterior attachment.

The Temporomandibular Ligament

The lateral ligament was identified as a thickening of the capsular tissue.

The Disc

- The disc was in good condition with no degeneration, deformation or perforations.
- The attachment of the anterior extremity of the disc to the area anterior to the crest of the eminence was firm on the medial aspect, but rather tenuous on the lateral aspect.

The Posterior Attachment

The posterior attachment was well defined as two strata separated by loose connective tissue, with the area just postero-inferior to the posterior band being rich in vascular elements.

The Lateral Pterygoid Muscle

- The inferior head was considerably larger than the superior head (Figure 3.52).
- The pterygoid plexus was identified between the two heads of the muscle.
- Fibres from the temporalis were inserting into the anterior part of the superior head.
- The origin of the superior head was from the infratemporal fossa as far forward as the inferior orbital fissure, and from the upper portion of the lateral pterygoid plate.
- The inferior head arose from most of the lateral surface of the lateral plate.
- Fusion of the two muscle heads took place some distance from there areas of insertion.

Measurements of the Lateral Pterygoid

As fusion of the two muscle heads took place approximately two-thirds the distance from origin to insertion, it was decided to calculate the volume of the total muscle mass of the two heads.

Superior head:

Anterior circumference = 45mm

Posterior circumference = 39mm

Length = 19mm

Volume = 2.8 cc

Inferior head:

Anterior circumference = 60mm

Posterior circumference = 51mm

Length = 21mm

Volume = 5.2 cc

Total muscle mass:

Anterior circumference = 105mm

Posterior circumference = 70mm

Length = 24mm

Volume = 14.3 cc

3.3.3 Conclusions from Macroscopic Study

3.3.3.1 The Capsular Attachments

Temporal Attachments

In the specimens where the capsule was intact the attachments were as follows:

- **Posteriorly:** To the tympanic plate from the area lying between the postglenoid process laterally and the spine of the spine of the sphenoid medially.
- **Laterally:** To the ridge of bone lateral to the glenoid fossa, lying between the postglenoid process posteriorly, and the articular tubercle anteriorly.
- **Medially:** To the medial glenoid plane and to the crest of bone on the medial, aspect of the articular eminence.
- **Antero-Medially:** No tough capsular tissue was identifiable. In many cases the attachment of the disc to the bone had been disrupted in this area, and the disc condyle could be directly observed.
- **Antero-Laterally:** From the tubercle of the zygomatic arch, and extending medially to the lateral one third of the preglenoid plane.
- **Fibres of the temporalis muscle** in a number of specimens were found inserting into the capsule (Table 3.1).
- **The superior capsular attachments** in a number of specimens were not clearly defined.

Mandibular Attachments

In all of the specimens the inferior capsular attachments were to the anterior, posterior, lateral and medial surfaces of the neck of the mandible, and to the inferior surface of the bilaminar zone.

Table 3.1 lists the specimens in which the capsule was or was not clearly defined, and also indicates the capsules where fibres of the temporalis muscle were found attaching into the capsule.

Well defined capsule	Poorly defined capsule
Specimen 1 Temporalis fibres inserting	**Specimen 2--**Fibres from Temporalis inserting hto capsule
Specimen 3 --- Temporalis fibres inserting hto capsule	**Specimen 8----** Capsule grossly damaged
Specimen 4	**Specimen 12----** Capsule poorly defined
Specimen 5--- Temporalis fibres inserting hto capsule	
Specimen 6	
Specimen 7---Temporalis fibres inserting into capsule.	
Specimen 9---Temporalis fibres inserting hto capsule	
Specimen 10---Temporalis fibres inserting into capsule	
Specimen 11---- Capsule intact but thinner than in the other Specimens.	
Specimen13----Fibres from posterior belly of Digastric inserting into capsule.	

Table 3.1: Condition of the capsule in the various specimens.

3.3.3.2 The Temporomandibular Ligament

- The Temporomandibular ligament was clearly defined in some specimens, but was ill defined or non-identifiable in others (Table 3.2).
- In no specimen was it possible to separate the ligament from the capsule by blunt dissection.
- Thus from this evidence the ligament can be considered as a thickening of capsular tissue.

In the light of the above findings it is more appropriate to consider the capsule and ligament together as a structure, which has a protective role and also has a biomechanical influence on joint movements.

Ligament clearly defined	Ligament not identifiable
Specimen 5	Specimen 1
Specimen 6	Specimen 2
Specimen 9	Specimen 3
Specimen 10	Specimen 4
Specimen 11	Specimen 7
Specimen 13	Specimen 8
	Specimen 12

Table 3.2: Specimens where Temporomandibular Ligament was identified/ not identified.

3.3.3.3 The Disc

In most cases the disc was well formed, but in some cases thinning and degeneration had taken place (Table 3.3). In one case the articular cartilage covering the glenoid fossa had undergone degeneration (Table 3.3). In no case was anterior displacement of the disc found.

UNDAMAGED DISCS	DAMAGED DISCS
Specimen 1	Specimen 2----Perforation of disc
Specimen 3---- Fibres of temporalis inserting into disc	Specimen 4--Thinning and degeneration
Specimen 5	Specimen 8 ----Degeneration of fossa and disc
Specimen 6	Specimen12---Degeneration and perforation
Specimen 7	
Specimen 9-Fibrous Tissue from the disc to the supero-medial aspect of the fossa	
Specimen 10	
Specimen11	
Specimen 13.	

Table 3.3: Condition of discs in the various specimens.

3.3.3.4 The Posterior Attachment

In most of the specimens the posterior attachment was divided into three distinct layers, viz. Superior stratum, inferior stratum, and a loose layer of connective tissue separating the two layers. In some specimens there was no clear division of the tissue into three layers (Table 3.4)

POSTERIOR ATTACHMENT LAMINATED	POSTERIOR ATTACHMENT NOT LAMINATED
Specimen1	
Specimen 2	**Specimen 4--- Fibrous tissue present**
Specimen 3	**Specimen 8--- Fibrous tissue present**
Specimen 5	**Specimen10--- Fibrous tissue present**
Specimen 6	**Specimen 11- Fibrous tissue present**
Specimen 7	**Specimen 12 ---Fibrous tissue present**
Specimen 9	
Specimen 13	

Table 3.4:Specimens, which were laminated and non- laminated

3.3.3.5 The Lateral Pterygoid Muscle

Considerable variations were found in the lateral pterygoid muscle.

- In most specimens the inferior head was found to be larger in dimension and in volume than the superior head.
- In one specimen however (Specimen 5) the superior head was found to be considerably greater in dimension and in volume than the inferior head.
- Variations were also found in the origin of both heads. For example in some specimens the origin of the superior head was from the infratemporal fossa as far forward and attached to the rim of the infraorbital fissure. In others the origin also included varying amounts of the lateral pterygoid plate.
- It was also seen that in two specimens (Specimens 3 and 10) the lateral pterygoid was essentially one muscle.

These variations may in part explain why various workers have reported different findings in the investigation of this muscle.

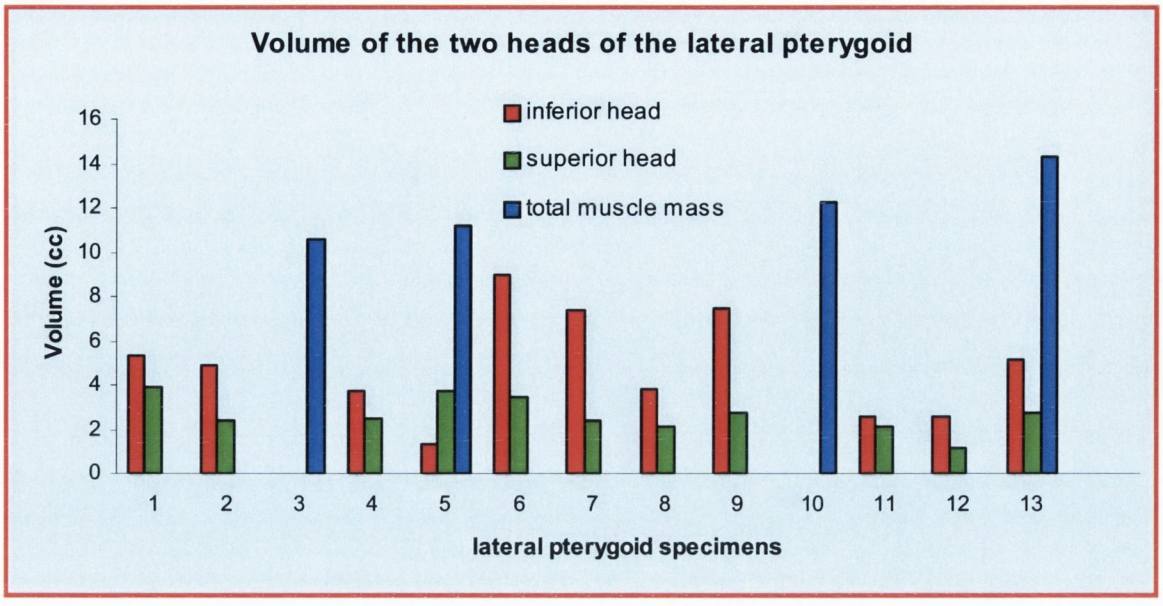


Figure 3.53: Graph of volume variations in both heads of lateral pterygoid

Figure 3.53 refers to the variations in volume between the two heads of the lateral pterygoid in the different specimens. The label of total muscle mass indicates the volume of the muscle where only one head was present or where the two heads fused at some distance from their areas of insertion. In most of the specimens the two heads were distinctly separate until they approached their sites of insertion, where they became fused in a common tendon.

However in Specimens 3 and 10 the two heads were fused throughout their entire lengths (Figures 3.31and 3.33), and in specimens 5 and 13 the two heads fused at some distance from their areas of insertion.

One particular area of controversy concerns the insertions of the lateral pterygoid into the disc and condyle respectively, with particular reference to the superior head. The distribution of these fibres may play a significant role in the displacement of the disc from the head of the condyle. Thus in order to evaluate more precisely the insertions of these it was decided to carry out a histological study on a number of the above specimens.

3.4 Histological Investigation of the Lateral Pterygoid Muscle

- The primary objective of the histological evaluation was to determine the proportion of fibres of the superior head of the Lateral Pterygoid muscle, which were inserting into the disc and condyle respectively as these may play a significant role in the susceptibility to displacement of the disc which may occur during rapid posterior displacement of the condyle which may occur in "whiplash". The specimens used in the investigation were chosen randomly.
- Observations were also made regarding the attachments of the inferior head, the condition of the disc, the profile shape of the condyle and any bony deformations, the muscle bulk in the various slices and the nature of the posterior attachment when present.

3.4.1 Materials and Methods

The intact condyle /disc assembly with the superior and inferior heads of the lateral pterygoid muscle was dissected from the glenoid fossa (Figures 3.54 and 3.55).

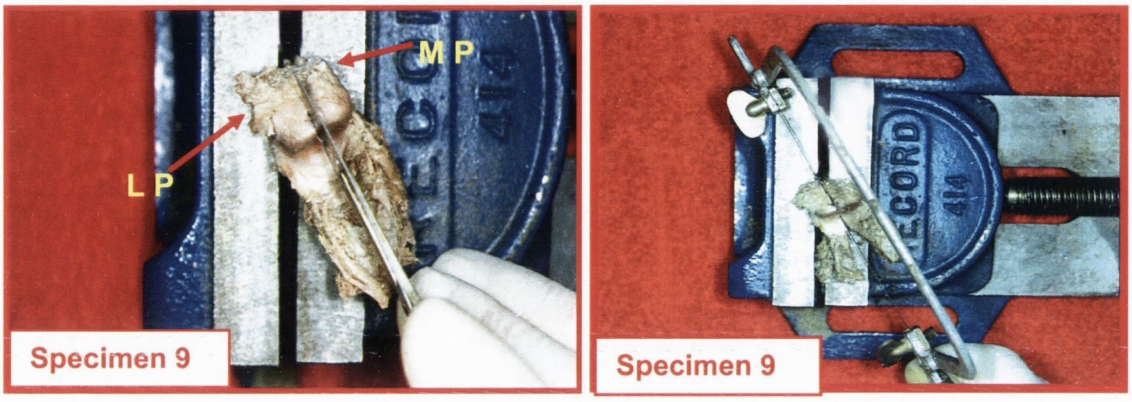


Figure 3.54: Disc /Condyle assembly (D C) with lateral pterygoid being dissected from fossa. A=anterior P=posterior



Figure 3.55: Disc/condyle assembly with lateral pterygoid removed from fossa

The disc/condyle assembly was now divided into two sections by making a mid-polar sagittal cut through the disc, head and neck of the condyle (Figures 3.56a /3.56b and 3.57). The initial incision through the disc and muscle was made with a scalpel to ensure a clean cut through the soft tissue. After this a sagittal cut in the same plane was made through the bony condyle using a fret saw.



3.56(a) *3.56(b)*

Figure 3.56(a): Mid-Polar Incision through disc and lateral pterygoid & Figure 3.56(b), mid-polar separation through condyle with fret saw. LP=lateral pole ofcondyle, MP=medial pole

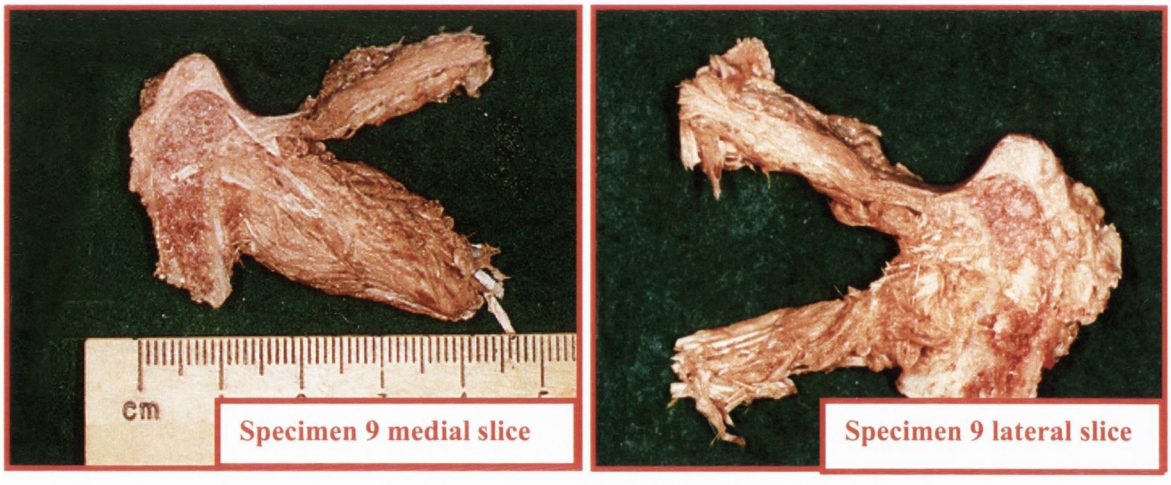


Figure 3.57: Medial and lateral sections of TMJ assembly with lateral pterygoid muscle after mid polar separation

This resulted in medial and lateral sections of the disc/condyle/ lateral pterygoid complex. As the greater part of the lateral pterygoid muscle lies on the medial aspect of the condyle it was decided to carry out the histological investigation on this portion of the muscle and condyle. The medial portion of the specimen was now embedded in paraffin wax (Figure 3.58) and the wax block trimmed from lateral to medial using a microtome.

Initially 150 microns (μ) was removed to reach a generous portion of the block. Now slices 5μ thick were made from the lateral to medial. A further 150μ was then removed and more 5-micron slices were made at this deeper level, and so on.



Figure 3.58: Medial portion of lateral pterygoid mounted in Paraffin Wax.

Most of the sections were stained with Haematoxylin and Eosin (H & E) and by the Masson Tri-chrome technique. The H & E gave a general picture of the relative sizes of the two heads of the muscle, and their posterior attachments.

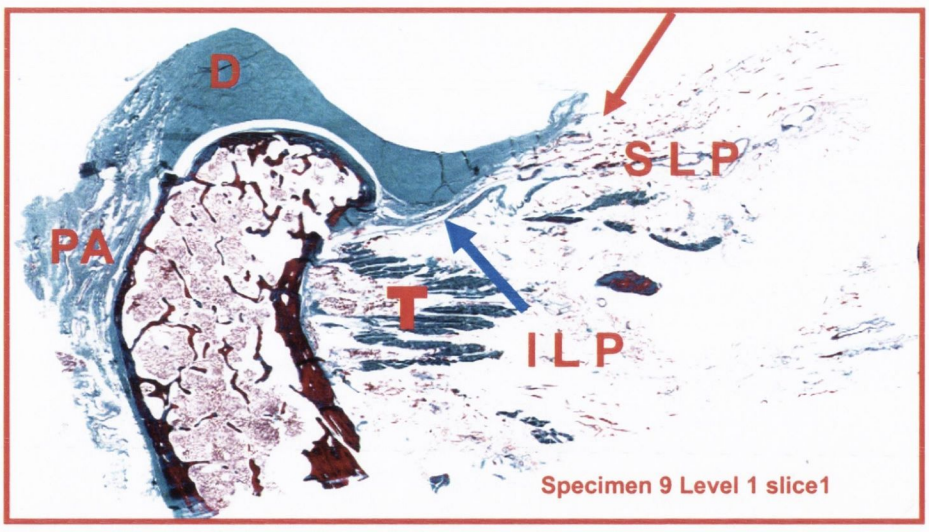


Figure 3.59: Histological slide of Specimen 9 at level 1, slice 1. Posterior attachment (PA), disc (D), tendinous insertion of ILP (T). The tendinous attachment of SLP is shown inserting into the head of the condyle (blue arrow), and muscle fibres of SLP are seen inserting into the disc (red arrow)

The H&E imparted a pink stain to all the tissues, whereas the Masson Tri-chrome gave a more specific staining of collagen (green) making it possible to differentiate between muscle and tendinous attachments. Specimen number 10 was stained with two different stains. Shore and Masson unichrome

The Masson unichrome imparted a green stain to collagen and a grey /black stain to the muscle tissue. The Shore stain had a similar effect.

A total of six specimens were chosen randomly and treated in the above manner. Histological slides were then made and scanned directly in the computer using an Epson 200 film and slide scanner.

In all specimens with the exception of specimen 10 the medial portion of the condyle and lateral pterygoid was used. An attempt was made to use the medial portion in specimen 10 but the results were not satisfactory as the tissue was friable and tended to fragment. The results from this were of no analytical value it was decided to take some slices from the lateral portion of the muscle.

All of the stains used proved to be a viable method of assessing the primary objective of evaluating the relative distribution of the fibres of the superior head into the disc and head of the condyle respectively.

The number of slices available from each specimen varied due to their dimensional differences and the quality of the tissue.

The results of the histological investigation are shown in figures 3.59 to 3.85*.

* Some additional histological slides are shown in appendix B

3.4.1.1 Histological samples of specimen 9

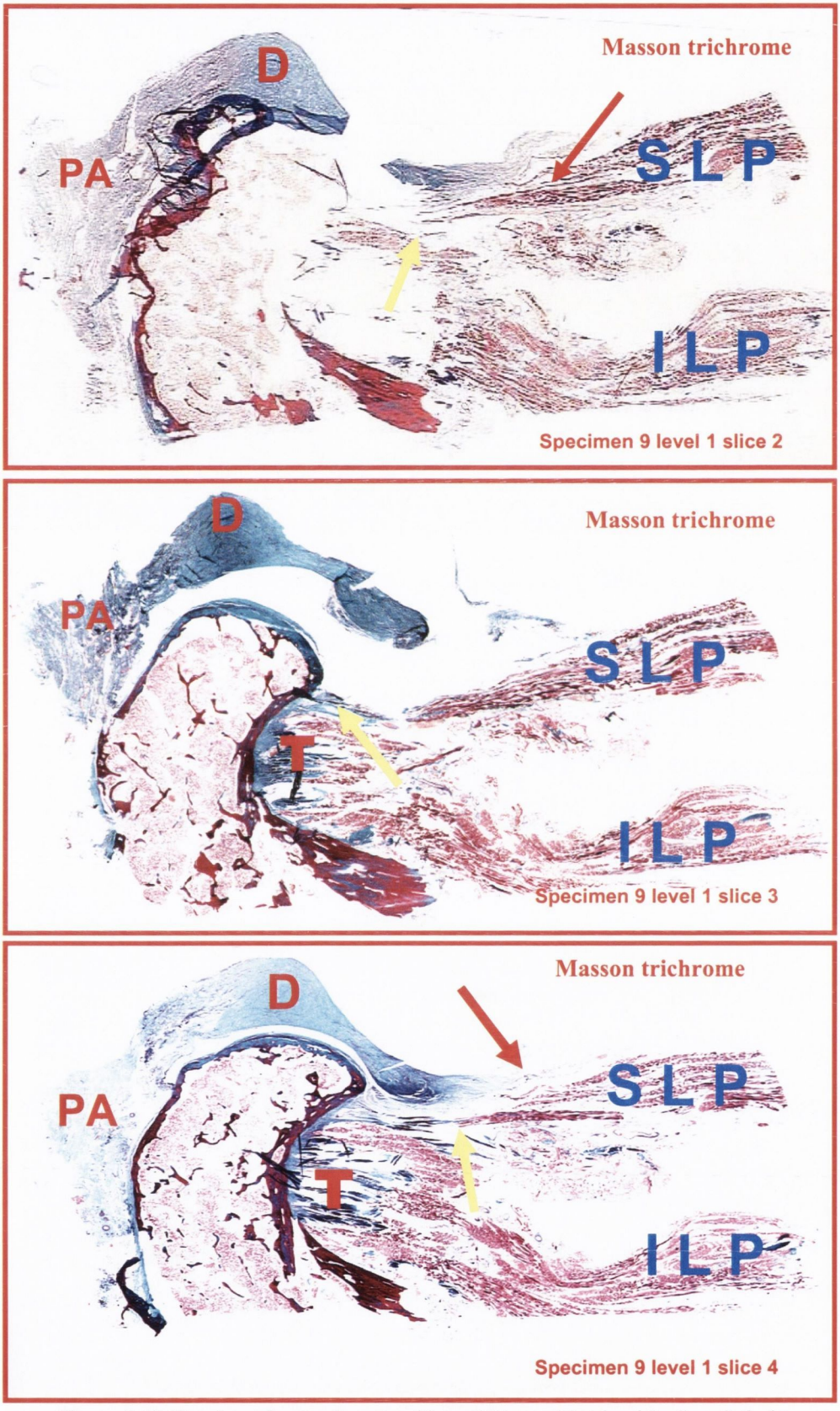


Figure 3.60: Specimen 9, attachments of lateral Pterygoid at level 1, slices 2, 3, 4. Fibres of superior head inserting into disc are marked with red arrow, & fibres passing under disc to insert into condyle are marked with yellow arrow

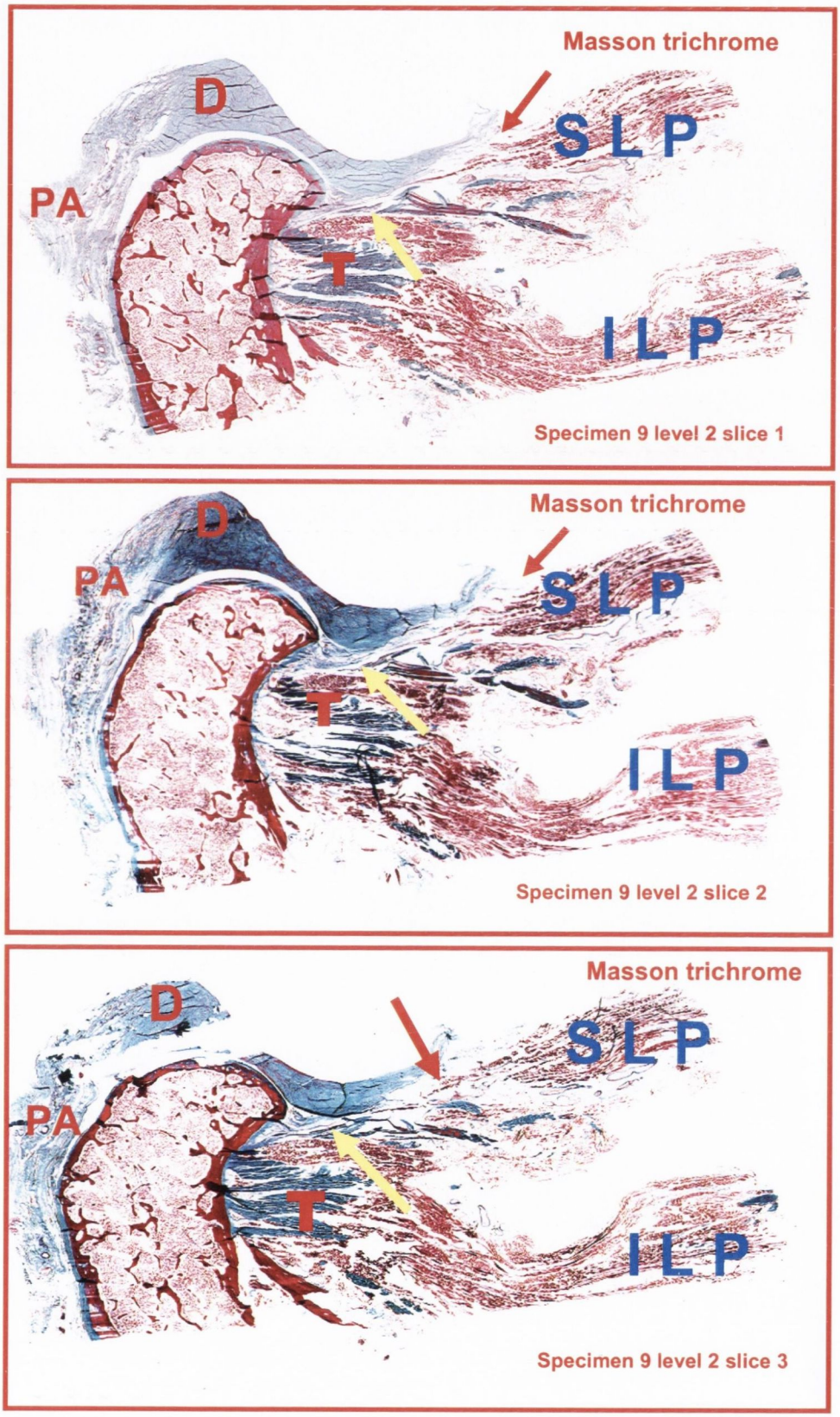


Figure 3.61: Specimen 9, attachments of Lateral Pterygoid, level 2, slices 1, 2, 3.

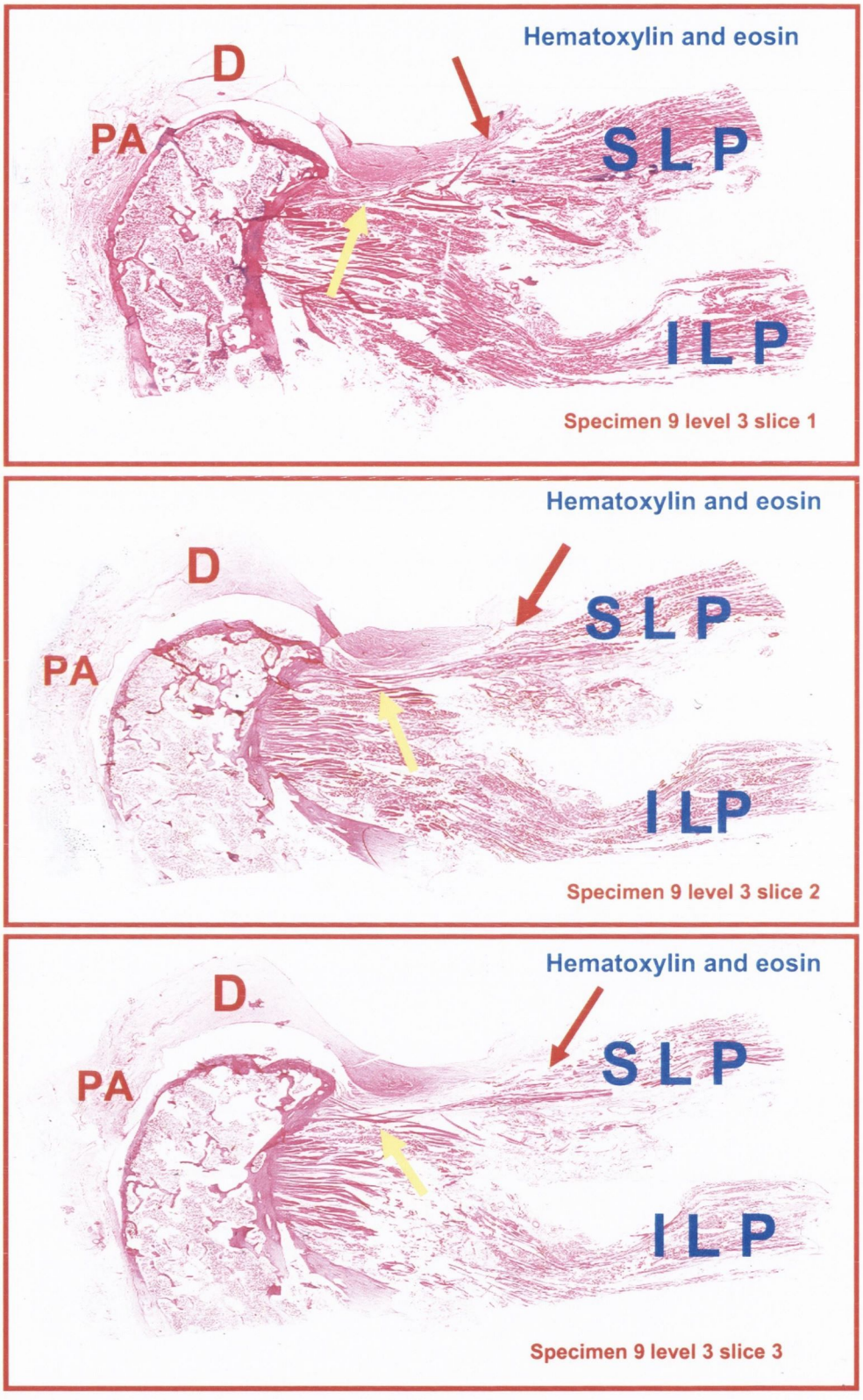


Figure 3.62: Specimen 9, attachments of lateral Pterygoid muscle, level 3 slices 1, 2, 3.

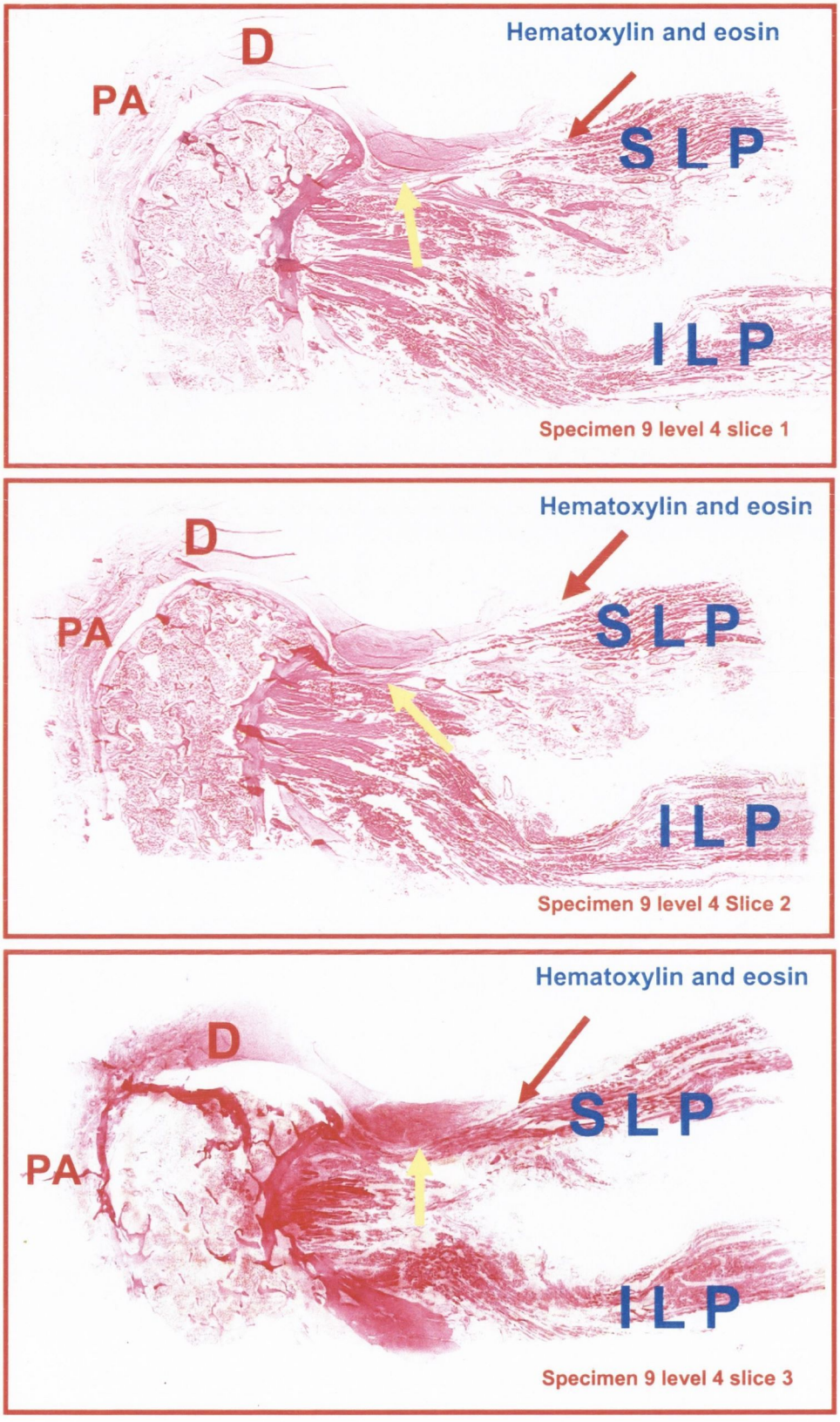


Figure 3.63: Specimen 9, attachments of lateral Pterygoid muscle, level 4, slices 1, 2, 3.

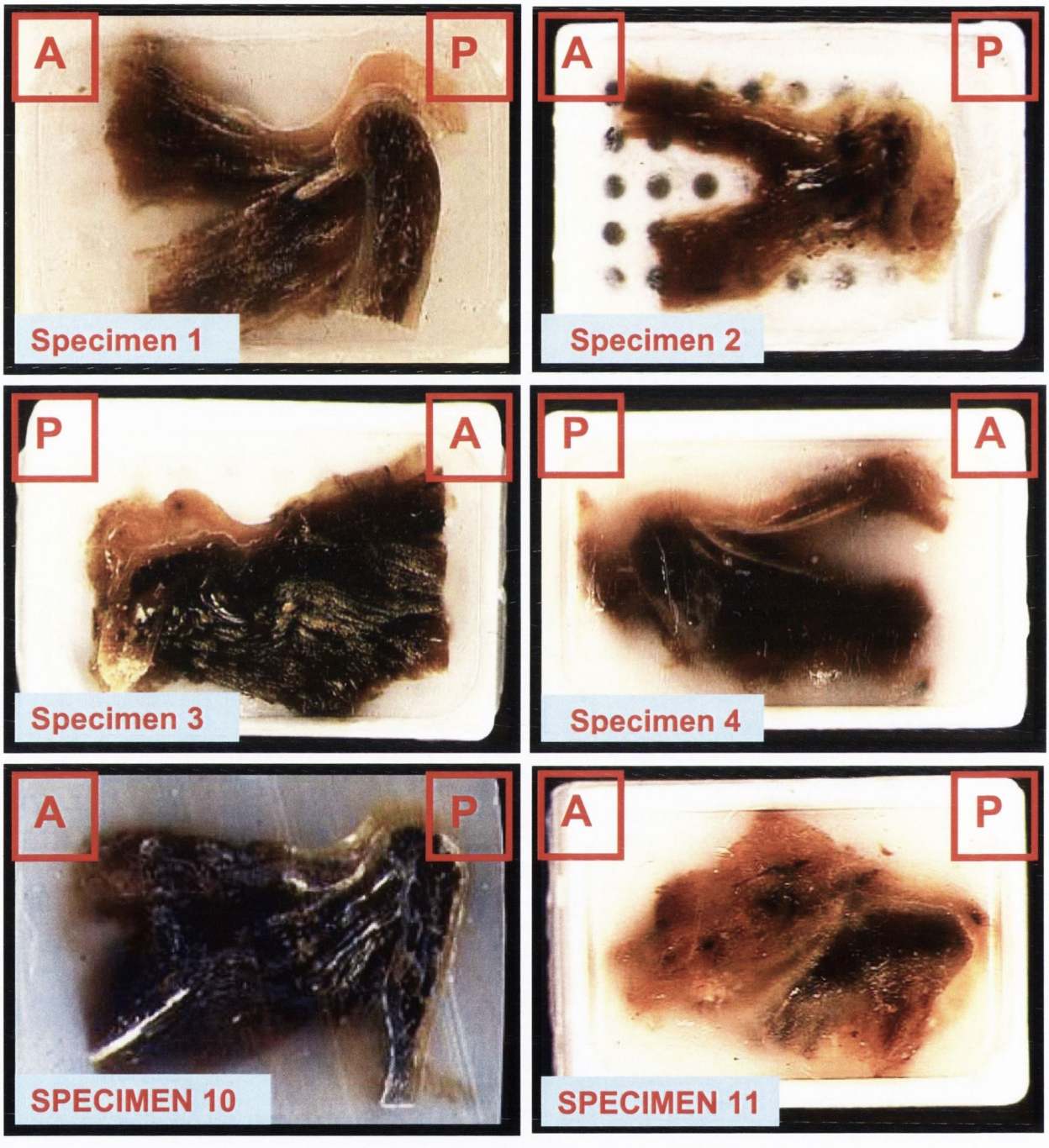


Figure 3.64: TMJ specimens mounted in paraffin wax.
A=anterior, P=posterior

3.4.1.2 Histological Samples of Specimen 1

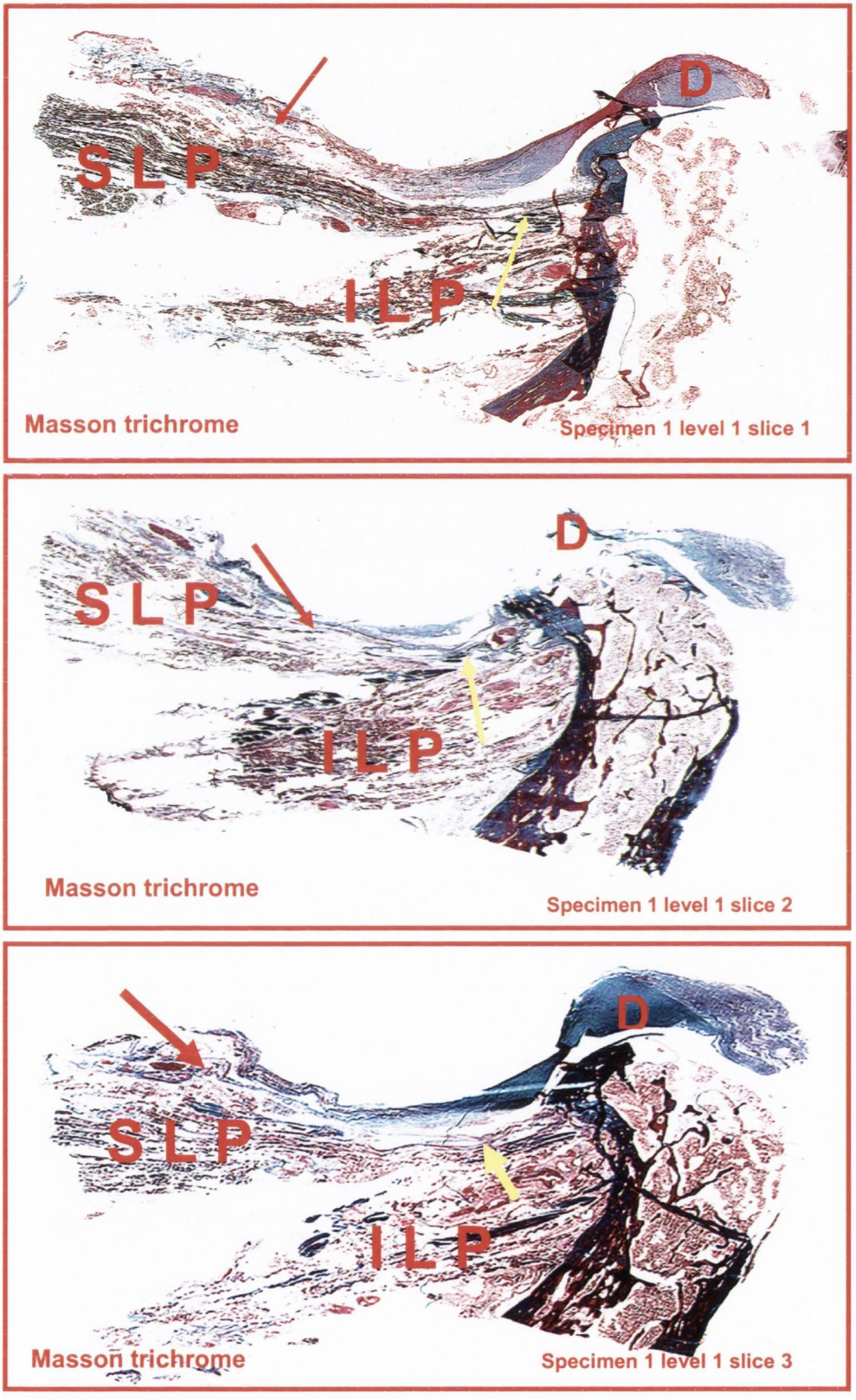


Figure 3.65: Specimen 1, attachments of Lateral Pterygoid at level 1, slices 1, 2 and 3. The yellow arrow indicates the fibres of the superior head passing under the disc and inserting into the head/neck of the condyle. The red arrow shows fibres of the superior head inserting into disc

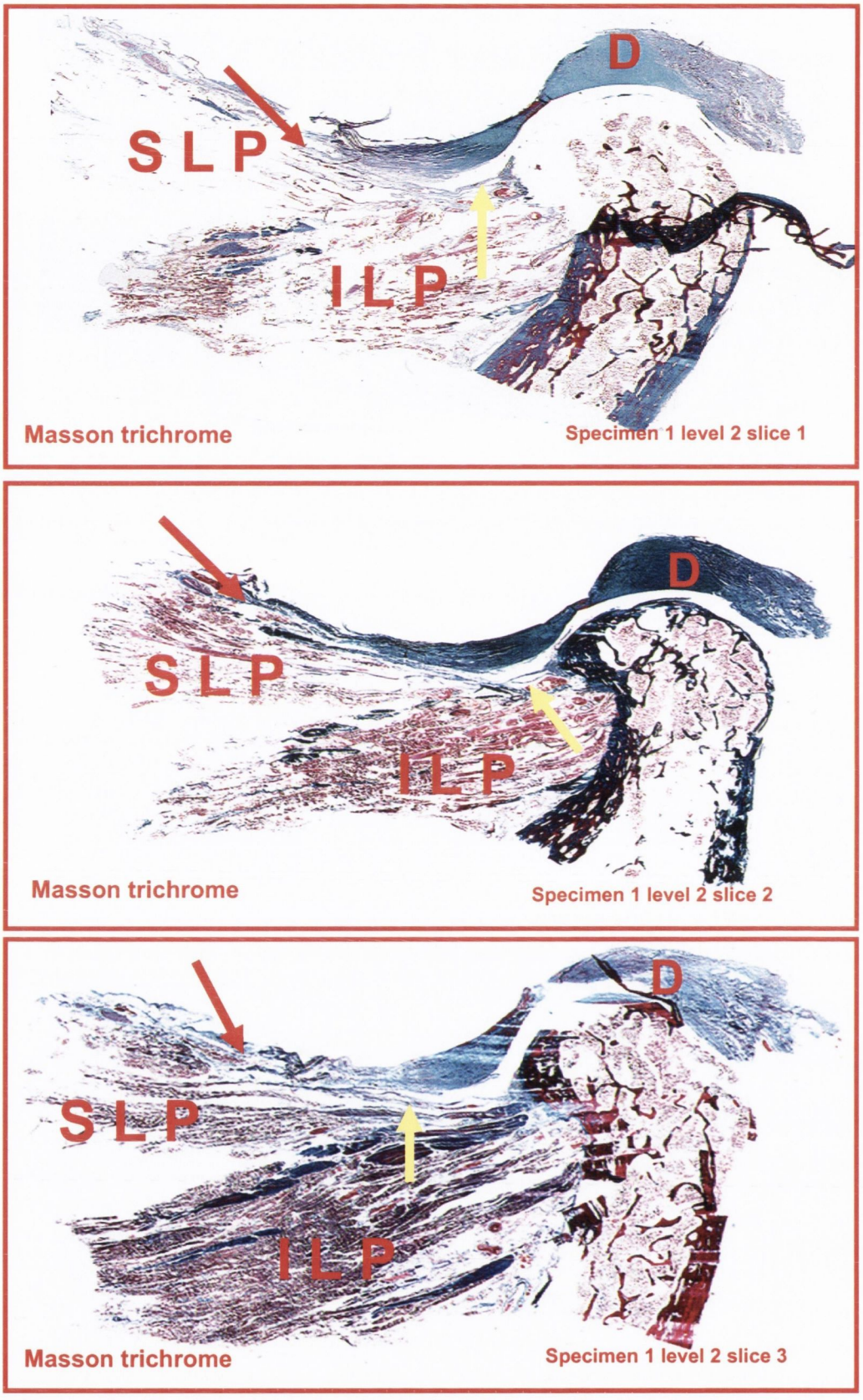


Figure 3.66: Specimen 1, attachments of Lateral Pterygoid at level 2, slices, 1,2,3.

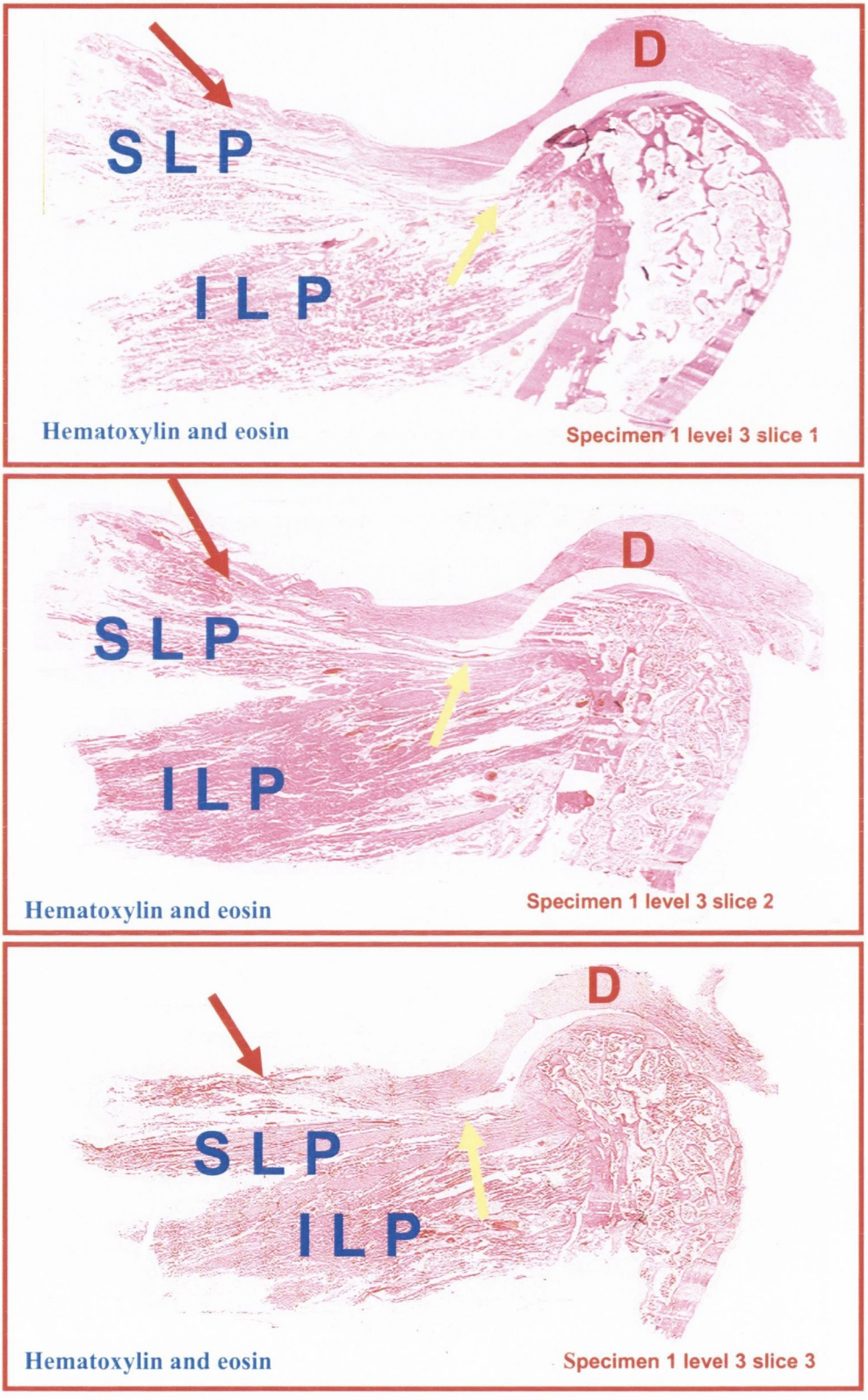


Figure 3.67: Specimen 1, attachments of Lateral Pterygoid at level 3,slices 1,2,3.

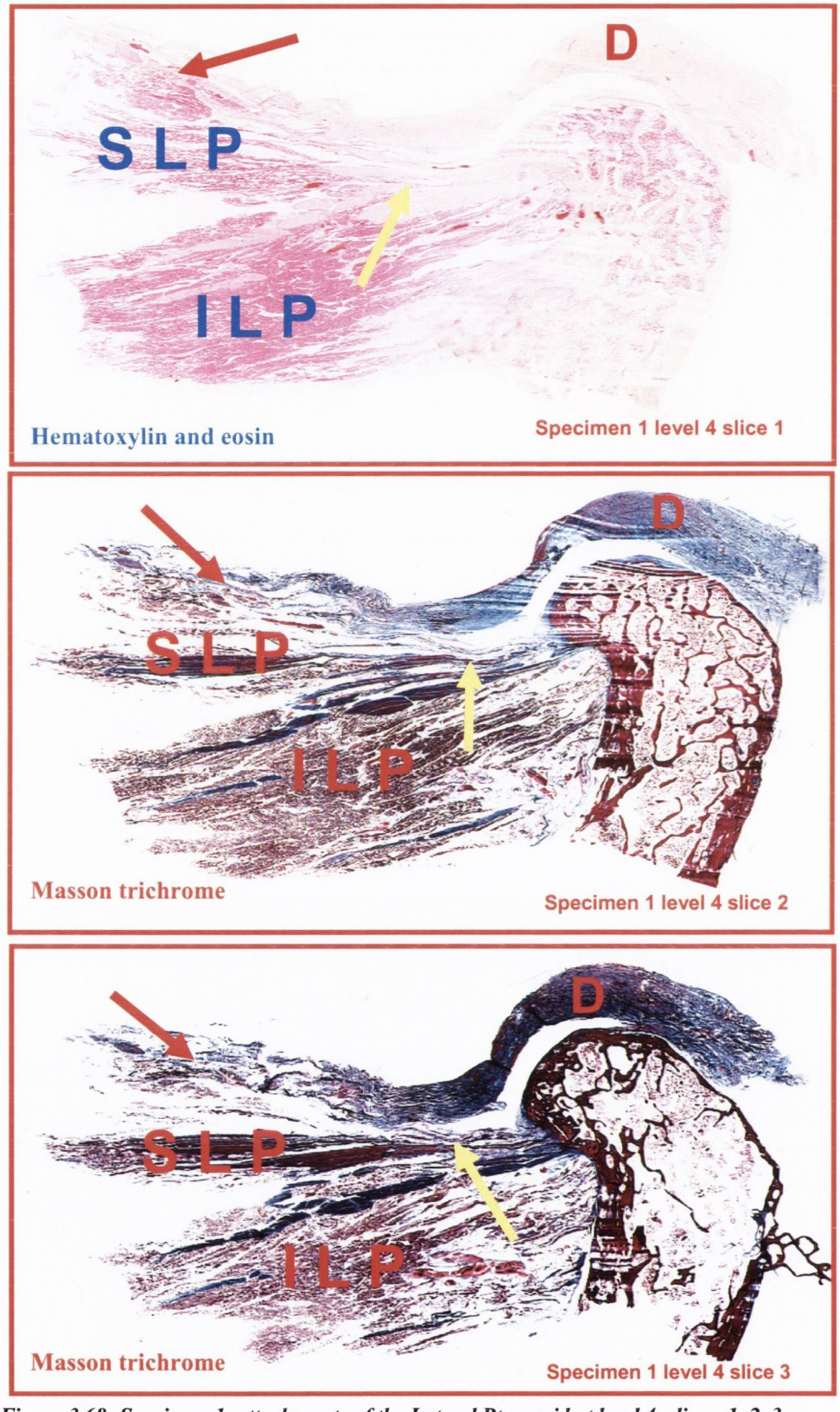


Figure 3.68: Specimen 1, attachments of the Lateral Pterygoid at level 4, slices, 1, 2, 3.

3.4.1 3 Histological Samples of Specimen 2

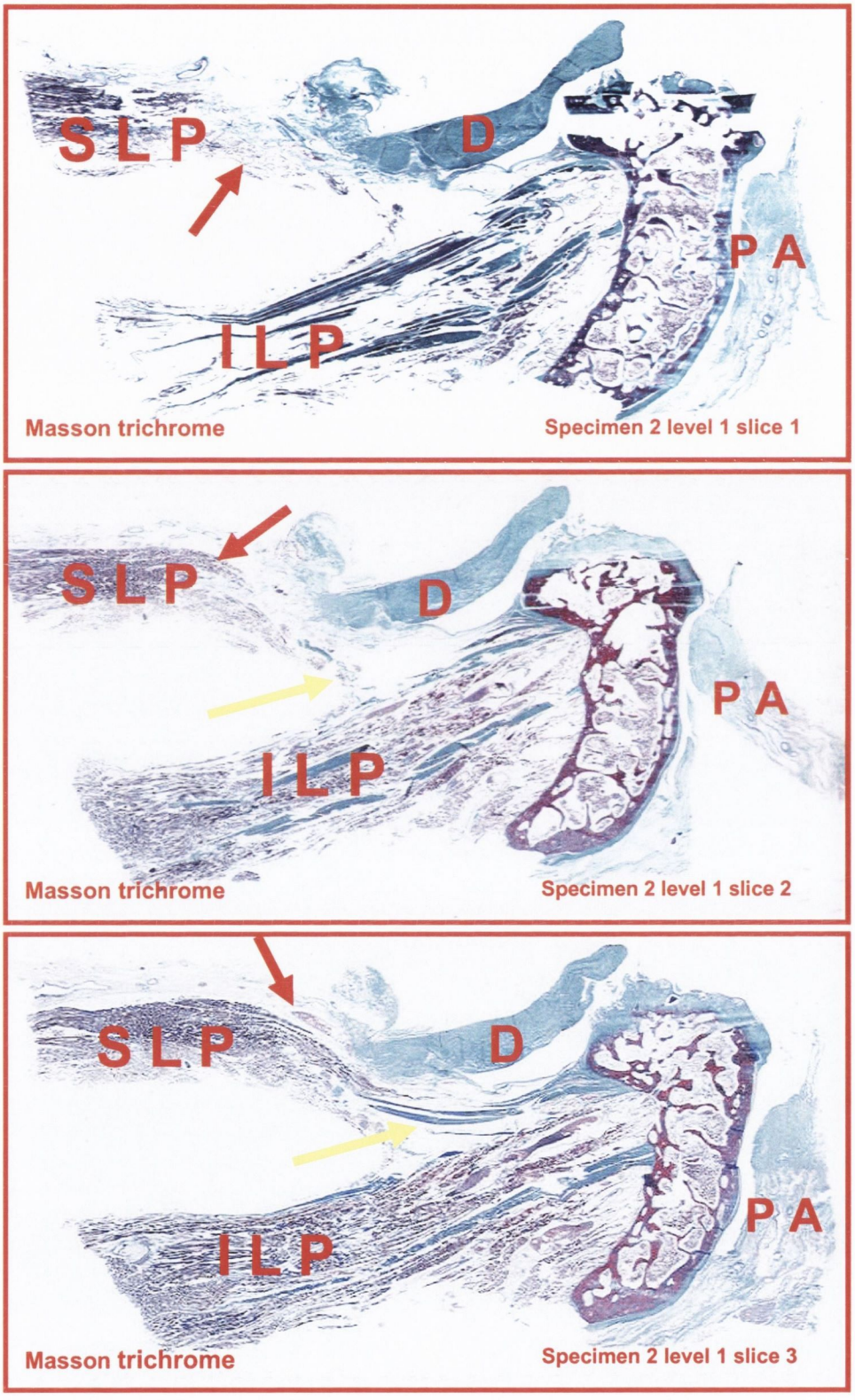


Figure 3.69: Specimen 2, attachments of Lateral Pterygoid at level 1, slices, 1,2,3.

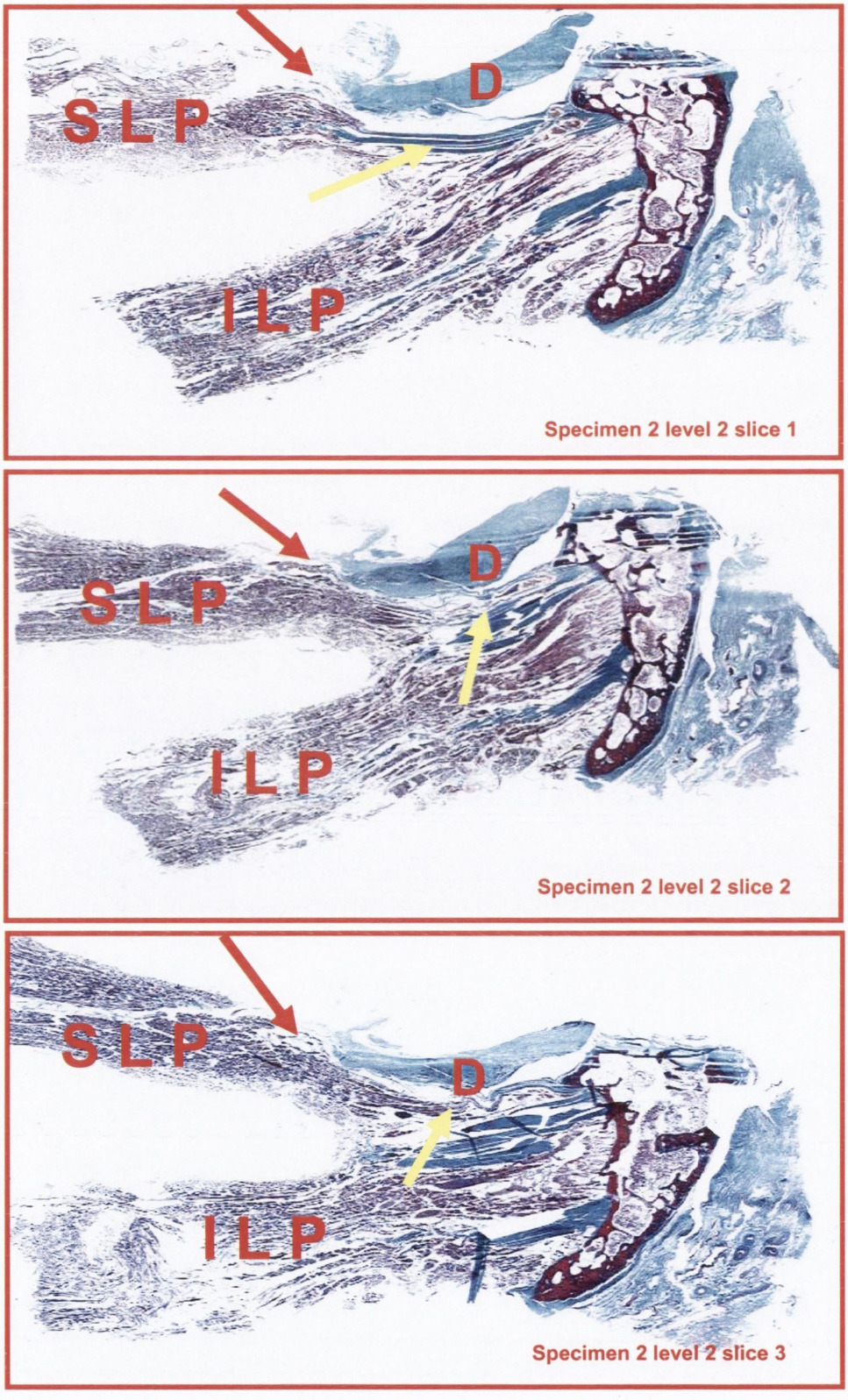


Figure 3.70: Specimen 2, attachments of the Lateral pterygoid at level 2, slices 1, 2, 3.

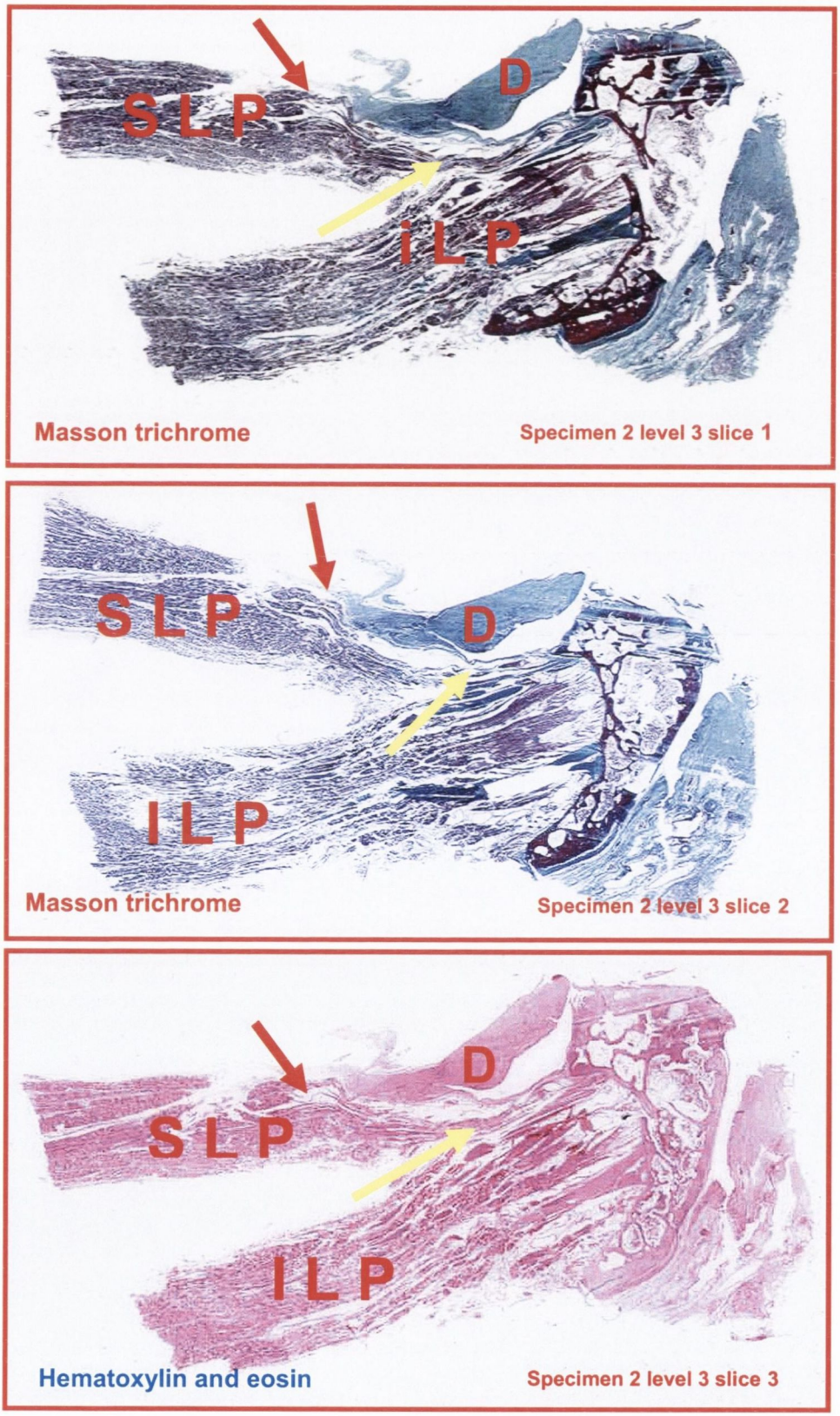


Figure 3.71: Specimen 2, attachments of Lateral Pterygoid at level 3, slices 1, 2, 3

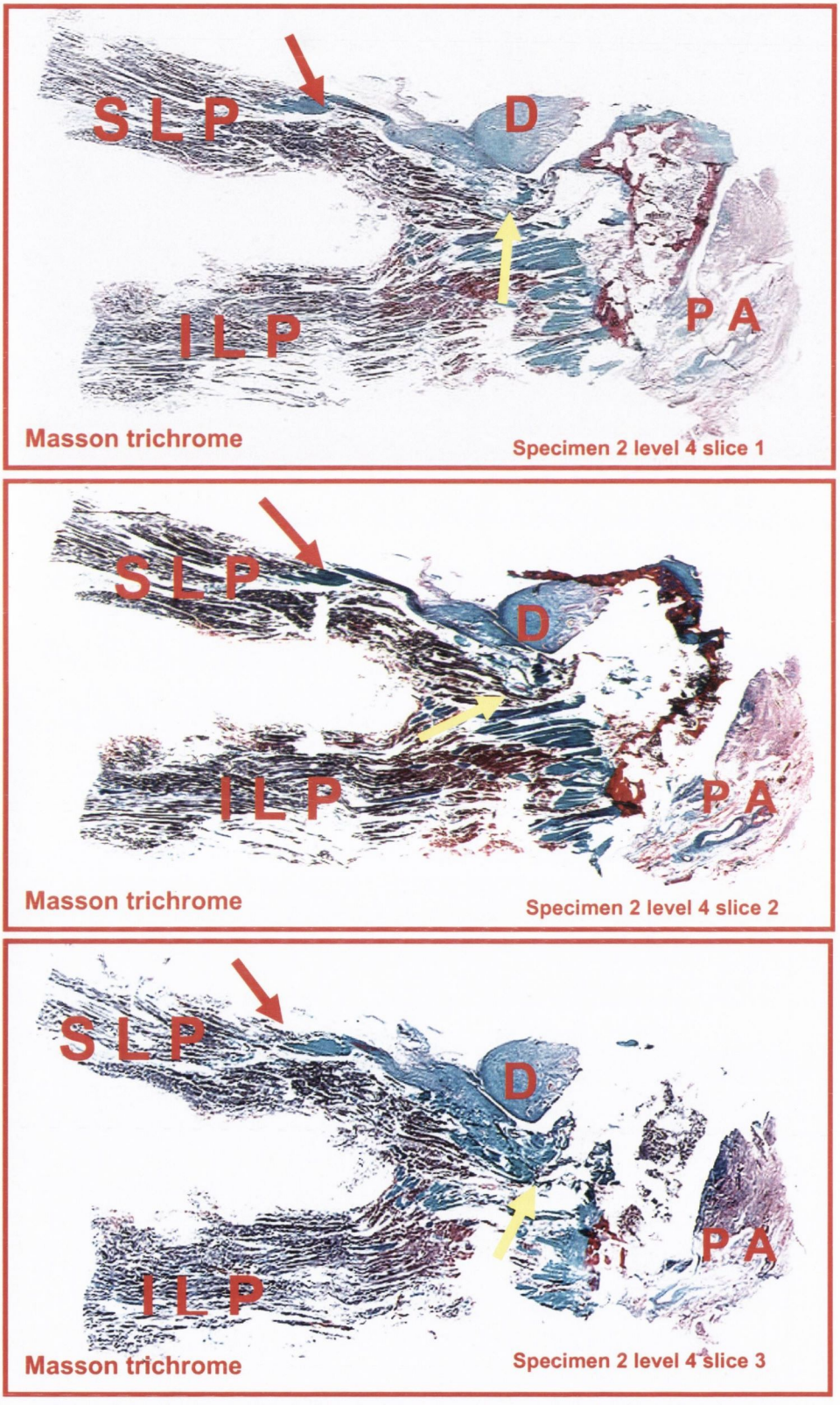


Figure 3.72: Specimen 2, attachments of Lateral Pterygoid, level 4, Slices 1, 2, 3.

3.4.1.4 Histological Samples of Specimen 3

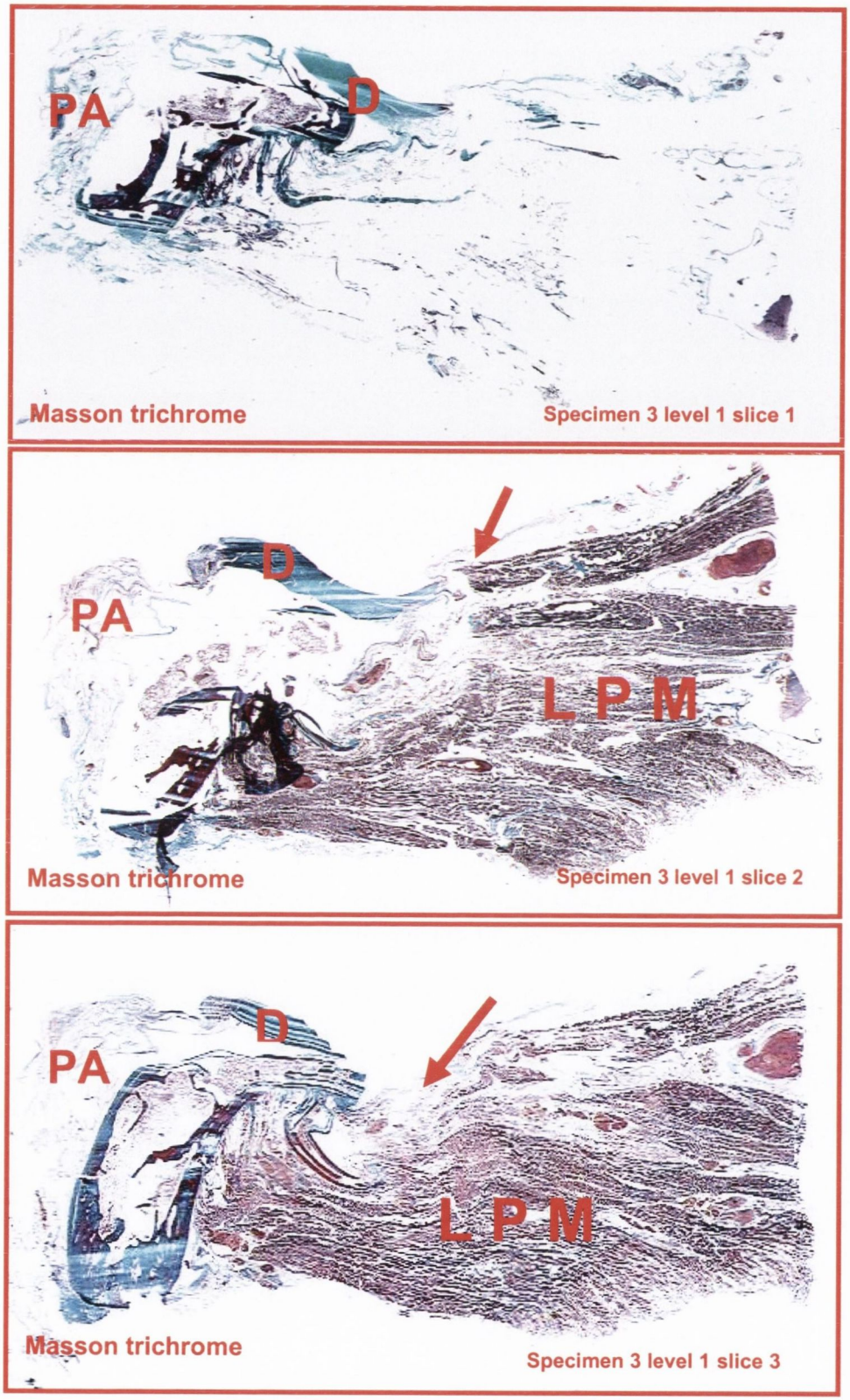


Figure 3.73: Specimen 3, attachments of Lateral Pterygoid at level 1, slices 1, 2, 3.

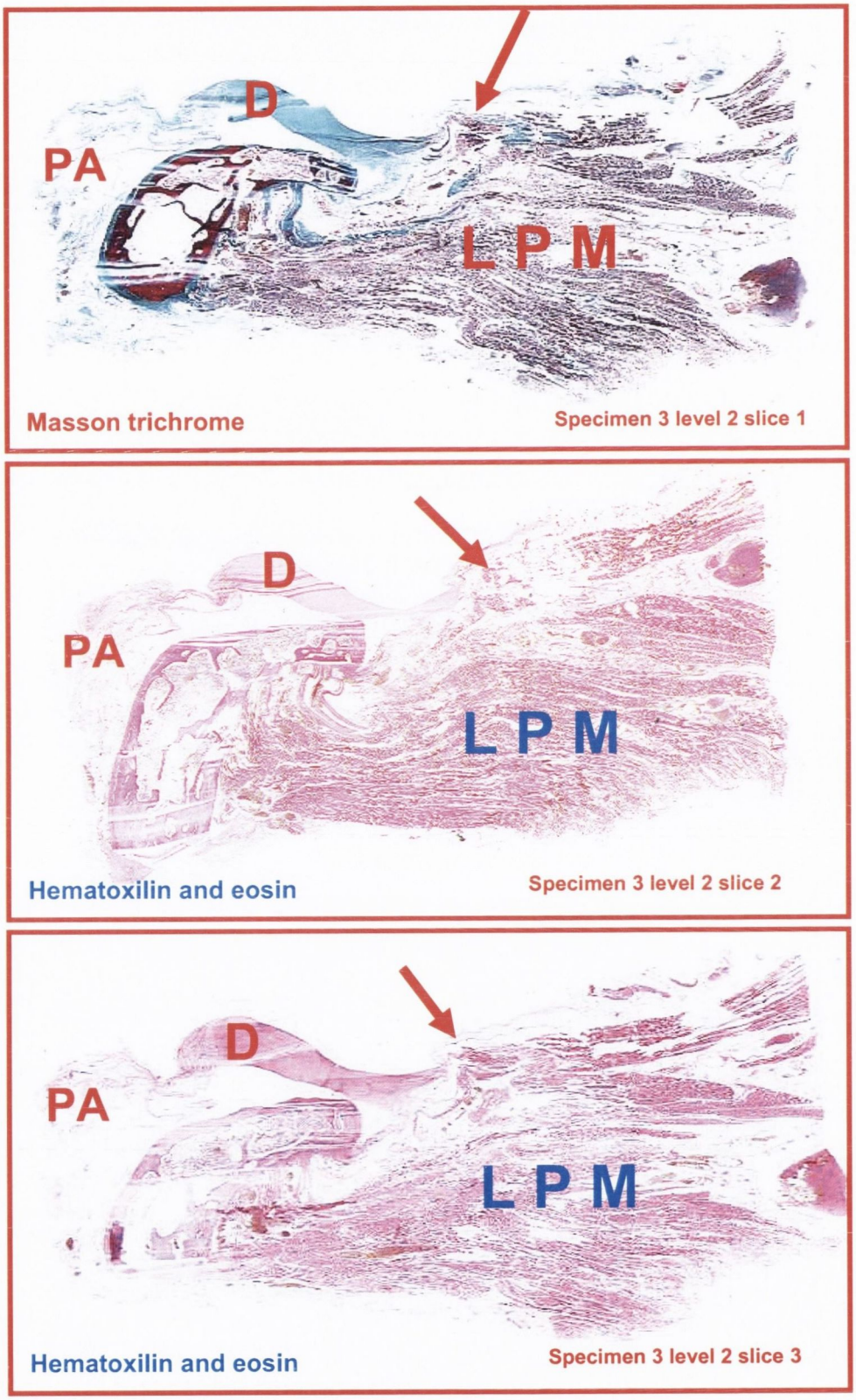


Figure 3.74: Specimen 3, attachments of Lateral Pterygoid at level 2, slices 1, 2, 3.

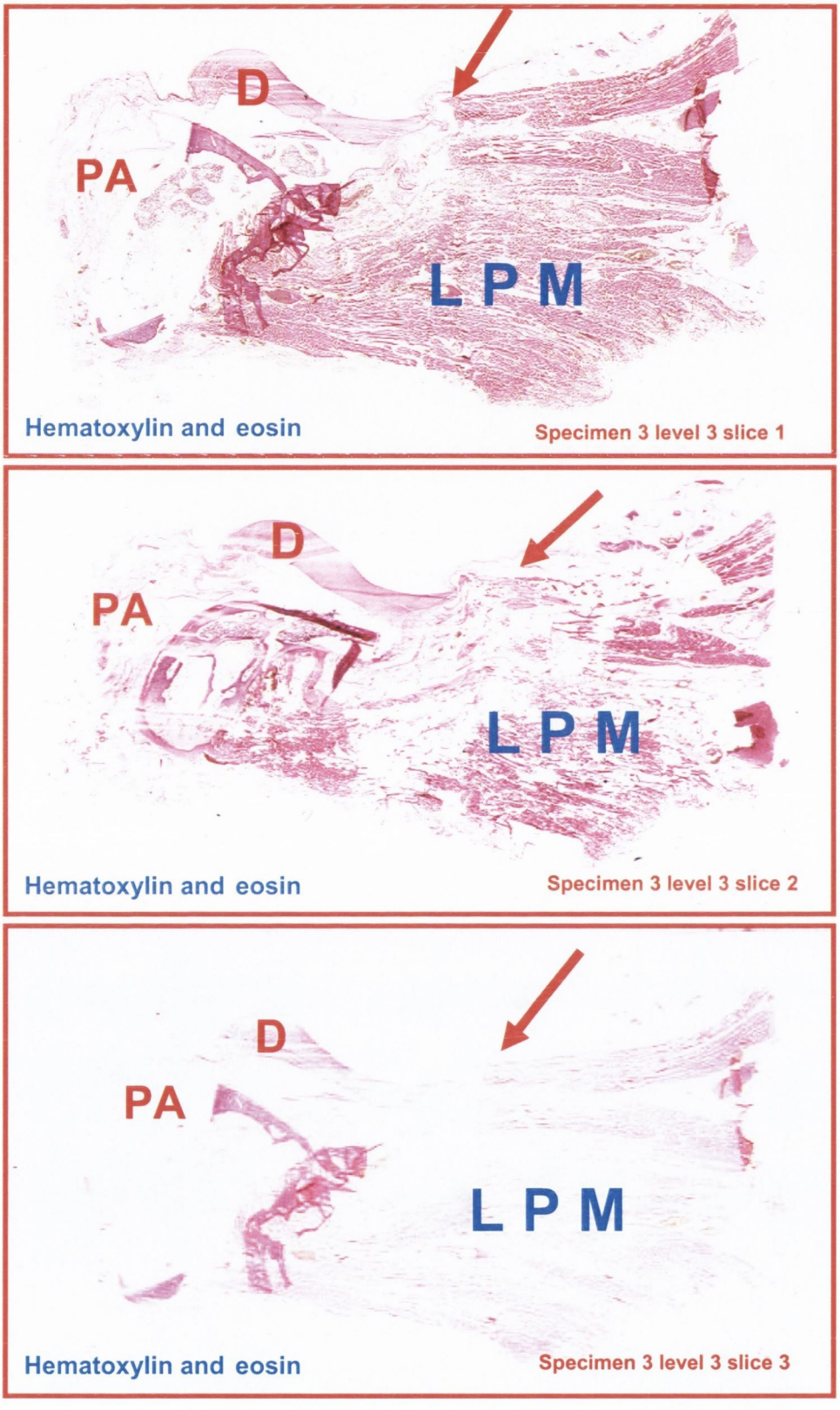


Figure 3.75: Specimen 3, attachments of Lateral Pterygoid, level 3, slices 1, 2, 3.

3.4.1.5 Histological Samples of Specimen 4

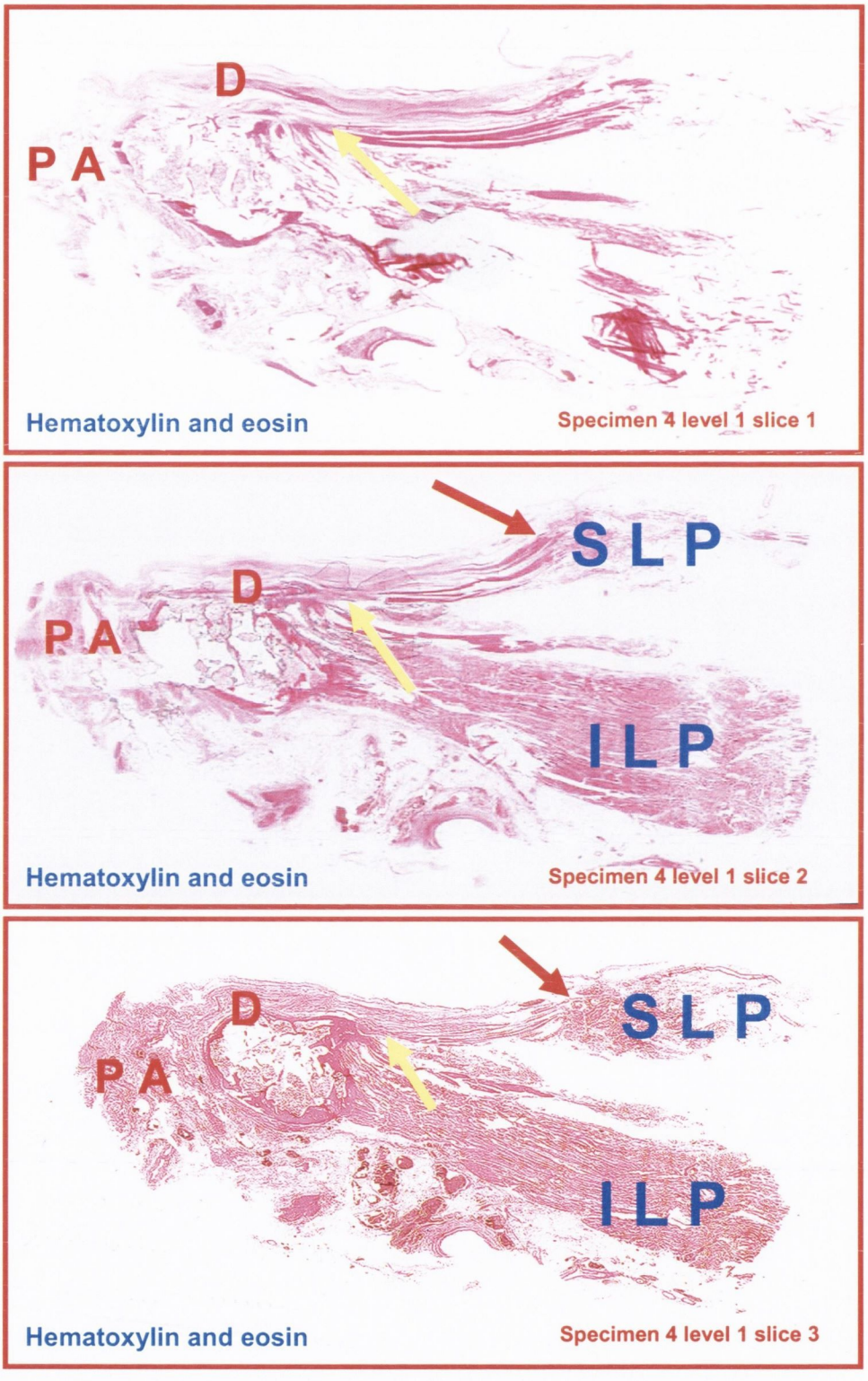


Figure 3.76: Specimen 4, attachments of Lateral Pterygoid, level 1, slices 1, 2, 3.

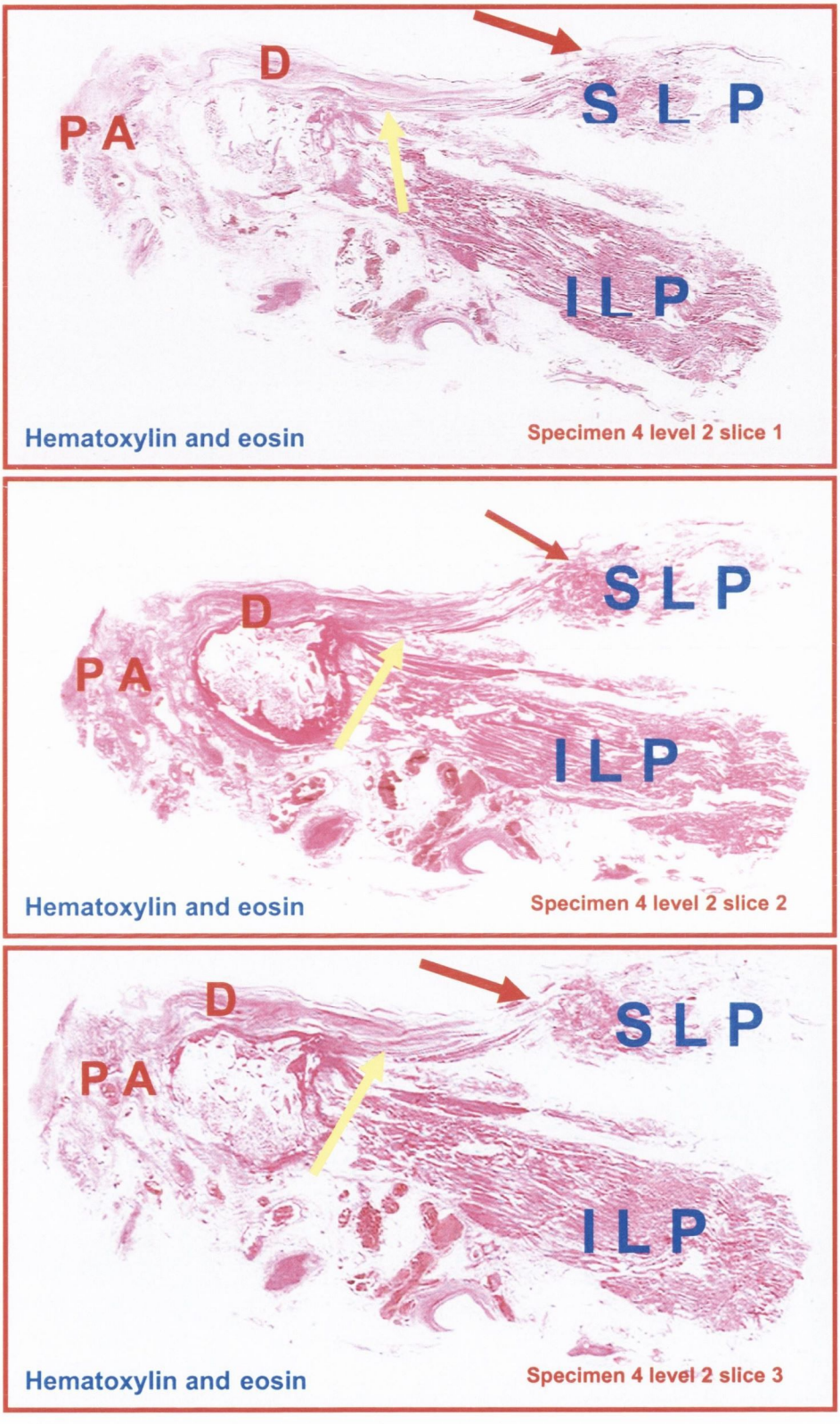


Figure 3.77: Specimen 4, attachments of Lateral Pterygoid, level 2, slices 1, 2, 3.

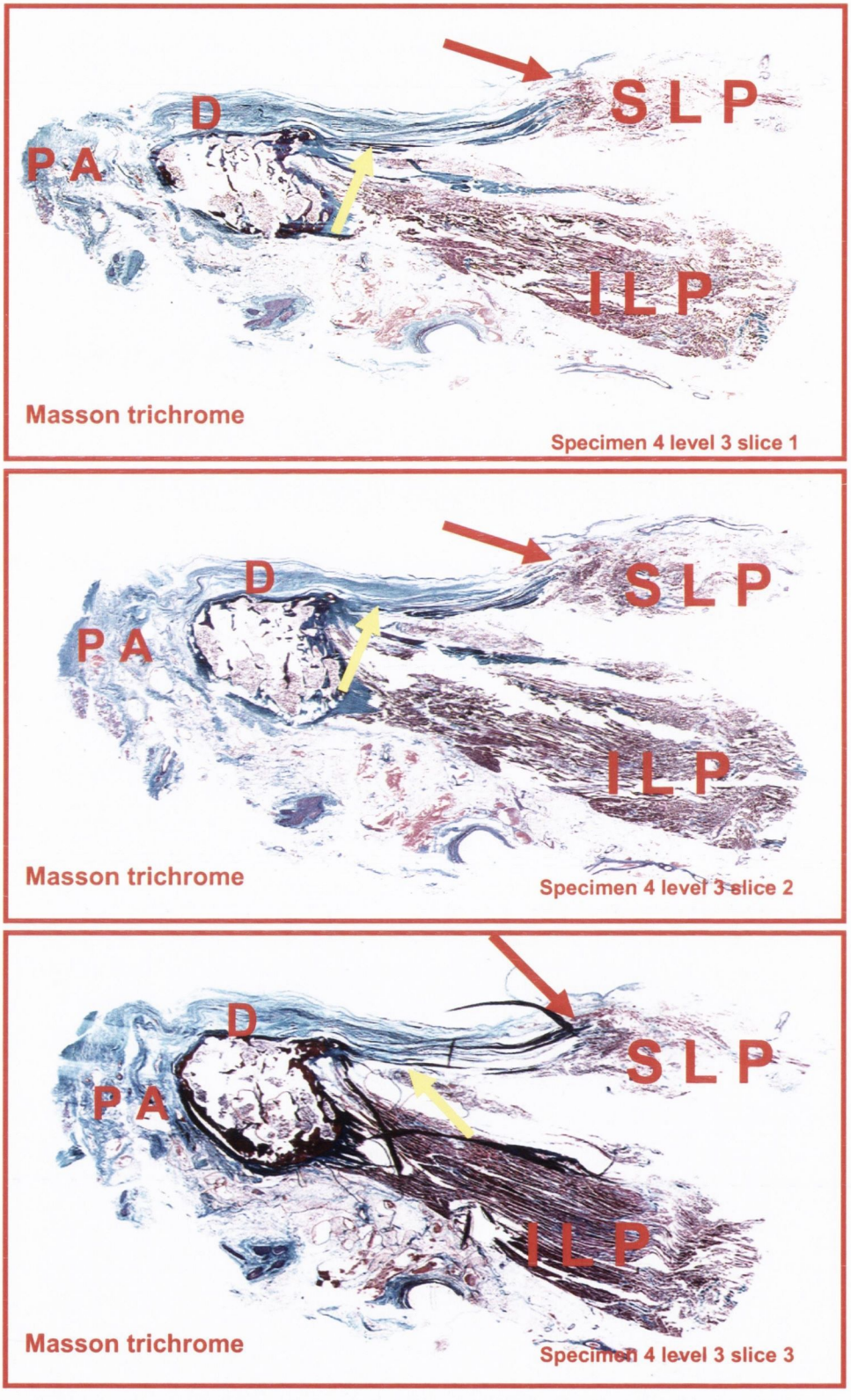


Figure 3.78: Specimen 4, attachments of Lateral Pterygoid level 3, slices 1, 2, 3.

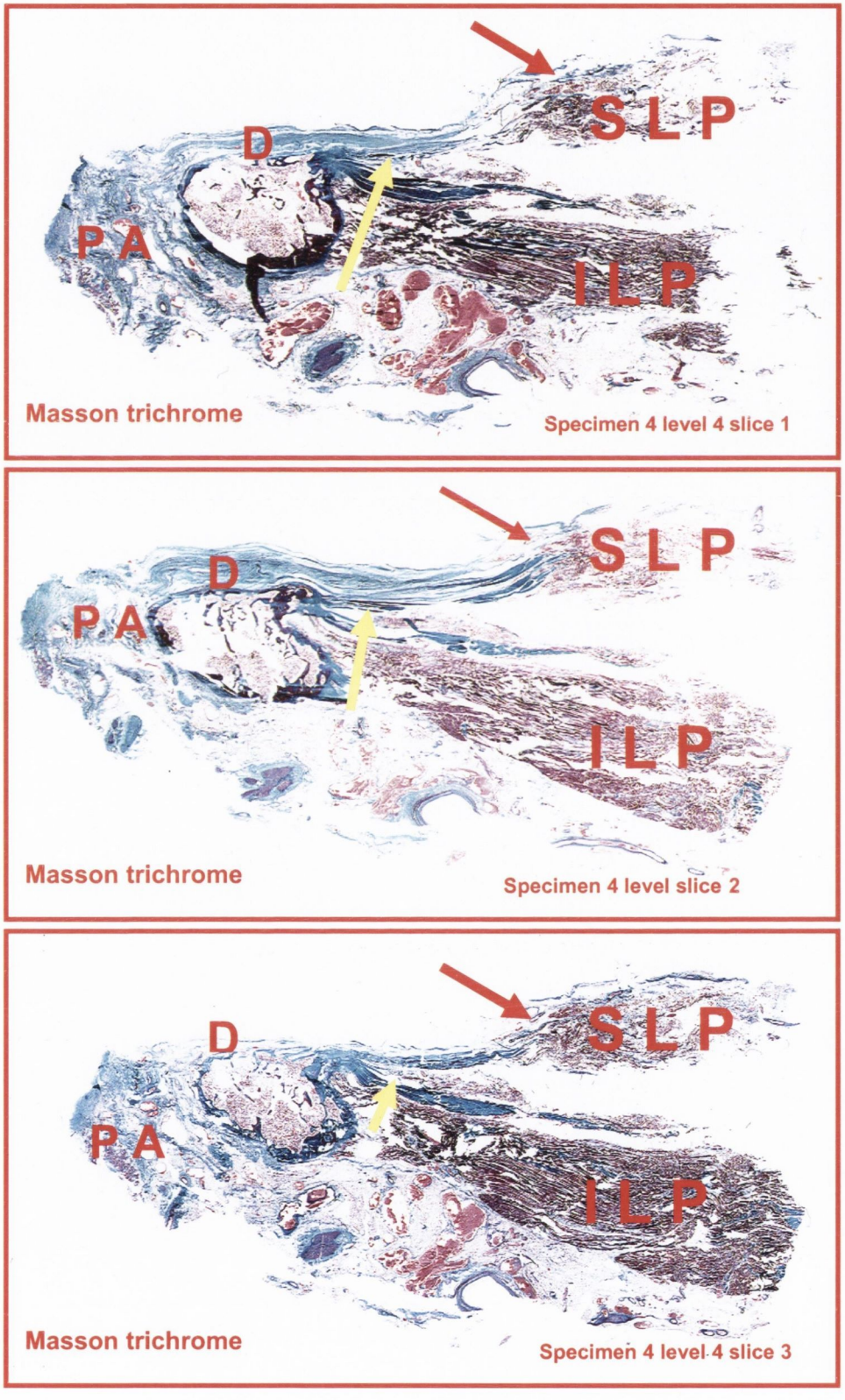


Figure 3.79: Specimen 4, attachments of Lateral Pterygoid, level 4, slices 1, 2, 3.

3.4.1.6 Histological Samples of Specimen 10 (Medial)

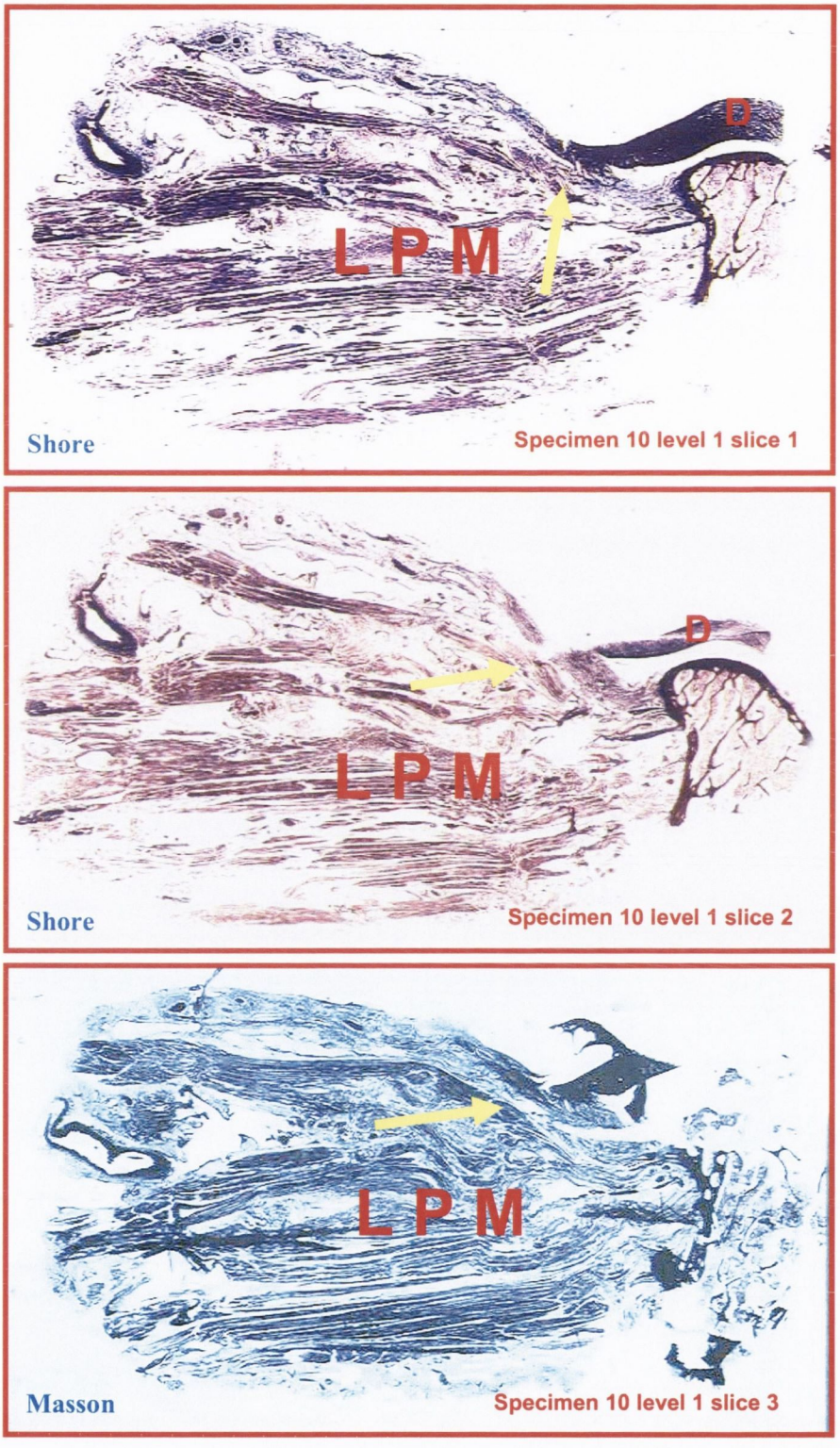


Figure 3.80: Specimen 10, attachments of Lateral Pterygoid, level 1, slices 1, 2, 3 (Medial).

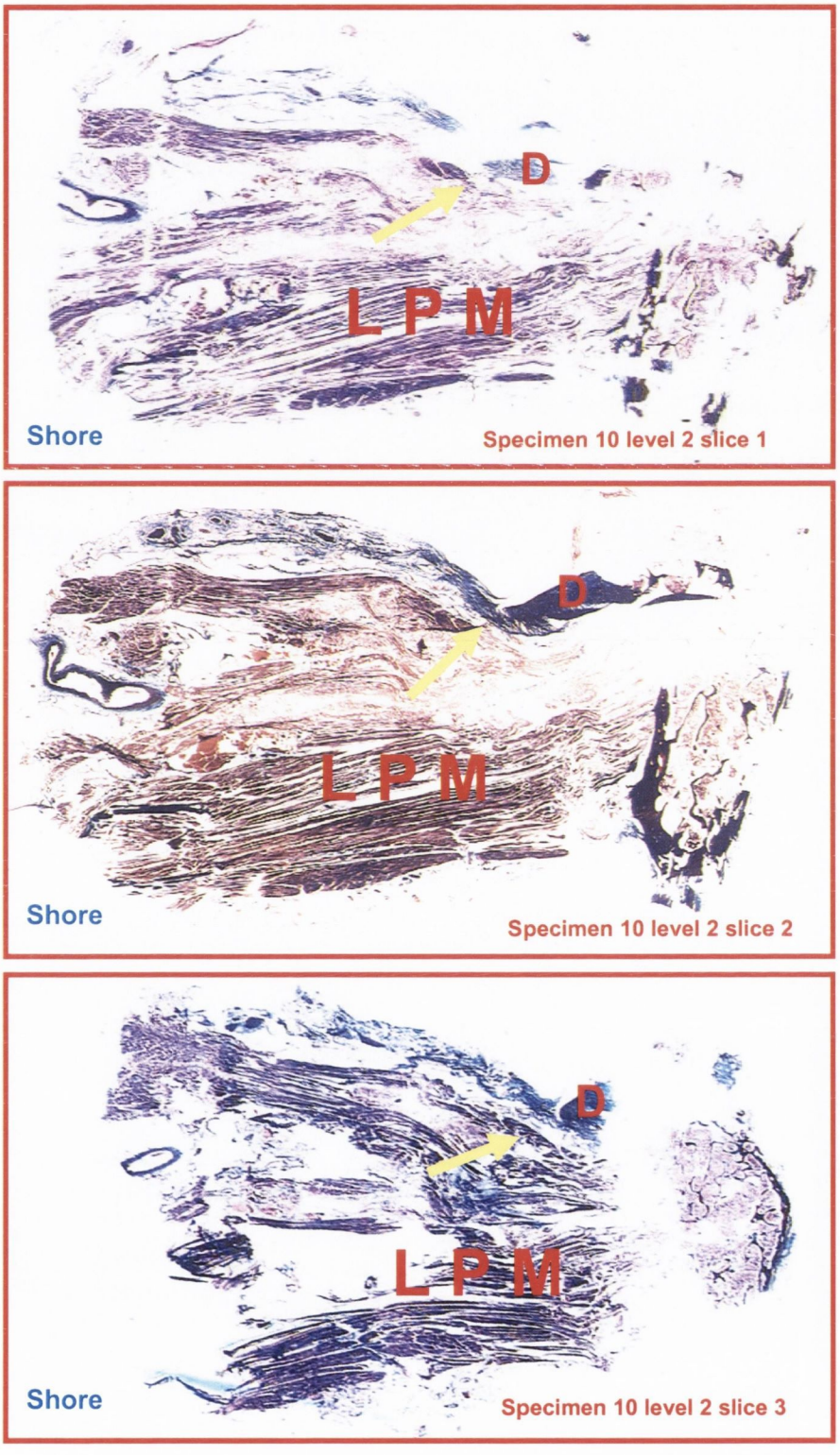


Figure 3.81: Specimen 10, Lateral Pterygoid attachments, level 2, slices 1, 2, 3 (Medial).

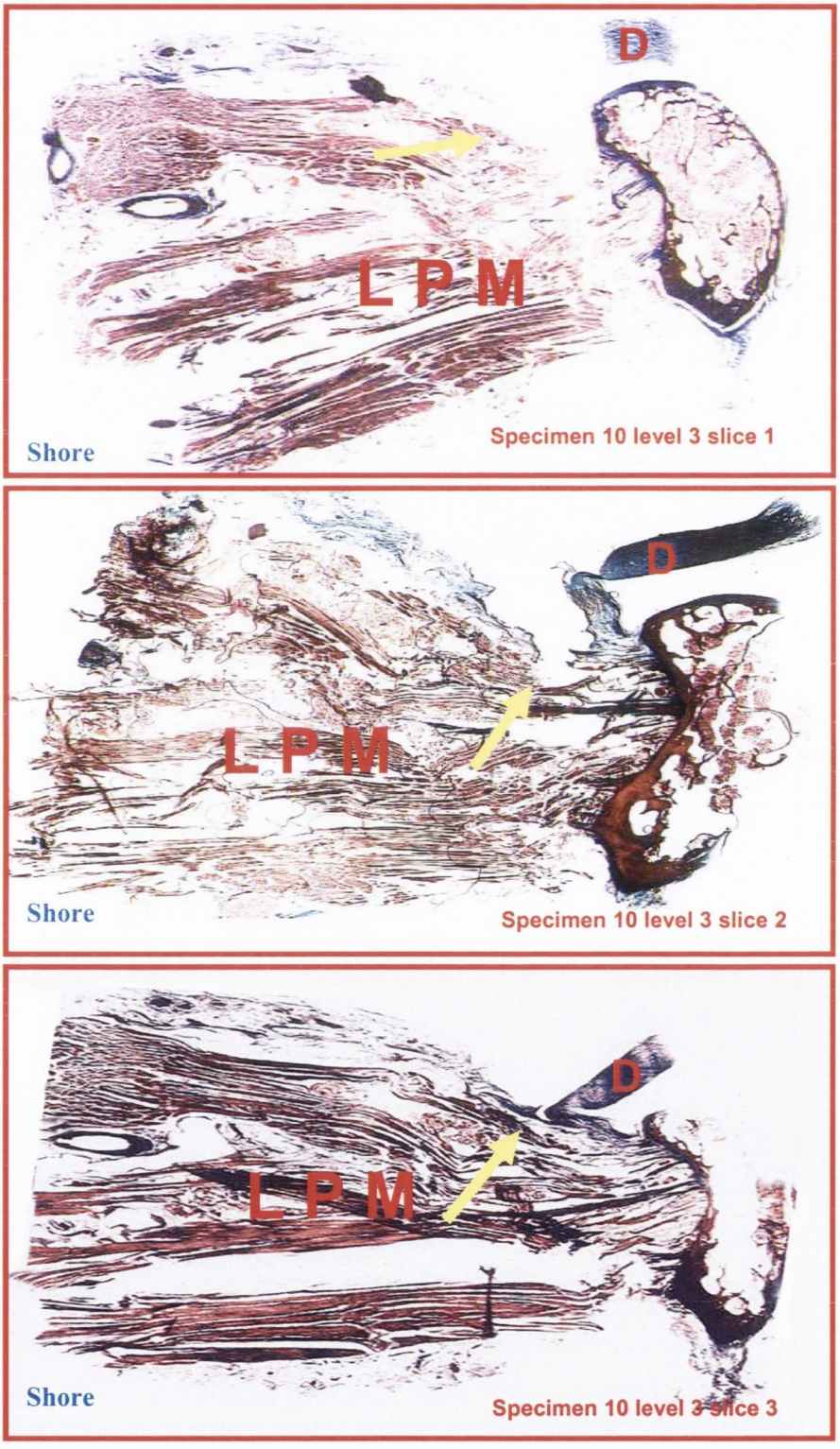


Figure 3.82: Specimen 10, Lateral Pterygoid attachments, Level 3 slices 1, 2, 3, (Medial).

3.4.1.7 Histological Samples of Specimen 10 (Lateral)

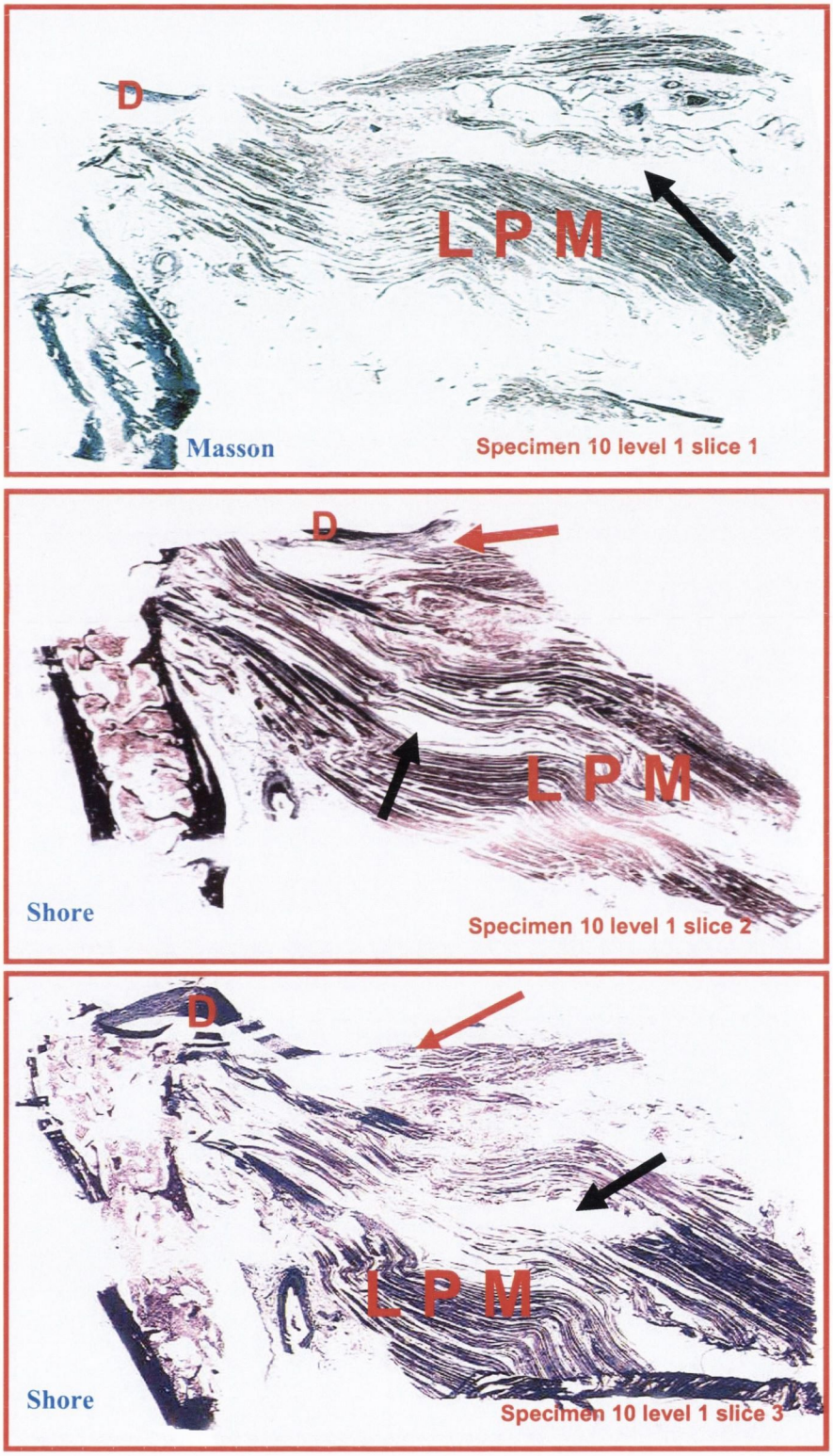


Figure 3.83: Specimen 10, Lateral Pterygoid attachments, level 1, slices 1, 2, 3 (Lateral). The black arrow indicates the space occupied by the pterygoid plexus, and the red arrow indicates the muscle fibres inserting in to the disc.

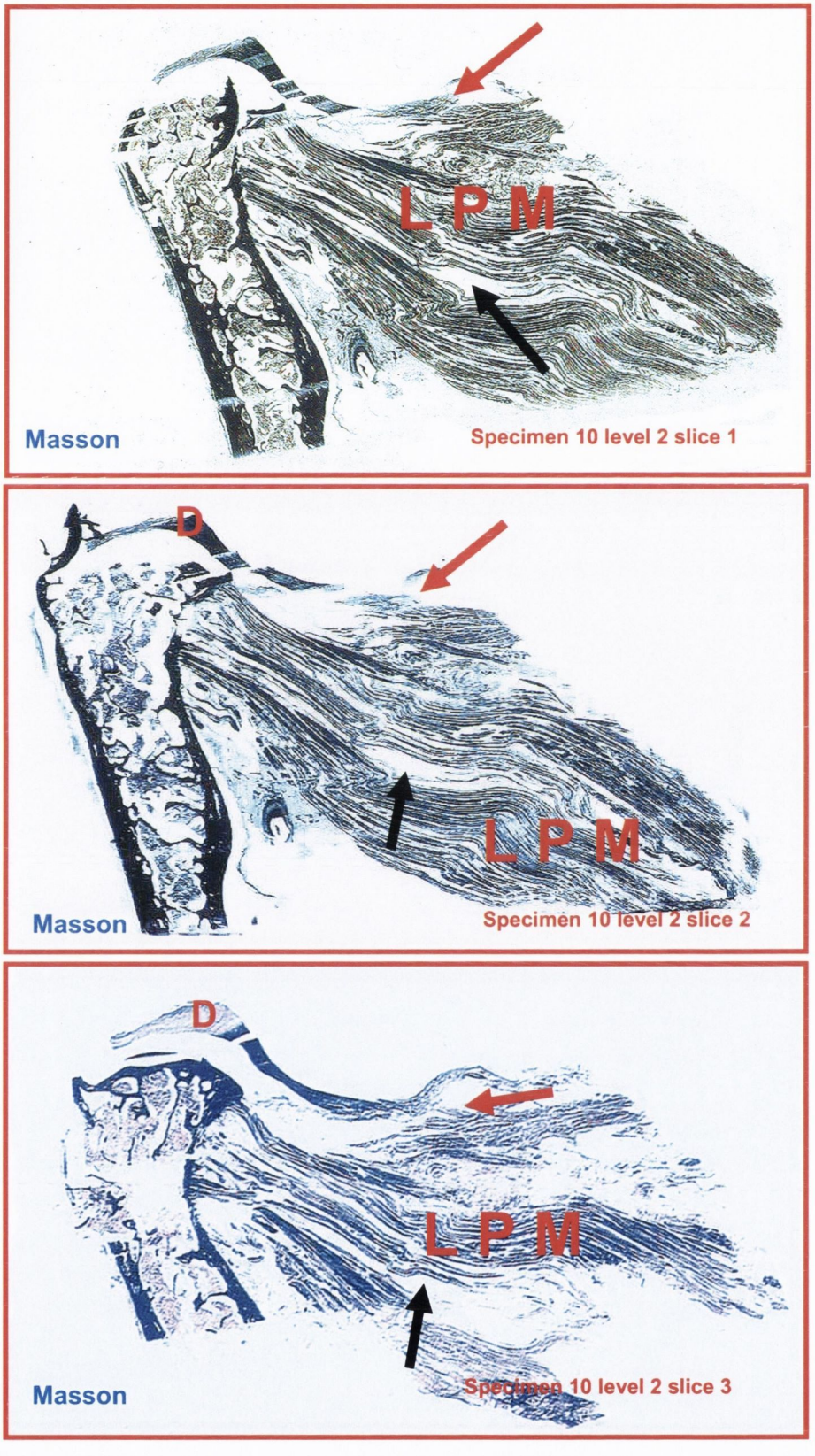


Figure 3.84: Specimen 10, Lateral Pterygoid attachments, level 2, slices 1, 2, 3 (lateral section).

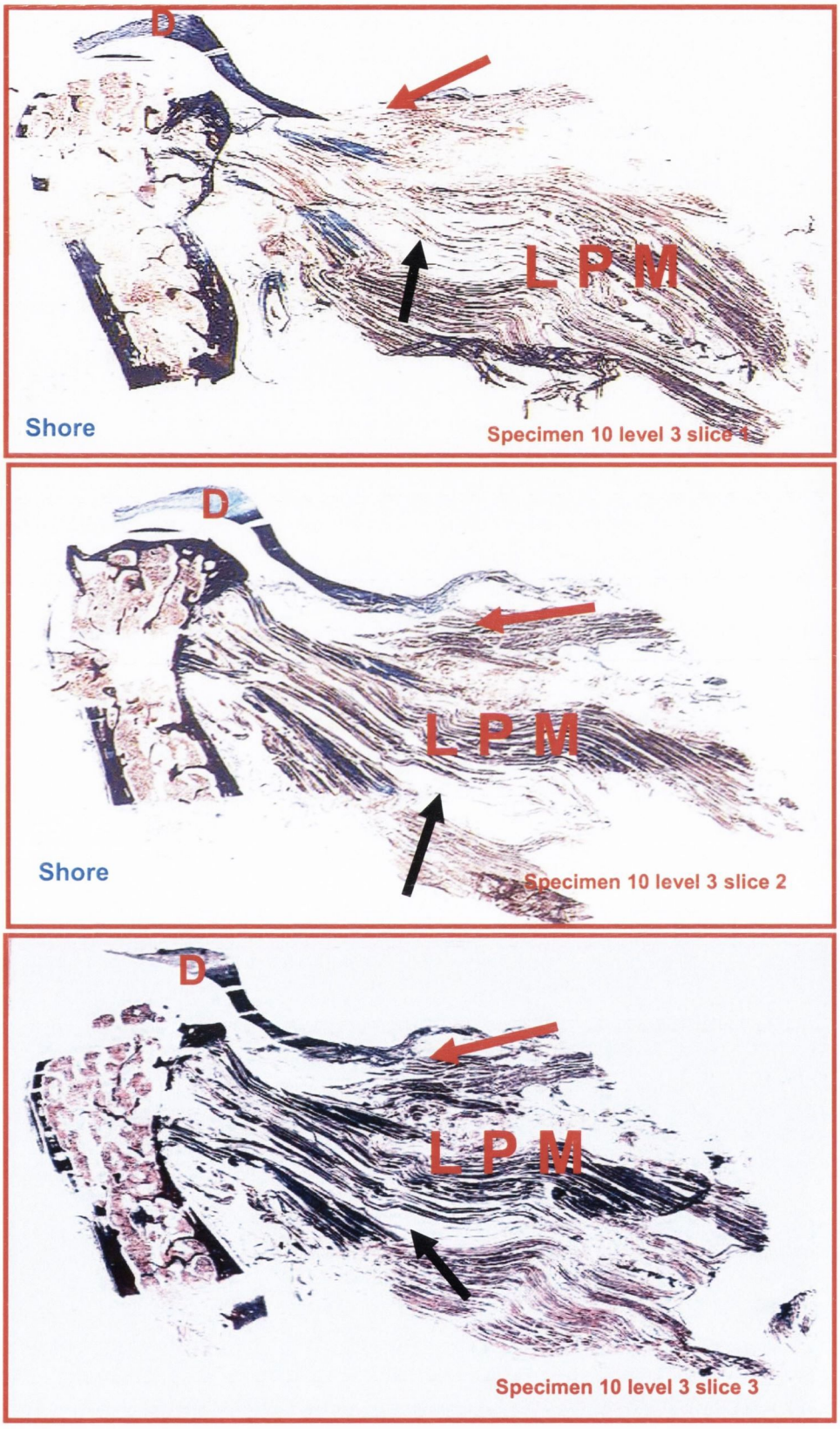


Figure 3.85: Specimen 10, Lateral Pterygoid attachments, level 3, slices 1, 2, 3 (lateral).

3.4.2 Results of histological investigation

Considerable variations were found in the Lateral Pterygoid muscle:

- In most cases the muscle consisted of two heads (Specimens 1, 2, 4, and 9).
- However in two specimens (Specimen 3 and 10), the muscle consisted of one head.

Specimen 9

1. The attachments of the superior head were approximately evenly divided between the disc and the condyle.
2. The fibres from the superior head passing under the disc to be inserted into the neck of the condyle were also attached en route to the inferior surface of the disc.
3. The nature of the attachment to the disc and condyle was mainly muscular, although some of the most inferior part of the insertion, where the two muscles fused was tendinous.
4. By comparison the insertion of the inferior head was predominantly tendinous.
5. An intermediate tendon found in this specimen
6. As the levels of the sections moved from lateral to medial some increase in the mass of both heads was observed, although this decreased again in the deeper sections
7. The shape of the condylar head in profile was rounded /pointed.
8. The disc was intact and well formed in most of the sections.
9. Only a small amount of the Posterior attachment was found in this specimen

Specimen 1

1. The attachment of the superior head was evenly divided between the disc and the condyle, although as the sections moved more medially more fibres were seen attaching to the condyle.
2. The fibres attaching to the condyle were also attached to the under surface of the disc.
3. The nature of the superior head insertion into the condyle was mainly muscular. However in the more medial sections some tendinous attachments were observed.
4. The nature of the attachment of the inferior head was also predominantly muscular.
5. An intermediate was not observed in this specimen.

6. As the levels moved from lateral to medial the amount of muscle mass increased.
7. The shape of the condylar head in profile was rounded pointed.
8. The disc was well formed and intact in most of the sections.
9. The posterior attachment was not seen in this specimen.

Specimen 2

1. The attachment of the superior head in the more lateral sections was predominately into the disc. In the more medial sections the attachments were more evenly divided between the disc and the condyle.
2. The fibres attaching to the head and neck of the condyle were also attached to the inferior surface of the disc.
3. The nature of the attachment of the superior head was muscular into the disc and tendinous into the condyle.
4. The insertion of the inferior head was tendinous superiorly and muscular inferiorly.
5. An intermediate tendon common to both heads was observed.
6. An increase in muscle mass was seen in both heads as the sections moved medially but decreased again slightly in the most medial sections.
7. The shape of the condylar head rounded pointed.
8. The disc was grossly degenerated, only the anterior band being clearly distinguishable.
9. Blood vessels were observed in the postero-inferior portion of the posterior attachment.

Specimen 3

1. The Lateral Pterygoid presented as single muscle mass
2. The most superior fibres were inserted into the disc.
3. The remainder of the muscle was inserted into the head and neck of the condyle.
4. The most superior of these fibres were attached to the inferior surface of the disc.
5. The nature of the insertion into the disc was muscular.

6. The nature of the insertion to the condyle was predominantly muscular except for the most superior part, which was tendinous.
7. No significant intermediate common tendon was observed.
8. The disc was intact throughout the slices, though there was no evidence of thinner intermediate zone.
9. The condyle in profile was rounded blunted with a distinctive beak like osseous growth on its antero-superior aspect

Specimen 4

1. The insertion of the superior head of the Lateral Pterygoid was predominantly into the disc
2. A small number of fibres were attaching to the under surface of the disc en route to the head of the condyle.
3. The nature of the attachment to the disc was muscular, and the attachment to the condyle was tendinous.
4. A slight increase in muscle mass was observed as the slices moved to the medial
5. The nature of the attachment of the inferior head to the condyle was predominantly muscular but partly tendinous.
6. A small intermediate tendon shared by both heads was observed.
7. The disc was grossly degenerated and presented as horizontal collagenous strands, rather than compact discal tissue.
8. Blood vessels were identified in the posterior attachment just postero-inferiorly to the posterior band of the disc.
9. The neck of the condyle was not captured in the histology sample, but the condylar head was rounded pointed in profile, with a small osteophytic projection on its' most antero-superior aspect.

Specimen 10

As the medial portion of this specimen was very fragile and did not give satisfactory results, some sections were also taken from the lateral portion.

Medial Portion

1. The two heads of the Lateral Pterygoid presented as one muscle mass.
2. The most superior fibres of the muscle were passing under the disc and into the head of the condyle. These fibres were also attached to the inferior surface of the disc.
3. The remainder of the muscle was inserted into the condyle.
4. The nature of the insertion was predominantly muscular.
5. No intermediate tendon was observed
6. The shape of the condylar head in profile was rounded pointed.
7. The disc was badly damaged in this portion.
8. The posterior attachment was not present in this specimen.

Lateral Portion

1. The two heads of the lateral presented as one muscle mass
2. Some fibres were found inserting into the disc, but the attachments were mainly the same as those seen in the medial portion.
3. Fibres attaching to the condyle were in the main not attached to the under surface of the disc.
4. A small space was identified in the central portion of the muscle, which had been found macroscopically to be occupied by the pterygoid plexus of veins.
5. The disc was in better condition in this portion.
6. As the slices moved from medial to lateral there was some reduction in muscle mass
7. The condylar profile was rounded/pointed.
8. Posterior attachment was not seen in this specimen.

3.4.3 Conclusions from the Histological Study

The main purpose of the histological study was to assess the proportion of fibres of the superior head of the Lateral Pterygoid, which inserted into the disc as opposed to that, which inserted into the condyle. Macroscopically the superior head in all cases appeared to be predominantly inserting into the disc. However on histological evaluation in some instances the superior head was found to be inserting directly into the disc, but in others the fibres were seen to be passing under the disc and inserting into the head/neck of the condyle.

Broadly speaking the ratio of fibres inserting into the disc and condyle respectively was 1:1, but these proportions varied from specimen to specimen, and also at different levels in the same specimen. For example specimens numbers 4 and 9, showed fibres inserting into the disc and condyle in almost equal proportions. However in specimen number 1, the insertion of the superior head was more or less equally divided between the disc and condyle in the lateral sections, but in the more medial sections the number of fibres, which inserted into the condyle slightly increased.

Specimen number 2 was somewhat unusual in that the more slices showed most of the fibres of the superior fibres passed under the disc en route to inserting into the condyle and the more medial slices a proportion of these fibres were inserting directly into the disc. In specimen 10, where the muscle presented as a single head some of the most superior fibres were attached to the disc and some were passing under the disc to be attached to the head of the condyle. As the medial slices in specimen 10 were not of a good quality due to the friability of the tissue, it was decided to take some slices from the lateral portion of the specimen.

Here it was found that more fibres were inserting directly into the anterior extremity of the disc, as well as those inserting into the condyle.

It was also noted that in the situations where fibres of the superior head (or single head) were passing under the disc to be attached to the condyle, they were also attached horizontally to the inferior surface of the disc, en route to their condylar insertions.

The nature of the insertions of the two heads of the Lateral Pterygoid also varied. In specimen 1 both heads were predominantly muscular, with a very narrow shared tendon observed in some of the slices. In specimen 2 the superior head insertion was muscular into the disc, and tendinous into the condyle. The inferior head was muscular inferiorly and tendinous superiorly.

Specimen 3, which consisted of a single head, had an insertion, which was almost entirely muscular except for a small tendinous insertion into the condyle.

In specimen 4 both heads were predominantly muscular, but the inferior head had a narrow tendon in its' upper part.

In specimen 9 the superior head was predominantly muscular, and the inferior head was predominantly tendinous.

Specimen 10, which consisted of a single head, had an almost entirely muscular insertion, with some narrow tendinous insertions centrally.
The condylar head profiles were predominantly rounded pointed, with one of the specimens (specimen 3) having a pronounced pointed profile due to remodelling. There was also some remodelling evident in specimen 4.

It was possible only to retain the most anterior portion of the posterior attachment due to cassette size restrictions. In the specimens where some of the posterior attachment was retained there was some evidence of vascular tissue just posterior and inferior to the posterior band of the disc.

3.5 Lateral Pterygoid and Anterior Disc Displacement

The activity of the Lateral Pterygoid muscle has been implicated in anterior displacement of the disc.
One proposed mechanism causing displacement in the whiplash event is that the superior head of the Lateral Pterygoid attempts to hold the disc in an anterior position while the condyle is moving rapidly posteriorly during mouth closure (Pringle 1918, Wakely 1948, Weinberg & Lapointe 1987). It is postulated that this challenges the strain rate capacity of the attachment of the disc to the lateral pole of the condyle.
Another proposed mechanism is that hyperactivity of the superior head of the Lateral Pterygoid causes detachment of the disc at the lateral pole due to gradual breakdown or to lengthening of the collagen fibres of the attachment (Weinberg & Lapointe 1987, Moffet & Westesson 1984). However other workers claim, that the attachment of the superior head of the Lateral Pterygoid to the neck of the condyle as well as to the disc, makes the above claims mechanically non-viable.

Carpentier et al (1988) refute claims that the superior head can be instrumental in tearing the disc from the head of the condyle, stating that the fibres inserting into the head of the condyle will protect the disc from this occurring. A number of workers have supported this claim (Mahan 1980, Wilkinson 1988, Wilkinson and Chan 1989).

While the above counter-claim would appear to have some validity it does not fully address the problem. Forces applied to the disc via the superior head of the pterygoid will certainly be modified by attachments of the muscle to the head of the condyle. However the issue, which needs to be addressed, is whether the division of forces between the disc and the condyle leads to a resultant, which is greater than the force of attachment of the disc to the lateral pole of the condyle, at which point detachment often occurs (Leopard 1984).

It was decided therefore to theoretically evaluate the possibility of disc displacement when a unit force was administered with varying proportions of fibres inserting into the disc and condyle respectively. This was achieved by carrying out a mechanical analysis, in which varying proportions of fibres inserting into the disc and condyle respectively were represented by springs of differing stiffness.

3.5.1 Spring Analysis of the Pterygoid Attachments

An assessment was made of the injury potential to the attachment of the disc to the condyle, for different anatomical variations in the insertions of the Lateral Pterygoid muscle. This was carried out by making a mechanical analysis in which the muscle insertions were represented by springs of differing stiffness. The muscles, which act on the condyle and on the disc, may be simplified for the purposes of elementary analysis to the following 2-dimensional representation, showing the contribution of the primary muscle systems. The muscles are modelled by springs of stiffness applied along their long axes (Figure 3.86).

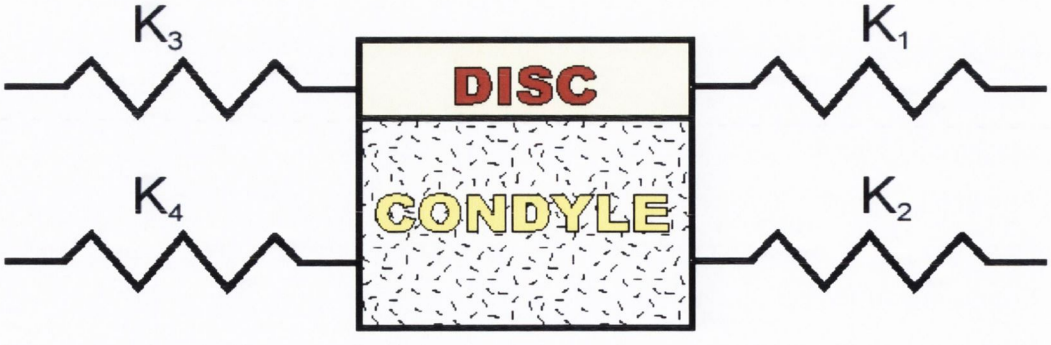


Figure 3.86: Schematic of condyle, disc, and soft tissues used in analysis

K_1 = superior head of the Lateral Pterygoid muscle

K_2 = inferior head of the Lateral Pterygoid

K_3 = elastin fibres of the posterior attachment

K4 = muscles which are involved in returning the condyle to the glenoid fossa viz. the masseter, medial pterygoid, and temporalis, and the influence of other soft tissues.

In equilibrium, before any rapid movement (closed position), it may be assumed that the forces applied by the muscles are balanced in the horizontal (x) and in the vertical (y) direction (Figure 3.87).

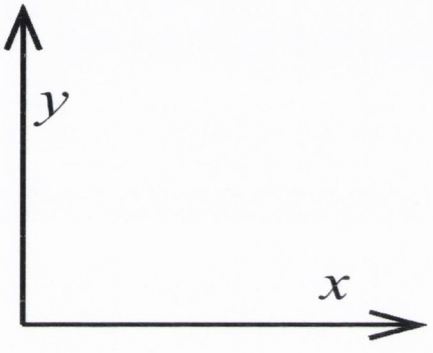


Figure 3.87: Co-ordinate system used in spring analysis

For this state of equilibrium to be achieved, the sum of forces in springs K_1 and K_2 in the X direction must be equal to the force in K_3 + K4 since K_3 and K4 act in the opposite direction to K_1 and K_2. It should be noted that K_3 contributes little to this force in the positive X direction due to the weakness of the elastin fibres, which is its main constituent (Mahan 1980). There is a build up of kinetic energy in the springs to the tension of K_3 and K4 and theoretically in the compression in K_1 and K_2. It should be noted that K_3 has a very low stiffness value and therefore applies very little force to the top of the disc, which is attached to the head of the condyle.

Analysis of the System - Assumption No. 1

In this example it is assumed that the superior head of the Lateral Pterygoid is attached only to the disc (Figure 3.88). Allowing a translation of one unit hyperextension, and taking the relative stiffness to be as follows in the equilibrium state, the sum of the forces in the X direction can be calculated using the formula:

$F = Kd$

Where: F = force

K = spring stiffness

d = the extension/compression of the spring.

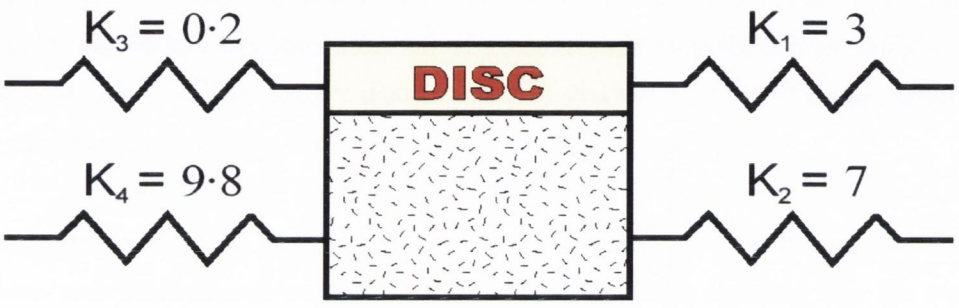


Figure 3.88: Schematic representation of assumption no.1

$K_1 = 0.3$

$K_2 = 0.7$

$K_3 = 0.2$

K4 = 9.8

The relative values assigned to K_1, K_2, K_3 and K4 are based on their relative sizes found from dissection. The strength of the muscle was assumed to be proportional to its measured cross-sectional area.

Calculation of the forces for the condyle and the disc

For the condyle: 9.8(K4) x 1 - 7(K_2) x 1 = 2.8

For the disc: 0.2(K_3) x 1 - 3(K_1) x 1 = -2.8

Therefore there was a difference of 5.6 units in the force guiding the mandible back to the fossa, and the force guiding the disc back to the fossa. It follows therefore that the force of the attachment (N) between the condyle and the disc would have to be greater than this to prevent relative motion between both assuming perfect attachment, according to the equation:

$F = \mu N$

Where F = nett force acting on the system

μ = Coefficient of friction/degree of attachment

N = normal reaction force/force of attachment between bodies.

Assuming $\mu = 1$, the force of the attachment must be at least 5.6 force units in magnitude, i.e. almost as strong as K4 to prevent overstretching and tearing of the attachment between the disc and the condyle.

The above statement will depend on the nature and the magnitude of the particular accident. In some instances the force of the attachment may be sufficient to resist the force of K4.

Assumption No. 2

In the second example it was assumed that the fibres of the superior head of the Lateral Pterygoid are attached to both the disc and to the condyle (Figure 3.89). Mahan (1980) reported that a large number of fibres are inserted into the condyle, and Wilkinson (1988) stated that 80% of the fibres of the superior head are inserted into the condyle. Our own findings show the attachments of the superior head are to the disc and the condyle in varying proportions.

The spring stiffnesses are therefore given as follows:

$K_{1\,(1)} = 0.6$, $K_{1\,(2)} = 2.4$, $K_2 = 7$, $K_3 = 0.2$, $K4 = 9.8$

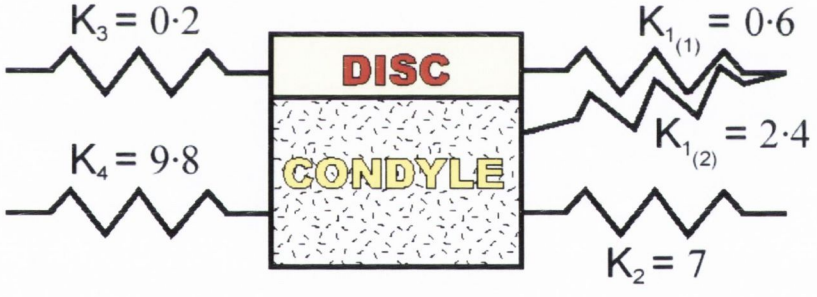


Figure 3.89: Schematic representation of assumption 2

The returning force for the condyle and the disc can be calculated as follows:

For the condyle: 9.8(K4) x 1 - 2.4(K1 (2)) - 7(K2) x 1 = 0.4

For the disc: 0.2(K3) x 1 - 0.6(K1 (1)) = -0.4

Therefore there was a difference of 0.8 units between the force returning the condyle to the fossa, as opposed to the force returning the disc to the fossa. In this instance therefore the integrity of the attachment between the disc and the condyle would be tested to a lesser degree, than in assumption 1.

Clearly the additional fibres of the superior head, which are attached to the neck of the condyle, modify the rate at which the condyle is returned to the fossa. However, the differential between the force returning the condyle to the fossa and that returning the disc to

the fossa is still considerable, particularly when it is remembered that the forces acting to carry the disc posteriorly, are close to zero.

3.5.2 Conclusions from the Spring Analysis

In both situations analysed K4 exerts a relatively large force on the system. Since K4 is acting on the condyle in guiding it back to its original position, this returning force causes the mandible to be pulled back at a much greater rate than the rate at which the disc is returned. Thus the combined force in the X direction is much greater for the condyle, than for the disc.
In assumption No. 2 the effect of K4 is modified so that it travels back to the fossa at a lower rate, which will decrease the differential between the returning force for the condyle and the disc. However the combined force in the X direction is still considerably greater for the condyle than for the disc.
There are two possible consequences to the above events:

- If the force is minimal the attachment of the disc to the condyle may remain intact.
- If the force is of sufficient magnitude to challenge the strength of the attachment of the disc to the condyle, partial or total separation of the disc to the condyle may result.

Therefore it can be stated that the attachment of the superior head of the Lateral Pterygoid to the condyle may modify the force to which the discal attachment to the condyle is subjected. However whether this modification is sufficient to prevent disruption of the attachment is open to question. This may be dependent on the force, which is generated in a particular accident. Furthermore it may be that some individuals are more susceptible to TMJ damage in this type of accident than others due to anatomical variations in the attachments of this muscle or due to previous damage, which has compromised the attachment of the disc to the condyle.

The above analysis does not consider the indirect attachment of the superior head to the under surface of the disc en route to insertion into the head of the condyle. These fibres would add to the force tending to displace the disc from the condyle. This is subject matter for further research.
In cases where the Lateral Pterygoid consists of one muscle mass the proportion of fibres inserting into the mandible would be overwhelmingly greater than those inserting into the disc and displacement of the disc would consequently be very unlikely.

Thus the disc may be displaced antero-medially as a result of a relatively minor tear in the attachment of the disc to the lateral pole of the condyle, leading to minimal displacement of the disc. If this is followed by chronic muscle hyperactivity, lengthening of the collagen tissue may lead to displacement of the disc over a period of time without a major rupture having taken place at the time of the initial insult.

Furthermore even loading, which would be normal in circumstances where the soft tissue support was in perfect condition, may become overloading in circumstances where partial damage has occurred. The TMJ is a more difficult joint to rest than other joints in the body, without taking extreme measures such as wiring the upper and lower jaws together to completely immobilise the mandible. The TMJ as opposed to other joints is an essential prerequisite to normal daily routine and is involved in many activities apart from eating. Thus during an individuals waking hours the jaw muscles are in an almost constant state of activity. This may explain why a number of post accident cases report clicking and locking of the TMJ at some time after the accident.

Chapter 4 Forces Sustained by the Temporomandibular Joint in Whiplash

4.1 Introduction

The purpose of this chapter was to categorise the various forces affecting the temporomandibular joint (TMJ) in the retroflexion and flexion phases of the whiplash event. During these movements forces resulting from linear acceleration, angular acceleration and gravity act across the TMJ. These forces were calculated separately and then summed, so that the resultant force could be shown at a particular time in the event.

The forces were assessed according to established principles of physics, being based on Newton's laws of motion. A brief review of the Newtonian principles, together with some basic definitions is therefore included for readers not familiar with the principles of mechanics*.

The aim of this work was to obtain a first estimate of the acceleration and forces involved, which would provide a basis for further research and to identify the various types of soft tissue damage, which might occur as result of this complex series of movements.

The calculations carried out in this work have relied on certain previous work found in the literature, in particular that of Clemens and Burrows (1972) Schneider et al (1989) and Merlini & Palla (1989).

Very little previous work has been carried out on this subject. Schneider et al (1989) looked at the dynamic response of the human jaw resulting from a 15mph rear impact and predicted mouth opening of 67^0. No estimate of the forces was made in their work.

West et al (1993) made visual observations of volunteers who were subjected to low velocity rear impacts and concluded that no mouth opening occurred and thus minimal forces were sustained by the TMJ.

In a similar study Szabo et al (1994) performed 10 mph rear impacts on volunteers and his findings were in agreement with West et al (1993) concerning the TMJ.

*See Appendix C

Both of these studies overlooked the important prerequisite that if the subject is aware of the imminent impact the craniomandibular muscles will tense keeping the lower jaw and cranium essentially as one body thus precluding mouth opening.

McConnell et al (1995) recorded no mouth opening from tests carried out on volunteers in a 5.5 mph Δv (post-impact velocity) rear impact. However the subjects in these tests were wearing bite blocks on their upper and lower teeth, which again would encourage jaw clenching.

Howard and Benedict (1991) in a rebuttal to the concept that injury to the TMJ is possible in "whiplash" state that the forces sustained by the joint in such an event are predominantly compressive. They calculated that these forces are far less than those which occur during normal chewing. Howard and Benedict (1991) state that "at no time in the extension –flexion maneuver is there an absolute rearward motion of the head and no significant tensile forces are generated across the temporomandibular joint, thus precluding the hypothesized mechanical tearing of the joint attachments. Howard and Benedict are correct in claiming that no absolute linear movement of the cranium takes place but absolute angular displacement of the cranium does occur and results in mouth opening causing tensile forces on the joint soft tissues. Howard and Benedict also make the incorrect supposition that the individual would have his/her teeth clenched during the event implying that there was prior warning to the impact.

Furthermore to make comparison between forces occurring in "whiplash" and those occurring during normal chewing/biting is not valid. The forces which are sustained by the TMJ soft tissues in "whiplash" are essentially tensile in character whereas the forces generated during functional chewing/ biting are essentially compressive in nature.

A clear distinction needs to be made between the act of chewing/ biting, which is a conscious voluntary act and is functioning well within the spatial and temporal physiological limits of the individual, with the neuromuscular feedback protective mechanisms functioning optimally. In "whiplash" however the event is involuntary with an event being imposed upon the individual, which is outside their spatial and temporal physiological limits.

It was assumed in this analysis that the cranium and mandible were in a 'pseudo static' state. This did not take into account the dynamic properties of the various soft tissues (e.g. muscles and ligaments), which connect the mandibular condyle to the cranium. Thus only the inertial properties of the cranium and mandible were considered. Including the damping effects of the soft tissues will embellish this basic analysis in the future. Theoretical and experimental work is currently being carried out in this area and will be published at a later date (See chapter 6).

4.2 Division of Forces on the TMJ in Whiplash

Figures 4.1(a) and 4.1(b) show the cranium and mandible in the rest position prior to retroflexion. During head retroflexion the cranium rotates backwards, away from the mandible, which tends to stay behind due to its inertia. During flexion the opposite occurs, the head rotating toward the mandible.

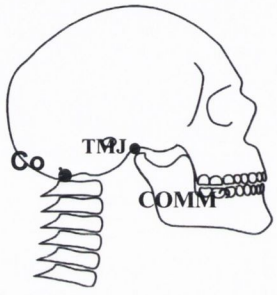


Figure 4.1(a): Anatomical diagram of mandible, TMJ, Co, and cranium at rest. Co=centre of rotation of cranium on first cervical vertebra

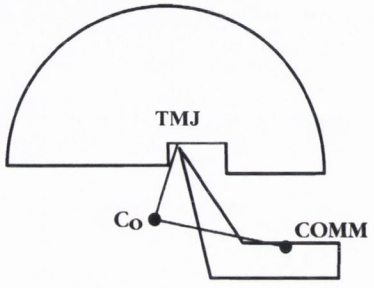


Figure 4.1(b): Schematic of cranium, mandible, Co, and TMJ in the rest position. COMM=Centre of mass of mandible

A pseudo-static analysis was performed in order to predict the forces and stresses on the temporomandibular joint, in retroflexion and flexion. To do this, the whiplash event was divided into phases in time, and the various forces occurring in each phase calculated. Where appropriate the forces were summed to find the nett force at a given time.

Initially constant acceleration was used in the calculations to obtain an approximation of the force magnitudes. This was followed by force calculations using variable acceleration to obtain more accurately the peaks in force magnitude and relate them to the strain rate characteristics of the various tissues.
The analysis was carried out under two main headings:

- **Forces in the retroflexion phase.**
- **Forces in the flexion phase.**

4.2.1 Forces on the TMJ in the Retroflexion Phase

After impact there is a time lag of approximately 100ms during which compression of the car seat, and occupant's back and torso occur. The torso is then accelerated forward leading to relative movement between the head and torso. This is achieved by a translatory movement in the lower segments of the cervical column, lasting for 30-40ms, and followed by rotation of the head (Clemens and Burrow 1972). The rotation of the head in retroflexion is complex. It is an absolute movement and lasts for 70-100ms depending on the impact velocity. As the head is rotating in

retroflexion the mandible due to its' inertia is attempting to remain behind (Figure 4.2).

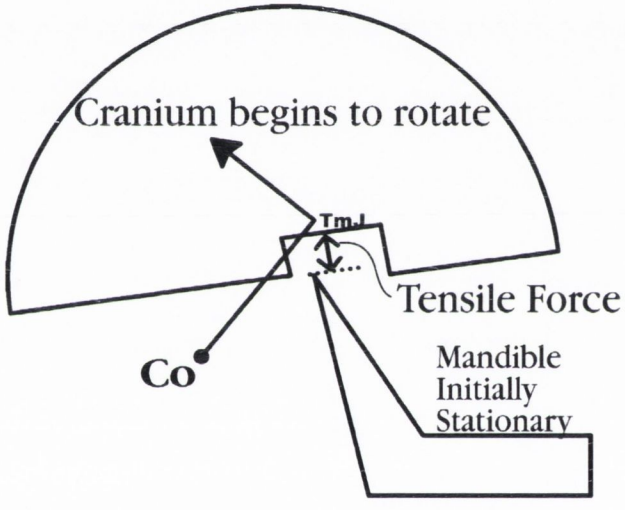


Figure 4.2: Forces reacting in tissues connecting the cranium to the mandible as the cranium rotates away from the mandible in retroflexion

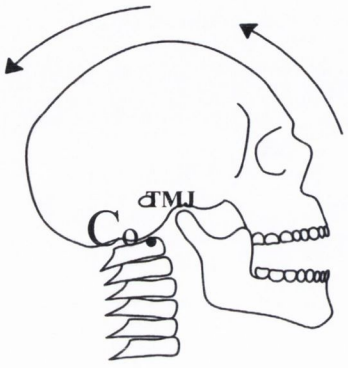
The centre of rotation is changing throughout the movement, being shared by the Vertebrae of the Cervical Spine. The length of the radius from the centre of rotation to the TMJ is critical in the calculation of the forces due to angular acceleration. Using the distance from C_o to TMJ as the length of the radius is probably therefore an underestimation of these forces.

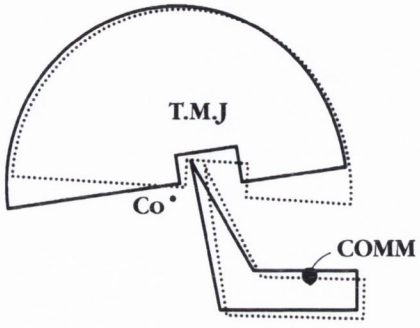
Retroflexion of the cranium consists of a combination of translation and rotation of the cranium / cervical spine complex. Translatory movements of the cervical vertebrae do not affect the TMJ and therefore only the forces, which result from cranial rotation, are being considered here.

Three distinct forces can be identified during the retroflexion stage:

(a) Forces on TMJ due to pulling effect of the cranium during retroflexion.

These are termed F1a1 (using constant acceleration) and F1a2 (using variable acceleration).





4.3(a) *4.3(b)*

Figure 4.3(a): Diagram and 4.3(b): Schematic representation of the first stage in mouth opening due to whiplash.

The cranium is rotating away from the mandible resulting in mouth opening

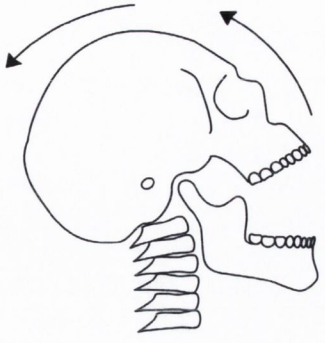
(b) Forces on TMJ due to relative rotation of condyle during mouth opening.

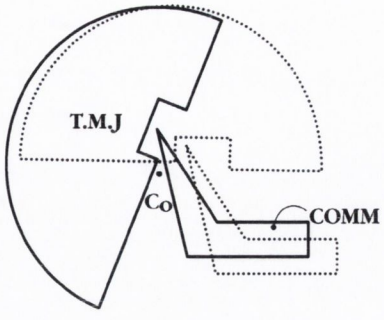
These are termed F1b1 and F1b2. During this phase the centre of mass of the mandible (COMM) tends to remain in the same horizontal plane due to its inertia. This causes mouth opening. The centre of rotation for mouth opening is at the TMJ inter-condylar axis. Mouth opening forces due to rotation therefore occur (Figures 4.3a and 4.3b). At this stage of the event both pulling forces and forces due to rotation are occurring.

(c) Forces on TMJ due to linear displacement of condyle during mouth opening.

These are termed F1c1and F1c2. After approximately 15° of mouth opening, biomechanical constraints impose a translatory (linear) movement on the mandibular condyle (Osborne 1985, McDevitt 1989), thereby creating linear forces, which are related to the angle of mouth opening. The biomechanical constraints are described in the anatomy chapter. From this point mouth opening is completed by a combination of rotation and translation (Figures 4.4a, 4.4b, 4.5a, and 4.5b). The rotation consists of angular displacement of the cranium on the mandibular condyle, while translation consists of absolute linear movement of the condyle on the cranium. During this stage of the event, pulling, rotation, and linear forces are all

occurring simultaneously. Each of these forces varies with time, the nett force at any given time being the vector sum of these individual forces.



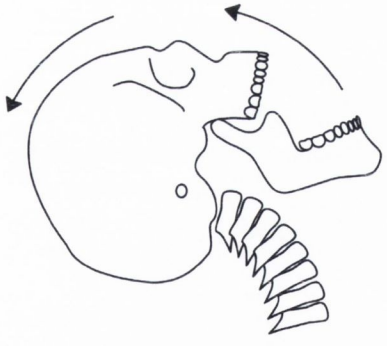


4.4(a) *4.4(b)*

Figure 4.4(a): and 4.4(b): Anatomical diagram and schematic of second phase of mouth opening.
The condyle translates on cranium, while rotation of the cranium continues

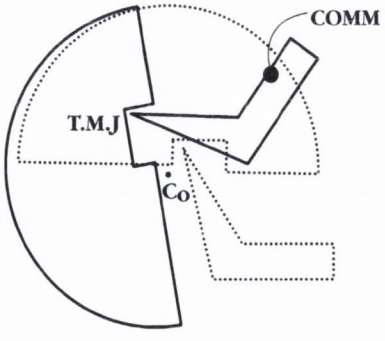
4.2.2 The End of Retroflexion

Mouth opening is completed after approximately 70° of head retroflexion. At the end of mouth opening, if the predictions of Schneider et al (1989)* are fulfilled, the mandibular condyle comes into contact with the soft tissues lying behind the posterior wall of the maxilla. However head retroflexion continues after mouth opening has been completed. The position of the condyle relative to the posterior aspect of the maxilla is maintained until head retroflexion is completed. The mandible then rotates away from the horizontal plane.



4.5(a)

Figure 4.5(a): Anatomical diagram of the end of mouth opening in whiplash



4.5(b)

Figure 4.5(b): Schematic illustrating the end of mouth opening in whiplash

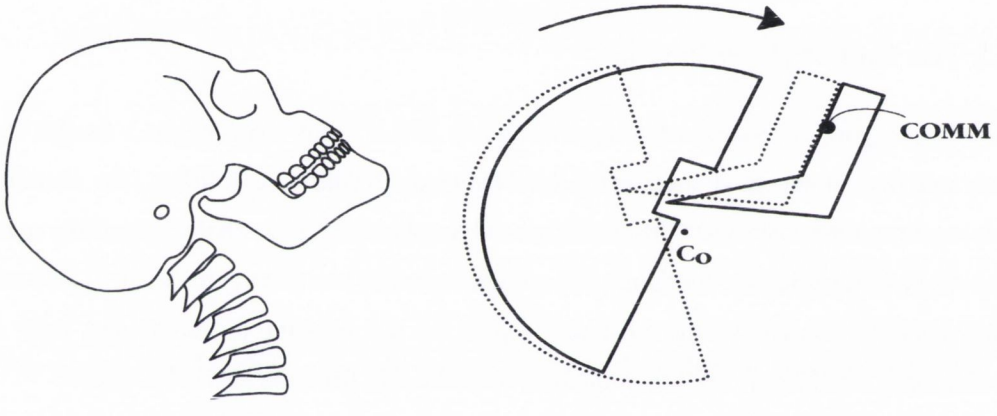
*See reference previous chapters

4.2.3 Forces on the TMJ in Flexion Phase

At the end of retroflexion the build up of potential energy in the neck tissues is converted into kinetic energy and the head is thrown forward into flexion. Forces occurring in this phase can be classified in the same way as those in the retroflexion phase.

(a) Forces due to the pushing effect of the cranium on the TMJ (F2a1 and F2a2)

As the cranium is rotating forward towards the mandible, there is a pushing force on the condyle (Figures 4.6a & 4.6b). This is analogous to the pulling forces occurring in retroflexion (Forces 1a1 and 1a2).



4.6(a) *4.6(b)*

Figure 4.6(a): Diagram and 4.6(b): Schematic representation of mouth closing due to rotation of the cranium on to the mandible, which creates pushing forces on the TMJ
The dotted line indicates the position of cranium and mandible at the end of retroflexion

(b) Forces due to rotation of the condyle in mouth closing (F2b1 and F2b2)

These are analogous to the mouth opening forces, occurring in retroflexion (Forces F1b1 & F1b2)

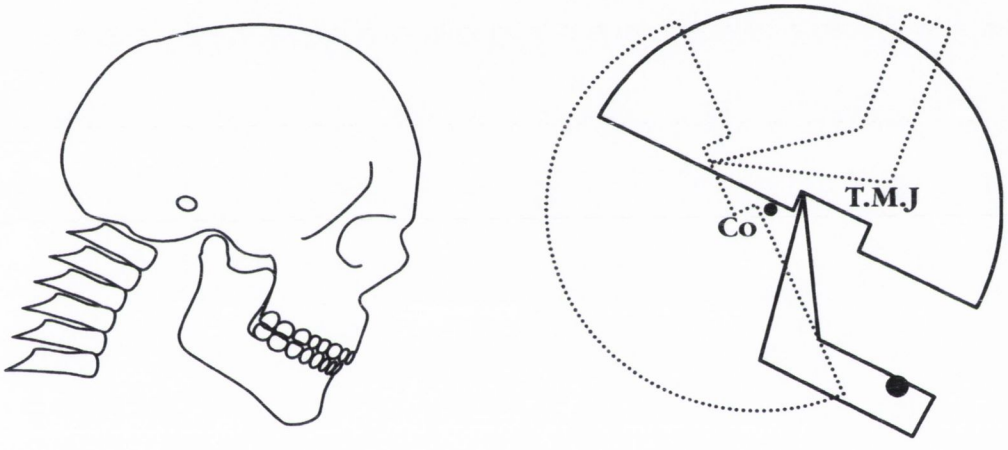
(c) Forces due to posterior translation in mouth closing. (F2c1 and F2c2)

These forces are analogous to the forces, occurring, in anterior translation (F1c1, &1c2).

As can be seen from figure 4.6 the mandible has moved away from the horizontal in retroflexion. Therefore, mouth closing is completed before the mandible has returned to the horizontal plane. Thus pushing forces continue after mouth closing has been completed.

4.2.4 The End of Flexion

At the end of mouth closing, the condyle makes contact with the tissues in the posterior part of the glenoid fossa (Figures 4.7a and 4.7b) The calculation of this stopping force due to both linear and angular acceleration was not carried out here, due to a lack of information regarding the time taken for stopping to occur. This calculation will be performed when data is available from experimental work, which is the subject of future work.



4.7(a) *4.7(b)*

Figure 4.7(a): Diagram and 4.7 (b): Schematic of the end of flexion with the condyle impacting the posterior wall of the glenoid fossa

4.3 Measurements, Weights, and Trigonometrical Data

Before force calculations could be made, basic data regarding the spatial relationship between C_o, the centre of mass of the mandible, and the TMJ were needed.

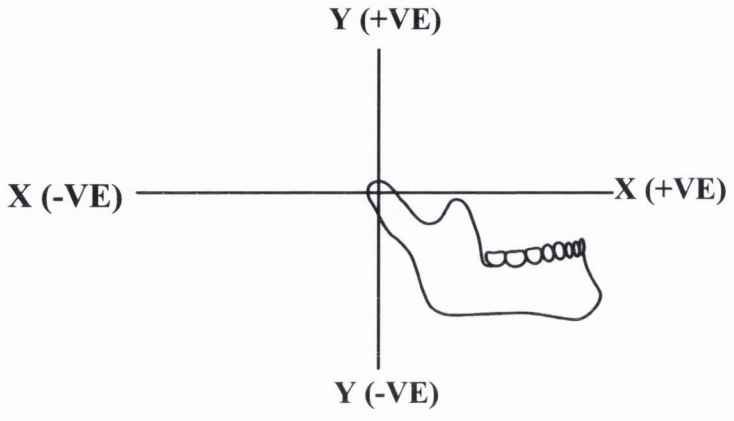


Figure 4.8: The x, y co-ordinate system for measurements and trigonometrical data.

The following measurements were made on three dried adult human skulls: -

- Centre of Mass of Mandible (COMM) locations with reference to the horizontal (x) axis and vertical (y) axis passing through the centre of rotation of the TMJ. The intersection of the lines of gravity when the mandible was suspended from two or more different points was taken as the centre of mass of the mandible. * The axes for the x, y co-ordinate systems were oriented as shown in figure 4.8.

Other data needed were as follows:

- The distance from the COMM to the TMJ (Centre of rotation).
- The distance from the COMM to C_o.
- The dry mass of the mandible.

These were found by measurement and simple Trigonometry, and the mean values were calculated (Table 4.1 and Figure 4.9).

*See appendix D

Material	COMM to x axis (mm)	COMM to y axis (mm)	COMM to Co (mm)	COMM to TMJ (mm)	COMM/Co/x-axis angle (deg)
Skull 1	44	54	70	32	20
Skull 2	51	52	73	34	15
Skull 3	53	55	75	36	14
Mean value	**49**	**54**	**73**	**34**	**16.3**

Table 4.1: Data taken from skulls for use in force calculations

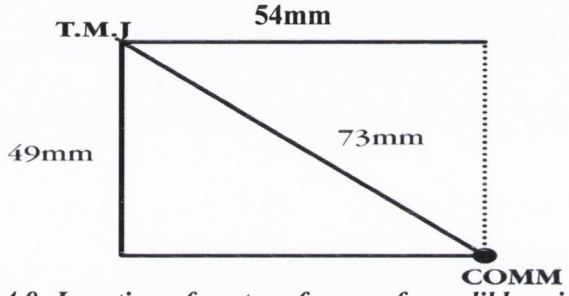


Figure 4.9: Location of centre of mass of mandible using mean values

From these data the following trigonometrical calculations were needed to make force calculations (Figure 4.10).

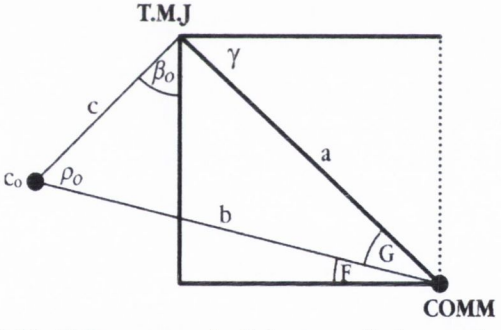


Figure 4.10: Trigonometrical data needed to make force calculations

Line a = distance from CO.M.M to TMJ= 73mm

Line b = distance from COMM to Co =71mm

Line c = distance from C_o to TM.J= 34mm

ε_o =47.2°

β =35.5°

θ_o =70.8°

F =16.3°

G =26.5°

The figures obtained by the above measurements compare closely to those of Schneider et al (1989), who found a value of 74.7mm, for the distance from COMM to the TMJ (x axis reference = 65.8mm., y axis reference - 35.4mm.) They did not supply figures for the distance from COMM to C_o or from C_o to TMJ intercondylar axis. With regard to the figures found for the dry mass of the mandible, it was found that this varied considerably from individual to individual (Table 4.2). A reliable method of relating dry to wet mass of the mandible was not available. This mass is a critical factor in determining the magnitude of the forces. It was therefore decided to use the value of 0.162 Kg., which Schneider et al (1989) obtained from a fresh adult male cadaver.

4.3.1 Frankfurt Plane

The Frankfurt plane is one of a number of cephalometric planes. It is a horizontal plane, which lies along a line extending from the upper border of the external auditory meatus to the lower margin of the orbital rim. When the head is in an upright position with the eyes looking straight ahead, the Frankfurt plane is horizontal.

The Frankfurt plane is the major reference plane, and the X-axis taken lies parallel to this (Figure 4.11).

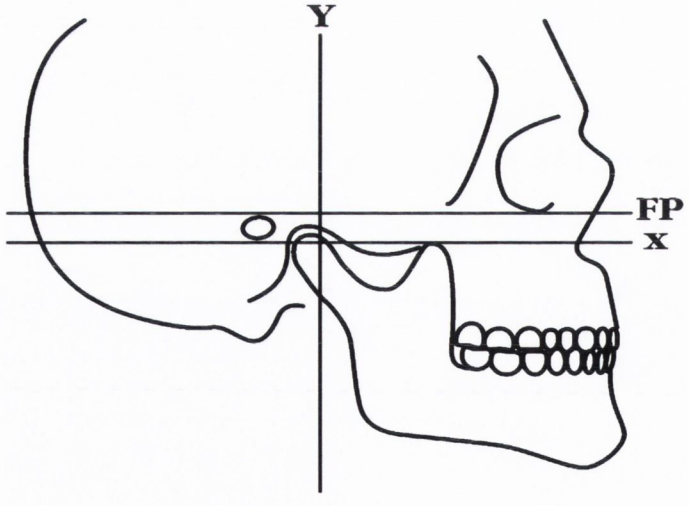


Figure 4.11: The Frankfurt plane co-ordinate system used in the calculations

The angle of the posterior slope and anterior slope of the articular eminence, with reference to the Frankfurt plane, was also needed in the calculation of the forces. Three human skulls were examined and measurements of the angles between the posterior and anterior slopes of the articular eminence with the Frankfurt plane were made. The mean values were thus calculated (Table 4.2 and Figure 4.12).

Material	Angle of post slope to F.P. (deg)	Angle of anterior slope to F.P. (deg)	Dry mass of cranium (g)	Dry mass of mandible (g)
Skull1	**51**	**28**	**540**	**91**
Skull 2	**46**	**30**	**499**	**64**
Skull 3	**55**	**28**	**562**	**64**
Mean value	**51**	**28**	**534**	**73**

Table 4.2: Mean values for slopes of articular eminence with reference to Frankfurt Plane and for dry mass of the Mandible and cranium.

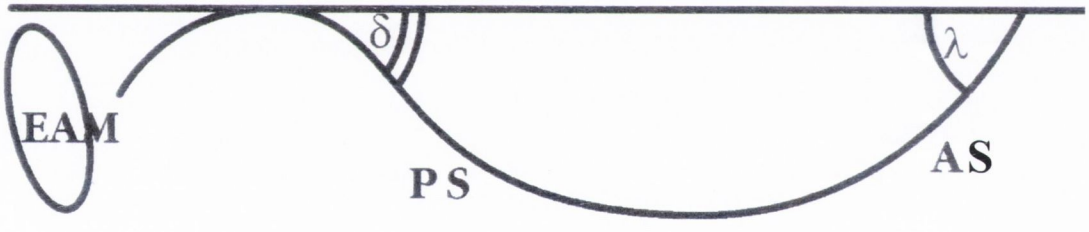


Figure 4.12: Schematic of the relationship between the posterior slope (PS) and anterior slope (AS) of the articular eminence with reference to the Frankfurt plane.

4.4 Effect of Gravity on Force Calculations

The force due to gravity (mg) is constant. However its influence on the forces described above is changing during head retroflexion and flexion. Thus in this "pseudo static" analysis gravity is effectively rotating. The forces are therefore affected by gravity in the following manner.

4.4.1 Effect of gravity on pulling/pushing force calculations

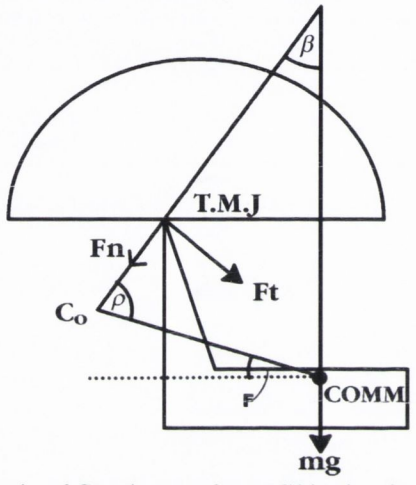


Figure 4.13: Schematic of Cranium and mandible showing how gravity affects the Normal and tangential components of pulling forces

During retroflexion the cranium is rotating around C_o. The force acting across the TMJ due to this rotation can be found by calculating the tangential force (F_t), which is due to angular acceleration, and the normal force (F_n), which is due to angular velocity. *

The force acting on the mandible due to gravity is acting through its centre of mass. To evaluate how this affects the pulling/pushing forces, mg was resolved into components acting along the same planes as F_t and F_n (Figure 4.13). Thus when calculating the pulling forces, the contribution of gravity to F_n is $mg\cos\beta$, which is added to F_n as they are acting in the same direction. The contribution of gravity to F_t is $mg \sin\beta$. This is added to F_t as it is acting in the same direction at the start of retroflexion when $(\rho - F)$ is less than 90°. During retroflexion however the TMJ moves so that the angle ρ increases. When $(\rho - F) > 90^\circ$, F_t and mg are acting in opposite directions (Figures 4.13 and 4.14).

* See appendix C

Effect of gravity on pushing force calculations

The same principle applies when considering the effect of gravity on the pushing forces (Figure 4.14). When the angle (ρ -F) is> 90°, F_t and mg sinβ are acting in opposite directions. During this phase mgCosβ and F_n are again acting in the same direction throughout the event. F_t and mg Sinβ are acting in the same direction when the angle (ρ - F) is> 90° and in the opposite direction when (ρ - F) is< 90°.

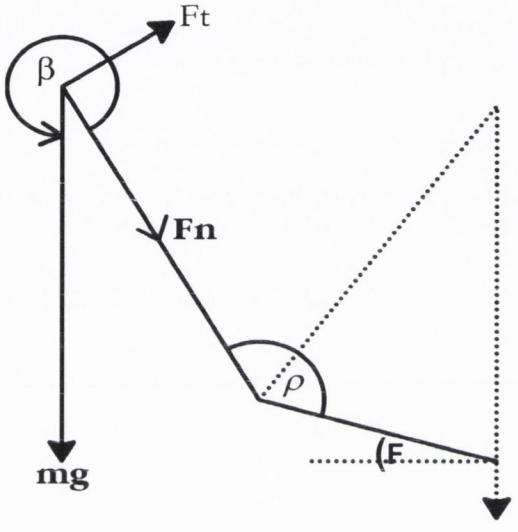


Figure 4.14: when the angle (ρ -F) is 90° F_t and mg are acting in opposite directions

4.4.2 The Effect of Gravity on Mouth Opening / Closing Forces

In evaluating the effect of gravity on mouth opening /closing forces, the same approach is used, except that F_n and F_t are defined with respect to a centre of rotation at the TMJ (Figure 4.15).

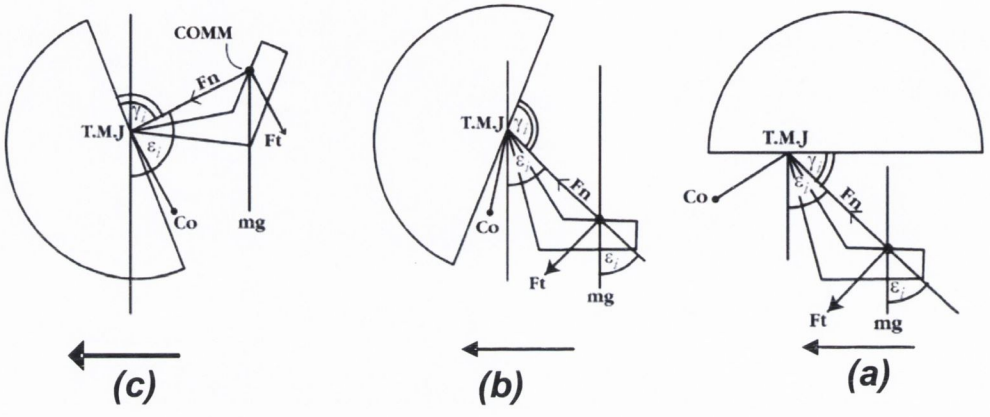


Figure 4.15: (a) The mandible at rest (b), during mouth opening and (c) after mouth opening is completed.

Therefore the contribution of gravity to F_n is mgCosβ and is subtracted from F_n as it is acting in the opposite direction (Figure 4.16). The contribution of gravity to F_t is mg Sin ε_o, which is added to F_t since it is acting in the same direction. The angle ε_o remains constant throughout mouth opening (Figures 4.15(a), (b) and (c)).

Mouth opening is completed after approximately 67° of retroflexion. Up to this the angle ε_0 has remained constant and therefore the effect of gravity is constant. However head retroflexion continues for 0.0276 seconds after the completion of mouth opening. During this period the horizontal position of the mandible is changing, the angle ε_1 is increasing, and therefore the effect of gravity is no longer constant (Figure 4.15c).

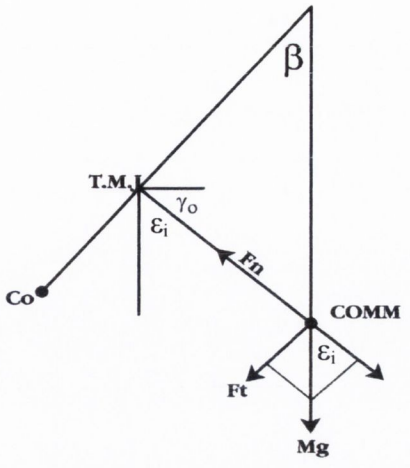


Figure 4.16: Resolution of mg in mouth opening acting along the same plane as F_n and F_t

The effect of gravity on mouth closing force calculations.

The same principles apply during mouth closing in flexion. At the end of head retroflexion the angle ε_i has reached a value of approximately 110 ° (Figure 4.17a). Mouth closing starts at the beginning of flexion and is completed before the end of flexion. The angle ε_i and thus the effect of gravity are a constant value throughout mouth closing. After the end of mouth closing ε_i decreases and the effect of gravity is no longer a constant.

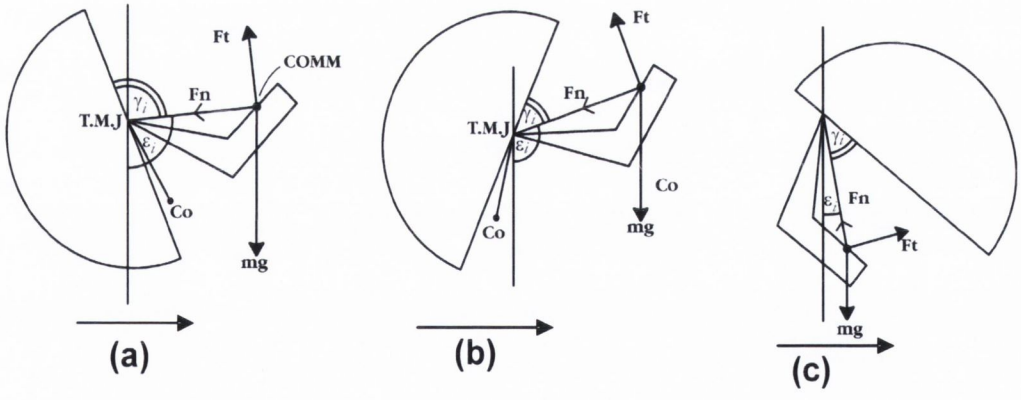


Figure 4.17: The stages of mouth closing due to flexion (a): The start of mouth closing (b): The mouth fully closed after 67° of flexion and (c): the end of flexion with the mouth still in the fully closed position.

4.4.3 Gravity and Forces Due To Linear Displacement

The translatory movement, which occurs in mouth opening/closing, results in linear displacement of the condyle.

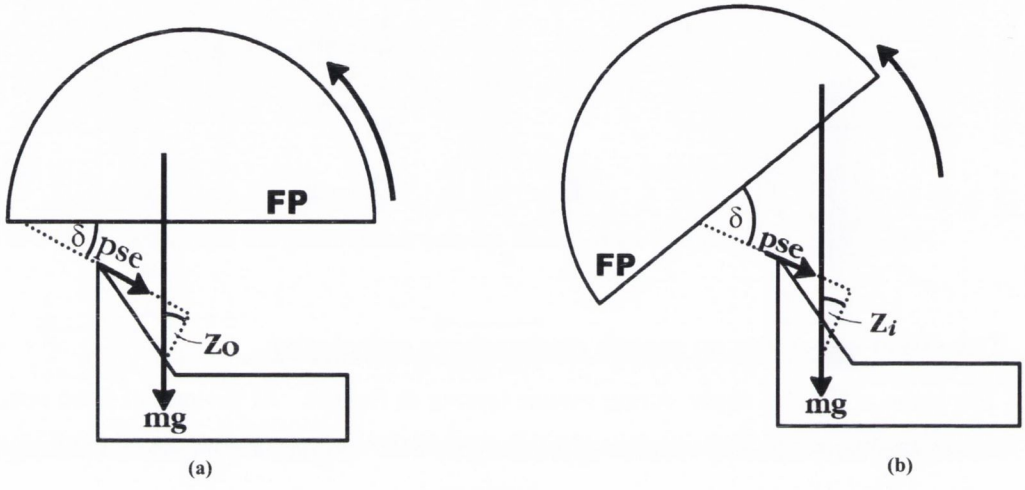


Figure 4.18: Schematic showing the effect of gravity on the condyle (a) prior to and (b) after the start of retroflexion. Pse = posterior slope of articular eminence

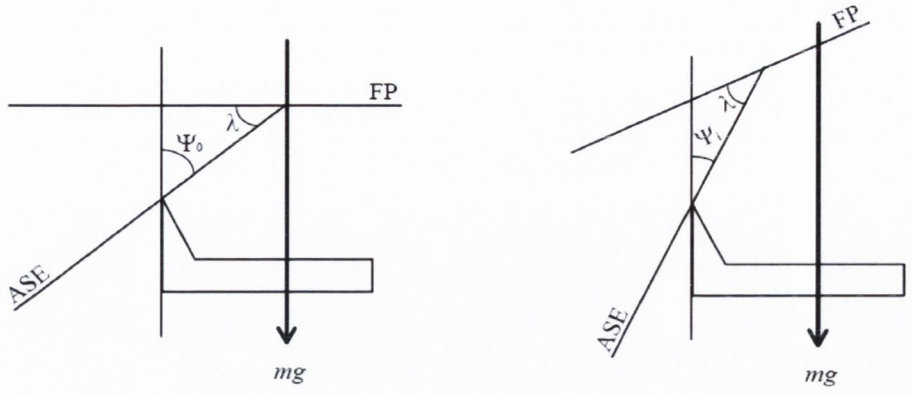
Prior to commencement of head retroflexion, the effect of gravity on the disc/condyle is as shown in Figure 4.18. At this stage the force due to gravity is calculated by $mgSinZ_0$. As the head undergoes retroflexion, the effect of gravity changes. The angle Z_0 is reduced by the degree of retroflexion. Therefore $Z_i = (z_0 - \theta_i)$, (where $z_0 = 51^o$). Therefore the total force on the condyle in anterior translation = $ma+mgSinZ_0$

Posterior Translation

Accordingly the effect of gravity on the condyle as it travels up the posterior slope in posterior translation (stage 2c) is calculated by: -

$F = ma - mgSinZ_i$

When the condyle is moving along the anterior slope of the eminence, it is affected by gravity in the manner shown in figures 4.19(a) and 4.19(b).



(a) *(b)*

Figure 4.19: The position of the condyle, (a) on the anterior slope of the articular eminence at rest and (b) during retroflexion. A.S.E. =Anterior Slope of Eminence.

Thus the instantaneous force on the condyle in anterior translation is calculated by: -

$F = ma - mgSin\psi_i$

Where: -

$\angle \lambda = 28^o$

$\psi_i = (\lambda + \theta_i)$

Posterior translation:

Accordingly the total force in posterior translation is found thus: -

$F = ma + mgSin(\psi_i)$

4.5 Estimation of Acceleration for Force Calculations

The force calculations Carried out in this thesis were based on the motions of the cranium resulting from of a 15m.p.h. impact collision.

In retroflexion and flexion, the head moves absolutely whilst the mandible is trying but failing to maintain its position in space. Therefore the mass of the mandible is a critical factor in the force calculations, head acceleration being the other. Thus in making calculations of forces across the T.M.J., existing data on head acceleration in retroflexion can be used. The data for

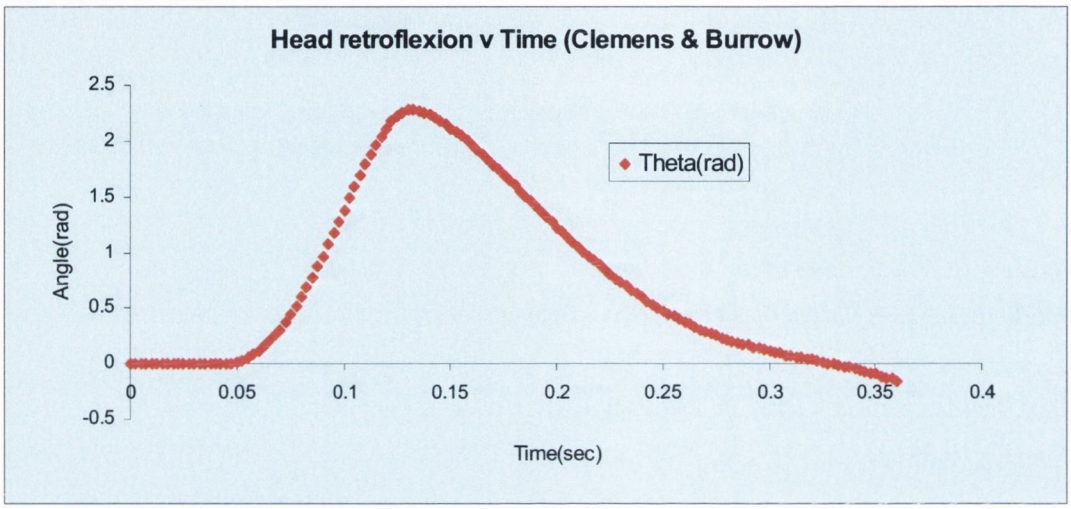


Figure 4.20: Angular displacement of head in retroflexion & flexion for 15m.p.h. impact. (From Clemens and Burrow 1972)

these calculations were taken from the work of Clemens and Burrow* (1972) who performed experimental work on unembalmed human cadavers by subjecting them to a variety of rear impacts.

From their work figure 4.20 shows a time versus displacement graph of the head in a 6.7m/sec (15m.p.h.) impact collision.

4.5.1 Estimation of Constant acceleration in retroflexion

It is evident from Figure 4.20, that acceleration is not constant. However, an initial estimate of forces was made using constant acceleration. This was carried out by noting that an angle of 129° is reached after 0.1sec. Constant angular acceleration (α) is given by $\theta = \frac{1}{2}\alpha t^2$, and was thus calculated to be 450 rad/s^2.

Similarly in the flexion phase angular displacement of the head from 129° to 0° was reached in 0.18 sec. Constant acceleration of the head in flexion was calculated at 138.9rad/s^2.

* See Appendix E

4.5.2 Estimation of variable acceleration in retroflexion

Force calculations made using constant acceleration are a rough guide to events, and may be misleading. To make an accurate evaluation, the variation of acceleration with time must be considered. Critical peaks and troughs in acceleration will thus be taken into account.

Therefore, a second series of force calculations was made using variable angular velocity and acceleration estimated by polynomial differentiation from the angular displacement versus time curve of Clemens & Burrow (1972)* (Figure 4.20). The retroflexion angular velocity curve derived from this is shown in Figure 4.21, and the retroflexion angular acceleration curve is shown in Figure 4.22.

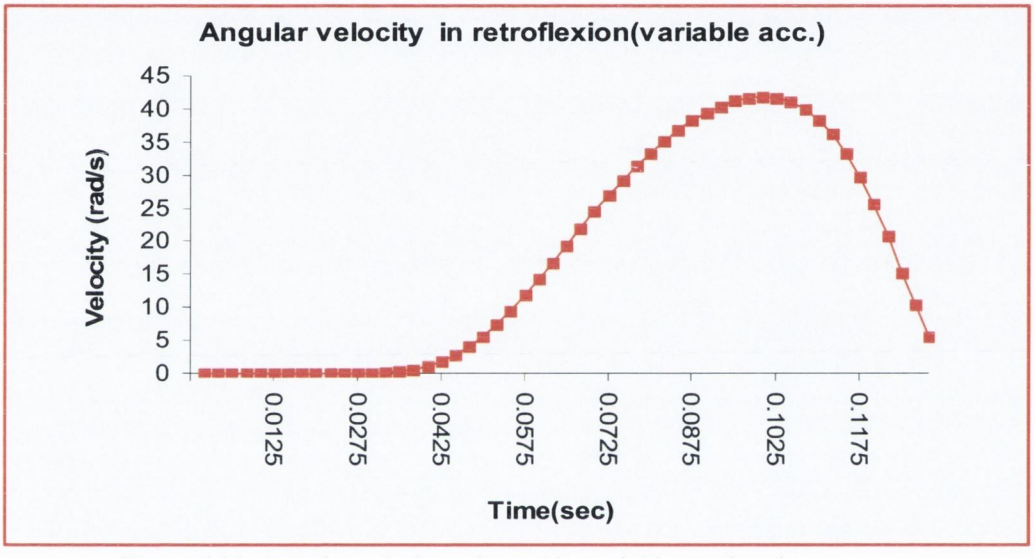


Figure 4.21: Angular velocity estimated in variable acceleration

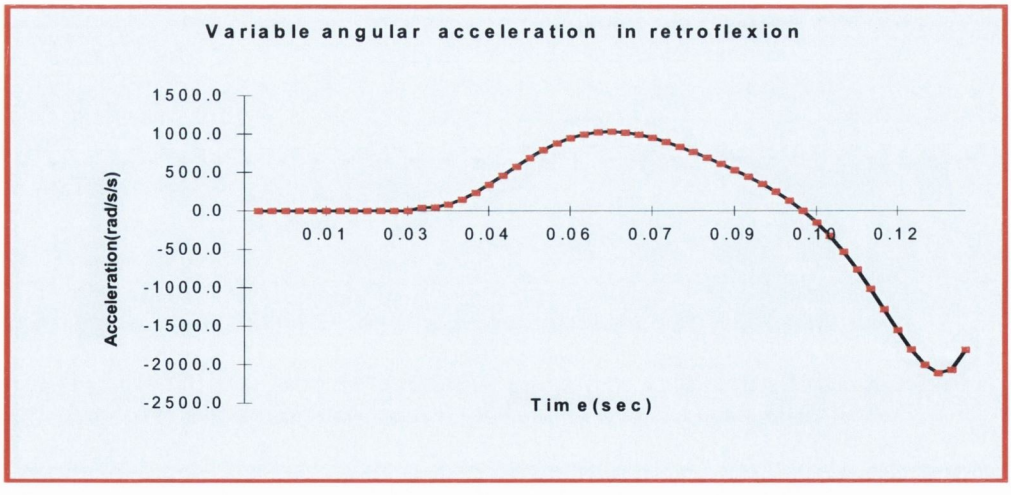


Figure 4.22: Variable angular acceleration in retroflexion

*See appendix E

4.6 Force Calculations

4.6.1 Introduction

The following sections outline the calculation of forces for the various stages as defined earlier.

4.6.2 Pulling Forces

Rotation (angular displacement) of the cranium in Retroflexion occurs around an axis at c_o. This results in forces occurring across the T.M.J. due to angular displacement of the joint around C_o

Two types of force occur, normal (F_n) due to angular velocity acting towards the centre of rotation, and tangential (F_t) due to angular acceleration, acting at right angles to F_n (Figures 4.23a & 4.23b). The radius of the arc of rotation is thus the distance from C_o to the T.M.J.

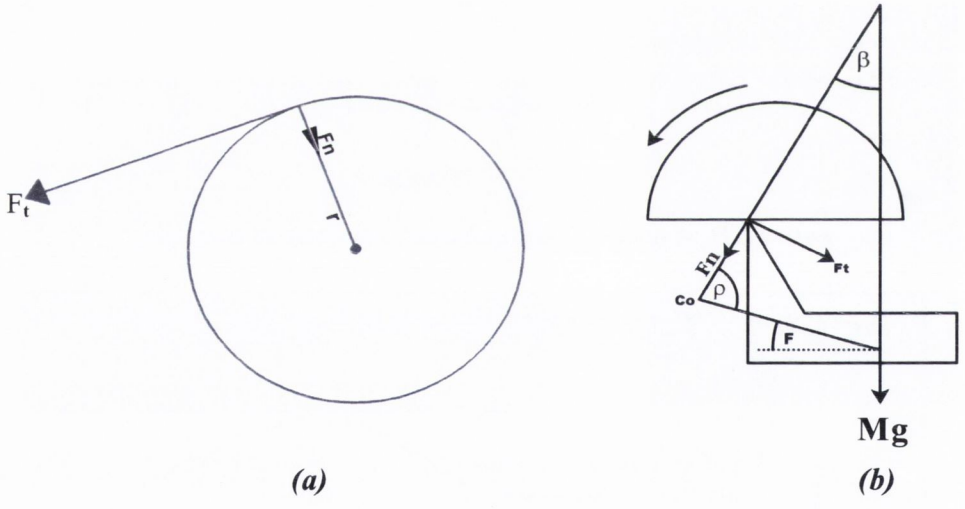


Figure 4.23(a) & 4.23(b): Direction of tangential & normal pulling forces at commencement of retroflexion.
Note that as the mass of the mandible is critical in force calculations, F_t is acting in a clockwise direction although the cranium is rotating in the opposite direction.

4.6.2.1 Calculation of pulling force 1a1

The values calculated and formulae used were as follows: -

- Constant angular acceleration (α) was calculated as 450 Rad/s^2.
- Angular velocity (ω) is calculated by $\omega=\alpha t$ (Figure 4.21).
- Angular displacement of the cranium after time t is calculated by $\theta = \frac{1}{2}\alpha t^2$. Since head retroflexion does not commence until .030sec this is subtracted from the time scale in order to find t for head retroflexion. The time increments used were .0025 seconds.
- The angles ρ_i and β_i being the instantaneous values of ρ and β at time t were calculated thus: -

  $\rho_i = \rho_o + \theta$

  $\beta_i = 90 - (\rho_i - F)$

- Calculation of forces.

F_n and F_t are calculated as the sum of the forces due to angular displacement and gravity.

The formulae used were therefore as follows:

(a) Normal force: -

$F_n = m(\omega^2) r + mg \cos\beta$. Note $\omega^2 = (\alpha t)^2$

(b) Tangential force: -

$F_t = m \alpha r + mg \sin\beta$

(c) Resultant force

$$F1a1 = \sqrt{Ft^2 + Fn^2}$$

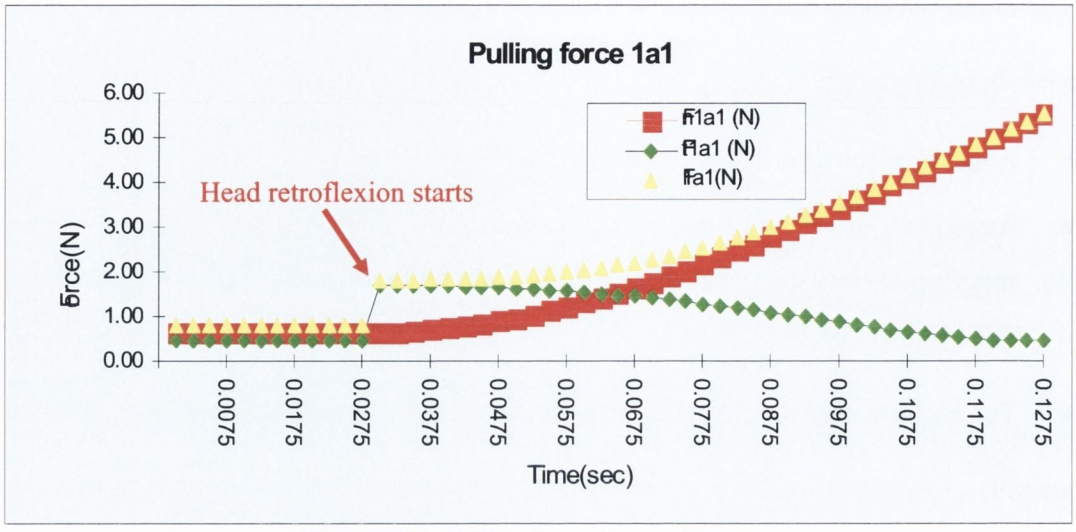


Figure 4.24: Pulling forces in retroflexion.

F_n1a1 represents the normal force, F_t1a1 the tangential force and F1a1 the resultant

Pulling forces are shown in Figure 4.24. Initially both F_n1a1 and F_t1a1 are affected only by gravity. When head retroflexion commences F_n1a1 is constantly increasing as it corresponds to the increasing value of angular velocity. Gravity and F_n1a1 are acting in the same direction for almost the entire event except for a brief period at t= 0.1275 sec when gravity is acting in the opposite direction. The increase is due to the increasing value of angular velocity.

The value for F_t1a1 increases at the start of retroflexion, and then falls throughout the event, as changes in its magnitude are due only to gravity. From t = 0.03 to t= 0.0775, mg and F_t1a1 are acting in the same direction. From t= 0.08 to the end of the event mg and F_t1a1 are acting in opposite directions. F_t1a1 predominantly influences the resultant pulling force F1a1 in the early part of the event, whereas F_n dominates in the later stages.

4.6.2.2 Calculation of the direction of resultant force 1a1

Referring to Figure 4.25 Fx and Fy are defined as the resolved portions of F in directions parallel and perpendicular to the FP.

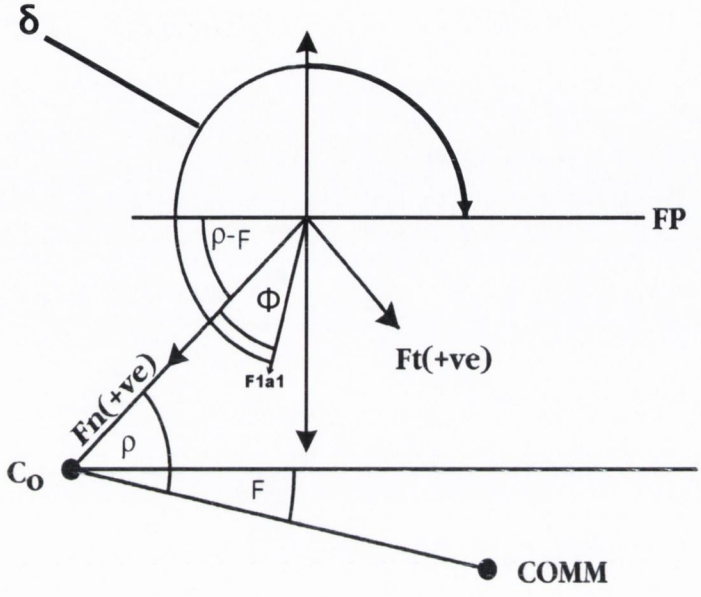


Figure 4.25: F_t and F_n components of resultant force F.
The angle delta (δ) represents the direction of F relative to the Frankfurt plane

The calculation was carried out as follows: -

(a) $\phi = \text{atan}\ (F_t / F_n)$

(b) $\delta = (\rho - F) + \phi + 180$

Where $\angle F = 16.3^0$

The direction of the resultant force F1a1 with reference to the Frankfurt plane co-ordinate system is represented by the angle δ and is measured from the positive x-axis of the system (Figure 4.26 & 4.27). Fx and Fy are defined as the resolved portions of F1a1, in directions parallel and perpendicular to the Frankfurt plane.

Initially F1a1 lies along the negative Y-axis of the Frankfurt plane, as gravity only is acting on the system. During this period F_n is dominant. From the start of retroflexion at t=0.03 sec to t=0.0725 sec F1a1 is in the 4th Quadrant of the Frankfurt plane complex. During this period F_t 1a1 is more dominant. However as angular velocity is increasing throughout the event and angular acceleration is a constant (only changing due to gravity), F_n becomes more

dominant in the latter stages of the event. Thus from t =.0750 to the end of the event F1a1 lies in the 3rd Quadrant.

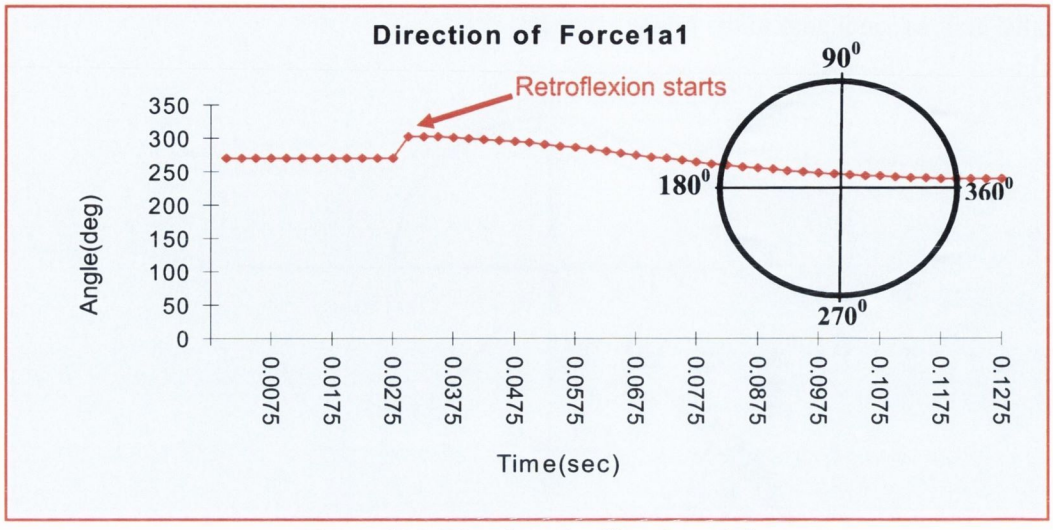


Figure 4.26: Direction of pulling force 1a1

4.6.2.3 Calculation of Fx and Fy components of resultant force F1a1

The resultant force F1a1 can also, be resolved into components parallel and perpendicular to the Frankfurt plane Fx and Fy (Figure 4.27).These will be needed for summation with the forces due to linear acceleration (F1c1) to find the total force affecting the condyle at a particular time (t) in the event.

Formulae: -

$Fx = \text{Cos } \delta$

$Fy = F \text{ Sin } \delta$

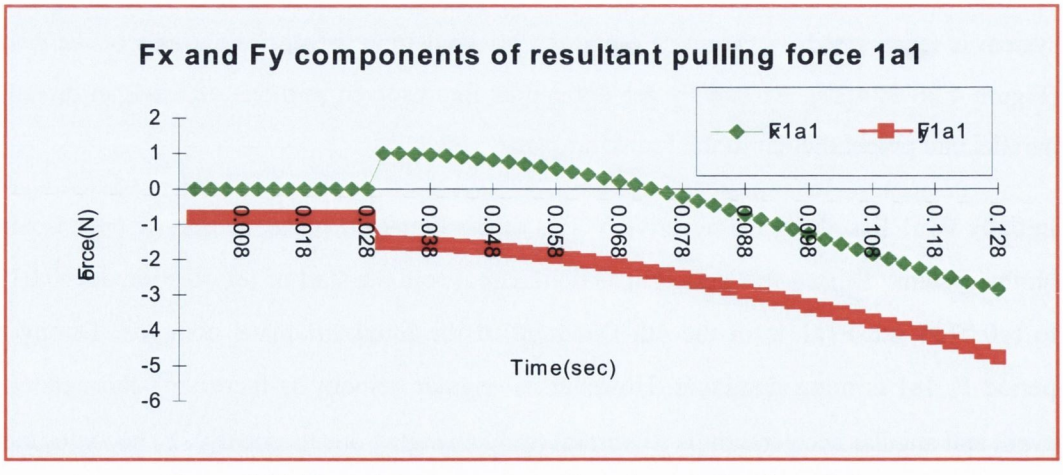
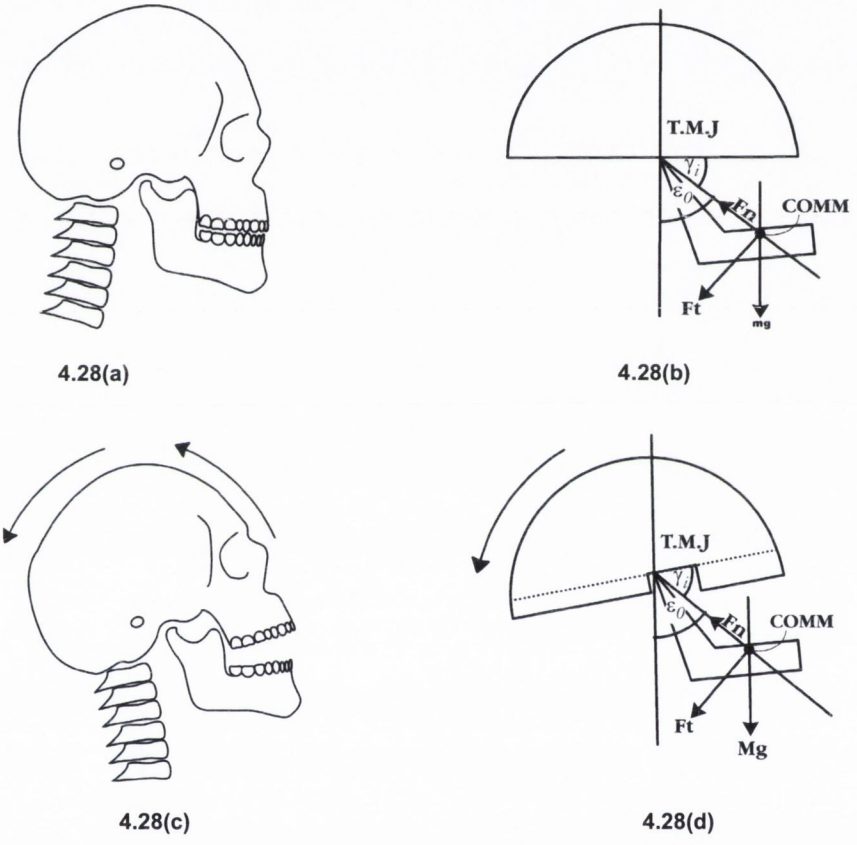


Figure 4.27: Fx and Fy components of resultant pulling force 1a1

4.6.3 Mouth opening forces - Force 1b1

Normal mouth opening consists of voluntary rotation/translation of the disc/condyle assembly on the cranium. Mouth opening caused by a rear end collision is due to involuntary retroflexion of the cranium, which results in rotation/translation of the cranial base on the disc/condyle assembly. This can be interpreted as relative movement of the mandible away from the cranium.



4.28(a) 4.28(b)

4.28(c) 4.28(d)

Figure 4.28 (a) & (b): The cranium prior to retroflexion and 4.28(c) & (d) Mouth opening due to angular displacement of the cranium.
ε is constant throughout mouth opening, but increases in the final part of retroflexion, when mouth opening is complete. γ_i increases during mouth opening and is constant in the final part of retroflexion

Figures 4.28a and 4.28b show the relationship between the cranium and the mandible prior to mouth opening. Figures 4.28c and 4.28d show the relationship between retroflexion of the cranium and mouth opening which by definition are occurring simultaneously, and start at t=0.03 sec. However mouth opening does not take place throughout the entire retroflexion period. Mouth opening ends at t=0.1sec, but retroflexion continues until t=0.1275 sec.

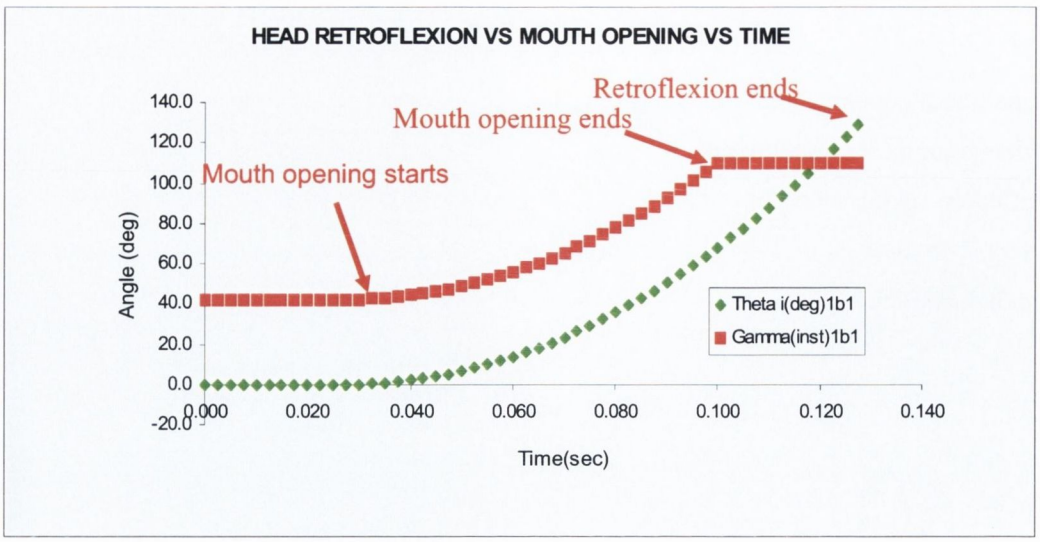


Figure 4.29: Relationship between mouth opening angle and head retroflexion. Note that mouth opening ends prior to the completion of head retroflexion.

4.6.3.1 Values calculated and formulae used

1. The values for angular acceleration and angular velocity were the same as those used in pulling force calculations F1a1.

2. θ instantaneous (θ_i) was calculated by $\theta_i=\theta_o + \frac{1}{2}\alpha t^2$

3. $\angle \varepsilon_o$ has a constant value of 47.2° until the end of mouth opening at t=0.1 (sec). After this the head continues in retroflexion. The $\angle \varepsilon_i$ accordingly increases and is calculated by the formula, $\varepsilon_i = \varepsilon_o + (\theta_2 - \theta_1)$ (Figures 4.28a and 4.28b). $\theta_1$is the amount of head retroflexion up to the end of mouth opening and θ_2 is the subsequent amount of retroflexion at each following time increment. The $\angle\gamma_i$ is changing throughout mouth opening and is calculated by $\gamma_i = \gamma_o + \theta_1$. After the end of mouth opening γ_1 remains constant until the completion of retroflexion.

4.6.3.2 Calculation of force 1b1.

The forces passing through the centre of mass of the mandible were divided into normal and tangential components. Taking gravity into consideration the calculations were as follows:

(a) $Fn=m\omega^2 r - mg\cos\varepsilon$

(b) $Ft = m\alpha r + mg \sin\varepsilon$

(c) Calculation of resultant force: -

$$Fib1=\sqrt{Ft^2 + Fn^2}$$

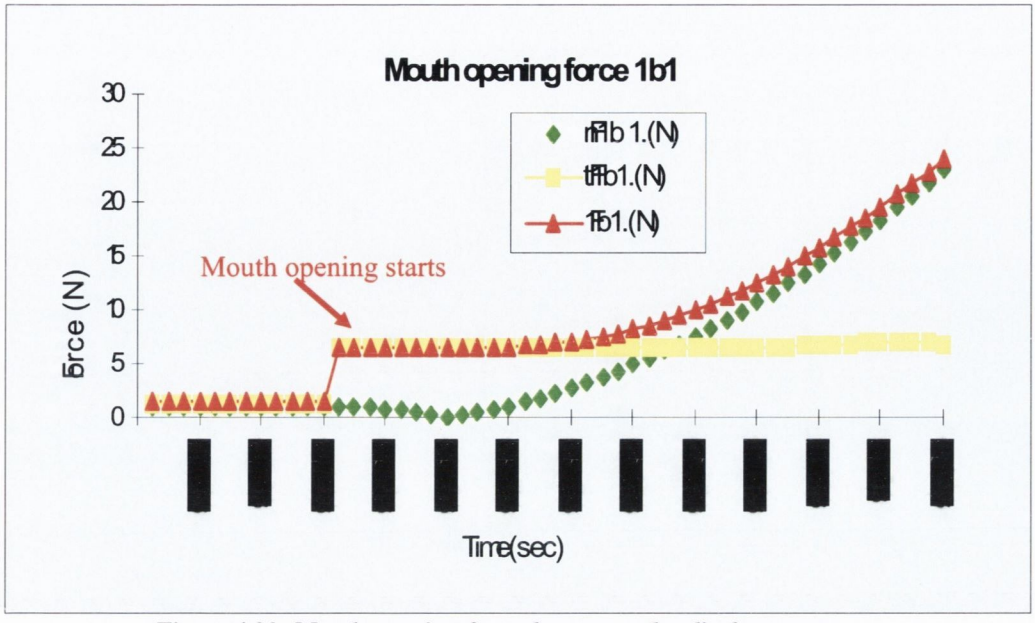


Figure 4.30: Mouth-opening force due to angular displacement.
F_n1b1 = the normal force, F_t 1b1= tangential force and F1b1= resultant force.

The pattern of forces occurring throughout the event is shown in Figure 4.30. Prior to the commencement of head retroflexion gravity only is acting on the mandible.

F_t1b is constant throughout mouth opening, as both acceleration and the effect of gravity are constant. When mouth opening has been completed the effect of gravity changes due to the value of ε_i increasing. F_t1b therefore changes slightly at this stage. F_n1b is increasing throughout the event as it is directly related to angular velocity.

4.6.3.3 Direction of force F 1b1

The direction of the forces and angles used to calculate them are seen in figures 4.31 and 4.32

(a) Calculation of ϕ_i: -

$\phi_i = \text{atan } F_t / F_n$

(b) Calculation of δ_i

(i) When F_n and F_t are both +ve the formula for δ_i is:

$\delta_i = (\phi - \gamma) + 180^o$

(ii) When F_n is -ve and F_t is +ve the formula for δ_i is:

$\delta_i = 360 - (\gamma - \phi)$

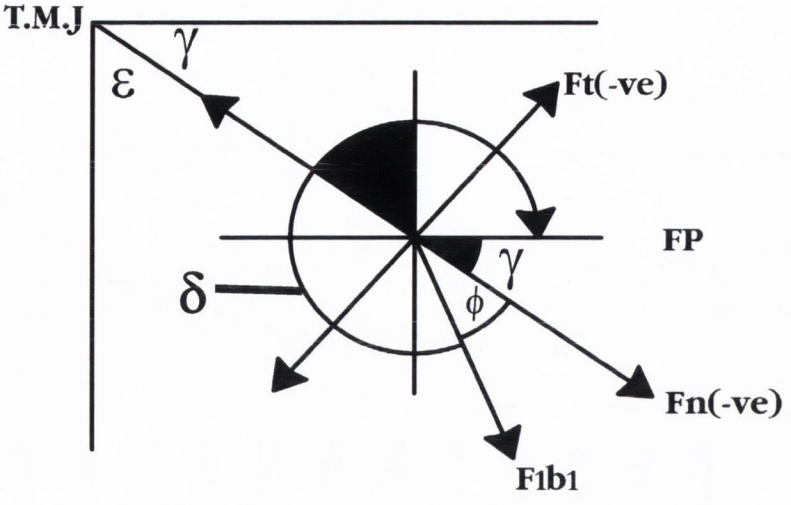


Figure 4.31: Angles ϕ and δ used to calculate direction of force F relative to Frankfurt plane, when F1b1 is in the 2nd quadrant of the Ft, Fn system

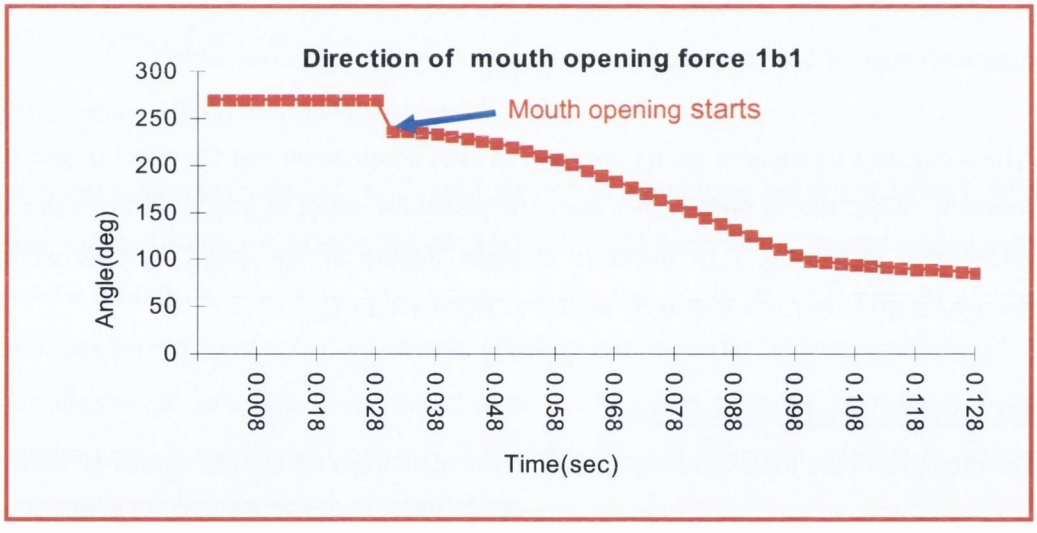
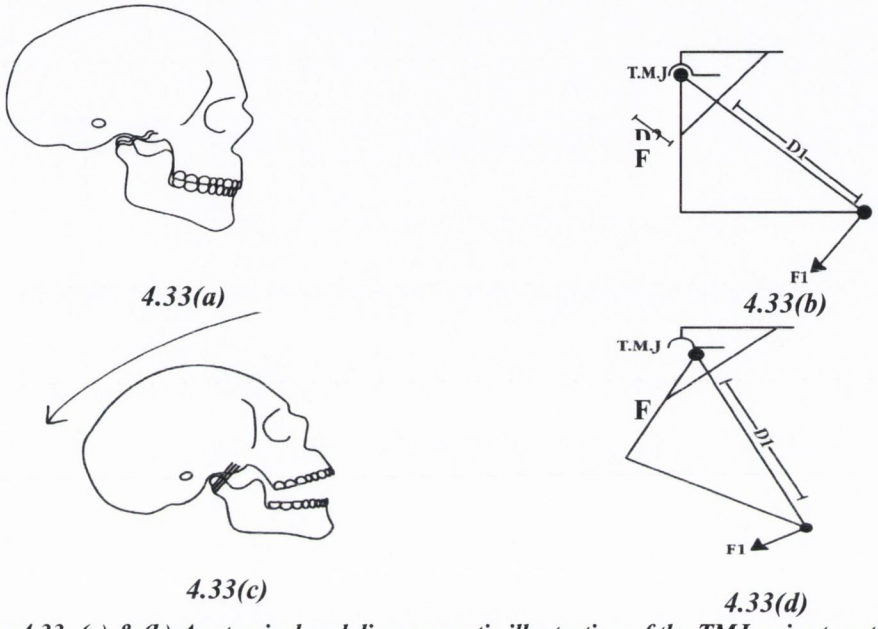


Figure 4.32: Direction of resultant mouth opening force 1b1

Although the direction of the resultant force relative to the Frankfurt plane is shown, the forces at the TMJ due to rotation are zero as it is the centre of rotation. Therefore summation of this force was not included with the other forces occurring across the joint. However reaction forces do occur in the tissues adjacent to the TMJ, as will be discussed below.

4.6.3.4 Force sustained by lateral ligament during mouth opening

The mouth opening forces calculated due to angular displacement (F1b1), act through the centre of mass of the mandible. As the centre of rotation lies in the condylar head, no forces are sustained in this region. However, reaction forces occur in the peripheral aspects of the TMJ, for example in the temporomandibular ligament/capsule complex.



4.33(a) *4.33(b)*

4.33(c) *4.33(d)*

Figure 4.33: (a) & (b) Anatomical and diagrammatic illustration of the TMJ, prior to retroflexion when lateral ligament is unloaded, and (c) & (d) after 15° of opening showing ligament loaded.

The first part of jaw opening in whiplash consists of rotation about the TMJ, and occurs as a result of the force F1b1 through the COMM. However, after approximately 15° of rotation in mouth opening the consequent tension in the lateral TMJ ligament creates a force (F_2), which starts to counteract the force passing through the COMM (figures.433a, 4.33b, 4.33c and 4.33d).

F_2 may be estimated by taking moments about the TMJ for the forces F_1 and F_2 thus: -

$$F_1.D_1 = F_2.D_2$$

Where: -

D_1 = vertical distance of the COM from the pivot = 73mm

D_2 = vertical distance from the ligament to the pivot = 2.5mm

In order for the moments to balance, force F_2 must be greater than the force F_1.

Thus if a force of 7 Newtons was passing through the centre of mass of the mandible the calculation would be:-

7 x 73/2.5 = 204 N. As the force is acting on both ligaments this result is divided by 2 giving a force of 102 Newtons on one ligament assuming symmetry.

The measured distance from the centre of rotation of the condyle to the centre of the ligament was found to be 2.5mm, on one cadaver specimen. This was measured by the use of hinge axis location to find the centre of rotation of the condyle.

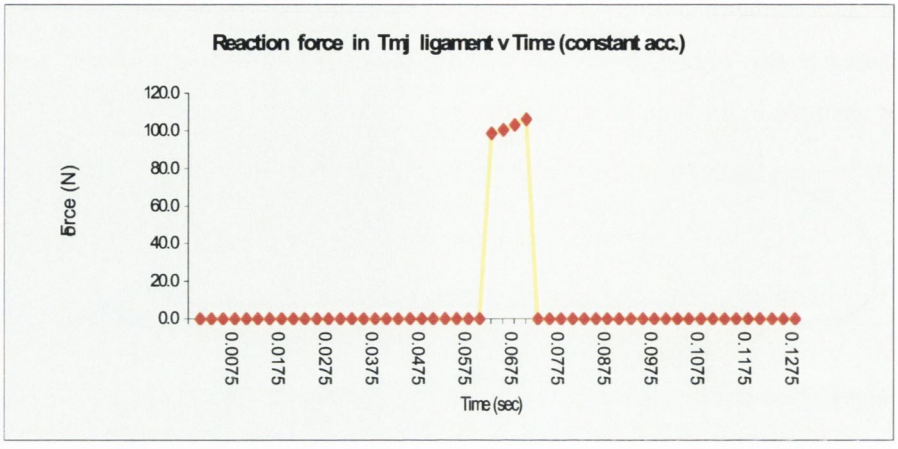


Figure 4.34: Reaction force in one TMJ ligament due to force 1b1

The centre of rotation distance to the mid-point of the ligament was then measured*. Therefore it can be stated that from 0 ° to 15° of mouth opening, "pure" rotation of the condyle occurs. After approximately 15° of opening the build up of tension creates a force (F2) in the lateral ligament. When F2 is large enough translation will occur. Translation in turn will reduce F2 due to the decrease in the tension of the ligament.

Figure 4.34 shows the reaction force in the TMJ ligament. It was assumed that the ligament is unloaded until 15° of rotation has taken place, and that it becomes unloaded when the condyle

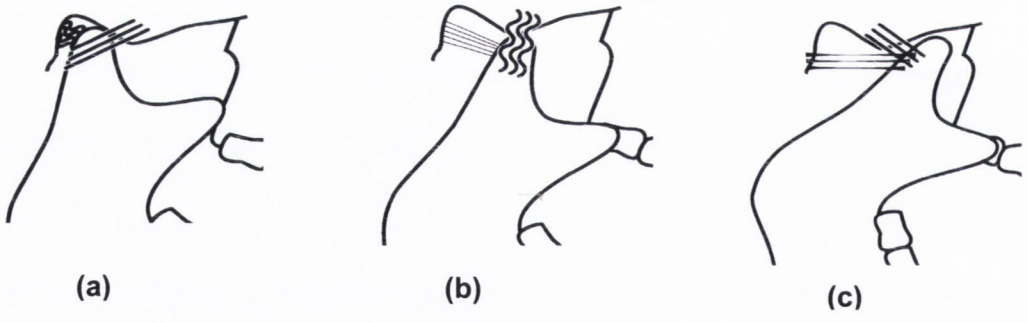


Figure 4.35: (a) Initial loading of ligament due to rotation, (b), unloaded as it translates to the articular eminence, and (c) undergoing tensile loading beyond its' normal range of function.

has translated as far forward as the crest of the articular eminence. At this point reaction forces in the ligament cease. It should be pointed out that the ligament may be subjected to tensile forces in situations where the condyle has translated beyond its' normal range of function (Figure 4.35).

*See Appendix G for details on hinge axis location.

4.6.4 Anterior Translation Forces - Force 1c1

Mouth opening consists of a combination of rotation and translation. When mouth opening is voluntary, translation and rotation occur simultaneously throughout.

Rees (1954) studied the relationship between rotation and translation in mouth opening. He found that for every 2° of rotation, 1mm of translation occurred. This was based on direct observation and measurement of anatomical specimens, and is consistent with the findings of Merlini and Palla (1989), who studied active mouth opening in ten live human subjects using a mandibular tracking technique. Merlini and Palla (1989) demonstrated that the relationship between rotation and translation in voluntary mouth opening was almost linear.

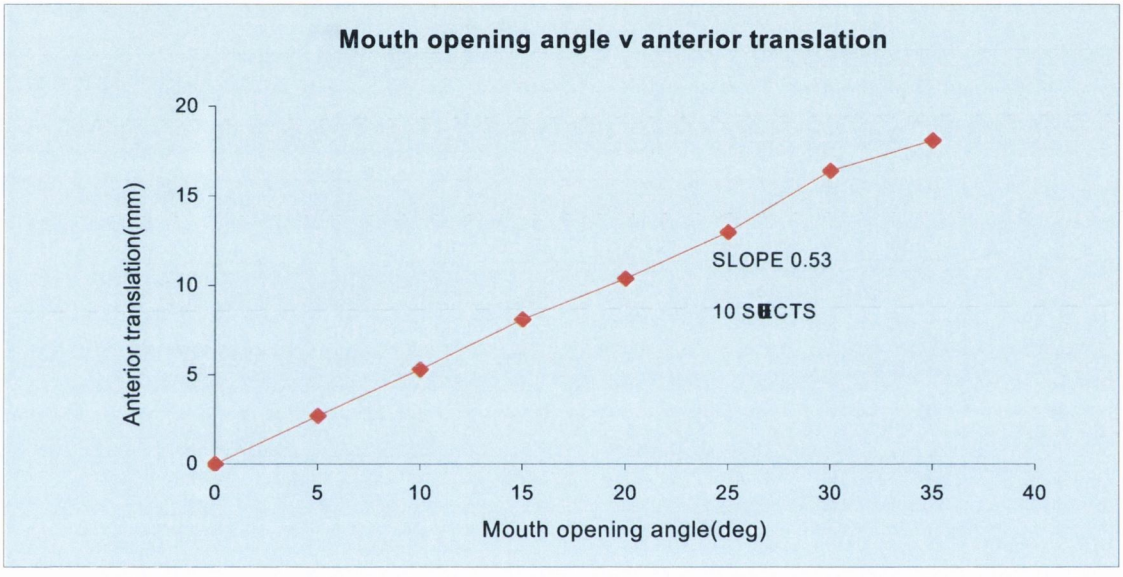


Figure 4.36: Relationship between rotation and translation in mouth opening (Merlini and Palla1989)

They plotted anterior translation against mouth opening angle and found that the slope was 0.53, which is approximately 1mm of Translation for every 2° of rotation (Figure 4.36). Posselt (1969) stated that in active mouth opening the condyles start to translate as soon as the mandibles open from the intercuspal (fully closed) position.

However he also stated that in passive mouth opening (by manipulation), with the condyles in the most unstrained, retruded position, (terminal hinge position) a pure rotation occurs for 15° after which a combination of rotation and translation takes place. A number of workers have confirmed the existence of the terminal hinge position (McCollum 1939, Stuart 1959).

In whiplash, retroflexion of the cranium is an involuntary movement, and therefore it was assumed that the mouth opening which results is passive. This will alter the relationship between rotation and translation in the second phase of mouth opening. Thus assuming that no translation takes place in the first 15° of mouth opening the slope of the curve when rotation is plotted against translation is 0.925.

Therefore if 67° of mouth opening occurs in whiplash as predicted by Schneider et al (1989), the calculation for the amount of anterior translation will be 48.1mm.

However only approximately 35 mm of translation is anatomically possible in the human even in extreme mouth opening. Some rotation probably occurs in the final part of mouth opening. This is consistent with the findings of Posselt (1969) and Osborne (1985).

The relationship between rotation and translation is shown in figure 4.37. Translation starts .0325 sec later than rotation and ends .01 sec before the end of mouth opening.

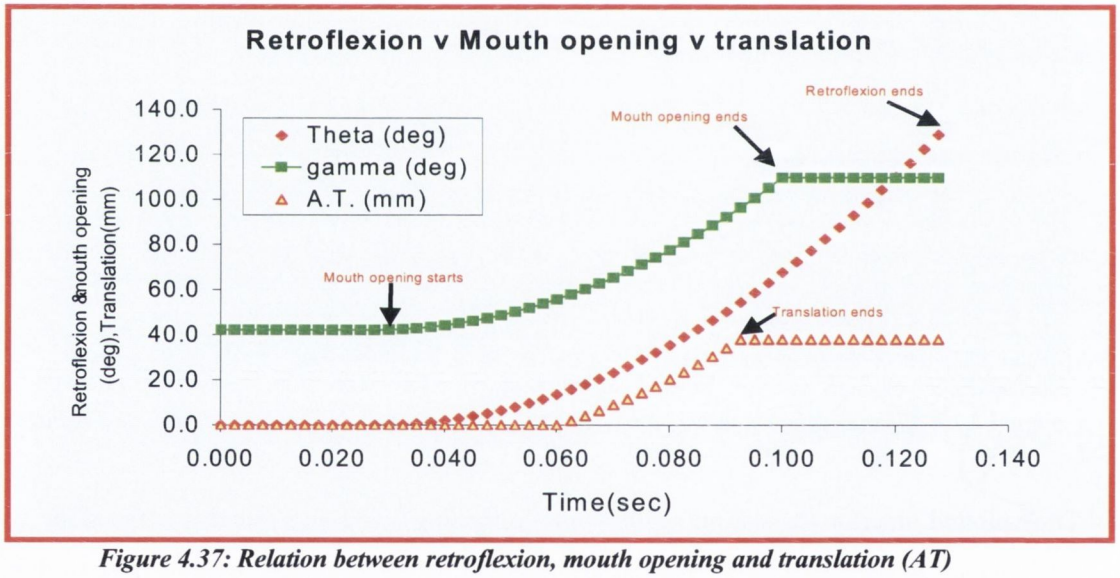


Figure 4.37: Relation between retroflexion, mouth opening and translation (AT)

4.6.4.1 Data needed for force calculations: -

1. Calculation of anterior translation (mm)

   Formula: $A.T = (\theta_i - 15^\circ) \times 0.93$

2. Calculation of Linear acceleration $a = \alpha \times 180 / pi \times 0.93/1000$

   $= 450 \times 180/pi \times 0.93/1000$

   $= 23.96$ m/s/s

4.6.4.2 Force Calculations

On the posterior slope of the articular eminence the force is calculated by:

$F = ma + mgSinz_i$

Where $z_i = (z_o - \theta_i)$

On the anterior slope of the eminence the force is calculated by $F=ma-mgSin\ \psi_i$ Where $\psi_i = (\Psi_o + \theta_i)$

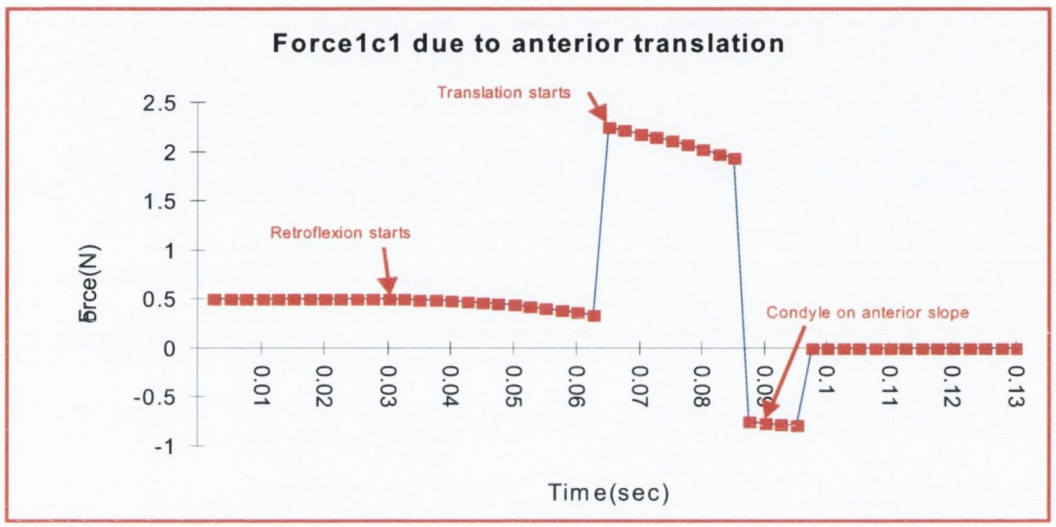


Figure 4.38: Force 1c1 due to linear acceleration in anterior translation (AT)

Figure 4.38 refers to the forces in anterior translation. Prior to mouth opening gravity only is acting on the condyle. Retroflexion begins at t =0. 03 sec, which results in small changes of force magnitude, due to the decreasing effect of mgsin z_i Translation on the posterior slope starts at t=0.625sec and lasts until t=0.0825sec. During this period the force magnitude at first rises suddenly, and then falls gradually due to the diminishing effect of mgsin z_i, which is acting in the same direction.

When the condyle moves to the anterior slope at t=0.0825 sec, the force value falls suddenly as $mgsin\Psi_i$ is now acting in the opposite direction. From this point to the end of retroflexion at t=0.0925sec the force magnitude increases gradually due to the diminishing effect of $mgsin\Psi_i$.

3. Calculation of Fx and Fy relative to the Frankfurt plane (Figure 4.39).

These components are needed for summation with pulling forces F1a1 in Final force 1.

The formulae used were:

(a) Condyle on posterior slope $Fx = F\cos\delta$, $Fy = FSin$

(b) Condyle on anterior slope $Fx = F\cos\lambda$, $Fy = F\sin\lambda$

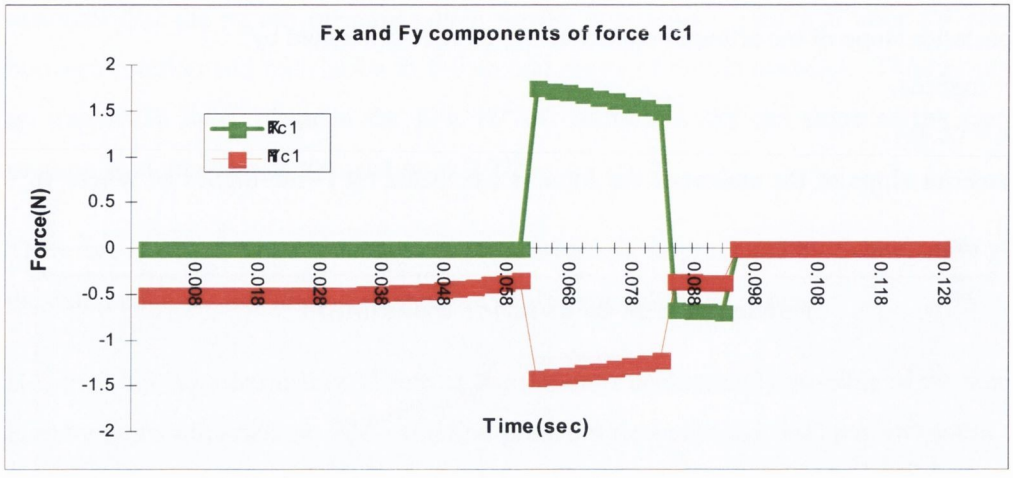


Figure 4.39: Fx and Fy components of linear force 1c1 in anterior translation

Prior to translation F1C1 is in the 4th Quadrant of the Frankfurt plane Cartesian system. While translating on the posterior slope of the eminence, F1C1 remains in the 4th Quadrant. While translating on the anterior slope of the eminence F1C1 is in the 3rd Quadrant due to gravity dominating and when translation has ended and gravity only is acting on the condyle, F1C1 remains in 3rd Quadrant.

The forces due to linear acceleration (F1c1) which occur as a result of anterior translation are acting on the condyle from t=0.0625 sec to t=0.0925 sec. From t=0.0625 sec to t=0.0825 sec the direction of the force is in the 4th Quadrant of the Frankfurt plane system. Thus it is tensile on the capsule/ ligament complex with a peak value of 2.25 Newtons on either joint (t=0.0625 sec). However, during this period the condyle is acting within its normal range of movement. The posterior attachment and the ligament /capsule complex can thus be regarded as unloaded. When the condyle has passed beyond the crest of the eminence, the posterior attachment is functioning beyond its normal range and becomes loaded, i.e. from t=0.0825 sec to t=0.0925 sec. However during this period the direction of the force is in the 3rd Quadrant of the Frankfurt plane Cartesian system. The force is therefore acting in the opposite direction as the condyle is slowing down due to overall deceleration.

Thus the integrity of the soft tissues is not being challenged at this stage, as the force is tending to move the ligaments posteriorly, thereby unloading them. Although the condyle is now fully occupying the anterior portion of the inferior joint space, the anterior capsular region is not being subjected to compressive forces and stresses by the leading edge of the condyle.

The nett value of the above forces will not be fully realised until summation with pulling forces F1a1 has been carried out.

4.6.5 Final Force 1

Pulling and translatory forces are acting on the mandibular condyle during retroflexion. Thus summation of F1a1 and F1c1 is needed to find the magnitude and direction of the nett forces acting on the condyle at a particular time in the event.

4.6.5.1 Calculation Final force 1 (F1)

FF1= $\sqrt{(Fxtotal)^2 + (Fytotal)^2}$ Where Fx total= Fx1a1+Fx1c1, and Fy total = Fy1a1+Fy1c1

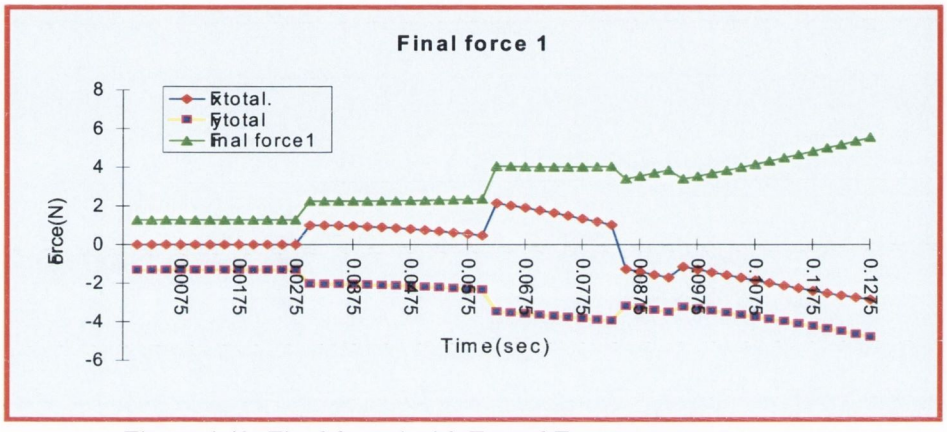


Figure 4.40: Final force 1 with Fx and Fy components

Figure 4.40 shows Final force 1 with its Fx and Fy components and figure 4.41 shows the direction of the force. From t = 0 sec to t =0.0275 seconds gravity only is acting on the condyle at an angle of 270 degrees relative to the Frankfurt plane. At this stage minimal

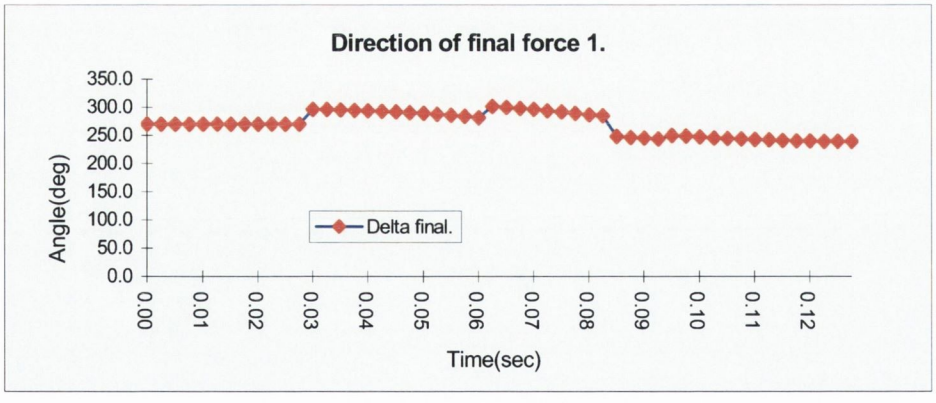
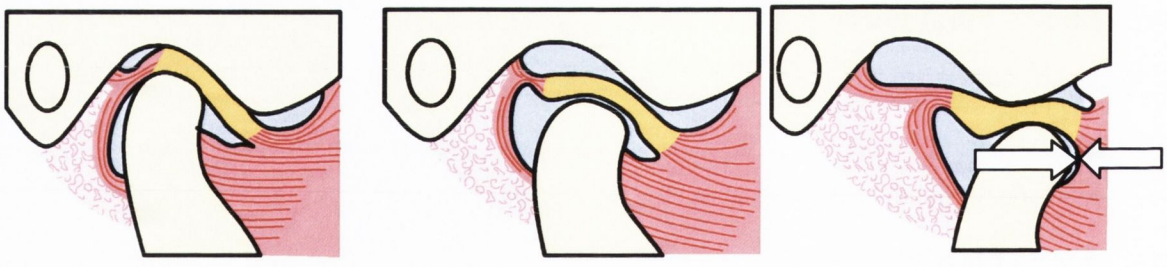


Figure 4.41: Direction of Final Force 1

tensile gravitational forces are acting on the soft tissues, which attach the mandible to the cranium, viz. the ligament/capsule complex. From t =0.03 sec to t =0.06 seconds pulling forces only are acting on the condyle. The peak force during this period is circa 2.3 Newtons on each condyle. The direction of the force is in the 4th Quadrant of the Frankfurt plane Cartesian complex and is thus pulling the condyle down and away from the cranium, resulting in a tensile force on the capsule / ligament complex.



(a) (b) (c)

Figure 4.42: Showing the condyle in relation to the inferior joint space at different stages in mouth opening.
(a) At rest (b) partially open and (c) fully when the anterior part of the inferior joint space is fully occupied by the condyle

4.6.6 Stress on Anterior Capsule Due To Final Force 1

Final force1 results in compression of the anterior part of the joint capsule by the leading edge of the condyle (Mahan, 1980). This compression does not occur until the condyle has reached the crest of the articular eminence, at which point the inferior joint space is fully occupied by the head of the condyle (Figure 4.42 a, b and c). The forces calculated are of a relatively modest nature (3 to 6 Newtons). However, the stresses on the tissues may be of greater significance.

The magnitude of the stress is dependent on the shape of the leading edge of the condyle. It has been seen earlier, that this can vary greatly from individual to individual (Chapter 3 page 32).

The more rounded the leading edge of the condyle the less stress will be applied to the capsule and therefore the less chance of damage. Evaluation of the stress sustained in different circumstances was facilitated by measurement of the area of the leading edge on a number of different condyles.

4.6.6.1 Method for measuring stress on anterior capsule

Measurement of the anterior condylar surface was carried out on seventeen condyles in eleven human mandibles. The leading edge of the condyle head was pressed onto carbon paper, which was superimposed on a plain sheet of white paper during a simulated movement of condylar translation (Figure 4.43).

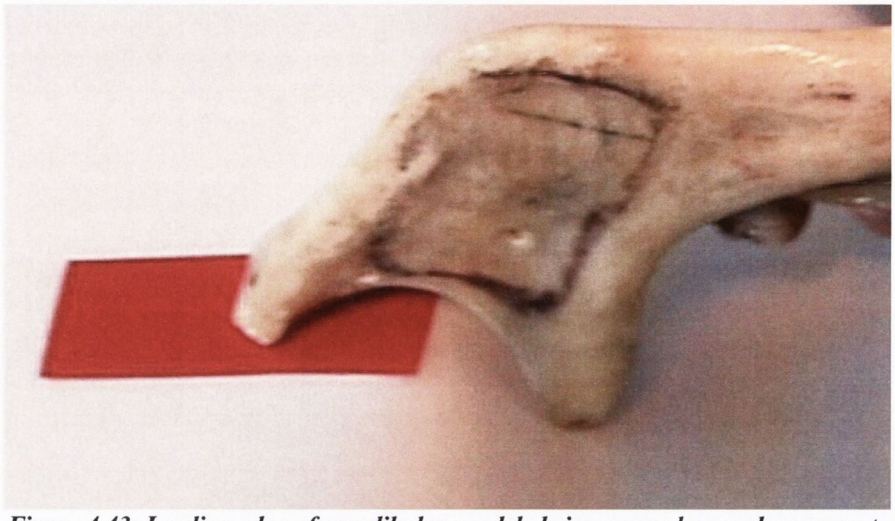


Figure 4.43: Leading edge of mandibular condyle being pressed on carbon paper to Obtain outline of primary contact area on the anterior capsule

This left marks of varying sizes and shapes on the sheet of paper, depending on topography of the particular condyle. In some instances the surface of the condylar head was too damaged to make a valid measurement.

The results of these measurements are shown in table 4.3. The minimum area of contact was found to be $1mm^2$. The maximum was $20mm^2$. The mean value was $4.9mm^2$. The above method has some drawbacks in that in vivo the condyle is contacting a pliable surface capable of deformation under load. Nonetheless it does give some idea regarding the penetrative characteristics of different condyles. The shape of the anterior portion of the condylar head may play a critical role in damaging or penetrating the synovial membrane and the anterior part of the joint capsule particularly when it considered that the capsule was consistently found to be weak in this area.

	LEFT	RIGHT
Mandible 1	Damaged	$20mm^2$
Mandible 2	$2mm^2$	$8mm^2$
Mandible 3	$2mm^2$	$2.5mm^2$
Mandible 4	$4mm^2$	$1mm^2$
Mandible 5	Damaged	$6mm^2$
Mandible 6	$4mm^2$	$4mm^2$
Mandible 7	Damaged	$6mm^2$
Mandible 8	Damaged	$8mm^2$
Mandible 9	$2mm^2$	$1mm^2$
Mandible 10	$3mm^2$	$3mm^2$
Mandible 11	Damaged	$7mm^2$
Mean Value (all)		$4.9mm^2$

Table 4.3: Measurements of areas of contact of the condyle on various condyle shapes

Figure 4.44, shows stress calculations for the three different shapes of condyle. These show that the stress values for $20mm^2$ and $4.9mm^2$ areas of contacts are insignificant, and even the $1mm^2$ stress values are of a relatively low magnitude. A further drawback to the above stress calculations is that the condyle is simultaneously rotating and translating during mouth opening.

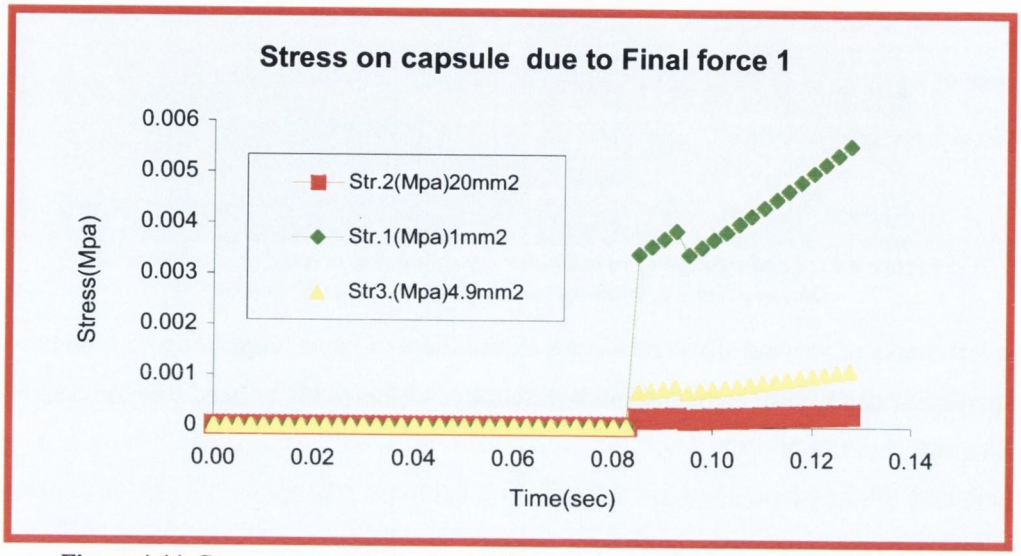


Figure 4.44: Stress on capsule for the minimum, maximum and mean area of contact

4.6.7 Discussion on Retroflexion Forces (constant acceleration)

At rest gravity is tending to separate the condyle from the glenoid fossa. This separation is prevented by the physical support of the capsule/ ligament complex.

The condyle is maintained in a state of constant readiness, by a complex feedback system. This system consists of proprioceptive neural receptors in the ligament /capsule complex, which relay information regarding condyle position to the higher centres. The higher centres in turn send commands to the muscles controlling mandibular movement (Kawamura et al 1967).

When retroflexion occurs the cranium is carried upward and backward away from the mandible, which is attempting, but failing to maintain its position in space. Thus a tensile force is created in the capsule/ligament complex connecting the mandible to the cranium. Depending on the amount of "slack" in the capsule ligament complex prior to retroflexion, some translation of the condyle on the posterior slope of the articular eminence may occur at this time. When sufficient tension has built up in these tissues the mandible is carried backward with the cranium.

Due to the resistance of the mandible to backward movement mouth opening occurs by rotation of the cranium away from the mandible. This results in a build up of tension in the TMJ ligament, which imposes a translatory force on the condyle. Thus the second stage of mouth opening consisting of a combination of rotation and translation occurs.

Therefore Final force 1 in the early part of retroflexion consists entirely of pulling forces (F1a1 from t = 0.03 sec to t = 0.06 sec).From t = 0.0625 sec to t = 0. 08 sec, Final force 1 consists of a combination of pulling forces (F1a1) and translatory forces (F1c1), and is acting while the condyle is on the posterior slope of the articular eminence. A peak force on each condyle of 4 Newtons is reached during this period.

The direction of the force acting on the condyle during this period is downward and forwards relative to the Frankfurt plane (Figure 4.41). This results in tensile force acting on the capsule ligament complex. Up to this point the posterior attachment is unfolding and lengthening to accommodate the normal range of condyle/disc movement, and thus is not challenged during this period.

From t = 0.0825 sec to t = 0.0925 sec the condyle is on the anterior slope of the eminence with Final force 1 still acting on it. The force magnitudes during this period are lower due to the increasing effect of gravity, with a peak force of approx 2.5 Newtons at t = 0.0925 sec. The direction of the force during this period is still downward and forward (Figure 4.42). This force is tensile on the capsule ligament complex and now also on the posterior attachment which is functioning beyond its normal limits. Compressive forces are now also occurring on the anterior part of the joint capsule, as the lower joint compartment is fully occupied by the condylar head.

From t = 0.095 sec. to the end of the event at t = 0.1275 sec., Final force 1, acting on the condyle consists of pulling forces only, translation having being completed. The peak force during this period is approx 5.5 Newtons and occurs at t = 0.1275 sec. The force direction at this stage is downward and backward (3rd Quadrant of the Frankfurt plane complex). This force is still tensile on the capsule/ligament complex but acting on different fibres. It is also tensile on the posterior attachments.

Superimposed on the Final force 1 are reaction forces due to mouth opening which occur in the TMJ/capsule complex.

Mouth opening forces due to angular displacement (F1b1), act through the centre of mass of the mandible. As the centre of rotation lies in the condylar head, no forces are sustained in this region. However, reaction forces occur in the peripheral aspects of the TMJ, for example in the ligament/capsule complex. Thus the force magnitude range affecting the middle fibres of the capsule/ligament complex of one joint was calculated at 100 to 106 Newtons (t = .0625 to 0.07sec). These forces are of a far greater magnitude than those occurring in Final force 1,

and may act by challenging the strain rate capacity of the tissues as they occur over a very short period of time. It should be mentioned that the jaw muscles and ligaments can be "taken by surprise", under relatively normal circumstances when the mouth is suddenly opened voluntarily in the absence of external trauma. Human tissues were fundamentally designed to function within certain time parameters. A sprinter will not tear a Hamstring due solely to the magnitude of the load, but also and maybe more significantly as a result of the time period over which the load is applied.

Damage to these capsular and ligamentous tissues may cause disruption of normal jaw movement by interfering with their proprioceptive function (Kawamura et al 1967, Okeson 1995). Furthermore at the attachment of the disc to the lateral pole of the condyle, the capsular and discal tissues are contiguous. Thus the attachment of the disc to the condyle may be indirectly challenged by any forces which are acting on the capsule /ligament complex. A common finding during TMJ corrective surgery is a loss of attachment of the disc to the lateral pole of the condyle and antero-medial displacement of the disc (Leopard 1984).

4.7 Force calculations using variable acceleration

The use of constant acceleration is a useful guide to the magnitude and direction of the forces. However, in order to gain greater insight into the more precise nature of the forces, it was decided to carry out a second set of calculations using variable acceleration. These calculations were performed in a similar manner to those using constant acceleration. However the estimated values for instantaneous acceleration, and velocity were used here.

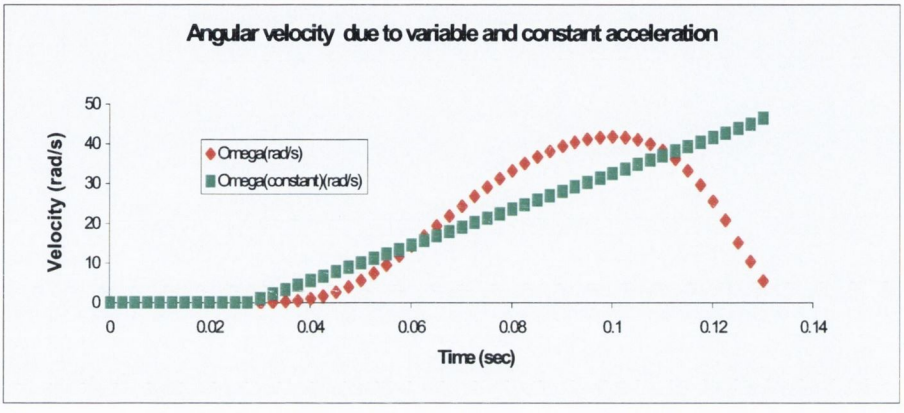


Figure 4.45: Comparison of angular velocity using variable and constant acceleration

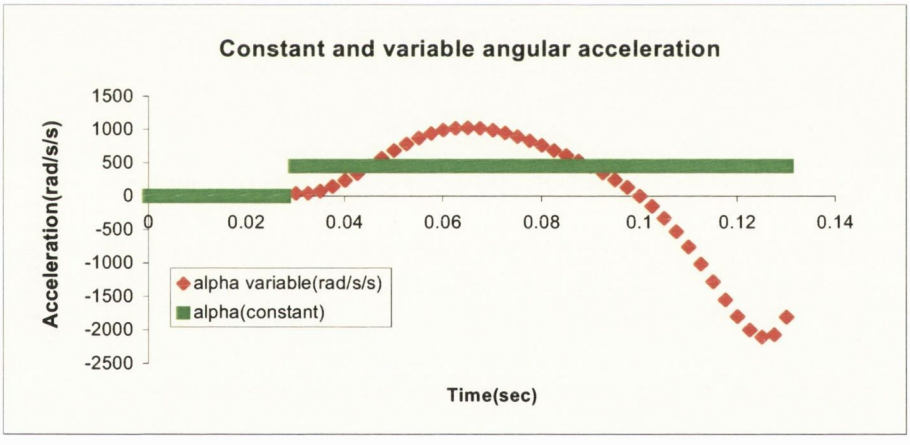


Figure 4.46: Comparison of variable and constant angular acceleration in retroflexion

Bearing in mind that F_n is dependent on angular velocity (ω) and F_t is dependent on angular acceleration (α), it is worth comparing the values for both when using constant and variable acceleration (Figures 4.45 & 4.46).

Variable ω peaks earlier than constant ω but the peak values for both are approximately the same. The peak values for F_n in both circumstances would therefore be similar.

Variable α reaches a peak value of approximately twice that of constant α and has an even greater negative peak value. Therefore F_t calculations using variable and constant acceleration would be expected to differ considerably.

4.7.1 Pulling Force 1a2

All values were calculated as in force 1a1, with the exception of F_n1a2 calculations where ω^2 was not substituted by $(\alpha t)^2$ in the formula: $F_n = m\omega^2 r$.

Figure 4.47 shows the pulling forces calculated using variable acceleration. The F_n1a2 curve has a similar outline to the angular velocity curve (Fig 4.45). Initially gravity only is acting on F_n and therefore it has a low +ve value. After the start of retroflexion the total value for F_n is increasing due to increasing angular velocity up to t = 0.1 sec, and due to the increasing influence of mgcosβ which is acting in the same direction. From t = 0.1025 sec, to the end of the event angular velocity is decreasing. During this period mgcosβ is still acting in the same direction as F_n but is decreasing in magnitude. Mgcosβ in fact is acting in the opposite direction to F_n for only one time increment at the end of the retroflexion event (t = 0.135 sec).

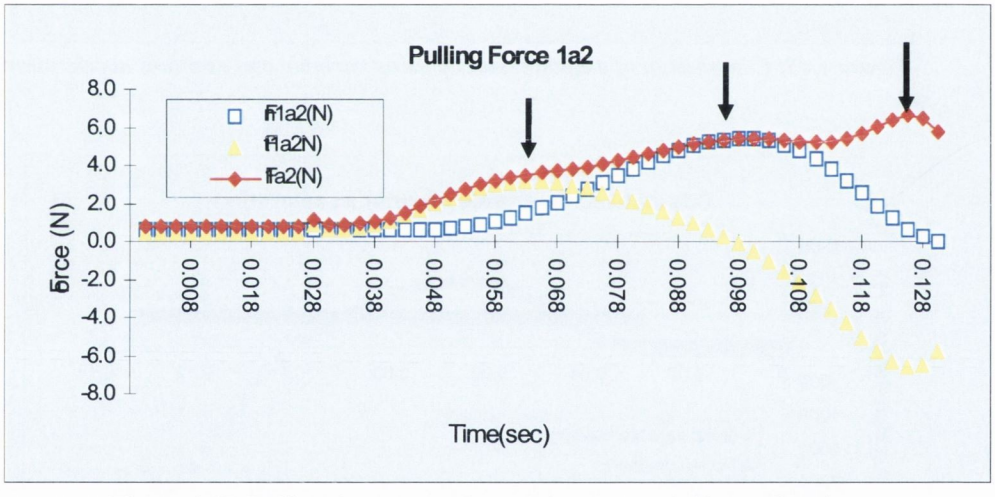


Figure 4.47: Pulling force on each condyle using variable acceleration. The peaks in force magnitude are arrowed.

From t = 0.03 sec to t = 0.065 sec angular acceleration is increasing. During this period mg Sinβ is acting in the same direction to F_t but with decreasing effect. From t = 0.0675 sec to t = 0.095 F_t is falling due to decreasing acceleration. During this period mg sinβ is acting in the same direction as F_t with decreasing effect up to t = 0.08 sec.

From t = 0.0825 to t = 0.1 sec mg Sinβ is acting in the opposite direction to F_t and is increasing in value. From t = 0.1025 sec to the end of the event the head is in -ve acceleration. During this period mg is acting in the same direction as F_t with increasing magnitude.

The resultant pulling force has three peaks. The first has a value of 3.6 Newtons on each condyle and occurs at t = 0.065 sec. This coincides with peak angular acceleration. The second has a value of 5.5 Newtons and is due to peak velocity which occurs at the end of the acceleration (t = 0.0975 sec). This is followed by a minor trough from t = 0.1 sec to t = 0.1175 sec, due to falling angular velocity and minimal negative acceleration. The final peak has a value of 6.6 Newtons and coincides with peak deceleration (t = 0.125 sec).

4.7.1.1 Direction of Pulling Force F1a2

As in F1a1 gravity only is acting on the system prior to head retroflexion. This places F1a2 on the negative Y-axis of the Frankfurt plane co-ordinate system. At the start of retroflexion from t = 0.03 sec to t = 0.075 sec F_t becomes more dominant. Thus the angle increases in value moving F1a2 into the 4th Quadrant of the Frankfurt plane system (Figure 4.48.). From t = 0.0775 sec to t = 0.115 sec F_n is dominating due to increasing angular velocity and decreasing angular acceleration. The angle accordingly falls in value, which places F1a1 in the 3rd Quadrant of the system.

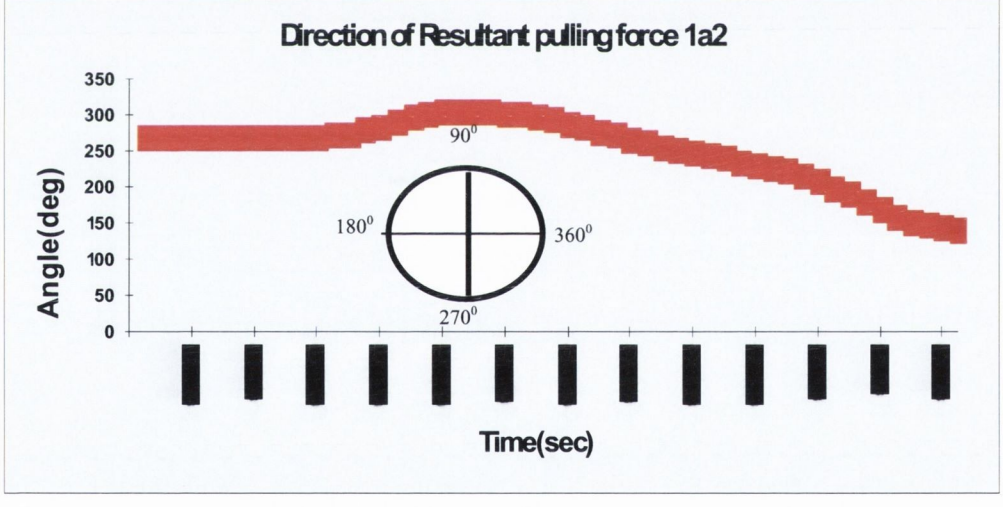


Figure 4.48: Direction of resultant pulling force 1a2 in head retroflexion

The direction, and Fx and Fy components of force 1a2 are shown in figure 4.48 and 4.49. The full implication of these forces will not be seen until summation with force 1c2 in Final force 2.

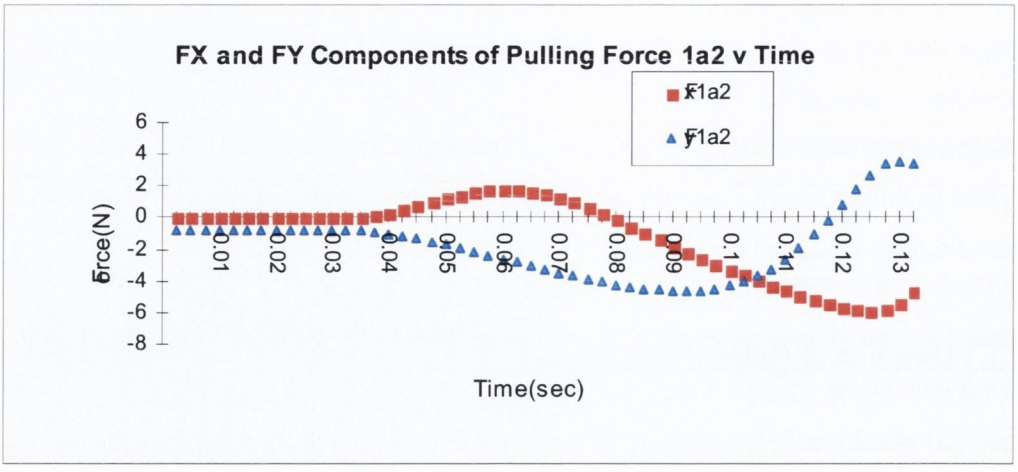


Figure 4.49: Fx and Fy components of pulling force relative to the Frankfurt plane

When the resultant force F1a1 is compared to the resultant force F1a2 it can be seen that constant acceleration gives a reasonable estimate of force magnitude. It does not however take into account the peaks and troughs of force given by using variable acceleration (Figure 4.50). The full effect of the pulling force F1a2 will not be realised until summation with forces due to anterior translation (F1c2) has been carried out, which will be seen in Final force 2.

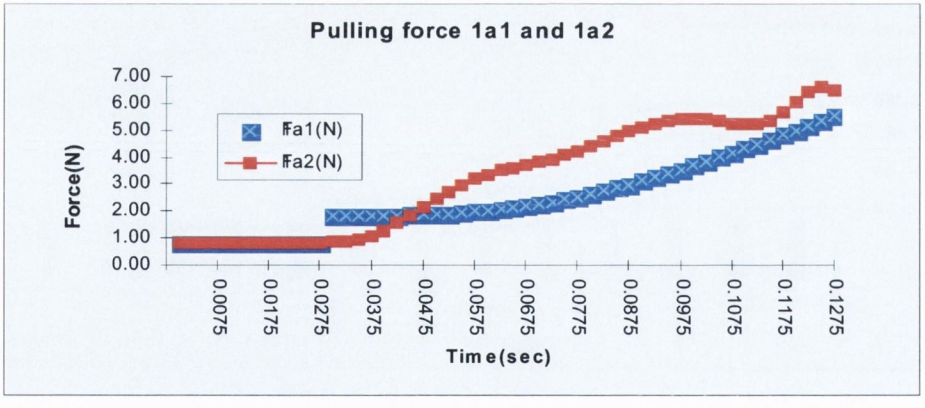


Figure 4.50: Comparison of resultant force due to constant (F1a1) and variable acceleration (F1a2)

4.7.2 Mouth opening force 1b2

Mouth opening forces due to angular displacement are shown in figure 4.51. The calculation of these forces was carried out in similar manner to those for force 1b1, with the exception that in the formula $F_n = m\omega^2 r$, ω^2 was not substituted by αt^2.

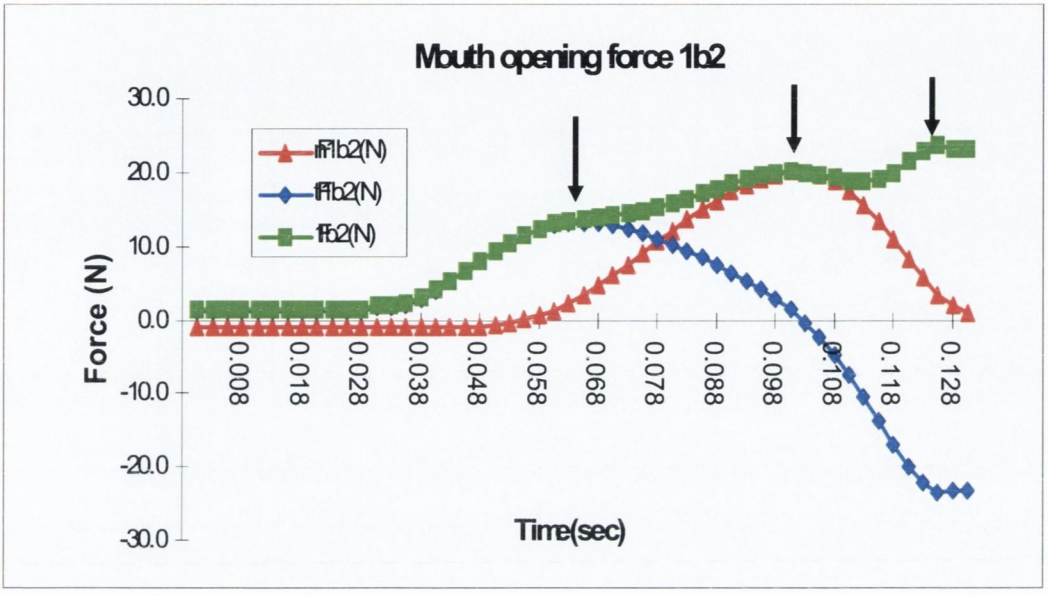


Figure 4.51: Mouth opening forces due to angular displacement (variable acceleration)

The tangential force F_t1b2 has a configuration similar to that representing angular acceleration of the cranium, as it is primarily dependent on this element.

Accordingly the normal force Fn1b2 has a shape similar to the angular velocity curve.

The resultant force F1b2 has three peaks in magnitude, which are related to peak angular acceleration, at t = 0.065sec peak angular velocity at t = 0.1sec and peak angular deceleration at t = 0.125Sec.

The forces calculated above are passing through the centre of mass of the mandible. As the centre of rotation lies on an axis which passes through the condyles no forces are occurring in this area.

Reaction forces are occurring in the soft tissues adjacent to the condyle and are considered below.

4.7.2.1 Direction of F1b2

Figures 4.52 and 4.53 show the direction of F1b2 relative to the Frankfurt plane. Prior to head retroflexion the angle δ lies on the negative y-axis of the Frankfurt plane.

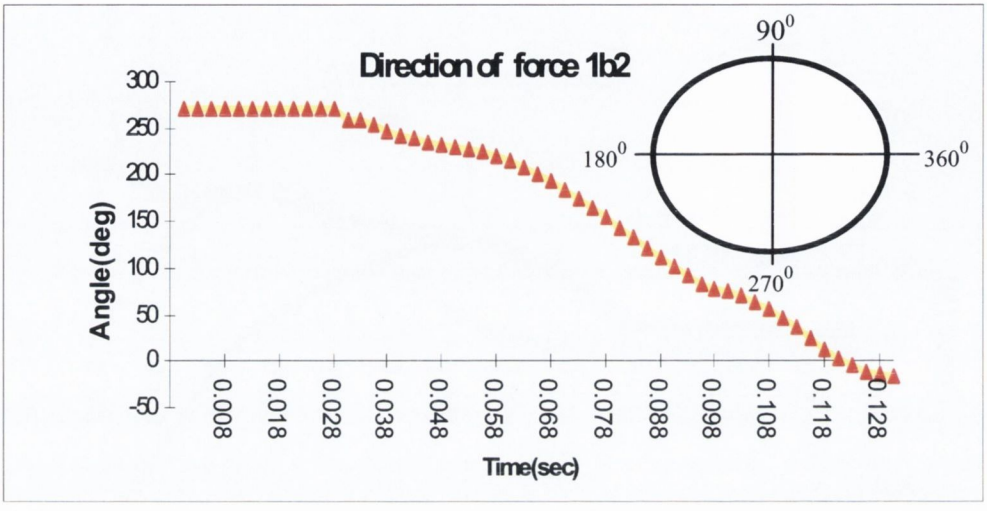


Figure 4.52: Direction of mouth opening force F1b2

As mouth opening continues the direction of the force moves through the 3rd, 2nd and 1st Quadrants of the Frankfurt plane co-ordinate system, until at the end of mouth opening it has entered the fourth Quadrant giving it a negative value at this point.

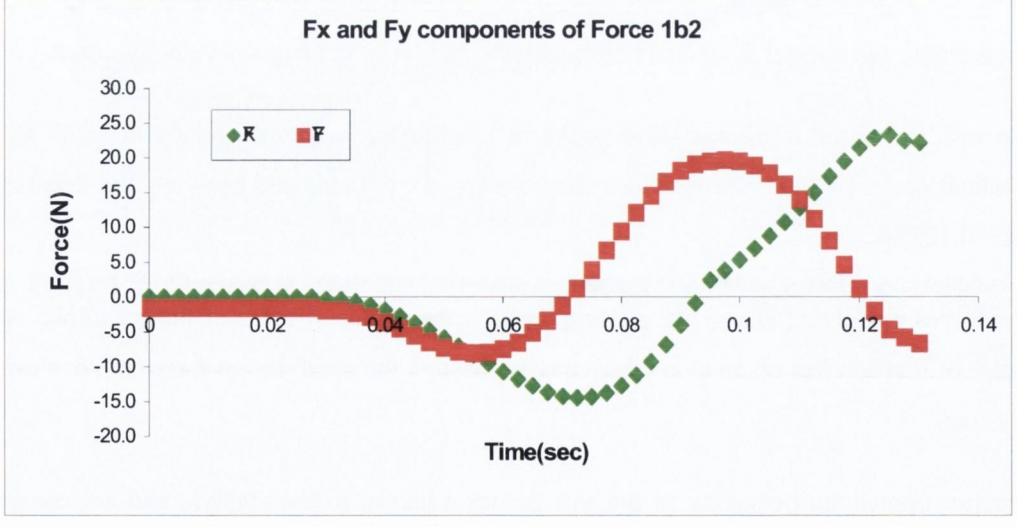


Figure 4.53: Fx and Fy components of resultant F1b2

4.7.2.2 Reaction force in the TMJ Ligament

The reaction force in the ligament is shown in figure 4.54. As translation of the condyle does not commence until 15° of mouth opening has taken place the ligament was assumed to be loaded for a short period of time (from t = 0.065sec to t = 0.0725sec).

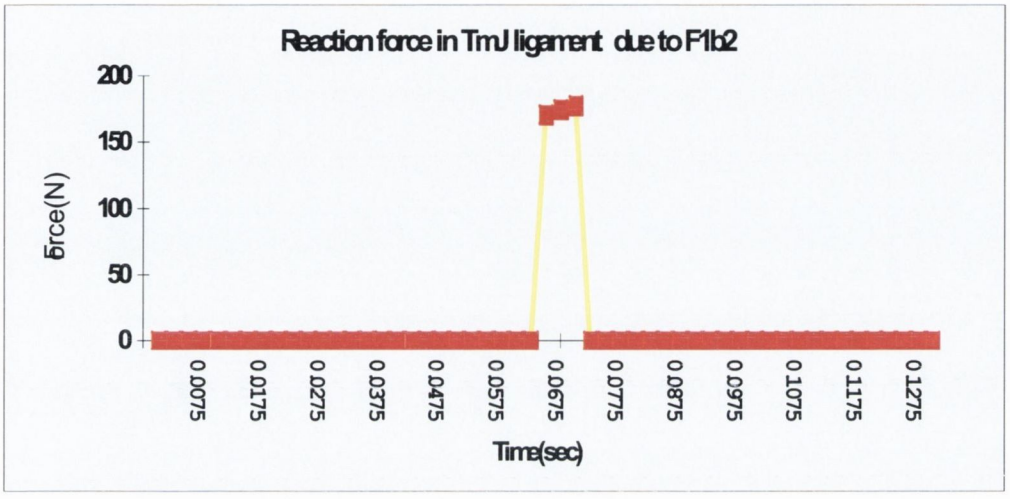


Figure 4.54: Reaction force in one TMJ ligament due to mouth opening force 1b2

As condylar translation is considered to be a "slip stick" type of mechanism any loading after initial movement would be insignificant.

Whereas mouth opening and retroflexion by definition commence simultaneously, some retroflexion occurs after the end of mouth opening (Figure 4.55).

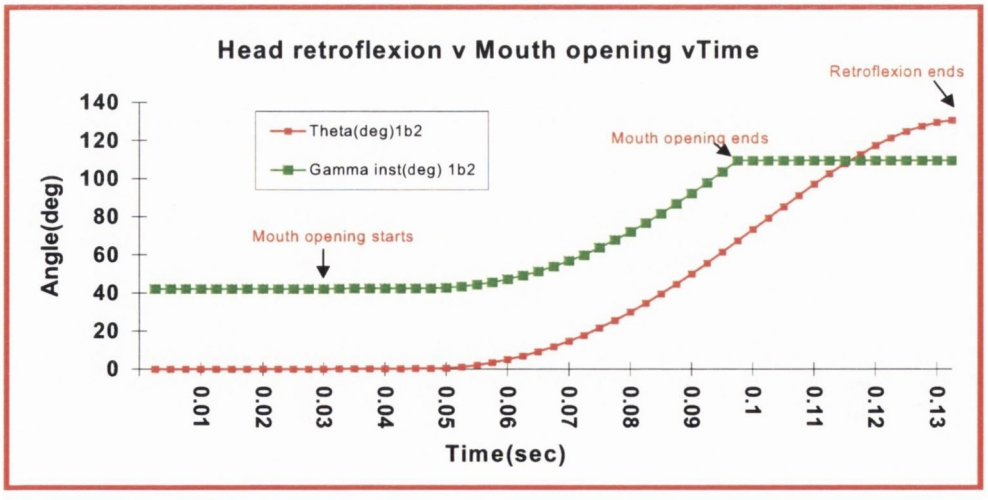


Figure 4.55: Relation of mouth opening to retroflexion using variable acceleration

4.7.3 Translation Force1c2

These calculations were made in the same manner as in force 1c1. Figure 4.56 shows the relationship between angular displacement and anterior translation in mouth opening.

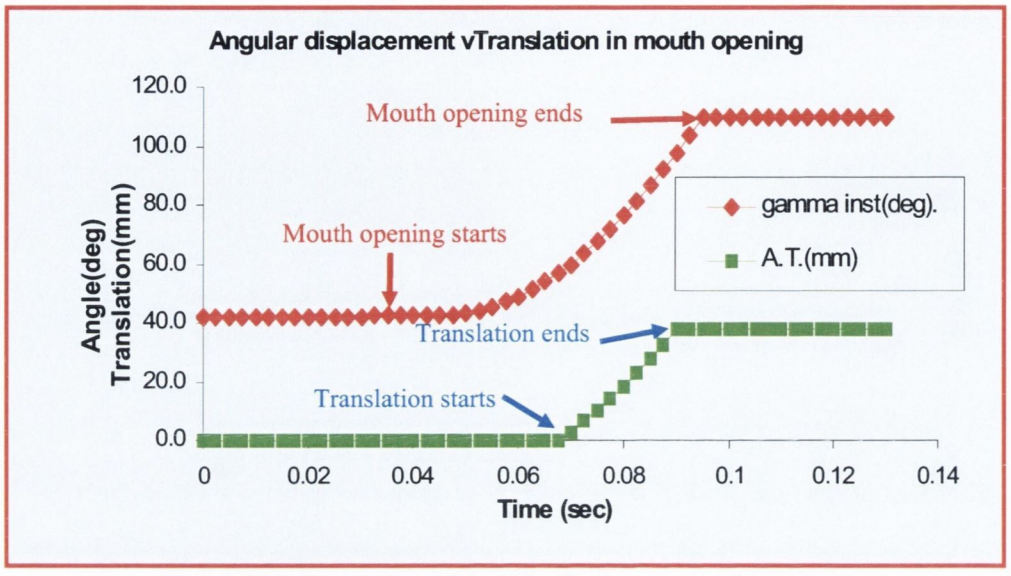


Figure 4.56: Comparison of Angular displacement and translation

When using variable acceleration, rotation is also a shorter event and mouth opening is completed earlier. Therefore, peak forces are reached at an earlier stage. With variable acceleration retroflexion continues for 0.035 sec after the end of mouth opening. Some jaw rotation also takes place after the end of translation (Figure 4.56). When compared to that seen in constant acceleration some variations are apparent. In the variable acceleration calculation, anterior translation is a shorter event, starting and finishing earlier than with constant acceleration (Figure 4.57).

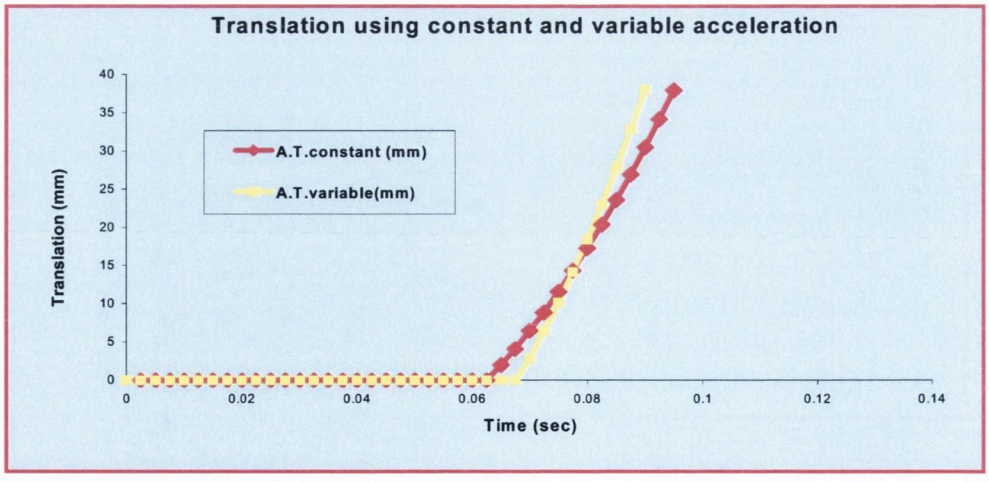


Figure 4.57: Comparison of translation using constant and variable acceleration

4.7.3.1 Calculation of linear variable acceleration

Variable linear acceleration (Figure 4.58) was calculated in the same manner as constant linear acceleration.

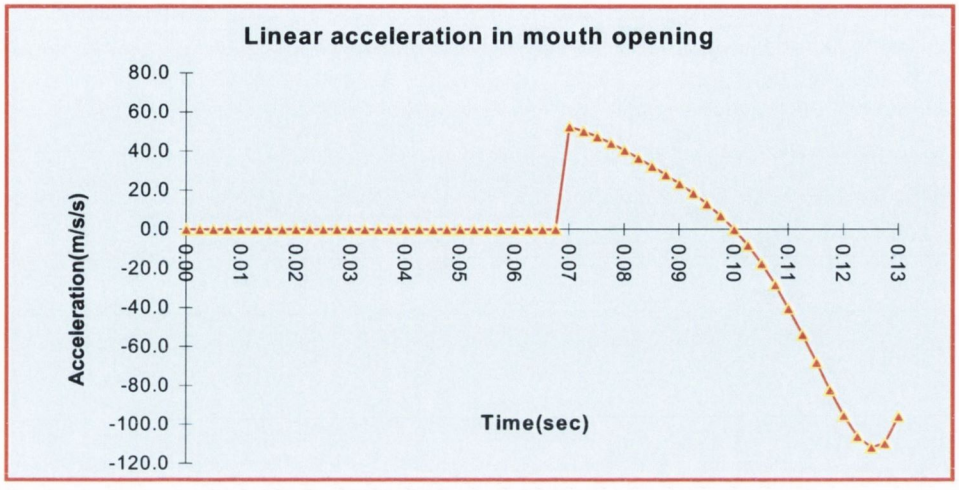


Figure 4.58: Linear acceleration in anterior translation

However as translation is taking place over a shorter time than angular displacement, linear acceleration was calculated from the period in the event from which translation starts (t=0.0675sec).

4.7.3.2 Calculated values for F1c2

F1c2 has a slightly different pattern to F1c1 (Figures 4.59 and 4.61). For example in F1c2, the condyle spends a relatively short time on the posterior slope of the articular eminence (0.0075sec), and the peak force (4.5Newtons) occurs at the outset of translation. This is due to peak acceleration occurring in the early stages of the event.

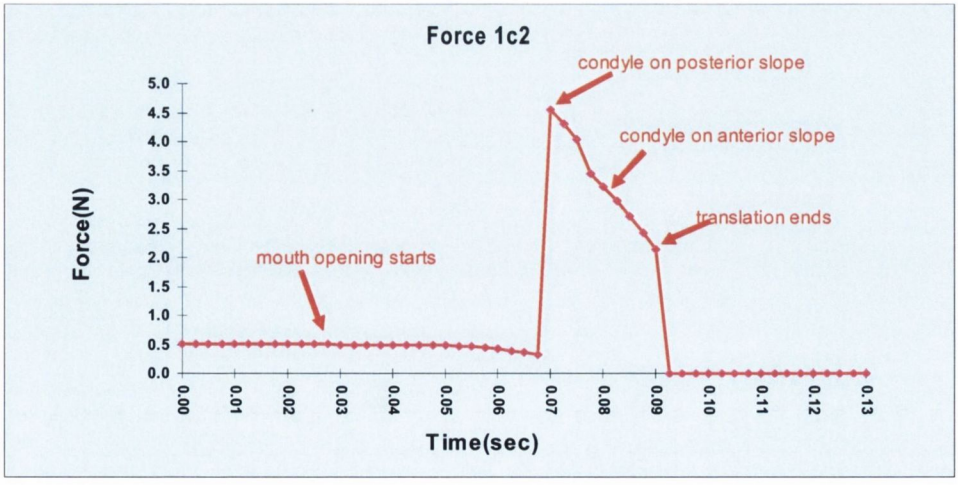


Figure 4.59: Force on each condyle due to linear acceleration in anterior translation

4.7.3.3 Fx and Fy components of F1c2

The Fx and Fy components of F1c2 are shown in figure 4.60

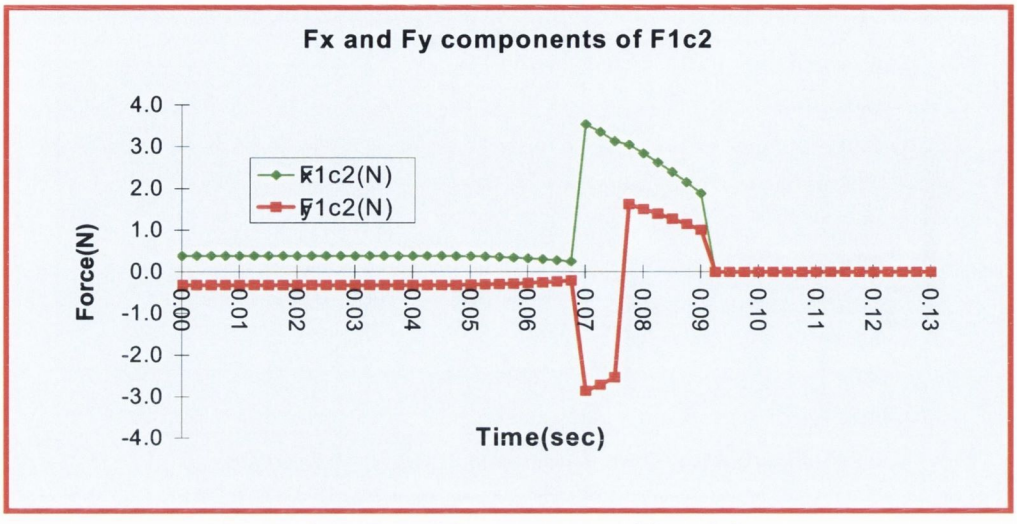


Figure 4.60: Fx and Fy components of force 1c2

4.7.3.4 Comparison of Forces 1c1 and 1c2

When forces F1c1and F1c2 are compared it can be seen that F1c2 reaches a value of Approximately twice that of F1c1, and that F1c1 has negative value at the end of translation not seen in F1c2 (Figure 4.61).

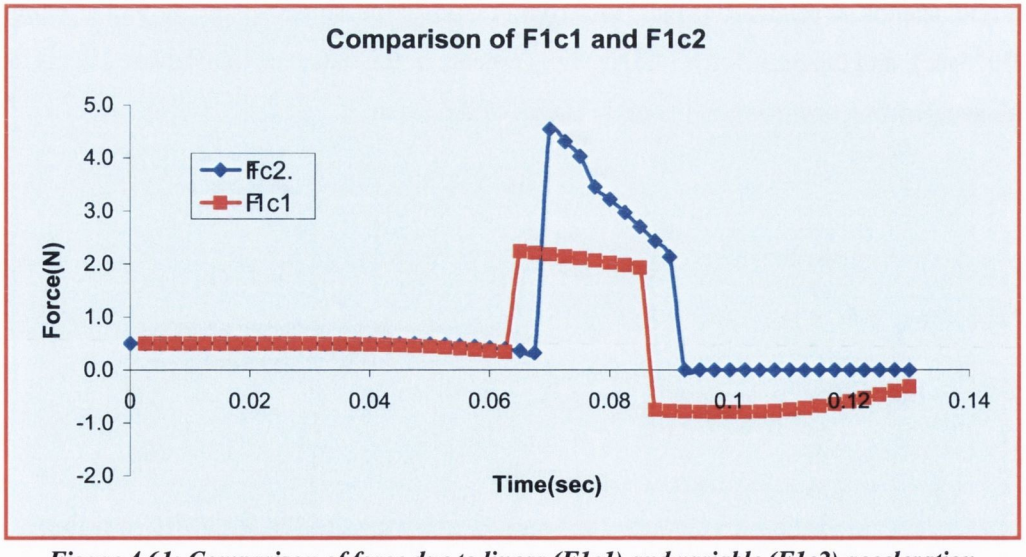


Figure 4.61: Comparison of force due to linear (F1c1) and variable (F1c2) acceleration

4.8 Final Force 2

Final Force 2 consists of a summation of force 1a2 and force 1c2 (Figure 4.62), and was calculated in the same manner as Final Force 1.

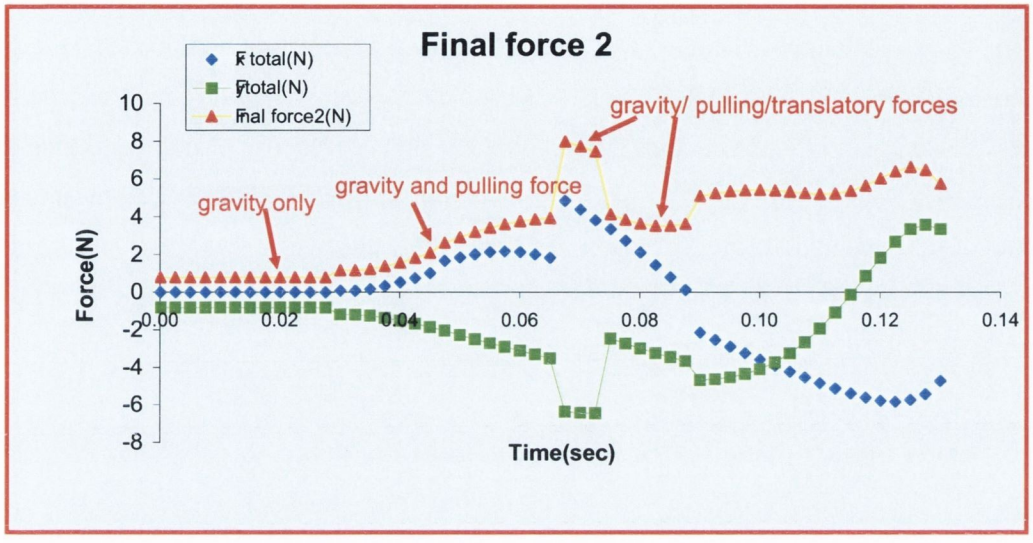


Figure 4.62: Final Force 2 with its Fx and Fy components

From t = 0.03 sec to t = 0.0675sec, gravity and pulling forces are acting on the condyle. The direction of the force during this period is downward and forwards (4th Quadrant of the Frankfurt plane system), (Figure 4.63). From t = 0.07 sec to t = 0.0775 sec gravity, pulling, and translation forces are acting, the condyle being on the posterior slope of the eminence. During this period the direction of the force continues to be downward and forward and is thus tensile on the capsule/ligament complex. From t = 0.08 sec to t = 0.09sec, gravity, pulling, and translatory forces are acting while the condyle is on the anterior slope of the eminence (Preglenoid Plane).

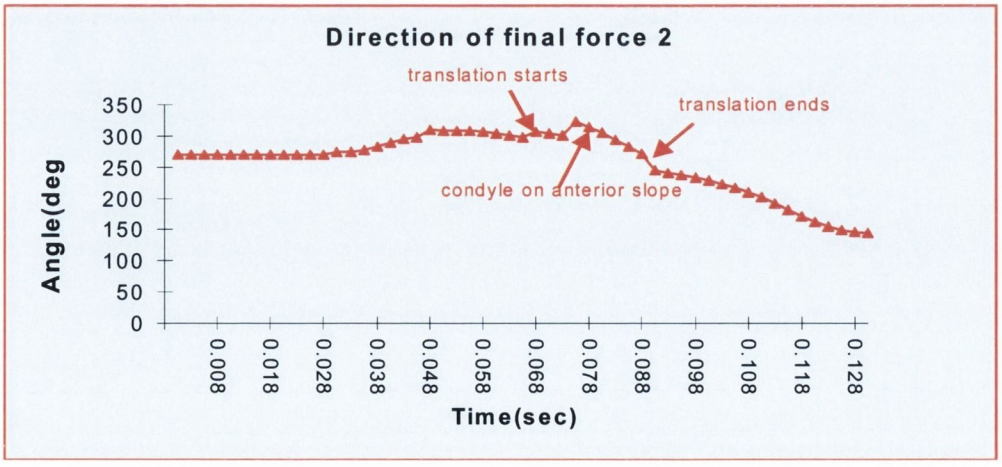


Figure 4.63: Direction of Final Force 2 relative to the Frankfurt plane

The direction of the force at this stage is still downward and forward being tensile on the capsule/ligament complex and on the attachment of the disc to the condyle. However at this stage the condyle has moved beyond its normal limits and thus the posterior attachment is also being subjected to tensile forces. Furthermore, the anterior compartment of the lower joint space is now fully occupied and the anterior part of the joint capsule and other soft tissues in this region are subjected to compressive forces. The peak force acting on the condyle during this period is 8 Newtons at t = 0.07 sec. From t = 0.0925 sec to the end of the event, pulling forces only are acting on the condyle, (translation having ended). The peak force during this period is 6.6 Newtons at t = 0.125 sec. The direction of the force is now downwards and backwards (3rd Quadrant). This is largely due to the high negative accelerations, occurring at this time. Superimposed on Final force 2 is the force reacted within the ligament (From 0.06 sec. to 0.0725 sec.), due to mouth opening (Force 1b2).

4.8.1 Stress on Anterior Capsule due to Final Force 2

Stress on the anterior capsule due to final force 2 was calculated in the same fashion as in Final force 1.

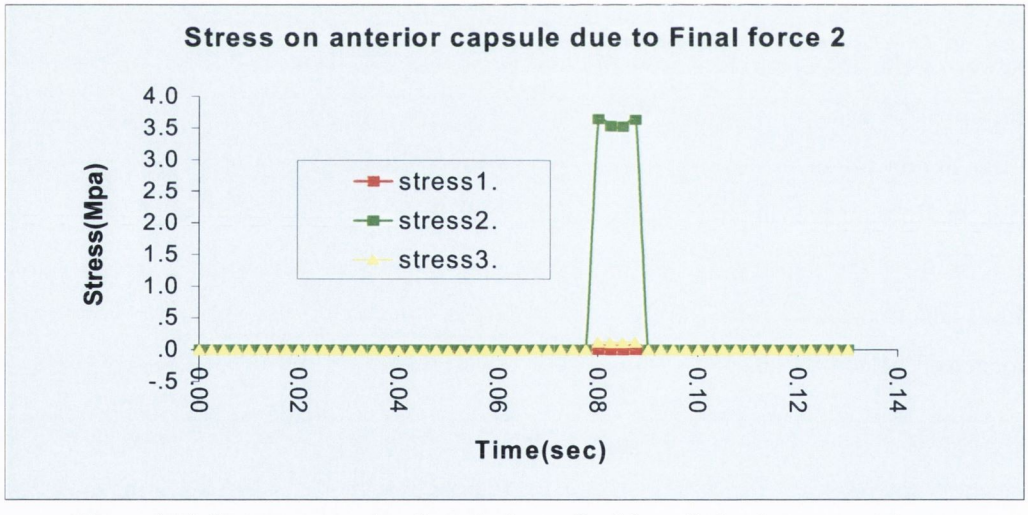


Figure 4.64: Stress on Anterior Capsule due to final force 2, for three areas of contact

Stress on the capsule only occurs when the anterior compartment of the inferior joint space is fully occupied (Figure 4.64), i.e., when the condyle is on the anterior slope of the articular eminence (from t = 0.08 sec to t = 0.09 sec). After anterior translation has been completed the direction of Final force 2 is downwards and backwards away from the capsule which is thus being decompressed.

4.8.2. Comparison of Final force 1 and Final force 2

When final Force 1 and 2 were compared it was seen that the build up of magnitude in Final force 2 was much more rapid than in Final Force 1, and also reached a considerably greater magnitude (Figure 4.65). Furthermore the peak value for Final force 2 occurs at a much earlier stage in the event. These factors bring in to question the strain rate response of the soft tissues of the joint. This may be a critical factor in the aetiology of soft tissue damage.

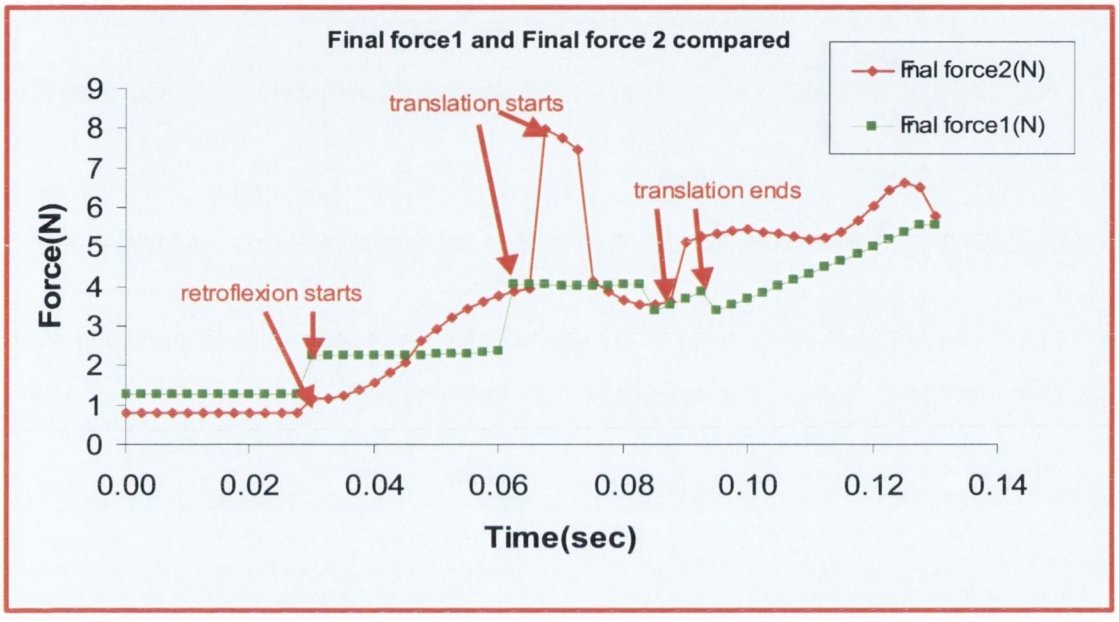


Figure 4.65: Comparison of Final force 1 and Final force 2

4.9 Conclusions on Forces in Retroflexion

The forces affecting the TMJ in the retroflexion phase of the whiplash event were identified as pulling forces, and mouth opening forces due to both linear and angular displacement. Pulling forces and forces due to linear displacement act directly on the TMJ and were summed to find the nett force on the condyle. This results in the capsule/ligament complex being subjected to tensile forces throughout most of the event. Damage to these tissues can adversely affect jaw movement and function by disruption of its proproceptive neuromuscular feed-back mechanism. Tensile forces are also sustained by the posterior attachment in the latter part of the event when the condyle has translated beyond the crest of the articular eminence. The posterior attachment, which has a rich nerve and blood supply, can be torn

causing micro bleeding and damage to nerve fibres (Murakami 1989). This can lead to post traumatic inflammation and considerable tenderness of the tissues in the posterior aspect of the joint (Kawamura 1968, Okeson 1995). The anterior part of the joint capsule is also subjected to compressive forces during the later stage of anterior translation. This force is converted into stress, the magnitude of which is dependent upon the shape of the anterior part of the head of the condyle. Whether damage occurs to any of the above tissues depends on the magnitude of the force, the length of time over which it is occurring, and the relative strength of the various tissues involved.

Mouth opening forces due to angular displacement of the cranium were also calculated. The peak forces passing through the centre of mass of the mandible were of the order of 25 Newtons. These forces were predicted to cause reaction forces, in the capsule ligament complex, which are much greater than those passing through the COMM. This force reaches a magnitude of approximately 180 Newtons on each condyle. This may cause ligament damage, and damage to the attachment of the disc to the lateral pole of the condyle. At this point of attachment the condyle, disc, and capsule are intimately attached to each other. Therefore forces sustained by the capsule are transmitted to the attachment of the disc to the condyle.

Tests carried out in this work show that the attachment of the disc to the lateral pole of the condyle is relatively weak. Impact testing showed an attachment breaking force of less that 10 Newtons. This is consistent with the clinical evidence, which shows that in a significant number of cases where anterior disc displacement has occurred there is loss of attachment of the disc to the lateral pole of the condyle. This results in the disc rotating anteriorly and medially whilst maintaining its attachment to the medial pole (Juniper 1981).

It should be noted that this work assumed a symmetrical distribution of forces. This implied that the forces affecting both joints would be identical. However it is reasonable to assume that in any MVA a degree of asymmetry will occur. Thus it is likely that the forces affecting one joint will be greater than those stated in this work.

4.10 Forces on TMJ in Flexion phase

The forces, which occur in flexion correspond to those, which occur in retroflexion but act in the opposite direction.

They can be listed as follows:

Force 2(a) Force due to pushing effect of the cranium on the TMJ during flexion. These will be termed 2a1 (using constant acceleration) and 2a2 (using variable acceleration).

Force 2(b) Force due to angular displacement of the cranium in mouth closing. These will be termed 2b1 (constant acceleration) and 2b2 (variable acceleration).

Force 2(c) Force on TMJ due to linear displacement of the condyle in mouth closing. These will be termed 2c1 and 2c2.

4.10.1 Pushing force 2a1

As in force 1a1 the cranium rotates around C_0. Again the forces were divided into tangential and normal (centripetal) components, and the effect of gravity was also taken into consideration.

4.10.1.1 Values calculated and formulae used

- Constant acceleration was (α) calculated at 138.9/rad/s^2 from the flexion portion of the Clemens and Burrow curve (1972), using the formula $\theta=\frac{1}{2}at^2$.
- Constant angular velocity (ω) was calculated by using the formula $\omega=\alpha t^2$.
- The total time in flexion was taken as t=0.19 sec.

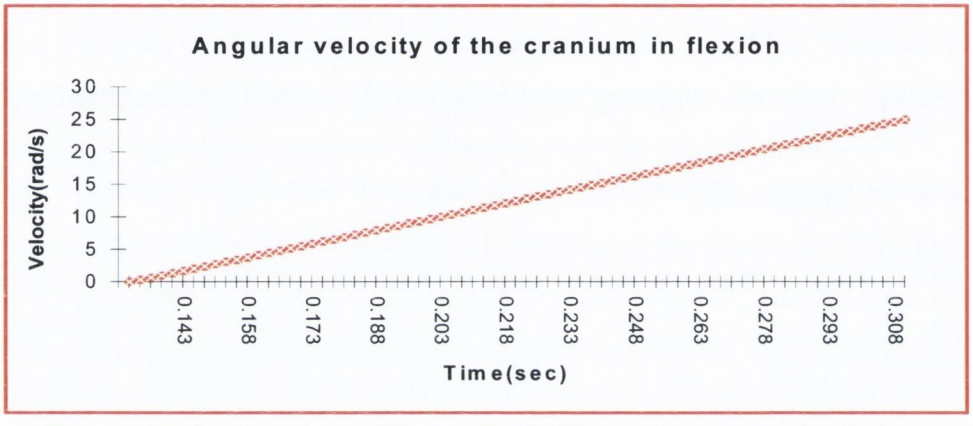


Figure 4.66: Angular velocity of the cranium in Flexion (constant acceleration)

It should be noted that flexion takes place over a time period of approximately twice that of retroflexion. The values for angular velocity (Figure 4.66), and angular acceleration are accordingly of lower magnitude.

4.10.1.2 Force Calculations

Pushing force calculations were made in a similar fashion to pulling forces in retroflexion, with the exception that tangential forces are in this instance calculated by $F_t=m\alpha r - mg\sin\beta$.

Pushing forces are shown in Figure 4.67. The value for F_t is of a low magnitude due to low angular acceleration. Gravity is acting in the same direction throughout most of the event but with decreasing effect. Therefore the total value is falling.

Toward the end of the event (from t = 0.323 sec to t = 0.35 sec) gravity is acting in the opposite direction to F_t . F_n starts as a negative value due to low initial angular velocity, and gravity acting in the opposite direction until t = 0.178 sec. From t = 0.18 sec., to the end of the event gravity is acting in the same direction as F_n. Thus the change in F_n throughout is

almost linear. The resultant force F2a1 is mainly under the influence of F_n2a1 due to the low values for F_t2a1.

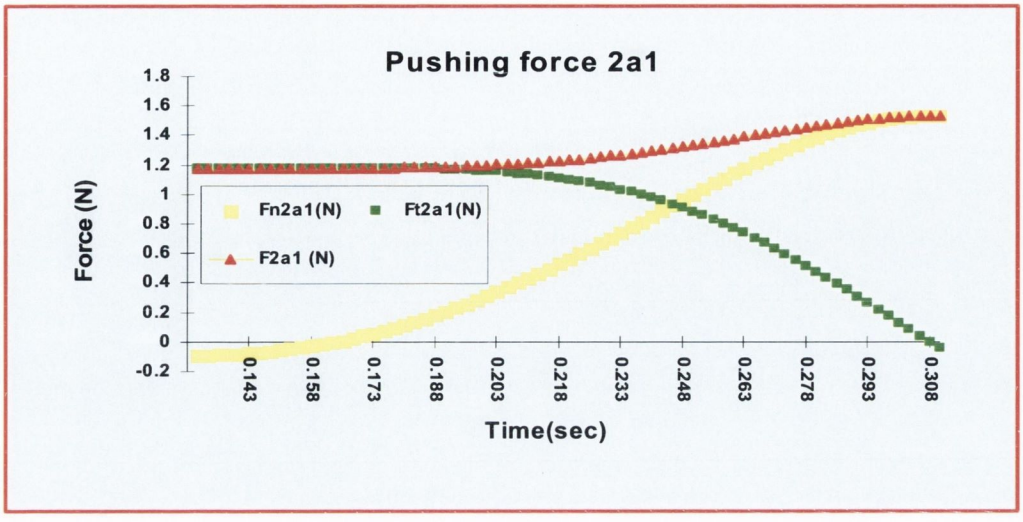


Figure 4.67: Pushing force 2a1 in Flexion (constant acceleration)

4.10.1.3 Direction of Resultant pushing force F2a1

From t = 0.130 sec to t = 0.215 sec, the direction of F2a1 is in the 2nd Quadrant of the Frankfurt plane system and is thus acting upward and backward (Figure 4.68). However during this period, the tissues in the posterior part of the joint are unloaded, as posterior translation is not completed until t = 0.230 sec.

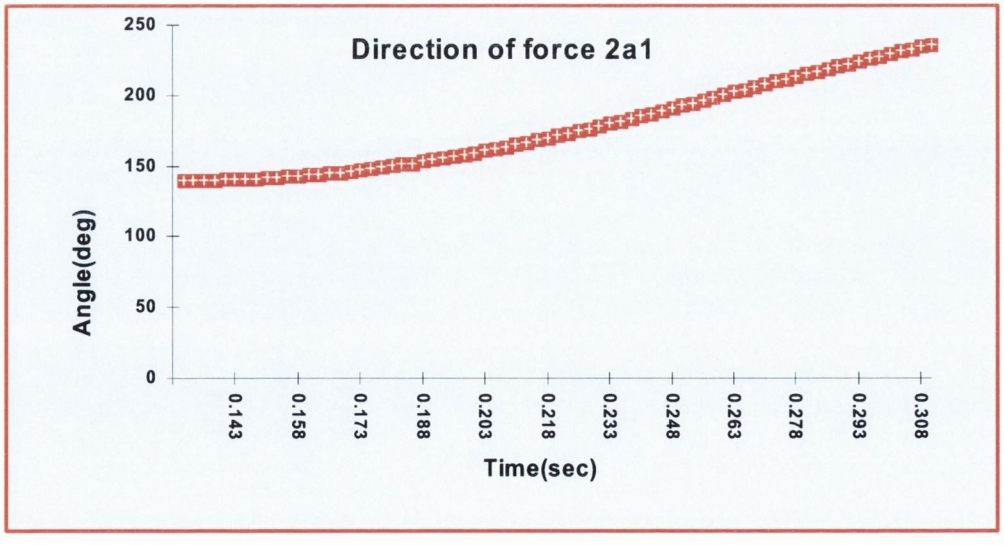


Figure 4.68: Direction of force F2a1

From t = 0.218 sec to the end of the event F2a1 is in the 3rd Quadrant (downward & backward). The posterior attachment tissues during this period are being subjected to compressive forces albeit of low magnitude. Fx and Fy components of F2a1 were needed for summation with F2c1 (Figure 4.69), in the calculation of Final force 3.

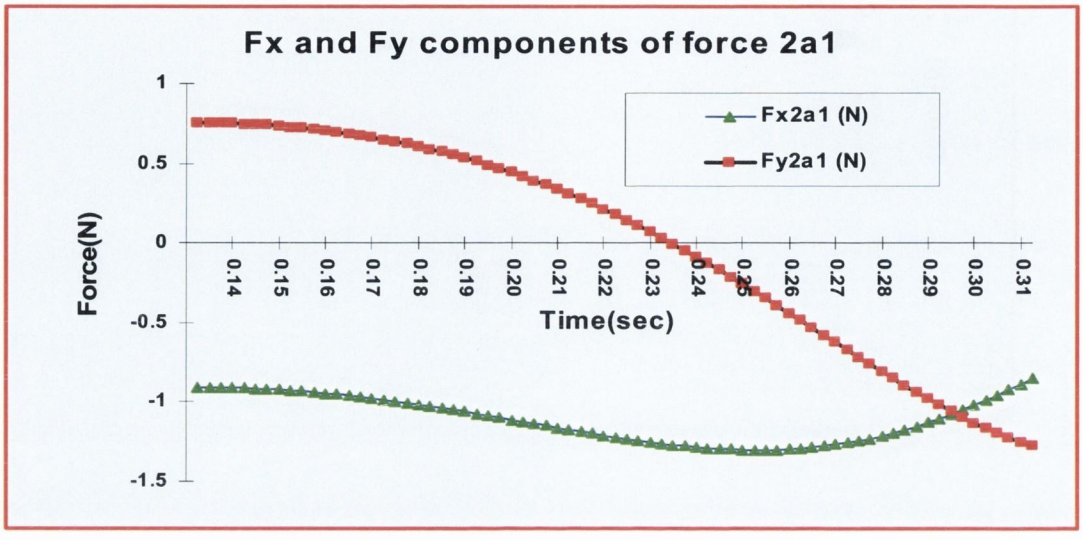


Figure 4.69: Fx and Fy components of pushing force F2a1

4.10.2 Mouth Closing Force 2b1

Mouth closing in whiplash is due to the involuntary movement of the cranium, which occurs in flexion, and is accomplished by the lowering of the maxilla on to the mandible. At the outset of mouth closing the mandible is not in a horizontal position but has rotated by approximately 60° due to the amount of retroflexion which has taken place after mouth opening has been completed (Figure 4.70). The angle epsilon and thus the effect of gravity on the centripetal and normal forces are constant until mouth closing is complete, after which the angle epsilon changes, thus altering the effect of gravity. Jaw closing is completed before the end of flexion (Figure 4.71).

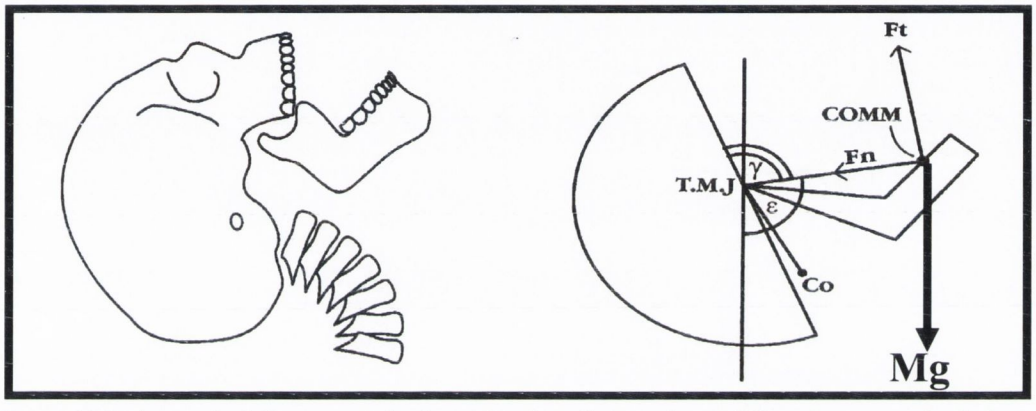


Figure 4.70: Anatomical diagram and schematic of cranium and mandible prior to mouth closing

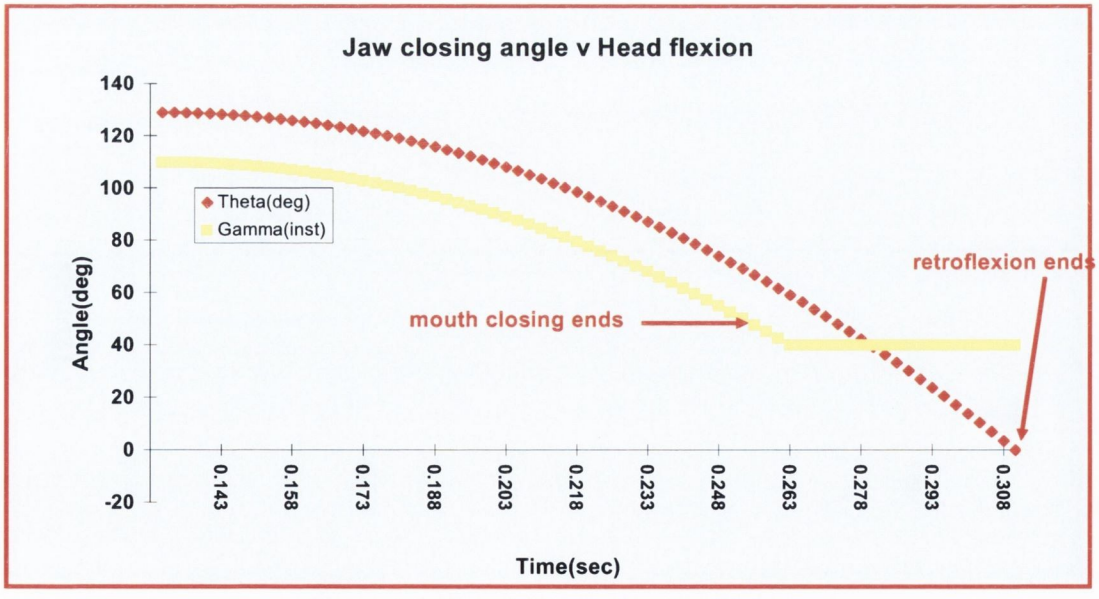


Figure 4.71: Jaw closing angle versus flexion

4.10.2.1 Values calculated in force 2b1

- The values for angular acceleration and velocity were the same as those used in pushing force F2a1 calculations.

- The forces were calculated in the same manner as those in force 1b1

Figure 4.72 shows the forces calculated. F_t 2b1 is influenced by angular acceleration, which is a constant. It is also affected by gravity which is acting in the opposite direction and is constant until mouth closing is completed (t = 0.2625 sec).

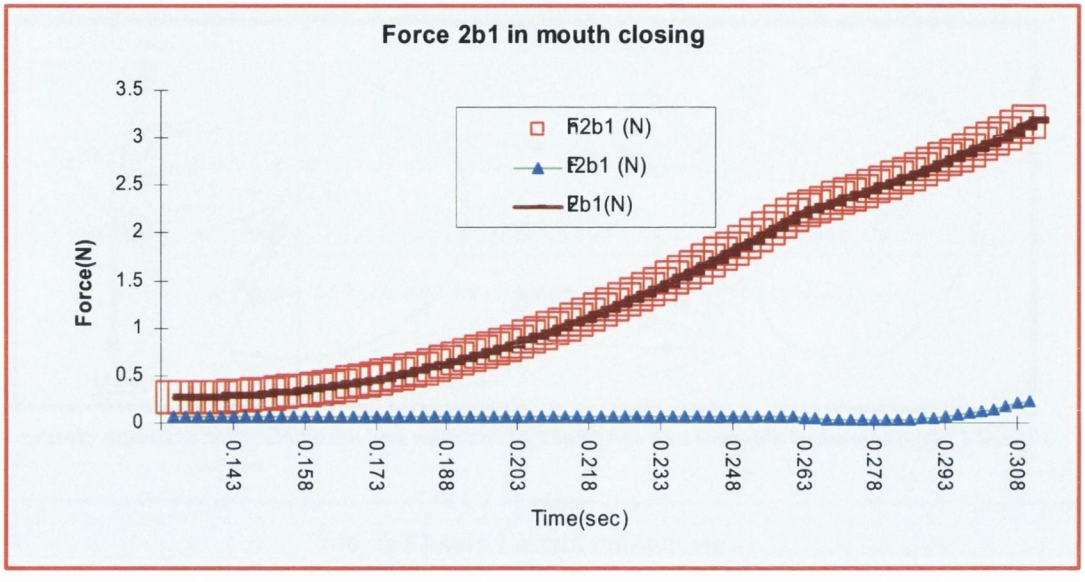


Figure 4.72: Mouth closing forces in flexion

After mouth closing is completed the value for the angle ε falls and the influence of gravity is reduced. The value for F_t is thus slightly increased (from t = 0.265sec to t = 0.310sec). F_n is influenced by angular velocity, which increases at a constant rate throughout the event.
From t = 0.130sec, to t = 0.2750 sec, gravity is acting in the same direction as F_n. After the end of mouth closing the influence of gravity on F_n is reduced. From t = 0.2775sec to the end of the event gravity is acting in the opposite direction to F_n. The resultant force F2b1 is superimposed on the F_n2b1 curve as the influence of F_t2b1 is negligible. During mouth closing the TM ligament is being unloaded. Therefore no reaction forces occur in the ligament/capsule complex as in mouth opening.

4.10.2.2 Direction of resultant force F2b1

Figures 4.73 and 4.74 show the direction of the resultant force F2b1 relative to the Frankfurt plane. F2b1 remains in the 1st Quadrant of the F_t/F_n co-ordinate system, throughout the event. Its' increasing value is largely due to the decreasing value of γ_l during flexion, and to a lesser extent the decreasing value ofϕ.

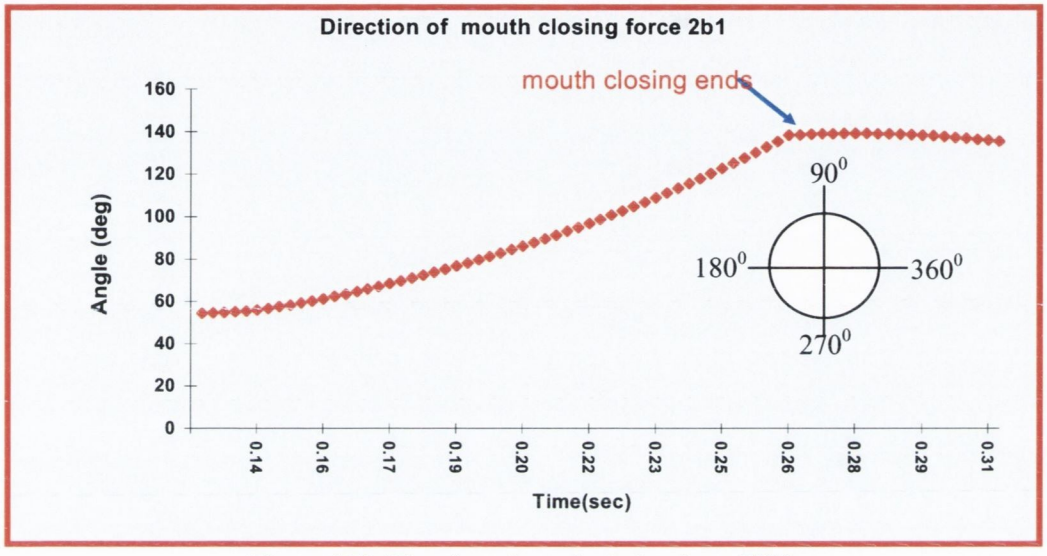


Figure 4.73: Direction of mouth closing force F2b1

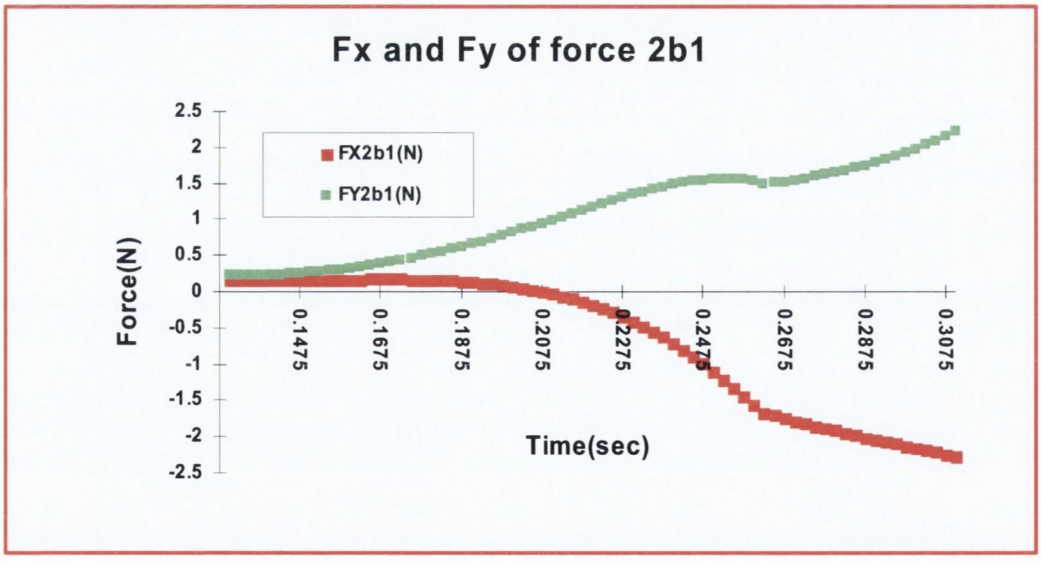


Figure 4.74: Fx and Fy components of mouth closing force F2b1

F2b1 is in the 1st Quadrant of the system up to t = 0.2075 seconds, and is thus acting on the condyle in an upward and forward direction. From t = 0.21 seconds to the end of the event F2b1 is in the 2nd Quadrant and is acting in an upward direction.

4.10.3 Force 2c1 due to Posterior Translation

In mouth closing rotation and translation were assumed to be occurring simultaneously, as the ligamentous reaction force influencing condylar movement in mouth opening does not occur in mouth closing. The calculations in F2c1 were made on the basis of the findings of Merlini and Palla (1989), which showed that the relationship between translation and rotation was similar to that which occurs in mouth opening. Figure 4.75 shows the slope of the curve from Merlini and Palla (1989) to be 0.54, which is again approximately 1mm of translation to every 2 degrees of rotation. The calculation of linear acceleration was therefore made as follows:

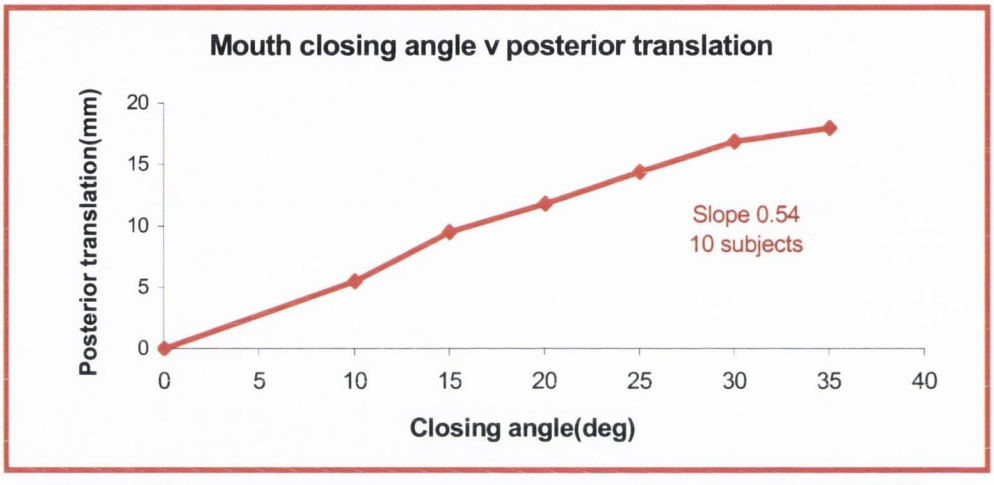


Figure 4.75: Posterior translation versus closing angle (from Merlini & Palla1989)

The curve shown in figure 4.75 was based on active (voluntary) mouth closing. Again it was assumed as in mouth opening that the final 15° of mouth closing was completed by pure rotation.

The slope in figure 4.75 was calculated by:

Slope = 18.5/ 34.2= 0.54

The modified slope calculates as:

Modified Slope =18.5/(34.2-15) = 0.96

Figure 4.76 shows the relationship between flexion of the cranium, and mouth closing due to translation and rotation. Posterior translation is completed at t = 0.225 sec, mouth closing is complete at t = 0.257, but flexion continues until t = 0.3075 seconds (at which point the chin comes into contact with the sternum). It can also be seen that some jaw rotation takes place after the end of translation.

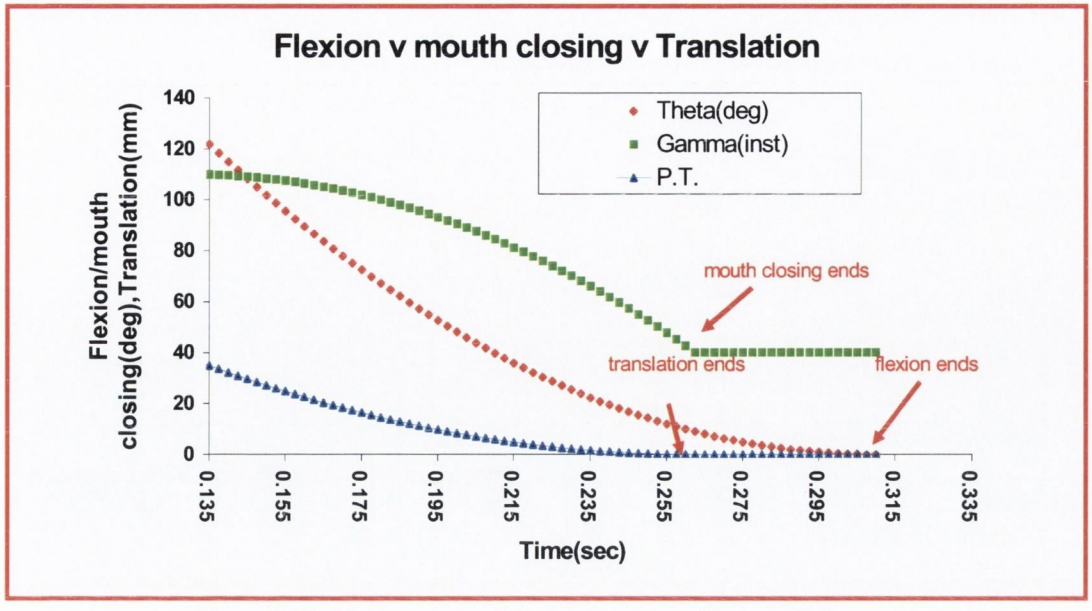


Figure 4.76: Flexion versus jaw rotation versus jaw translation.
Theta = flexion, P.T. = posterior translation and gamma= rotation in mouth closing

4.10.3.1 Values calculated in force 2c1

The calculations were carried out in the same manner as in F1c1. The force magnitudes are shown in figure 4.77 and force direction is shown in figure 4.78.

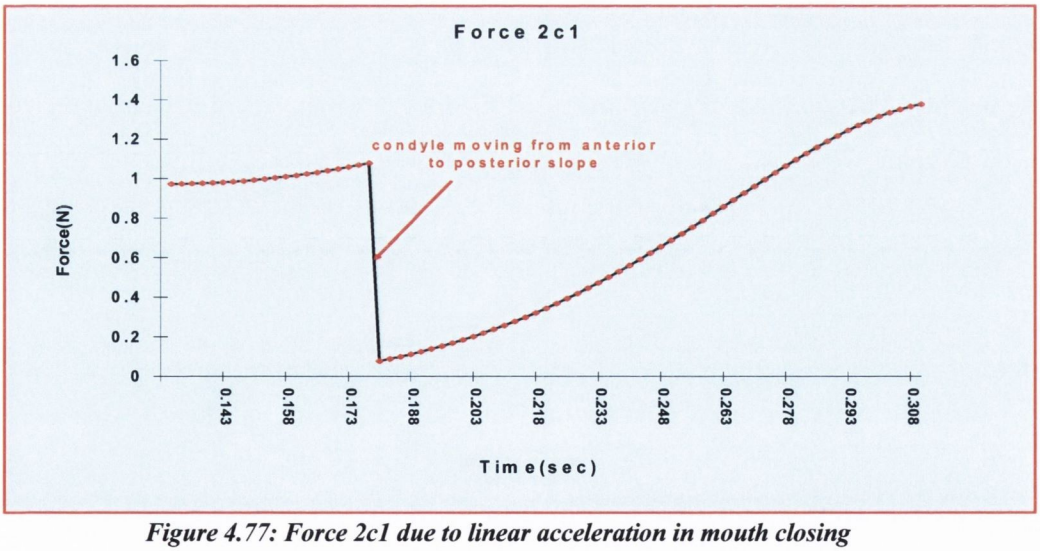


Figure 4.77: Force 2c1 due to linear acceleration in mouth closing

Due to low linear acceleration the force values are minimal throughout. The condyle is on the anterior slope of the eminence form t = 0.130 to t = 0.155 sec. During this time the force value is rising slightly due to the increasing effect of gravity, which is acting in the same direction. At t = 0.1575 the condyle moves onto the posterior slope. From this point until the

end of translation the total force value is falling, due to the increasing effect of gravity, which is acting, in the opposite direction

4.10.3.2 Direction of force 2c1

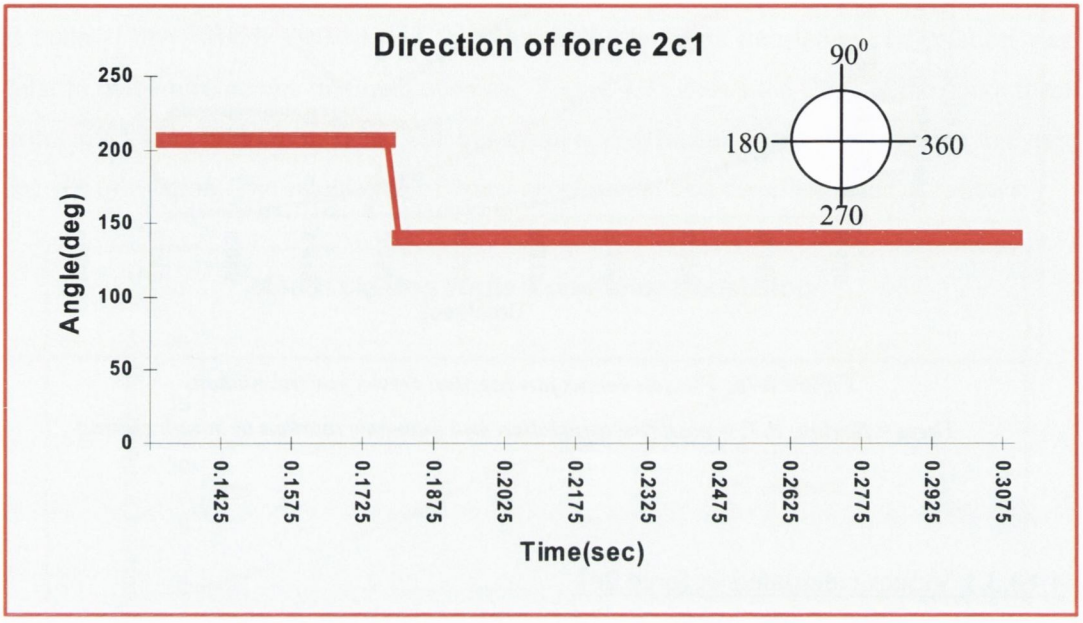


Figure 4.78: Direction of force 2c1 in posterior translation

The full implication of the forces in posterior translation will not be fully realised until they have been with summed pushing forces F2a1 (See Final Force 3).

At the end of flexion the chin is impacted against the sternum, which will drive the condyle upwards and backwards against the soft tissues in the posterior aspect of the glenoid fossa. It was not possible to calculate this compressive force acting on the posterior attachment due to a lack of data regarding the stopping time. This is a subject for further research.

4.10.4 Final Force 3

Final force 3 consists of the summation of pushing forces F2a1 and translating forces F2c1. It was calculated in the same manner as Final force1 and Final force 2. In this way the nett force on each condyle during flexion was found.

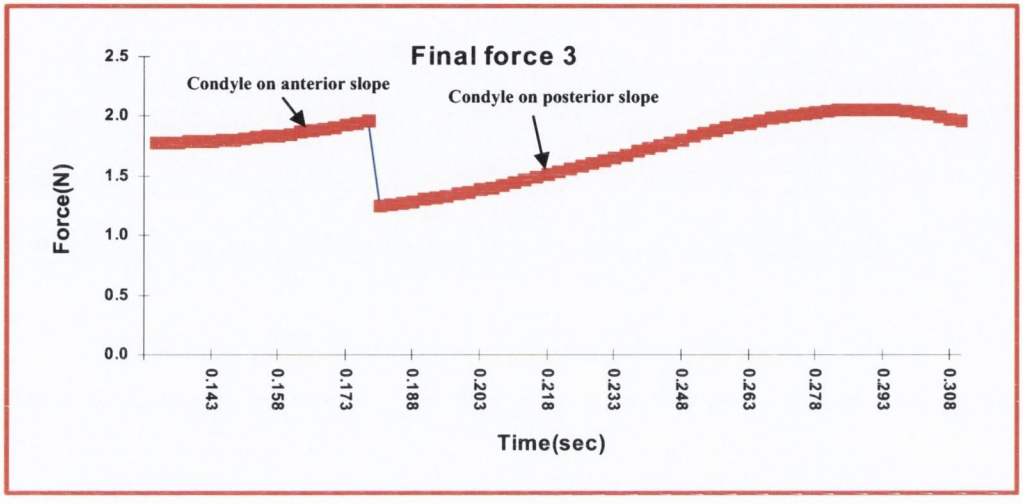


Figure 4.79: Final force 3

Final force 3 is shown in figure 4.79. From t = 0.135 sec to t = 0.1775 sec pushing forces and translatory forces are acting while the condyle is on the anterior slope of the eminence. From t = 0.18 sec to t = 0.230 sec pushing and translatory forces are acting while the condyle is on the posterior slope of the eminence. From t = 0.2325 sec to the end of flexion, pushing forces only are acting on the condyle.

4.10.4.1 Direction of Final Force 3

At the start of flexion Final force 3 is in the 2nd Quadrant of the Frankfurt plane co-ordinate system. The force is therefore directing the condyle upwards and backwards (Figures 4.80 & 4.81).

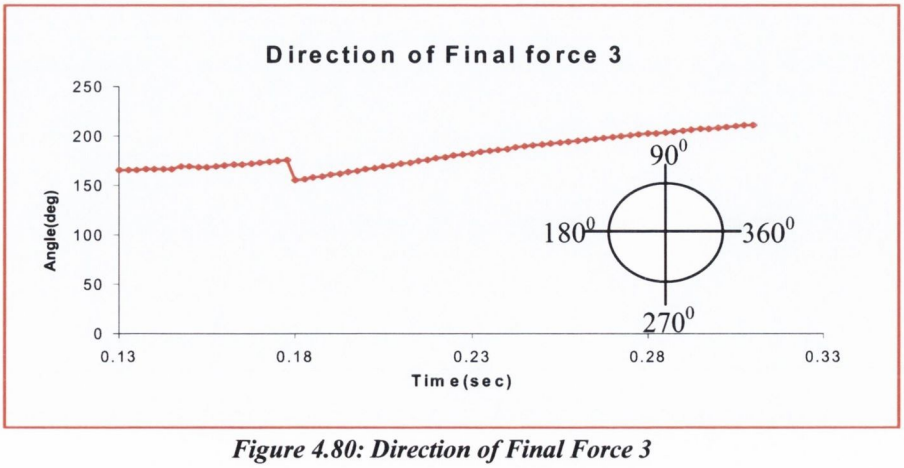


Figure 4.80: Direction of Final Force 3

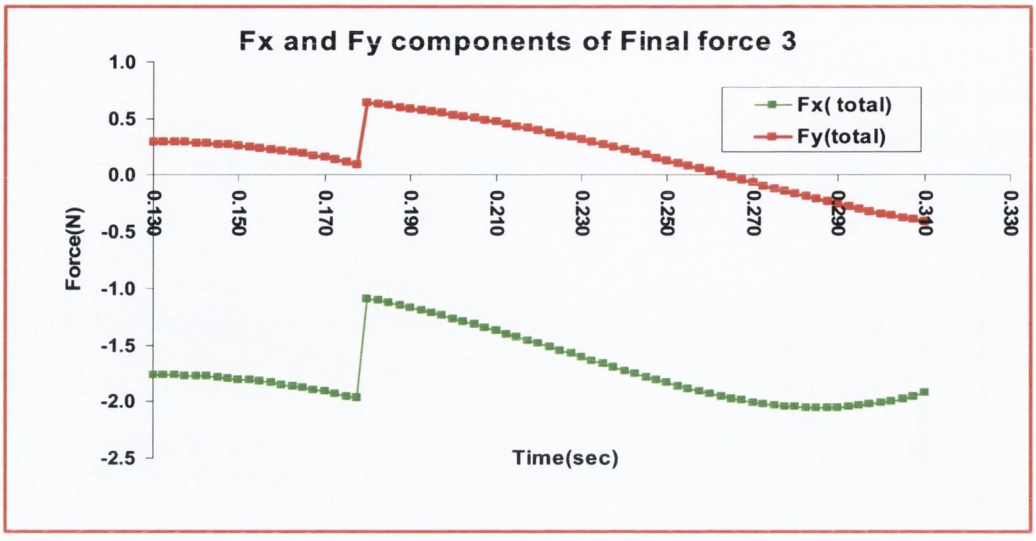


Figure 4.81: Fx and Fy components of Final force 3

From t = 0.2325 sec to the end of the event F3 is in the 3rd Quadrant and is moving the condyle backwards and slightly downwards. However the disc/condyle in returning to the glenoid fossa from a hypertranslated position is not loading any of the soft tissues, except possibly the lateral pterygoid muscle which some authors claim react by contracting as a result of the trauma sustained during the retroflexion phase of the event (Pringle 1918, Wakely 1948, Weinberg and Lapointe 1987). Otherwise the tissues anterior to the condyle are being decompressed. Compressive forces act on the posterior attachment in the final stages of Final force 3, when the condyle has returned to the fossa.

4.11 Forces in flexion using Variable Acceleration

These forces were calculated in the same manner as in the retroflexion phase. The values for angular velocity (Figure 4.82) and angular acceleration (Figure 4.83) were derived by polynomial regression, from the flexion component of the Clemens & Burrow (1972) displacement curve (Figure 4.20).

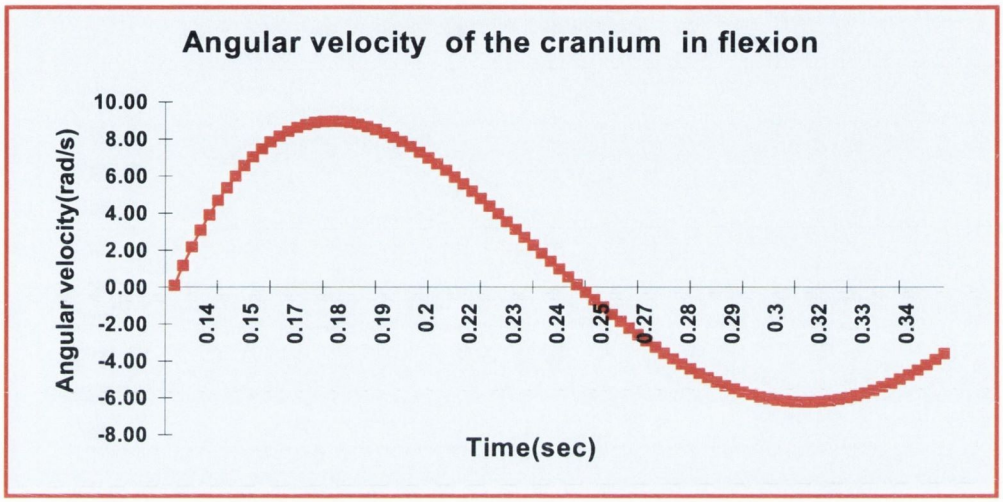


Figure 4.82: Variable angular velocity of the cranium versus time in flexion

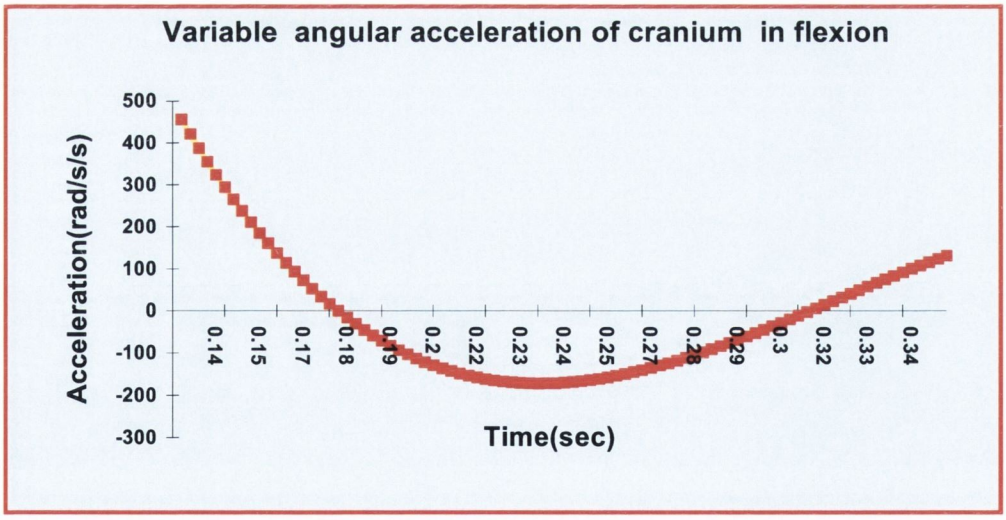


Figure 4.83: Variable angular acceleration of the cranium versus time in flexion

4.11.1. Pushing force 2a2

These forces were calculated in the same manner as pulling force 1a2. Figure 4.84 shows that peak (albeit moderate) forces occur in the early part of flexion. This is due to the peak accelerations, which occur, in the early part of the flexion phase. Thus F2a2 is initially predominantly influenced by F_t 2a2.

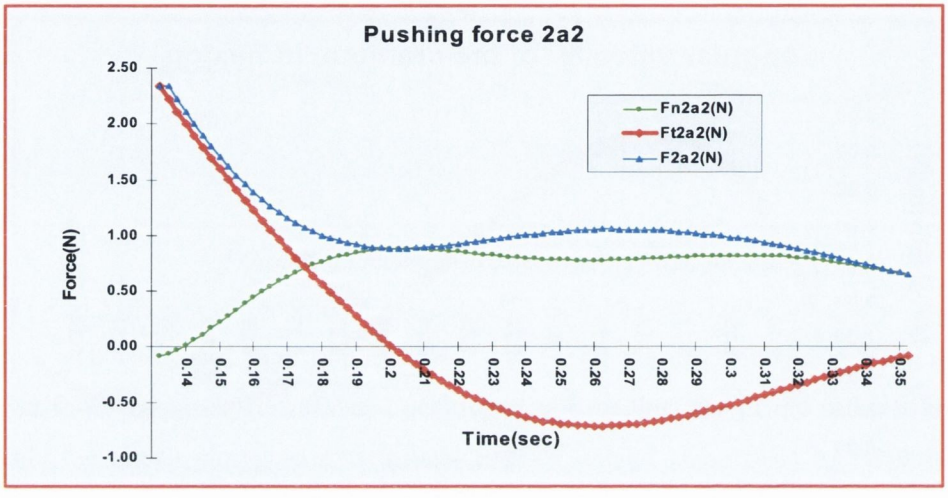


Figure 4.84: Pushing forces 2a2 in flexion

Whereas tangential acceleration reaches a negative value at t = 0.1775 seconds, F_t2a2 does not become negative until t = 0.1975 seconds because gravity is acting in the same direction and initially outweighs the low value of the force due to negative acceleration. However as the angular velocity rises the influence of F_n2a2 increases, until at t = 0.170 seconds both F_n2a2 and F_t2a2 are making an equal contribution to F2a2. F_n2a2 continues to rise, until t = 0.2075 seconds where it reaches a peak value of 1.76 Newtons at t = 0.2075 seconds.

During this period F2a2 reaches a plateau of approximately two Newtons. After this F_n2a2 remains relatively constant until the end of the flexion, because the effect of negative angular velocity on F_n2a2 is largely outweighed by the effect of gravity. Thus in the latter part of the flexion phase F2a2 is mainly influenced by F_t2a2 due to the negative acceleration during this period.

4.11.1.1 Direction of pushing force 2a2

The direction of force 2a2 is shown in figures 4.85 and 4.86.

Initially (t = 0.135sec to t = 0.1775 sec) the direction of the force lies in the 2nd Quadrant of the system, which is tending to move the condyle upwards and back towards the glenoid fossa.

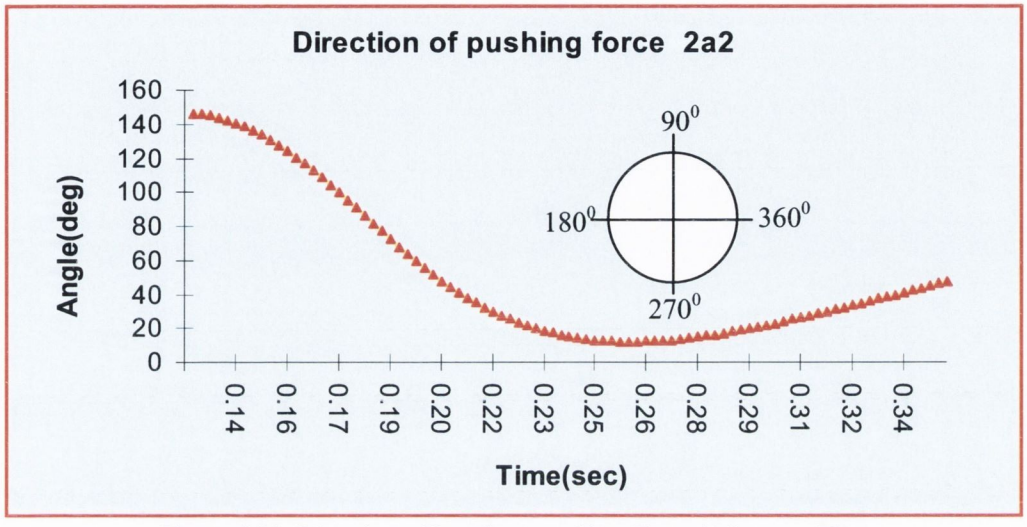


Figure 4.85: Direction of Resultant pushing Force 2a2 versus Time

For the remainder of the event the direction of the force on the condyle is in the 1st Quadrant, which is carrying the condyle upwards and forwards away from the glenoid fossa. The significance of these pushing forces will not be realised until summation with translatory forces (F2c2) has been carried out.

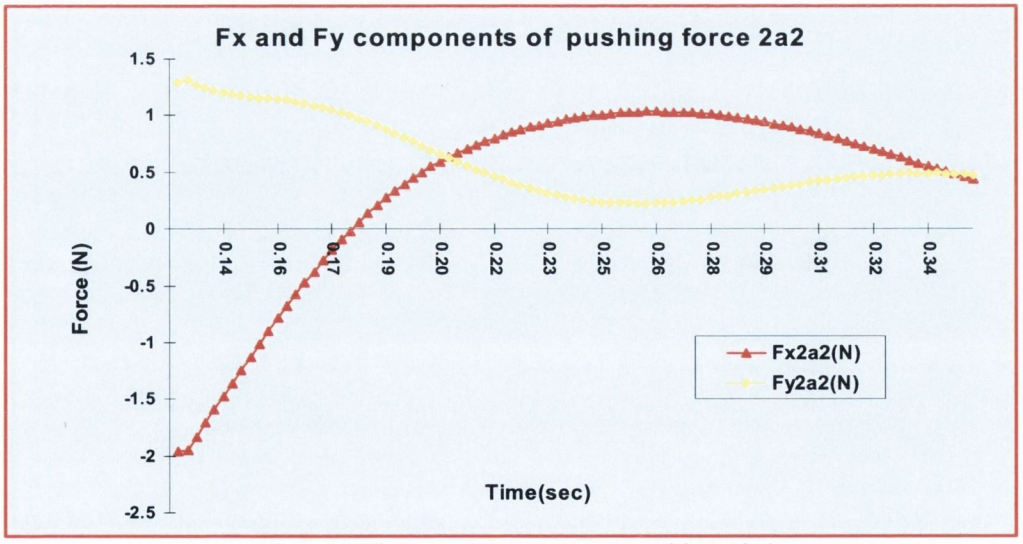


Figure 4.86: Fx and Fy components of force 2a2

4.11.2 Mouth closing Force 2b2

These forces were calculated in the same manner as mouth opening forces F1b2. Figure 4.87 shows that mouth closing ends before the completion of flexion and mouth closing is completed at an earlier stage than in F2a1.

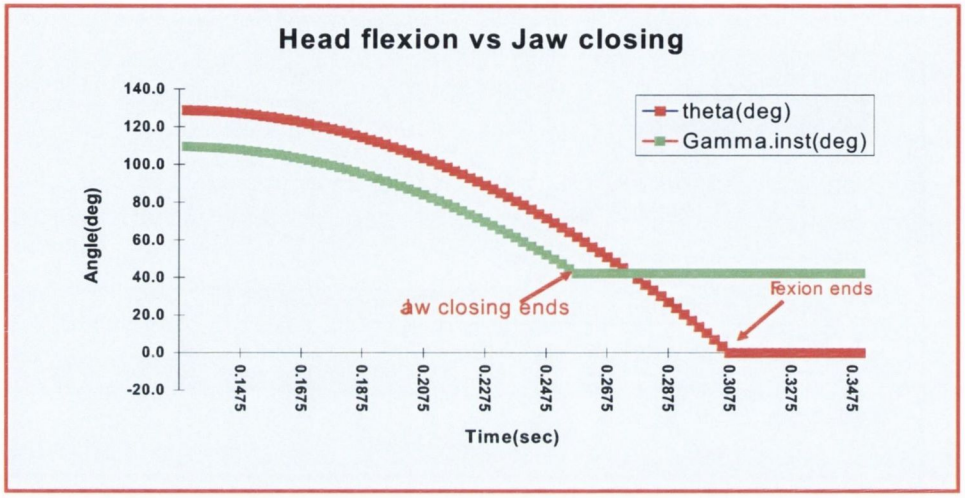


Figure 4.87: Jaw closing angle v flexion (jaw closing finishes prior to end of flexion)

4.11.2.1 Values calculated in force 2b2

The values for angular acceleration and velocity were the same as those used in pushing force

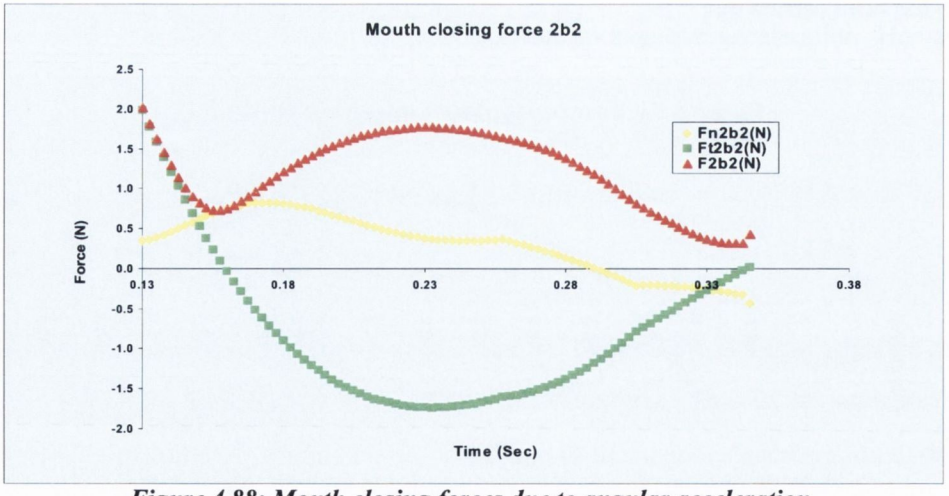


Figure 4.88: Mouth closing forces due to angular acceleration

calculations (F2a2). The forces calculated in F2b2 are shown in figure 4.88, and the direction of the forces is shown in figures 4.89 and 4.90.

As in pushing force calculations F2b2 is initially influenced predominantly by F_t2b2 due to the peak acceleration occurring at the start of flexion. In the early part of flexion Fn2a2 has little effect on F2b2, but gradually rises until it reaches a peak of 1.7 Newtons at t = 0.1725 seconds. The influence of F_t2b2 steadily falls until the point where angular acceleration becomes a negative value (t = 0.1775 sec.).

Thus a second peak of 3.6 Newtons in F2b2 occurs at t = 0. 2275 due mainly to F_t2b2. From this point to the end of flexion the value for F2b2 falls off, except for a short period after mouth closing is completed, when the influence of gravity increases and F_t2b2 increases slightly (from t = 0.2675 to t = 0.3075 sec). After this the angle ε falls below 90° and therefore the effect of gravity falls thus increasing the overall value for F_t2b2.

4.11.2.2 Direction of Force 2b2

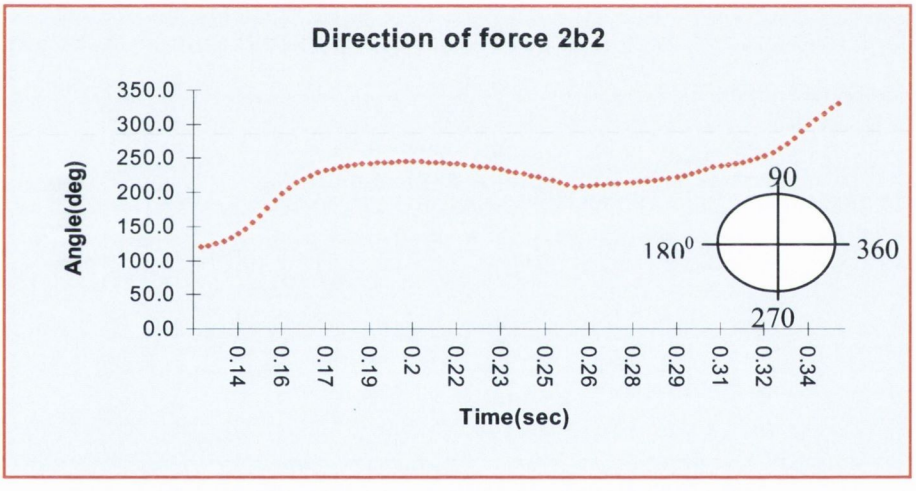


Figure 4.89: Direction of mouth closing force due to angular acceleration

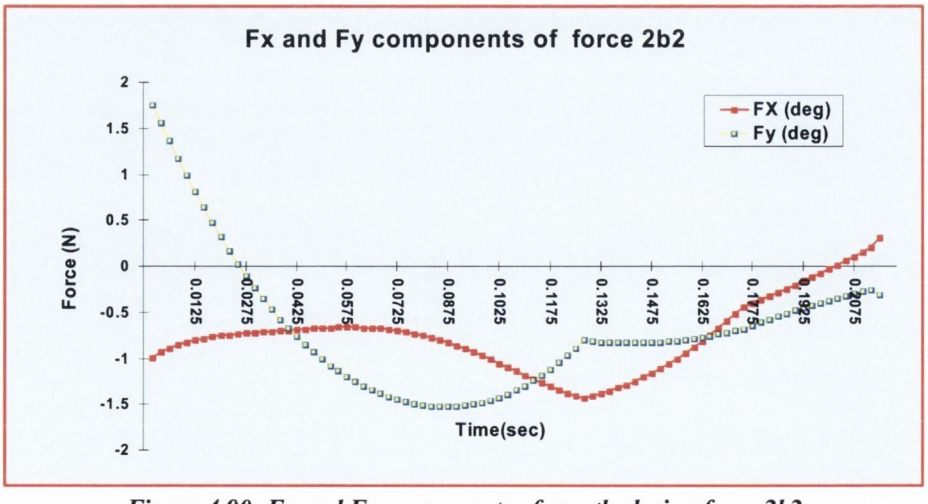


Figure 4.90: Fx and Fy components of mouth closing force 2b2

4.11.3 Posterior translation forces 2c2

These forces were calculated in the same manner as force 2c1. Figure 4.91 shows the relationship between flexion, mouth closing and posterior translation. Posterior translation is completed at t = 0.225 seconds, mouth closing continues until t = 0.2575 seconds, whereas flexion continues until t = 0.3075 sec.

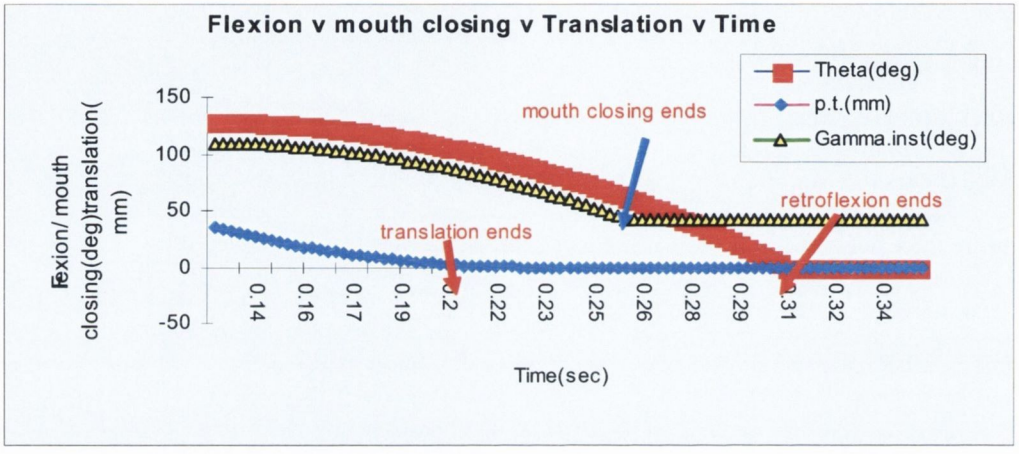


Figure 4.91: Relationship between flexion, mouth closing and posterior translation

4.11.3.1 Forces calculated

Figure 4.92 shows linear acceleration and figure 4.93 shows forces 2c2 in posterior translation. Peak forces occur in the early stages (from 0.1325 sec to 0.1750 sec). During this period the condyle is travelling down and backward on the anterior slope of the articular eminence (preglenoid plane).

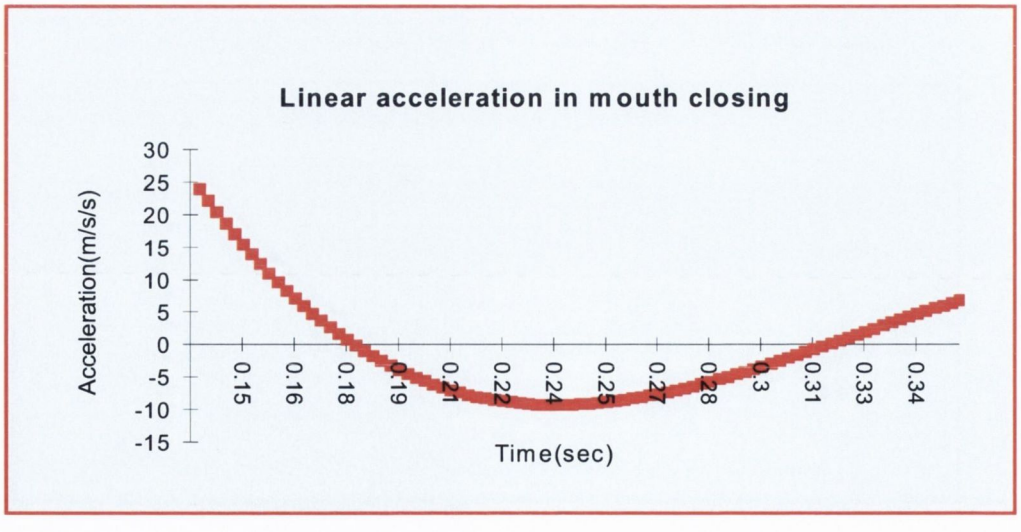


Figure 4.92: Variable acceleration in mouth closing

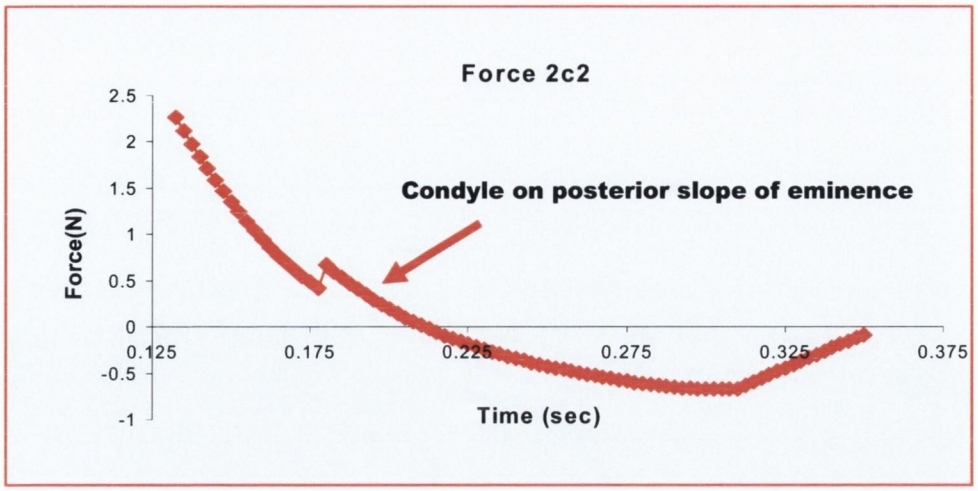


Figure 4.93: Forces in posterior translation due to linear acceleration

When the condyle moves to the posterior slope of the eminence (t = 0.18 sec) gravity is initially acting positively on the translatory force albeit with diminishing value. In the final part of translation (from 0.25 sec, to the end of the event), forces are of a very low magnitude due to both diminishing linear deceleration, and to the increasing effect of gravity. After the end of translation gravity only is acting on the condyle.

4.11.3.2 Direction of Force 2c2

Figure 4.94 shows the direction of force 2c2. From t = 0.130 sec to t = 0.170 sec, the condyle is on the anterior slope of the eminence, and from t = 0.1725 sec to the end of the event the condyle is on the posterior slope of the eminence.

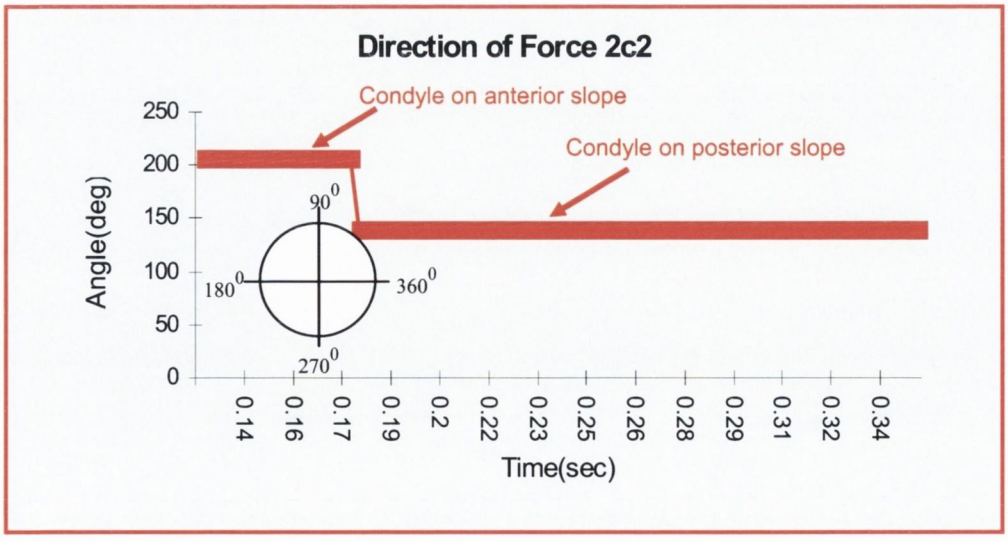


Figure 4.94: Direction of force 2c2 in posterior translation

4.11.4 Final force 4

Final force 4 consists of the summation of F2a2 and F2c2 and is shown in figure 4.95. Maximum forces occur in the early stages due to high angular and linear acceleration. A peak force of 4 Newtons acts on each condyle at the start of flexion assuming that the event provoked a symmetrical response, which would rarely be the case. Both angular and linear acceleration decrease throughout the flexion phase and reach a negative value in the later part of the event.

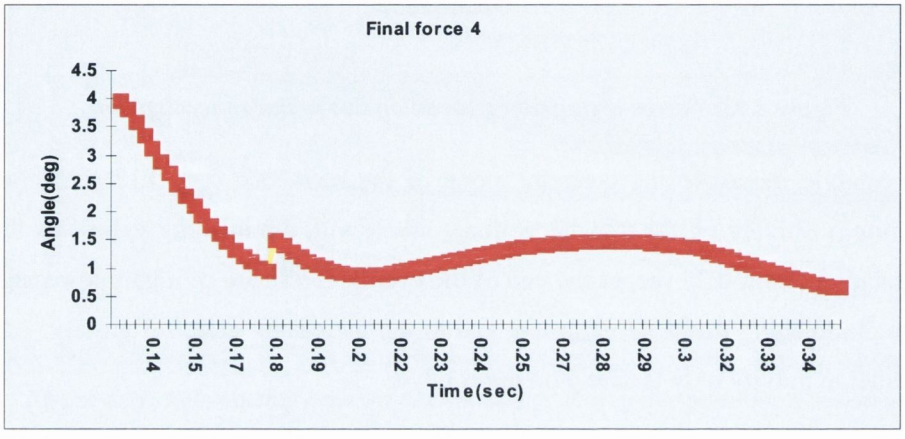


Figure 4.95: Final force 4

4.11.4.1 Direction of Final force 4

Figure 4.96 shows the direction of Final force 4. Initially the direction of the force is in the 2nd Quadrant of the Frankfurt plane system (from t = 0.135 to t = 0.1375 sec). At this stage the condyle is being moved upwards and backwards towards the fossa with the condyle on the anterior slope of the eminence (preglenoid plane). During this period the capsule /ligament complex and the posterior attachment tissues are unloaded. However the rapid posterior movement of the condyle may challenge the strain rate characteristics of the lateral pterygoid muscle, thereby causing damage to this tissue, or it may affect the attachment of the disc to the condyle due to the attachment of the superior being attached to it.(See chapter 3page 147).

From t = 0.14 seconds to the end of the event the direction of the force is in the 3rd Quadrant, which is carrying the condyle downward and backward away from the fossa. This again may be also challenging the integrity of the lateral pterygoid, but would not be loading any of the other soft tissues. At the end of flexion the chin impacts against the sternum resulting in forces due to sudden deceleration. This results in compression on the posterior attachment by the posterior aspect of the head of the condyle. It was not possible to calculate these forces here, due to a lack of information regarding the stopping time.

However it is worth noting that these forces will be influenced by the combined mass of the cranium and mandible.

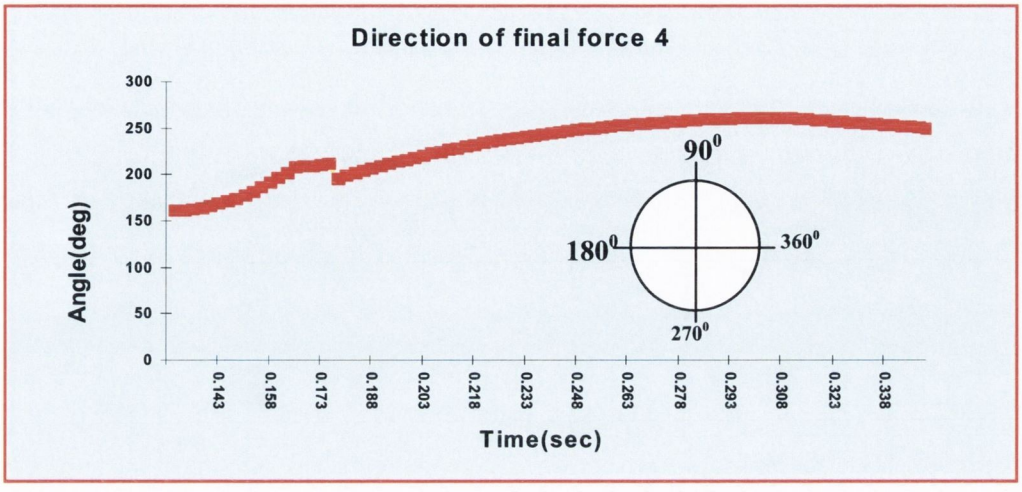


Figure 4.96: Direction of Final Force 4

4.12 Conclusions on Forces on TMJ

The forces acting on the TMJ in the retroflexion phase are of considerably greater magnitude than those occurring during flexion.

When Final force 2 is evaluated it is seen that there are two peaks in force magnitude. The first of 8 Newtons occurs at t=0.07 seconds. It is tensile and acts on the posterior attachment. The second peak of 6.6 Newtons occurs at t=0.125 seconds and is tensile on the posterior attachment, but also on the capsule/ ligament complex, as the condyle has now moved beyond its' normal range of function.

However the forces reacting within the capsule / ligament complex as a result of relative displacement due to rotation of the cranium are of a much greater magnitude, and may be also of greater significance. The loading of the ligament takes place over a very short time period (0.0075 sec), which thus challenges the strain rate capacity of the tissues involved viz.,the ligament /capsule complex, and the attachment of the ligament to the disc in the region where the disc is attached to the lateral pole of the condyle.

The relative angular displacement of condyle in retroflexion will also subject the mandibular elevator muscles to tensile forces. The forces reacted within these muscles are dependent on the vertical distance of individual muscles from the centre of rotation. The significance of

these forces is dependent on the strength of the various tissues under challenge. Further work is needed in this area.

The forces occurring in the flexion phase are of a lower magnitude. It can be seen in Final force 4 that a peak magnitude of 4 Newtons occurs at the start of flexion. However these forces are acting on the condyle while the capsule/ ligament complex, and posterior attachment are unloaded and are probably not of great significance.
The rapid posterior movement of the condyle may however challenge the strain rate capacity of the lateral pterygoid muscle, thereby causing damage to this tissue and the attachment of this muscle to the condyle.

Mouth closing forces are similarly not acting on the soft tissues as the ligament / capsule complex and the mandibular elevator muscles are being unloaded during this movement and the centre of rotation is at the condyle.

Compressive forces on the tissues in the posterior area of the joint occur in the final part of flexion. These forces may be of considerable significance as they depend on the deceleration, which occurs when the chin comes into contact with the sternum and the combined mass of the cranium and mandible.

These will be considered in future work when data is available from experimental work, which is ongoing.
It is also worthy of note that it is more than likely that in any whiplash event that the distribution of forces is not symmetrical and that the load on one disc/condyle assembly is therefore greater than the figures given. This may explain why in many cases TMJ damage resulting from whiplash events is unilateral.

Chapter 5 Testing the Strength of the TMJ Soft Tissues

5.1 Introduction

Knowledge of the forces affecting the soft tissues of the TMJ is only of value if it can be related to the strength of the various tissues of the joint and their attachments. Accordingly if the forces across the joint are greater than the strength of the soft tissues being challenged, damage will occur.

The most vulnerable TMJ soft tissues in retroflexion/flexion injuries are those, which are challenged by sudden and/or excessive mouth opening (Figure 5.1a& 5.1b).



5.1(a) **5.1(b)**

Figure 5. 1: (a) TMJ Capsule/ ligament (TML) & (b) Attachment of disc to lateral pole of condyle (DC)

The most relevant of these tissues are listed as follows:

- The lateral ligament /capsule complex of the joint (Figure 5.1a).
- The posterior attachment of the disc/condyle assembly.
- The attachment of the disc to the lateral pole of the condyle (Figure 5.1b).
- The anterior capsular region

Two of the most common clinical findings in temporomandibular joint dysfunction (TMD) are damage to the temporomandibular ligament and, partial or total rupture of the attachment of the disc to the lateral pole of the condyle. This in turn can cause partial or total displacement of the disc, often in an antero-medial direction, leaving the attachment of the disc to the medial pole intact (Leopard 1984). In some cases complete displacement of the disc occurs immediately post-accident, causing clicking and/or locking of the jaw. In other cases there is a delay of some days or weeks before disc displacement occurs. This delay in

onset may be due to a gradual breakdown of the attachment of the disc to the condyle, which has been compromised as a result of the accident.

The calculations carried out in Chapter 4 indicated that the lateral TMJ ligament sustained the greatest magnitude of forces. It was therefore decided to measure the strength of this ligament. The choice of specimens to be tested was randomly made from specimens where there was a clearly defined ligament.

It was also decided to test the strength of the attachment of the disc to the lateral pole of the condyle, as the tissues of the disc and ligament are contiguous in this region and firmly bound down to the lateral aspect of the disc. Forces sustained by the ligament are thus transmitted to the disc and to its attachment to the lateral pole of the condyle. The selection was made randomly from specimens where the attachment to the lateral pole was undamaged.

Depending on the magnitude of the forces sustained in a particular event, and on the strength of the particular attachment, disruption of the tissue may vary from complete to partial. This may explain why in some instances clicking and/or locking of the TMJ is not reported until some time after the accident. Normal forces on damaged tissue in any part of the body can result in further tissue breakdown. This can require the resting or even the immobilisation of the body part until healing has taken place.

It has been demonstrated experimentally that surgically sectioned retrodiscal tissue of female goats when subjected to strength tests 30 days later after the tissue had reformed, showed less than half the strength of normal tissue (Cooper et al, 1999). The above tests also showed that the development of tissue strain had shifted from a relatively even distribution to a confined area near the retrodiscal attachment zone.

When it is considered that the jaw is in almost constant motion, being required for many functions other than eating, it is not too difficult to see how repetitive normal loading may exacerbate a moderate injury.

5.2. Structure of the Temporomandibular Ligament

A lateral view of the TMJ is seen in figure 5.2.The temporomandibular ligament and the attachment of the disc to the condyle are composed mainly of type 1 collagen. Collagen is a generic name for a family of related proteins, which are a chemically and genetically distinct species and often aggregate to form visible fibres and basement or pericellular membranes of connective tissues. The joint capsule consists of irregular type 1 collagen, which facilitates movement in all directions. The ligament itself consists of regular type 1 collagen, which gives it high tensile strength. However the ligament also contains a non-fibrous component known as the ground substance. The ground substance contains glycosaminoglycans, which are linked to the proteins to form proteoglycans. In connective tissues such as ligaments, the proteoglycans combine with water to form a proteoglycan aggregate. The water content accounts for approximately 70% of the total tissue weight. The proteoglycan acts as a gel, which lubricates the collagen fibres and maintains a space between the fibres known as the critical fibre distance.

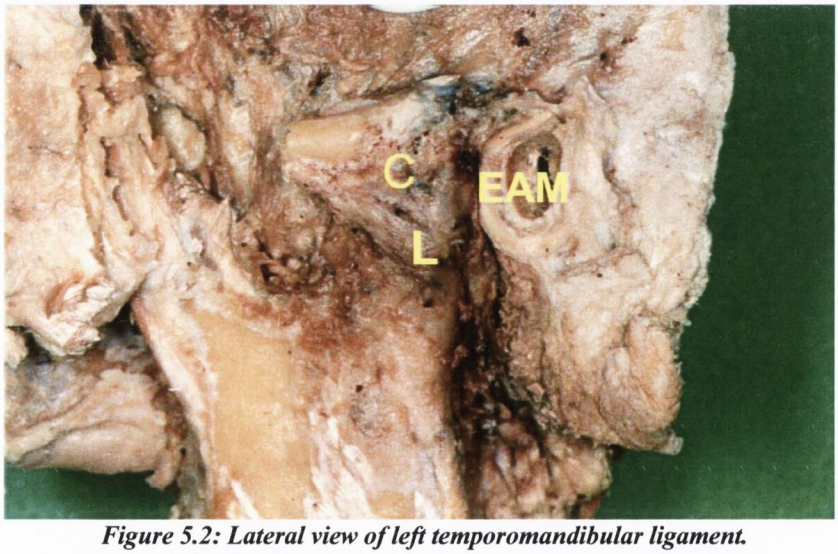


Figure 5.2: Lateral view of left temporomandibular ligament. Eam= external auditory meatus, C= joint capsule, and L=ligament

The critical fibre distance permits free movement of the fibres in relation to each other, which in turn facilitates the property of connective tissue known as viscoelasticity (Cage et al 1989). This permits the collagen fibres to slide freely, which is an essential prerequisite for movement of connective tissue.

Microscopically collagenous fibres are seen to be crimped or folded, which allows elongation of the ligament by 20-30% without stretching the material (Cage et al, 1989). If stress is applied to a collagen fibre a strain will be induced which is directly proportional to the stress.

However if the applied stress exceeds the yield stress of the tissue, there is a loss of proportionality between stress and strain, which is followed by rupture.

Thus at a certain critical stage in loading, elongation of the collagen fibres occurs with a lower stress application. This results in progressive reduction in the cross-sectional area of the tissue, and ultimate failure.

A theoretical stress/ strain curve can therefore be plotted for the ligament (Figure 5.3).

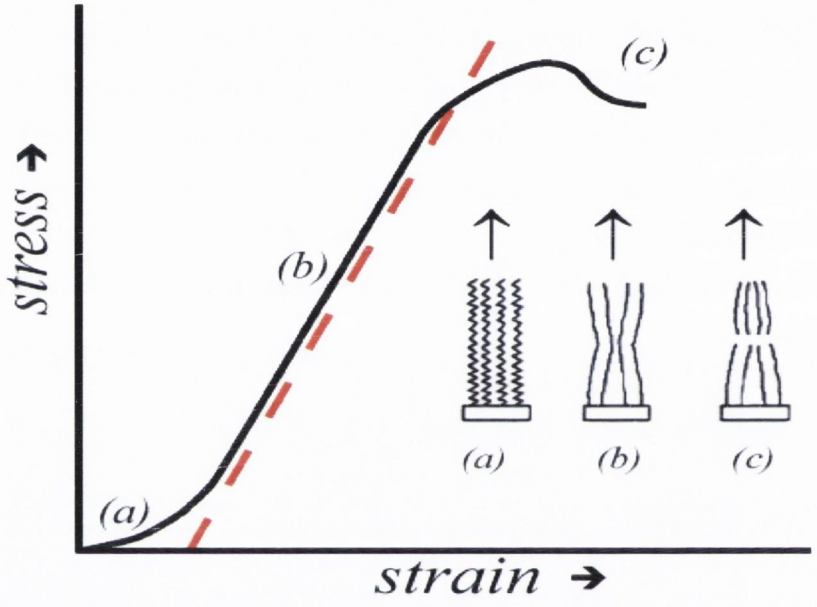


Figure 5.3:Graphic & curve showing stress strain behaviour of collagen under load (Cage et al 1989) (a)=crimping of collagen fibres, (b) =normal elongation and (c) =failure point

5.2.1 Viscoelasticity and Strain Rate Testing

Some materials, notably plastics, and rubbers do not exhibit a linear elastic range, but have an interdependence of stress and strain with time. These materials possess a "physical memory" so that current strain or stress is dependent on the loading history of the material.

Even after unloading considerable recovery of residual strain can occur at zero loads. This behaviour is termed Viscoelasticity.

For linear viscoelasticity, the simplest relationship between stress, strain, and time is:

$$\sigma = E\,\dot{\varepsilon}\,\eta\,\dot{\varepsilon}$$

Where $\dot{\varepsilon}$ = strain rate and η = Coefficient of viscosity

Because of the dependence on time and the behaviour called *creep,* experimentally determined stress/strain relationships demonstrate a strain-rate dependence and non-linearity. Thus the modulus of a viscoelastic material is not a constant, but depends on the magnitude and nature of the loading applied to the material.
The most common method of evaluating the mechanical properties of ligaments and tendons is by carrying out uniaxial tensile tests. In high strain rate tests on ligaments and tendons the stiff and viscoelastic nature of the collagen fibres are believed to take a greater proportion of the applied load and are therefore more likely to rupture.

Tendons are thought to function in the body at strains of ~ 0.04, which is believed to be their yield strain (εy) (Nordin 1956). Tendons rupture at about 0.1(ultimate strain, εu), or stresses of about 60 MPa (ultimate stress, σu).

When a tendon is stretched rapidly, the ground substance does not have time to flow, and thus the tendon becomes stiffer.
Ligaments in comparison contain a higher degree of elastic fibres, which accounts for their greater extensibility, but lower strength and stiffness. They are also viscoelastic, but deform elastically up to strains of about σy=5 MPa. They rupture at a stress of about 20 MPa.

A number of studies have been carried out on the failure pattern of the knee joint ligaments.

Viidik (1965) studied the effects of training in a running machine on rabbits and demonstrated that the weakest point in the tibia-ligament-femur system was one of the bony attachments, most frequently the tibial one.

Noyes et al, (1974) investigated the effect of strain rate changes on the failure mode using rhesus monkeys. The approximate strain rates were 0.62 % sec^{-1} at the slow rate and 67% sec^{-1} at the fast rate. Ligament tearing was seen more often at the fast strain rate, with bone avulsion occurring more often at the slow strain rate.

Woo et al, (1990) studied the effect of strain rate on medial cruciate ligament (MCL) failures in skeletally immature and mature rabbits. The range of strain rate used was from 0.011 to 222 % sec^{-1}. Tibia avulsion developed in all specimens from skeletally immature rabbits with the strain rate from 0.011 to 155 %/sec. Results for these groups were not reported above 155 % sec^{-1}. However, ligament tearing occurred from skeletally mature rabbits with the strain rate from 0.011 to 222 %/sec.

Schenck et al, (1999) looked at two "clinically applicable" strain rates, 100 and 5400 %/sec^{-1} to study the human anterior cruciate ligament (ACL) and Posterior cruciate ligament (PCL) hyperextension. In the PCL ligament, tearing occurred at the lower strain rate with bone avulsion occurring at the higher strain rate. The order of these results was contrary to that of most of the other studies. In the ACL, the major failure mode at the low stain rate was similar to the PCL, with a mixed failure pattern at the higher strain rate.

Lee and Hyman (2002) having carried out a literature review published a qualitative analytical model in an attempt to explain these various results. Their model takes into account the individual rate sensitivity of the strength of both the ligament and the bony insertion points. Lee and Hyman (2002) claimed that this provides an integrated view of the strength and failure mode of the combined system. Their model demonstrated that the stiffness and peak failure loads of the ligament and bone both increase as the strain rate increases. The relationship between the ultimate stress and strain with loading rates for ligament alone is shown in figure 5.4 and for bone alone is shown in figure 5.5.

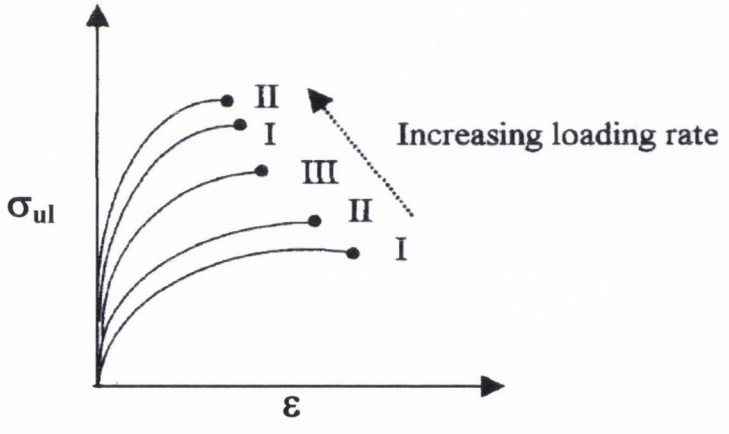


Figure: 5.4 Relationship between stress and strain for ligament with loading rates

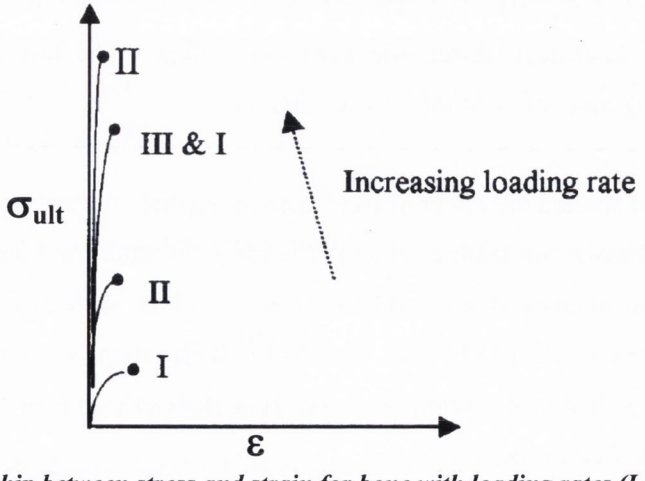


Figure: 5.5 Relationship between stress and strain for bone with loading rates (Lee&Hyman)

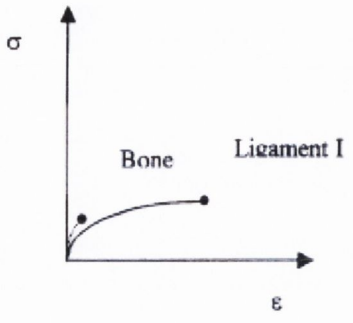
While the exact mechanisms of these changes are not fully understood, it is thought to be greatly influenced by internal viscosity and energy dissipation. Individually, these properties can be viewed as providing a protective mechanism under many circumstances, in that they make the joint stiffer and stronger at high loading rates, at least up to their strength limits. When reported failure modes are considered for the bone-ligament-bone complex, the effect of the changing strain rate on the bone must be greater than that on the ligament.

Failure mode I occurs more commonly at lower strain rates and where bone avulsion occurs, rather than ligament tearing (Figure 5.6). The ultimate failure stress of both bone and ligament is relatively small at these strain rates compared to the strengths at higher loading rates. The strength of the ligament at these rates was generally found to be greater than the strength of bone. Lee and Hyman (2002) concluded from this that bony avulsion failure is more common at low strain rates because the bone failure point is reached first.

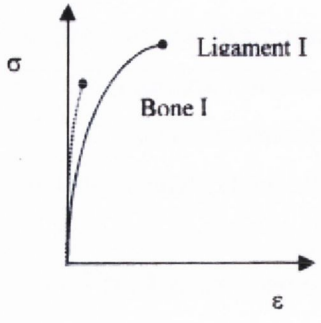
Failure mode II consists of ligament tearing or bony avulsion occurring at similar frequency, i.e., where the ultimate stress of bone and ligament are similar (Figure 5.6). This mode occurs at higher strain rates than those of mode I. Because there is not a clearly preferred type of failure in mode II, Lee and Hyman (2002) concluded that the type of failure, which occurs is more likely to be due to variations in the physical characteristics of the individual.

Failure mode III occurs at higher strain rates in which ligament tearing predominates over bone avulsion. As the strain rate increases further above that of mode II, the ultimate stress of bone and ligament continue to increase, but now the strength of the bone becomes greater than that of the ligament (Akeson et al, 1984).

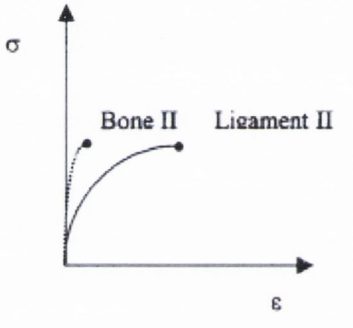
When the strain rate increases overwhelmingly over that of mode III, the ultimate stress of bone stays about the same as in mode III but the ultimate stress of the ligament increases over that of mode III and failure mode I shows again. Finally failure mode II occurs as the strain rate increases further still.



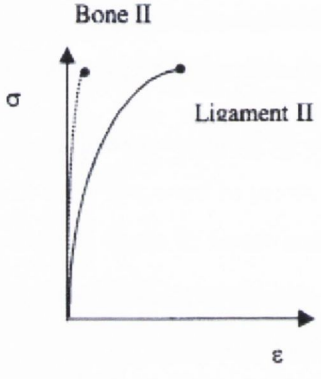
Mode I. Avulsion > Ligament tearing



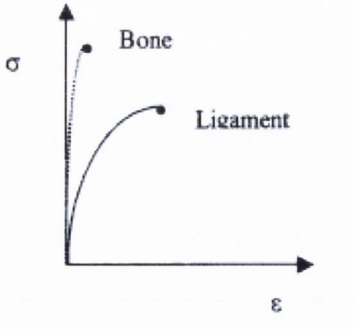
Mode I. Avulsion > Ligament tearing



Mode II. Avulsion ≈ Ligament tearing



Mode II. Avulsion ≈ Ligament tearing



Mode III. Avulsion < Ligament tearing

Figure 5.6: The sequence of failure modes resulting from increasing loading (Lee&Hyman)

The effect of strain rate on the failure modes of the bone/ligament/bone complex has also been investigated by Hawkins (1993), who noted three types of failure.

1. The first was mid-ligament tearing in which the fibers of the ligament pull apart within the body of the tissue, usually as a result of a fast loading rate.

2. The second mode of failure was ligament-bone interface failure in which the fibers fail at the ligament-bone insertion without fracture of the underlying bone.

3. The third mode of failure was tibia or femoral avulsion fractures, usually resulting from relatively slow loading rates.

Ligament failure mode has also been found to vary with different types of ligament, due to their different viscosities (Pioletti et al, 1998).

5.2.2 Anatomy of the Knee joint

The Tibiofemoral (knee) joint is another complex and vulnerable joint in the human body. It is a complex diarthrosis, which, in addition to flexion and extension, permits limited rolling and gliding movements (Van de Graff and Fox 1992). Strong collagen ligaments support the medial and lateral side of the joint (Figure 5.7). These ligaments are similar in microstructure to TMJ ligaments and are often injured in sporting activity.

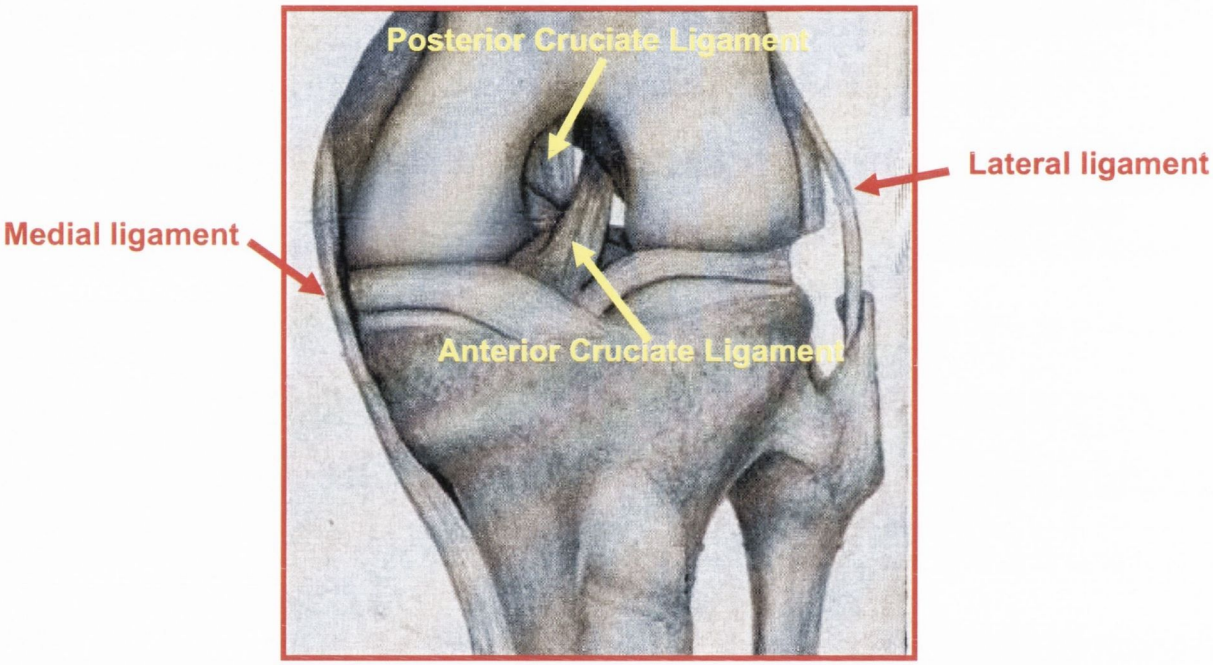


Figure 5.7: Anterior view of knee joint showing lateral and medial ligaments (Last Regional Anatomy 1966)

The stability of the joint is dependent on a number of powerful muscles, a meniscus and four major ligaments. The knee ligaments are the medial collateral ligament (MCL), the lateral collateral ligament (LCL), the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL).

5.3 Materials and Methods

5.3.1 The Design of the Testing Rig

The objective of this project was to subject TMJ soft tissues to high strain rates (impact tests) and to compare the results with the theoretical behaviour of viscoelastic materials.
It was therefore decided to focus attention on testing the lateral ligament of the TMJ and on the strength of the attachment of the disc to the lateral pole of the condyle.
It was decided to carry out initial testing on the lateral and medial ligaments of the knee. This allowed comparison of results between the two joints and also acted as an initial test of the method being used without damaging the TMJ soft tissues, which were the main consideration in the tests.

The principal design requirements for the testing rig were as follows:

- That the direction of the force application would be along the long axis of the tissue being tested.
- That the clamps would securely hold the specimen at either extremity.
- That the rig would accept a variety of sizes and shapes of specimens.
- That the rig be as light as possible to minimise loading of the specimen prior to testing.
- That the rig would perform with accuracy at high strain rates.

5.3.2 Direction of the Force Application

Impact loading is defined as the sudden application of a load to a structure. Thus if a load w is dropped from a height (h) onto a material resulting in a deflection δ in that material, work done by the load w at the end of the impact with the structure deflected by a distance of d is:

$$W = w(h + d) = \int_0^{\delta} (w)d\delta$$

Assuming that the load action is the equivalent to a gradually applied load qw, which produces a deflection δ, the work becomes:

$$W = w(h + d) = \int_0^{\delta} (qw)d\delta$$

Where q= dynamic multiplier=2((h/δ) +1)

It can be seen therefore that if the load is placed just in contact with the material (h=0) the q=2, i.e. all effects are double those where the load is applied gradually. In the testing design it was decided therefore that a mass m* would be dropped from a height h** to apply an impact force to the tissues.

*, **~ Values to be inserted experimentally

5.3.3 Clamping the Specimens

Two clamps were needed to grip the opposite extremities of the tissue being tested:

- A stationery clamp
- A moveable clamp

5. 3.3.1 Stationary clamp requirements

- To ensure no slippage of the tissue during the tests
- To ensure ease of mounting to a fixed and stable structure (e.g., a solid wall).
- To permit uniaxial loading of the collagen fibres.

5.3.3.2 Moveable clamp requirements

- To ensure no slippage of the tissue being tested
- To be of lightweight design for minimal affect on the tissue prior to testing
- To allow easy application of the weights mechanism
- To accept a variety of specimen sizes and shapes.

5.3.4 Mass of rig

In order to minimise errors in the stress and strain, it was essential to minimise the load caused by the weights system. Therefore all of the elements of the design were kept to the lowest possible mass.

5.3.5 Accuracy of rig at high strain rates

A design was needed which would allow measurements at high strain rates in the tests. An INSTRON 1011 machine has an upper limit of 500mm/min, therefore it was not a suitable instrument to use, as the high strain rate test to be performed, were expected to take place in less than 0.5 sec (~4mm). This time increment was based on a study, which showed that the entire whiplash event is completed in approximately 0.3sec (Clemens and Burrow 1972).

5.3.6 Detail of the Testing Rig

5.3.6.1 The fixed (stationery) Clamp

This was constructed from mild steel and allowed free rotation of the plastic housing containing the tissue in the vertical plane (Figure 5.8).

5.3.6.2 The Moveable Clamp

This was constructed from aluminium using a pinned structure to make sure that no slippage would occur when the impact load was applied (Figure 5.8).

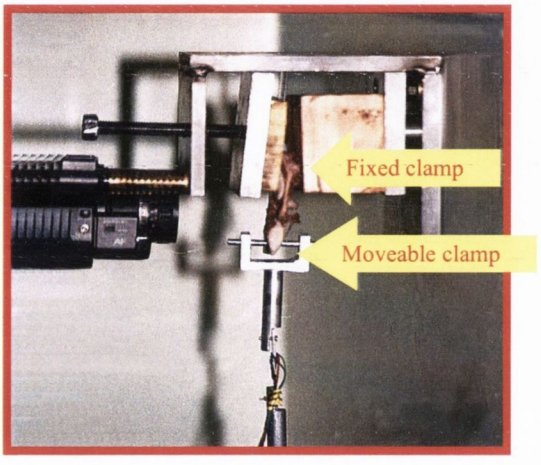


Figure 5.8: Section of the testing rig showing the fixed and moveable clamps

The complete structure consisted of aluminium weights, rod and pan (Figure 5.9). The function of the rod was to guide mass m as it was dropped from a height h and to connect the weights system to the moveable clamp. The function of the pan was to catch the falling mass.

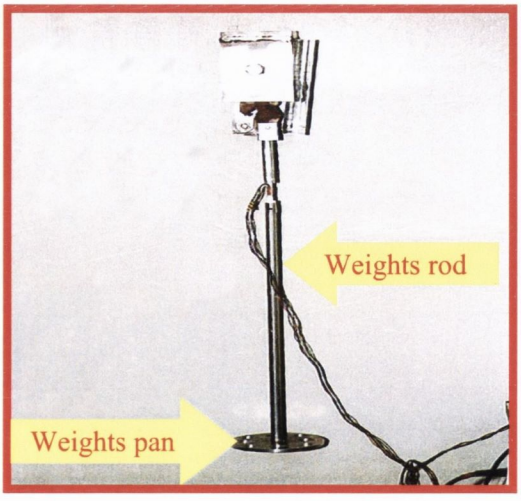


Figure 5.9: weights' rod and pan attached to the moveable clamp

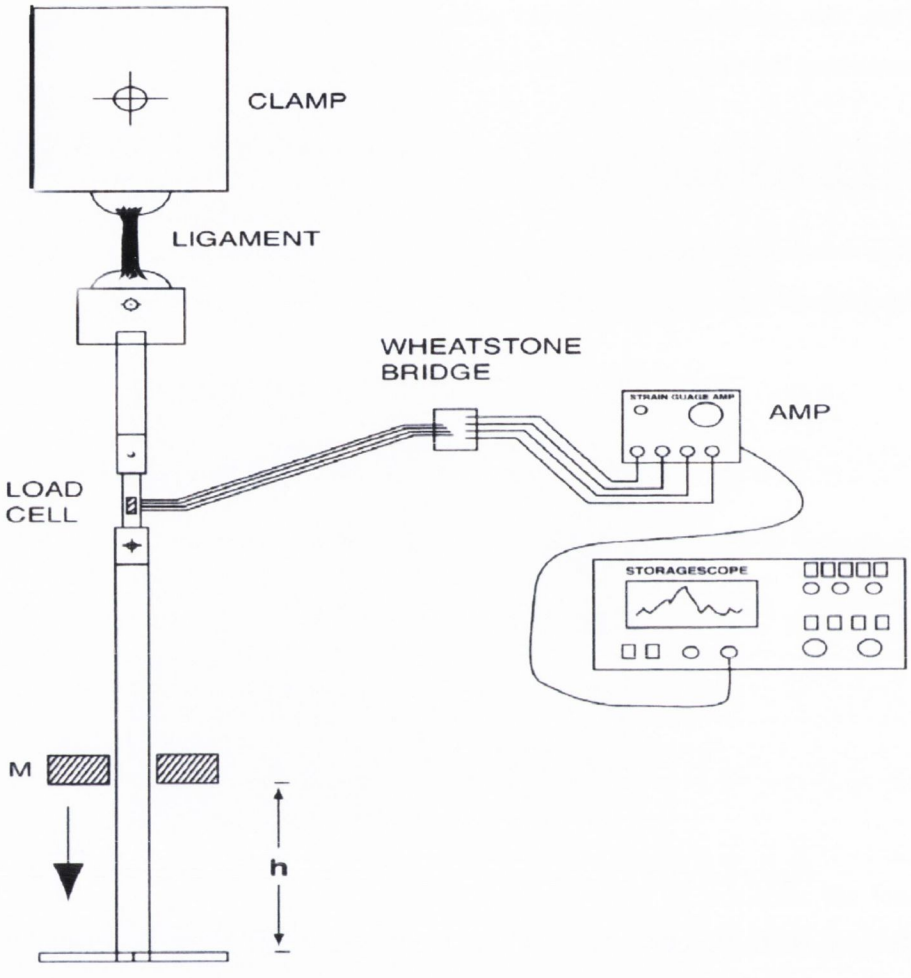


Figure 5.10: Diagram of the completed testing rig set up

5.3.7 The Force Transducer

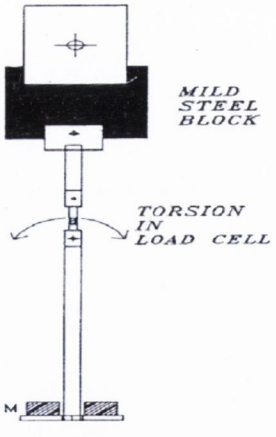
This was used to measure the force transmitted through the system during the loading. It involved the use of a load cell constructed from 1.5mm aluminium sheet and two strain gauges attached to the aluminium rod, as close as possible to the moveable clamp. The load cell was connected to a storage oscilloscope via a strain gauge amplifier (Figure 5.10), which stored the impact waveform as a plot of Voltage versus time and Force versus time.

5.3.8 Testing the Rig

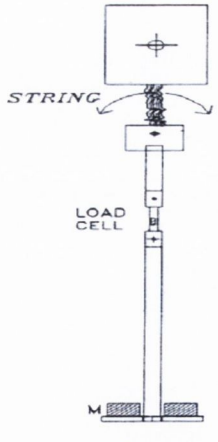
Prior to testing the tissues, it was necessary to thoroughly test the function of the rig. This involved testing the clamps, weights' mechanism, video analysis, and load cell.

5.3.9 Calibration of the load cell

Before making force measurements it was necessary to calibrate the load cell. This involved connecting the strain gauges via the half-circuit Wheatstone bridge through the strain gauge amplifier to a multimeter (Figure 5.10). The multimeter was set to give an output reading in millivolts (mV). The load cell was connected to the weights system and this system was then connected to a mild steel block (Figure 5.11a). The load cell was then calibrated by reducing a static load of 120N to 0N to the weights pan, in steps of 10N. At each step, output voltage was recorded from the multimeter.



5.11(a)



5.11(b)

Figure 5.11(a): The load system connected to a mild steel block and 5.11(b): A piece of string substituted for the mild steel block for re-calibration

Readings were recorded as the load was reduced from 120N to 0N. Theoretically the voltage reading for a particular load should be constant when the static load is being increased and decreased. However, in practice, this was not the case, due to some rotation of the pan when the weights were applied to the system. As the load cell had the lowest value for the G Modulus* in the system, a torsional force was being applied to the strain gauges. This invalidated the readings because the strain gauges, due to their alignment were only capable of taking readings in tension or in compression (Figure 5.11a).

However as the tissues being tested would have a lower G Modulus than the load cell, any rotation in the system, would occur in the tissue.

A piece of string was now substituted for the mild steel block and the load cell re-calibrated (Figure 5.11b). This time, the results were sufficiently accurate. The load cell was calibrated twice, results averaged and a graph of Voltage versus Load established. These results were averaged and graphed using a spreadsheet package and the equation for the "best fit" calibration curve was calculated using a grapher program.

5.3.9.1 Calibration Results

The calibration results are shown in table 5.1 and figure 5.12. From these results the calibration equation was calculated to be: Voltage = 4.7 (Force) +9.1

Voltage (mv)	Voltage (mv)	Average voltage (mv)	Force(N)
0	0	0	0
56	56	55.0	10
106	125	111.3	20
165	177	165.7	30
209	223	208.7	40
245	255	244.0	50
282	294	283.7	60
338	350	338.7	70
388	395	387.0	80
447	447	441.3	90
485	491	482.3	100
530	531	521.7	110
570	575	566.3	120
528	531	520.7	110
487	490	481.0	100
452	450	444.3	90
390	398	387.7	80
340	348	338.7	70
282	290	282.7	60
241	246	239.7	50
199	201	196.3	40
156	151	149.3	30
110	102	102.0	20
57	56	54.3	10
0	1	-0.3	0

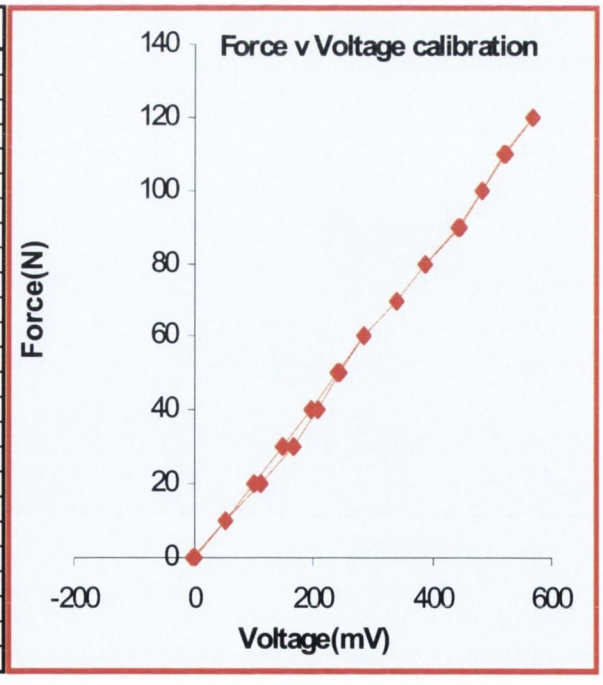


Table 5.1 & Figure 5.12: Calibration of force / voltage& Graph of force versus voltage

*G= *modulus of rigidity* or *shear modulus*, defined as ratio of shear stress to shear strain. Hence τ/χ = constant = G.

5.3.10 Video analysis

A SONY video camera recorder (Model SONY CCD-V800E) was used to carry out the video analysis of the various tests.

This camera was capable of recording 25 frames per second. However the video recording was converted to digital images by using a sophisticated piece of equipment called a studio PCTV-USB made by Pinnacle.

It was thus possible to produce still images of the tests at different stages of the event.

This facilitated the calculation of the amount of strain, which had occurred at particular stages in the event and the strain rate by measuring the amount of strain, which had taken place in a measured time period.

5.4 Preliminary testing of Knee Ligaments

5.4.1 Low strain rate tests

Prior to carrying out the soft tissue high strain rate (impact) tests it was decided to perform some preliminary tensile tests on cadaver specimens of human knee ligaments.

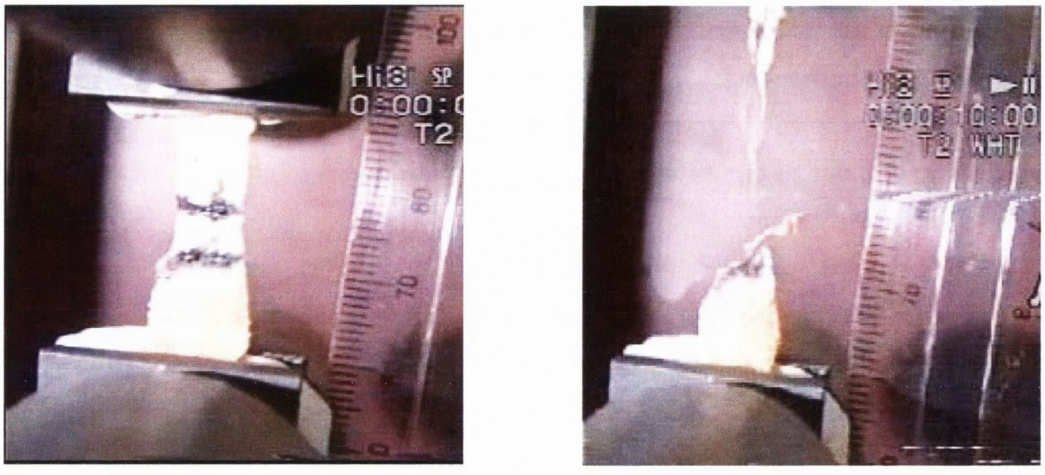
This was done to evaluate the viability of stabilizing tissue specimens embedding them in acrylic blocks at their caudal and cephalic extremities before proceeding to tests on TMJ tissues .

The securing of the specimens in acrylic blocks was carried out as follows:-

- Small acrylic plates were constructed measuring approximately 4 cm^2 and 5mm in thickness.
- A trough was cut into one plate sufficiently wide to accommodate the individual specimen.
- One end of the ligament was now set into this trough using Loctite 406 rubber and plastic adhesive, an adhesive specifically designed for moist conditions.
- A further layer of cold cure acrylic was now cured on to the fixed end of the ligament thus constituting the third layer of the sandwich.

The other end of the ligament was treated in the same fashion, resulting in a ligament embedded at either end in an acrylic block, with approximately 10mm length of ligament between the blocks (Figures 5.13a & 5.13b).

One block was secured in the fixed clamp, and the other was fixed in the moveable clamp. The load was then applied and measurements of stress/force were made using the load cell (Figure 5.14a & 5.14b).



5.13(a) 5.13(b)

Figure 5.13(a) & 5.13(b): Tensile testing of lateral knee ligament No.1 in INSTRON 1011 before testing and at failure.

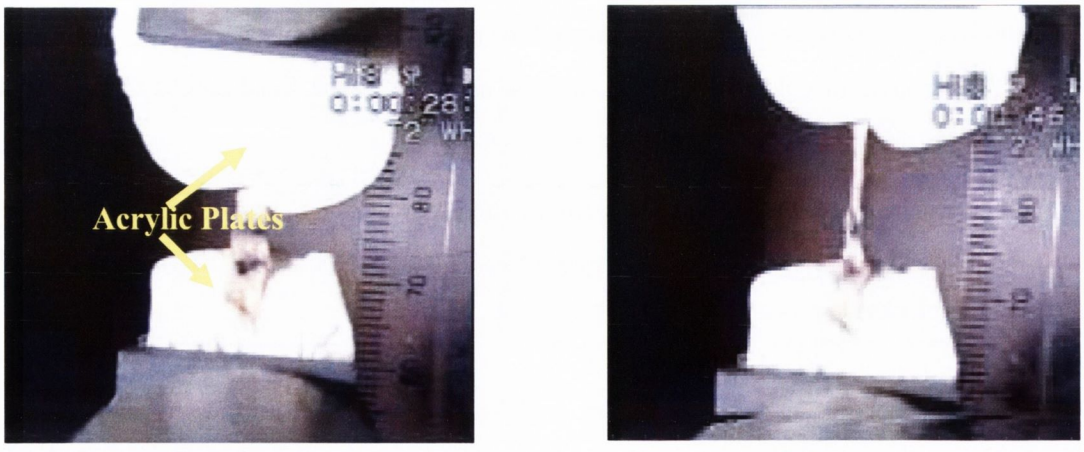
5.4.1.1 Results of low strain rate tests

The results for the low strain rate tests showed on knee ligaments that the stress at failure was between 0.75 and 1.5Mpa.

These rather low figures for stress at failure may be due to the considerable thinning of the tissue during testing.

Two conclusions were made as a result of these preliminary tests.

1. Securing the extremities of the ligaments in acrylic blocks was a viable method of carrying out the tests.
2. The low figures for stress at failure made it imperative that the weights mechanism used in the high strain rate tests should be of minimum value.



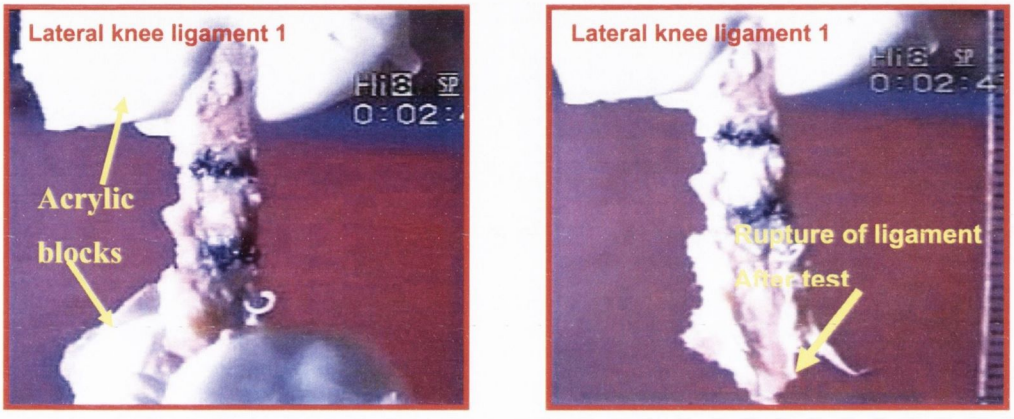
5.14(a) 5.14(b)

Figures 5.14(a) and 5.14(b): Tensile testing of lateral knee ligament No.2 in Instron 1011 before testing and at the point of failure

5.4.2 High strain rate tests of knee ligaments

Two lateral ligaments and one medial knee ligament were dissected from cadaver specimens. They were embedded in acrylic blocks as described above. The blocks were inserted into the clamps of the test rig, subjected to high strain rate tests and, force measurements taken. Figure 5.15 (a) and 5.15(b), show lateral knee ligament 1, mounted before and after testing.

All the high strain rate tests were performed by dropping a 10N weight from a height of 0.1m from the weights pan. Again the on knee ligaments were used to test the viability of using acrylic blocks for high strain tests.



(a) (b)

Figure 5.15: Lateral knee ligament number 1 (a) before, and (b) after testing

5.4.2.1 Results for lateral knee Ligament 1

The results for the tests on lateral knee ligament 1 are shown in table 5.2 and figure 5.16.

Dimensions:

Width =8.8 mm

Length =18 mm

Thickness =2.0 mm

Cross Sectional Area = 10 mm^2

Temp= 21°

Voltage (mV)	Time (ms)	Force (N)
0	0	-1.94
33.5	2.5	5.19
-83	16	-19.6
93	24.5	17.85
91	28.5	17.43
117	30.5	22.96
112	35	21.89
182	41.5	36.79
117	54.5	22.96
177	63.5	35.72
171	66.5	34.45
347	91.5	71.9
169	112.5	34.02

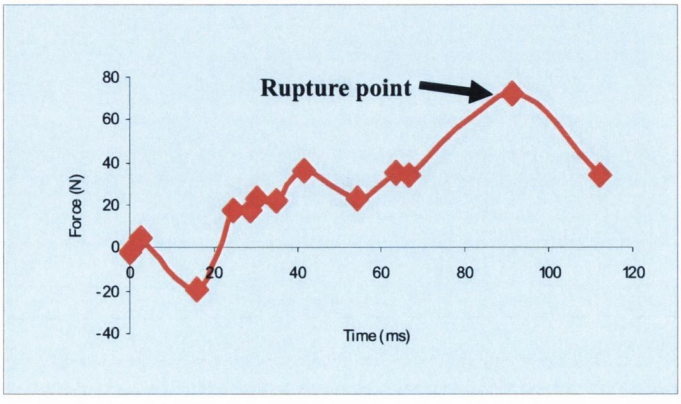
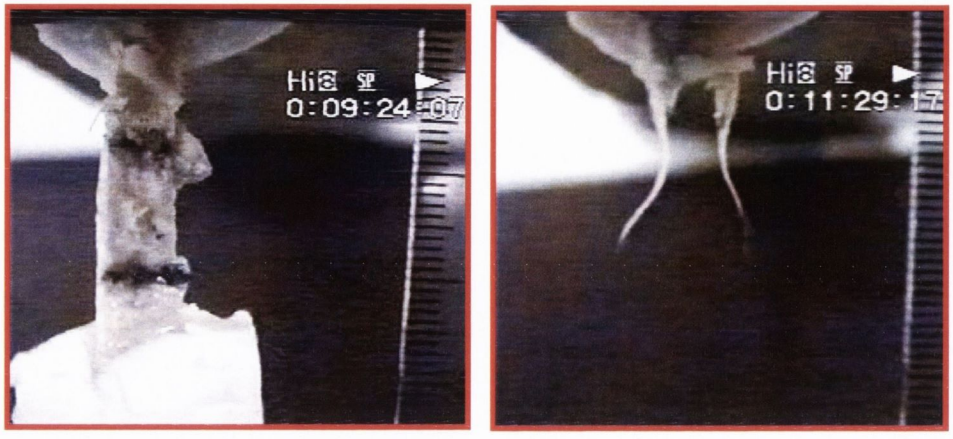


Table 5.2 & figure 5.16: Voltage /force V time and deformation of lateral knee ligament 1.

5.4.2.2. Results for lateral knee ligament 2

Figures 5.17(a) and 5.17(b) show the before and after frames of the test and the results of the test are shown in table 5.3 and figure 5.18.



(a) (b)

Figure 5.17(a) & (b): Lateral knee ligament number 2 (a) before, and (b) after testing

Width=5.76mm

Length=24.5mm

Thickness=1.5mm

Cross-sectional area=8.64mm^2

Temp=21°

Time (ms)	Voltage (mV)	Force (N)
0	1.75	-1.56
3	50.7	8.85
5.5	61.2	11.09
7	56	9.98
8.5	84	15.94
13.5	19.2	2.15
18	-31.5	-8.64
21.5	0	-1.94
30	56	9.98
33	66.5	12.21
39	45.5	7.75
47	231	47.21
61	113	22.11
69	61.2	11.09
74	75.2	14.06
80	43.7	7.36
84	61.2	11.09
87	7	-0.45

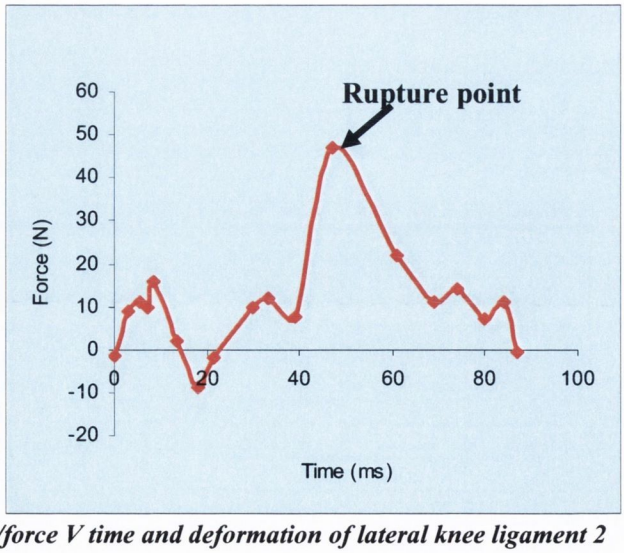
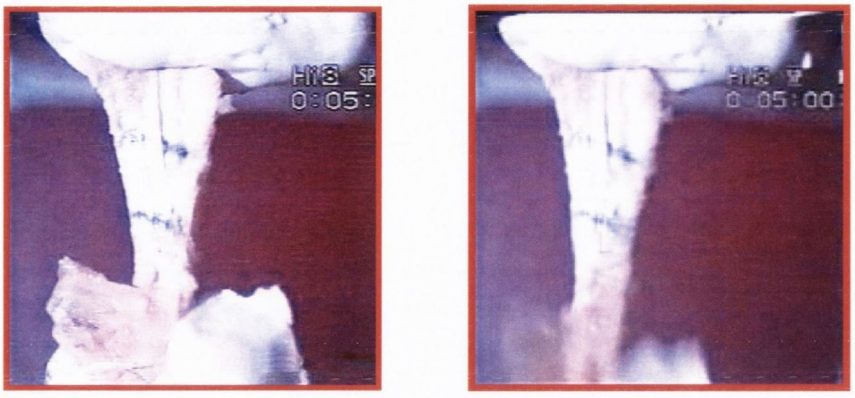


Table 5.3 & figure 5.18: Voltage /force V time and deformation of lateral knee ligament 2

5.4.2.3 Result for medial knee ligament



(a) (b)

Figure 5.19: (a) Medial knee ligament before testing & 5.19 (b) Rupturing after impact

Figure 5.19(a) and 5.19(b) show the ligament before and after the application of the load and the results of testing are shown in table 5.4 and figure 5.20.

Width=5.02mm

Length=21.9mm

Thickness=2.01mm

Cross-sectional area=10.0mm^2

Temperature=20°

Time (ms)	Voltage (mV)	Force(N)
0	0	-1.94
7.5	122	24.02
14.5	192	38.92
15	199	40.41
17	231	47.21
19.5	262	53.81
22.5	305	62.96
25.5	262	53.81
34.5	161	32.32
42	105	20.41
43.5	112	21.89
49	82.2	15.55
51	85.7	16.3
58	66.5	12.21

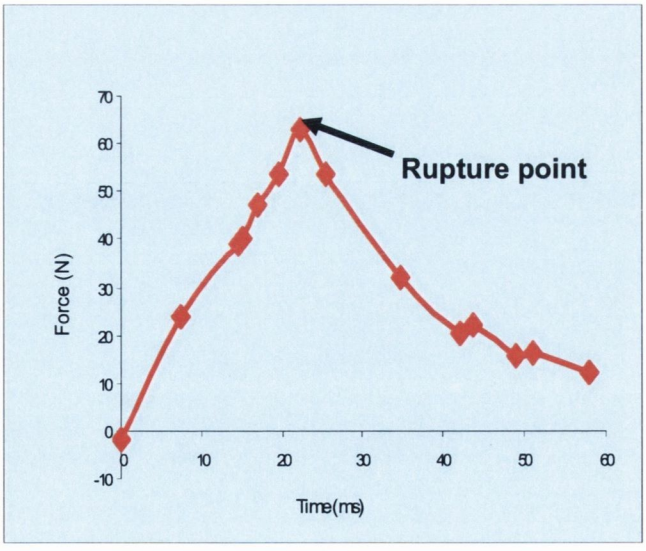


Table 5.4 & figure 5.20: Voltage /force V time and deformation of medial knee ligament 2

5.4.2.4 Discussion on high strain rate testing of the knee Ligaments

The impact test on the lateral knee ligament 1 took place over a period of 91.5ms. During this period the video analysis strain readings were taken at t=40 ms and t=80 ms.
The strain rate was calculated by measuring the change in length of the tissue during a known period of time taken from the video analysis described on page 241 and using the formula:-
L_2-L_1/T_2-T_1.

t = 40ms Strain = ~0.14

t = 80ms Strain = ~0.22

At t =16 ms the load cell showed a negative reading of –19N. This discrepancy could be due to the load not being evenly distributed at the time of impact, or that the system was not entirely rigid i.e. some rattling occurred.

From the readings recorded, the following results were calculated:

t = 40 ms σ = 2.98 MPa
t = 80 ms σ =5.45 MPa
t = 91.5 ms σ_f =7.19 MPa
Therefore the Modulus of viscoelasticity of the material at:-
t = 40 ms = 21.3 MPa
t = 80 ms = 24.8 MPa

The high strain rate test on the lateral knee ligament 2, took place over a period of 47 ms.
The video analysis allowed strain readings to be taken at 40 ms.

Therefore t = 40 ms Strain = ~0.18

As in the testing of lateral ligament A, a negative force of –8.64N was recorded at t=18 ms. This variation occurred at approximately the same time as in the previous test.

From the readings recorded, the following results were calculated:

t = 40 ms $\sigma = [7.75/8.64x10^{-6}] = 0.89$ MPa

t = 47 ms $\sigma = [47.21/8.64x10^{-6}] = 5.4$ MPa

Therefore the Modulus of the Material at t = 40 ms = 4.94 MPa

For the medial knee ligament the impact test took place over 22.25 ms. Unfortunately this time period did not enable the recording of any strain readings (i.e. in one frame the ligament was intact, in the next frame the ligament had fractured completely). There is no variation in the force readings at ~15ms, suggesting that the load was applied evenly at the time of the impact.

From the readings recorded the following result was calculated:

t =22.25 ms $\sigma_f = [62.96/10x^{-6}]=6.296$ MPa

5.5 High Strain Rate Testing of TMJ Soft Tissues

It was also decided to carry out tests on the lateral ligament of the TMJ, and on the attachment of the disc to the lateral pole of the condyle, as both of these tissues are commonly found clinically, to be damaged.

5.5.1 Lateral ligament tests

The TMJ lateral ligament being of small dimensions (approx 20-25 mm in length) is very difficult, not only to dissect but also to locate and secure in acrylic blocks. Therefore in order to secure the ends of the ligament in acrylic it was decided not to dissect the ligament from the bony attachments, but to cut the cranial and mandibular bony attachments whilst leaving the ligaments intact and attached to the bone.

The two bony elements were then secured in acrylic blocks, ready for testing as previously described (Figure 5.21).

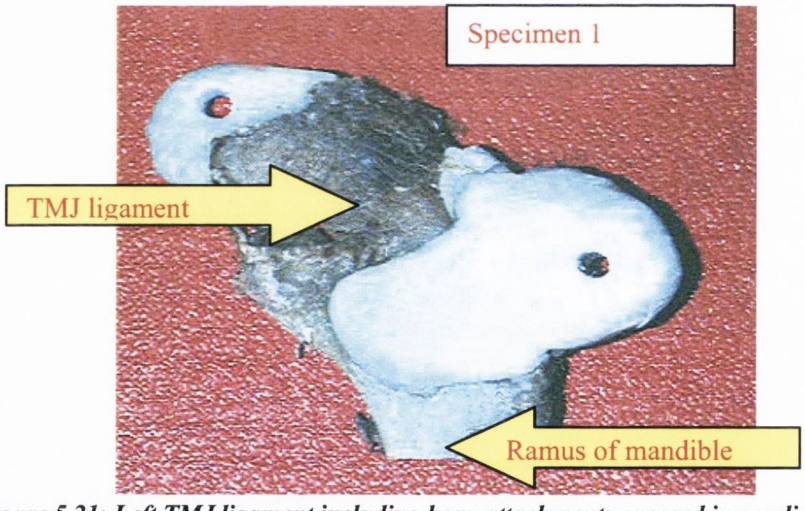


Figure 5.21: Left TMJ ligament including bony attachments encased in acrylic blocks

Two TMJ ligaments were now tested in the same manner as the knee ligaments. Unfortunately while testing the first lateral ligament, the acrylic setting became separated from the mandibular attachment. It was therefore no longer possible to carry out a high strain rate test on this specimen.

5.5.1.1 Result for lateral ligament 2:

The other ligament was tested successfully (figure 5.22(a) and 5.22 (b)).The results of the test are shown in table 5.5 and figure 5.23.

Dimensions:

Cross sectional area
Width=7.5mm.
Length=22.9mm.
Thickness=1.8mm.
Temperature=20°C





Figure 5.22 (a) & (b): TMJ ligament 2 before testing & figure 5.22 (b) TMJ ligament after testing

Time (ms)	Voltage (mV)	Force (N)	Time (ms)	Voltage (mV)	Force (N)
0	0	-1.94	68	285.25	58.76
1	1.75	-1.56	69	314.25	64.93
2	1.75	-1.56	70	339.25	70.25
3	3.5	-1.19	71	362.25	75.14
4	7	-0.45	73	398.25	82.8
5	7	-0.45	75	428.25	89.18
6	8.75	-0.07	75.5	435.25	90.67
7	8.75	-0.07	84.5	448.25	93.44
13.5	15.75	1.42	93.5	437.25	90.1
19.5	12.25	0.67	98.5	342.25	70.88
34.5	17.45	1.78	103.5	243.25	49.82
29.5	24.45	3.27	108	178.25	35.99
34.5	22.75	2.91	115	127.25	25.14
39.5	20.95	2.52	119.5	125.25	24.71
44.5	40.25	6.63	135.5	169.25	34.08
46	68.25	12.59	140.5	164.25	33.01
55	68.25	12.59	150.5	176.25	35.57
60	92.75	17.9	165	152.25	30.46
61	106.25	20.67	200.5	57.75	10.36
52	124.25	24.5	210.5	80.45	15.18
53	148.25	29.61	221	83.95	15.93
64	173.25	34.93	231	103.25	20.03
65	199.25	40.46	241	78.75	14.82
66	227.25	46.42	250.5	71.75	13.33
67	256.25	52.37	261.5	38.45	6.25

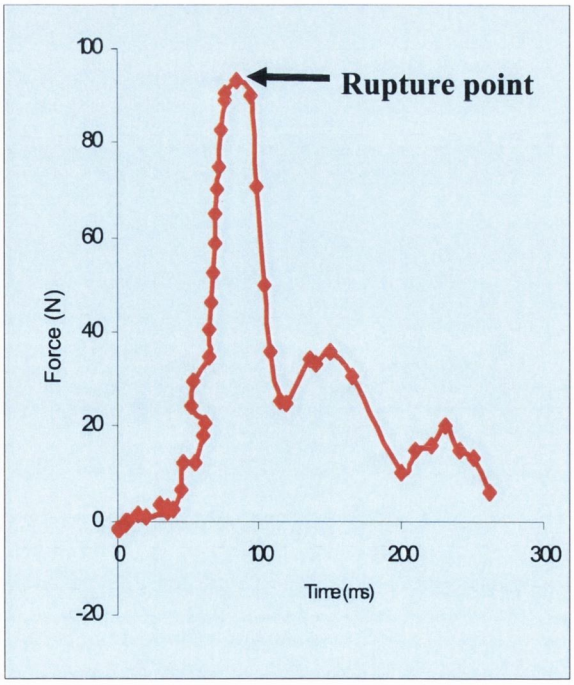


Table 5.5& figure 5.23: Voltage / force and rupture force v time for TMJ ligament 2

5.5.2 Tests on Disc Attachment to lateral pole of Condyle

The testing of the strength of the attachments of the disc to the lateral pole of the condyle posed a different problem when it came to mounting the specimen in the testing rig. A satisfactory method was found whereby the disc was dissected off the condyle on the anterior, posterior and medial sides, leaving only the attachment of the disc to the lateral pole intact (Figure 5.24).

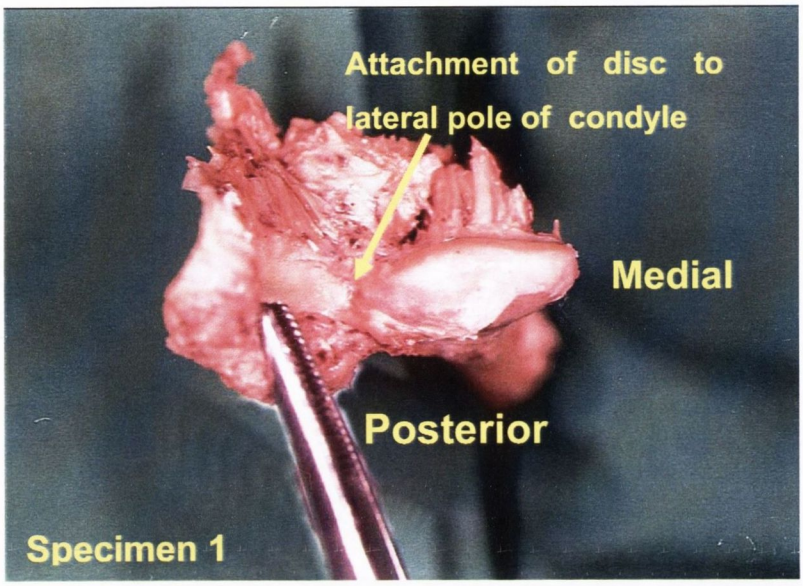


Figure 5.24: TMJ Disc dissected off the condyle except at the attachment to the lateral pole

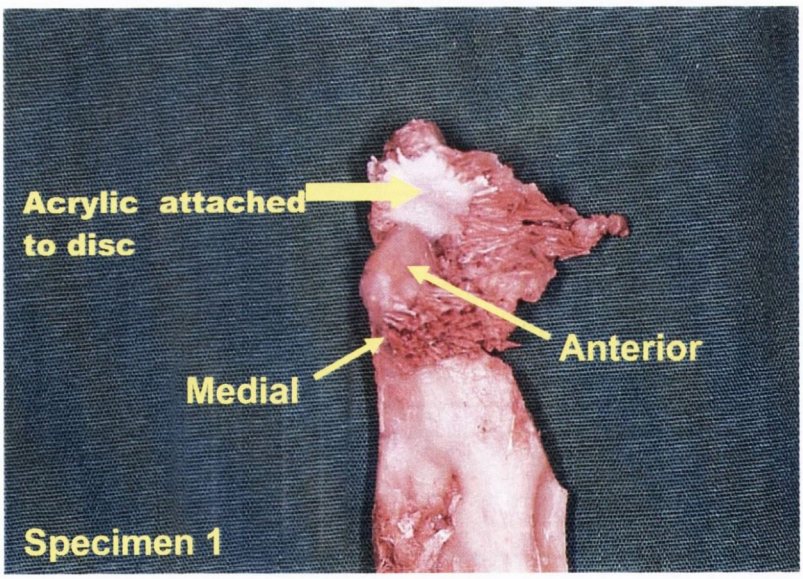


Figure 5.25: Acrylic attached to the inferior surface of TMJ disc

Acrylic resin was now inserted into the inferior surface of the disc and allowed to cure (Figure 5.25).A further mix of acrylic was now bonded to the already cured acrylic and wrapped around the anterior, posterior and medial borders of the disc so that the disc was encased in acrylic except around its' lateral border.

5.5.2.1 Result for specimen 1

The before and after testing frames of the attachment of the disc to the condyle are shown in figures 5.26(a) and 5.26(b) and the result of the test are shown in table 5.6 and figure 5.27. Average dimensions were recorded for analysis of the TMJ attachments. The dimensions used were:

Diameter = 7.5mm.

Thickness =0.5mm.

Cross sectional area=22.1mm^2

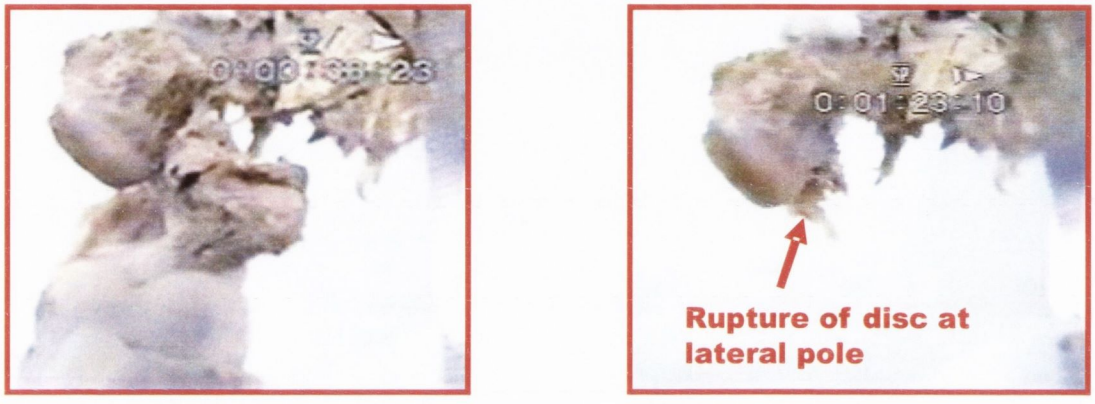


Figure 5.26 (a): Specimen 1 before testing and (b) after testing

Time (ms)	voltage (mv)	Force (N)
0	0	-1.94
16	-5.6	-3.13
24	-1.4	2.23
30	1.4	-1.64
	2.8	-1.34
54	2.8	-1.34
59.5	3.3	-1.23
67	1.4	-1.64
75	-3.6	-2.7
80	-8.4	-3.72
81	-9.8	-4.02
87.5	7.7	-0.3
92.5	16.2	1.15
93.5	22.4	2.83
95.5	25.9	3.58
98	26	3.6
100.5	27.3	3.87
101	28	4.02
102	28	4.02
104.5	27.3	3.87
107	22.4	2.83
110	18.9	2.09
113.5	16.2	1.51
116.5	15.4	1.34
119	15.4	1.34

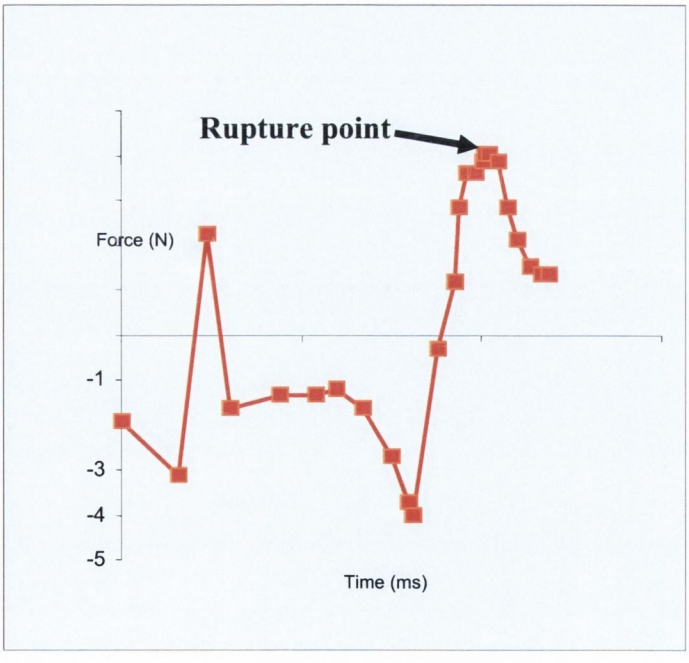


Table 5.6: Voltage/time v force & figure. 5.27:Graph of deformation rate of disc attachment No 1.

5.5.2.2 Result for specimen 2

This specimen had a perforation in the intermediate zone of the disc, but otherwise had no damage, with the atachment to the lateral pole of the condyle being intact (Figure 5.28). It was treated in the same fashion as specimen 1 prior to testing (Figures 5.28, 5.29, 5.30 (a) & 5.30(b).

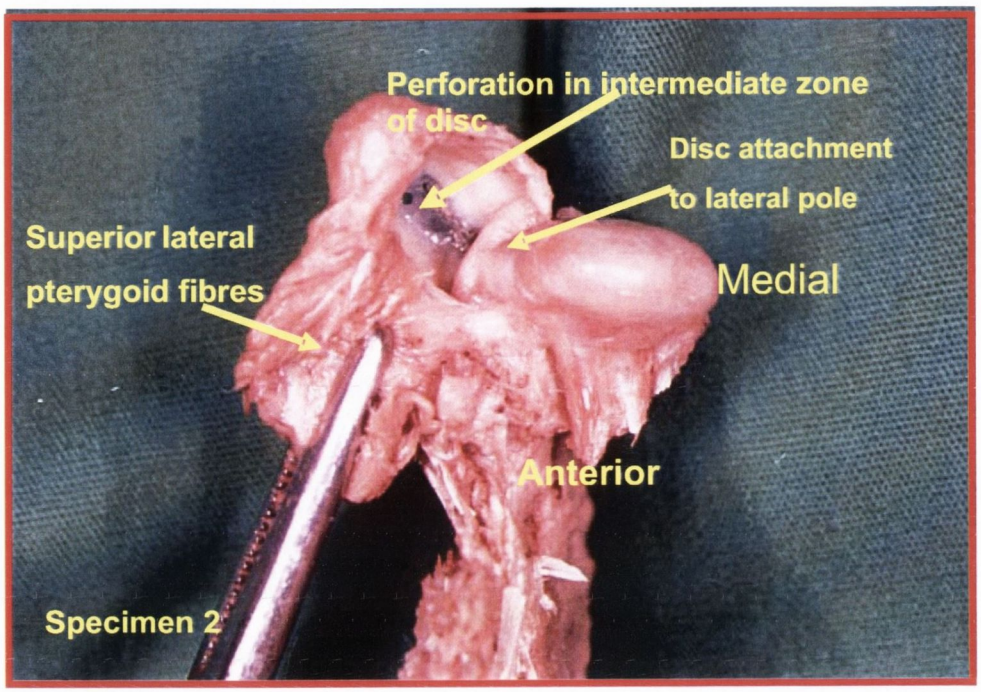


Figure 5.28: Specimen 2 dissected off the condyle, but left attached on lateral side

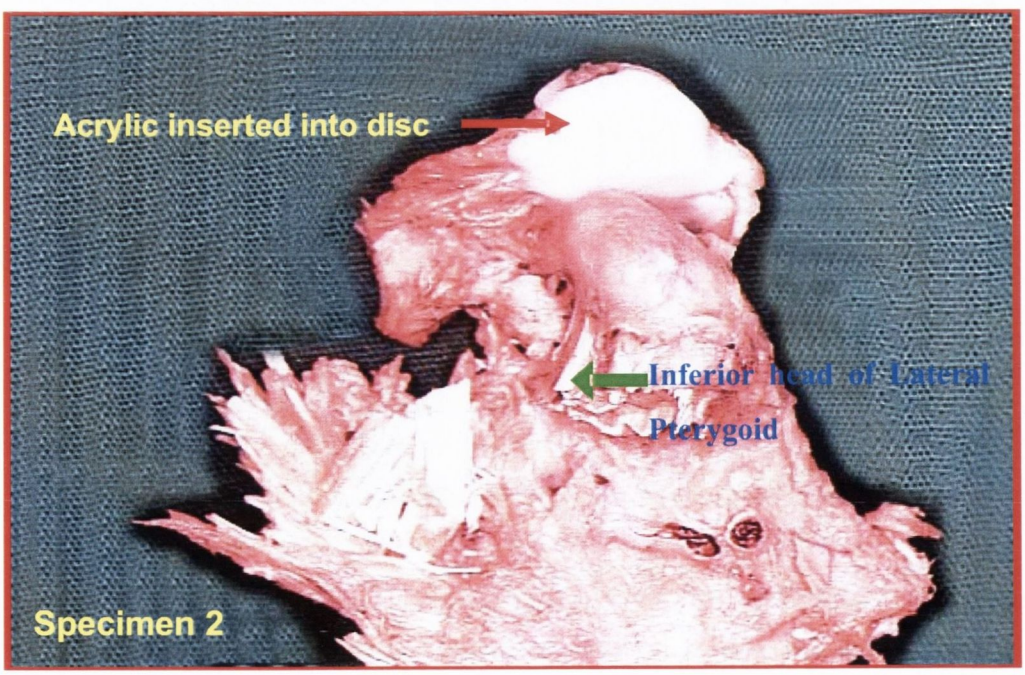


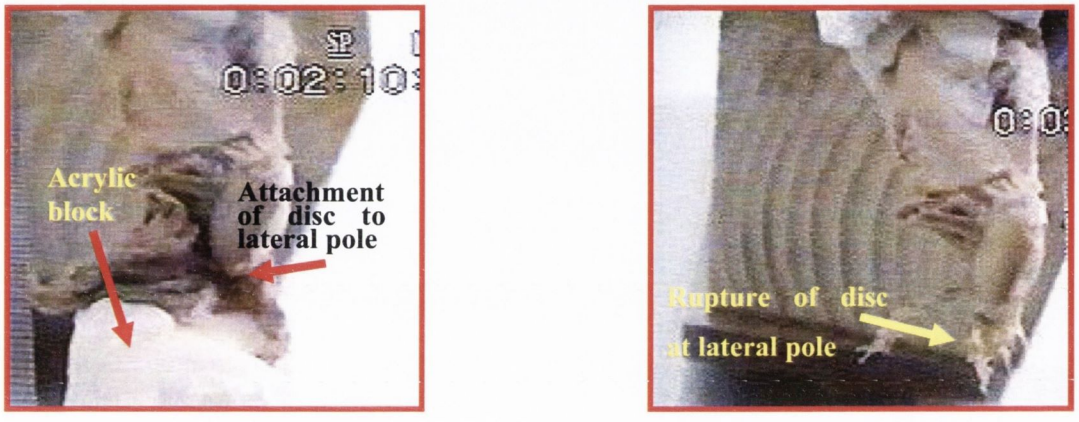
Figure 5.29: Acrylic inserted into the inferior surface of disc

Average dimensions were recorded for analysis of the TMJ attachments. The dimensions used were:

Diameter = 7.5mm.

Thickness =0.5mm.

Cross sectional area=22.1mm^2



(a) (b)

Figure 5.30: Specimen 2 (a) before testing& (b) after testing

The results of the test are shown in table 5.7 & figure 5.31.

Time(ms)	voltage(mV)	Force(N)
0	0	-1.94
18	-1.4	-2.23
19.5	4.2	-1.04
21.5	9.1	0
23	13.3	0.89
23.5	12.6	0.75
26	16.1	1.49
29	19.6	2.24
32	23.8	3.13
33.5	30.8	4.62
35.5	36.4	5.81
37	39.9	6.55
42	31.5	4.77
46	24.5	3.28
48	18.2	1.94
51	6.3	-0.59
53	-3.5	-2.68
54.5	-8.4	-3.72
56	-11.9	-4.47

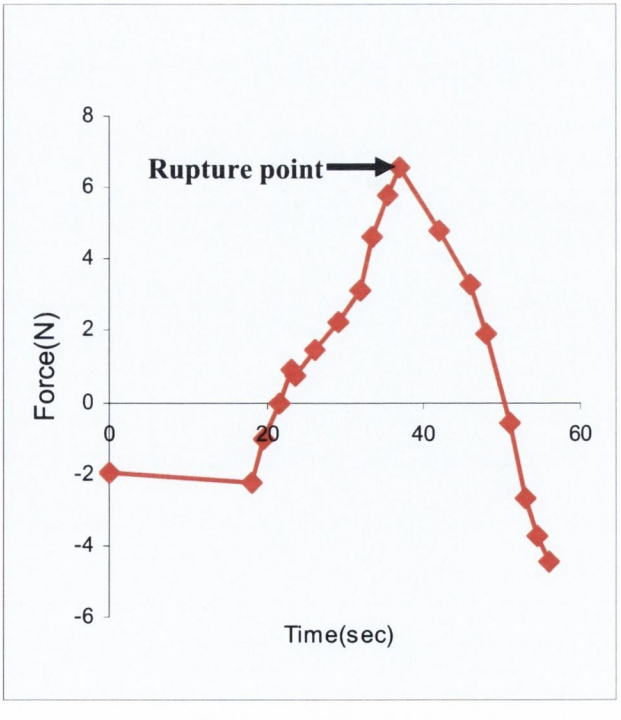


Table 5.7 & figure 5.31: Voltage /force v time and strain rate of disc attachment No.2

5.5.2.3 Conclusions on tests of TMJ soft tissues

The impact on lateral ligament 2 took place over a time period of 84ms. This allowed video analysis of two frames during the test.

Therefore t=40ms Strain = ~ 0.22
t =80ms Strain = ~ 0.31

A fluctuation in the force can be seen from t=0ms to t =10ms, due to "noise" being picked up by the strain gauges. "This noise" was transmitted at 50 Hz from the mains supply and was detected, because the low pass filter had been cut from the strain gauge amplifier.

The following results were calculated from the readings recorded:

t=40ms σ =0.16Mpa (cross sectional area 13.5mm^2)

t=80ms σ =6.8Mpa (cross sectional area 13.5mm^2)

t=84.5ms σ = 6.9Mpa (cross sectional area 13.5mm^2)

Therefore the modulus of elasticity of the tissue at t = 40ms and t = 80 ms was 0.86MPa and 21.9MPa respectively. For the tests on the TMJ discal attachments it was not possible to use video analysis due to the difficulty in focussing on this minute area.

Attachment 1 test took place over a time period of 102ms. The video analysis permitted two frames to be viewed at 40ms and 80ms.

From the readings the following result was calculated:

t=102ms σ_f =0.18Mpa (Cross sectional area 22.1mm^2)

The test on attachment 2 took place over a period of 37ms. The trough in the curve was due to difficulty in loading the weights pan uniformly. From the readings the following result was calculated.

t=37ms $\sigma_{f=}$ =0.29Mpa

5.5.3 Discussion on high strain rate testing of TMJ soft tissues

The object of the tests carried out was to analyse the behaviour of the TMJ soft tissue under high strain rates in an attempt to approximate the type of loading experienced by these tissues during the "whiplash" event. By using video analysis it was possible to take preliminary readings for strain and also it facilitated visual examination of the effects of a high strain rate on the tissue.

In the tests performed on the ligaments extracted from human knees in this project similar results were seen.

Knee ligaments tested in tension at a rate of 500mm/min, gave values for the stress at failure between 0.75 and 1.5Mpa.The time taken for failure to occur in these tests was approximately 4 seconds. When similar ligaments were tested within a test time of <90ms, failure stresses were seen to range between 5 Mpa and 7Mpa.

These results support the theory put forward by Noyes and Grood (1976) that in the high strain rate testing on the knee the attachment of the ligament to the bone is always the weak link in the bone-ligament-bone attachment.

The results recorded for the TMJ soft tissue tests showed that the lateral ligament failed at a force of 93.4N and at a strain of ~ 0.31, however the attachments of the disc to the lateral pole of the condyle failed at much smaller loads viz. 4N and 6N.
These results suggest that when forces are reacted within the ligament /capsule /disc complex, the discal attachment to the condyle would be the most likely to fail first or suffer irreversible damage.
When these forces are compared to those calculated in Chapter 4 for Final force 2, it can be seen that the force sustained by each condyle due to Final force 2 in the retroflexion phase of the event peaked at 8 Newtons and the force sustained by the lateral ligament due to force F1b2 peaked at 178 Newtons (assuming symmetrical loading of the two joints, which is unlikely). If head movement was asymmetrical the loading would also be asymmetrical resulting in loads of even greater magnitude on one joint. This would be consistent with the clinical findings that unilateral TMJ damage is a more frequent finding than bilateral damage. Although the tests were limited in number due to time constraints, the results were consistent.

Chapter 6 Discussion

The pseudo-static model, which was used in this research, predicted that mouth opening would occur in a "whiplash" event. The model also predicted that forces would occur, of sufficient magnitude to challenge the integrity of the attachment of the TMJ disc to the lateral pole of the condyle, based on the results of the tests carried out on the TMJ soft tissues.
These findings are supported by the clinical studies which indicate a causal relationship between TMD and "whiplash" although its prevalence is uncertain.

6.1 Discussion on research results

The initial objective in this research was to assess whether the concept of indirect injury to the TMJ was viable, or whether anecdotal claims that injury to the TMJ could only occur as a result of direct trauma were correct.
The starting point was Newton's first law of motion which states that all bodies possess mass and therefore tend to maintain their position in space unless acted directly upon by an external force.
Based on this and taking the mass of the mandible into consideration the "pseudo-static" model used in this work showed clearly that mouth opening would occur if the subject was unaware of the impending impact with the lower jaw in a relaxed and passive mode. More importantly it was necessary to estimate the forces resulting from these motions and their relationship to the strength of the TMJ soft tissues
The use of constant acceleration in the "pseudo-static" model predicted that pulling/pushing forces as well as mouth opening / closing forces, due to rotation and translation would be sustained by the joint and surrounding soft tissues during retroflexion and flexion.
The use of variable acceleration in the model, estimated more accurately the magnitude of these forces due to peaks and troughs in acceleration and velocity.
The variable acceleration calculations predicated that during retroflexion, forces on one condyle resulting from a combination of linear and angular displacement of the cranium peaked at a magnitude of 8 Newtons (assuming symmetry) and forces reacted within one TMJ ligament due to mouth opening were in the order of 180 Newtons.
The forces occurring in flexion were estimated to be of a much lower magnitude.
However the peak force of 4 Newtons occurred at the initial point in flexion having reached insignificant levels at the end of retroflexion (theoretically reaching zero velocity and acceleration just prior to flexion). This sudden change in force direction implied that at the point of change from retroflexion to flexion further insult may be sustained by the joint tissues.

Using the results predicted by the "pseudo-static" model a hypothesized injury sequence has been proposed as follows:-

From t=0.065 sec. to 0.072 sec the TMJ ligament is subjected to a load of approximately 175 Newtons due to mouth opening forces (F1b2). This load is transmitted to the TMJ ligament and to the attachment of the disc to the lateral pole of the condyle. Superimposed on this during this time period is a load of 8 Newtons due to Final force 2.
A second peak of force on the condyle of 6.6 Newtons acting in a downward and backward direction occurs at 0.125 sec.
This is followed at the beginning of flexion by a further insult of 4 Newtons acting on the condyle in a posterior direction. During this period the capsule/ligament complex is unloaded.

At the end of flexion the "pseudo-static" model predicted that the chin would impact against the sternum resulting in forces driving the condyle posteriorly, causing compression of the posterior attachment and at the same time offering a further challenge to the integrity of the attachment of the disc to the condyle. It was not possible to calculate these forces here, due to lack of information regarding the stopping time.

During the rapid posterior movement of the condyle, which occurs during flexion the lateral ligament is unloaded. However this rapid movement of the condyle may adversely affect the attachment of the disc to the condyle due to its attachment to the superior head of the Lateral pterygoid muscle. This subject was addressed in chapter 3 using a theoretical "Spring Model". Incorporated into this model were variations in the proportions of the fibres of the superior head of the lateral pterygoid inserting into the disc and condyle respectively.
The model was thus used to estimate the effect that these variations would have on forces acting in a posterior direction on the condyle and disc respectively.
The Spring model predicted that the fibres inserting into the condyle would modify forces sustained by the attachment of the disc to the condyle but this would not necessarily prevent partial or complete displacement of the disc from the head of the condyle.
The Spring Model also showed that variations in the distribution of the attachments of this muscle to the disc and condyle respectively would make some individuals more susceptible to disc displacement.
The macroscopic evaluation of the lateral pterygoid also demonstrated that variations in the size of the muscle heads may influence the likelihood of disc displacement in different individuals.

It was shown in two specimens that the Lateral Pterygoid (specimens 3 and 10) was not separated into 2 individual heads and consisted of a single muscle. In these specimens the percentage of fibres inserting into the condyle greatly exceeded those inserting into the disc giving considerable protection against disc displacement.

The high strain rate tests performed on the TMJ soft tissues were an attempt to simulate the type of loading that might be reacted within these tissues during a "whiplash" event, which has been seen to take place over a very short period of time (approximately 0.25 sec from start of retro flexion to end of flexion).

The results recorded for the TMJ soft tissue tests showed that the lateral ligament failed at a force of 93.4N. However the attachments of the disc to the lateral pole of the condyle failed at much smaller loads viz. 4N and 6N.
These results suggest that when forces are reacted within the ligament /capsule /disc complex, the discal attachment to the condyle would be the most likely to fail first or suffer irreversible damage.

When all of the variables are taken into consideration , such as the velocity of impact , the previous condition of the TMJ tissues, the variations in the Lateral Pterygoid attachments and variations in head restraints it could be concluded that anterior displacement of the disc could occur in a few different ways, for example:-

- Complete rupture of the attachment of the disc to the condyle at the time of the accident.
- Partial rupture of the attachment with subsequent displacement under normal functional loading.
- Disc displacement due to moderate or severe loading on a previously damaged attachment.

The work in this thesis has relied on certain previous studies found in the literature. This applies in particular to Clemens and Burrows (1972) for the retroflexion / flexion movements of the cranium in a 15mph rear impact, Schneider et al (1989) who looked at the dynamic response of the human jaw resulting from a 15mph rear impact and Merlini and Palla (1989) who calculated the relationship between angular displacement and linear movement of the condyle in mouth opening (See Chapter 4).

The results of the 'pseudo static' analysis carried out in this work led to further collaborative research in the Trinity Centre for Bioengineering.

Initially a collaborative study was carried out using SUPERCRASH, a multi-body dynamic simulator to measure the transient motion and the acceleration time history of the jaw. This model predicted the maximum jaw opening permitted by the model (30^0) and accelerations of (Lemmon et al 1994).

These results stimulated further experimental work using a mechanical model for both qualitative and quantitative analysis of the behaviour of the jaw in low velocity rear impacts.

Initially a Senior Sophister student At TCD (Simms 1995) was encouraged to develop a mechanistic model of the jaw and cranium for impact testing as a final year project.

The mouth opening predicted in the above work was confirmed in the low velocity impact tests and even included in some of the tests complete condylar dislocation.

This led to further research designed to make a quantitative analysis using a mechanistic model. This showed an angular peak acceleration for mouth opening of 750 $rad.s^{-2}$ and a peak angular velocity of 15 $rads^{-1}$ at 47ms., resulting from of Δv of approximately 9 km/h (5.5mph).

The results of this work were published and presented at the proceedings of the Association for the Advancement of Automotive Medicine (Lyons et al 1997).

Subsequent to this a PhD thesis (Simms 1999) was written on further sled tests carried out on an even more sophisticated model. Simms found that the maximum reaction forces generated were in the TMJ during mouth opening were 10N and 6.6 N.

A further collaborative study carried on seat and head restraint, showed that by suitable redesign of the automobile seat /head restraint, the time differenced accelerations of the head and torso can be inhibited (Lyons et al 1994), at the same time limiting jaw movements and the likelihood of TMJ injury.

6.2 Limitations in the research

The use of the pseudo–static model was a preliminary evaluation of the concept that rapid mouth opening and consequently TMJ damage could occur as a result of a "whiplash" event, without sustaining direct trauma.

In effect the "Pseudo-static" model considered the mandible as a free body in space, not under the constraints of soft tissues which might inhibit or augment its movement.

Factors not incorporated into the model include:-

- The Infrahyoid, suprahyoid and platysma muscles which would tend to hold the mandible down during retroflexion thereby adding to its inertial characteristics.

- The mandibular elevator muscles which would tend to inhibit the degree and rapidity of mouth opening in retroflexion.

- The soft tissues posterior to the ascending ramus of the mandible, which would tend to increase the rate and degree of condylar translation, as a result of angular displacement of the mandible during retroflexion,

- The varying strengths of the lateral ligament which would also influence the degree and rate of translation. It was observed in the macroscopic anatomical evaluation that the lateral ligament had varying dimensions and in some cases was indistinguishable from the capsular tissue

- The potential for injury to the mandibular elevator muscles due to the rapidity of mouth opening not allowing the muscles time to relax.

- The differential calculus carried out on the Clemens & Burrows (1972) curve treated the event as two separate phases in the event. This was due to the difficulty in analyzing by differential calculus such a minute segment of the curve where the transition from retroflexion to flexion occurs.

- Retroflexion of the cranium was assumed to take place at the junction of C_0 and C_1 whereas retroflexion is in fact shared by the cervical vertebrae. This meant that the magnitude of the pulling forces derived from the model were an underestimate, as these forces are in part predicated by the length of the radius from the centre of rotation of the cranium to the TMJ.

Chapter 7 Conclusions

- Indirect injury to the TMJ can occur as a result of a "whiplash" event. This conclusion has been arrived at using a theoretical model of the forces and motions in the TMJ combined with experimental testing of the strength of the relevant tissues. Forces resulting from angular and linear motion of the mandibular condyle and to pulling/pushing forces resulting from posterior and anterior movement of the cranium are predicted to cause damage to the TMJ ligament and particularly to the attachment of the disc to the condyle at the lateral pole.

- There are significant variations in the anatomy of the TMJ, which will put some individuals at risk of whiplash injury than others. In particular the histological evaluation of the posterior attachments of the Lateral Pterygoid muscle showed that there was a variation in the attachments of the superior head into the disc and condyle respectively in different specimens and at different levels in the same specimen. The "Spring Model" showed that the variations in these attachments made some individuals more prone to disc displacement than others. Variations found in the macroscopic anatomical study supported these findings.

- The most vulnerable tissue in the TMJ is the attachment of the disc to the lateral pole of the condyle, as shown by tests carried out on the TMJ ligament and on that attachment. This , plus the direction of the fibres of the lateral pterygoid inserting into the disc, could explain why in a number of clinical situations the disc is displaced antero- medial to the condyle.

- The review of clinical studies indicates a causal relationship between whiplash and TMD. However some important shortcomings were noted in the evaluation protocols used, suggesting the need for systematic studies of the clinical evidence.

Future Work

The theoretical "Pseudo static" model used in this work is very basic and does not take into account all of the damping effects on the temporomandibular joints. Nevertheless the model does show that potentially injurious mouth opening could occur as a result of head retroflexion. There are a number of factors needed to be taken into consideration for any future work carried out in this area to give a more accurate assessment of the degree of mouth opening, the forces involved and their prospective injury potential.

Some examples of this are as follows:-

- The Suprahyoid, Infrahyoid and Platysma muscles would tend to add to the inertial behaviour of the mandible by holding it down during retroflexion tending to increase the rate and degree of mouth opening.

- Compression of the soft tissues posterior to the ascending ramus of the mandible during retroflexion would tend to increase the rate and degree of condylar translation.

- Alternatively the mandibular elevator muscles would tend to passively resist mouth opening due to their attachments from the cranium to the mandible.

A resolution of the forces resulting from the above three factors needs to be taken into consideration and built into any future model or analysis.

- The incorporation of the TMJ lateral ligament into any future work.

- The forces arising during the transition from retroflexion to flexion needs further analysis.

- The future work in this area is probably best carried out by a combination of finite element analysis and mechanical modelling. Using these methods varying strengths of tissues can be tested in response to various velocity impacts with a variety of seat and headrest design to predict the likelihood of injury in a variety of circumstances.

- Investigation of what effect a raised hyoid has on the function of the Digastric muscle

- Evaluation of the forces sustained by the Mandibular elevator muscles during the retroflexion phase of the event?

- Finally the above discussion could become a virtual irrelevance if adequate seat and headrest design were adhered to. If the factors dealt with in appendix F were taken into consideration by the construction of a seat and headrest versatile enough to be used by a variety of anthropomorphic types injurious head retroflexion in rear impact collisions could be eliminated thus removing any threat to the cervical tissues. Furthermore in the absence of retroflexion potentially damaging mouth opening as described in this document would no longer be a problem*.

*See Appendix J for further information regarding headrest design

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Appendix A

Diagnosis of temporomandibular joint Dysfunction

In the absence of objective signs of temporomandibular joint dysfunction it is important for the examining clinician to be aware of what defines TMD and also that there are a number of other conditions which can cause pain in the cranio-facial region.

The principle dysfunctions affecting the TMJ are as follows:-

1. Posterior capsulitis i.e. inflammation of the posterior aspect of the joint capsule.
2. Myalgia of the muscles controlling TMJ movement.
3. In-coordination of the muscles controlling TMJ movement
4. Muscle hypertrophy which usually affects the Masseter muscle and is due to hyperactivity due to bruxing clenching or parafunctional behaviour.
5. Trigger points in the muscles controlling TMJ movement.
6. Internal derangements of the TMJ, i.e. locking, clicking, and dislocation.
7. Damage to the TMJ ligament

The most common signs of TMD are:-

- Restriction of mouth opening.
- Noises in the TMJ i.e. painful clicking or crepitus.
- Reducing or non-reducing locking of the jaws.
- Tenderness to palpation in muscles controlling jaw movement.

Evaluation for TMD

Although evaluation for TMD can be carried out by the general dental practitioner it is more appropriate for it to be performed by a dentist who has had special training in that area.
The evaluation for TMD should broadly consist of the following:-

History

Adequate time should be given to this interview as it may give an insight into the type of complaint that is being dealt with prior to clinical examination.
The principle information required is as follows:-

- ❖ The patients' chief complaint.
- ❖ Quality,location,character,duration,onset,intensity,history,aggravating, relieving factors and referral patterns of the pain.
- ❖ Medical history with particular reference to any past head/neck trauma and also keeping in mind that facial pain can also be due to more obscure causes such as cardiac angina.

Clinical examination

- ➢ Evaluation for clicking /crepitus of the joint should be carried out by digital palpation and by the use of a stethoscope. The point where the clicking occurs in opening and closing recorded in order to establish whether the disc is recapturable by conservative means.
- ➢ Digital palpation for painful responses in the preauricular region and via the external auditory meatus during the opening and closing cycle.
- ➢ Digital palpation of the mandibular elevator/depressor muscles for painful responses
- ➢ Myoclonus during any jaw movements should be noted
- ➢ Measurements of mandibular movements in vertical and horizontal movements with the teeth together and with teeth apart.
- ➢ Deviations in the line of movement of the mandible during opening and closing should be noted.
- ➢ Evaluation of the occlusion; Looking for non-simultaneous centric stops, working and non–working side interferences, evidence on the surfaces of the teeth of bruxing and clenching or locking in of the occlusion
- ➢ Digital palpation of the principle muscles of the neck for painful responses
- ➢ Palpation of the cervical facet joints should be carried out for painful responses

If there is a negative diagnosis for TMD referral should be made to an appropriate specialist

Special tests

Conventional radiography of the joint is a useful diagnostic tool to investigate any bony changes that might be present as a result of arthralgia, fractures or more rarely the presence of a cyst.

MRI evaluation should usually only be needed to confirm clinical findings such as the position of the disc in a closed lock situation and should not be necessary routinely.

Differential Diagnosis

As there are a number of conditions which can cause pain in the cranio-facial region it is important for the dentist to have a working knowledge of differential diagnosis of facial pain. Although the psychological aspect of facial pain is well established and should not be overlooked it is not being dealt with here. This work is concerned with pain arising from the macro-trauma induced by a "whiplash" event.

Thus Okeson (1994) divides the physical component of facial pain into Somatic and Neuropathic and subdivides both of these categories into a number of orofacial pain conditions (Table A.1).

Somatic pain	Neuropathic Pain
(A) Superficial somatic pain 1.Cutaneous pain 2.Mucogingival pain **(B) Deep somatic Pain** (a) Muscle Pain İ. Protective contraction İİ. Delayed onset muscle soreness İİİ.Myofascial Pain İV.Myospasm V.Myositis b. Temporomandibular joint pain İ. Ligamentous pain İİ. Retrodiscal pain İİİ.Capsular pain İV.Arthritic Pain c.Osseous and Periosteal pain d. Soft connective pain e. Periodontal dental pain 2. Visceral pain a. Pulpal dental pain b.Vascular pain İ. Arteritis İİ.Carotidnya c. Neurovascular pain İ Migraine with aura İİ Migraine without aura İ İ İ Cluster headache İV. Paroxysmal hemicrania V. Neurovascular variants d. Visceral muscle pain e. Glandular, ocular and auricular pain	**A. Episodic neuropathic pain** 1. Paroxysmal neuralgia a. Trigeminal neuralgia b.Glossopharyngeal neuralgia c.Geniculate neuralgia d. Superior laryngeal neuralgia e.Nervus intermedius **B. Continuous neuropathic pains** 1. Neuritis a.Peripheral neuritis b.Herpes Zoster c.Post herpathic neuralgia 2.Deafferentation pain a.Neuroma b. Atypical odontalgia 3. Sympathetically maintained pain.

Figure A.1. Classification of orofacial pain, not including Psychological conditions Okeson(1994)

Appendix B Additional Histological slides

Specimen 1

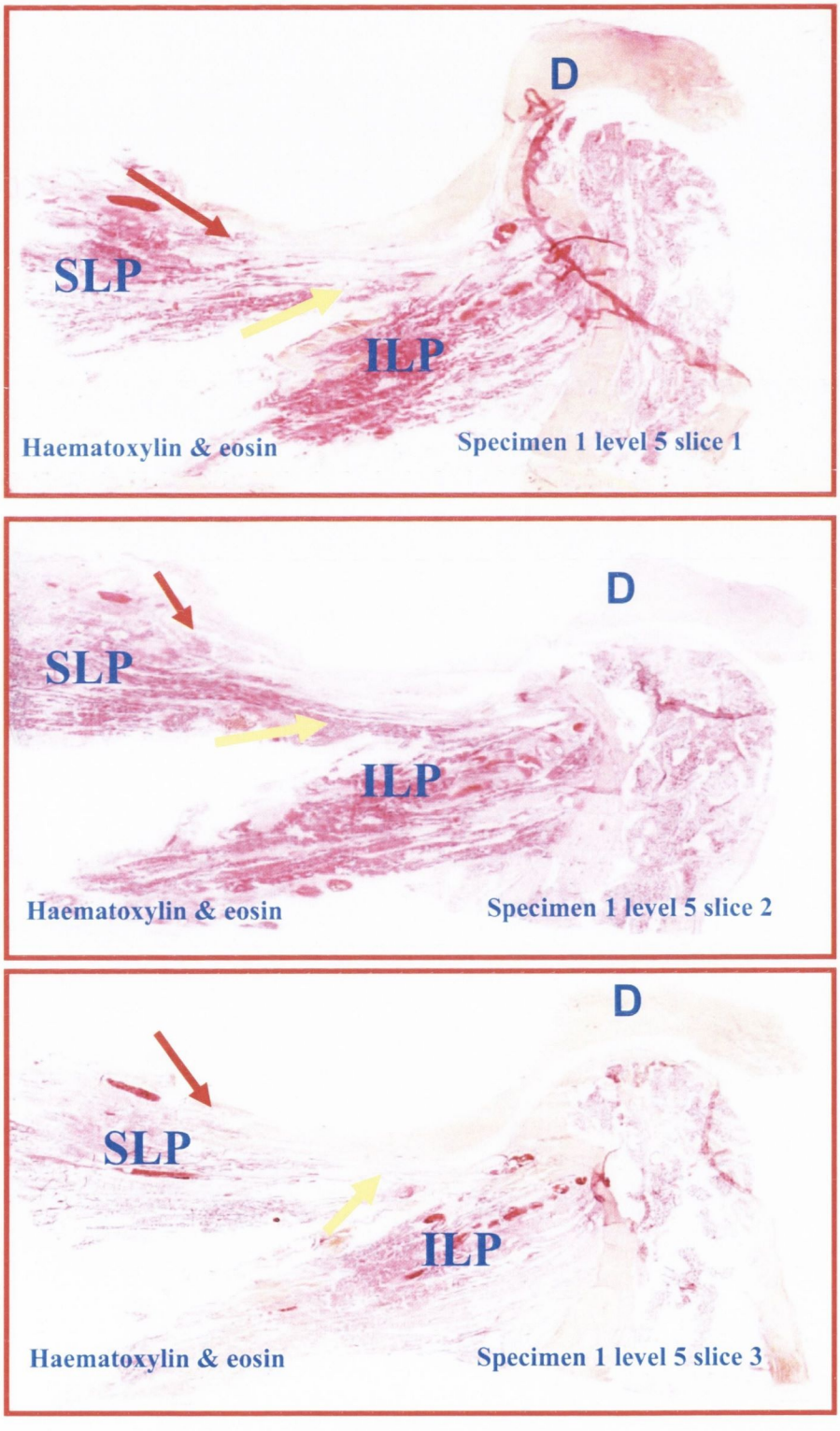

Figure B.1: Specimen 1 Lateral Pterygoid attachments at level 5 slice 1, 2, 3.

Specimen 2

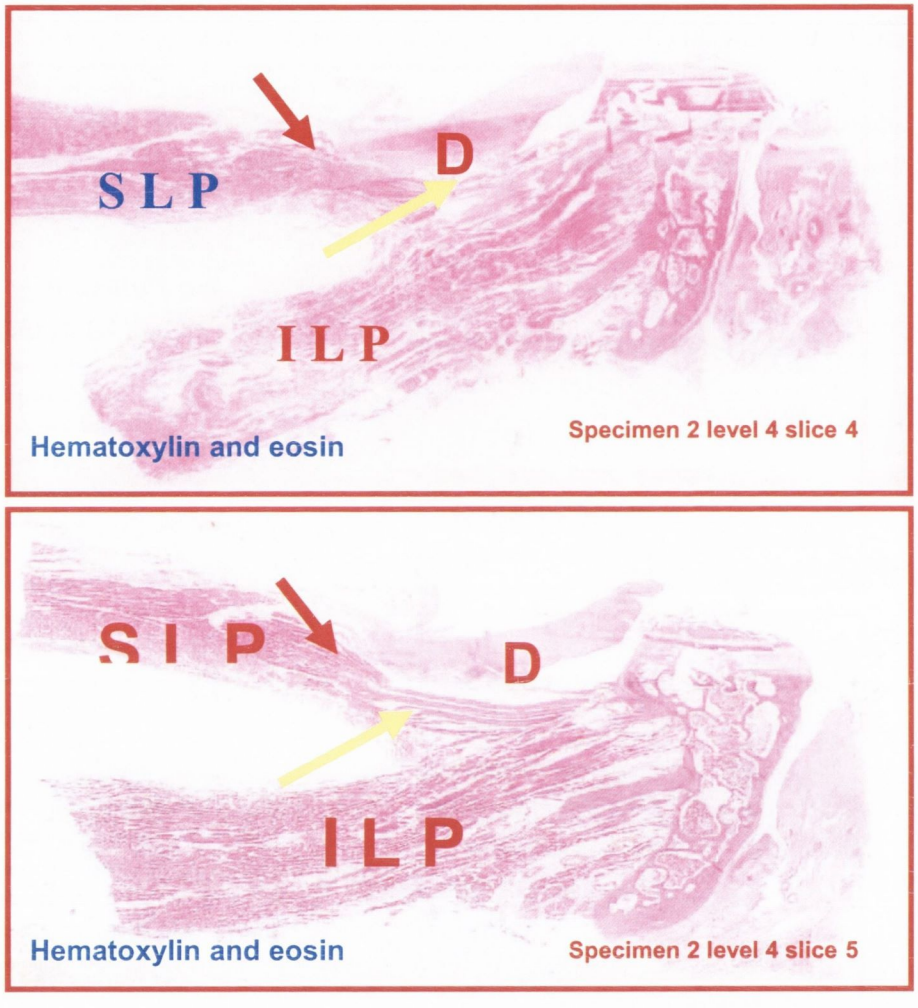

Figure B.2: Specimen 2 attachments of Lateral Pterygoid at level 4, slices 4, *5*

Specimen 3

As the number of slices available from the medial section of specimen 3 were limited it was decided to take some further slides from the lateral section. Unfortunately although good staining of the Pterygoid muscle was achieved the condyle was in such poor condition that it did not show on the slides.

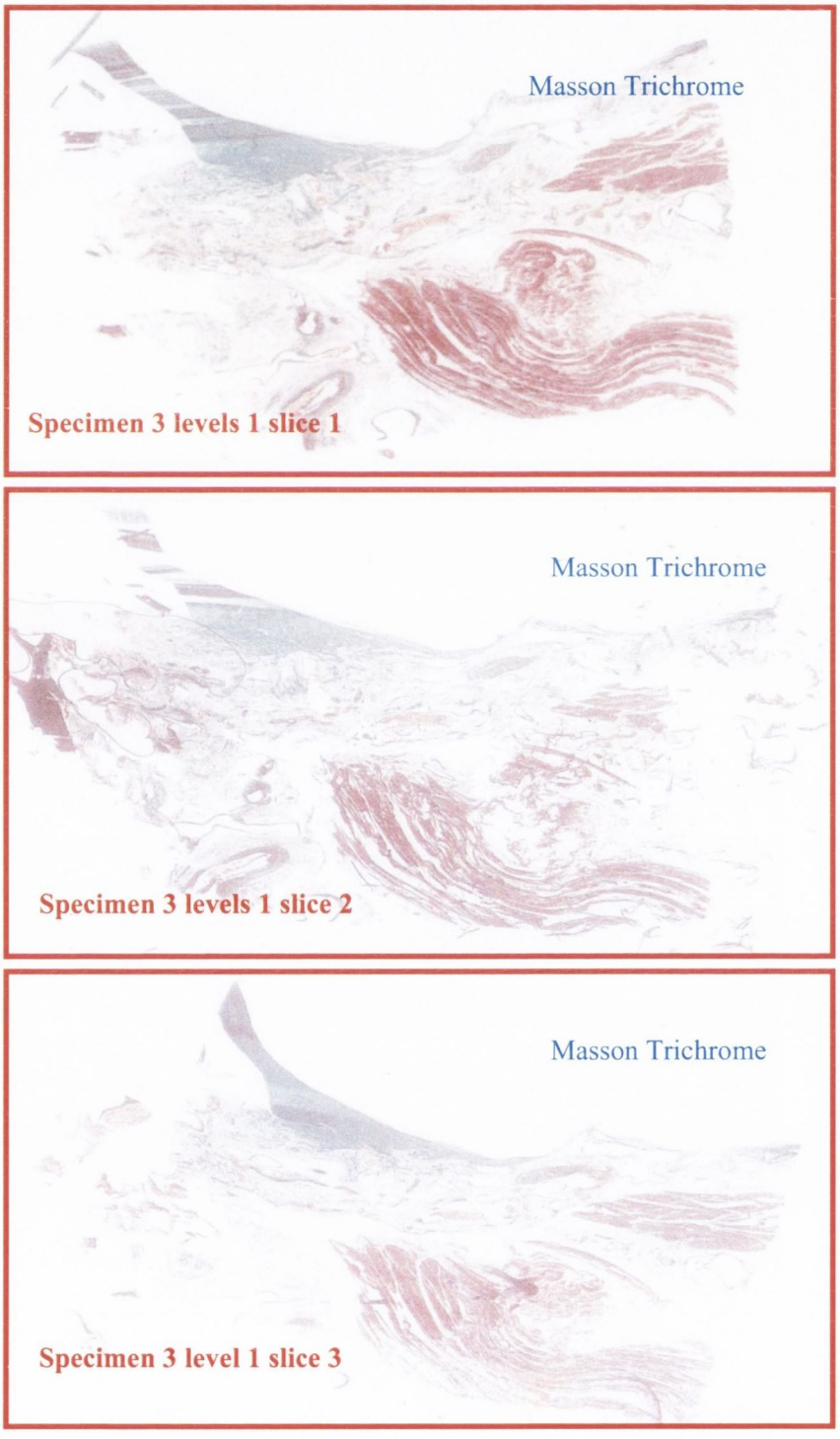

Figure B.3: Specimen 3 at level 1 lateral pterygoid slices 1,2,3, (Lateral section).

Specimen 4

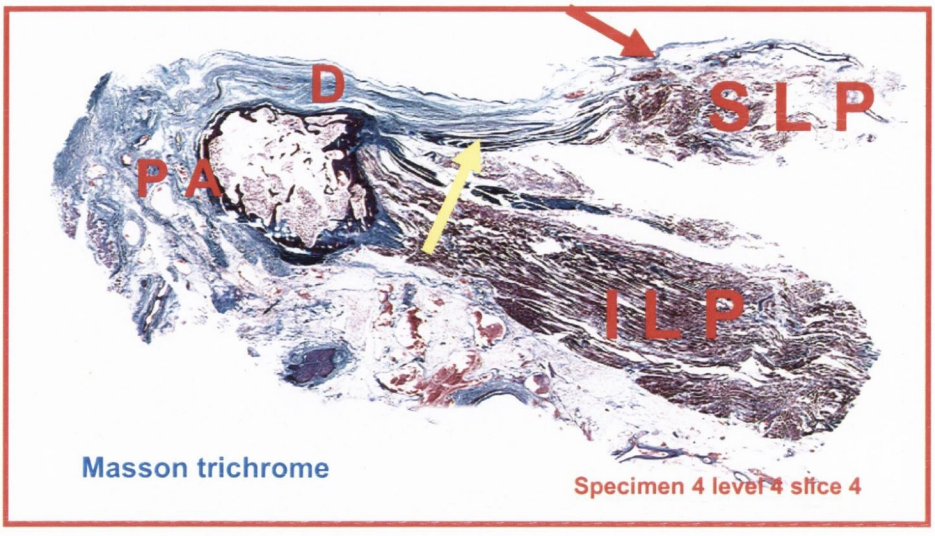

Figure B 4: Specimen 4, attachments of Lateral Pterygoid level 4, slice 4



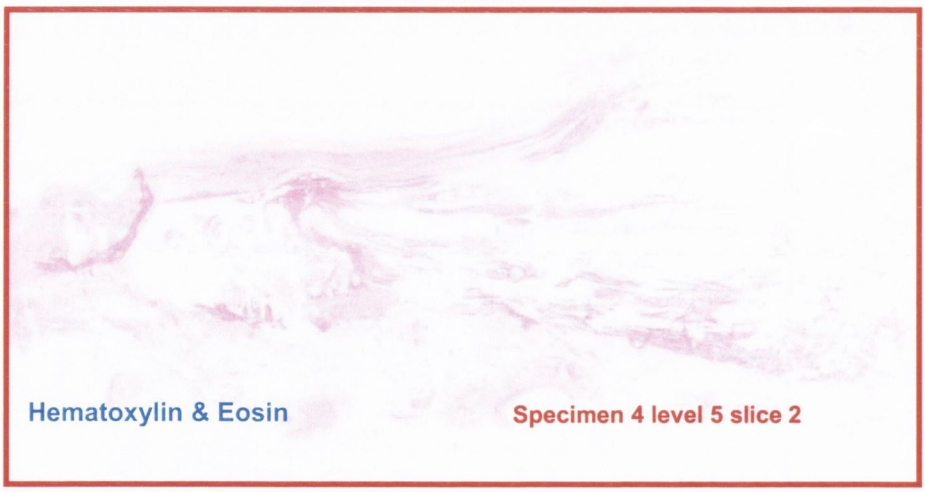

Figure B 5: Specimen 4 Attachments of Lateral Pterygoid level 5 slices 1& 2

Specimen 9

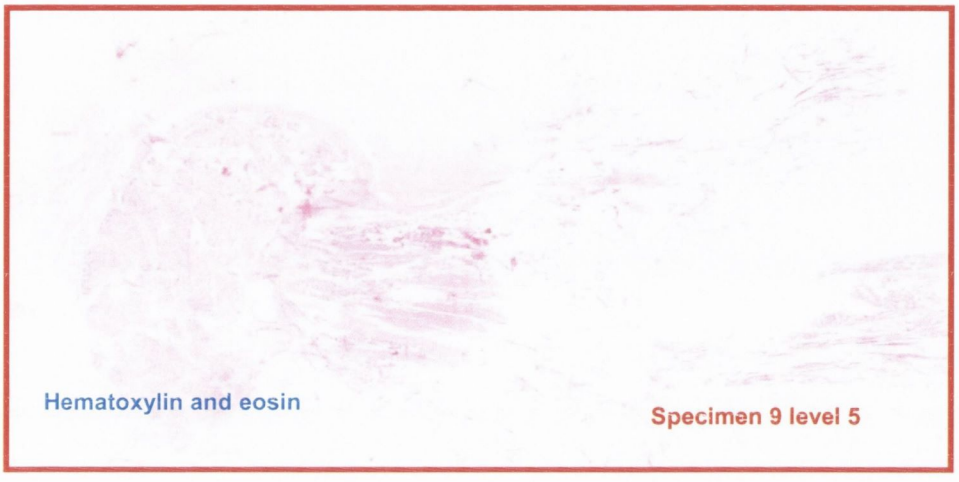

Figure B.6: Specimen 9, Lateral pterygoid attachments at level 5

Appendix C

Definitions

Force: Is that which causes acceleration of a body. Force is a vector quantity, which means that it possesses both magnitude and direction. It can be calculated by the equation **F = ma.** (Eq 1).

It is important to stress that a body is rarely acted on by a single force. Acceleration is caused by the nett force acting upon a body. If for example a body is acted on by two equal and opposite forces, there will be no nett force to cause acceleration. This condition is called equilibrium.

Equilibrium: is the condition of constant velocity which exists when the forces acting on a body are balanced.

This state of a body on which no nett force acts is defined in Newton's First Law of Motion.

Newton's First Law of Motion: The velocity of body will not change unless it is acted upon by a nett external force.

Newton's first law of motion implies that all bodies possess the property of inertia which can be defined thus:

Inertia: Is the tendency of an object to remain in a state of rest or uniform motion until an external force is applied.

The inertia of a body is related to its mass.

Thus:-

Mass: is the quantity of matter in a body as measured by its inertia.

OR

Mass: is a measure of the ability of a body to resist acceleration, which makes it a quantitative measure of inertia.

The masses of two bodies can be compared by acceleration experiments. For example, applying the same force to two bodies of different mass and comparing the acceleration of the two bodies is a measure of mass. Mass can therefore be calculated using Newton's Second law.

Newton's Second Law of Motion: The acceleration produced by a nett force acting on a body is proportional to the magnitude of the force, is in the same direction as the force and is

inversely proportional to the mass of the body. This can be written as **F = ma,** where **F** = Force, **m** = mass, **a** = acceleration.

Newton's Third Law of Motion: In any interaction between two bodies A and B, the force exerted by A on B is equal in magnitude but opposite in direction to the force exerted by B on A.

Newton called these paired forces 'action' and 'reaction'. It is important to emphasize that these forces are acting on different bodies and therefore cannot add up to zero. In effect Newton's Third Law means that in an interaction between two bodies it is not possible to have action without reaction.

Velocity: Is the rate of change of displacement of a body with respect to time in a given direction. It is a vector quantity, i.e. it possesses both magnitude and direction. Velocity can be either linear (in a straight line) or angular (describing motion in a circle).

Speed: is a term usually used to describe the rate of change of displacement with respect to time without considering the direction.

Acceleration: is the rate of change of velocity with respect to time. There are two different types of acceleration: -

1. Linear acceleration is the rate of change of velocity in a straight line. The unit for linear acceleration is metres.second^{-2}(metres per second per second)

2. Angular acceleration is the rate of change of angular velocity with respect to time. The unit of angular acceleration is radians/second^{-2}(Radians per second per second),

Radian (rad): Is the angle subtended by the arc of a circle when a body in uniform circular motion travels the same distance as the radius of the circle (Figure C.1).

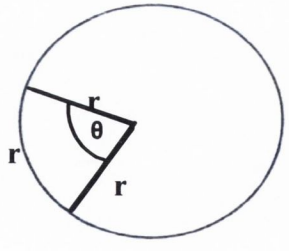

Figure C.1: Showing the arc of ∠θ= 1 rad. The arc of the circle equal in length to the radius. Therefore ∠θ in this instance is 1 radian.

There are 2π radians in any circle and therefore radians can be converted to degrees by multiplying by: -

$\frac{360}{2\pi}$ or $\frac{180}{\pi}$

Some important examples of angular acceleration are: -

(a) Centripetal (Normal) acceleration:- Is the acceleration which takes place towards the centre of the circle when a body is in circular motion. It takes place at right angles to the angular (tangential) acceleration (Figure C.2).

(b) Tangential acceleration :-Is the rate of change of angular velocity. The direction of angular is at right angles to the centripetal acceleration (Figure C.2).

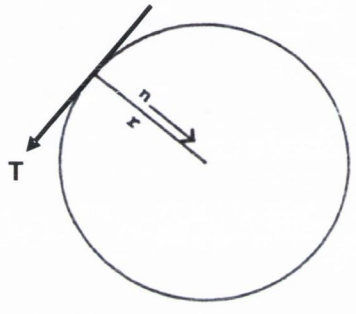

Figure C.2: n = centripetal acceleration, t = tangential acceleration

(c) Acceleration due to gravity is the acceleration of a free-falling body if air resistance is ignored. This acceleration is constant and occurs at the rate of $9.81 ms^{-2}$. It is commonly referred to as 'g'.

All of the above types of acceleration were considered in calculating the forces sustained by the temporomandibular joints in the jaw opening and closing which occurs in whiplash.

All linear displacement, velocity and acceleration equations are equally valid in angular measure.

Thus for circular motion: -

$S = r\theta$ where s is = linear displacement around the circumference of a circle

r = radius of arc of rotation

θ = the degree of angular displacement

$v = r\omega$

Where v =linear velocity around the circumference of a circle

r = radius of arc of rotation

ω = Angular velocity

[Also a = rα where a = acceleration etc.]

Equations for a body under constant acceleration

The following equations can be derived for the calculation of constant acceleration whether linear or angular.

[Note formula for centripetal acc = a = $\omega^2 r$]

Linear	Angular
$A = \frac{v_1 - v_o}{t}$	$\alpha = \frac{\omega_1 - \omega_o}{t}$
$S = \frac{v_o + v_1}{2} t$	$\theta = \frac{\omega_o + \omega_1}{2} t$
$V^2 = v_o^2 + 2as$	$\omega^2 = \omega_o^2 + 2\alpha\theta$
$S = v_o t + \frac{1}{2}\alpha t^2$	$= \omega_o t + \frac{1}{2}\alpha t^2$

Where V_0 = initial linear velocity

V_1 = instantaneous linear velocity

t = time

s = linear displacement

a = linear acceleration

ω_0 = initial angular velocity

ω_1 = instantaneous angular velocity

θ = Angular displacement

α = Angular acceleration

Force Calculations for different types of acceleration

1.Linear acceleration Force Calculation

This is the simplest kind of force calculation, and is made by using the formula: -

$F = ma$.

Where F= Force, m=Mass, and a = linear acceleration

For example:-

A body of mass 1Kg with an acceleration of 10m sec^{-2} will exert a force of 10N.

2. Angular acceleration Force Calculations

Two types of force result if a body is accelerating as it moves in a circular path:

- **Centripetal (Normal) Acceleration Force Calculations**

The normal force (F_n) acts towards the centre of the circle (Figure C.3) and is calculated by the equation:-

$F_n = m\omega^2 r$, where F_n=Centripetal force, r = radius of the circle and ω =angular velocity

- **Tangential force**

The tangential force (F_t) acts at right angles to the Normal force and in the direction of the circular movement (figure C.3).

The formula for tangential force calculations is as follows: -

$F_t = m\alpha r$, where F_t=Tangential force, m = Mass and α = angular acceleration

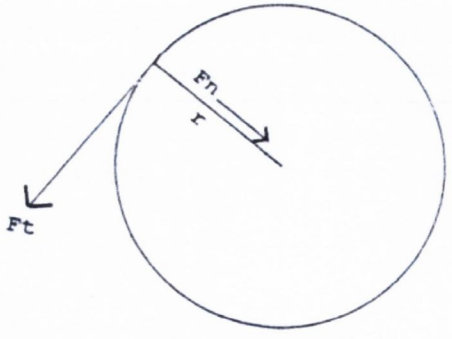

Figure C. 3: Normal force* (F_n) *acting toward the centre of rotation and Tangential force* (F_t) *acting at right angles to the normal force

3. Gravitational Acceleration Force Calculations

As stated above, a body falling through the air towards the earth will accelerate at $9.81ms^{-2}$ (g). Therefore a body of mass 10Kg falling to earth is being acted on by a gravitational force of:-

F = ma

10 x 9.81= 98.1 Newtons

A combination of linear, centripetal, angular and gravitational forces are involved in jaw movements during whiplash and the force calculations shown in this thesis are based on these equations.

Stress (also called Pressure)

Whilst force can be calculated when a body is accelerated, it is not necessarily an accurate reflection of the resulting damage which may occur to tissue structure. For example, a large force spread over a wide area of tissue may cause relatively little damage. Conversely the same force spread over a smaller area may result in considerable damage.

Stress is defined as force per unit area:

$$\text{Stress} = \frac{F}{A}$$

Where F= force and A= the area over which the force is distributed

Stress is a scalar quantity (having only magnitude and not direction).

The unit of stress is the Pascal. We define one Pascal (Pa) as one N/m^2.

Therefore one Mega Pascal (MPa) = $1MN/m^2 = 1N/mm^2$.

The classic example used to illustrate the significance of stress is the effect of the elephant's foot on a floor. If an elephant with a mass of 2,000Kg is standing on a flat surface and the area of each foot in contact with the floor is $400cm^2$, the downward force under each foot will be:-

$$F = \frac{ma}{4}$$

Taking 'g' as 10m/s/s

The force exerted by each foot =5,000N.

However, the stress under each foot will be:-

$$P=\frac{F}{A}$$

$$=\frac{5{,}000}{400/10{,}000}$$

$$= 1{,}250\text{Pa}$$

$$=1.25\text{kPa or } 0.00125\text{MPa.}$$

If on the other hand a ballet dancer of 100Kg is balanced on the toes of both feet, and the area of contact under one foot is 10mm^2, the downward force under one foot will be:-

$$\frac{100 \times 10}{2} = 500\text{N.}$$

However, the stress under the toes of one foot will be:-

$$\frac{500}{10\text{x}10^{-6}}$$

$$= 50{,}000\text{Pa}$$

$$= 50\text{kPa.}$$

This simple example shows that although the downward force created by the large mass (elephant) is much greater than that created by the small mass, the stress created by the small mass may be much higher, dependent on the area of surface contact.

Appendix D

Finding the centre of mass of the Mandible

The centre of mass of the mandible (COMM) and the distance of COMM from the centre of rotation of the mandible and from the centre of rotation of the cranium was carried out in the following manner

Firstly the mandible was suspended from the horizontal arm of a metal stand. The suspending cord was allowed to project from the point of suspension and had a pointer of minimal mass hanging from its' lower end at a distance just sufficient to touch the lingual aspect of the mandible (Figure D.1).This exercise was carried out bilaterally and the point where the two pieces of cord intersected was taken as the COMM (Figure D.2).



Figure D.1: Mandible suspended from horizontal arm of stand for calculation of centre of mass

The distance between the centre points of the head of the condyle was measured and its' point was marked. The distance from the COMM to the mid-point of the inter-condylar distance was now measured and the distance of the COMM to the mid point of the centre of rotation of the cranium was also measured (Figure D.3)

This procedure was carried out on a number of mandibles and skulls and the mean figures used in the trigonometrical calculations used for the force calculations.

The distance from the centre of mass of the mandible to the mid point of the intercondylar distance between the occipital condyles on the base of the skull around which point retroflexion takes place (Figure D.3).

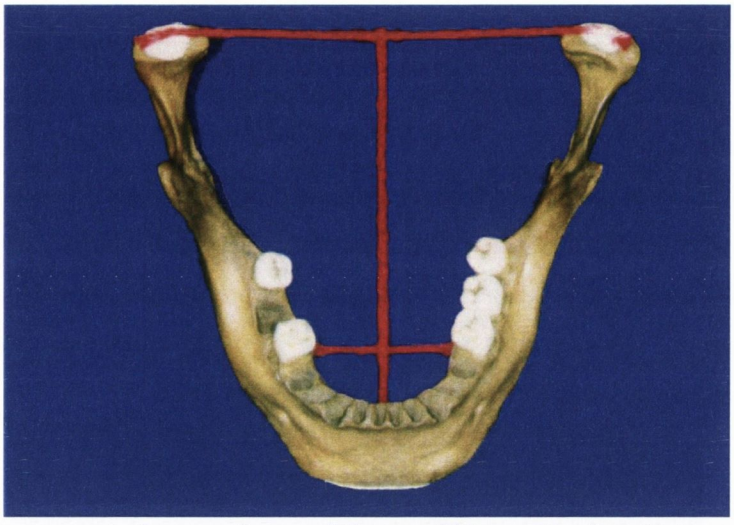

Figure D.2: Measurement of centre of mass of the mandible to mid point of intercondylar distance

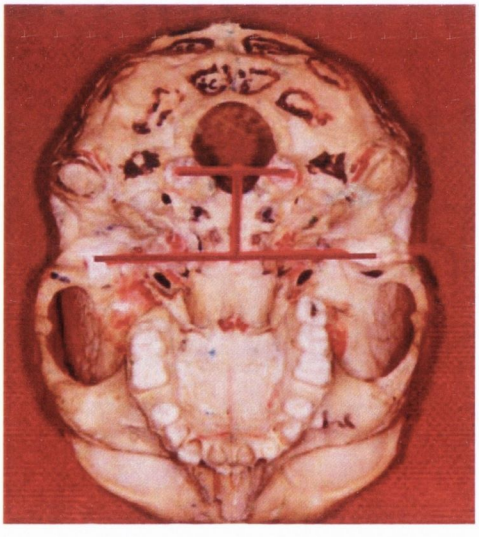

Figure D.3: Measurement of the distance between the mid point of intercondylar distance and the mid point of the centre of rotation of the cranium

Appendix E Estimation of Variable Acceleration

Force calculations made using constant acceleration are a rough guide to events, and may be misleading.

In order to make a more accurate evaluation of the forces, it is necessary to take account of the fact that acceleration varies with time. In this way peaks in acceleration will be taken into account.

Clemens and Burrow (1972) present an angular displacement curve (θ/t) showing both retroflexion and flexion.

In order to estimate velocity versus time and acceleration versus time, it was necessary to fit this curve by means of polynomial regression.

Due to the complexity of the curve it was necessary to split it into two elements i.e. retroflexion (from t=0 to t=130ms) and flexion (from t=130ms to t=310ms).

The retroflexion portion of the Clemens and Burrow curve is shown in figure E.1.

Estimation of Acceleration/Time in Retroflexion phase:

The differentiation of θ twice to produce values for angular acceleration (α) was attempted but gave unreliable data. Therefore equation (1) for was used to calculate values for angular velocity (ω) in the time range 0-130ms.

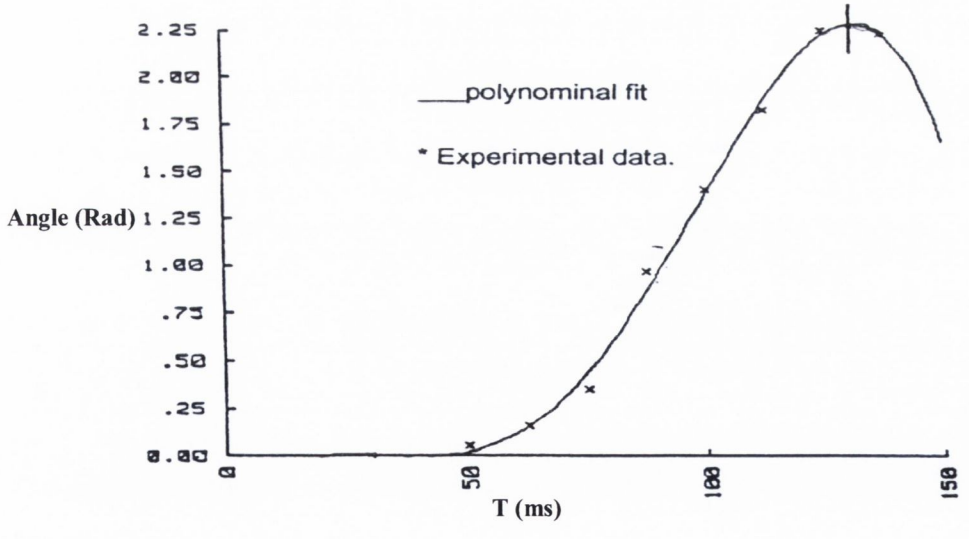

Figure E.1: Data points selected on retroflexion element of the Clemens and Burrow curve

The retroflexion curve was adequately represented by a 5 term polynomial. The first differential of the polynomial gave velocity/time (Figure E.2).

The retroflexion equation for angular displacement (θ) was differentiated to produce an equation for angular velocity (ω).

The retroflexion equation for angular velocity was as follows:-

$$\theta = x_0+x_1t +x_2t^2+ x_3t^3+x_4t^4 +x_5t^5 \text{ (EQ 1).}$$

$$\text{Thus: - } \delta\theta/\delta t = x_1+2x_2t+3x_3t+4x_4t+5x_5t = \omega$$

$$\text{Therefore angular velocity } (\omega) = x_1+2x_2t +3x_3t^2+4x_4t^3 + 5x_5t$$

The regression coefficients used in the above equation are shown in table E.1.

	REGRESSION COEFFICIENTS		STANDARD ERROR	
Variable	STD.FORMAT	E- Format	Reg. Coefficient	T-Value
Constant	-.38756	-.38756338570E+ 00	. 98571	- .39
X ^1	.04127	.412732333850E- 01	. 06040	.68
X ^2	-.00146	-.146339975886E-02	. 00125	-1.17
X ^3	.00002	.197773128913E-04	.00001	1.87
X ^4	-.00000	-.749899865026E-07	.00000	-2.39

Table E.1: Showing regression coefficients used in equation (1).

This resulted in an angular velocity /time curve seen in figure E.2.

From the "T-value" of the fit it was observed that the statistical value was low. However a best fit was all that was being attempted.

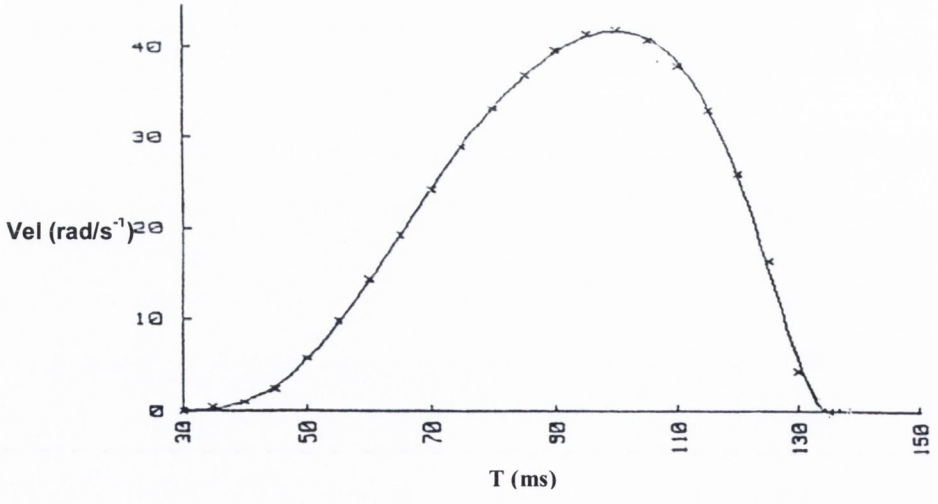

Figure E.2: Data points selected on the velocity v time curve derived from equation 1.

The differentiation of θ twice to produce values for angular acceleration (α) was attempted but gave unreliable data. Therefore data points on the velocity versus time curve were selected from which another polynomial was used to estimate angular acceleration by regression.

These data were fitted by regression to another polynomial to produce angular acceleration (α), (Table E.2 & Figure E.3).

Thus :-

$$\theta = x_0 + x_1 t + x_2 t^2 + x_3 t^3 + x_4 t^4 + x_5 t^5 + x_6 t^6 + x_7 t^7 + x_8 t^8 \quad \text{----------} r^{-1}$$

(α). The parameters of fit for this regression are given in table E.2.

	REGRESSION COEFFICIENTS		STANDARD ERROR	
	STD.Format	E-Format	Reg. Coefficient	T-value
Variable/ Constant	13.26629	.1326622872700E	235.94087	.06
X ^1	-5.0536	-.505369187500E + 01	28.85232	-.18
X^2	-.51069	. 5106869331370E+00	1.48314	.34
X ^3	-.02377	-.237658425321E - 00	0.4195	-.57
X ^4	.00059	.5941011733950E- 03	.00072	.83
X ^5	-.00001	-.839812106510E-05	.00001	-1.11
X ^6	.0000	.676664642039E-07	.00000	1.40
X ^7	-.0000	-.290758955098E-09	.00000	- 1.69
X ^8	.0000	.517339216494E-12	.00000	1.98

Table E.2: Regression coefficients use for the estimation of angular acceleration

It should be noted that the absolute accuracy of this fit and its' first differential (acc/time) should be considered with caution. A similar procedure was carried out for the flexion segment of the Clemens and Burrow (1972) curve and velocity/time, acceleration/time were estimated for this period of the event.

Data points on the flexion portion of the Clemens and Burrows curve were selected and angular velocity was estimated by a polynomial using a regression technique.

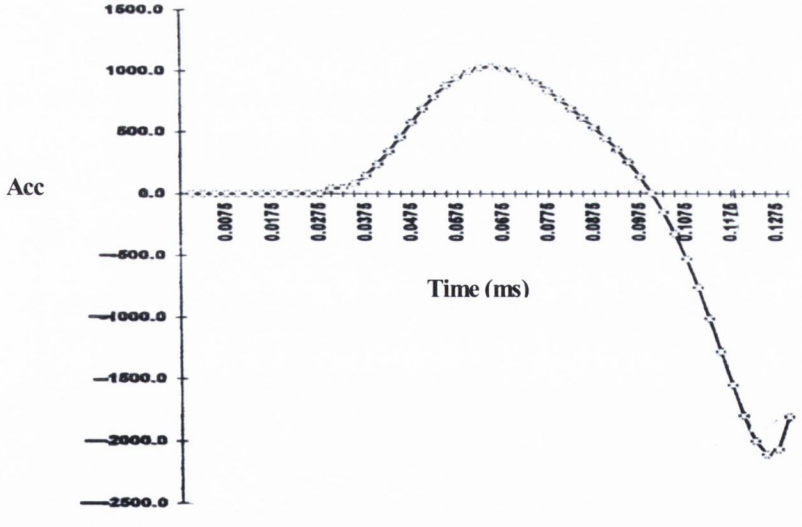

Figure E.3: Angular acceleration v time curve in flexion with selection of data points.

It should be noted that the absolute accuracy of this fit and its' first differential should be considered with caution. However a "best fit" was all that was being attempted.

Estimation of Acceleration/Time in Flexion Phase:

A similar procedure was carried out for the flexion segment of the Clemens and Burrows curve.

Again data points were selected and angular velocity was estimated was estimated using a polynomial regression technique (Figure E.4).

The regression coefficients used in the estimation of angular velocity are shown in table E.3.

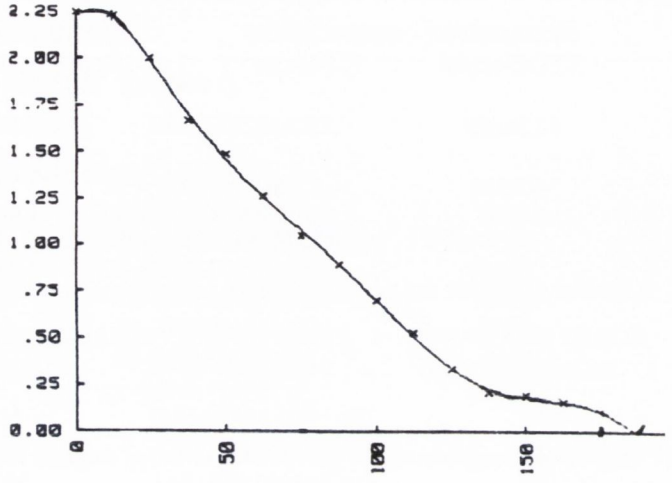

Figure E.4: Flexion segment of Clemens and Burrows curve with selected data points

	REGRESSION COEFFICIENTS		STANDARD ERROR	
Variable	STD. Format	E-Format	Reg- Coefficent	T-Value
/Constant	-4.59047	-.459046985032E-+01	3.47521	-1.32
X ^1	.16315	.163150431327E+00	.06918	2.36
X ^2	-.00128	-.128350970203E-02	.00050	-2.56
X ^3	.00000	.385632137391E-05	.00000	2.46
X ^4	-.00000	-.405977703461E-08	.00000	-2.27

Table E.3: Regression coefficients used in the estimation of angular velocity.

This resulted in an angular velocity versus time curve from which a further series of data points were selected for the estimation of angular acceleration (figure E.5).

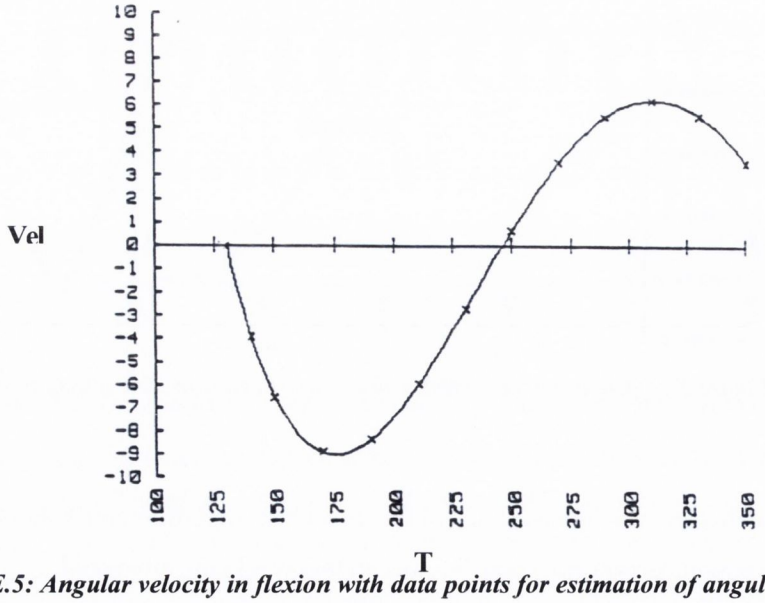

Figure E.5: Angular velocity in flexion with data points for estimation of angular acceleration

The regression coefficients for the estimation of angular acceleration are shown in table E.4 and the curve for angular acceleration is shown in figure E.6.

Variable	REGRESSION COEFFICIENTS STD. Format	E-Format	STANDARD ERROR Reg- Coefficient	T-Value
/Constant	263.37652	.263376520328E+03	3.72209	70.76
X ^1	-4360.40600	-.436040599509E+04	86.209	-50.58
X ^2	24705.29629	.247052962944E+05	776.00379	31.84
X ^3	-58801.21913	-.588012191321E+05	3397.71811	-17.31
X ^4	54287.14589	.542871458944E+05	7248.10819	7.49
X ^5	-10204.08151	-.102040815083E+05	6037.20210	-1.69

Table E.4: Regression coefficients used in the estimation of angular acceleration in flexion

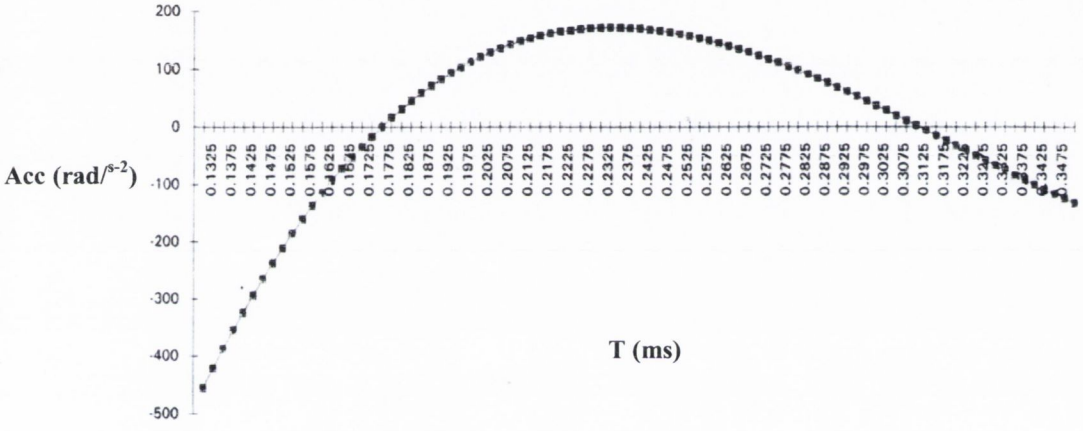

Figure E.6: Acceleration curve in flexion estimated by polynomial regression

It should be noted that in the curves for angular velocity and angular acceleration in the flexion phase the initial part of the curve is shown as negative velocity and acceleration and the latter part of the curves are shown as positive velocity and acceleration. This mathematical conclusion was drawn from the fact that in flexion the head was moving in the opposite direction to that which took place in retroflexion.

However as retroflexion and flexion were being considered and compared as separate entities it was more logical that in the force for the flexion phase of the event that the opposite was assumed. Therefore in the force calculations for the flexion phase the initial velocity and acceleration were taken as positive as the head movement was increasing in velocity and negative velocity and acceleration in the latter part of acceleration where the head movement was slowing down (See chapter 4).

Appendix F Spreadsheets of force calculations

Force 1a1 Spreadsheet 1

VALUES		Row	t (sec)	Rho(deg)	Beta (deg)	Theta (rad)	Theta i(deg)	F_{1a1} (N)
M (kg) =	0.1621	1	0.0000	70.80	35.50	0.00	0.00	0.65
r (m) =	0.034	2	0.0025	70.80	35.50	0.00	0.00	0.65
Rho [(init), deg] =	70.80	3	0.0050	70.80	35.50	0.00	0.00	0.65
Thetha (rad) =	2.25	4	0.0075	70.80	35.50	0.00	0.00	0.65
Time (sec) =	0.10	5	0.0100	70.80	35.50	0.00	0.00	0.65
Alpha (rad/s/s) =	450.00	6	0.0125	70.80	35.50	0.00	0.00	0.65
		7	0.0150	70.80	35.50	0.00	0.00	0.65
		8	0.0175	70.80	35.50	0.00	0.00	0.65
		9	0.0200	70.80	35.50	0.00	0.00	0.65
		10	0.0225	70.80	35.50	0.00	0.00	0.65
		11	0.0250	70.80	35.50	0.00	0.00	0.65
		12	0.0275	70.80	35.50	0.00	0.00	0.65
		13	0.0300	70.88	35.42	0.00	0.08	0.65
		14	0.0325	71.12	35.18	0.01	0.32	0.66
		15	0.0350	71.53	34.77	0.01	0.73	0.68
		16	0.0375	72.09	34.21	0.02	1.29	0.71
		17	0.0400	72.81	33.49	0.04	2.01	0.75
		18	0.0425	73.70	32.60	0.05	2.90	0.80
		19	0.0450	74.75	31.55	0.07	3.95	0.85
		20	0.0475	75.96	30.34	0.09	5.16	0.91
		21	0.0500	77.33	28.97	0.11	6.53	0.98
		22	0.0525	78.86	27.44	0.14	8.06	1.05
		23	0.0550	80.55	25.75	0.17	9.75	1.14
		24	0.0575	82.40	23.90	0.20	11.60	1.23
		25	0.0600	84.42	21.88	0.24	13.62	1.33
		26	0.0625	86.59	19.71	0.28	15.79	1.43
		27	0.0650	88.93	17.37	0.32	18.13	1.54
		28	0.0675	91.43	14.87	0.36	20.63	1.66
		29	0.0700	94.09	12.21	0.41	23.29	1.79
		30	0.0725	96.91	9.39	0.46	26.11	1.91
		31	0.0750	99.89	6.41	0.51	29.09	2.05
		32	0.0775	103.03	3.27	0.56	32.23	2.19
		33	0.0800	106.33	-0.03	0.62	35.53	2.33
		34	0.0825	109.80	-3.50	0.68	39.00	2.48
		35	0.0850	113.42	-7.12	0.74	42.62	2.63
		36	0.0875	117.21	-10.91	0.81	46.41	2.79
		37	0.0900	121.16	-14.86	0.88	50.36	2.95
		38	0.0925	125.27	-18.97	0.95	54.47	3.11
		39	0.0950	129.54	-23.24	1.03	58.74	3.27
		40	0.0975	133.97	-27.67	1.10	63.17	3.44
		41	0.1000	138.56	-32.26	1.18	67.76	3.61
		42	0.1025	143.31	-37.01	1.27	72.51	3.77
		43	0.1050	148.23	-41.93	1.35	77.43	3.94
		44	0.1075	153.31	-47.01	1.44	82.51	4.11
		45	0.1100	158.54	-52.24	1.53	87.74	4.28
		46	0.1125	163.94	-57.64	1.63	93.14	4.46
		47	0.1150	169.50	-63.20	1.72	98.70	4.63
		48	0.1175	175.22	-68.92	1.82	104.42	4.81
		49	0.1200	181.10	-74.80	1.93	110.30	4.98
		50	0.1225	187.15	-80.85	2.03	116.35	5.16
		51	0.1250	193.35	-87.05	2.14	122.55	5.35
		52	0.1275	199.72	-93.42	2.25	128.92	5.53

Force 1a1 Spreadsheet 2

Row	F1a1 (N)	F1a1(N)	Phi (deg)	Delta(deg)	Fx1a1	Fy1a1	Omega(rad/s)	Alpha (rad/s/s)
1	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
2	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
3	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
4	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
5	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
6	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
7	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
8	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
9	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
10	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
11	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
12	0.46	0.80	35.50	270.00	0.00	-0.80	0.00	0.00
13	1.70	1.82	69.04	303.54	1.01	-1.52	1.13	450.00
14	1.70	1.82	68.65	303.15	1.00	-1.53	2.25	450.00
15	1.69	1.83	67.99	302.49	0.98	-1.54	3.38	450.00
16	1.69	1.83	67.08	301.58	0.96	-1.56	4.50	450.00
17	1.68	1.84	65.92	300.42	0.93	-1.59	5.63	450.00
18	1.67	1.85	64.51	299.01	0.90	-1.62	6.75	450.00
19	1.66	1.86	62.87	297.37	0.86	-1.65	7.88	450.00
20	1.64	1.88	61.02	295.52	0.81	-1.69	9.00	450.00
21	1.63	1.90	58.96	293.46	0.76	-1.74	10.13	450.00
22	1.61	1.92	56.72	291.22	0.70	-1.79	11.25	450.00
23	1.59	1.95	54.33	288.83	0.63	-1.85	12.38	450.00
24	1.56	1.99	51.80	286.30	0.56	-1.91	13.50	450.00
25	1.54	2.03	49.18	283.68	0.48	-1.97	14.63	450.00
26	1.51	2.08	46.48	280.98	0.40	-2.04	15.75	450.00
27	1.48	2.14	43.75	278.25	0.31	-2.11	16.88	450.00
28	1.44	2.20	41.00	275.50	0.21	-2.19	18.00	450.00
29	1.41	2.27	38.27	272.77	0.11	-2.27	19.13	450.00
30	1.37	2.35	35.59	270.09	0.00	-2.35	20.25	450.00
31	1.33	2.44	32.96	267.46	-0.11	-2.44	21.38	450.00
32	1.29	2.54	30.42	264.92	-0.22	-2.53	22.50	450.00
33	1.24	2.64	27.98	262.48	-0.35	-2.62	23.63	450.00
34	1.19	2.75	25.65	260.15	-0.47	-2.71	24.75	450.00
35	1.14	2.87	23.43	257.93	-0.60	-2.81	25.88	450.00
36	1.09	2.99	21.33	255.83	-0.73	-2.90	27.00	450.00
37	1.04	3.13	19.36	253.86	-0.87	-3.00	28.13	450.00
38	0.98	3.26	17.52	252.02	-1.01	-3.10	29.25	450.00
39	0.93	3.40	15.80	250.30	-1.15	-3.20	30.38	450.00
40	0.87	3.55	14.21	248.71	-1.29	-3.31	31.50	450.00
41	0.82	3.70	12.75	247.25	-1.43	-3.41	32.63	450.00
42	0.76	3.85	11.41	245.91	-1.57	-3.51	33.75	450.00
43	0.71	4.01	10.19	244.69	-1.71	-3.62	34.88	450.00
44	0.66	4.17	9.09	243.59	-1.85	-3.73	36.00	450.00
45	0.61	4.33	8.12	242.62	-1.99	-3.84	37.13	450.00
46	0.57	4.49	7.27	241.77	-2.13	-3.96	38.25	450.00
47	0.53	4.66	6.53	241.03	-2.26	-4.08	39.38	450.00
48	0.50	4.83	5.92	240.42	-2.39	-4.20	40.50	450.00
49	0.47	5.01	5.42	239.92	-2.51	-4.33	41.63	450.00
50	0.46	5.18	5.04	239.54	-2.63	-4.47	42.75	450.00
51	0.45	5.36	4.77	239.27	-2.74	-4.61	43.88	450.00
52	0.45	5.55	4.61	239.11	-2.85	-4.76	45.00	450.00

Force 1b1 Spreadsheet 1

VALUES		Row	t (sec)	Theta i(deg)1b1	Gamma(inst)1b1	epsilon(deg)	Fn1b 1(N)	Ft1b1(N)
M (kg) =	0.1621	1	0.0000	0.0	42.2	47.8	-1.1	1.2
r (m) =	0.073	2	0.0025	0.0	42.2	47.8	-1.1	1.2
Gamma(init)deg=	42.2	3	0.0050	0.0	42.2	47.8	-1.1	1.2
Theta final(rad)	2.25	4	0.0075	0.0	42.2	47.8	-1.1	1.2
length(lig)m=	0.0025	5	0.0100	0.0	42.2	47.8	-1.1	1.2
Time (s) =	0.1	6	0.0125	0.0	42.2	47.8	-1.1	1.2
Alpha (rad/s/s)=	450	7	0.0150	0.0	42.2	47.8	-1.1	1.2
		8	0.0175	0.0	42.2	47.8	-1.1	1.2
		9	0.0200	0.0	42.2	47.8	-1.1	1.2
		10	0.0225	0.0	42.2	47.8	-1.1	1.2
		11	0.0250	0.0	42.2	47.8	-1.1	1.2
		12	0.0275	0.0	42.2	47.8	-1.1	1.2
Mouth opening starts→		13	0.0300	0.1	42.3	47.8	-1.1	6.5
		14	0.0325	0.3	42.5	47.8	-1.0	6.5
		15	0.0350	0.7	42.9	47.8	-0.9	6.5
		16	0.0375	1.3	43.5	47.8	-0.8	6.5
		17	0.0400	2.0	44.2	47.8	-0.7	6.5
		18	0.0425	2.9	45.1	47.8	-0.5	6.5
		19	0.0450	3.9	46.1	47.8	-0.3	6.5
		20	0.0475	5.2	47.4	47.8	-0.1	6.5
		21	0.0500	6.5	48.7	47.8	0.1	6.5
		22	0.0525	8.1	50.3	47.8	0.4	6.5
		23	0.0550	9.7	51.9	47.8	0.7	6.5
		24	0.0575	11.6	53.8	47.8	1.1	6.5
		25	0.0600	13.6	55.8	47.8	1.5	6.5
		26	0.0625	15.8	58.0	47.8	1.9	6.5
		27	0.0650	18.1	60.3	47.8	2.3	6.5
		28	0.0675	20.6	62.8	47.8	2.8	6.5
		29	0.0700	23.3	65.5	47.8	3.3	6.5
		30	0.0725	26.1	68.3	47.8	3.8	6.5
		31	0.0750	29.1	71.3	47.8	4.3	6.5
		32	0.0775	32.2	74.4	47.8	4.9	6.5
		33	0.0800	35.5	77.7	47.8	5.5	6.5
		34	0.0825	39.0	81.2	47.8	6.2	6.5
		35	0.0850	42.6	84.8	47.8	6.9	6.5
		36	0.0875	46.4	88.6	47.8	7.6	6.5
		37	0.0900	50.4	92.6	47.8	8.3	6.5
		38	0.0925	54.5	96.7	47.8	9.1	6.5
		39	0.0950	58.7	100.9	47.8	9.8	6.5
		40	0.0975	63.2	105.4	47.8	10.7	6.5
Mouth opening ends →		41	0.1000	67.8	110.0	47.8	11.5	6.5
		42	0.1025	72.5	110.0	52.6	12.4	6.6
		43	0.1050	77.4	110.0	57.5	13.3	6.7
		44	0.1075	82.5	110.0	62.5	14.3	6.7
		45	0.1100	87.7	110.0	67.8	15.2	6.8
		46	0.1125	93.1	110.0	73.2	16.2	6.8
		47	0.1150	98.7	110.0	78.7	17.3	6.9
		48	0.1175	104.4	110.0	84.5	18.3	6.9
		49	0.1200	110.3	110.0	90.3	19.4	6.9
		50	0.1225	116.3	110.0	96.4	20.6	6.9
		51	0.1250	122.6	110.0	102.6	21.7	6.9
		52	0.1275	128.9	110.0	109.0	22.9	6.8

Force 1b1 Spreadsheet 2

Row	F1b1(N)	Phi(deg)	Delta(deg)	Fx1b1 (N)	Fy1b1.(N)	F(N).lig.
1	1.6	-47.8	270.0	0.0	-1.6	0.0
2	1.6	-47.8	270.0	0.0	-1.6	0.0
3	1.6	-47.8	270.0	0.0	-1.6	0.0
4	1.6	-47.8	270.0	0.0	-1.6	0.0
5	1.6	-47.8	270.0	0.0	-1.6	0.0
6	1.6	-47.8	270.0	0.0	-1.6	0.0
7	1.6	-47.8	270.0	0.0	-1.6	0.0
8	1.6	-47.8	270.0	0.0	-1.6	0.0
9	1.6	-47.8	270.0	0.0	-1.6	0.0
10	1.6	-47.8	270.0	0.0	-1.6	0.0
11	1.6	-47.8	270.0	0.0	-1.6	0.0
12	1.6	-47.8	270.0	0.0	-1.6	0.0
→13	6.6	-80.8	236.9	-3.6	-5.5	0.0
14	6.6	-81.2	236.3	-3.7	-5.5	0.0
15	6.6	-81.8	235.2	-3.7	-5.4	0.0
16	6.6	-82.7	233.8	-3.9	-5.3	0.0
17	6.5	-83.9	231.9	-4.0	-5.1	0.0
18	6.5	-85.3	229.6	-4.2	-5.0	0.0
19	6.5	-87.1	226.8	-4.5	-4.7	0.0
20	6.5	-89.0	223.6	-4.7	-4.5	0.0
21	6.5	88.7	220.0	-5.0	-4.2	0.0
22	6.5	86.2	216.0	-5.3	-3.8	0.0
23	6.5	83.5	211.5	-5.6	-3.4	0.0
24	6.6	80.5	206.7	-5.9	-3.0	0.0
25	6.7	77.3	201.5	-6.2	-2.4	0.0
26	6.8	74.0	196.0	-6.5	-1.9	98.8
27	6.9	70.5	190.2	-6.8	-1.2	100.7
28	7.1	67.0	184.1	-7.0	-0.5	103.2
29	7.3	63.4	177.9	-7.3	0.3	106.2
30	7.5	59.8	171.5	-7.4	1.1	0.0
31	7.8	56.3	165.0	-7.6	2.0	0.0
32	8.2	52.9	158.4	-7.6	3.0	0.0
33	8.5	49.6	151.9	-7.5	4.0	0.0
34	9.0	46.5	145.3	-7.4	5.1	0.0
35	9.4	43.5	138.7	-7.1	6.2	0.0
36	10.0	40.7	132.1	-6.7	7.4	0.0
37	10.5	38.1	125.5	-6.1	8.6	0.0
38	11.1	35.7	119.0	-5.4	9.7	0.0
39	11.8	33.4	112.5	-4.5	10.9	0.0
40	12.5	31.4	106.0	-3.4	12.0	0.0
→41	13.2	29.4	99.5	-2.2	13.1	0.0
42	14.1	28.0	98.0	-2.0	13.9	0.0
43	14.9	26.6	96.6	-1.7	14.8	0.0
44	15.8	25.3	95.3	-1.5	15.7	0.0
45	16.7	24.0	94.1	-1.2	16.6	0.0
46	17.6	22.9	92.9	-0.9	17.6	0.0
47	18.6	21.7	91.8	-0.6	18.6	0.0
48	19.6	20.6	90.7	-0.2	19.6	0.0
49	20.6	19.6	89.6	0.1	20.6	0.0
50	21.7	18.6	88.6	0.5	21.7	0.0
51	22.8	17.6	87.6	0.9	22.8	0.0
52	23.9	16.6	86.6	1.4	23.9	0.0

Force 1c1 spreadsheet 1

VALUES		Row	t (s)	Theta(deg)	gamma inst.(deg)	A.T. (mm)	Lin.. vel.(m/s)	Lin. acc.(m/s/s)
Gamma init(deg)=	42.2	2	0	0.0	42.2	0	0	0
MASS(mandible)kg=	0.1621	3	0.0025	0.0	42.2	0	0	0
ACC(rads/s)=	450	4	0.005	0.0	42.2	0	0	0
		5	0.0075	0.0	42.2	0	0	0
		6	0.01	0.0	42.2	0	0	0
		7	0.0125	0.0	42.2	0	0	0
		8	0.015	0.0	42.2	0	0	0
		9	0.0175	0.0	42.2	0	0	0
		10	0.02	0.0	42.2	0	0	0
		11	0.0225	0.0	42.2	0	0	0
		12	0.025	0.0	42.2	0	0	0
		13	0.0275	0.0	42.2	0	0.	0
		14	0.03	0.1	42.3	0	0.000	0.000
Jaw rotation starts →		15	0.0325	0.3	42.5	0	0.000	0.000
		16	0.035	0.7	42.9	0	0.000	0.000
		17	0.0375	1.3	43.5	0	0.000	0.000
		18	0.04	2.0	44.2	0	0.000	0.000
		19	0.04	2.9	45.1	0	0.000	0.000
		20	0.045	3.9	46.1	0	0.000	0.000
		21	0.0475	5.2	47.4	0	0.000	0.000
		22	0.05	6.5	48.7	0	0.000	0.000
		23	0.0525	8.1	50.3	0	0.000	0.000
		24	0.055	9.7	51.9	0	0.000	0.000
		25	0.0575	11.6	53.8	0	0.000	0.000
		26	0.06	13.6	55.8	0	0.000	0.000
		27	0.0625	15.8	58.0	2.02	0.058	23.849
Jaw translation starts →		28	0.065	18.1	60.3	4.20	0.112	23.849
		29	0.0675	20.6	62.8	6.52	0.163	23.849
		30	0.07	23.3	65.5	8.99	0.212	23.849
		31	0.0725	26.1	68.3	11.61	0.258	23.849
		32	0.075	29.1	71.3	14.39	0.303	23.849
		33	0.0775	32.2	74.4	17.31	0.346	23.849
		34	0.08	35.5	77.7	20.38	0.388	23.849
		35	0.0825	39.0	81.2	23.60	0.429	23.849
		36	0.085	42.6	84.8	26.98	0.469	23.849
		37	0.0875	46.4	88.6	30.50	0.508	23.849
		38	0.09	50.4	92.6	34.17	0.547	23.849
		39	0.0925	54.5	96.7	37.99	0.584	23.849
		40	0.095	58.7	100.9	37.99	0.000	23.849
		41	0.0975	63.2	105.4	37.99	0.000	23.849
		42	0.1	67.8	110.0	37.99	0.000	23.849
		43	0.1025	72.5	110.0	37.99	0.000	23.849
Jaw opening ends →		44	0.105	77.4	110.0	37.99	0.000	23.849
		45	0.1075	82.5	110.0	37.99	0.000	23.849
		46	0.11	87.7	110.0	37.99	0.000	23.849
		47	0.1125	93.1	110.0	37.99	0.000	23.849
		48	0.115	98.7	110.0	37.99	0.000	23.849
		49	0.1175	104.4	110.0	37.99	0.000	23.849
		50	0.12	110.3	110.0	37.99	0.000	23.849
		51	0.1225	116.3	110.0	37.99	0.000	23.849
		52	0.125	122.6	110.0	37.99	0.000	23.849
		53	0.1275	128.9	110.0	37.99	0.000	23.849

Force 1c1 spreadsheet 2

Row	F 1c1(N)	Delta (deg)	FX1c1	FY1c1	Str.2(Mpa)20mm	Str.1(Mpa)1mm	Str3.(Mpa)5.5mm
2	0.50	321.0	0.4	-0.3	0	0	0
3	0.50	321.0	0.4	-0.3	0	0	0
4	0.50	321.0	0.4	-0.3	0	0	0
5	0.50	321.0	0.4	-0.3	0	0	0
6	0.50	321.0	0.4	-0.3	0	0	0
7	0.50	321.0	0.4	-0.3	0	0	0
8	0.50	321.0	0.4	-0.3	0	0	0
9	0.50	321.0	0.4	-0.3	0	0	0
10	0.50	321.0	0.4	-0.3	0	0	0
11	0.50	321.0	0.4	-0.3	0	0	0
12	0.50	321.0	0.4	-0.3	0	0	0
13	0.50	321.0	0.4	-0.3	0	0	0
14	0.50	321.0	0.4	-0.3	0.001	0.50	0.0165
15	0.50	321.0	0.4	-0.3	0.001	0.50	0.0153
16	0.49	321.0	0.4	-0.3	0.001	0.49	0.0152
17	0.49	321.0	0.4	-0.3	0.001	0.49	0.0150
18	0.48	321.0	0.4	-0.3	0.001	0.48	0.0147
19	0.47	321.0	0.4	-0.3	0.001	0.47	0.0144
20	0.46	321.0	0.4	-0.3	0.001	0.5	0.0141
21	0.44	321.0	0.3	-0.3	0.001	0.4	0.0136
22	0.43	321.0	0.3	-0.3	0.001	0.4	0.0131
23	0.41	321.0	0.3	-0.3	0.001	0.4	0.0126
24	0.39	321.0	0.3	-0.2	0.001	0.4	0.0120
25	0.37	321.0	0.3	-0.2	0.001	0.4	0.0113
26	0.34	321.0	0.3	-0.2	0.001	0.3	0.0105
27	2.25	321.0	1.7	-1.4	0.006	2.2	0.0691
28	2.22	321.0	1.7	-1.4	0.006	2.2	0.0682
29	2.18	321.0	1.7	-1.4	0.005	2.2	0.0672
30	2.15	321.0	1.7	-1.4	0.005	2.1	0.0661
31	2.11	321.0	1.6	-1.3	0.005	2.1	0.0649
32	2.07	321.0	1.6	-1.3	0.005	2.1	0.0637
33	2.03	321.0	1.6	-1.3	0.005	2.0	0.0624
34	1.98	321.0	1.5	-1.2	0.005	2.0	0.0610
35	1.93	321.0	1.5	-1.2	0.005	1.9	0.0595
36	1.88	28.0	1.7	0.9	0.005	1.9	0.0579
37	1.83	28.0	1.6	0.9	0.005	1.8	0.0563
38	1.78	28.0	1.6	0.8	0.004	1.8	0.0547
39	1.72	28.0	1.5	0.8	0.004	1.7	0.0530
40	1.66	28.0	1.5	0.8	0.004	1.7	0.0512
41	1.61	28.0	1.4	0.8	0.004	1.6	0.0495
42	1.55	28.0	1.4	0.7	0.004	1.6	0.0477
43	1.49	28.0	1.3	0.7	0.004	1.5	0.0460
44	1.44	28.0	1.3	0.7	0.004	1.4	0.0443
45	1.39	28.0	1.2	0.7	0.003	1.4	0.0426
46	1.34	28.0	1.2	0.6	0.003	1.3	0.0411
47	1.29	28.0	1.1	0.6	0.003	1.3	0.0396
48	1.25	28.0	1.1	0.6	0.003	1.2	0.0384
49	1.21	28.0	1.1	0.6	0.003	1.2	0.0372
50	1.18	28.0	1.0	0.6	0.003	1.2	0.0363
51	1.16	28.0	1.0	0.5	0.003	1.2	0.0356
52	1.14	28.0	1.0	0.5	0.003	1.1	0.0352
53	1.14	28.0	1.0	0.5	0.003	1.1	0.0350

Final force 1

Row	t (sec)	Fx1a1.(N)	FX1c1	Fxtotal	Fy1a1(N)	FY1c1	Fytotal	Final force1	Delta final	Str 1	Str 2	Str3
2												
3	0.000	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
4	0.003	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
5	0.005	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
6	0.008	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
7	0.010	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
8	0.013	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
9	0.015	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
10	0.018	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
11	0.020	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
12	0.023	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
13	0.025	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
14	0.028	0.00	0.0	0.00	-0.80	-0.50	-1.3	1.3	270.0	0	0	0.000
15	0.030	1.01	0.0	1.01	-1.52	-0.50	-2.0	2.3	296.5	0	0	0.000
16	0.033	1.00	0.0	1.00	-1.53	-0.50	-2.0	2.3	296.2	0	0	0.000
17	0.035	0.98	0.0	0.98	-1.54	-0.49	-2.0	2.3	295.8	0	0	0.000
18	0.038	0.96	0.0	0.96	-1.56	-0.49	-2.0	2.3	295.1	0	0	0.000
19	0.040	0.93	0.0	0.93	-1.59	-0.48	-2.1	2.3	294.3	0	0	0.000
20	0.043	0.90	0.0	0.90	-1.62	-0.47	-2.1	2.3	293.3	0	0	0.000
21	0.045	0.86	0.0	0.86	-1.65	-0.46	-2.1	2.3	292.1	0	0	0.000
22	0.048	0.81	0.0	0.81	-1.69	-0.44	-2.1	2.3	290.7	0	0	0.000
23	0.050	0.76	0.0	0.76	-1.74	-0.43	-2.2	2.3	289.2	0	0	0.000
24	0.053	0.70	0.0	0.70	-1.79	-0.41	-2.2	2.3	287.5	0	0	0.000
25	0.055	0.63	0.0	0.63	-1.85	-0.39	-2.2	2.3	285.7	0	0	0.000
26	0.058	0.56	0.0	0.56	-1.91	-0.37	-2.3	2.3	283.8	0	0	0.000
27	0.060	0.48	0.0	0.48	-1.97	-0.34	-2.3	2.4	281.7	0	0	0.000
28	0.063	0.40	1.7	2.14	-2.04	-1.41	-3.5	4.1	301.8	0	0	0.000
29	0.065	0.31	1.7	2.03	-2.11	-1.39	-3.5	4.1	300.0	0	0	0.000
30	0.068	0.21	1.7	1.91	-2.19	-1.37	-3.6	4.0	298.2	0	0	0.000
31	0.070	0.11	1.7	1.78	-2.27	-1.35	-3.6	4.0	296.2	0	0	0.000
32	0.073	0.00	1.6	1.64	-2.35	-1.33	-3.7	4.0	294.1	0	0	0.000
33	0.075	-0.11	1.6	1.50	-2.44	-1.30	-3.7	4.0	291.8	0	0	0.000
34	0.078	-0.22	1.6	1.35	-2.53	-1.28	-3.8	4.0	289.5	0	0	0.000
35	0.080	-0.35	1.5	1.19	-2.62	-1.25	-3.9	4.0	287.2	0	0	0.000
36	0.083	-0.47	1.5	1.03	-2.71	-1.22	-3.9	4.1	284.7	0	0	0.000
37	0.085	-0.60	-0.7	-1.26	-2.81	-0.35	-3.2	3.4	248.2	0.00017	0.0034	0.00069
38	0.088	-0.73	-0.7	-1.41	-2.90	-0.36	-3.3	3.6	246.6	0.00018	0.0036	0.00073
39	0.090	-0.87	-0.7	-1.56	-3.00	-0.37	-3.4	3.7	245.2	0.00019	0.0037	0.00076
40	0.093	-1.01	-0.7	-1.70	-3.10	-0.37	-3.5	3.9	243.9	0.00019	0.0039	0.00079
41	0.095	-1.15	0.0	-1.15	-3.20	0.00	-3.2	3.4	250.3	0.00017	0.0034	0.00069
42	0.098	-1.29	0.0	-1.29	-3.31	0.00	-3.3	3.5	248.7	0.00018	0.0035	0.00072
43	0.100	-1.43	0.0	-1.43	-3.41	0.00	-3.4	3.7	247.2	0.00018	0.0037	0.00075
44	0.103	-1.57	0.0	-1.57	-3.51	0.00	-3.5	3.8	245.9	0.00019	0.0038	0.00079
45	0.105	-1.71	0.0	-1.71	-3.62	0.00	-3.6	4.0	244.7	0.00020	0.0040	0.00082
46	0.108	-1.85	0.0	-1.85	-3.73	0.00	-3.7	4.2	243.6	0.00021	0.0042	0.00085
47	0.110	-1.99	0.0	-1.99	-3.84	0.00	-3.8	4.3	242.6	0.00022	0.0043	0.00088
48	0.113	-2.13	0.0	-2.13	-3.96	0.00	-4.0	4.5	241.8	0.00022	0.0045	0.00092
49	0.115	-2.26	0.0	-2.26	-4.08	0.00	-4.1	4.7	241.0	0.00023	0.0047	0.00095
50	0.118	-2.39	0.0	-2.39	-4.20	0.00	-4.2	4.8	240.4	0.00024	0.0048	0.00099
51	0.120	-2.51	0.0	-2.51	-4.33	0.00	-4.3	5.0	239.9	0.00025	0.0050	0.00102
52	0.123	-2.63	0.0	-2.63	-4.47	0.00	-4.5	5.2	239.5	0.00026	0.0052	0.00106
53	0.125	-2.74	0.0	-2.74	-4.61	0.00	-4.6	5.4	239.3	0.00027	0.0054	0.00109
54	0.128	-2.85	0.0	-2.85	-4.76	0.00	-4.8	5.6	239.1	0.00028	0.0056	0.00113

F1a2 Spreadsheet 1

VALUES		Row	TIME(sec)	Rho.i.(deg)	Beta(deg)	Theta(rad)	Theta(deg)
M(kg) =	0.1621	1	0	70.8	35.5	0.000	0.
r(m) =	0.034	2	0.0025	70.8	35.5	0.000	0.
Rho ([init].deg) =	70.8	3	0.005	70.8	35.5	0.000	0.
w(init).(rad/s) =	0	4	0.0075	70.8	35.5	0.000	0.
		5	0.01	70.8	35.5	0.000	0.
		6	0.0125	70.8	35.5	0.000	0.
		7	0.015	70.8	35.5	0.000	0.
		8	0.0175	70.8	35.5	0.000	0.
		9	0.02	70.8	35.5	0.000	0.
		10	0.0225	70.8	35.5	0.000	0.
		11	0.025	70.8	35.5	0.000	0.
		12	0.0275	70.8	35.5	0.000	0.
		13	0.03	70.9	35.4	0.002	0.140
		14	0.0325	71.0	35.3	0.003	0.192
		15	0.035	71.0	35.3	0.003	0.200
		16	0.0375	71.0	35.3	0.004	0.220
		17	0.04	71.0	35.3	0.004	0.240
		18	0.0425	71.1	35.2	0.005	0.260
		19	0.045	71.1	35.2	0.005	0.300
		20	0.0475	71.3	35.0	0.009	0.512
		21	0.05	72.0	34.3	0.021	1.208
		22	0.0525	73.0	33.3	0.038	2.173
		23	0.055	74.2	32.1	0.060	3.433
		24	0.0575	75.8	30.5	0.087	5.008
		25	0.06	77.7	28.6	0.121	6.911
		26	0.0625	80.0	26.3	0.160	9.156
		27	0.065	82.5	23.8	0.205	11.749
		28	0.0675	85.5	20.8	0.256	14.694
		29	0.07	88.5	17.8	0.309	17.694
		30	0.0725	92.4	13.9	0.378	21.636
		31	0.075	96.4	9.9	0.447	25.619
		32	0.0775	100.7	5.6	0.522	29.927
		33	0.08	105.3	1.0	0.603	34.545
		34	0.0825	110.3	-4.0	0.689	39.452
		35	0.085	115.4	-9.1	0.779	44.623
		36	0.0875	120.8	-14.5	0.873	50.029
		37	0.09	126.4	-20.1	0.971	55.638
		38	0.0925	132.2	-25.9	1.072	61.412
		39	0.095	138.1	-31.8	1.175	67.311
		40	0.0975	144.1	-37.8	1.279	73.291
		41	0.1	150.1	-43.8	1.384	79.302
		42	0.1025	156.1	-49.8	1.489	85.291
		43	0.105	162.0	-55.7	1.592	91.202
		44	0.1075	167.8	-61.5	1.693	96.974
		45	0.11	173.3	-67.0	1.790	102.541
		46	0.1125	178.6	-72.3	1.882	107.835
		47	0.115	183.3	-77.0	1.964	112.541
		48	0.1175	188.1	-81.8	2.047	117.306
		49	0.12	192.1	-85.8	2.118	121.326
		50	0.1225	195.6	-89.3	2.177	124.756
		51	0.125	198.3	-92.0	2.225	127.508
		52	0.1275	200.3	-94.0	2.260	129.487
		53	0.13	201.4	-95.1	2.279	130.598

F1a2 Spreadsheet 2

Row	Fn1a2(N)	Ft1a2N)	F1a2(N)	phi(deg)	Delta(deg)	Fx1a2.(deg)	fY1a2.(deg)	alpha(rad/s/s)	Omega(rad/s)
1	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
2	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
3	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
4	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
5	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
6	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
7	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
8	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
9	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
10	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
11	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
12	1.3	0.9	1.6	35.5	270.0	0.0	-1.6	0.0	0.000
13	1.3	0.7	1.5	27.8	262.3	-0.2	-1.5	42.9	0.044
14	1.3	0.7	1.5	27.5	262.0	-0.2	-1.4	44.3	0.155
15	1.3	0.5	1.4	20.2	254.7	-0.4	-1.3	79.9	0.304
16	1.3	0.1	1.3	5.1	239.6	-0.7	-1.1	145.5	0.580
17	1.3	-0.4	1.4	-16.1	218.4	-1.1	-0.8	235.0	1.051
18	1.3	-1.0	1.6	-36.2	198.3	-1.5	-0.5	341.4	1.769
19	1.3	-1.6	2.1	-50.1	184.4	-2.1	-0.2	456.9	2.765
20	1.4	-2.3	2.6	-58.3	176.2	-2.6	0.2	574.4	4.055
21	1.5	-2.9	3.3	-62.7	171.8	-3.2	0.5	687.0	5.633
22	1.6	-3.5	3.8	-64.8	169.7	-3.8	0.7	789.1	7.481
23	1.9	-4.0	4.4	-65.1	169.4	-4.3	0.8	876.3	9.566
24	2.1	-4.4	4.9	-64.0	170.5	-4.8	0.8	945.2	11.847
25	2.5	-4.7	5.3	-61.9	172.6	-5.3	0.7	994.1	14.276
26	3.0	-4.9	5.8	-58.8	175.7	-5.7	0.4	1022.3	16.801
27	3.5	-5.0	6.1	-55.0	179.5	-6.1	0.1	1030.2	19.371
28	4.1	-5.1	6.5	-50.7	183.8	-6.5	-0.4	1019.3	21.936
29	4.8	-5.0	6.9	-46.0	188.5	-6.8	-1.0	991.5	24.453
30	5.5	-4.9	7.4	-41.3	193.2	-7.2	-1.7	949.4	26.882
31	6.3	-4.7	7.8	-36.7	197.8	-7.4	-2.4	895.8	29.190
32	7.0	-4.4	8.3	-32.4	202.1	-7.7	-3.1	833.3	31.353
33	7.7	-4.2	8.8	-28.5	206.0	-7.9	-3.9	764.1	33.351
34	8.4	-3.9	9.3	-25.0	209.5	-8.1	-4.6	690.1	35.170
35	9.0	-3.6	9.7	-21.9	212.6	-8.2	-5.2	612.2	36.798
36	9.6	-3.3	10.2	-19.1	215.4	-8.3	-5.9	530.5	38.228
37	10.1	-3.0	10.5	-16.6	217.9	-8.3	-6.5	444.0	39.447
38	10.4	-2.6	10.8	-14.1	220.4	-8.2	-7.0	351.0	40.442
39	10.7	-2.2	10.9	-11.7	222.8	-8.0	-7.4	248.7	41.194
40	10.8	-1.7	11.0	-9.0	225.5	-7.7	-7.8	133.4	41.675
41	10.8	-1.1	10.9	-5.9	228.6	-7.2	-8.2	1.4	41.874
42	10.6	-0.4	10.6	-2.1	232.4	-6.5	-8.4	-151.4	41.664
43	10.2	0.5	10.2	2.8	237.3	-5.5	-8.6	-328.4	41.070
44	9.6	1.5	9.7	9.1	243.6	-4.3	-8.7	-531.5	40.001
45	8.7	2.7	9.2	17.3	251.8	-2.9	-8.7	-760.9	38.390
46	7.7	4.1	8.7	27.9	262.4	-1.2	-8.6	-1013.2	36.177
47	6.5	5.5	8.5	40.4	274.9	0.7	-8.5	-1280.8	33.312
48	5.1	7.0	8.6	53.7	288.2	2.7	-8.2	-1550.2	29.771
49	3.7	8.3	9.1	65.9	300.4	4.6	-7.9	-1800.2	25.577
50	2.4	9.4	9.7	75.7	310.2	6.3	-7.4	-2000.2	20.812
51	1.2	10.0	10.1	83.1	317.6	7.5	-6.8	-2108.3	15.161
52	0.5	9.8	9.8	87.2	321.7	7.7	-6.1	-2068.2	10.393
53	0.0	8.4	8.4	89.8	324.3	6.8	-4.9	-1807.5	5.490

F1b2 Spreadsheet 1

VALUES		Row	TIME(sec)	Theta(deg)1b2	Gamma inst(deg) 1b2	epsilon (deg)	Vel(rad/s)	ACC(rad/s/s)
Gamma init (deg)=	42.2							
MASS mandible(kg)=	0.1621	1	0	0.00	42.2	47.8	0.00	0
RADIUS(m)=	0.07316	2	0.0025	0.00	42.2	47.8	0.00	0
Vert.Dist.Lig.from pivot(m)=	0.0025	3	0.005	0.00	42.2	47.8	0.00	0
		4	0.0075	0.00	42.2	47.8	0.00	0
		5	0.01	0.00	42.2	47.8	0.00	0
		6	0.0125	0.00	42.2	47.8	0.00	0
		7	0.015	0.00	42.2	47.8	0.00	0
		8	0.0175	0.00	42.2	47.8	0.00	0
		9	0.02	0.00	42.2	47.8	0.00	0
		10	0.0225	0.00	42.2	47.8	0.00	0
		11	0.025	0.00	42.2	47.8	0.00	0
		12	0.0275	0.00	42.2	47.8	0.00	0
Mouth opening starts →		13	0.03	0.14	42.3	47.8	0.04	42.9
		14	0.0325	0.19	42.4	47.8	0.16	44.3
		15	0.035	0.20	42.4	47.8	0.30	79.9
		16	0.0375	0.22	42.4	47.8	0.58	145.5
		17	0.04	0.24	42.4	47.8	1.05	235.0
		18	0.0425	0.26	42.5	47.8	1.77	341.4
		19	0.045	0.30	42.5	47.8	2.77	456.9
		20	0.0475	0.51	42.7	47.8	4.05	574.4
		21	0.05	1.21	43.4	47.8	5.63	687.0
		22	0.0525	2.17	44.4	47.8	7.48	789.1
		23	0.055	3.43	45.6	47.8	9.57	876.3
		24	0.0575	5.01	47.2	47.8	11.85	945.2
		25	0.06	6.91	49.1	47.8	14.28	994.1
		26	0.0625	9.16	51.4	47.8	16.80	1022.3
		27	0.065	11.75	53.9	47.8	19.37	1020.1
		28	0.0675	14.69	56.9	47.8	21.94	1019.3
		29	0.07	17.69	59.9	47.8	24.45	991.5
		30	0.0725	21.64	63.8	47.8	26.88	949.4
		31	0.075	25.62	67.8	47.8	29.19	895.8
		32	0.0775	29.93	72.1	47.8	31.35	833.3
		33	0.08	34.55	76.7	47.8	33.35	764.1
		34	0.0825	39.45	81.7	47.8	35.17	690.1
		35	0.085	44.62	86.8	47.8	36.80	612.2
		36	0.0875	50.03	92.2	47.8	38.23	530.5
		37	0.09	55.64	97.8	47.8	39.45	444.0
Mouth opening ends →		38	0.0925	61.41	103.6	47.8	40.44	351.0
		39	0.095	67.31	109.5	53.7	41.19	248.7
		40	0.0975	73.29	109.5	59.7	41.67	133.4
		41	0.1	79.302	109.5	65.7	41.87	1.4
		42	0.1025	85.291	109.5	71.7	41.66	-151.5
		43	0.105	91.202	109.5	77.6	41.07	-328.4
		44	0.1075	96.974	109.5	83.4	40.00	-531.5
		45	0.11	102.541	109.5	88.9	38.39	-760.9
		46	0.1125	107.835	109.5	94.2	36.18	-1013.2
		47	0.115	112.541	109.5	98.9	33.31	-1280.8
		48	0.1175	117.306	109.5	103.7	29.77	-1550.2
		49	0.12	121.326	109.5	107.7	25.58	-1800.2
		50	0.1225	124.756	109.5	111.1	20.81	-2000.2
		51	0.125	127.508	109.5	113.9	15.16	-2108.3

F1b2 Spreadsheet 2

Row	Fn1b2(N)	Ft1b2(N)	F1b2(N)	Phi(deg)	Delta(deg)	F. lig(N)
1	-1.1	1.2	1.6	-47.8	270.0	19.8
2	-1.1	1.2	1.6	-47.8	270.0	19.8
3	-1.1	1.2	1.6	-47.8	270.0	19.8
4	-1.1	1.2	1.6	-47.8	270.0	19.8
5	-1.1	1.2	1.6	-47.8	270.0	19.8
6	-1.1	1.2	1.6	-47.8	270.0	19.8
7	-1.1	1.2	1.6	-47.8	270.0	19.8
8	-1.1	1.2	1.6	-47.8	270.0	19.8
9	-1.1	1.2	1.6	-47.8	270.0	19.8
10	-1.1	1.2	1.6	-47.8	270.0	19.8
11	-1.1	1.2	1.6	-47.8	270.0	19.8
12	-1.1	1.2	1.6	-47.8	270.0	19.8
13	-1.1	1.7	2.0	-57.7	260.0	24.9
14	-1.1	1.7	2.0	-57.9	259.7	25.0
15	-1.1	2.1	2.4	-63.3	254.3	29.6
16	-1.1	2.9	3.1	-69.9	247.7	38.5
17	-1.1	4.0	4.1	-75.1	242.5	51.1
18	-1.0	5.2	5.3	-78.8	238.7	66.3
19	-1.0	6.6	6.7	-81.6	235.9	83.0
20	-0.9	8.0	8.0	-83.8	233.5	100.1
21	-0.7	9.3	9.4	-85.8	230.8	116.4
22	-0.4	10.5	10.5	-87.8	227.8	131.3
23	0.0	11.6	11.6	89.9	224.3	144.0
24	0.6	12.4	12.4	87.2	220.0	154.4
25	1.3	13.0	13.0	84.1	215.0	162.3
26	2.3	13.3	13.5	80.3	208.9	168.0
27	3.4	13.3	13.7	75.7	201.8	170.6
28	4.6	13.3	14.1	70.7	193.8	175.0
29	6.0	12.9	14.3	65.0	185.1	177.7
30	7.5	12.4	14.5	58.9	175.1	180.8
31	9.0	11.8	14.9	52.6	164.7	185.1
32	10.6	11.1	15.3	46.2	154.1	190.6
33	12.1	10.2	15.9	40.2	143.4	197.6
34	13.6	9.4	16.5	34.5	132.9	205.6
35	15.0	8.4	17.2	29.4	122.6	214.2
36	16.3	7.5	17.9	24.7	112.4	222.8
37	17.4	6.4	18.5	20.3	102.5	230.8
38	18.3	5.3	19.1	16.2	92.6	237.7
39	19.2	4.2	19.6	12.4	82.9	244.6
40	19.8	3.0	20.0	8.5	79.0	249.2
41	20.1	1.5	20.2	4.2	74.7	251.4
42	20.1	-0.3	20.1	-0.8	69.7	250.1
43	19.7	-2.3	19.8	-6.8	63.7	246.5
44	18.8	-4.7	19.4	-14.1	56.4	241.2
45	17.4	-7.4	19.0	-23.1	47.4	236.1
46	15.6	-10.4	18.8	-33.7	36.8	234.0
47	13.4	-13.6	19.1	-45.4	25.0	237.9
48	10.9	-16.8	20.1	-57.1	13.4	249.6
49	8.2	-19.8	21.5	-67.4	3.1	267.4
50	5.7	-22.2	23.0	-75.6	-5.1	285.8
51	3.4	-23.5	23.8	-81.9	-11.4	296.2
52	2.0	-23.1	23.2	-85.1	-14.6	288.6

F1c2 Spreadsheet 1

MASS mandible(kg)= 0.1621	Row	Time(sec)	Theta(deg)	gamma inst(deg)	Epsilon(deg)	A.T.(mm)
	2	0	0.00	42.2	47.8	0.0
	3	.00250	0.00	42.2	47.8	0.0
	4	.00500	0.00	42.2	47.8	0.0
	5	.00750	0.00	42.2	47.8	0.0
	6	.01000	0.00	42.2	47.8	0.0
	7	.01250	0.00	42.2	47.8	0.0
	8	.01500	0.00	42.2	47.8	0.0
	9	.01750	0.00	42.2	47.8	0.0
	10	.02000	0.00	42.2	47.8	0.0
	11	.02250	0.00	42.2	47.8	0.0
	12	.02500	0.00	42.2	47.8	0.0
	13	.02750	0.00	42.2	47.8	0.0
Mouth opening starts →	14	.03000	0.14	42.3	47.8	0.0
	15	.03250	0.19	42.4	47.8	0.0
	16	.03500	0.20	42.4	47.8	0.0
	17	.03750	0.22	42.4	47.8	0.0
	18	.04000	0.24	42.4	47.8	0.0
	19	0.0425	0.26	42.5	47.8	0.0
	20	.04500	0.30	42.5	47.8	0.0
	21	.04750	0.51	42.7	47.8	0.0
	22	.05000	1.21	43.4	47.8	0.0
	23	.05250	2.17	44.4	47.8	0.0
	24	.05500	3.43	45.6	47.8	0.0
	25	.05750	5.01	47.2	47.8	0.0
	26	.06000	6.91	49.1	47.8	0.0
	27	.06250	9.16	51.4	47.8	0.0
	28	.06500	11.75	53.9	47.8	0.0
	29	.06750	14.69	56.9	47.8	0.0
Translation starts →	30	.07000	17.69	59.9	47.8	2.8
	31	.07250	21.64	63.8	47.8	6.5
	32	.07500	25.62	67.8	47.8	10.2
	33	.07750	29.93	72.1	47.8	14.2
	34	.08000	34.55	76.7	47.8	18.5
	35	.08250	39.45	81.7	47.8	23.0
	36	.08500	44.62	86.8	47.8	27.8
	37	.08750	50.03	92.2	47.8	32.9
Mouth opening ends →	38	.09000	55.64	97.8	47.8	38.1
	39	.09250	61.41	103.6	47.8	38.1
	40	.09500	67.31	109.5	47.8	38.1
	41	.09750	73.29	109.5	47.8	38.1
	42	.10000	79.302	109.5	47.8	38.1
	43	.10250	85.291	109.5	47.8	38.1
	44	.10500	91.202	109.5	47.8	38.1
	45	.10750	96.974	109.5	47.8	38.1
	47	.11000	102.541	109.5	47.8	38.1
	47	.11250	107.835	109.5	47.8	38.1
	48	.11500	112.541	109.5	47.8	38.1
	49	.11750	117.306	109.5	47.8	38.1
	50	.12000	121.326	109.5	47.8	38.1
	51	.12250	124.756	109.5	47.8	38.1
	52	.12500	127.508	109.5	47.8	38.1
	53	.12750	129.487	109.5	47.8	38.1

F1c2 Spreadsheet 2

Row	Alpha(rad/s/s)	Lin.acc.(m/s/s)	Lin.vel.(m/s)	F1c2	Delta 1c2(deg)	Fx1c2(N)	Fy1c2(N)	stress1	stress2	stress 3
2	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
3	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
4	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
5	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
6	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
7	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
8	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
9	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
10	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
11	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
12	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
13	0.0	0.0	0.00	0.5	321	0.4	-0.3	.0	0.0	0.0
→ 14	42.9	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.50	.0165
15	44.3	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.50	.0165
16	79.9	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.50	.0165
17	145.5	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.50	.0165
18	235.0	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.50	.0165
19	341.4	0.0	0.00	0.5	321	0.4	-0.3	0.00	0.50	0.02
20	456.9	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.50	.0164
21	574.4	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.49	.0164
22	687.0	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.49	.0161
23	789.1	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.48	.0158
24	876.3	0.0	0.00	0.5	321	0.4	-0.3	.0012	0.46	.0153
25	945.2	0.0	0.00	0.4	321	0.3	-0.3	.0011	0.44	.0147
26	994.1	0.0	0.00	0.4	321	0.3	-0.3	.0011	0.42	.0140
27	1022.3	0.0	0.00	0.4	321	0.3	-0.2	.0010	0.40	.0131
28	1030.2	0.0	0.00	0.4	321	0.3	-0.2	.0009	0.36	.0120
29	1019.3	0.0	0.00	0.3	321	0.3	-0.2	.0008	0.33	.0108
→ 30	991.5	52.5	0.13	4.5	321	3.5	-2.9	.0114	4.55	.1503
31	949.4	50.3	0.26	4.3	321	3.4	-2.7	.0108	4.32	.1427
32	895.8	47.5	0.38	4.0	321	3.1	-2.5	.0101	4.03	.1333
33	833.3	44.2	0.49	3.5	28.0	3.0	1.6	.0086	3.45	.1142
34	764.1	40.5	0.59	3.2	28.0	2.8	1.5	.0081	3.22	.1065
35	690.1	36.6	0.68	3.0	28.0	2.6	1.4	.0074	2.97	.0982
36	612.2	32.4	0.76	2.7	28.0	2.4	1.3	.0068	2.71	.0895
37	530.5	28.1	0.83	2.4	28.0	2.1	1.1	.0061	2.43	.0804
→ 38	444.0	23.5	0.89	2.1	28.0	1.9	1.0	.0053	2.14	.0706
39	351.0	18.6	0.94	0.0	28.0	0.0	0.0	.0000	0.00	.0000
40	248.7	13.2	0.97	0.0	28.0	0.0	0.0	.0000	0.00	.0000
41	133.4	7.1	0.99	0.0	28.0	0.0	0.0	.0000	0.00	.0000
42	1.4	0.1	0.99	0.0	28.0	0.0	0.0	.0000	0.04	.0000
43	-151.4	-8.0	0.97	0.0	28.0	0.0	0.0	.0000	-5.01	.0000
44	-328.4	-17.4	0.92	0.0	28.0	0.0	0.0	.0000	-10.85	.0000
45	-531.5	-28.2	0.85	0.0	28.0	0.0	0.0	.0000	-17.57	.0000
46	-760.9	-40.3	0.75	0.0	28.0	0.0	0.0	.0000	-25.15	.0000
47	-1013.2	-53.7	0.62	0.0	28.0	0.0	0.0	.0000	-33.49	.0000
48	-1280.8	-67.9	0.45	0.0	28.0	0.0	0.0	.0000	-42.34	.0000
49	-1550.2	-82.2	0.24	0.0	28.0	0.0	0.0	.0000	-51.25	.0000
50	-1800.2	-95.4	0.00	0.0	28.0	0.0	0.0	.0000	-59.51	.0000
51	-2000.2	-106.0	-0.26	0.0	28.0	0.0	0.0	.0000	-66.12	.0000
52	-2108.3	-111.7	-0.54	0.0	28.0	0.0	0.0	.0000	-69.69	.0000
53	-2068.2	-109.6	-0.81	0.0	28.0	0.0	0.0	.0000	-68.37	.0000

Final force 2 Spreadsheet

Row	TIME(sec)	Fx1a2.(deg)	Fx1c2(N)	Fx total(N)	fY1a2.(deg)	Fy1c2(N)	Fytotal(N)	Final force2(N)	Delta final 2 (deg)	Stress1.	Stress2.	Stress3.
2												
3	0.0000	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
4	0.0025	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
5	0.0050	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
6	0.0075	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
7	0.0100	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
8	0.0125	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
9	0.0150	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
10	0.0175	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
11	0.0200	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
12	0.0225	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
13	0.0250	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
14	0.0275	0		0.00	-0.80		-0.8	0.8	270.0	.0000	.0000	.0000
15	0.0300	0.094		0.09	-0.86	-0.3	-1.2	1.2	274.6	.0000	.0000	-.0104
16	0.0325	0.097		0.10	-0.87	-0.3	-1.2	1.2	274.7	.0000	.0000	-.0104
17	0.0350	0.176		0.18	-0.92	-0.3	-1.2	1.2	278.1	.0000	.0000	-.0104
18	0.0375	0.323		0.32	-1.03	-0.3	-1.3	1.4	283.6	.0000	.0000	-.0104
19	0.0400	0.524		0.52	-1.17	-0.3	-1.5	1.6	289.4	.0000	.0000	-.0104
20	0.0425	0.762		0.76	-1.34	-0.3	-1.7	1.8	294.7	.0000	.0000	-.0104
21	0.0450	1.021		1.02	-1.53	-0.3	-1.8	2.1	299.0	.0000	.0000	-.0103
22	0.0475	1.281	0.38	1.67	-1.71	-0.3	-2.0	2.6	309.4	.0000	.0000	-.0103
23	0.0500	1.474	0.38	1.85	-1.97	-0.3	-2.3	2.9	309.2	.0000	.0000	-.0101
24	0.0525	1.651	0.37	2.02	-2.18	-0.3	-2.5	3.2	309.1	.0000	.0000	-.0099
25	0.0550	1.772	0.36	2.13	-2.40	-0.3	-2.7	3.4	308.4	.0000	.0000	-.0096
26	0.0575	1.827	0.35	2.17	-2.62	-0.3	-2.9	3.6	306.8	.0000	.0000	-.0092
27	0.0600	1.809	0.33	2.14	-2.84	-0.3	-3.1	3.8	304.5	.0000	.0000	-.0088
28	0.0625	1.715	0.31	2.02	-3.05	-0.2	-3.3	3.9	301.5	.0000	.0000	-.0082
29	0.0650	1.549	0.28	1.83	-3.27	-0.2	-3.5	3.9	297.6	.0000	.0000	-.0076
30	0.0675	1.315	3.53	4.85	-3.48	-2.9	-6.3	8.0	307.4	.0000	.0000	.0000
31	0.0700	1.026	3.35	4.38	-3.69	-2.7	-6.4	7.8	304.4	.0000	.0000	.0000
32	0.0725	0.680	3.13	3.81	-3.88	-2.5	-6.4	7.5	300.7	.0000	.0000	.0000
33	0.0750	0.302	3.05	3.35	-4.06	1.6	-2.4	4.1	323.9	.0000	.0000	.0000
34	0.0775	-0.100	2.84	2.74	-4.23	1.5	-2.7	3.9	315.3	.0000	.0000	.0000
35	0.0800	-0.517	2.62	2.11	-4.37	1.4	-3.0	3.6	305.3	.0091	3.65	.1206
36	0.0825	-0.936	2.39	1.45	-4.49	1.3	-3.2	3.5	294.3	.0088	3.54	.1169
37	0.0850	-1.352	2.15	0.79	-4.58	1.1	-3.4	3.5	283.0	.0088	3.53	.1168
38	0.0875	-1.758	1.89	0.13	-4.64	1.0	-3.6	3.6	272.0	.0091	3.64	.1203
39	0.0900	-2.150	0.00	-2.15	-4.65	0.0	-4.7	5.1	245.2	.0000	.0000	.0000
40	0.0925	-2.528	0.00	-2.53	-4.61	0.0	-4.6	5.3	241.3	.0000	.0000	.0000
41	0.0950	-2.891	0.00	-2.89	-4.51	0.0	-4.5	5.4	237.3	.0000	.0000	.0000
42	0.0975	-3.242	0.00	-3.24	-4.34	0.0	-4.3	5.4	233.2	.0000	.0000	.0000
43	0.1000	-3.584	0.00	-3.58	-4.08	0.0	-4.1	5.4	228.7	.0000	.0000	.0000
44	0.1025	-3.910	0.00	-3.91	-3.72	0.0	-3.7	5.4	223.6	.0000	.0000	.0000
45	0.1050	-4.231	0.00	-4.23	-3.24	0.0	-3.2	5.3	217.5	.0000	.0000	.0000
46	0.1075	-4.542	0.00	-4.54	-2.64	0.0	-2.6	5.3	210.2	.0000	.0000	.0000
47	0.1100	-4.842	0.00	-4.84	-1.92	0.0	-1.9	5.2	201.6	.0000	.0000	.0000
48	0.1125	-5.124	0.00	-5.12	-1.07	0.0	-1.1	5.2	191.8	.0000	.0000	.0000
49	0.1150	-5.384	0.00	-5.38	-0.14	0.0	-0.1	5.4	181.4	.0000	.0000	.0000
50	0.1175	-5.603	0.00	-5.60	0.86	0.0	0.9	5.7	171.3	.0000	.0000	.0000
51	0.1200	-5.765	0.00	-5.76	1.83	0.0	1.8	6.0	162.4	.0000	.0000	.0000
52	0.1225	-5.834	0.00	-5.83	2.68	0.0	2.7	6.4	155.3	.0000	.0000	.0000
53	0.1250	-5.728	0.00	-5.73	3.34	0.0	3.3	6.6	149.7	.0000	.0000	.0000
54	0.1275	-5.426	0.00	-5.43	3.57	0.0	3.6	6.5	146.6	.0000	.0000	.0000
55	0.1300	-4.707	0.00	-4.71	3.34	0.0	3.3	5.8	144.6	.0000	.0000	.0000

Force 2a1 Spreadsheet 1

VALUES		Row	t (sec)	t(sec)	Rho(deg)	Beta (deg)	Theta (rad)	Theta(deg)
M (kg) =	0.1621	1	0.000	0.130	199.7	-96.3	2.25	128.9
r (m) =	0.034	2	0.003	0.133	199.7	-96.3	2.25	128.9
Rho [(init), deg] =	199.72	3	0.005	0.135	199.6	-96.2	2.25	128.8
Thetha (rad) =	2.25	4	0.008	0.138	199.5	-96.1	2.25	128.7
Time (sec) =	0.18	5	0.010	0.140	199.3	-95.9	2.24	128.5
Alpha (rad/s/s) =	138.9	6	0.013	0.143	199.1	-95.7	2.24	128.3
		7	0.015	0.145	198.8	-95.4	2.23	128.0
		8	0.018	0.148	198.5	-95.1	2.23	127.7
		9	0.020	0.150	198.1	-94.7	2.22	127.3
		10	0.023	0.153	197.7	-94.3	2.21	126.9
		11	0.025	0.155	197.2	-93.8	2.21	126.4
		12	0.028	0.158	196.7	-93.3	2.20	125.9
		13	0.030	0.160	196.1	-92.7	2.19	125.3
		14	0.033	0.163	195.5	-92.1	2.18	124.7
		15	0.035	0.165	194.8	-91.4	2.16	124.0
		16	0.038	0.168	194.1	-90.7	2.15	123.3
		17	0.040	0.170	193.4	-90.0	2.14	122.5
		18	0.043	0.173	192.5	-89.1	2.12	121.7
		19	0.045	0.175	191.7	-88.3	2.11	120.9
		20	0.048	0.178	190.7	-87.3	2.09	119.9
		21	0.050	0.180	189.8	-86.4	2.08	119.0
		22	0.053	0.183	188.8	-85.4	2.06	117.9
		23	0.055	0.185	187.7	-84.3	2.04	116.9
		24	0.058	0.188	186.6	-83.2	2.02	115.8
		25	0.060	0.190	185.4	-82.0	2.00	114.6
		26	0.063	0.193	184.2	-80.8	1.98	113.4
		27	0.065	0.195	182.9	-79.5	1.96	112.1
		28	0.068	0.198	181.6	-78.2	1.93	110.8
		29	0.070	0.200	180.2	-76.8	1.91	109.4
		30	0.073	0.203	178.8	-75.4	1.88	108.0
		31	0.075	0.205	177.3	-73.9	1.86	106.5
		32	0.078	0.208	175.8	-72.4	1.83	105.0
		33	0.080	0.210	174.3	-70.9	1.81	103.5
		34	0.083	0.213	172.6	-69.2	1.78	101.8
		35	0.085	0.215	171.0	-67.6	1.75	100.2
		36	0.088	0.218	169.3	-65.9	1.72	98.5
		37	0.090	0.220	167.5	-64.1	1.69	96.7
		38	0.093	0.223	165.7	-62.3	1.66	94.9
		39	0.095	0.225	163.8	-60.4	1.62	93.0
		40	0.098	0.228	161.9	-58.5	1.59	91.1
		41	0.100	0.230	159.9	-56.5	1.56	89.1
		42	0.103	0.233	157.9	-54.5	1.52	87.1
		43	0.105	0.235	155.9	-52.5	1.48	85.0
		44	0.108	0.238	153.7	-50.3	1.45	82.9
		45	0.110	0.240	151.6	-48.2	1.41	80.8
		46	0.113	0.243	149.4	-46.0	1.37	78.6
		47	0.115	0.245	147.1	-43.7	1.33	76.3
		48	0.118	0.248	144.8	-41.4	1.29	74.0
		49	0.120	0.250	142.4	-39.0	1.25	71.6
		50	0.123	0.253	140.0	-36.6	1.21	69.2
		51	0.125	0.255	137.6	-34.2	1.16	66.7
		52	0.128	0.258	135.0	-31.6	1.12	64.2
		53	0.130	0.260	132.5	-29.1	1.08	61.7
		54	0.133	0.263	129.9	-26.5	1.03	59.1
		55	0.135	0.265	127.2	-23.8	0.98	56.4
		56	0.138	0.268	124.5	-21.1	0.94	53.7
		57	0.140	0.270	121.7	-18.3	0.89	50.9
		58	0.143	0.273	118.9	-15.5	0.84	48.1
		59	0.145	0.275	116.1	-12.7	0.79	45.3
		60	0.148	0.278	113.2	-9.8	0.74	42.4
		61	0.150	0.280	110.2	-6.8	0.69	39.4
		62	0.153	0.283	107.2	-3.8	0.63	36.4
		63	0.155	0.285	104.1	-0.7	0.58	33.3
		64	0.158	0.288	101.0	2.4	0.53	30.2
		65	0.160	0.290	97.9	5.5	0.47	27.1
		66	0.163	0.293	94.7	8.7	0.42	23.8
		67	0.165	0.295	91.4	12.0	0.36	20.6
		68	0.168	0.298	88.1	15.3	0.30	17.3
		69	0.170	0.300	84.7	18.7	0.24	13.9
		70	0.173	0.303	81.3	22.1	0.18	10.5
		71	0.175	0.305	77.9	25.5	0.12	7.1
		72	0.178	0.308	74.4	29.0	0.06	3.6
		73	0.180	0.310	70.8	32.6	0.00	0.0

Force 2a1 Spreadsheet 2

Row	Fn2a1(N)	Ft2a1(N)	F2a1 (N)	Phi (deg)	Delta(deg)	Fx2a1 (N)	Fy2a1 (N)
1	-0.088	1.173	1.2	-85.7	140.23	-0.9	0.8
2	-0.087	1.173	1.2	-85.8	140.26	-0.9	0.8
3	-0.085	1.173	1.2	-85.8	140.33	-0.9	0.8
4	-0.083	1.173	1.2	-86.0	140.46	-0.9	0.7
5	-0.079	1.174	1.2	-86.1	140.63	-0.9	0.7
6	-0.075	1.174	1.2	-86.4	140.85	-0.9	0.7
7	-0.069	1.174	1.2	-86.6	141.13	-0.9	0.7
8	-0.063	1.175	1.2	-87.0	141.45	-0.9	0.7
9	-0.055	1.175	1.2	-87.3	141.82	-0.9	0.7
10	-0.046	1.176	1.2	-87.7	142.25	-0.9	0.7
11	-0.037	1.176	1.2	-88.2	142.72	-0.9	0.7
12	-0.026	1.177	1.2	-88.7	143.24	-0.9	0.7
13	-0.014	1.177	1.2	-89.3	143.81	-0.9	0.7
14	-0.001	1.177	1.2	-89.9	144.44	-1.0	0.7
15	0.012	1.178	1.2	89.4	145.11	-1.0	0.7
16	0.027	1.178	1.2	88.7	145.83	-1.0	0.7
17	0.043	1.178	1.2	87.9	146.60	-1.0	0.6
18	0.060	1.178	1.2	87.1	147.42	-1.0	0.6
19	0.078	1.177	1.2	86.2	148.29	-1.0	0.6
20	0.097	1.177	1.2	85.3	149.20	-1.0	0.6
21	0.117	1.176	1.2	84.3	150.17	-1.0	0.6
22	0.138	1.175	1.2	83.3	151.18	-1.0	0.6
23	0.160	1.174	1.2	82.3	152.24	-1.0	0.6
24	0.183	1.172	1.2	81.2	153.35	-1.1	0.5
25	0.206	1.170	1.2	80.0	154.50	-1.1	0.5
26	0.231	1.168	1.2	78.8	155.70	-1.1	0.5
27	0.257	1.165	1.2	77.6	156.95	-1.1	0.5
28	0.284	1.161	1.2	76.3	158.24	-1.1	0.4
29	0.311	1.157	1.2	74.9	159.57	-1.1	0.4
30	0.340	1.152	1.2	73.6	160.94	-1.1	0.4
31	0.369	1.147	1.2	72.1	162.36	-1.1	0.4
32	0.400	1.141	1.2	70.7	163.81	-1.2	0.3
33	0.431	1.134	1.2	69.2	165.31	-1.2	0.3
34	0.463	1.126	1.2	67.7	166.84	-1.2	0.3
35	0.495	1.118	1.2	66.1	168.40	-1.2	0.2
36	0.529	1.108	1.2	64.5	170.00	-1.2	0.2
37	0.563	1.098	1.2	62.9	171.64	-1.2	0.2
38	0.597	1.087	1.2	61.2	173.30	-1.2	0.1
39	0.632	1.074	1.2	59.5	174.99	-1.2	0.1
40	0.668	1.061	1.3	57.8	176.71	-1.3	0.1
41	0.704	1.046	1.3	56.0	178.45	-1.3	0.0
42	0.741	1.030	1.3	54.3	180.22	-1.3	0.0
43	0.778	1.013	1.3	52.5	182.01	-1.3	0.0
44	0.815	0.995	1.3	50.7	183.81	-1.3	-0.1
45	0.852	0.975	1.3	48.9	185.64	-1.3	-0.1
46	0.889	0.954	1.3	47.0	187.47	-1.3	-0.2
47	0.926	0.932	1.3	45.2	189.32	-1.3	-0.2
48	0.963	0.908	1.3	43.3	191.19	-1.3	-0.3
49	1.000	0.883	1.3	41.4	193.06	-1.3	-0.3
50	1.037	0.857	1.3	39.6	194.93	-1.3	-0.3
51	1.073	0.829	1.4	37.7	196.82	-1.3	-0.4
52	1.109	0.800	1.4	35.8	198.70	-1.3	-0.4
53	1.144	0.769	1.4	33.9	200.59	-1.3	-0.5
54	1.178	0.737	1.4	32.0	202.47	-1.3	-0.5
55	1.212	0.704	1.4	30.1	204.36	-1.3	-0.6
56	1.244	0.669	1.4	28.3	206.24	-1.3	-0.6
57	1.276	0.633	1.4	26.4	208.11	-1.3	-0.7
58	1.306	0.596	1.4	24.5	209.98	-1.2	-0.7
59	1.335	0.557	1.4	22.7	211.84	-1.2	-0.8
60	1.362	0.517	1.5	20.8	213.70	-1.2	-0.8
61	1.388	0.477	1.5	19.0	215.54	-1.2	-0.9
62	1.411	0.435	1.5	17.1	217.36	-1.2	-0.9
63	1.434	0.393	1.5	15.3	219.18	-1.2	-0.9
64	1.454	0.350	1.5	13.5	220.97	-1.1	-1.0
65	1.472	0.306	1.5	11.7	222.76	-1.1	-1.0
66	1.488	0.262	1.5	10.0	224.52	-1.1	-1.1
67	1.501	0.217	1.5	8.2	226.26	-1.0	-1.1
68	1.513	0.173	1.5	6.5	227.98	-1.0	-1.1
69	1.521	0.128	1.5	4.8	229.68	-1.0	-1.2
70	1.528	0.084	1.5	3.1	231.36	-1.0	-1.2
71	1.531	0.040	1.5	1.5	233.00	-0.9	-1.2
72	1.533	-0.003	1.5	-0.1	234.62	-0.9	-1.2
73	1.531	-0.046	1.5	-1.7	236.21	-0.9	-1.3

Force 2b1 Spreadsheet 1

VALUES		Row	t1(sec)	t(sec)	Theta(deg)	Gamma(inst)	epsilon(deg)	Fn2b1 (N)
		2						
M (kg) =	0.1621	3	0.0000	0.1300	128.9	110.0	109.0	0.3
r (m) =	0.07316	4	0.0025	0.1325	128.9	109.9	109.0	0.3
Gamma(init)deg=	110.0	5	0.0050	0.1350	128.8	109.9	109.0	0.3
Theta final(deg)	128.9	6	0.0075	0.1375	128.7	109.7	109.0	0.3
		7	0.0100	0.1400	128.5	109.6	109.0	0.3
		8	0.0125	0.1425	128.3	109.3	109.0	0.3
Time (s) =	0.175	9	0.0150	0.1450	128.0	109.1	109.0	0.3
Alpha (rad/s/s)=	138.9	10	0.0175	0.1475	127.7	108.7	109.0	0.3
		11	0.0200	0.1500	127.3	108.4	109.0	0.3
		12	0.0225	0.1525	126.9	107.9	109.0	0.3
		13	0.0250	0.1550	126.4	107.5	109.0	0.3
		14	0.0275	0.1575	125.9	107.0	109.0	0.3
		15	0.0300	0.1600	125.3	106.4	109.0	0.4
		16	0.0325	0.1625	124.7	105.8	109.0	0.4
		17	0.0350	0.1650	124.0	105.1	109.0	0.4
		18	0.0375	0.1675	123.3	104.4	109.0	0.4
		19	0.0400	0.1700	122.5	103.6	109.0	0.4
		20	0.0425	0.1725	121.7	102.8	109.0	0.5
		21	0.0450	0.1750	120.8	101.9	109.0	0.5
		22	0.0475	0.1775	119.9	101.0	109.0	0.5
		23	0.0500	0.1800	119.0	100.0	109.0	0.5
		24	0.0525	0.1825	117.9	99.0	109.0	0.6
		25	0.0550	0.1850	116.9	97.9	109.0	0.6
		26	0.0575	0.1875	115.7	96.8	109.0	0.6
		27	0.0600	0.1900	114.6	95.6	109.0	0.7
		28	0.0625	0.1925	113.4	94.4	109.0	0.7
		29	0.0650	0.1950	112.1	93.1	109.0	0.7
		30	0.0675	0.1975	110.8	91.8	109.0	0.8
		31	0.0700	0.2000	109.4	90.5	109.0	0.8
		32	0.0725	0.2025	108.0	89.0	109.0	0.9
		33	0.0750	0.2050	106.5	87.6	109.0	0.9
		34	0.0775	0.2075	105.0	86.1	109.0	0.9
		35	0.0800	0.2100	103.4	84.5	109.0	1.0
		36	0.0825	0.2125	101.8	82.9	109.0	1.0
		37	0.0850	0.2150	100.2	81.2	109.0	1.1
		38	0.0875	0.2175	98.4	79.5	109.0	1.1
		39	0.0900	0.2200	96.7	77.7	109.0	1.2
		40	0.0925	0.2225	94.9	75.9	109.0	1.2
		41	0.0950	0.2250	93.0	74.0	109.0	1.3
		42	0.0975	0.2275	91.1	72.1	109.0	1.3
		43	0.1000	0.2300	89.1	70.2	109.0	1.4
		44	0.1025	0.2325	87.1	68.2	109.0	1.5
		45	0.1050	0.2350	85.0	66.1	109.0	1.5
		46	0.1075	0.2375	82.9	64.0	109.0	1.6
		47	0.1100	0.2400	80.8	61.8	109.0	1.6
		48	0.1125	0.2425	78.5	59.6	109.0	1.7
		49	0.1150	0.2450	76.3	57.3	109.0	1.8
		50	0.1175	0.2475	74.0	55.0	109.0	1.8
		51	0.1200	0.2500	71.6	52.7	109.0	1.9
		52	0.1225	0.2525	69.2	50.2	109.0	2.0
		53	0.1250	0.2550	66.7	47.8	109.0	2.0
		54	0.1275	0.2575	64.2	45.3	109.0	2.1
		55	0.1300	0.2600	61.7	42.7	109.0	2.2
		56	0.1325	0.2625	59.0	40.1	106.3	2.2
		57	0.1350	0.2650	56.4	40.1	103.7	2.3
		58	0.1375	0.2675	53.7	40.1	101.0	2.3
		59	0.1400	0.2700	50.9	40.1	98.2	2.4
		60	0.1425	0.2725	48.1	40.1	95.4	2.4
		61	0.1450	0.2750	45.2	40.1	92.5	2.4
		62	0.1475	0.2775	42.3	40.1	89.6	2.5
		63	0.1500	0.2800	39.4	40.1	86.7	2.5
		64	0.1525	0.2825	36.4	40.1	83.7	2.6
		65	0.1550	0.2850	33.3	40.1	80.6	2.6
		66	0.1575	0.2875	30.2	40.1	77.5	2.7
		67	0.1600	0.2900	27.0	40.1	74.3	2.7
		68	0.1625	0.2925	23.8	40.1	71.1	2.8
		69	0.1650	0.2950	20.6	40.1	67.9	2.8
		70	0.1675	0.2975	17.3	40.1	64.6	2.9
		71	0.1700	0.3000	13.9	40.1	61.2	2.9
		72	0.1725	0.3025	10.5	40.1	57.8	3.0
		73	0.1750	0.3050	7.0	40.1	54.3	3.0

Force 2b1 Spreadsheet 2

Row	Ft2b1 (N)	F2b1(N)	Phi2b1 (deg)	Delta2b1(deg)	FX2b1(N)	FY2b1(N)	omega2b1(rad/s)
2							
3	0.07	0.3	15.5	54.5	0.2	0.2	0.0
4	0.07	0.3	15.5	54.6	0.2	0.2	0.3
5	0.07	0.3	15.3	54.8	0.2	0.2	0.7
6	0.07	0.3	15.1	55.1	0.2	0.2	1.0
7	0.07	0.3	14.9	55.6	0.2	0.2	1.4
8	0.07	0.3	14.5	56.1	0.2	0.2	1.7
9	0.07	0.3	14.2	56.8	0.2	0.2	2.1
10	0.07	0.3	13.7	57.5	0.2	0.3	2.4
11	0.07	0.3	13.3	58.4	0.2	0.3	2.8
12	0.07	0.3	12.8	59.3	0.2	0.3	3.1
13	0.07	0.3	12.3	60.3	0.2	0.3	3.5
14	0.07	0.4	11.7	61.3	0.2	0.3	3.8
15	0.07	0.4	11.2	62.4	0.2	0.3	4.2
16	0.07	0.4	10.7	63.5	0.2	0.3	4.5
17	0.07	0.4	10.2	64.7	0.2	0.4	4.9
18	0.07	0.4	9.7	65.9	0.2	0.4	5.2
19	0.07	0.4	9.2	67.2	0.2	0.4	5.6
20	0.07	0.5	8.8	68.5	0.2	0.4	5.9
21	0.07	0.5	8.3	69.8	0.2	0.5	6.3
22	0.07	0.5	7.9	71.1	0.2	0.5	6.6
23	0.07	0.5	7.5	72.5	0.2	0.5	6.9
24	0.07	0.6	7.1	73.9	0.2	0.6	7.3
25	0.07	0.6	6.8	75.3	0.2	0.6	7.6
26	0.07	0.6	6.4	76.8	0.1	0.6	8.0
27	0.07	0.7	6.1	78.3	0.1	0.7	8.3
28	0.07	0.7	5.8	79.8	0.1	0.7	8.7
29	0.07	0.7	5.5	81.3	0.1	0.7	9.0
30	0.07	0.8	5.3	82.9	0.1	0.8	9.4
31	0.07	0.8	5.0	84.5	0.1	0.8	9.7
32	0.07	0.9	4.8	86.2	0.1	0.9	10.1
33	0.07	0.9	4.5	87.9	0.0	0.9	10.4
34	0.07	0.9	4.3	89.6	0.0	0.9	10.8
35	0.07	1.0	4.1	91.4	0.0	1.0	11.1
36	0.07	1.0	4.0	93.2	-0.1	1.0	11.5
37	0.07	1.1	3.8	95.0	-0.1	1.1	11.8
38	0.07	1.1	3.6	96.9	-0.1	1.1	12.2
39	0.07	1.2	3.5	98.8	-0.2	1.2	12.5
40	0.07	1.2	3.3	100.8	-0.2	1.2	12.8
41	0.07	1.3	3.2	102.8	-0.3	1.3	13.2
42	0.07	1.3	3.0	104.8	-0.3	1.3	13.5
43	0.07	1.4	2.9	106.9	-0.4	1.3	13.9
44	0.07	1.5	2.8	109.0	-0.5	1.4	14.2
45	0.07	1.5	2.7	111.2	-0.6	1.4	14.6
46	0.07	1.6	2.6	113.4	-0.6	1.5	14.9
47	0.07	1.6	2.5	115.7	-0.7	1.5	15.3
48	0.07	1.7	2.4	118.0	-0.8	1.5	15.6
49	0.07	1.8	2.3	120.3	-0.9	1.5	16.0
50	0.07	1.8	2.2	122.7	-1.0	1.5	16.3
51	0.07	1.9	2.2	125.2	-1.1	1.6	16.7
52	0.07	2.0	2.1	127.7	-1.2	1.6	17.0
53	0.07	2.0	2.0	130.2	-1.3	1.6	17.4
54	0.07	2.1	1.9	132.8	-1.4	1.6	17.7
55	0.07	2.2	1.9	135.4	-1.6	1.5	18.1
56	0.06	2.2	1.6	138.3	-1.7	1.5	18.4
57	0.05	2.3	1.3	138.6	-1.7	1.5	18.8
58	0.04	2.3	1.1	138.8	-1.7	1.5	19.1
59	0.04	2.4	0.9	139.0	-1.8	1.5	19.4
60	0.03	2.4	0.8	139.1	-1.8	1.6	19.8
61	0.03	2.4	0.7	139.2	-1.8	1.6	20.1
62	0.03	2.5	0.7	139.2	-1.9	1.6	20.5
63	0.03	2.5	0.7	139.2	-1.9	1.7	20.8
64	0.03	2.6	0.7	139.2	-1.9	1.7	21.2
65	0.04	2.6	0.9	139.0	-2.0	1.7	21.5
66	0.05	2.7	1.0	138.9	-2.0	1.8	21.9
67	0.06	2.7	1.2	138.7	-2.0	1.8	22.2
68	0.07	2.8	1.5	138.4	-2.1	1.8	22.6
69	0.09	2.8	1.8	138.1	-2.1	1.9	22.9
70	0.11	2.9	2.1	137.8	-2.1	1.9	23.3
71	0.13	2.9	2.5	137.4	-2.2	2.0	23.6
72	0.15	3.0	2.9	137.0	-2.2	2.0	24.0
73	0.18	3.0	3.3	136.6	-2.2	2.1	24.3

Force 2c1 spreadsheet 1

		Row	t(sec)	theta(deg)	Gamma(inst)	pt(mm)	Lin.vel(m/s)	lin..acc.(m/s/s)	delta(deg)	F(N)
		2								
M (kg) =	0.1621	3	0.1300	0.0	110.0	0.0	0.00	7.4	208	0.973
r (m) =	0.07316	4	0.1325	0.0	109.9	0.0	0.02	7.4	208	0.973
Theta(init)deg=	157.216	5	0.1350	0.1	109.9	0.1	0.04	7.4	208	0.974
Theta init(rad)	2.25	6	0.1375	0.2	109.7	0.1	0.06	7.4	208	0.976
		7	0.1400	0.4	109.6	0.2	0.07	7.4	208	0.978
		8	0.1425	0.6	109.3	0.3	0.09	7.4	208	0.981
Time (s) =	0.175	9	0.1450	0.9	109.1	0.5	0.11	7.4	208	0.984
Alpha (rad/s/s)=	138.9	10	0.1475	1.2	108.7	0.7	0.13	7.4	208	0.988
		11	0.1500	1.6	108.4	0.9	0.15	7.4	208	0.993
		12	0.1525	2.0	107.9	1.1	0.17	7.4	208	0.998
		13	0.1550	2.5	107.5	1.3	0.19	7.4	208	1.003
		14	0.1575	3.0	107.0	1.6	0.20	7.4	208	1.009
		15	0.1600	3.6	106.4	1.9	0.22	7.4	208	1.016
		16	0.1625	4.2	105.8	2.3	0.24	7.4	208	1.024
		17	0.1650	4.9	105.1	2.6	0.26	7.4	208	1.031
		18	0.1675	5.6	104.4	3.0	0.28	7.4	208	1.040
		19	0.1700	6.4	103.6	3.4	0.30	7.4	208	1.049
		20	0.1725	7.2	102.8	3.9	0.31	7.4	208	1.058
		21	0.1750	8.1	101.9	4.4	0.33	7.4	208	1.068
		22	0.1775	9.0	101.0	4.8	0.35	7.4	208	1.078
		23	0.1800	9.9	100.0	5.4	0.37	7.4	141	0.08
		24	0.1825	11.0	99.0	5.9	0.39	7.4	141	0.09
		25	0.1850	12.0	97.9	6.5	0.41	7.4	141	0.10
		26	0.1875	13.2	96.8	7.1	0.43	7.4	141	0.11
		27	0.1900	14.3	95.6	7.7	0.44	7.4	141	0.12
		28	0.1925	15.5	94.4	8.4	0.46	7.4	141	0.14
		29	0.1950	16.8	93.1	9.1	0.48	7.4	141	0.15
		30	0.1975	18.1	91.8	9.8	0.50	7.4	141	0.17
		31	0.2000	19.5	90.5	10.5	0.52	7.4	141	0.18
		32	0.2025	20.9	89.0	11.3	0.54	7.4	141	0.20
		33	0.2050	22.4	87.6	12.1	0.56	7.4	141	0.22
		34	0.2075	23.9	86.1	12.9	0.57	7.4	141	0.24
		35	0.2100	25.5	84.5	13.8	0.59	7.4	141	0.26
		36	0.2125	27.1	82.9	14.6	0.61	7.4	141	0.28
		37	0.2150	28.7	81.2	15.5	0.63	7.4	141	0.30
		38	0.2175	30.5	79.5	16.5	0.65	7.4	141	0.32
		39	0.2200	32.2	77.7	17.4	0.67	7.4	141	0.34
		40	0.2225	34.0	75.9	18.4	0.68	7.4	141	0.37
		41	0.2250	35.9	74.0	19.4	0.70	7.4	141	0.39
		42	0.2275	37.8	72.1	20.4	0.72	7.4	141	0.42
		43	0.2300	39.8	70.2	21.5	0.74	7.4	141	0.45
		44	0.2325	41.8	68.2	22.6	0.76	7.4	141	0.47
		45	0.2350	43.9	66.1	23.7	0.78	7.4	141	0.50
		46	0.2375	46.0	64.0	24.8	0.80	7.4	141	0.53
		47	0.2400	48.1	61.8	26.0	0.81	7.4	141	0.56
		48	0.2425	50.4	59.6	27.2	0.83	7.4	141	0.59
		49	0.2450	52.6	57.3	28.4	0.85	7.4	141	0.62
		50	0.2475	54.9	55.0	29.7	0.87	7.4	141	0.65
		51	0.2500	57.3	52.7	30.9	0.89	7.4	141	0.69
		52	0.2525	59.7	50.2	32.2	0.91	7.4	141	0.72
		53	0.2550	62.2	47.8	33.6	0.93	7.4	141	0.75
		54	0.2575	64.7	45.3	34.9	0.94	7.4	141	0.79
		55	0.2600	67.2	42.7	36.3	0.96	7.4	141	0.82
		56	0.2625	69.9	40.1	37.7	0.98	7.4	141	0.86
		57	0.2650	72.5	40.1	37.7	1.00	7.4	141	0.89
		58	0.2675	75.2	40.1	37.7	1.02	7.4	141	0.93
		59	0.2700	78.0	40.1	37.7	1.04	7.4	141	0.96
		60	0.2725	80.8	40.1	37.7	1.05	7.4	141	1.00
		61	0.2750	83.7	40.1	37.7	1.07	7.4	141	1.03
		62	0.2775	86.6	40.1	37.7	1.09	7.4	141	1.06
		63	0.2800	89.5	40.1	37.7	1.11	7.4	141	1.10
		64	0.2825	92.5	40.1	37.7	1.13	7.4	141	1.13
		65	0.2850	95.6	40.1	37.7	1.15	7.4	141	1.16
		66	0.2875	98.7	40.1	37.7	1.17	7.4	141	1.19
		67	0.2900	101.9	40.1	37.7	1.18	7.4	141	1.22
		68	0.2925	105.1	40.1	37.7	1.20	7.4	141	1.24
		69	0.2950	108.3	40.1	37.7	1.22	7.4	141	1.27
		70	0.2975	111.6	40.1	37.7	1.24	7.4	141	1.29
		71	0.3000	115.0	40.1	37.7	1.26	7.4	141	1.31
		72	0.3025	118.4	40.1	37.7	1.28	7.4	141	1.33
		73	0.3050	121.9	40.1	37.7	1.30	7.4	141	1.35

Force 2c1 spreadsheet 2

Row	Fx2c1(N)	Fy2c1(N)	t(sec)	Theta(deg)	Gamma(inst)	P.T.
2						
3	-0.86	-0.5	0.13	128.9	109.96	37.7
4	-0.86	-0.5	0.1325	125.4	109.94	36.3
5	-0.86	-0.5	0.135	121.9	109.86	34.9
6	-0.86	-0.5	0.1375	118.4	109.74	33.6
7	-0.86	-0.5	0.14	115.0	109.56	32.2
8	-0.87	-0.5	0.1425	111.6	109.34	30.9
9	-0.87	-0.5	0.145	108.3	109.07	29.7
10	-0.87	-0.5	0.1475	105.1	108.74	28.4
11	-0.88	-0.5	0.15	101.9	108.37	27.2
12	-0.88	-0.5	0.1525	98.7	107.95	26.0
13	-0.89	-0.5	0.155	95.6	107.47	24.8
14	-0.89	-0.5	0.1575	92.5	106.95	23.7
15	-0.90	-0.5	0.16	89.5	106.38	22.6
16	-0.90	-0.5	0.1625	86.6	105.76	21.5
17	-0.91	-0.5	0.165	83.7	105.09	20.4
18	-0.92	-0.5	0.1675	80.8	104.37	19.4
19	-0.93	-0.5	0.17	78.0	103.59	18.4
20	-0.9	-0.5	0.1725	75.2	102.77	17.4
21	-0.9	-0.5	0.175	72.5	101.90	16.5
22	-1.0	-0.5	0.1775	69.9	100.98	15.5
23	-0.1	0.0	0.18	67.2	100.01	14.6
24	-0.1	0.1	0.1825	64.7	98.99	13.8
25	-0.1	0.1	0.185	62.2	97.92	12.9
26	-0.1	0.1	0.1875	59.7	96.80	12.1
27	-0.1	0.1	0.19	57.3	95.64	11.3
28	-0.1	0.1	0.1925	54.9	94.42	10.5
29	-0.1	0.1	0.195	52.6	93.15	9.8
30	-0.1	0.1	0.1975	50.4	91.83	9.1
31	-0.1	0.1	0.2	48.1	90.46	8.4
32	-0.2	0.1	0.2025	46.0	89.05	7.7
33	-0.2	0.1	0.205	43.9	87.58	7.1
34	-0.2	0.1	0.2075	41.8	86.06	6.5
35	-0.2	0.2	0.21	39.8	84.49	5.9
36	-0.2	0.2	0.2125	37.8	82.88	5.4
37	-0.2	0.2	0.215	35.9	81.21	4.8
38	-0.2	0.2	0.2175	34.0	79.50	4.4
39	-0.3	0.2	0.22	32.2	77.73	3.9
40	-0.3	0.2	0.2225	30.5	75.91	3.4
41	-0.3	0.2	0.225	28.7	74.05	3.0
42	-0.3	0.3	0.2275	27.1	72.13	2.6
43	-0.3	0.3	0.23	25.5	70.17	2.3
44	-0.4	0.3	0.2325	23.9	68.15	1.9
45	-0.4	0.3	0.235	22.4	66.09	1.6
46	-0.4	0.3	0.2375	20.9	63.98	1.3
47	-0.4	0.4	0.24	19.5	61.81	1.1
48	-0.5	0.4	0.2425	18.1	59.60	0.9
49	-0.5	0.4	0.245	16.8	57.34	0.7
50	-0.5	0.4	0.2475	15.5	55.02	0.5
51	-0.5	0.4	0.25	14.3	52.66	0.3
52	-0.6	0.5	0.2525	13.2	50.25	0.2
53	-0.6	0.5	0.255	12.0	47.79	0.1
54	-0.6	0.5	0.2575	11.0	45.27	0.1
55	-0.6	0.5	0.26	9.9	42.71	0.0
56	-0.7	0.5	0.2625	9.0	40.10	0.0
57	-0.7	0.6	0.265	8.1	40.10	0.0
58	-0.7	0.6	0.2675	7.2	40.10	0.0
59	-0.7	0.6	0.27	6.4	40.10	0.0
60	-0.8	0.6	0.2725	5.6	40.10	0.0
61	-0.8	0.6	0.275	4.9	40.10	0.0
62	-0.8	0.7	0.2775	4.2	40.10	0.0
63	-0.9	0.7	0.28	3.6	40.10	0.0
64	-0.9	0.7	0.2825	3.0	40.10	0.0
65	-0.9	0.7	0.285	2.5	40.10	0.0
66	-0.9	0.7	0.2875	2.0	40.10	0.0
67	-0.9	0.8	0.29	1.6	40.10	0.0
68	-1.0	0.8	0.2925	1.2	40.10	0.0
69	-1.0	0.8	0.295	0.9	40.10	0.0
70	-1.0	0.8	0.2975	0.6	40.10	0.0
71	-1.0	0.8	0.3	0.4	40.10	0.0
72	-1.0	0.8	0.3025	0.2	40.10	0.0
73	-1.0	0.9	0.305	0.1	40.10	0.0

Final force 3 spreadsheet

Row	t (sec)	Fx2a1 (N)	Fy2a1 (N)	Fx2c1(N)	Fy2c1(N)	Fx(total)	Fy(total)	Ffinal(N)	Delta final(deg)
1	0.130	-0.904	0.752	-0.9	-0.5	-1.763	0.296	1.788	170.485
2	0.133	-0.904	0.752	-0.9	-0.5	-1.764	0.295	1.788	170.505
3	0.135	-0.905	0.751	-0.9	-0.5	-1.766	0.293	1.790	170.565
4	0.138	-0.907	0.749	-0.9	-0.5	-1.769	0.291	1.792	170.666
5	0.140	-0.909	0.746	-0.9	-0.5	-1.773	0.287	1.796	170.805
6	0.143	-0.912	0.743	-0.9	-0.5	-1.778	0.282	1.800	170.984
7	0.145	-0.916	0.738	-0.9	-0.5	-1.785	0.276	1.806	171.202
8	0.148	-0.920	0.733	-0.9	-0.5	-1.792	0.269	1.812	171.457
9	0.150	-0.925	0.727	-0.9	-0.5	-1.801	0.261	1.820	171.750
10	0.153	-0.930	0.720	-0.9	-0.5	-1.811	0.252	1.828	172.079
11	0.155	-0.936	0.713	-0.9	-0.5	-1.822	0.242	1.838	172.444
12	0.158	-0.943	0.704	-0.9	-0.5	-1.834	0.230	1.849	172.843
13	0.160	-0.950	0.695	-0.9	-0.5	-1.847	0.218	1.860	173.276
14	0.163	-0.958	0.685	-0.9	-0.5	-1.861	0.204	1.873	173.741
15	0.165	-0.966	0.674	-0.9	-0.5	-1.877	0.189	1.886	174.237
16	0.168	-0.975	0.662	-0.9	-0.5	-1.893	0.174	1.901	174.762
17	0.170	-0.984	0.649	-0.9	-0.5	-1.910	0.156	1.916	175.316
18	0.173	-0.994	0.635	-0.9	-0.5	-1.928	0.138	1.933	175.896
19	0.175	-1.004	0.620	-0.9	-0.5	-1.947	0.119	1.950	176.502
20	0.178	-1.014	0.605	-1.0	-0.5	-1.966	0.098	1.969	177.133
21	0.180	-1.025	0.588	-0.1	0.0	-1.086	0.637	1.259	149.605
22	0.183	-1.037	0.570	-0.1	0.1	-1.105	0.626	1.270	150.476
23	0.185	-1.048	0.552	-0.1	0.1	-1.126	0.615	1.283	151.372
24	0.188	-1.060	0.532	-0.1	0.1	-1.147	0.603	1.296	152.290
25	0.190	-1.072	0.511	-0.1	0.1	-1.170	0.590	1.310	153.227
26	0.193	-1.085	0.490	-0.1	0.1	-1.193	0.577	1.325	154.181
27	0.195	-1.097	0.467	-0.1	0.1	-1.216	0.563	1.340	155.150
28	0.198	-1.110	0.443	-0.1	0.1	-1.241	0.549	1.357	156.130
29	0.200	-1.123	0.418	-0.1	0.1	-1.266	0.534	1.374	157.120
30	0.203	-1.135	0.392	-0.2	0.1	-1.292	0.519	1.392	158.116
31	0.205	-1.148	0.365	-0.2	0.1	-1.318	0.503	1.411	159.117
32	0.208	-1.161	0.337	-0.2	0.1	-1.346	0.487	1.431	160.120
33	0.210	-1.173	0.308	-0.2	0.2	-1.373	0.470	1.451	161.124
34	0.213	-1.186	0.277	-0.2	0.2	-1.401	0.452	1.472	162.125
35	0.215	-1.198	0.246	-0.2	0.2	-1.430	0.434	1.494	163.122
36	0.218	-1.209	0.213	-0.2	0.2	-1.459	0.415	1.517	164.114
37	0.220	-1.221	0.179	-0.3	0.2	-1.488	0.396	1.540	165.098
38	0.223	-1.231	0.145	-0.3	0.2	-1.517	0.376	1.563	166.073
39	0.225	-1.242	0.109	-0.3	0.2	-1.547	0.356	1.588	167.037
40	0.228	-1.251	0.072	-0.3	0.3	-1.577	0.335	1.612	167.990
41	0.230	-1.261	0.034	-0.3	0.3	-1.607	0.314	1.637	168.931
42	0.233	-1.269	-0.005	-0.4	0.3	-1.636	0.293	1.662	169.858
43	0.235	-1.276	-0.045	-0.4	0.3	-1.666	0.271	1.688	170.770
44	0.238	-1.283	-0.085	-0.4	0.3	-1.695	0.248	1.713	171.667
45	0.240	-1.289	-0.127	-0.4	0.4	-1.724	0.225	1.739	172.549
46	0.243	-1.293	-0.170	-0.5	0.4	-1.753	0.202	1.764	173.415
47	0.245	-1.297	-0.213	-0.5	0.4	-1.780	0.179	1.789	174.265
48	0.248	-1.299	-0.257	-0.5	0.4	-1.808	0.155	1.814	175.099
49	0.250	-1.300	-0.301	-0.5	0.4	-1.834	0.131	1.839	175.917
50	0.253	-1.300	-0.347	-0.6	0.5	-1.860	0.107	1.863	176.718
51	0.255	-1.298	-0.392	-0.6	0.5	-1.884	0.082	1.886	177.504
52	0.258	-1.295	-0.438	-0.6	0.5	-1.908	0.058	1.908	178.273
53	0.260	-1.291	-0.485	-0.6	0.5	-1.930	0.033	1.930	179.028
54	0.263	-1.284	-0.531	-0.7	0.5	-1.950	0.008	1.950	179.767
55	0.265	-1.277	-0.578	-0.7	0.6	-1.969	-0.017	1.970	180.492
56	0.268	-1.267	-0.625	-0.7	0.6	-1.987	-0.042	1.987	181.203
57	0.270	-1.256	-0.671	-0.7	0.6	-2.003	-0.066	2.004	181.900
58	0.273	-1.243	-0.717	-0.8	0.6	-2.016	-0.091	2.018	182.585
59	0.275	-1.228	-0.763	-0.8	0.6	-2.028	-0.115	2.031	183.258
60	0.278	-1.212	-0.808	-0.8	0.7	-2.038	-0.140	2.043	183.920
61	0.280	-1.194	-0.853	-0.9	0.7	-2.045	-0.164	2.052	184.571
62	0.283	-1.174	-0.896	-0.9	0.7	-2.050	-0.187	2.058	185.213
63	0.285	-1.152	-0.939	-0.9	0.7	-2.052	-0.210	2.063	185.846
64	0.288	-1.129	-0.980	-0.9	0.7	-2.052	-0.233	2.065	186.471
65	0.290	-1.104	-1.021	-0.9	0.8	-2.049	-0.255	2.065	187.090
66	0.293	-1.077	-1.059	-1.0	0.8	-2.044	-0.276	2.062	187.703
67	0.295	-1.049	-1.096	-1.0	0.8	-2.035	-0.297	2.057	188.311
68	0.298	-1.019	-1.131	-1.0	0.8	-2.024	-0.317	2.048	188.915
69	0.300	-0.988	-1.164	-1.0	0.8	-2.009	-0.337	2.037	189.518
70	0.303	-0.955	-1.195	-1.0	0.8	-1.992	-0.356	2.024	190.119
71	0.305	-0.922	-1.224	-1.0	0.9	-1.972	-0.373	2.007	190.720
72	0.308	-0.887	-1.250	-1.1	0.9	-1.949	-0.390	1.987	191.322
73	0.310	-0.852	-1.273	-1.1	0.9	-1.922	-0.406	1.965	191.928

Force 2a2 spreadsheet 1.

VALUES		Row	t1(sec)	t(sec)	Rho.inst(deg)	Beta(deg)	theta(rad)	theta(deg)	omega(rad/s)	alpha(rad/s/s)
		1								
M(kg) =	0.1621	2	0	0.13	199.09	-95.7	2.24	128.3	0.09	455.7
r(m) =	0.042	3	0.0025	0.1325	197.95	-94.5	2.22	127.1	1.18	421.1
Rho ([init].deg) =	70.8	4	0.005	0.135	196.23	-92.8	2.19	125.4	2.17	387.6
w(init).(rad/s) =	0	5	0.0075	0.1375	194.51	-91.1	2.16	123.7	3.09	355.3
		6	0.01	0.14	192.22	-88.8	2.12	121.4	3.93	324.2
		7	0.0125	0.1425	190.50	-87.1	2.09	119.7	4.70	294.2
		8	0.015	0.145	188.20	-84.8	2.05	117.4	5.39	265.3
		9	0.0175	0.1475	185.91	-82.5	2.01	115.1	6.01	237.5
		10	0.02	0.15	183.62	-80.2	1.97	112.8	6.57	210.9
		11	0.0225	0.1525	181.33	-77.9	1.93	110.5	7.06	185.2
		12	0.025	0.155	178.46	-75.1	1.88	107.7	7.49	160.7
		13	0.0275	0.1575	176.17	-72.8	1.84	105.4	7.86	137.2
		14	0.03	0.16	173.31	-69.9	1.79	102.5	8.17	114.6
		15	0.0325	0.1625	171.02	-67.6	1.75	100.2	8.43	93.1
		16	0.035	0.165	168.15	-64.8	1.70	97.4	8.63	72.6
		17	0.0375	0.1675	165.86	-62.5	1.66	95.1	8.79	53.0
		18	0.04	0.17	162.99	-59.6	1.61	92.2	8.90	34.4
		19	0.04	0.17	160.13	-56.7	1.56	89.3	8.96	16.8
		20	0.045	0.175	157.27	-53.9	1.51	86.5	8.98	0.0
		21	0.0475	0.1775	154.97	-51.6	1.47	84.2	8.96	-15.9
		22	0.05	0.18	152.11	-48.7	1.42	81.3	8.91	-30.9
		23	0.0525	0.1825	149.24	-45.8	1.37	78.4	8.81	-45.0
		24	0.055	0.185	146.95	-43.6	1.33	76.2	8.68	-58.3
		25	0.0575	0.1875	144.09	-40.7	1.28	73.3	8.52	-70.7
		26	0.06	0.19	141.22	-37.8	1.23	70.4	8.33	-82.4
		27	0.0625	0.1925	138.93	-35.5	1.19	68.1	8.12	-93.2
		28	0.065	0.195	136.07	-32.7	1.14	65.3	7.87	-103.3
		29	0.0675	0.1975	133.77	-30.4	1.10	63.0	7.60	-112.6
		30	0.07	0.2	130.91	-27.5	1.05	60.1	7.30	-121.1
		31	0.0725	0.2025	128.62	-25.2	1.01	57.8	7.00	-128.9
		32	0.075	0.205	126.33	-22.9	0.97	55.5	6.67	-136.1
		33	0.0775	0.2075	124.03	-20.6	0.93	53.2	6.32	-142.5
		34	0.08	0.21	121.74	-18.3	0.89	50.9	5.96	-148.2
		35	0.0825	0.2125	119.45	-16.0	0.85	48.6	5.58	-153.3
		36	0.085	0.215	117.16	-13.8	0.81	46.4	5.19	-157.7
		37	0.0875	0.2175	114.87	-11.5	0.77	44.1	4.80	-161.5
		38	0.09	0.22	113.15	-9.7	0.74	42.3	4.39	-164.7
		39	0.0925	0.2225	110.86	-7.5	0.70	40.1	3.97	-167.2
		40	0.095	0.225	109.14	-5.7	0.67	38.3	3.55	-169.2
		41	0.0975	0.2275	106.84	-3.4	0.63	36.0	3.13	-170.7
		42	0.1	0.23	105.13	-1.7	0.60	34.3	2.70	-171.5
		43	0.1025	0.2325	103.41	0.0	0.57	32.6	2.27	-171.9
		44	0.105	0.235	101.69	1.7	0.54	30.9	1.84	-171.7
		45	0.1075	0.2375	99.97	3.4	0.51	29.2	1.41	-171.0
		46	0.11	0.24	98.25	5.1	0.48	27.5	0.98	-169.9
		47	0.1125	0.2425	96.53	6.9	0.45	25.7	0.56	-168.2
		48	0.115	0.245	95.39	8.0	0.43	24.6	0.14	-166.1
		49	0.1175	0.2475	93.67	9.7	0.40	22.9	-0.27	-163.6
		50	0.12	0.25	92.52	10.9	0.38	21.7	-0.68	-160.7
		51	0.1225	0.2525	91.37	12.0	0.36	20.6	-1.08	-157.3
		52	0.125	0.255	90.23	13.2	0.34	19.4	-1.47	-153.5
		53	0.1275	0.2575	88.51	14.9	0.31	17.7	-1.85	-149.4
		54	0.13	0.26	87.36	16.0	0.29	16.6	-2.22	-144.9
		55	0.1325	0.2625	86.79	16.6	0.28	16.0	-2.57	-140.1
		56	0.135	0.265	85.65	17.8	0.26	14.8	-2.92	-134.9
		57	0.1375	0.2675	84.50	18.9	0.24	13.7	-3.25	-129.4
		58	0.14	0.27	83.35	20.0	0.22	12.6	-3.57	-123.6
		59	0.1425	0.2725	82.78	20.6	0.21	12.0	-3.87	-117.5
		60	0.145	0.275	81.63	21.8	0.19	10.8	-4.15	-111.2
		61	0.1475	0.2775	81.06	22.3	0.18	10.3	-4.42	-104.6
		62	0.15	0.28	80.49	22.9	0.17	9.7	-4.68	-97.8
		63	0.1525	0.2825	79.34	24.1	0.15	8.5	-4.90	-90.7
		64	0.155	0.285	78.77	24.6	0.14	8.0	-5.13	-83.4
		65	0.1575	0.2875	78.20	25.2	0.13	7.4	-5.33	-75.9
		66	0.16	0.29	77.62	25.8	0.12	6.8	-5.51	-68.3
		67	0.1625	0.2925	77.05	26.3	0.11	6.3	-5.67	-60.5
		68	0.165	0.295	76.48	26.9	0.10	5.7	-5.81	-52.5
		69	0.1675	0.2975	75.33	28.1	0.08	4.5	-5.93	-44.4
		70	0.17	0.3	74.76	28.6	0.07	4.0	-6.03	-36.2
		71	0.1725	0.3025	74.19	29.2	0.06	3.4	-6.11	-27.9
		72	0.175	0.305	74.19	29.2	0.06	3.4	-6.17	-19.4
		73	0.1775	0.3075	73.61	29.8	0.05	2.8	-6.21	-10.9
		74	0.18	0.31	73.04	30.4	0.04	2.2	-6.22	-2.4
		75	0.1825	0.3125	72.47	30.9	0.03	1.7	-6.22	6.2
		76	0.185	0.315	71.89	31.5	0.02	1.1	-6.19	14.9
		77	0.1875	0.3175	71.32	32.1	0.01	0.5	-6.14	23.5
		78	0.19	0.32	70.75	32.7	0.00	-0.1	-6.07	32.2
		79	0.1925	0.3225	70.18	33.2	-0.01	-0.6	-5.98	40.9
		80	0.195	0.325	69.60	33.8	-0.02	-1.2	-5.87	49.5
		81	0.1975	0.3275	69.03	34.4	-0.03	-1.8	-5.73	58.1
		82	0.2	0.33	68.46	34.9	-0.04	-2.3	-5.57	66.7
		83	0.2025	0.3325	67.88	35.5	-0.05	-2.9	-5.40	75.1
		84	0.205	0.335	66.74	36.7	-0.07	-4.1	-5.20	83.5
		85	0.2075	0.3375	66.16	37.2	-0.08	-4.6	-4.98	91.9
		86	0.21	0.34	65.59	37.8	-0.09	-5.2	-4.74	100.1
		87	0.2125	0.3425	64.45	39.0	-0.11	-6.4	-4.48	108.3
		88	0.215	0.345	63.87	39.5	-0.12	-6.9	-4.20	116.1
		89	0.2175	0.3475	63.30	40.1	-0.13	-7.5	-3.90	123.9
		90	0.22	0.35	62.15	41.2	-0.15	-8.6	-3.59	131.5

Force 2a2 spreadsheet 2.

Row	Fn2a2(N)	Ft2a2(N)	F2a2(N)	phi(deg)	delta(deg)	Fx2a2(N)	Fy2a2(N)
1							
2	-0.08	2.34	2.34	-88.1	146.4	-1.95	1.30
3	-0.06	2.23	2.34	-88.5	146.0	-1.94	1.31
4	-0.02	2.11	2.23	-89.4	145.1	-1.83	1.27
5	0.02	2.00	2.11	89.5	144.0	-1.71	1.24
6	0.07	1.90	2.01	87.9	142.4	-1.59	1.22
7	0.12	1.80	1.90	86.3	140.8	-1.47	1.20
8	0.17	1.69	1.80	84.2	138.7	-1.36	1.19
9	0.23	1.60	1.71	81.9	136.4	-1.24	1.18
10	0.28	1.50	1.62	79.4	133.9	-1.12	1.17
11	0.34	1.41	1.54	76.6	131.1	-1.01	1.16
12	0.40	1.32	1.46	73.3	127.8	-0.90	1.16
13	0.45	1.23	1.39	70.0	124.5	-0.79	1.14
14	0.50	1.14	1.32	66.2	120.7	-0.68	1.14
15	0.54	1.05	1.26	62.6	117.1	-0.57	1.12
16	0.59	0.97	1.21	58.5	113.0	-0.47	1.11
17	0.63	0.89	1.15	54.5	109.0	-0.38	1.09
18	0.67	0.80	1.11	50.1	104.6	-0.28	1.08
19	0.71	0.72	1.07	45.5	100.0	-0.19	1.06
20	0.74	0.64	1.04	40.8	95.3	-0.10	1.03
21	0.77	0.57	1.00	36.5	91.0	-0.02	1.00
22	0.79	0.49	0.98	31.8	86.3	0.06	0.98
23	0.82	0.42	0.95	27.0	81.5	0.14	0.94
24	0.83	0.35	0.93	22.8	77.3	0.21	0.91
25	0.85	0.28	0.92	18.1	72.6	0.28	0.88
26	0.86	0.21	0.91	13.5	68.0	0.34	0.84
27	0.87	0.14	0.90	9.4	63.9	0.39	0.80
28	0.88	0.08	0.89	5.0	59.5	0.45	0.77
29	0.88	0.02	0.89	1.2	55.7	0.50	0.73
30	0.89	-0.04	0.89	-2.9	51.6	0.55	0.69
31	0.89	-0.10	0.89	-6.4	48.1	0.59	0.66
32	0.88	-0.15	0.89	-9.9	44.6	0.63	0.62
33	0.88	-0.20	0.89	-13.1	41.4	0.67	0.59
34	0.88	-0.25	0.90	-16.2	38.3	0.71	0.56
35	0.87	-0.30	0.91	-19.1	35.4	0.74	0.52
36	0.86	-0.35	0.92	-21.9	32.6	0.77	0.49
37	0.86	-0.39	0.93	-24.5	30.0	0.80	0.46
38	0.85	-0.43	0.94	-26.6	27.9	0.83	0.44
39	0.84	-0.47	0.94	-29.0	25.5	0.85	0.41
40	0.83	-0.50	0.96	-30.8	23.7	0.87	0.38
41	0.83	-0.53	0.96	-32.8	21.7	0.90	0.36
42	0.82	-0.56	0.98	-34.3	20.2	0.92	0.34
43	0.81	-0.59	0.99	-35.8	18.7	0.93	0.32
44	0.81	-0.61	1.00	-37.0	17.5	0.95	0.30
45	0.80	-0.63	1.01	-38.2	16.3	0.96	0.28
46	0.80	-0.65	1.01	-39.3	15.2	0.98	0.27
47	0.79	-0.67	1.02	-40.2	14.3	0.99	0.25
48	0.79	-0.68	1.03	-40.7	13.8	1.00	0.25
49	0.78	-0.69	1.04	-41.4	13.1	1.01	0.23
50	0.78	-0.70	1.04	-41.7	12.8	1.02	0.23
51	0.78	-0.70	1.05	-41.9	12.6	1.02	0.23
52	0.78	-0.70	1.05	-42.0	12.5	1.03	0.23
53	0.78	-0.71	1.05	-42.4	12.1	1.03	0.22
54	0.78	-0.71	1.06	-42.4	12.1	1.03	0.22
55	0.78	-0.70	1.06	-41.9	12.6	1.03	0.23
56	0.79	-0.70	1.06	-41.7	12.8	1.03	0.23
57	0.79	-0.70	1.06	-41.5	13.0	1.03	0.24
58	0.79	-0.69	1.05	-41.3	13.2	1.03	0.24
59	0.80	-0.68	1.05	-40.5	14.0	1.02	0.25
60	0.80	-0.67	1.05	-40.2	14.3	1.02	0.26
61	0.80	-0.66	1.05	-39.4	15.1	1.01	0.27
62	0.81	-0.64	1.04	-38.5	16.0	1.00	0.29
63	0.81	-0.63	1.03	-38.1	16.4	0.99	0.29
64	0.81	-0.62	1.03	-37.1	17.4	0.98	0.31
65	0.82	-0.60	1.02	-36.2	18.3	0.97	0.32
66	0.82	-0.58	1.01	-35.2	19.3	0.96	0.33
67	0.82	-0.56	1.00	-34.2	20.3	0.94	0.35
68	0.82	-0.54	1.00	-33.2	21.3	0.93	0.36
69	0.82	-0.53	0.98	-32.6	21.9	0.91	0.37
70	0.82	-0.50	0.98	-31.5	23.0	0.90	0.38
71	0.82	-0.48	0.96	-30.5	24.0	0.88	0.39
72	0.82	-0.45	0.95	-28.9	25.6	0.86	0.41
73	0.82	-0.43	0.94	-27.8	26.7	0.84	0.42
74	0.82	-0.41	0.93	-26.6	27.9	0.82	0.43
75	0.81	-0.39	0.91	-25.5	29.0	0.80	0.44
76	0.81	-0.36	0.90	-24.3	30.2	0.77	0.45
77	0.80	-0.34	0.88	-23.1	31.4	0.75	0.46
78	0.79	-0.32	0.87	-21.9	32.6	0.73	0.47
79	0.79	-0.30	0.85	-20.6	33.9	0.71	0.47
80	0.78	-0.27	0.83	-19.4	35.1	0.68	0.48
81	0.77	-0.25	0.82	-18.1	36.4	0.66	0.48
82	0.76	-0.23	0.80	-16.8	37.7	0.63	0.49
83	0.75	-0.21	0.78	-15.4	39.1	0.61	0.49
84	0.73	-0.19	0.76	-14.6	39.9	0.58	0.49
85	0.72	-0.17	0.74	-13.2	41.3	0.56	0.49
86	0.70	-0.15	0.72	-11.8	42.7	0.53	0.49
87	0.69	-0.13	0.70	-10.8	43.7	0.51	0.48
88	0.67	-0.11	0.69	-9.3	45.2	0.48	0.49
89	0.66	-0.09	0.67	-7.8	46.7	0.46	0.49
90	0.64	-0.08	0.65	-6.8	47.7	0.44	0.48

Force 2b2 Spreadsheet 1

VALUES		Row	Time(sec)	T(sec)	Theta (rad)	theta(deg)
	128.9	1				
MASS mandible(Kg)=	0.1621	2	0	0.13	2.2	128.9
RADIUS(m)=	0.07316	3	0.0025	0.1325	2.2	128.8
Gamma Init(deg)=	109.5	4	0.005	0.135	2.2	128.7
		5	0.0075	0.1375	2.2	128.5
Theta Init(deg)=	128.9	6	0.01	0.14	2.2	128.3
		7	0.0125	0.1425	2.2	128.0
		8	0.015	0.145	2.2	127.7
		9	0.0175	0.1475	2.2	127.3
		10	0.02	0.15	2.2	126.9
		11	0.0225	0.1525	2.2	126.4
		12	0.025	0.155	2.2	125.9
		13	0.0275	0.1575	2.2	125.3
		14	0.03	0.16	2.2	124.7
		15	0.0325	0.1625	2.2	124.0
		16	0.035	0.165	2.2	123.3
		17	0.0375	0.1675	2.1	122.5
		18	0.04	0.17	2.1	121.7
		19	0.0425	0.1725	2.1	120.9
		20	0.045	0.175	2.1	119.9
		21	0.0475	0.1775	2.1	119.0
		22	0.05	0.18	2.1	117.9
		23	0.0525	0.1825	2.0	116.9
		24	0.055	0.185	2.0	115.8
		25	0.0575	0.1875	2.0	114.6
		26	0.06	0.19	2.0	113.4
		27	0.0625	0.1925	2.0	112.1
		28	0.065	0.195	1.9	110.8
		29	0.0675	0.1975	1.9	109.4
		30	0.07	0.2	1.9	108.0
		31	0.0725	0.2025	1.9	106.5
		32	0.075	0.205	1.8	105.0
		33	0.0775	0.2075	1.8	103.5
		34	0.08	0.21	1.8	101.8
		35	0.0825	0.2125	1.7	100.2
		36	0.085	0.215	1.7	98.5
		37	0.0875	0.2175	1.7	96.7
		38	0.09	0.22	1.7	94.9
		39	0.0925	0.2225	1.6	93.0
		40	0.095	0.225	1.6	91.1
		41	0.0975	0.2275	1.6	89.1
		42	0.1	0.23	1.5	87.1
		43	0.1025	0.2325	1.5	85.0
		44	0.105	0.235	1.4	82.9
		45	0.1075	0.2375	1.4	80.8
		46	0.11	0.24	1.4	78.6
		47	0.1125	0.2425	1.3	76.3
		48	0.115	0.245	1.3	74.0
		49	0.1175	0.2475	1.3	71.6
		50	0.12	0.25	1.2	69.2
		51	0.1225	0.2525	1.2	66.7
		52	0.125	0.255	1.1	64.2
		53	0.1275	0.2575	1.1	61.7
		54	0.13	0.26	1.0	59.1
		55	0.1325	0.2625	1.0	56.4
		56	0.135	0.265	0.9	53.7
		57	0.1375	0.2675	0.9	50.9
		58	0.14	0.27	0.8	48.1
		59	0.1425	0.2725	0.8	45.3
		60	0.145	0.275	0.7	42.4
		61	0.1475	0.2775	0.7	39.4
		62	0.15	0.28	0.6	36.4
		63	0.1525	0.2825	0.6	33.3
		64	0.155	0.285	0.5	30.2
		65	0.1575	0.2875	0.5	27.1
		66	0.16	0.29	0.4	23.8
		67	0.1625	0.2925	0.4	20.6
		68	0.165	0.295	0.3	17.3
		69	0.1675	0.2975	0.2	13.9
		70	0.17	0.3	0.2	10.5
		71	0.1725	0.3025	0.1	7.1
		72	0.175	0.305	0.1	3.6
		73	0.1775	0.3075	0.0	0.0
		74	0.18	0.31	0.0	0.0
		75	0.1825	0.3125	0.0	0.0
		76	0.185	0.315	0.0	0.0
		77	0.1875	0.3175	0.0	0.0
		78	0.19	0.32	0.0	0.0
		79	0.1925	0.3225	0.0	0.0
		80	0.195	0.325	0.0	0.0
		81	0.1975	0.3275	0.0	0.0
		82	0.2	0.33	0.0	0.0
		83	0.2025	0.3325	0.0	0.0
		84	0.205	0.335	0.0	0.0
		85	0.2075	0.3375	0.0	0.0
		86	0.21	0.34	0.0	0.0
		87	0.2125	0.3425	0.0	0.0
		88	0.215	0.345	0.0	0.0
		89	0.2175	0.3475	0.0	0.0
		90	0.22	0.35	0.0	0.0
		91	0.2225	0.3525	0.0	0.0
		92	0.225	0.355	0.0	0.0
		93	0.2275	0.3575	0.0	0.0

Force 2b2 Spreadsheet 2.

Row	omega(rad/s)	alpha(rad/s/s)	Fh2o2(N)	Fv2o2(N)	Fz2o2(N)	Phi(deg)	delta(deg)	FX(deg)
1								
2	0.09	455.7	0.3	1.99	2.0	9.9	119.4	-1.0
3	1.18	421.1	0.4	1.78	1.8	11.5	120.9	-0.9
4	2.17	387.6	0.4	1.58	1.6	13.7	123.0	-0.9
5	3.09	355.3	0.4	1.39	1.5	16.8	125.9	-0.9
6	3.93	324.2	0.5	1.21	1.3	20.7	129.6	-0.8
7	4.70	294.2	0.5	1.03	1.1	25.8	134.4	-0.8
8	5.39	265.3	0.5	0.86	1.0	32.2	140.5	-0.8
9	6.01	237.5	0.6	0.69	0.9	40.0	147.9	-0.8
10	6.57	210.9	0.6	0.54	0.8	49.3	156.8	-0.8
11	7.06	185.2	0.7	0.38	0.8	59.9	166.9	-0.7
12	7.49	160.7	0.7	0.24	0.7	71.1	177.7	-0.7
13	7.86	137.2	0.7	0.10	0.7	82.3	188.2	-0.7
14	8.17	114.6	0.8	-0.04	0.8	92.7	198.0	-0.7
15	8.43	93.1	0.8	-0.16	0.8	101.8	206.5	-0.7
16	8.63	72.6	0.8	-0.28	0.8	109.7	213.6	-0.7
17	8.79	53.0	0.8	-0.40	0.9	116.3	219.5	-0.7
18	8.90	34.4	0.8	-0.51	1.0	121.9	224.3	-0.7
19	8.96	16.8	0.8	-0.62	1.0	126.7	228.2	-0.7
20	8.98	0.0	0.8	-0.72	1.1	130.9	231.5	-0.7
21	8.96	-15.9	0.8	-0.81	1.2	134.6	234.2	-0.7
22	8.91	-30.9	0.8	-0.90	1.2	137.9	236.4	-0.7
23	8.81	-45.0	0.8	-0.98	1.3	140.8	238.3	-0.7
24	8.68	-58.3	0.8	-1.06	1.3	143.5	239.8	-0.7
25	8.52	-70.7	0.8	-1.13	1.4	145.9	241.1	-0.7
26	8.33	-82.4	0.7	-1.20	1.4	148.1	242.1	-0.7
27	8.12	-93.2	0.7	-1.27	1.5	150.2	242.9	-0.7
28	7.87	-103.3	0.7	-1.33	1.5	152.1	243.5	-0.7
29	7.60	-112.6	0.7	-1.38	1.5	153.9	244.0	-0.7
30	7.30	-121.1	0.7	-1.43	1.6	155.6	244.2	-0.7
31	7.00	-128.9	0.6	-1.48	1.6	157.1	244.3	-0.7
32	6.67	-136.1	0.6	-1.52	1.6	158.6	244.2	-0.7
33	6.32	-142.5	0.6	-1.56	1.7	159.9	244.0	-0.7
34	5.96	-148.2	0.5	-1.59	1.7	161.1	243.6	-0.7
35	5.58	-153.3	0.5	-1.62	1.7	162.3	243.0	-0.8
36	5.19	-157.7	0.5	-1.65	1.7	163.3	242.4	-0.8
37	4.80	-161.5	0.5	-1.67	1.7	164.2	241.5	-0.8
38	4.39	-164.7	0.5	-1.69	1.8	165.1	240.6	-0.9
39	3.97	-167.2	0.4	-1.71	1.8	165.8	239.4	-0.9
40	3.55	-169.2	0.4	-1.72	1.8	166.5	238.2	-0.9
41	3.13	-170.7	0.4	-1.73	1.8	167.0	236.8	-1.0
42	2.70	-171.5	0.4	-1.73	1.8	167.5	235.2	-1.0
43	2.27	-171.9	0.4	-1.73	1.8	167.9	233.5	-1.1
44	1.84	-171.7	0.4	-1.73	1.8	168.2	231.7	-1.1
45	1.41	-171.0	0.4	-1.73	1.8	168.4	229.8	-1.1
46	0.98	-169.9	0.4	-1.72	1.8	168.5	227.7	-1.2
47	0.56	-168.2	0.3	-1.71	1.7	168.5	225.4	-1.2
48	0.14	-166.1	0.3	-1.70	1.7	168.5	223.0	-1.3
49	-0.27	-163.6	0.3	-1.69	1.7	168.3	220.5	-1.3
50	-0.68	-160.7	0.4	-1.67	1.7	168.1	217.9	-1.3
51	-1.08	-157.3	0.4	-1.65	1.7	167.8	215.1	-1.4
52	-1.47	-153.5	0.4	-1.63	1.7	167.4	212.2	-1.4
53	-1.85	-149.4	0.4	-1.60	1.6	166.9	209.2	-1.4
54	-2.22	-144.9	0.3	-1.59	1.6	167.7	208.9	-1.4
55	-2.57	-140.1	0.3	-1.58	1.6	168.4	210.7	-1.4
56	-2.92	-134.9	0.3	-1.56	1.6	169.1	211.4	-1.4
57	-3.25	-129.4	0.3	-1.54	1.6	169.9	212.2	-1.3
58	-3.57	-123.6	0.2	-1.51	1.5	170.7	212.9	-1.3
59	-3.87	-117.5	0.2	-1.48	1.5	171.5	213.7	-1.2
60	-4.15	-111.2	0.2	-1.45	1.5	172.3	214.6	-1.2
61	-4.42	-104.6	0.2	-1.41	1.4	173.3	215.5	-1.2
62	-4.68	-97.8	0.1	-1.38	1.4	174.3	216.5	-1.1
63	-4.90	-90.7	0.1	-1.33	1.3	175.4	217.6	-1.1
64	-5.13	-83.4	0.1	-1.29	1.3	176.5	218.8	-1.0
65	-5.33	-75.9	0.0	-1.23	1.2	177.9	220.2	-0.9
66	-5.51	-68.3	0.0	-1.18	1.2	179.4	221.7	-0.9
67	-5.67	-60.5	0.0	-1.12	1.1	181.1	223.4	-0.8
68	-5.81	-52.5	-0.1	-1.06	1.1	183.1	225.4	-0.7
69	-5.93	-44.4	-0.1	-1.00	1.0	185.4	227.7	-0.7
70	-6.03	-36.2	-0.1	-0.93	0.9	188.0	230.3	-0.6
71	-6.11	-27.9	-0.2	-0.86	0.9	191.2	233.4	-0.5
72	-6.17	-19.4	-0.2	-0.78	0.8	194.9	237.2	-0.4
73	-6.21	-10.9	-0.2	-0.73	0.8	196.7	238.0	-0.4
74	-6.22	-2.4	-0.2	-0.68	0.7	196.8	238.1	-0.4
75	-6.22	6.2	-0.2	-0.63	0.7	198.2	240.5	-0.3
76	-6.19	14.9	-0.2	-0.58	0.6	199.9	242.2	-0.3
77	-6.14	23.5	-0.2	-0.53	0.6	202.1	244.4	-0.2
78	-6.07	32.2	-0.2	-0.47	0.5	204.8	247.1	-0.2
79	-5.98	40.9	-0.2	-0.42	0.5	208.2	250.5	-0.2
80	-5.87	49.5	-0.2	-0.37	0.4	212.3	254.6	-0.1
81	-5.73	58.1	-0.2	-0.32	0.4	217.4	259.7	-0.1
82	-5.57	66.7	-0.3	-0.27	0.4	223.5	265.8	0.0
83	-5.40	75.1	-0.3	-0.22	0.3	230.6	272.9	0.0
84	-5.20	83.5	-0.3	-0.17	0.3	238.8	281.1	0.1
85	-4.98	91.9	-0.3	-0.12	0.3	247.8	290.0	0.1
86	-4.74	100.1	-0.3	-0.07	0.3	256.9	299.1	0.2
87	-4.48	108.3	-0.3	-0.02	0.3	265.9	308.1	0.2
88	-4.20	116.1	-0.3	0.02	0.3	274.0	316.2	0.2
89	-4.20	116.1	-0.3	0.02	0.3	274.0	316.2	0.2
90	-4.20	116.1	-0.3	0.02	0.3	274.0	316.2	0.2
91	-4.20	116.1	-0.3	0.02	0.3	274.0	316.2	0.2
92	-4.20	116.1	-0.3	0.02	0.3	274.0	316.2	0.2
93	-4.20	116.1	-0.4	0.02	0.4	273.0	315.3	0.3

Final Force 4 spreadsheet

Row	T(sec)	Fx2a2(N)	Fy2a2(N)	f(x)2c2(N)	Fy2c2(N)	Fxtotal(N)	Fytotal(N)	Final force 4(N)	Delta 4
1									
2	0.13	-2.0	1.3	-2.0	-1.1	-4.0	0.2	4.0	176.7
3	0.1325	-1.9	1.3	-1.9	-1.0	-3.8	0.3	3.8	175.3
4	0.135	-1.8	1.3	-1.7	-0.9	-3.6	0.3	3.6	174.5
5	0.1375	-1.7	1.2	-1.6	-0.9	-3.3	0.4	3.4	173.6
6	0.14	-1.6	1.2	-1.5	-0.8	-3.1	0.4	3.1	172.3
7	0.1425	-1.5	1.2	-1.4	-0.7	-2.9	0.5	2.9	171.0
8	0.145	-1.4	1.2	-1.3	-0.7	-2.7	0.5	2.7	169.3
9	0.1475	-1.2	1.2	-1.2	-0.6	-2.4	0.5	2.5	167.4
10	0.15	-1.1	1.2	-1.1	-0.6	-2.2	0.6	2.3	165.2
11	0.1525	-1.0	1.2	-1.0	-0.5	-2.0	0.6	2.1	162.8
12	0.155	-0.9	1.2	-0.9	-0.5	-1.8	0.7	1.9	159.8
13	0.1575	-0.8	1.1	-0.8	-0.4	-1.6	0.7	1.8	156.7
14	0.16	-0.7	1.1	-0.8	-0.4	-1.4	0.7	1.6	152.8
15	0.1625	-0.6	1.1	-0.7	-0.4	-1.3	0.8	1.5	148.9
16	0.165	-0.5	1.1	-0.6	-0.3	-1.1	0.8	1.3	144.0
17	0.1675	-0.4	1.1	-0.5	-0.3	-0.9	0.8	1.2	139.1
18	0.17	-0.3	1.1	-0.5	-0.3	-0.8	0.8	1.1	133.0
19	0.1725	-0.2	1.1	-0.4	-0.2	-0.6	0.8	1.0	126.5
20	0.175	-0.1	1.0	-0.4	-0.2	-0.5	0.8	1.0	119.3
21	0.1775	0.0	1.0	-0.5	0.4	-0.5	1.4	1.5	110.7
22	0.18	0.1	1.0	-0.5	0.4	-0.4	1.4	1.4	106.6
23	0.1825	0.1	0.9	-0.4	0.3	-0.3	1.3	1.3	102.0
24	0.185	0.2	0.9	-0.4	0.3	-0.2	1.2	1.2	97.5
25	0.1875	0.3	0.9	-0.3	0.3	0.0	1.1	1.1	92.1
26	0.19	0.3	0.8	-0.3	0.2	0.1	1.1	1.1	266.3
27	0.1925	0.4	0.8	-0.2	0.2	0.2	1.0	1.0	260.6
28	0.195	0.5	0.8	-0.2	0.2	0.3	0.9	1.0	254.1
29	0.1975	0.5	0.7	-0.2	0.1	0.3	0.9	0.9	247.8
30	0.2	0.6	0.7	-0.1	0.1	0.4	0.8	0.9	241.0
31	0.2025	0.6	0.7	-0.1	0.1	0.5	0.7	0.9	234.6
32	0.205	0.6	0.6	0.0	0.0	0.6	0.7	0.9	228.4
33	0.2075	0.7	0.6	0.0	0.0	0.7	0.6	0.9	222.6
34	0.21	0.7	0.6	0.0	0.0	0.7	0.5	0.9	217.1
35	0.2125	0.7	0.5	0.0	0.0	0.8	0.5	0.9	212.0
36	0.215	0.8	0.5	0.1	-0.1	0.8	0.4	0.9	207.3
37	0.2175	0.8	0.5	0.1	-0.1	0.9	0.4	1.0	203.1
38	0.22	0.8	0.4	0.1	-0.1	0.9	0.3	1.0	199.6
39	0.2225	0.9	0.4	0.1	-0.1	1.0	0.3	1.0	196.2
40	0.225	0.9	0.4	0.2	-0.1	1.0	0.2	1.1	193.5
41	0.2275	0.9	0.4	0.2	-0.2	1.1	0.2	1.1	190.6
42	0.23	0.9	0.3	0.2	-0.2	1.1	0.2	1.1	188.5
43	0.2325	0.9	0.3	0.2	-0.2	1.2	0.1	1.2	186.5
44	0.235	1.0	0.3	0.2	-0.2	1.2	0.1	1.2	184.8
45	0.2375	1.0	0.3	0.3	-0.2	1.2	0.1	1.2	183.2
46	0.24	1.0	0.3	0.3	-0.2	1.3	0.0	1.3	181.8
47	0.2425	1.0	0.3	0.3	-0.2	1.3	0.0	1.3	180.5
48	0.245	1.0	0.2	0.3	-0.3	1.3	0.0	1.3	179.7
49	0.2475	1.0	0.2	0.3	-0.3	1.3	0.0	1.3	178.6
50	0.25	1.0	0.2	0.3	-0.3	1.4	0.0	1.4	178.0
51	0.2525	1.0	0.2	0.4	-0.3	1.4	-0.1	1.4	177.5
52	0.255	1.0	0.2	0.4	-0.3	1.4	-0.1	1.4	177.0
53	0.2575	1.0	0.2	0.4	-0.3	1.4	-0.1	1.4	176.3
54	0.26	1.0	0.2	0.4	-0.3	1.4	-0.1	1.4	176.0
55	0.2625	1.0	0.2	0.4	-0.3	1.4	-0.1	1.4	176.0
56	0.265	1.0	0.2	0.4	-0.3	1.5	-0.1	1.5	175.7
57	0.2675	1.0	0.2	0.4	-0.4	1.5	-0.1	1.5	175.6
58	0.27	1.0	0.2	0.4	-0.4	1.5	-0.1	1.5	175.4
59	0.2725	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	175.6
60	0.275	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	175.5
61	0.2775	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	175.8
62	0.28	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	176.0
63	0.2825	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	175.9
64	0.285	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	176.3
65	0.2875	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	176.6
66	0.29	1.0	0.3	0.5	-0.4	1.5	-0.1	1.5	177.0
67	0.2925	0.9	0.3	0.5	-0.4	1.5	-0.1	1.5	177.3
68	0.295	0.9	0.4	0.5	-0.4	1.4	-0.1	1.4	177.7
69	0.2975	0.9	0.4	0.5	-0.4	1.4	-0.1	1.4	177.8
70	0.3	0.9	0.4	0.5	-0.4	1.4	0.0	1.4	178.3
71	0.3025	0.9	0.4	0.5	-0.4	1.4	0.0	1.4	178.8
72	0.305	0.9	0.4	0.5	-0.4	1.4	0.0	1.4	179.7
73	0.3075	0.8	0.4	0.5	-0.4	1.4	0.0	1.4	180.2
74	0.31	0.8	0.4	0.5	-0.4	1.3	0.0	1.3	181.6
75	0.3125	0.8	0.4	0.5	-0.4	1.3	0.1	1.3	183.2
76	0.315	0.8	0.5	0.4	-0.3	1.2	0.1	1.2	184.9
77	0.3175	0.8	0.5	0.4	-0.3	1.2	0.1	1.2	186.6
78	0.32	0.7	0.5	0.4	-0.3	1.1	0.2	1.1	188.5
79	0.3225	0.7	0.5	0.3	-0.3	1.0	0.2	1.1	190.5
80	0.325	0.7	0.5	0.3	-0.3	1.0	0.2	1.0	192.7
81	0.3275	0.7	0.5	0.3	-0.2	0.9	0.3	1.0	195.0
82	0.33	0.6	0.5	0.3	-0.2	0.9	0.3	0.9	197.5
83	0.3325	0.6	0.5	0.2	-0.2	0.8	0.3	0.9	200.1
84	0.335	0.6	0.5	0.2	-0.2	0.8	0.3	0.8	202.4
85	0.3375	0.6	0.5	0.2	-0.1	0.7	0.3	0.8	205.5
86	0.34	0.5	0.5	0.1	-0.1	0.7	0.4	0.8	208.8
87	0.3425	0.5	0.5	0.1	-0.1	0.6	0.4	0.7	211.8
88	0.345	0.5	0.5	0.1	-0.1	0.6	0.4	0.7	215.5
89	0.3475	0.5	0.5	0.1	-0.1	0.5	0.4	0.7	219.5
90	0.35	0.4	0.5	0.1	0.0	0.5	0.4	0.7	221.6

Appendix G

Measurement of distance from centre of rotation of mandible to TMJ Ligament.

In order to calculate the forces sustained by the TMJ capsule /ligament complex due to rotation in mouth opening, it was necessary to find the precise centre of rotation of the mandible and its' distance from the centre of mass of the mandible.
From this the amount of force acting within the capsule/ligament complex due to mandibular rotation could be calculated (Chapter 4, page 177-178).

Materials

The location of the centre of rotation of the mandible during purely rotatory movement was carried out on a single cadaver, which had a clearly defined TMJ ligament, on which it was possible to take an impression of the mandibular teeth and on which it was possible to rotate the mandible freely by approximately 15°.
The technique used is called hinge axis location, which is a long established method of measuring the centre of rotation of the mandible using a mechanical device called a hinge axis locator (Posselt 1969).

Posselt (1969) stated that in active mouth opening the condyles start to translate as soon as the mandibles open from the intercuspal (fully closed) position. This has been more recently confirmed by other workers (Merlini and Palla 1989).

However Posselt (1969) also stated that in passive mouth opening (accomplished by external manipulation), with the condyles in the most unstrained, retruded position, (terminal hinge position) a pure rotation occurs for 15° after which a combination of rotation and translation takes place. A number of workers have confirmed the existence of the terminal hinge position (McCollum 1939, Stuart 1959). In whiplash, retroflexion of the cranium is an involuntary movement, and it was therefore assumed that the mouth opening which occurs in retroflexion in whiplash is passive.

Method

An Almore hinge axis locator was used to make the measurement (Figure G.1).

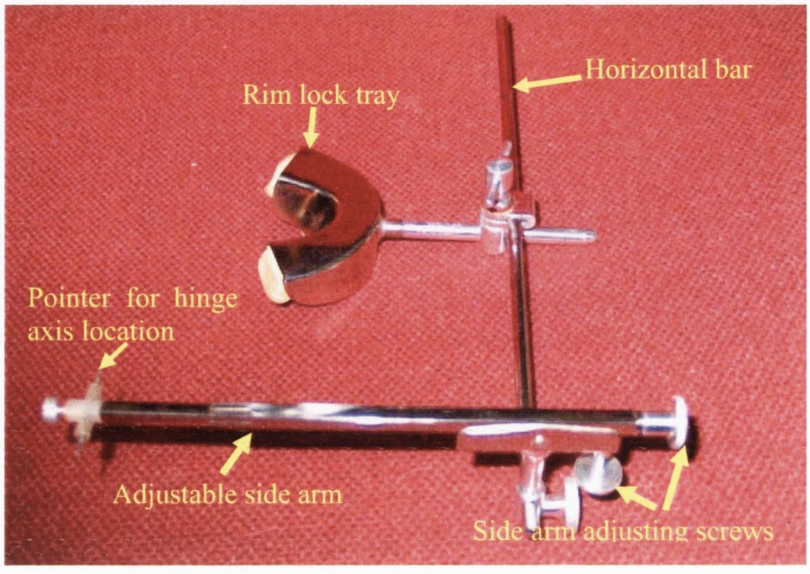

Figure G.1: The Almore hinge axis locator with its component parts

Initially an impression of the lower teeth was taken in a rim lock tray using a silicone material to establish a firmly located tray which will allow movement of the mandible without rocking of the tray (Figure G.2).

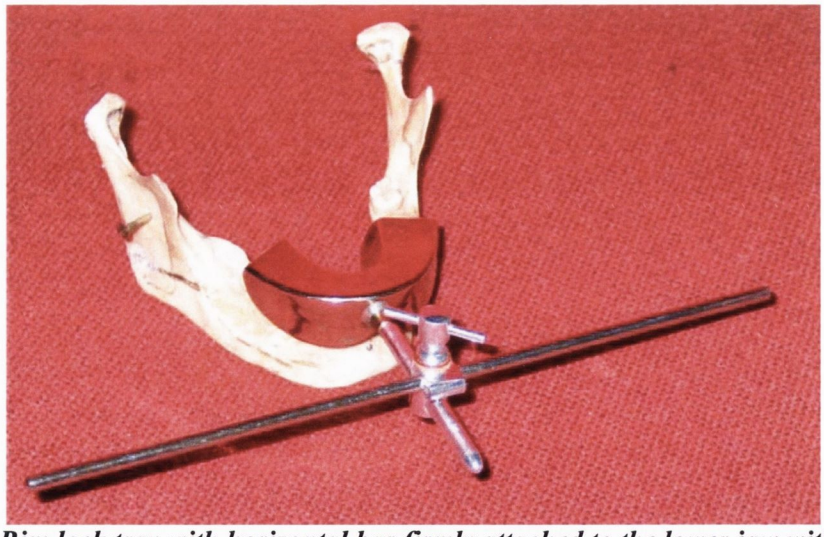

Figure G.2: Rim lock tray with horizontal bar firmly attached to the lower jaw with silicone impression material

The arm projecting from the back of the impression tray was now attached to a horizontal bar (Figure G.3).

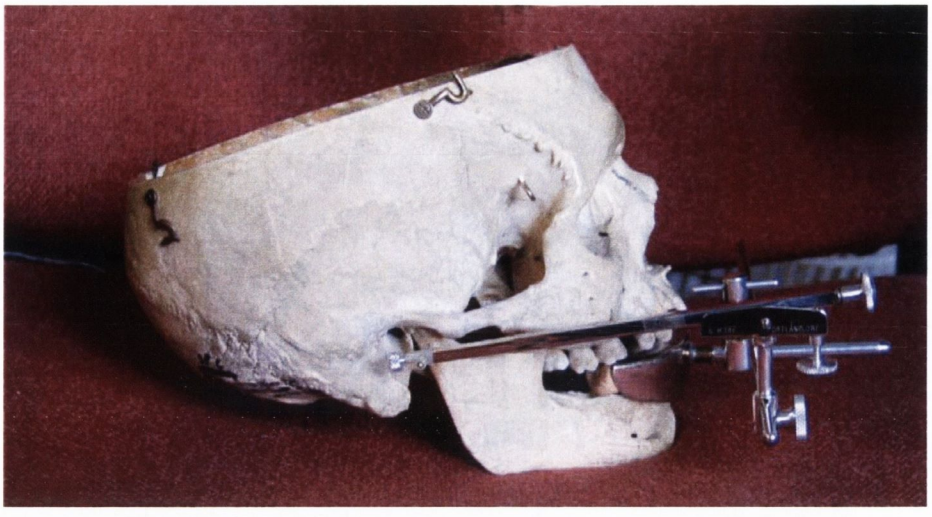

Figure G.3: The complete Almore hinge axis locator prior to recording hinge axis location

An adjustable side arm was now attached to the horizontal bar at right angles to it and extending to the vicinity of the temporomandibular joint just anterior to the external auditory meatus (Figure G.3).The approximate centre of rotation was established by digital pressure on the mandibular condyle while the jaw was gently rotated in the vertical plane.

The pointer attached to the horizontal arm was now placed over the arbitrarily estimated hinge axis location with the apparatus as described above firmly secured in position by the rim lock tray, which was attached to the lower jaw. This was achieved by adjusting the position of the side arm which has the facility to move in an anterior and posterior direction (Figure G.4).

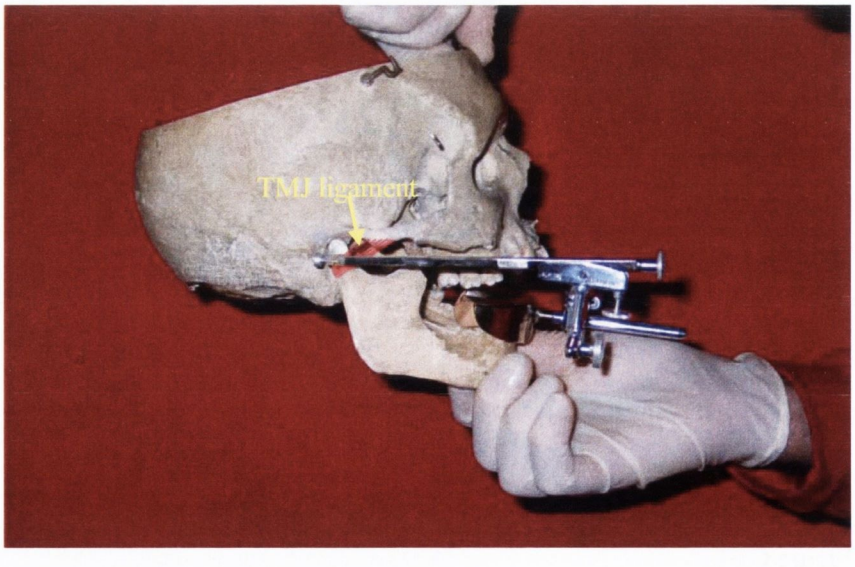

Figure G.4 Representation of method used to measure the centre of rotation of the mandible to midpoint the TMJ ligament. A representation of the TMJ ligament is illustrated in red and arrowed.

The lower jaw was now rotated in the vertical plane while the movement of the pointer was closely observed using magnification loops. At first the pointer described small circular arcs which indicated that it was not at the precise centre of rotation (Figure G.4).

The pointer was thus adjusted by moving it towards the centre of the arc until no arc was described. This indicated that the pointer was on the exact centre of rotation.

The centre of rotation was thus marked and its distance to the midpoint of the TMJ ligament was measured and was found to be 2.5mm.

Appendix H

Impact Velocities in "whiplash" injuries

Before considering the effects of two cars impacting it is important to review the basic principles which govern the post-impact velocities and accelerations of two cars.

When bodies collide, their post impact velocities are dependent on the fundamental law of conservation of momentum.

Momentum: is the product of the mass of a body and its velocity. The formula for momentum is:

p = mv

Where:-

p = momentum

m = mass

v = velocity

H.1 Conservation of Momentum

This is a fundamental law of physics, which states that the total momentum of all bodies in a closed system is constant and unaffected by processes occurring within the system. In simple terms this means that the sum of the momentum of two impacting cars will be the same before and after impact.

Impact collisions can be divided into 3 categories, according to their degree of elasticity:-

(a) **Non-elastic collisions** e.g. where permanent deformation occurs to the impacting object(s) e.g. putty impacting a wall (Figure H.1). The coefficient of restitution in this instance is 0.

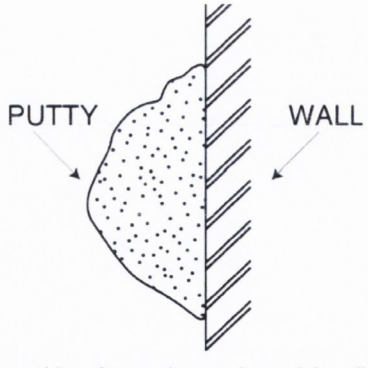

Figure H.1: graphic of putty impacting with a flat rigid surface

(b) **Elastic collisions** e.g. pool balls colliding, in which instance the objects deform, but return to their original shape after impact (Figure H.2). A completely elastic collision is said to have a coefficient of restitution (e) of 1.

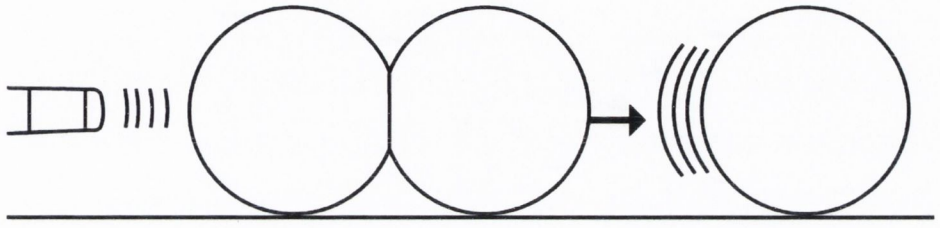

Figure H.2: Diagrammatic of elastic materials colliding

(c) **A combination of (a) and (b)** above i.e. some elasticity and some deformation. Impacting cars come into this category (Figure H.3), with (e) having a value somewhere between 0 and 1.

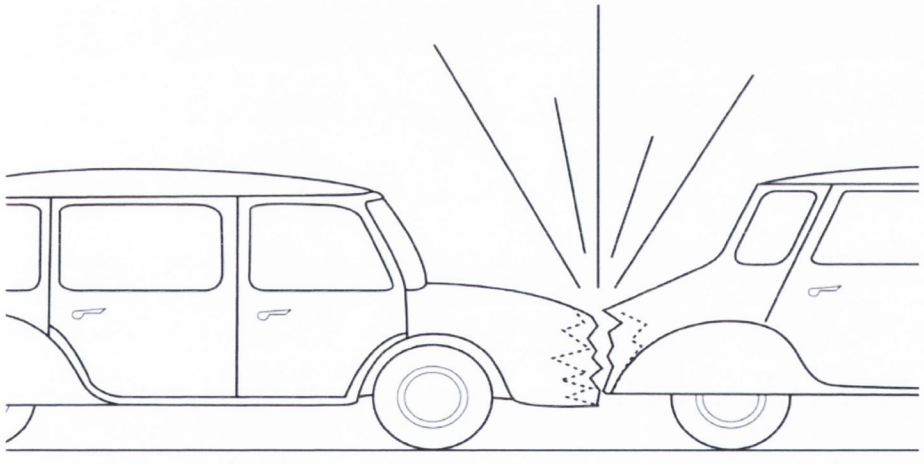

Figure H. 3: Diagram of impact between partially elastic materials.
The dotted line indicates the initial deformation and the continuous line shows the degree of deformation after restitution has occurred

H.2 Momentum Calculations for Non-Elastic Bodies

The post-impact velocities of non-elastic bodies can be calculated using the formula:

$M_aV_{1a} + M_bV_{1b} = (M_a + M_b)V_2$. This assumes the same velocity for both bodies after impact (since they stay together).

Where: M_a = mass of the impacting object

M_b = mass of the impacted object

V_{1a} = initial velocity of the impacting object

V_{1b} = initial velocity of the impacted object

V_2 = post impact velocity of the combined bodies

In this example V_{1b} is always assumed to be = 0.

If the masses of the two objects are assumed to be equal and unity, the following calculation will give the post-impact velocity for an initial velocity of 20mph: -

$1(20) + 1(0) = (Ma + Mb)\ V_2$

Therefore $20 = 2V_2$

$V_2 = 10$

If the mass of the impacting object is twice the mass of the impacted object, then the following calculation will give the post-impact velocity of the combined masses: -

$2(20) + 1(0) = (2Ma + Mb)\ V_2$

Therefore $40 = 3V_2$

V =13.3mph.

If the mass of the impacting object is half the mass of the impacted object, i.e. $M_a = 2M_b$, then the following will give the post-impact velocity: -

$1(20) + 2(0) = (Ma + 2Mb)\ V_2$

Therefore $3V_2 = 20$

$V_2 = 6.7$mph

H.3 Impacts between Elastic Bodies

When calculating the post-impact velocities of elastic bodies, it is necessary to take account of the elasticity of the impacting bodies. In order to allow for this, a co-efficient of restitution between 1 and 0 is incorporated into the equation. When the collision is totally elastic the coefficient is given as 1. Collisions in which kinetic energy is conserved are said to be elastic and all others are inelastic.

In every collision or interaction, momentum is conserved, i.e. the total momentum before the collision is equal to the total momentum after the collision. Energy is conserved in the collision, but the type of energy usually changes. Therefore where elasticity exists, it is necessary to use simultaneous equations, one for kinetic energy and one for momentum. In any ordinary collision the total kinetic energy never increases, and usually decreases.

Therefore in a collision of two bodies A and B having masses of M_A and M_B, initial velocities of V_{1A} and V_{1B}, and final velocities V_{2A} and V_{2B}, the momentum equation gives:

Momentum EQ (1):

$M_aV_{1a} + M_bV_{1b} = M_aV_{2a} + M_bV_{2b}$ (Vector sum) (1)

Where M_a = mass of the impacting car

M_b = mass of the impacted car

V_{1a} = pre-impact velocity of the impacting car

V_{1b} = pre-impact velocity of the impacted car

V_{2a} = post-impact velocity of the impacting car

V_{2b} = post-impact velocity of the impacted car.

Similarly the kinetic energy equation will give:-

Kinetic Energy EQ (2): $\frac{1}{2}M_aV_{2a}^2 + \frac{1}{2}M_bV_{2b}^2 < \frac{1}{2}M_aV_{1b}^2 + \frac{1}{2}M_bV_{2b}^2$ (Scaler sum) (2)

Rearranging equations (1) and (2)

$M_a(V_{2a} - V_{1a}) = M_b(V_{1b} - V_{2b})$ (EQ3).

and

$M_a(V_{2a}^2 - V_{1a}^2) < M_b(V_{1b}^2 - V_{2b}^2)$ (EQ4).

If we divide EQ (4) by EQ (3) we have:

$$\frac{V_{2a}^2 - V_{1a}^2}{V_{2a} - V_{1a}} < \frac{V_{1b}^2 - V_{2b}^2}{V_{1b} - V_{2b}}$$

or

$$V_{2a} + V_{1a} < V_{1b} + V_{2b} \quad (6)$$

and after rearrangement:

$$V_{2a} - V_{2b} < V_{1b} - V_{1a} \quad (7)$$

Therefore the relative velocity after impact $V_{2a} - V_{2b}$ is less than or equal to the relative velocity before collision.

The negative ratio of the relative velocity before collision is called the coefficient of restitution, e.

$$e = \frac{V_{2a} - V_{2b}}{V_{1a} - V_{1b}} = \frac{V_{2a} - V_{2b}}{V_{1b} - V_{1a}} \quad (9)$$

or

$$e\,(V_{1b} - V_{1a}) = V_{2a} - V_{2b} \quad (10)$$

Where e = coefficient of restitution

V_{1a} = pre-impact velocity of the impacting car

V_{1b} = pre-impact velocity of the impacted car

V_{2a} = post-impact velocity of the impacting car

V_{2b} = post-impact velocity of the impacted car.

If the collision is perfectly elastic, e is equal to 1. If the collision is completely inelastic, e = 0.

These formulae enable us to calculate the post-impact velocities of the two bodies as follows. Assuming that the two bodies have equal masses, the following formulae are combined : -

(1) $M_aV_{1a} + M_bV_{1b} = M_aV_{2a} + M_bV_{2b}$

and

(2) $e\,(V_{1b} - V_{1a}) = V_{2a} - V_{2b}$

If $V_{1a} = 20$ and $V_{1b} = 0$, we can find V_{2a} and V_{2b} as follows:

$M_aV_{1a} + M_bV_{1b} = M_aV_{2a} + M_bV_{2b}$

Cancel M and we get:

$V_{1a} + V_{1b} = V_{2a} + V_{2b}$

$20 + 0 = V_{2a} + V_{2b}$

KE $e\,(V_{1b} - V_{1a}) = V_{2a} - V_{2b}$

$(0 - 20) = V_{2a} - V_{2b}$

$-20 = V_{2a} - V_{2b}$.

Now using simultaneous equations:

$-20 = V_{2a} - V_{2b}$.

$20 = V_{2a} + V_{2b}$

$0 = 2V_{2a}$

$0 = V_{2a}$

Therefore V_{2a} is equal to 0, i.e. the post-impact velocity of the impacting body.

Now substitute this value for V_{2a} into either of the above equations:

$-20 = V_{2a} - V_{2b}$

$-20 = 0 - V_{2b}$

Therefore $20 = V_{2b}$, i.e. the post-impact velocity of the impacted body.

H.4 Impacts between Partially Elastic Bodies (Vehicles)

In motor vehicle accidents some deformation and some restitution occur. This will be dependent on the force of impact, the material from which the cars are made and the masses of the cars.

Hence to evaluate the post-impact velocity in a situation where the bodies are partly elastic, we proceed as follows:

$M_aV_{1a} + M_bV_{1b} = M_aV_{2a} + M_bV_{2b}$

and

KE $e(V_{1b} - V_{1a}) = V_{2a} - V_{2b}$.

In the fully elastic collision e = 1. In the situation where the collision is 50% elastic and 50% non-elastic for instance, we take e = 0.5.

The variables for the equation are:

$M_a = M_b = 1$

$V_{1a} = 20$

$V_{1b} = 0$

Therefore with equation (1)

$1(20) + 1(0) = 1(V_{2a}) + 1(V_{2b})$

$20 = V_{2a} + V_{2b}$

From equation (2)

$0.5(0 - 20) = V_{2a} - V_{2b}$

$-10 = V_{2a} - V_{2b}$

Now simultaneous equations are used:

$20 = V_{2a} + V_{2b}$

$\underline{-10 = V_{2a} - V_{2b}}$

$10 = 2V_{2a}$

Therefore $V_{2a} = 5$mph

Now the value for V_{2a} is substituted into either equation:

$20 = V_{2a} + V_{2b}$

$20 = 5 + V_{2b}$.

Therefore $V_{2b} = 15$mph.

Severy et al (1955), demonstrated that in a 19.8mph impact collision, the maximum mutual deformation of the two cars was 24.4 inches, and that the total mutual deformation post-accident was 11.3 inches. This constitutes a restitution of approx 50%. Therefore if we calculate the post-impact velocity of the two cars involved, we can include a figure of 0.5 (50%) to represent e which is the coefficient of restitution. Thus, if the impact velocity of the collision is 20mph, the post-impact velocities of the two cars can be calculated thus:

$1x20 + 1x0 = 1xV_{2a} + 1xV_{2b}$ (Momentum equation)

$V_{2A}+V_{2B} = 20$

$(0.5)(0-20) = V_{2a}-V_{2b}$ (Kinetic energy equation)

$V_{2a}-V_{2b} = -10$

$V_{2a}+V_{2b} = 20$

$2V_{2a} = 10$

$V_{2a} = 5$

Another important factor which needs to be considered in evaluating the post-impact velocities of the two cars is their relative masses. For example, if the mass of the impacting car is much greater than that of the impacted car, it may make a significant difference to the post-impact velocity of the impacted car (Figure H.4).

If we make the assumption that the mass of the impacting vehicle is three times that of the impacted vehicle, the calculation will show the following:

EQ (1) $MV_{1a} + MV_{1b} = MV_{2a} + MV_{2b}$

$3(20) + 1(0) = 3MV_{2a} + MV_{2b}$

$3V_{2a} + V_{2b} = 60$

EQ (2) $e(V_{1b} - V_{1a}) = V_{2a} - V_{2b}$

$0.5(0-20) = V_{2a} - V_{2b}$

$V_{2a} - V_{2b} = -10$

Now using simultaneous equations:

$3V_{2a} + V_{2b} = 60$

$V_{2a} - V_{2b} = -10$

$4V_{2a} = 50$

$V_{2a} = 12.5$

Now substituting:

$V_{2a} - V_{2b} = -10$

$12.5 - V_{2b} = -10$

$V_{2b} = 22.5$

It can be seen from this that in this instance, the post-impact velocity of the impacted car exceeds that of the initial impact velocity.

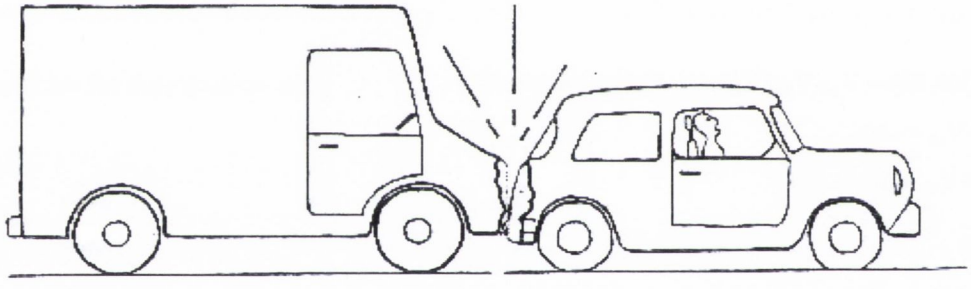

Figure H.4: Mass of Impacting Car Greater than Impacted Car

On the other hand, if the mass of the impacted car is less than that of the impacted car, the opposite effect prevails (Figure H.5). Assuming that the mass of the impacted car is three times that of the impacting one, the following calculation will apply:

EQ (1) $MV_{1a} + MV_{1b} = MV_{2a} + MV_{2b}$

$(20) + 3(0) = V_{2a} + 3V_{2b}$

$20 = V_{2a} + 3V_{2b}$

EQ (2) $e(V_{1b} - V_{1a}) = V_{2a} - V_{2b}$

$0.5(0-20) = V_{2a} - V_{2b}$

$-10 = V_{2a} - V_{2b}$

Now changing the signs in equation (1) above and using simultaneous equations we get:

$-20 = -V_{2a} - 3V_{2b}$

$-10 = V_{2a} - V_{2b}$

$-30 = -4V_{2b}$

$V_{2b} = 7.5$

Now substituting into one of the above equations, we get:

$20 = V_{2a} + 3V_{2b}$

$V_{2a} = 20 - 22.5$

$V_{2a} = -2.5$ (which is a rebounding of the impacting car into a negative velocity)

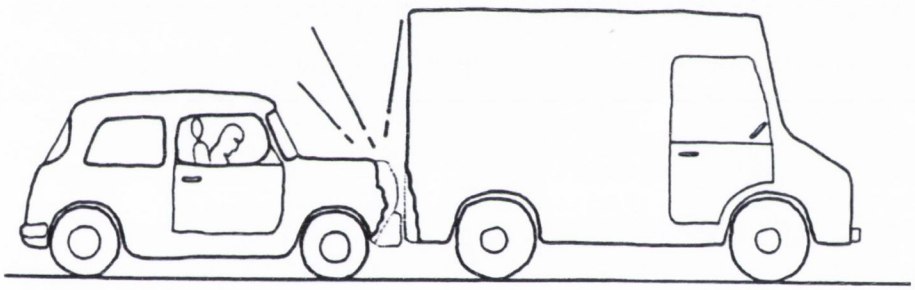

Figure H.5: Mass of Impacting car less than Impacted Car

It can be seen therefore that the relative masses of the impacting cars can play a significant role in influencing the post-impact velocity of the impacted car. If the mass of the impacting car is significantly greater than that of the impacted car, seemingly innocuous impact velocities can cause significant post impact velocities of the impacted car. However, velocity alone is not the critical feature of the event. The peak post-impact acceleration, i.e. the rate of change of velocity, is of far greater significance.

Appendix J

The Role of the Headrest in the Prevention of Whiplash

In order for cervical whiplash and TMJ damage to occur it is necessary for retroflexion to be followed by flexion of the cervical spine to occur.

It follows therefore that if the retroflexion / flexion event were prevented that neither cervical or TMJ damage would result.

An adequate support for the posterior aspect of the head would fulfil this requirement.

To be of optimum benefit, the headrest should be in contact with the back of the head at the moment of rear-end impact, so that all of the body parts are subjected to the same degree of acceleration simultaneously. The magnitude of the acceleration is not the significant factor which results in tissue damage. Accelerations of a relatively large magnitude can be tolerated if all the body parts are accelerated at the same time.

However, relatively low accelerations can cause damage if the body parts are being accelerated at different times and at different or the same rates. When this type of event occurs, torqueing of the body parts relative to each other results over short periods of time, which in turn challenges the integrity of the soft tissues joining these body parts.

It can be calculated that the space between the back of the head and the headrest should not be greater than I inch. Otherwise the head is likely to go into maximum retroflexion/flexion before the headrest has time to function (Morris 1989).

It is important that the head does not travel backwards to make contact with the headrest.

Rather the headrest travels forward to meet the back of the head.

A reasonably safe distance between the back of the head and the headrest can be calculated in order to minimize the damage that might occur, using the formula:

$S = ut + \frac{1}{2}at^2$

Where S=the distance of the back of the head from the headrest

U= the initial velocity

t =time

a = acceleration

For example:

let a = acceleration

g =10

t = 50ms

The head starts to move into relative extension after 50ms.

Therefore:

$S = 0\ (0.5) + \frac{1}{2}\ at^2$

S = 0.0306 metres i.e. 30mm

It should be emphasized that the quality of the headrest will also influence jaw movement in this type of accident, eg:

(a) If there is space between the back of the head and headrest the jaw will open to a degree directly related to the space between head and headrest (Figure J.1a).

(b) If there is no headrest or if the headrest is two low, e.g. behind the neck, the jaw is subjected to a high degree of inertial force and is likely to open to a greater degree (Figure J.1b).

(c) When the headrest is ideal and all body parts are accelerated simultaneously no jaw movement will take place. This is due to the head not being permitted to go into retroflexion, which prevents the maxilla being lifted up off the mandible (Figure J.1c).

It is important to note that the term ideal headrest implies that the headrest is in contact or just out of contact with the back of the head with the subject in his/her natural posture and that the subject is not extending the head backward to achieve contact with the headrest in an unnatural postural position.

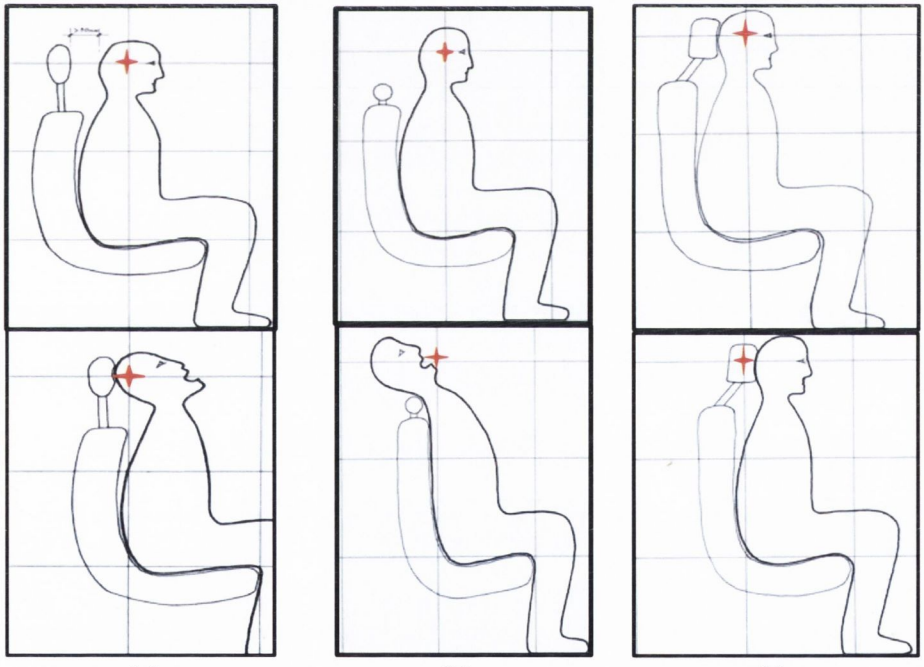

Figure J.1: Three types of headrest: (a) The distance between the back of the head and headrest is too great, allowing time for retroflexion to occur, (b) Headrest is too low and acts as fulcrum in the cervical region (c) Headrest in contact with back of head prior to impact, preventing retroflexion after impact. The red markers show the position of the head in space before and after impact.

It is important to emphasise that the design of an ideal headrest is a complex problem in that it has to deal with a variety of shapes and sizes and is therefore related to both seat and headrest designs which will cater for a wide variety of anthropomorphic types.