JOINT LOADS IN THE PRESENCE OF CHIN CUP FORCES.

(9)

BY

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ABSTRACT

Orthodontists have used chin cup therapy for the treatment of mandibular prognathism with the belief that a constant force applied to the chin and in line with the mandibular condyles would restrain growth. However, the evidence for the increased joint loads with a chin cup device has not been provided. The objective of this study was to test the hypothesis that a chin cup force does affect the load on the joints in a manner that would inhibit growth of the mandibular condyles.

This investigation used a theoretical model tailored individually by incorporating *in vivo* geometrical data collected from the anatomy of 8 volunteer subjects. Model predictions of muscle recruitment patterns in response to an externally applied chin load were validated by comparing these recruitment patterns with those generated from EMG experiments of chin cup loading. The range of chin cup loading angles employed included jaw-opening and jaw-closing angles. The magnitude of the force applied to the chin varied from 500 to 900 grams.

Since validation was confirmed by the demonstration of similar muscular activity patterns, it was possible to determine from the model, the joint loads in response to chin cup forces. Relative comparisons were then undertaken with regards to joint loads produced during normal biting. In addition, general stresses on articular surface of the condyle were calculated for the loading conditions described in the study.

Joint loads associated with chin cup forces in line with the condyles were predicted to be the lowest. Furthermore, these loads were revealed to be one third of those found in normal molar biting. General stresses produced by chin

cup forces were found to be below the threshold for inhibition of collagen and glycosaminoglycans synthesis in immature condyles. Consequently, chin cup therapy appears to have minimal effect on condylar growth.

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ABBREVIATIONS

N	Newton (force)
g	gram (force)
mm	millimetres
cm	centimetres
g/mm^2	gram per millimetre squared
RMS	Root-Mean-Square
EMG	Electromyography
mA	milliampere
GAG	glycosaminoglycan
DNA	desoxyribonucleic acid
S.D.	standard deviation
FOP	functional occlusal plane
θ_y	theta y angle
MCD	mid-condylar distance
MPa	megapascal
SCM	sternocleidomastoid muscle
Hz	hertz

CHAPTER 1 - INTRODUCTION

Traditionally, orthodontists have been recognized as the specialists for the correction of malaligned teeth. However, skeletal antero-posterior jaw discrepancies have been a subject of significant concern for the profession. Thus, different approaches were suggested for the treatment of mandibular prognathism, which is characterized by an excessive size of the lower jaw (Appendix D).

The desire to change mandible size and patient's profile by restraining the condylar growth has been traditionally expressed by orthodontic clinicians. The chin cup appliance has been the primary means employed by clinicians to treat mandibular prognathism in growing patients.

The use of the chin cup appliance (Figure 1.1) was based on the premise that a force indirectly applied at the chin and directed towards the condyles could inhibit condylar growth, and therefore reduce the forward development of the mandible. Most of the conclusions with respect to the success of chin cup therapy in humans have been drawn from cephalometric studies. However, these studies were vague as to the characteristics of the applied force system (magnitude, direction and duration of the force) to the chin.

In order to understand the mechanisms which give rise to the clinical changes observed for the treatment of mandibular prognathism, it is essential to determine the nature of the mechanical stresses transmitted to the condyles from chin cup forces.

The investigation described here involved the use of a theoretical model to determine condylar loads in response to chin cup forces, since direct measurements are not possible. In addition, a comparison was carried out between chin cup and normal molar biting with regard to their respective condylar loads. Also, limited attention is given to the neuromuscular mechanisms necessary to produce static equilibrium of the mandible. It is hoped that this investigation will provide some understanding on the effect of chin cup therapy as a method of growth manipulation.

Figure 1.1. Chin cup appliance used for clinical purposes comprises a head cap with the loading springs, and the chin cup itself.

CHAPTER 2 - REVIEW OF THE LITERATURE.

2.1. GROWTH OF THE MANDIBLE.

The growth and development of the mandible have been discussed extensively in the last fifty years (Brodie, 1941; Moss, 1972; Koski, 1974; Petrovic, 1982; Enlow, 1982; Björk and Skieller, 1983; Sarnat, 1986). The mandible has been described as a long bone bent in the shape of a "U" with cartilage growth plates at each end that are responsible for growth and offer articulation. Growth of the mandible occurs by both endochondral proliferation at the condyle and apposition and resorption of bone at cortical surfaces (Enlow, 1982). The body of the mandible grows longer by periosteal apposition of bone on its posterior surface, while the ramus grows higher by endochondral replacement at the condyle accompanied by surface remodeling (Ranly, 1988).

Moss and Salentijn (1970) and Dibbets (1985, 1990), using craniometric studies on American Indians skulls, where anatomical mandibular landmarks were superimposed at different ages, postulated that the mandible growth followed a counterclockwise circular path. However, because of the complex general and regional remodeling changes in the craniofacial skeleton, generalizing the human mandibular growth pattern by a universal curve may be controversial. Other growth studies have suggested the maintenance of a specific growth pattern (Popovich and Thompson, 1977).

The study from the Burlington Growth Center reported the peak of mandibular growth to appear simultaneously with the peak period of statural growth (Ranly, 1988). Hunter (1966) stated that there was a 4-year range for males and 5-year range for females in which the growth spurt occurred.

There is some evidence that growth is strongly influenced by genetic factors, but it can also be significantly affected by the environment in the form of nutritional status, degree of physical activity, health or illness, and a number of similar factors (Ware and Fujimoto, 1992). What determines exactly the growth of the jaws remains unclear and continues to be the subject of research.

2.2. DEVELOPMENT OF THE CONDYLE AND ARTICULAR EMINENCE.

It has been shown by numerous authors that, at birth, both the condyle and the articular eminence express an anatomical and histologic immaturity (Scott, 1955, Enlow and Harris, 1964; Wright and Moffet, 1974; Keith, 1982). On the basis of its secondary nature, a limited intrinsic growth potential and an inferior tissue-separating capacity, Copray and associates (1986) stated that the mandibular condylar cartilage could not be classified as a primary growth center. In order for the condyle and the articular eminence to reach their typical shapes, the chondroblasts and osteoblasts must be submitted to a specific environment. Engelsma *et al.* (1980) concluded from a study of rat condyles, that articular function was necessary for differentiation of condylar progenitor cells into chondroblasts to occur and, thus to maintain chondrogenesis and condylar growth. Buchner (1982) and Copray *et al.* (1985a; 1985b) also emphasized the importance of functional load on the regulation of condylar growth with respect to hyaline cartilage. Wong and Carter (1990) stated that, in regions of high shear strain, there was inhibition of chondrogenesis resulting in acceleration of cartilage ossification. Thus, the asymmetric growth pattern of the condyle may be explained by the distribution of shear stress and strain accross the mediolateral and anteroposterior aspects of the condyle (Nickel, Iwasaki McLachlan; in press).

The articular eminence develops in response to condylar loading against the temporal bone. This statement is supported by findings of Hall (1979) and Thorogood (1979) suggesting that mechanical loading is necessary to produce secondary cartilage of the eminence. Seward (1976), Hinton (1981) and Hinton and Carlson (1979) concluded that functional stresses play a significant role in defining joint morphology. Nickel and co-workers (1988) claimed that the temporospatial loading of the immature TMJ before the age of four years resulted in the development of a secondary cartilage which accounted for the timing and position of the immature eminence.

Therefore, mechanical stresses are needed not only for the normal development of the anatomy of the temporomandibular joint, as in other synovial joints, but also for the maintenance of the health of the fibrous connective tissue lining the articular surfaces of the TMJ. Stress and the resulting deformation of the soft connective tissues are essential in the fluid transport system which moves metabolites through the articular tissues (Nickel, 1991).

2.3. TREATMENT MODALITIES FOR MANDIBULAR PROGNATHISM.

For the treatment of mandibular prognathism, orthopedic methods utilizing Class III functional appliance, facemask, or chin cup therapy have been employed for growing patients, prior to and during the adolescent growth spurt (Graber *et al.*, 1967; Frankell, 1970; Irie and Nakamura, 1975; Graber, 1977; Haskell and Farman, 1985; Proffitt, 1986). Orthognathic surgery may be indicated for some non-growing patients showing excessive mandibular development (Graber and Swain, 1985; Proffitt and White, 1992).

Growth modification of mandibular prognathism involves two options: (1) redirection of growth without decreasing the size of skeletal structures, in which the chin appears to move downward and backward relative to the profile, (2) preventing an increase in size of the lower jaw relative to the maxilla.

Most functional appliances for the treatment of Class III malocclusion make no pretence of changing the relative size of the jaws. Labial tipping of the maxillary anterior teeth and lingual tipping of the mandibular incisors coupled with extrusion of upper molars have been associated with the correction pattern of the malocclusion with functional appliances (Robertson, 1983). Consequently, the use of these appliances produces a downward and backward rotation of the mandible creating a camouflage effect without restraining mandibular growth (Frankell, 1970; Proffitt, 1986).

Several studies have demonstrated maxillary advancement and backward rotation of the mandible following the use of the facemask (Irie and Nakamura, 1975; Nanda, 1978; Itoh *et al*, 1985; Ishii *et al*, 1987; Hata *et al*, 1987, Tanne and Sakuda, 1991). The facemask usually consists of a chin cup and a forehead rest connected by a wire framework, the activation being provided by elastics stretched between dentition and framework. A reciprocal posterior force is produced on the chin from the elastic activation.

Another treatment modality is that of chin cup therapy. This appliance is the object of the work reported here and is discussed in greater detail in the following sections.

2.4. CHIN CUP THERAPY.

2.4.1. Introduction.

The chin cup appliance is conventionally described as having three parts; an anchorage component comprised of a headcap firmly seated on the postero-superior aspect of the cranium, an active component comprised of with metal coil springs or elastic bands which are attached bilaterally to the headcap, and the chin cup itself. The force on the chin is produced when the springs or elastics are stretched and attached to the headcap.

Chin cup therapy has been used since the 19th century in clinical orthodontics for controlling mandibular growth of patients manifesting large and/or anteriorly-positioned mandibles. The first important historical reference relative to chin cup was recorded by Cellier in 1802 (Weinberger, 1926). One year later Joseph Fox used the device in an attempt to correct mandibular prognathism. With the demonstration in the 1960s of skeletal changes resulting from the cranio-occipital force of the headgear appliance to the maxilla (Weislander, 1963), interest in chin cups was revived for the treatment of mandibular skeletal protrusion.

2.4.2. Magnitude, direction and duration of chin cup force.

Proffitt (1986) has proposed two main approaches to chin cup therapy. The first is to apply a force to the chin on a line directly through the mandibular condyle with the intent of impeding mandibular growth in exactly the same way that an extraoral force against the maxilla impedes its growth. The second approach is to orient the line of force application below the mandibular condyle, so that the chin is rotated downward and backward by the opening moment thus generated. In clinical studies, several authors have used a chin cup force applied in line with the mandibular condyle (Graber, 1977; Sakamoto, 1981; Mitani and Fukazawa, 1986; Ishii *et al.*, 1987; Tanne *et al.*, 1993). Two studies have used a chin cup with a line of force from the mandibular symphysis through the sella turcica (Wendell *et al.*, 1985; Sugawara *et al.*, 1990). However, none of these studies has presented evidence to substantiate the merit of using a particular line of force. Ritucci and Nanda (1986) proposed the use a force direction below the condyle for patients with short faces and as vertical as possible for patients with long faces.

In clinical studies, orthopedic forces in the range of 400 (3.92N) to 900 (8.82N) grams were produced by chin cup appliance to reduce a mandibular prognathism (Irie and Nakamura, 1975; Graber, 1977; Mitani, 1977; Sakamoto, 1981; Wendell *et al.*, 1985; Mitani and Fukazawa, 1986; Ritucci and Nanda, 1986; Ishii *et al.*, 1987; Sugawara *et al.*, 1990; Gavakos and Witt, 1991; Tanne *et al.*, 1993). Graber (1975) considered the chin cup forces utilized in Thilander's study (1963; 1965) to be insufficient, suggesting a range of 680-900 grams to be necessary for good clinical results. Although, no evidence was presented to substantiate his statement.

Few descriptions were found in the literature concerning the duration of application of the chin cup force or its effects on mandibular growth. Traditionally, the duration of the chin cup force ranged from 12 to 16 hours per day, the period of activation was principally determined by patient cooperation The active treatment time with chin cup therapy varied between 24 and 72 months (Graber, 1977; Sakamoto, 1981; Mitani and Fukazawa, 1986; Ritucci and Nanda, 1986; Sugawara *et al.*, 1990).

2.4.3. Timing of chin cup therapy.

Some authors have given considerable attention to the growing phase of the mandible and patient, and the timing of the force application (Graber, 1977; Sakamoto, 1981; Mitani and Sakamoto, 1984; Mitani and Fukazawa, 1986). Graber (1977), Sakamoto (1981), Wendell *et al* (1985), and Sugawara *et al.* (1990) found an orthopedic force to be more effective in children of younger ages (under 7 years). Sugawara *et al.* (1990) stated that chin cup therapy was more effective before the pubertal growth spurt. Mitani and Fukazawa (1986) and Sugawara *et al.* (1990) reported that the application of chin cup force does not appreciably alter the mandibular growth pattern during puberty.

The work of Mitani and Sakamoto (1984) suggested that the changes in the direction of mandibular growth achieved by an orthopaedic chin cup force were temporary. After removal of the chin cup force, the growth of the mandible returned to the pretreatment direction. Sugawara *et al.* (1990) explained that facial profiles have a tendency to return to their original shapes, which may have been determined morphogenetically. Conflicting evidence has been reported with respect to the possibility of a "catch-up" growth behaviour after removal of the chin cup force (Asano, 1986; Sugawara *et al.*, 1990).

Mitani and Fukazawa (1986) examined serial lateral cephalometric radiographs and hand-wrist roentgenograms of 26 Japanese girls and reported some increments of growth in the mandible during the three growth phases. They stated that complete inhibition of mandibular growth was difficult, if not impossible, to achieve with "conventional" chin cup therapy in human subjects. From their findings, they concluded that the inherited growth potential plays a major role in the development of the mandible, regardless of the influence of the orthopedic force. This was supportive of earlier findings by Broadbent (1937) and Brodie *et al.* (1938) on skeletal growth from which they concluded that skeletal pattern should be regarded as fixed and unalterable, unless a surgical procedure was performed.

2.4.4. Biomechanical effects of chin cup forces.

Baume (1961), Levy (1964) and Ranley (1988) have defined the mandibular condyle as a growth center. Therefore, it was postulated that the mandibular retraction force produced by a chin cup could inhibit growth of the mandible and enhance other orthopedic effects (Proffitt, 1986). This postulate has been tested and, the results were reported for numerous experimental and clinical studies. Among the most common effects of chin cup therapy were **(1)** a change in direction of mandibular growth to a downward and/or backward vector (Janzen and Bluher, 1965; Sakamoto, 1981; Wendel and Nanda, 1985), **(2)** a decrease of the gonial angle in animals (Janzen and Bluher, 1965; Matsui, 1965; Joho, 1973) and humans (Graber, 1977; Irie and Nakamura, 1975; Sakamoto, 1981; Mitani and Sakamoto, 1984), **(3)** histologic changes in the temporomandibular joint under the retractive force in various animal experiments (Janzen and Bluher, 1965; Matsui, 1965; Charlier *et al.*, 1969; Petrovic *et al.*, 1979; Sakamoto *et al.*, 1984; Asano, 1986), **(4)** backward repositioning of the mandible (Armstrong, 1961; Thilander, 1963; Graber, Chung and Aoba, 1968; Cleall, 1974; Nanda, 1980; Mitani and Sakamoto, 1984), **(5)** retardation of mandibular growth (Janzen and Bluher, 1965; Matsui, 1965; Graber, 1977; Sakamoto *et al.*, 1984), and **(6)** remodeling of the mandible (Matsui, 1965; Wendell *et al.*, 1985; Asano, 1986; Mitani and Fukazawa, 1986). These effects may produce temporary skeletal changes which alter the prognathic skeletal profile, (particularly when applied at early ages) as expressed by Graber (1977), Sakamoto (1981), Wendell and Nanda (1985) and, Sugawara *et al.* (1990).

Wendell *et al.* (1985) attributed profile changes following chin cup therapy to rotational changes, which were produced by the line of force of the appliance, coupled with remodeling changes that occur throughout the mandible. Furthermore, the remodeling of the chin morphology at the pogonion area, as a result of chin cup wear, was presented as a significant contributor to the decrease in mandibular body length.

Graber (1977), Wendell *et al.* (1985), and Ritucci and Nanda (1986) have observed retardation of vertical growth of the ramal height. Pearson (1978), Heckman (1974), and Hirose *et al.* (1981) stated that the chin cup could control dentoalveolar growth and reduce lower facial height. Wendell *et al.* (1985) and Ritucci and Nanda (1986) have associated a closing of the cranial flexure angle with chin cup therapy.

2.5. EVIDENCE AND RATIONALE REGARDING CHIN CUP THERAPY.

2.5.1. Clinical studies.

Previous studies on the use of chin cup appliances with human subjects have reported varying levels of success (Graber *et al.*, 1967; Matsui, 1965; Armstrong, 1961; Thilander, 1963; 1965; Irie and Nakamura, 1975; Sugawara *et al*, 1990).

Some clincians have attempted to explain the inconsistencies in the success of chin cup therapy. Cleall (1974) suggested (1) lack of cooperation from the patient, (2) patient discomfort, (3) intermittent nature of the force application, (4) inability to deliver enough force to the growth sites to achieve any substantial change in the growth pattern, (5) incorrect direction of force application.

Graber (1977) explained that the differences in clinical results may be related to the variability of appliance design, duration of treatment, magnitude of force utilized in the appliance, and age of the subjects being treated.

It is easy to realize that a non-cooperative patient or a maladjusted appliance may signify a decrease in the number of hours of wear and therefore a treatment failure independent of the treatment approach. However, the evidence necessary to support an ideal duration, magnitude or direction of applied force in regard to chin cup therapy and on its effects on mandibular growth is lacking from the literature. As a result, the suggestions offered by Cleall (1974) or Graber (1977) represent little value.

Certain clinicians have made statements about the detrimental effects of chin cup therapy without supporting their allegations with genuine scientific evidence. Wyatt (1987) has raised the possibility of posterior condylar displacement in developing TMJ internal derangement, when posteriorly directed force was applied to the chin. Some concerns were formulated about the long-term effects of chin cup therapy on the temporomandibular joint health. Major and Elbadrawy (1993) postulated that forces of sufficient magnitude to inhibit condylar growth may cause the ligaments to stretch, increasing the risk of TMJ dysfunction.

2.5.2 Animal experiments.

Animal experiments have presented inconsistent evidence depending on the animal model used. Investigations in which rat mandibles were submitted to a retracting force showed definite histologic changes (Charlier *et al.*, 1969; Asano, 1986). In experiments with monkeys using a chin cup-like device, radiologic evaluations confirmed significant skeletal variations while microscopic examinations reported little histologic reactions. (Janzen and Bhuler, 1965; Joho, 1973).

Janzen and Bluher (1965) demonstrated from experiments on monkeys using 300 grams of force applied to the mandible, an absence of inflammatory or apparent degenerative changes. The findings suggested that the experimental force did little damage to the joint and its surrounding structures. Cephalometric changes were the most significant. They postulated that the factors responsible for the protection of the TMJ against non-physiologic forces are the articular discs and most importantly, the "external pterygoid" muscles, which were found to be definitively hypertrophied. In addition, they suggested a functional reaction of the masseter and "internal pterygoid" muscles from the observation of antegonial notching at the mandibular borders.

Joho (1973) used a 350 gram downward and backward force applied on the lower molars of monkeys. For most animals, he observed a cellular activity at the condylar cartilage close to normal at the end of treatment. However, no control animals were used.

Charlier *et al.* (1969) failed to describe the force magnitude and direction used in their rat study of the histologic changes of the mandibular condyle in response to a retractive force. Moreover, this unknown load was applied intermittently for 6 hours per day for a period varying between 14 and 28 days. A decrease of the prechondroblastic layer was observed, though this may have represented a transitory adaptive reaction. However, the transitory nature could not be assessed, since no longer term histologic examinations were performed after 28 days of load application. Asano (1986) described a similar histologic response with respect to the prechondroblastic layer, to a thirty gram retractive force on the growing rat mandibles.

Belhobek (1974) investigated the effects of traction on the mandibular condyles of growing guinea pigs, and found that a force equivalent to 700 grams in humans did retard the condylar growth. However, this comparison of a animal model with humans bears little credence.

It was reported from animal studies that mechanical stress acts directly on the chondrocytes to modulate their proliferation (Engelsma *et al.*, 1980; Buchner, 1982; Copray *et al.*, 1985a; 1985b). However, growth processes in the condylar cartilage were found to be dependent on the magnitude and duration of the static compressive force. Copray *et al.* (1985b) stated that a small continuous compressive force of 3 grams reduced the synthesis of the glycosaminoglycans (GAG) and collagen by the functional chondroblasts. However, Copray and coworkers (1985b) did not measure the surface area over which the compressive force was applied. Takano-Yamamoto and coworkers (1991) observed an inhibitory effect on GAG and chondrocyte DNA synthesis by a larger magnitude or a longer duration of continuous compressive force in cultured mandibular condylar cartilage of rabbits. The analysis of the graphical results revealed, in fact, a force magnitude threshold for maximal synthesis of GAG and DNA at $200 gm/cm^2$, rather than an inhibitory effect.

Studies on cellular behaviour could offer some rationale for the use of chin cups in treating mandibular prognathism assuming that the applied force on the chin increases condylar loads and consequently, impedes chondrocyte proliferation and matrix synthesis. However, the choice of the rat as an animal model for condylar loading experiments creates some scepticism when it comes to relate the results to humans. It becomes difficult to determine a comparable force magnitude for human studies. Moreover, the joint morphology and function, the masticatory muscles and the jaw bones of the rat are far from presenting any similarity to the human chewing apparatus. In addition, no evidence was found showing that loads at the temporomandibular joints were effectively augmented during chin cup therapy in humans. The difficulty is likely to be associated with the inability to measure directly the joint loads. Thus, in the present study, indirect modalities had to be considered in order to obtain a reasonable estimation of the joint reactions.

2.5.3. Theoretical modelling approaches.

A few investigations have used modelling as a means to determine the effects of a mid-sagittally applied mandibular load.

In a study using photoelastic skulls, de Alba y Levy *et al.* (1976) demonstrated that stress induced from a chin cup load was distributed on the outer surface of the lateral pterygoid plates and the posterior aspect of the glenoid fossa. However, this modeling did not take into account the presence of forces generated by muscles and ligaments and, therefore, does not allow any valid comparisons with *in vivo* conditions.

Trainor (1992) tested a numerical model of TMJ loading by comparing model calculations to measured EMG in individuals subjected to a 25N force on the chin. From his findings, he emphasized that the joint morphology had developed primarily to allow minimization of joint load.

Tanne *et al.* (1993) investigated the potential biomechanical changes of the mandible resulting from orthopedic chin cup forces by using a theoretical three-dimensional finite element model of the mandible to analyse stress distribution in the mandible. An orthopedic force of 400 grams (3.92N) applied on the mandible at pogonion (most anterior point on the chin) was directed toward the condyle. Tanne and coworkers (1993) reported that for the condition tested, uniform tensile stresses were produced at the outer borders of the mandible, which were regarded as bending stresses. Also, the compressive stresses on the condyle were larger on the posterior and lateral aspects. Stresses on the condyle were smaller in magnitude than those in the mandibular corpus and ramus. The investigators suggested an association of stresses with remodelling of the mandible from chin cup therapy applied to adolescent patients with mandibular prognathism. In this study, no consideration was given to the muscles with respect to their existence and to the appropriate force direction, when investigating external loading on the mandible. Therefore, any conclusions drawn from this study should be formulated with extreme caution.

In summary, the effects of chin cup force on craniofacial growth, in particular on the mandible, have been investigated extensively mainly by means of cephalometric and animal experiments. Redirection of the chin point and inhibition of mandibular growth, backward repositioning of the mandible and remodelling of the mandibular shape have been reported. However, the disparity within the results of human and experimental animal studies, added to the inconsistency of findings within the human experiments themselves, have produced uncertainty about the effectiveness of this treatment modality. Moreover, the majority of theoretical modelling studies have excluded important parameters which makes the interpretation of the results very difficult. In addition, the use of mathematical modelling to study mandibular loading remains the only way to explore certain hypotheses, but must be tested for validity by corroborating the theoretical results with results obtained from *in vivo* experiments.

CHAPTER 3. STATEMENT OF THE PROBLEM AND OBJECTIVES OF THE STUDY.

Clinicians have been known to favour certain treatment modalities based on empirical observations. Little evidence is often presented to substantiate the treatment methods employed and to demonstrate their indisputable efficacy. The data collected from the considerable number of studies, most of them of cephalometric nature, have shown results based mainly on skeletal jaw relationships. No definite conclusion may be drawn from any cephalometric study regarding a condylar response to chin cup therapy by simply measuring the length of the mandibular ramus. The two dimensional static character of these studies of the jaw positions has limited the capability of clinicians to understand comprehensively the mechanism producing ant observed skeletal changes.

Historically, chin cup therapy has been used by orthodontists to restrain mandibular growth. It has been suggested that the application of a force to the chin resulting in an increase in the magnitude of loading of the condyle against the temporal bone of the temporomandibular joints, can retard growth of the condyles and thus mandibular growth.

No studies were found that addressed the issue of joint load with respect to chin cup force, nor were any found that investigated how the neuromuscular system responds to a sagittal force applied to the chin. No attempt has been made to present a reasonable argument that a posterior force applied to the chin or the mandible damages the retrodiscal tissues of the temporomandibular joint. Without evidence from human studies, it is hazardous to extrapolate the results obtained from animal experiments (Janzen and Bluher, 1965; Charlier *et al.*, 1969) to human temporomandibular joints. Although it has been well established that human TMJ's are loaded during isometric biting (Smith *et al.*,1986; Faulkner *et al.*, 1987; Boyd *et al.*, 1990;), it appears essential to determine the joint loads in response to a chin cup force, and to compare the loads with those produced by normal biting.

The purpose of this study was to test the hypothesis that the chin cup force does affect the load on the joints in a manner that would be consistent with inhibiting growth of the mandibular condyles.

In order to investigate the validity of this hypothesis, the pattern of muscle activity produced in reaction to chin cup forces was measured using electromyography. The measurements (Root-Mean-Square) of raw EMG signals were then compared to muscle forces calculated by a numerical model of joint loading. The numerical model calculated the muscle and joint forces needed to satisfy an objective function such as the minimization of muscle effort or minimization of joint forces. Validation of the model calculations using EMG recording as a measure of muscle recruitment has received significant support among investigators (Barbenel, 1974; Pruim *et al.*, 1980; Faulkner, Hatcher and Hay, 1987; Koolstra *et al.* 1988; Koolstra and Van Eijden, 1992). Therefore, the present study was an effort to obtain an adequate understanding of the neuromuscular response of the masticatory apparatus generated by the chin cup force, as well as the effect that chin cup loading may have on the growth of the condyles.

However, in order to verify the main hypothesis, a secondary hypothesis was tested that whether joint loading from chin cup forces generated significantly larger joint loads than those produced during normal functional biting.

CHAPTER 4. MATERIALS AND METHODS.

4.1. INTRODUCTION.

It has been assumed that chin cup therapy has a restraining effect on mandibular growth by way of the application of a force on a line directly through the mandibular condyles (Irie and Nakamura, 1975; Graber, 1977; Sakamoto *et al*, 1984). It is suggested that there is an increase in the magnitude of loading of the condyle against the temporal bone of the temporomandibular joints. Such an increase of load is presumed to inhibit chondrocyte mitosis (Copray *et al.*, 1985a, 1985b; Takano-Yamamoto *et al.*, 1991; Gray *et al.*, 1988, 1989).

The purpose of this investigation was to test the assumption that chin cup therapy increases the magnitude of condylar load against the temporal bone which in turn, impedes condylar growth. The investigation used a theoretical model to calculate the loading of the temporomandibular joints for a given force applied to the chin. The numerically determined condylar loads were verified by comparing numerically determined muscle activity with *in vivo* measurement of muscle activity during the application of chin cup force. It was not possible to use a commercial chin cup since it allows only a single point of force application. A significant instability of the chin cup would result from a change in the direction of the applied force. Therefore, an experimental chin cup was designed to prevent moments produced by the applied force to occur when the line of force was changed to different directions (Figure 4.1). Muscle activity was recorded on these subjects using electromyography. The subjects for this investigation were chosen to fulfill certain geometric and functional requirements based on a clinical examination and cephalometric analyses. The research proposal approved by the Faculty Committee on the Use of Human Subjects in Research, University of Manitoba. The experimental design of the study is displayed in Table 4.1.

	HEAD POSITION		TEETH		CHIN CUP LOAD ANGLE	CHIN CUP FORCE MAGNITUDE
	Supported	unsupported	together	apart		
Session 1	X	X	X		variable	500 - 900 grams
Session 2	X	X		X	variable	600 - 900 grams

Table 4.1. Experimental design as followed in the present investigation.

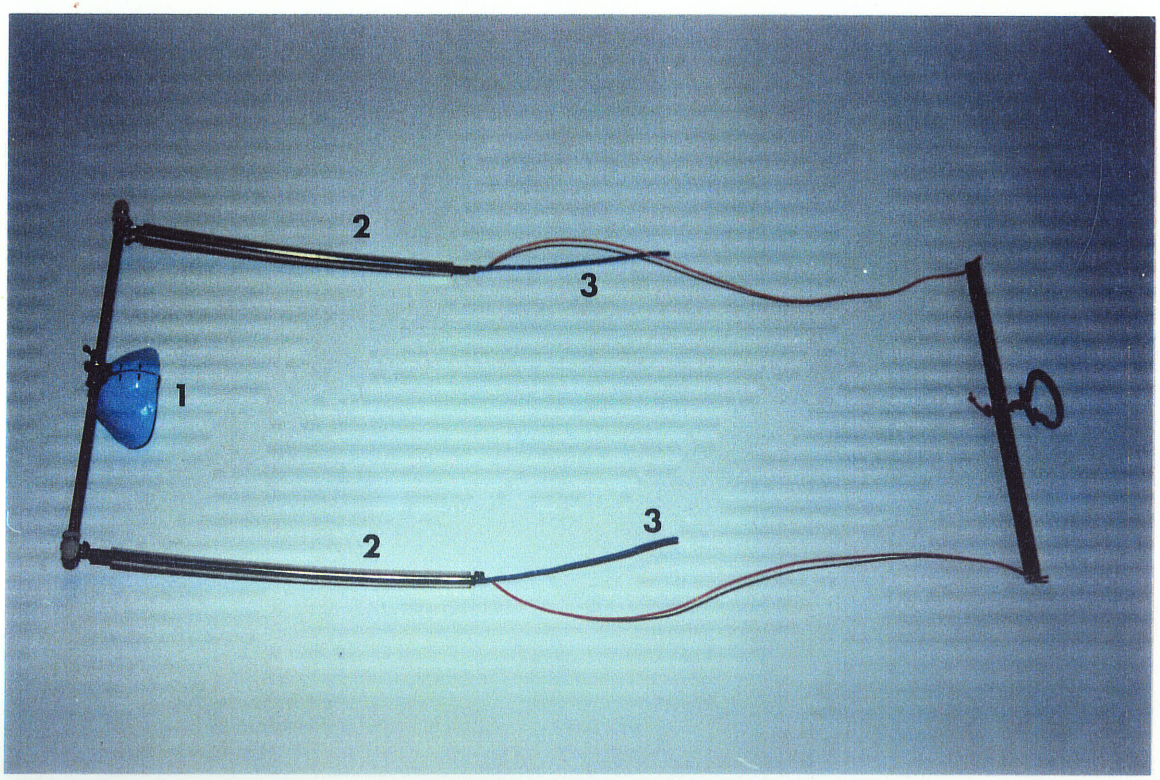


Figure 4.1. Experimental chin cup (1) used in the study with bilateral loading device (2) and wire gauge (3). A more detailed description is provided in section 4.3.

4.2. DESCRIPTION OF THE CLINICAL SAMPLE.

4.2.1. Clinical examination.

A clinical examination and a cephalometric assessment were performed to demonstrate the mesognathic Angle Class I dentoskeletal relationships of the individuals included in the study. The clinical evaluation was divided into three components: static intra-oral, cervico-facial and temporomandibular examinations. The static intra-oral analysis was part of the pre-orthodontic records and involved dento-alveolar classification, overjet and overbite appraisal, midline coordination assessment, tooth position and alignment, dental and periodontal health. The skeletal assessment was achieved by using a method employing the cephalometric radiographic records commonly used by orthodontists as a diagnostic aid. The extra-oral facial examination was done to assist the evaluation of the skeletal relationship. The skeletal symmetry was assessed clinically as well, and was considered as an important element of the clinical evaluation. Finally, the dynamic analysis was performed to investigate functional shifts of the mandible, working and protrusive excursions, range of movements, and any signs or symptoms of temporomandibular disorders.

4.2.2. Radiographic assessment.

The method described was aimed at investigating the link between a normal dentoskeletal relationship and a muscle recruitment pattern as related to the plane of occlusion. The dental and skeletal classifications were confirmed cephalometrically by analysis of tracings produced from lateral cephalometric radiographs. The Manitoba Cephalometric Analysis (Beaton, 1973) was used to quantify and compare the different values to the normative ranges (Appendix B).

The cephalometric radiographs were obtained in the Graduate Orthodontic Clinic, Department of Preventive Dental Science, Faculty of Dentistry, University of Manitoba using a Gendex GX-CEPH 900 machine. The focal spot-midsagittal plane distance was 152.4 centimeters, and the film-midsagittal plane distance was 15 centimeters. The roentgenographic source was fixed. The radiographs were recorded on Kodak T - MAT G (registered trademark) film with regular speed screens. For the lateral cephalometric views, the machine settings were 15mA and 90 kVP for an exposure of 3/10 second. An erect stance, with teeth in maximal occlusion and the lips relaxed, was the standard position for all of the radiographs made of the patients involved in the study. These radiographs were part of the initial orthodontic records made at the University of Manitoba and were therefore available for the study.

The Burlington Growth Centre Cephalometric Analysis (Popovich and Thompson, 1977) was also used by means of templates to evaluate the facial form.

4.2.3. Characteristics of the sample group.

The patients in this study were selected to represent normality of the dentoskeletal structures. Thus, eight subjects, three females and five males, were recruited from the pool of patients seeking orthodontic treatment at the Graduate Orthodontic Clinic, University of Manitoba. These individuals were North American Caucasians. Their ages ranged from 13 to 27 years, with a mean age of 19 years. All subjects were in good health with no reported physical problems.

Participation in this research project was on a voluntary basis. Subjects were clearly informed that they could withdraw from the study at any time and continue with their orthodontic treatment without penalty. Authorization was obtained by the signature on a consent form by every subject or parent (Appendix A).

The facial profile type was initially assessed demonstrating in every subject a mesognathic straight facial profile type, a craniofacial symmetry, normal apparent muscular balance with adequate lip seal. The Manitoba Cephalometric Analysis used to quantify and compare the normative ranges showed one degree (S.D.; 1.8°) as a mean value for ANB angle. The Burlington Growth Center templates demonstrated a trend toward a downward and forward growth of the mandible in all subjects.

Five subjects demonstrated a Class I molar relationship, two presented a very slight Class III (1.0mm) molar relationship, and one was very slightly Class II (1.5mm) molar relationship. All subjects presented with either spaces between the teeth or mild crowding without exceeding 3.0mm of total crowding. Lower curve of Spee was minimal for every individual (<2.0mm).

The patients were screened to ensure there were no disorders of the temporomandibular joint or disorders of the muscles of mastication. No patients had a prior history of orthognathic or orthodontic treatment.

4.2.4. Justification for sample size.

It was decided to choose individuals that, as closely as possible, had normal skeletal and dental anatomies, and therefore were a reasonable test of the theoretical model. Despite all the efforts expended to recruit subjects, the sample was relatively small. It is possible that the strictness of the selection criteria may have represented a limiting factor in getting a larger number of subjects. However, in an electromyographic study, it is more valuable and meaningful to compare the pattern of muscle activity from the EMG recordings with a theoretical model of muscle behaviour. Thus, the model/EMG comparisons were done on an individual basis. Importantly, when investigating the clinical significance of a treatment modality, the number of involved subjects does not represent a significant factor if similar results can be found for every subject. Consequently, the sample size was not as critical in order to validate the study. In addition, the sample size was comparable to other studies where predictions of recruitment patterns of the masticatory muscles were validated in *in vivo* experiments (Koolstra and Van Eijden, 1992).

4.2.5. Marking of muscle coordinates and photographic records.

The numerical model used in this study to generate predictions of muscle recruitment and joint loads was originally developed to investigate different biting situations such as unilateral biting. Therefore, three-dimensional coordinates of specific parameters had to be determined in order to make the model functional (Figure 4.2.). However, since these coordinates were measured relative to the midsagittal plane, certain anatomical structures could not be measured in the z plane. The technique employed to calculate the z coordinate is discussed further in this chapter.

Thus, the geometric anatomical relationships between the mandibular condyles, the origins and insertions of the superficial masseter, anterior temporalis, anterior digastric, and the tooth row (occlusal plane) were determined by doing direct linear measurements on each subject's face. A metallic occlusal template (Fox plane; Trubyte, Dentsply) was introduced in the subject's mouth over the lower dentition, having the subject gently biting on it to hold the device in place. A line was then traced using a black Staedtler Lumocolor non-permanent fine pen (Steadtler, AV; West Germany) to define the occlusal plane. Spatial relationships were expressed using the mutually perpendicular x, y, z axes of an orthogonal system (Figure 4.2.). The origin of the system was the midpoint of the intercondylar axis, and the occlusal plane was parallel to the x-z plane. Consequently, any point could be defined by three coordinates in the orthogonal axis system.

Lateral and frontal photographs were taken of the subject's face, with the anatomical coordinates marked for future reference. The camera used for photographic data collection was a mono-lens reflex Canon T70 35mm camera (Canon Canada Inc. 10652 Côte de Liesse, Lachine, Qc) and color film for photographic slide transparencies (Fuji, Fujichrome, ASA 100 (RD 135): Fuji Photo Film Canada Inc, Mississauga, ON.).

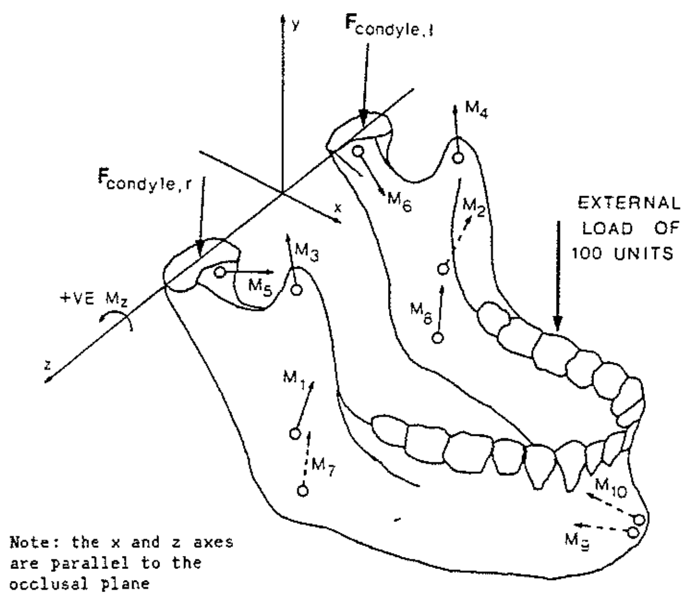


Figure 4.2. Orthogonal axis system used for the spatial relationships of the anatomical structures. to be modelled (From Trainor, 1992).

4.3. FABRICATION OF CHIN CUP AND LOADING DEVICE.

4.3.1. Chin impression.

A chin impression of each individual was made at the initial appointment using a perforated acrylic impression tray (Fastray; Bosworth) filled with a Polysiloxane impression material (Reprosil; Caulk Division, Dentsply International Incorporated, Milford, Delaware).

The impression was poured with orthodontic white plaster (Modern Materials, Miles inc, South Bend, Indianna, USA). Once set, the gypsum castings were recovered from the impression material and inspected. The base of the chin impression was then trimmed. The average width of the chin replicas was 98mm and the average height 73mm.

4.3.2. Chin cup fabrication.

The chin cup had to be as light and thin as possible. It had to be rigid to withstand deformation upon loading. The chin cup had to cover a large area in order to allow distribution of the force over a wide surface of the chin and to increase resistance against the moments generated by the applied force. Furthermore, the midsagittal point of force application on the chin cup, had to be changed to different locations in an inferior/superior direction in a simple and quick way.

The chin cup was fabricated on the plaster chin reproduction. A separator liquid (Cold Mold Seal; DeTrey, Dentsply.) was painted on the plaster model in preparation for the addition of acrylic. The base of the chin cup was made from self-curing blue acrylic (Fastray; Bosworth) which was molded on the cast to cover as much surface as possible. Then, an inverted "T" template of pink denture base-plate wax (NeoWax Baseplate Wax, 0.050 inch thick: Dentsply/York Division, Dentsply International Incorporated, York, Pennsylvania.) was carved and affixed onto the chin cup base to form the future slot (Figure 4.3). This slot would eventually be used for the insertion and displacement of a sliding loop where the point of force application would be located. Another layer of self-curing acrylic was added over the wax and allowed to set. The wax was removed with boiling water and the chin cup was thinned down and polished. The sliding loop was made from end stops for curtain beam tracks (Newell Window Furnishings, Prescott, Ont). The base of each of the end stops was ground and curved to slide easily in the chin cup slot.

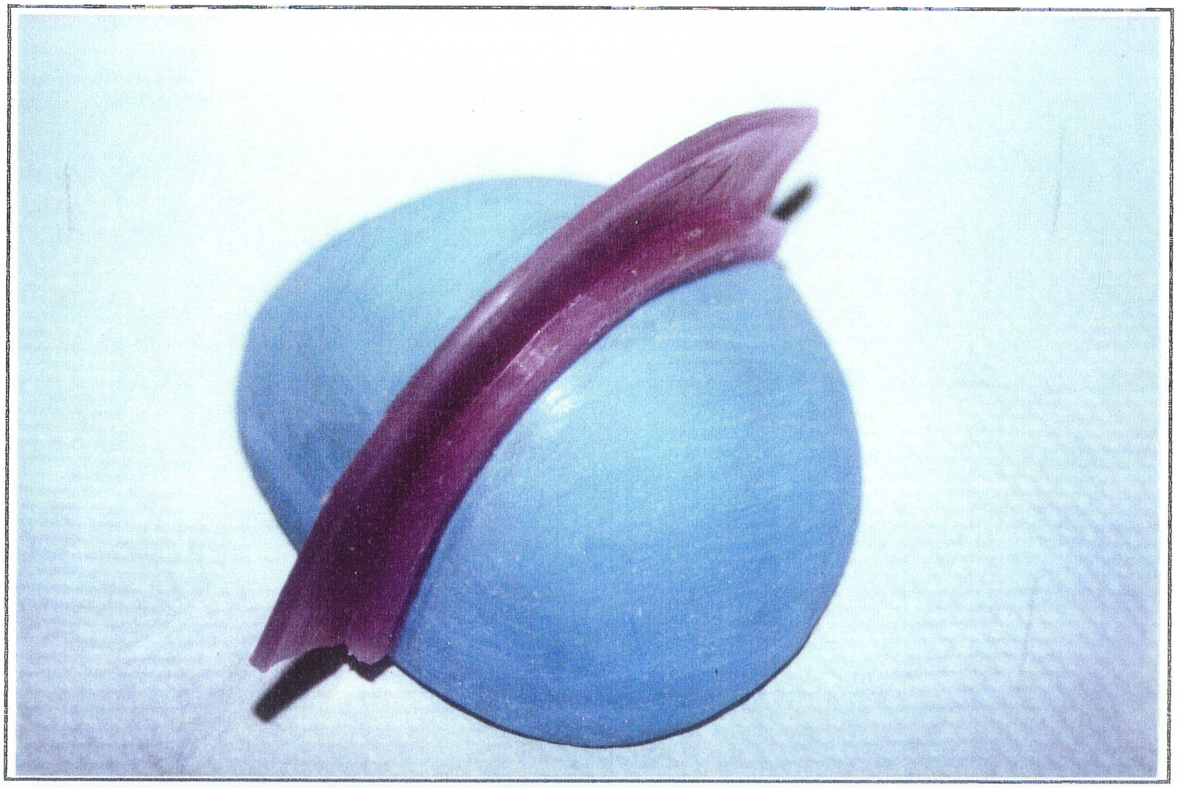


Figure. 4.3. A waxed template was affixed to the acrylic chin cup base and then covered with another layer of acrylic. After completing the application of acrylic, and removal of the wax pattern, this procedure produced a slot of a predetermined size which allows varying the point of force application in any location.

4.3.3. Loading device.

On the external portion of the chin cup, five equidistant lines were marked along the midsagittal slot to identify the different points of load application to be tested. The adjustable sliding loop was inserted at one end of the slot and tightened in place by a "butterfly" nut at an identified location. A transverse brass rod 240mm in length and 4.5mm in diameter weighing 40 grams was used as a "yoke". The rod was introduced through the sliding loop and secured in place using aluminum rings which were screwed into place (Figure 4.4). At each end of the brass rod, a tension spring was attached, using plastic nuts which restricted transverse movement of the springs on the yoke

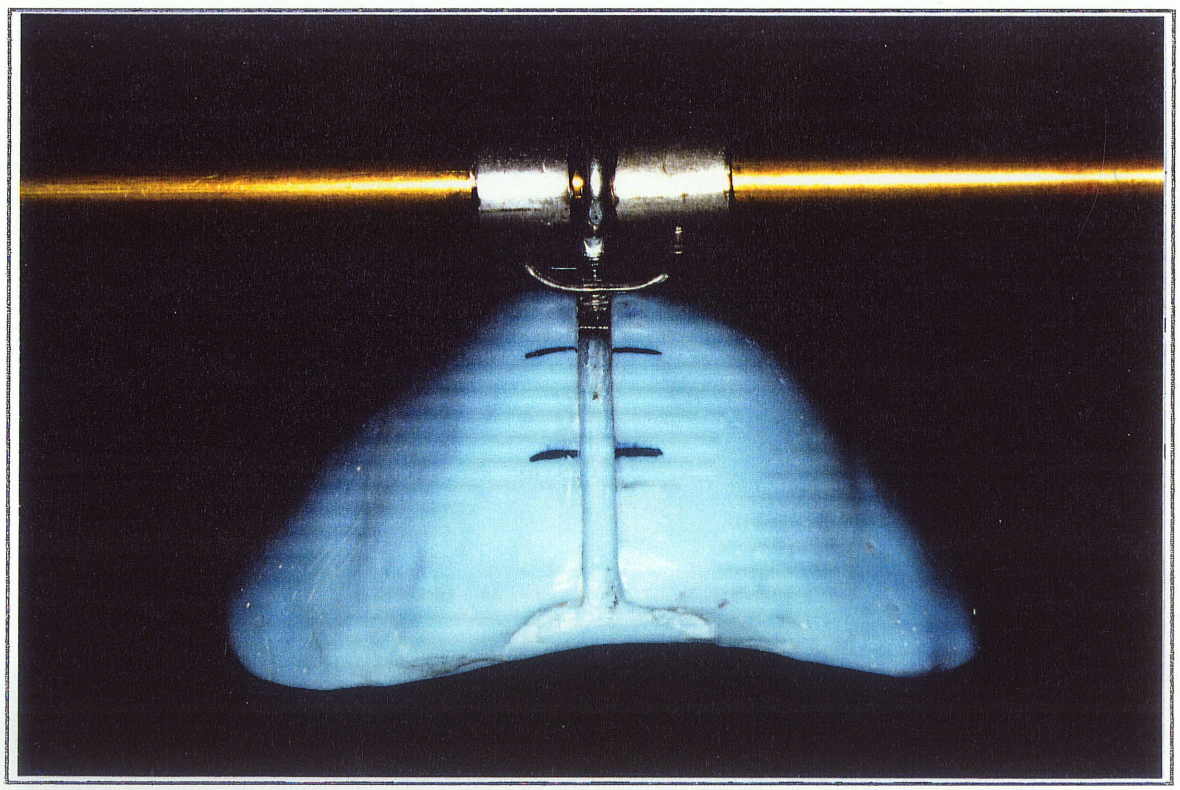


Figure 4.4 Details of the grooved chin cup and of the attachment to the loading yoke.

The springs were calibrated to produce known forces to the chin cup. The lowest force applied to the chin was 500 grams, and increased at 100 gram intervals, to a maximum of 900 grams. The two tension springs were reunited behind the subject's head to another transverse rod to which was fixed a midpoint handle. This handle simply transferred the line of the two lateral forces to the mid-sagittal point behind the subject's head.

4.4. ELECTROMYOGRAPHIC ANALYSIS.

All the experimental sessions were conducted in a designated EMG recording and data analysis room (room 411, Department of Civil Engineering, University of Manitoba). During a recording session, the doors were kept shut and the window shaded, in order to minimize exposure of the subject to external stimuli.

4.4.1. Description of equipment.

The electrical activity of the muscles being tested was monitored using Grass silver cup 7mm diameter bipolar surface electrodes. Four pairs of electrodes and four amplifiers were utilized. Each electrode pair was connected to a very high (> 10^8 Ohms) input impedance and strong (100 dB) common mode rejection preamplifier (Biological Amplifier System: BioSys, Winnipeg, Manitoba) having a voltage gain of 100. The four preamplifiers were fixed to a grounded wall unit. The output from the preamplifier was input to the second stage amplifier using an optical coupler.

The second stage amplifier (Biological Amplifier System: BioSys, Winnipeg, Manitoba) had adjustable, first order, low and high pass filters. There was an adjustable gain control which provided up to 100 times gain. Thus, the maximum system voltage gain was 10,000. The second stage amplifier was limited to an output of ten volts peak to peak. Both the preamplifier and the second stage amplifier were powered by a rechargeable battery.

The output from the second stage amplifier was directed to a Hewlett Packard Model 1200A dual trace oscilloscope; and to a Hewlett Packard 3960 Series Instrumentation, Frequency Modulated, four channel FM Tape Recorder. The signals were recorded on magnetic tape (3M Recording Tape, 809-¼-1800 PR7: 3M Magnetic Media Division, St. Paul, Minnesota) for later replay and analysis using a computer (Figure 4.5).

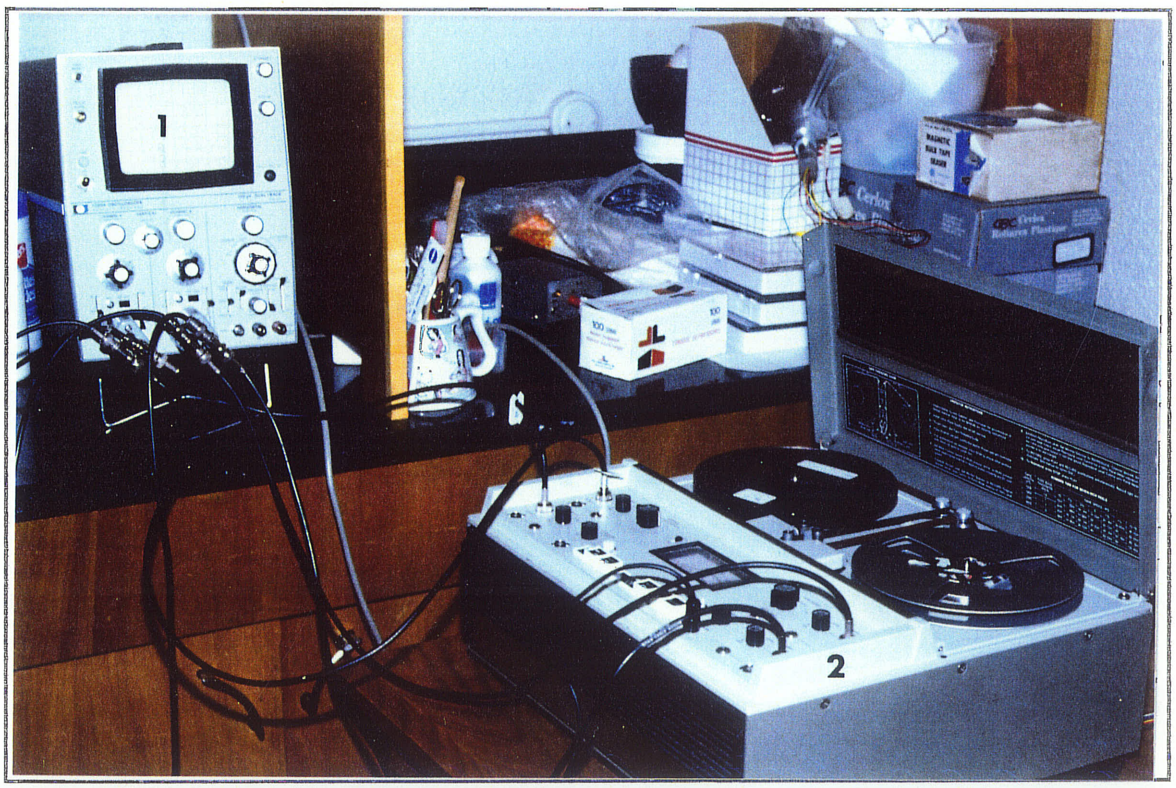


Figure. 4.5. EMG output signals were also directed from the oscilloscope (1) to a four channel tape recorder (2) where the signals could be stored.

The oscilloscope was used to provide the operator with continuous visual information about the functioning of the recording apparatus throughout each recording session. It was possible to see the activity of any two muscles simultaneously and switching between muscle outputs was easily performed.

4.4.2. Muscles to be assessed and skin preparation.

In preparation for a recording session, each male subject was asked to shave his face prior to the session, and all subjects were asked to refrain from applying facial ointments. At the beginning of each session the subject was seated in an upright position in a dental chair. Only four channels were available for the EMG recordings, but the chin cup load was applied symmetrically. Thus, the muscle recruitment pattern was assumed to be similar for the right and left side. This was confirmed by a preliminary EMG testing done on a selected subject. As a result, muscles assessed in all recording sessions, were the left anterior temporalis, left masseter, left sternocleidomastoid muscle, and the combined anterior digastric muscles. The identification of origin, insertion, and line of pull of these muscles was accomplished by digital palpation. The center of the most active portion of these muscles was determined in different ways. The subject was asked to gently clench the teeth together for the masseter and anterior temporalis muscles. For the anterior digastric muscles, the subject was asked to push with the tongue against the anterior portion of the hard palate (Jankelson; 1984). The sternocleidomastoid muscle was identified by asking the subject to resist a pressure applied at the forehead. Following muscle identification, the skin was prepared for the application of the EMG surface electrode. The skin over each muscle, and one ear lobe (for the ground) was cleansed using a 45 second wipe with gauze soaked in 70 percent isopropyl alcohol, followed by a 30 second period which allowed the alcohol to dry.

4.4.3. Placement of electrodes.

Grass silver electrodes were stuck onto self adhering foam pads (Reston (TM) Adhering Foam Pads, 1560M: 3M Medical-Surgical Division, St.Paul, Minnesota) at a distance of 25mm apart, and a small amount of Liqui-Cor (Burdick Corporation, Milton, Wisconsin) liquid ECG conductor was applied to each electrode. The foam pads with the electrodes and the conducting paste were then applied to the prepared skin over each muscle. The electrode pair was positioned over and in line with the muscle fibers (Jankelson; 1984). The ground consisted of only one electrode affixed to a foam pad that was pressed firmly in place on the prepared earlobe, and held in place with a small plastic clip.

The surface impedance of each prepared muscle site was measured using a Hewlett Packard E2377A multimeter. Impedance levels of less than 20 kilo-ohms were considered acceptable. If impedance was greater than 20 kilo-ohms, the skin site was prepared again with alcohol, In some cases, different electrode pairs were used until satisfactory impedance level was achieved.

4.5. INSTRUCTIONS TO SUBJECTS.

Figure 4.6 presents the EMG electrode positions and the loading device. Following EMG electrode placement, each subject was seated upright in a dental chair, with his/her back supported. For the first part of each recording session, the subject had the head braced against a headrest. In the second half of the session, the head was unsupported. The chin cup traction routine practiced once. The following instructions were given to the subject: 1. Remain as quiet and relaxed as possible through out the recording session. 2. Remember to sit up straight. 3. Do not move your head, keep it stable. 4. Do not swallow or move until the tape recorder has stopped. 5. Keep your teeth together without biting (first session). 6. Keep your teeth slightly apart (1-3mm at the incisors) to avoid tooth contacts. If you feel any tooth contact, please report it after the tape has stopped (second session).

Having the subject with the teeth slightly apart without tooth contacts allowed a situation of static equilibrium for the mandible to be investigated. In another session, the subject was also required to keep the teeth together without biting, which was thought to be representative of a clinical condition.

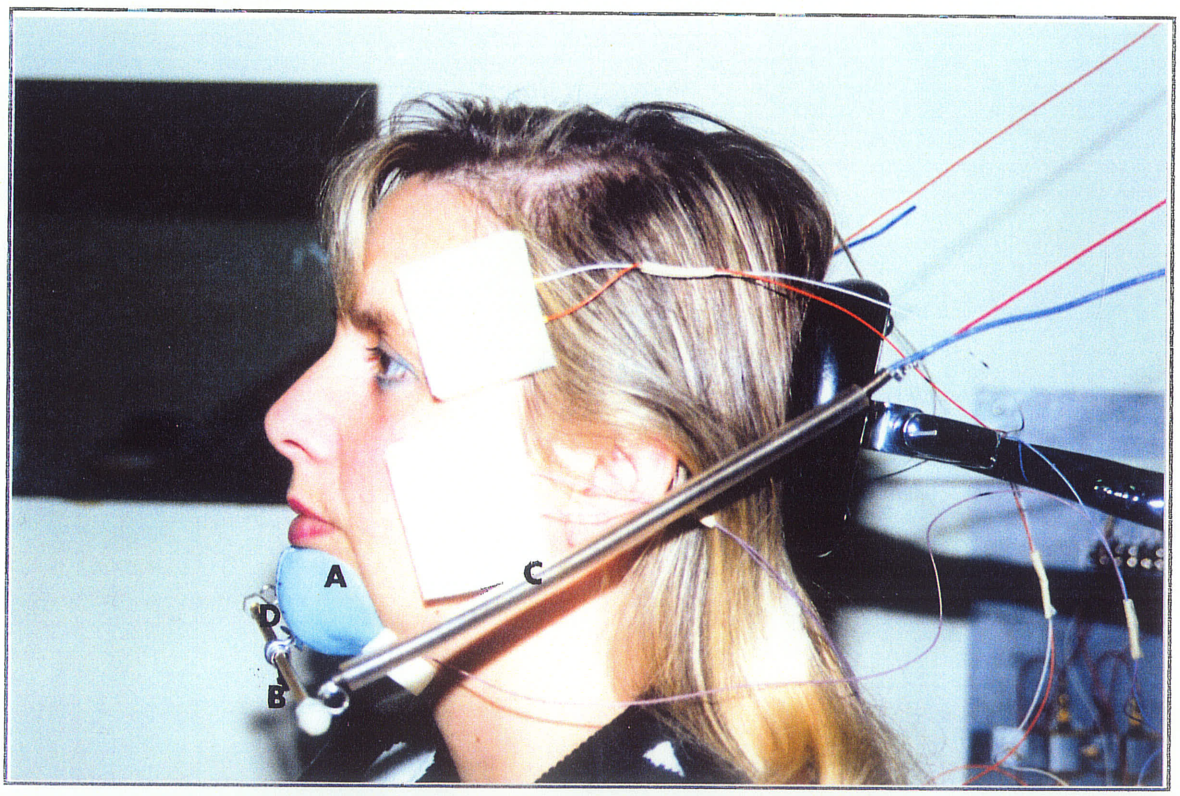


Figure 4.6 View of the E.M.G. electrode positions and the loading mechanism. (A) chin cup, (B) loading yoke, (C) loading spring (left), (D) groove to permit adjustment of the point of force application.

4.6. RECORDING OF CHIN LOAD ANGULATIONS.

Prior to the start of the recording session, the occlusal plane had been identified and marked on the subject's right cheek (see section 4.2.5). In order to record the angulation of the force vector on the chin, and to measure any change in head posture, the subject was monitored with an Auto Handycam Sony 8mm video camera. The video camera was mounted on a tripod in a stationary position approximately 2.5m from the subject to reduce potential parallax error.

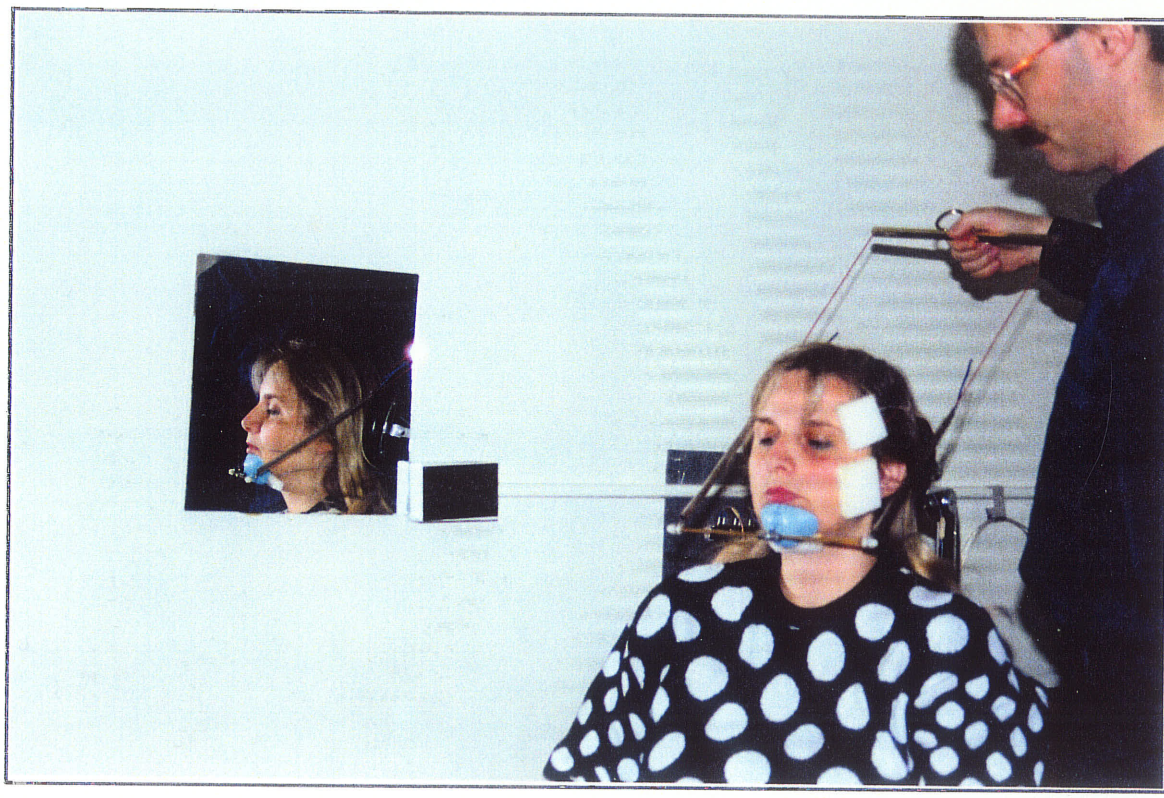


Figure. 4.7. A video camera located 2.5mm from the subject was utilized to indirectly measure line of force relative to the occlusal plane which was marked on the right side of the subject's face. Note that this represents a reconstruction of the experiment.

A mirror (12 in x 12 in) was placed at the side of the subject so that the video camera recorded a perpendicular image of the subject's profile with the chin cup and loading device in place (Figure 4.7.). The experimental session involved simultaneous videotape and EMG recording of each subject. The videotape recording was continuous throughout each data collection session. Once the session finished, the videotape was replayed on a 30 X 40 cm television set from which direct measurements were made of the direction of force applied to the chin.

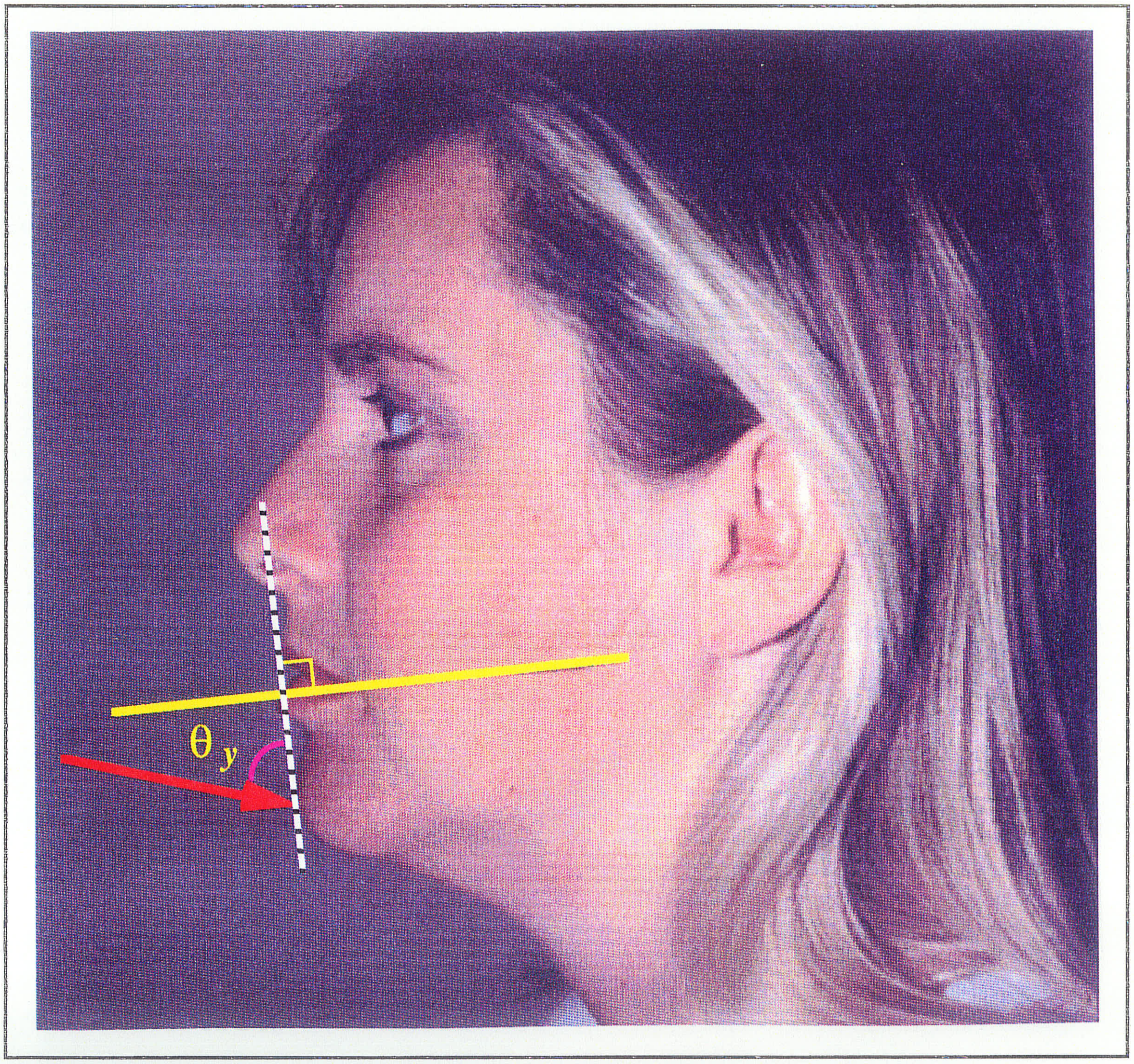


Figure. 4.7. Diagram showing determination of the angle (θ_y) between a vertical line to the occlusal plane and the direction of the force application on the chin.

A cephalometric protractor (Ormocépha; 3M Unitek, Monrovia, California) was utilized to measure the angulation of the extended spring relative to the functional occlusal plane (FOP) during an activation. This angle θ_y was then transferred to the chin using a 90 degree vertical line to the FOP, for further use in the numerical model (Figure 4.8).

4.7. METHODS OF DATA COLLECTION FROM EMG RECORDINGS.

The EMG signal recordings were converted from analogue format (analogue band width; 500 Hz) on magnetic tape to digital format (sampling rate; 1 kilohertz) and saved on the microcomputer's hard disk drive.

Each digitized sample of the raw EMG signals was squared, resulting in only positive EMG values. For each muscle, the root-mean-squared (RMS) EMG value was then calculated for a period of at least three seconds. The use of RMS values was preferred as a method of analysing the EMG signals, because of its direct computation of an energy related quantity which is independent of the signal waveform. In addition, a linear relationship between the EMG signal and the force magnitude was demonstrated by several authors (Basmajian and De Luca, 1985; McCall *et al*, 1986; Kull *et al*, 1988). Thus, for each application of load to the chin, coincident muscle forces, in the form of the RMS values of the EMG signals, were determined.

4.8. METHODS OF ANALYSIS.

4.8.1. Use of the numerical model.

The model used for this study is a three-dimensional numerical model of the masticatory system, developed originally by McLachlan and Smith (Smith *et al.*, 1986). It was initially conceived to investigate different biting situations such as unilateral biting. The McLachlan-Smith model employed Newtonian principles to calculate muscle forces and condylar loads in response to a load on the mandible. The postulate that the temporomandibular joints should be minimally loaded for any given bite force, and consistent with mechanical equilibrium, is the basis for this model. That model was modified and extended (Trainor and McLachlan, in press) by addition of muscles which allowed study of the effects of an external force on the mandibular posture.

The term "load" has been conventionally associated with the temporomandibular joint. It has been defined in this model as a force acting upon the condyle and transferring to the condyle a tendency for movement perpendicular to the articular eminence. Also, "load" and "force" will be used synonymously when related to the chin cup activation, and thus will have the properties of magnitude, direction, and point of application.

The spatial relationships of the dentition and the chin to be represented in the model were measured orthogonally relative to the plane of occlusion and the intercondylar axis. Thus, the major data set for the model is expressed by the relative positions of the tooth row, condyles, and muscles involved in biting, which are all described by coordinates (x, y, z) from the origin located at the center of the inter-condylar axis. For use in the model, the occlusal plane drawn on the subject's face represented a plane averaging the points of posterior occlusal contact from the distobuccal cusp of the mandibular second permanent molar, anteriorly through the bicuspid region to the most anterior mandibular tooth. The x-z plane is parallel to this occlusal plane, while the x-y plane and y-z plane are perpendicular to this occlusal plane and are coincident with the centre of the intercondylar axis.

It was important to include subjects that had minimally crowded intact mandibular teeth. Also, it was ideal for each subject to have minimal curve of Spee (the curve to the plane formed by the biting surfaces of the teeth) in order to approximate the model definition of an occlusal plane. Subjects with malpositioned teeth and severe curve of Spee are susceptible to more variability in the determination of the occlusal plane. These subjects were therefore, excluded from the study.

The medio-lateral coordinates completing the three-dimensional description of the tooth row were given by the positions of the cusp tip of the mandibular canine and the distobuccal cusp tip of the mandibular second permanent molar which were obtained intra-orally. The tooth row was thus approximated by two straight line segments representing the right and the left mandibular teeth from the distobuccal cusp of the second permanent molar to the canine, and by the arc of a circle representing the mandibular anterior teeth.

The most anterosuperior point on the sagittal profile view of the condyle, and approximately midway between the medial and lateral poles of each condyle, represented the temporomandibular articulation for the right and left condyles. A line joining these two points has been defined here as the intercondylar axis.

The resultant force and the resultant moment acting on the mandible are zero when static equilibrium is satisfied. For example, a bite force applied at a point on the tooth row must therefore be resisted by forces on the condyles and by the forces generated by the muscles. Six muscles of mastication that are involved in jaw closure were represented in the model; these were right and left masseter muscles, the right and left temporalis muscles, and the right and left medial pterygoid muscle. The opening muscles were represented by the right and left digastric muscles, and by the right and left lateral pterygoid muscles.

The muscle vectors were determined from estimates of the muscle centroids corresponding to muscle insertions and origins, as determined by anatomic landmarks. Each muscle contraction force required to satisfy static equilibrium was thus represented as a single resultant vector being of a set direction and point of application. The relationship between these muscle vectors, for a given loading situation, will depend on the anatomical relationships of the origins and insertions for an individual, and on the location and direction of the applied force.

4.8.2. Production of geometry files.

The basic information required for the numerical model analysis of a particular biting or mandibular loading situation was provided by the geometric anatomical data representing a given subject. The relative positions of the occlusal plane, the mandibular condyles, and the muscle vectors of the masseter, temporalis, and digastric were measured as previously described, from dental and facial landmarks and therefore were known. However, it was also necessary to determine the coordinates of the medial and lateral pterygoid muscles, which could not be done with direct measurement.

4.8.3. Indirect measurement of muscle coordinates (osteological sample)

Although lateral cephalometric radiographs were available for each patient, some of the origins and insertions of the muscles were very difficult to determine. This was the case for the medial and lateral pterygoid muscle pairs. Specialized radiographs such as computed tomography may have improved the identification of these muscles as recommended by Pruim *et al* (1980), Weijs and Hillen (1984), Christiansen *et al* (1988), and Koolstra and Van Eijden (1992). However, this radiographic approach has a major drawback, namely exposing the subjects to unnecessary ionizing radiation. Current imaging techniques, which use non-ionizing radiation were not readily available. Thus, coordinates of the medial and lateral pterygoid muscles had to be obtained by an indirect method using a sample of dry skulls. The sample consisted of five human skulls selected from the osteological collection of the Gross Anatomy department at University of Manitoba. Each skull presented a normal jaw relationship, an apparent skeletal symmetry, and normal vertical skeletal proportions. The selected skulls had relatively intact natural dentitions.

The selected skulls were inspected carefully and areas of the origins and insertions of all muscle pairs were identified and the centroids marked with a small pencil dot. The regions of muscle attachment were identified by the observed bony scarring, guided by the anatomical descriptions of Sicher and Dubrul (1975). Anatomical descriptions by Romanes (1986) were also helpful.

Once the measurements were compiled, the objective was to find common relationships between each specimen regarding the origin and insertion of internal muscle coordinates. Since direct measurements of these muscles were not possible, this approach, which involved calculation of mean values, was essential in obtaining anatomical coordinates and completing a geometric file for each subject's craniomandibular anatomy. These files would then provide the best possible estimates of the orientation of the "hidden" muscles of each subject for use in the numerical model. To validate this method, the geometric files derived from the skull sample were used in a computerized program producing the sagittal shape of the articular eminence of the specimens. The results were compared visually with the actual specimens. The eminence shapes were found reasonably similar to the predicted ones. This finding is consistent with results reported by Trainor (1992).

4.8.4. Creation of eminence shape files.

Using the coordinates from the geometry file of each subject, a computer program was utilized to generate an effective sagittal morphology of the articular eminence. The computer program calculated the eminence morphology based on an objective function of unconstrained minimization of joint load (Trainor, 1992; Trainor and McLachlan, in press). The computed effective shape of the eminence was represented by a cubic polynomial which was then used in a numerical model which predicted muscle forces and joint load directions and magnitudes.

4.8.5. Chin cup angulation analysis.

The selection of the chin cup angulations was guided by the shape and geometry of the appliance. The five equidistant points marked on the external surface of the chin cup, represented the different angulations to be tested. The line of pull was kept at right angle to the outer surface in order to prevent the generation of a moment by the force. Also, a pull directed beyond the chosen range of angles could have resulted in an unstable position of the chin cup due to the moment induced by the load. Such angles may have generated more variability in the muscular response. It was therefore, decided to remain within the structural limits of the chin cup.

Furthermore, because of some concerns expressed regarding subject and operator fatigue, it was decided to limit the number of fixed angles that could be used in the investigation.

The EMG activity of the four muscles during chin cup loading was recorded simultaneously for different chin cup angulations and calculations of the root-mean-square (RMS) of the raw EMG data were performed following the method described in section 4.7. The results were plotted graphically for every subject.

4.8.6. Generation of muscle forces and joint load predictions.

Several modes of operation of the numerical model could be selected such as minimization of the mean-square (MS) values of the joint loads, or the minimization of the mean-square values of the muscle forces. The mode of minimization of the MS values of joint loads was initially selected for use in this study. However, some controversial issues have been raised with respect to the selection of the objective function. Certain investigators have proposed the minimization of muscle effort as a theoretical neuromuscular principle (Barbenel, 1972; Osborne and Baragar, 1985; Koolstra *et al.*, 1988). Therefore, it was decided to explore the minimization of muscle effort as an objective function. It is possible that the system could have more than one objective function since it has to perform many different tasks including biting, chewing and posture of the mandible (Trainor, 1992). In the model, each of the modes solved for the muscle force magnitudes and the magnitudes and directions of the forces on the condyles needed to produce static equilibrium of the mandible in the presence of an externally applied load. A comparison of the muscle forces and joint loads of each optimization was performed to identify any differences between these objective functions. However, no significant difference was revealed between each mode.

The applied external force was set at one hundred units. It could be applied at any point on the mandible and could be set at any angle in the three-dimensional space defined by x, y, z axes. With this arrangement all muscle and joint forces could be expressed as a percentage of the applied force. Thus, when a chosen load was applied at a specified point on the chin cup, the model could readily be scaled to suit this load. The chin cup force, its point of application, and the direction of its action on the mandible were specified by the investigator, and therefore were also known. The point of force application on the chin was defined as a point described by x, y, z coordinates, and measured orthogonally relative to the intercondylar axis.

4.8.7. Joint load analysis.

Once the joint load predictions were obtained from the numerical model, a comparative analysis was performed looking at the joint loads induced during chin cup therapy relative to the predicted joint loads during normal biting.

The method involved dividing the square root of the sum of the joint forces (x,y,z) squared during chin cup loading by the square root of the sum of the joint forces (x,y,z) squared during normal biting. The results were plotted as a percentage of joint forces produced by first molar biting.

4.8.8. Force magnitude analysis.

EMG signals were recorded on the FM tape recorder while loads were applied at a particular angle. Thus, a starting load of 900gm was applied for five seconds followed by a pause of three seconds. This was followed by a series of loads, each 100gm less than the previous load, and maintained for five seconds interrupted with pauses of three seconds each. The last chin load in the first session, was 500gm and 600 gm in the second session. It was assumed that progressively reducing the chin load in the series of activations would tend to reduce the likelihood of muscle fatigue in the subject. The results involving the masseter and digastric muscles were displayed graphically in different ways to; a) demonstrate the effect of force magnitude when load angles produced maximum opening and closing mandibular moments, b) determine the relationship of force magnitude with every load angulation. A linear relationship between the EMG signal and chin cup force must be demonstrated for both the theoretical predictions and the *in vivo* experiments to validate the use of the numerical model.

4.8.9. Chin cup force and posterior bite force relationships.

In order to obtain a force calibration for a given chin cup load, each individual was asked to bite moderately hard on a half width tongue blade on the left first molar for the recording of the muscle activity. The RMS value of the EMG activity was then calculated for the four muscles for the described biting situation. Plots of muscle EMG (RMS) due to chin cup loading were dysplayed as a percentage of muscle EMG (RMS) for first molar biting for each angulation in every subject.

4.8.10. Energy cost measurements.

The literature supports the application of muscle EMG as a measure of muscle energy costs (Kuroda *et al.*, 1970; Osborne and Baragar, 1992). In the present study, the objective was to estimate the energy used by the jaw system during chin cup therapy and compare it with the estimated energy used in normal biting. The method involved dividing the sum of the predicted joint force squared for a chin cup load with sum of predicted muscle forces squared for the same chin cup load. The result would be related to the energy cost of a given chin cup load. This was then compared with the estimated energy cost of the first molar biting, determined by the same method as that just described.

4.9. ERROR CONSIDERATIONS.

4.9.1. Error in determining muscle centroids directly and indirectly.

Although it is uncertain whether the centroid of a muscle represents the centre of muscle function, it is reasonable to think that the line of muscle action passes near the centroid of the areas of attachment. Therefore, the centroid of each region of muscle origin and insertion was approximated, and the line of action was presumed to act through the approximated centroids of the muscle origin and insertion.

The identification of the masseter and anterior temporalis muscle centroids was relatively easy because of the possibility for direct measurement. The centroids for the origin and insertion of the medial and lateral pterygoid muscles, and anterior digastric muscle, were difficult to identify without using an indirect approach. Thus, the technique employed could involve three sources of error.

Firstly, the direct measurement done on the osteological sample could have generated variations in determining the centroid location. Nickel (1987) has reported a possible variation in determining the origin of temporalis and lateral pterygoid muscles of +/- three millimeters (3mm).

Secondly, the small osteological sample size used to produce the indirect coordinates may not represent a good protection against unusual observations. Therefore, using indirect measurements obtained from a sample size of five specimens is likely to have generated more variability in calculating a mean for certain insertion or origin muscle coordinates. However, testing chin cup loads symmetrically applied with respect to the midsagittal plane, may have reduced the impact of the technique errors.

Thirdly, errors produced during the indirect measurement of muscle origins and insertions may affect the composition of the geometry file and therefore, influence the predictions by the numerical model. Consequently, a comparison between muscular recruitment pattern generated by EMG study with the numerical model would be made more difficult to interpret.

In order to test the effects of geometry errors on the calculations of the numerical model, it was decided to vary the origin coordinates of lateral pterygoid, and anterior digastric muscles. The modifications were done through the use of the numerical model by varying the x and y origin coordinates of the lateral pterygoid and digastric muscles antero-posteriorly and supero-inferiorly respectively. Starting with the derived geometry file for subject HP, the lateral pterygoid muscle origin was successively moved up by 3mm and 5mm, down by 3mm, anteriorly by 3mm, and finally, posteriorly by 3mm. A similar exercise was conducted for the digastric muscle, where its origin was displaced up and down by 3mm and antero-posteriorly by 3mm as well. The results are shown in Appendix E.

4.9.2. Errors in chin cup activations by operator.

It was important that symmetrical loads be applied to the mandible from the chin cup activations. The use of unilateral recording of muscle activity was based on the premise of symmetrical muscle activity during loading. Any deviation from symmetry would induce an asymmetric response from the muscles, thus invalidating the EMG recordings. In order to test the consistency of the chin cup activation method, a vertical line was traced in the middle of the subject's face using a Staedtler Lumocolor non-permanent marking pen (Staedtler, AV, West Germany). Then, the subject was filmed from vertically above and frontally with an Autofocus Handycam 8mm Sony videocamera. During recording, the operator activated the chin cup device ten times. Measurements were made to determine if there were any angular deviation of the springs relative to the sagittal midline (Figure E.1). It was found that the tension springs of the chin cup were extended back with a slight tendency towards the left of the subject. Deviation of the chin cup loading device was found to be -1.0 ± 0.85 degree relative to the facial midline.

CHAPTER 5. RESULTS

5.1. INTRODUCTION

The present study was undertaken to investigate joint loads during chin cup therapy. Since those loads cannot be measured directly, a numerical model was employed to generate joint loading predictions. However, studying the biomechanics of the human masticatory system with a model constructed from an average geometry is valid to investigate only the general principles. Therefore, the model was tailored individually towards the subjects available for experiments, by incorporating *in vivo* geometrical data collected from the anatomy of the living subjects. Thereafter, the validation of the model was achieved by comparing EMG muscle recruitment patterns with numerically predicted muscle recruitment patterns.

The aim of this study was to apply and validate a three-dimensional numerical model of the human masticatory system *in vivo*, in order to determine joint loads in reaction to chin cup forces. A comparison is made later in this chapter, with regards to joint loads produced during normal biting. In the interest of clarity of description, the results of one subject representative of the findings, will be described. However, results of all subjects are included in appendix C.

5.2 MODEL PREDICTIONS OF JOINT LOADS

The numerical model of minimization of the magnitude of the joint loads was used with the subject's geometric anatomical data. The numerical model provided predictions for the muscle activity patterns and condylar loads, for each of the individuals in the clinical sample, needed to produce static equilibrium of the mandible in the presence of an external load symmetrically applied to the chin. The chin load was assigned a magnitude of one hundred units, and was applied using the same angulations and position as used in the *in vivo* experiment. The results obtained from the model were represented in a graphic form.

The numerical model predicted condylar loads for subject HP as shown in Figure 5.1. In this figure, and ensuing similar figures, the chin cup angles range from 70 to 180 degrees. At 70 degrees, the chin cup load tends to open the jaw and at 180 degrees, it tends to close the jaw. Condylar loads tended to decrease as the line of force application approximated the condyles (about 120 degrees in this case) and to rise again as the line of force diverged from 120 degrees. These condylar loads were predicted to be 77 percent higher at 90 degree chin cup loading angle than at 175 degrees. A legitimate appreciation of these loads can be realized if, instead of being related to each other, chin loads were compared to functional loads during normal molar biting. However, it was necessary to validate the model predictions of condylar loads beforehand, by comparing the predicted muscle activity patterns with the *in vivo* muscular recruitments.

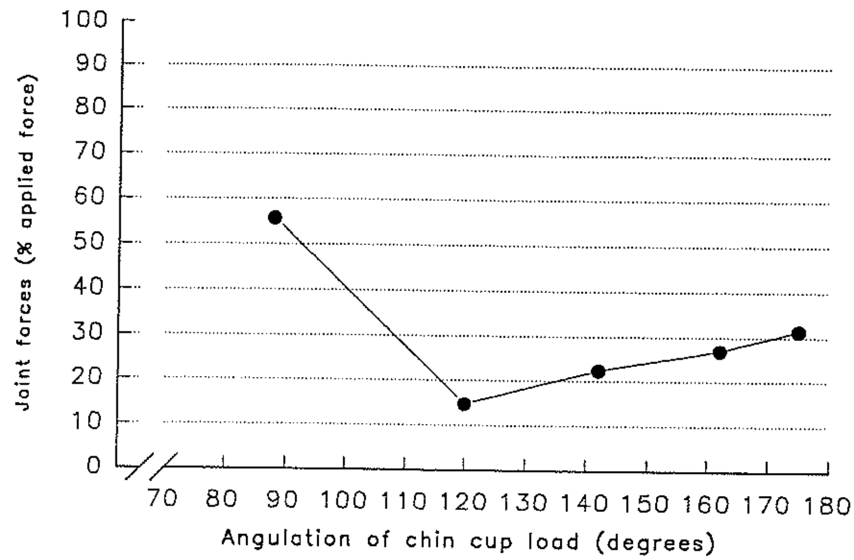


Figure 5.1. Graph presenting the relationship between the predicted joint forces and chin cup load angles for geometric anatomical coordinates of subject HP. Selected angles coincide with those used in the EMG experiments.

Figure 5.2 shows the plotted results for the muscle recruitment pattern in response to an externally applied load on the chin, for subject HP, predicted by the numerical model using the subject's geometric anatomical file. Temporalis muscle activity was predicted to be minimal and independent of the load angle tested. Also, the predicted muscle recruitment pattern showed a decreasing activity of the masseter muscle as jaw-closing moments increased, while digastric muscle activity increased concomitantly. Between 120 and 175 degrees, masseter was recruited minimally and digastric, maximally. The model predicted a definite switch to a progressive digastric activity at a Theta$_y$ (θ_y) angle of 120 degrees. Thus, when a chin cup force was applied in line with the condyles, the activity of the masseter and digastric muscles was predicted to be minimal. However, the model predicted an important role for the lateral pterygoid muscle for a line of force approximating the condylar area, since the numerical model offered the possibility of knowing the behaviour of the lateral and medial pterygoid muscles during the tested conditions.

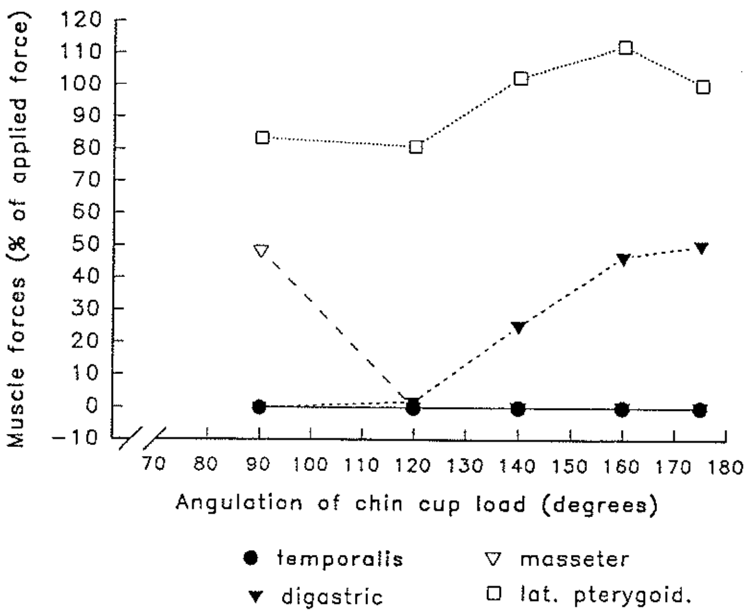


Figure 5.2. Muscle recruitment from model predictions using geometry data of subject HP. Note the predicted activity of the lateral pterygoid muscle when the recruitment of the masseter and digastric muscles is minimal.

5.3. VALIDATION OF THE NUMERICAL MODEL

5.3.1 Effects of chin load angular variations on muscle recruitments.

Surface EMG was used in order to determine the muscles recruitment associated with the application of a load symmetrically placed on the chin. When the head was braced against the headrest, two muscles in turn were particularly active; masseter and digastric muscles. Figure 5.3 shows an example of muscle activity (Root Mean Squared EMG) plotted against the angulation of chin load (degrees). RMS EMG values were obtained by subtracting RMS values of the muscles during a rest phase from RMS values during chin cup activations. On some occasions, this produced small but fictitious negative RMS values. Since the interest was directed toward the muscle activity during chin cup activation, it was necessary to eliminate the activity associated with unwanted signals (muscle activity to resist gravity force or electrical and thermal noise from the equipment).

For subject HP, angulations of the load on the chin varied from 88 degrees to 175 degrees. It is essential to remember that these angles were measured from a 90 degree vertical line to the FOP. When the load was applied so as to create an opening moment (88 degrees) on the mandible, masseter muscle exhibited its maximum activity. This muscle was recruited progressively less as the load was directed towards the condyles. When a closing moment (175 degrees) on the mandible was produced by the chin load, masseter muscle was at its minimum level, maintaining this minimal activity for all the closing angles tested. Opening angles tested did not recruit the digastric muscle until 120 degrees, after which activity rose rapidly as the closing angles increased. A crossover point was noted at about 127 degrees where masseter and digastric muscles were both active, showing that the muscular activity was not switched from one muscle to the other. However, loading angles between 120 and 142 degrees are required to confirm this last statement.

Limiting the number of fixed angles used in this study was done to avoid fatigue of subject and operator. Therefore, straight lines connect the points relating EMG activity and angle of load. Thus, the cross-over point of muscle activity was assumed to be at the intersection of the two lines.

The temporalis muscle kept a constant minimal level of activity throughout the first phase (head supported) of the session. Also, the sternocleidomastoid muscle (SCM) did not show any activity for this segment of the experiments.

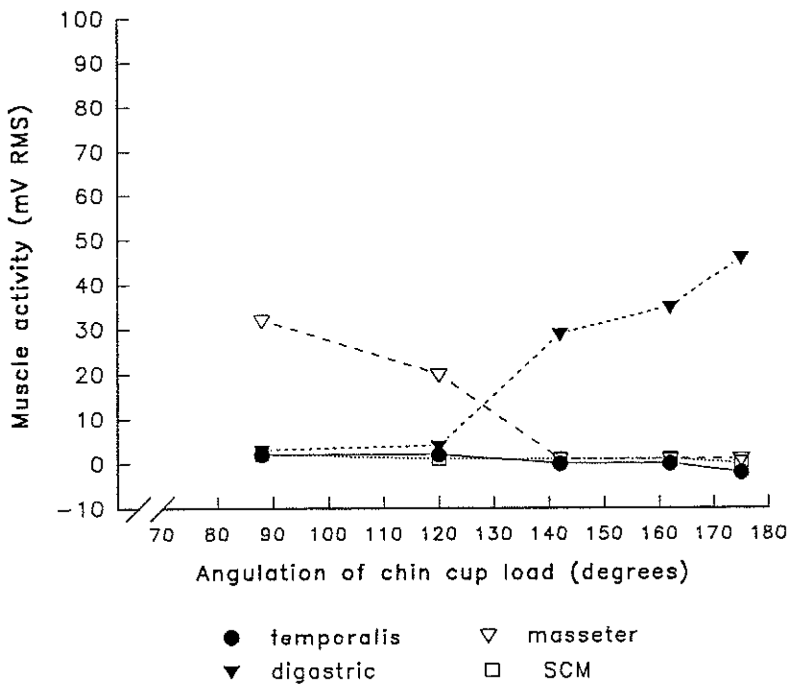


Figure 5.3. Muscle recruitment generated from 900 grams of chin cup loading in a head supported situation. Subject HP.

In the second part of the session when subject HP had the head unsupported, a similar pattern of muscular activity was found (Figure 5.4). Thus, when an opening moment was produced by the chin load, the masseter muscle showed its maximum activity decreasing progressively as the opening angulation was decreased and remained minimal for tested closing angles. The digastric muscle which showed very low activity for the opening angulations, but rose quickly up to the 140 degree angle after which the increase was not as marked. Again, the crossover point was noted at about 122 degrees. The temporalis muscle behaved in the same way as in the first part showing a minimal level of activity while the sternocleidomastoid muscle responded earlier with the opening angles and rose progressively as higher closing angulations were tested, following a pattern similar to that of the digastric muscle.

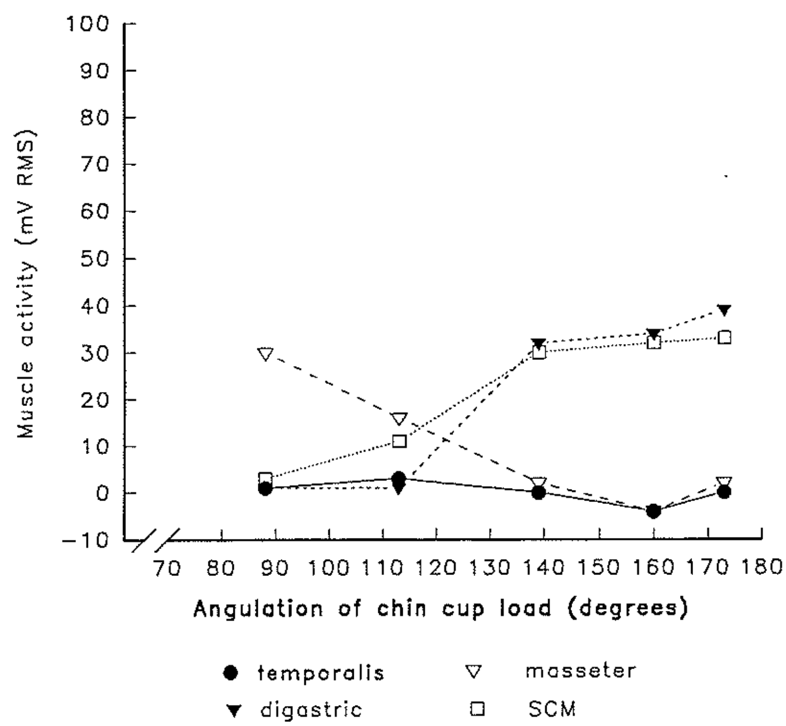


Figure 5.4. Muscle recruitment generated from 900 grams of chin cup loading with head unsupported. Subject HP. Note that SCM was recruited for this segment of the experiment.

All the other subjects showed a similar pattern by having masseter muscle more active when an opening moment was generated from the chin load, and digastric muscle more active when an upward force was used (Appendix C.1). The temporalis muscle was consistent in its tendency to very low levels of activity throughout the experiments. More SCM activity was observed in the head unsupported situation whilst head was supported, the SCM showed very little activity. The mean value over all subjects for the masseter-digastric muscles crossover point in the head supported situation was calculated to be 121.6 degrees (S.D. 18.8 degrees) and, 110 degrees (S.D. 18.0 degrees) when the head was unsupported.

In all subjects, activity in the masseter muscle dropped on average to a minimal level at 132 degrees (SD 14 degrees) in head supported experiments, and 131 degrees (SD 21 degrees) in head unsupported experiments. However, there was a tendency for the digastric activity to be evoked earlier when the head was unsupported (114.7 degrees vs 97.6 degrees). Furthermore, for two of the subjects (HR and IY), there was a definite switch from masseter to digastric activity at 133 degrees and 150 degrees respectively when the head was braced against the headrest of the dental chair. Table 5.1 presents the comparative results for the masseter and digastric muscles regarding the supported and unsupported head positions.

5.3.2. *In vivo* experiments and numerical model comparisons.

A reasonable similarity was observed between the model predictions and the *in vivo* experiments. Figure 5-3 showed that the muscle recruitment pattern generated from the EMG experiment of subject HP (head supported) was comparable to the predicted muscle recruitment pattern. It presented the same trend where the masseter muscle reduced its activity as jaw-closing moments increased, while digastric muscle activity increased concomitantly. The model

MASSETER MUSCLE			DIGASTRIC MUSCLE		
	subject			subject	
supported		unsupported	supported		unsupported
142°	HP	139°	120°	HP	113°
133°	HR	130°	133°	HR	102°
135°	VO	158°	90°	VO	90°
150°	IY	147°	150°	IY	102°
135°	KH	136°	110°	KH	112°
105°	CS	102°	105°	CS	92°
125°	CL	119°	95°	CL	82°

TABLE 5.1 - ACTIVITY TRANSFER ANGLES. Loading angles at which the masseter and digastric muscles became minimally active for a chin cup load of 900 grams.

subject	CROSSOVER ANGLE
HP	120°
HR	140°
VO	130°
IY	125°
KH	127°
CS	127°
CL	123°

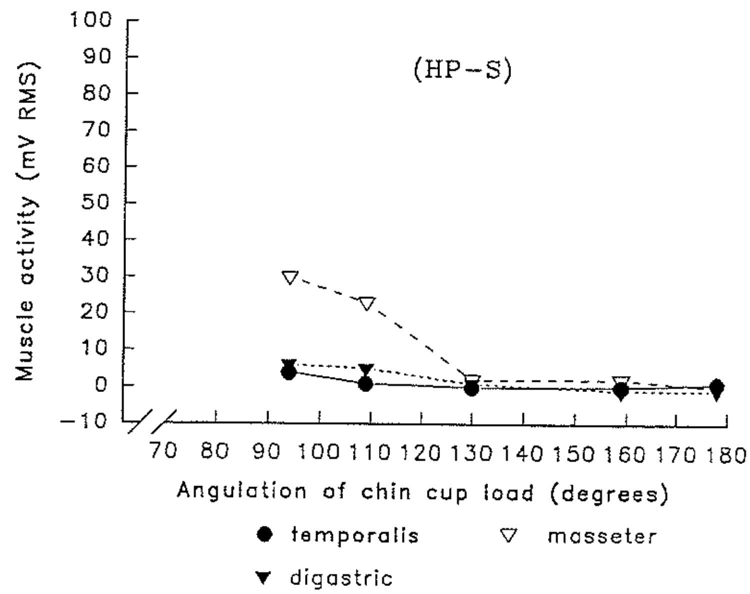
TABLE 5.2 MASSETER-DIGASTRIC ACTIVITY SWITCH FROM MODEL PREDICTIONS. Mean θ_v angle for masseter-digastric activity switch; 127.4 ± 6.4°.

predicted a definite switch to a progressive digastric activity at a θ_y angle of 120 degrees (Table 5.2.). The predicted absence of temporalis muscle activity was in close correspondence with the EMG results recorded throughout the experiment session.

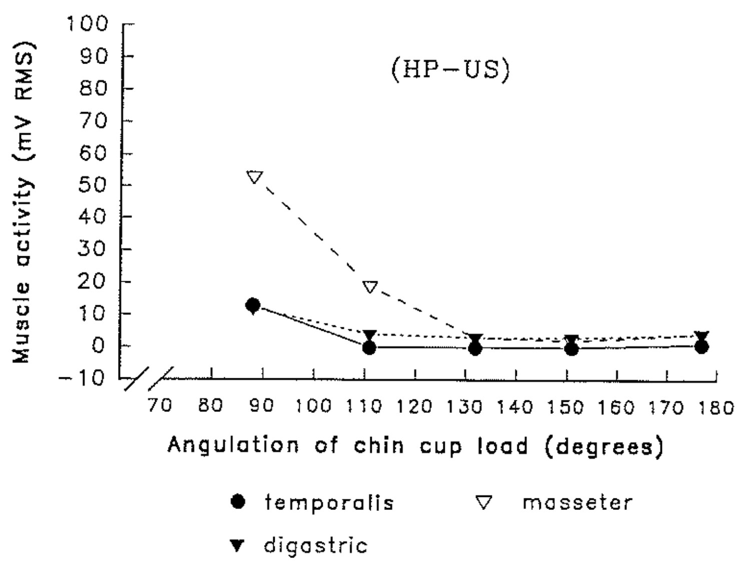
For all subjects, similarity was found between the individualized EMG recruitment pattern and the numerically predicted muscle recruitment pattern (Appendix C.2.). Moreover, a theoretical mean θ_y angle for masseter-digastric activity switch was 127.4 ± 6.4 degrees, with values ranging from 120 to 140 degrees for the different subjects (Table 5.2). The EMG experiment had provided a mean θ_y angle of 121.6 degrees for the crossover point from masseter activity to digastric activity.

5.3.3. Muscular recruitment with interarch occlusal contacts.

Because the activation of a chin cup appliance for treatment use has usually a tendency to close the jaw, it was thought to be clinically relevant to examine the muscle recruitment pattern when the teeth are brought together upon chin cup forces. Thus, in the initial session each subject was asked to keep their teeth together without biting. Jaw-opening and closing angles were tested using the same approach previously described. For subject HP, the observed recruitment pattern was characterized by a marked activity of only the masseter muscle when opening moments were produced since additional muscle effort was required to maintain the teeth together. But more importantly, all muscles were minimally recruited when the teeth were brought together from the chin cup activation for all jaw-closing angles. This was demonstrated for both head supported and unsupported (Figure 5.5 and 5.6).



(Figure 5.5.)



(Figure 5.6.)

Figure 5.5 and 5.6. Muscle recruitment produced from 900 grams of chin load. Subject HP had his teeth together with head supported (Figure 5.5) and head unsupported (Figure 5.6.).

Figure 5.7 displays the plotted results for subject IY using the same experimental protocol as subject HP, showing that the temporalis and digastric muscles were recruited during jaw-opening angles as a result of unwanted biting and/or need for additional stiffness of the jaw in maintaining the occlusal position. But, more importantly, the same muscle recruitment pattern prevailed for jaw-closing loading angles showing that minimal muscle activity was required to keep the teeth together.

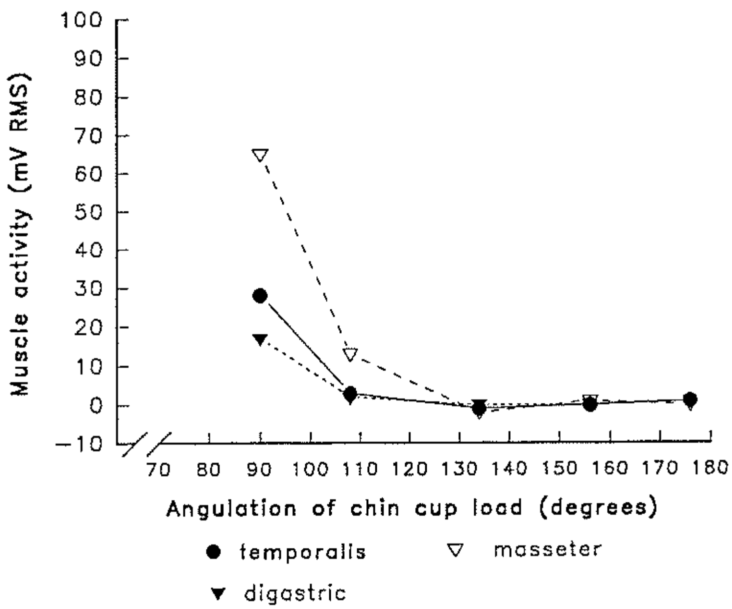


Figure 5.7. Muscle recruitment produced from 900 grams of chin cup load. Subject IY had his teeth together with head supported.

5.3.4. Effect of magnitude of chin load on muscle recruitment.

It was important to demonstrate that both model predictions and EMG experiments present a linear relationship between the muscle recruitment and the force magnitude for the validation process to be possible. Thus, it was decided to examine the muscle response to different magnitudes of force for extreme jaw-opening and closing loading angles.

Figure 5.8 presents results recorded from subject HP and muscle activity was plotted for the four different magnitudes of applied chin loads. In this plot, the head was supported, and the angle of loading was 88 degrees. The results show minimal variation in temporalis, digastric and SCM muscles activity for the different magnitudes tested, while masseter muscle presented almost a linear relationship as the magnitude decreased. For a thirty per cent decrease of chin cup force, masseter activity decreased by thirty percent.

The same exercise was done looking at the load angle that produced the maximal closing moment (175°). Figure 5.9 demonstrates that, for subject HP, temporalis, masseter and SCM muscles remained minimally active, whilst digastric muscle showed a reduced activity as the force magnitude was decreased. From 600 to 800 grams, the relationship was almost linear. Thus, unlike the masseter response, the reduction in digastric activity was non-linear and reduced by 75% for a 30% decrease in chin cup load.

From these results, it was decided to establish the EMG signal to chin cup force relationship for the masseter and digastric muscle separately. Thus, RMS values of masseter and digastric muscles were plotted for every load angle (Fig. 5.10a and Fig. 5.10b). Only the head supported condition was investigated.

Figure 5.10a shows that at 88 degrees, the masseter muscle had almost a perfect linear relationship but, for the other angles, more variation could be observed. The digastric muscle did not show much variation between 900gr and 800gr but, from 800gr to 600gr, the relationship was almost linear (Figure 5.10b).

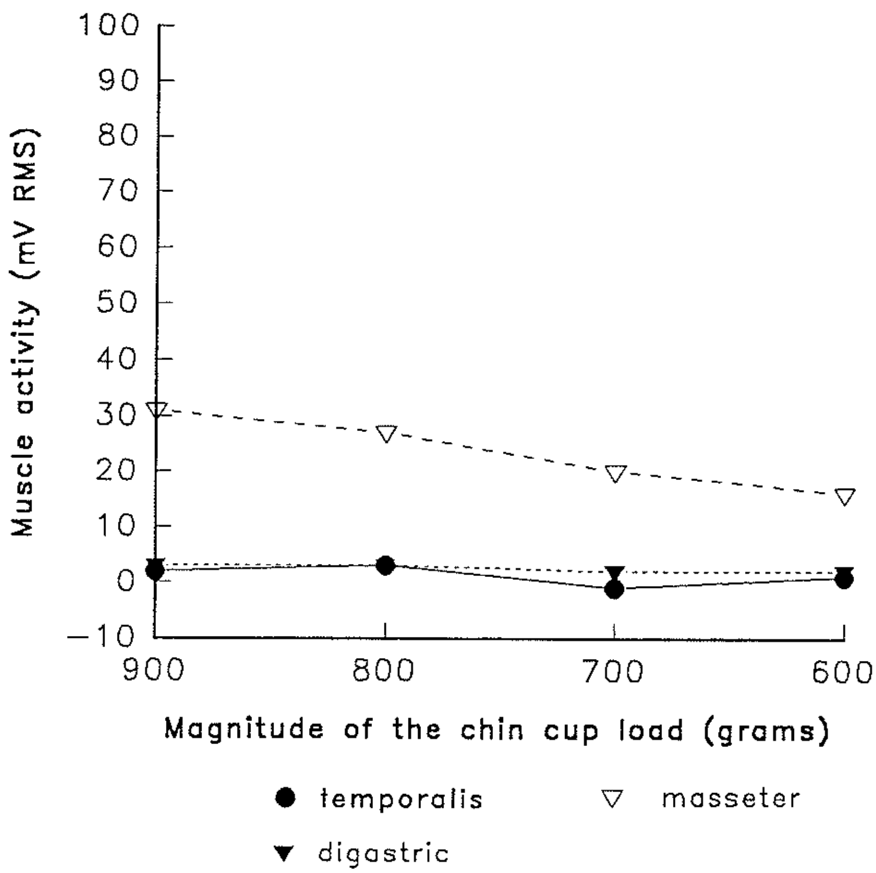


Figure 5.8. Muscular response to variations in force magnitude with 88 degrees of chin load angle. The results are presented for the head supported situation involving subject HP.

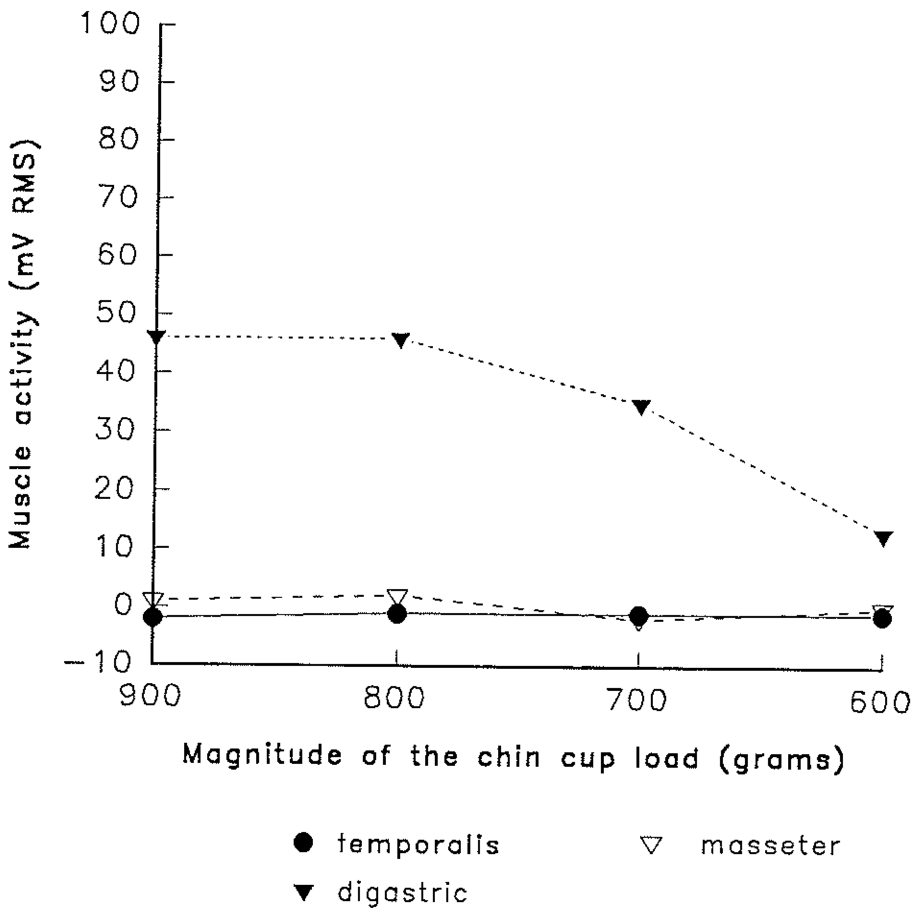
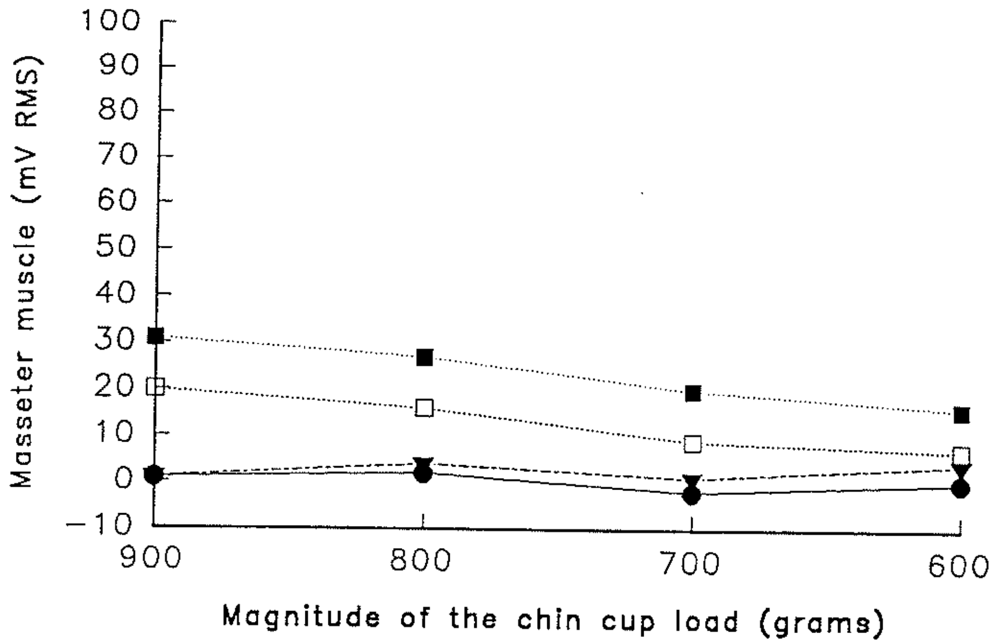
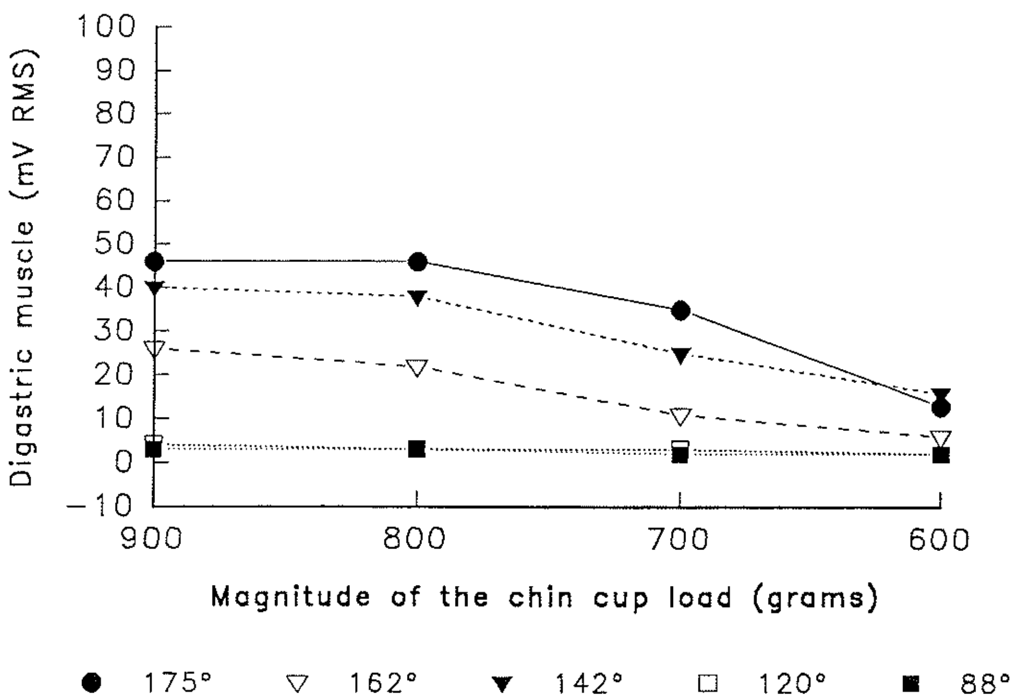


Figure 5.9. Muscular response to variations in force magnitude for a chin load angle of 175 degrees. The results are presented for subject HP for the head supported situation.



(Figure 5.10a)



(Figure 5.10b)

Figure 5.10a and 5.10b Effects of varying force magnitude on masseter (5.10a) and digastric (5.10b) muscles response for each chin load angle. Subject HP in head supported situation.

The behaviour of the masseter muscle with respect to varying the magnitude of the chin load was comparable with the numerical model predictions as displayed in Figure 5.11.

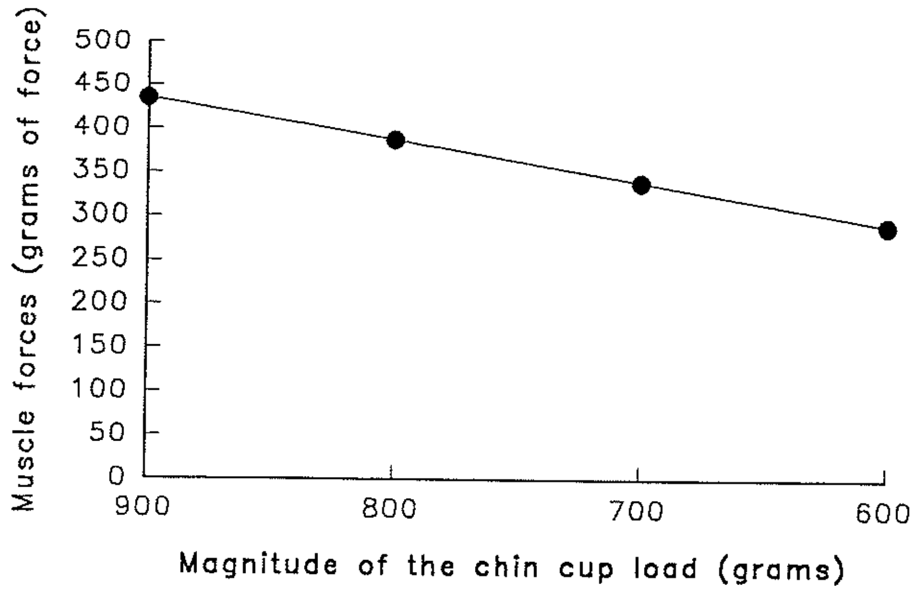


Fig. 5.11 Plot showing the linear relationship between the magnitude of chin load and the predicted masseter muscle forces.

5.4. ENERGY COST MEASUREMENTS DURING CHIN CUP THERAPY

Prior to chin cup activations, while recording EMG signals for the muscle, each individual was asked to bite moderately hard on a tongue blade which was placed between the left first molars. After calculating the RMS values of the EMG activity for first molar biting, respective chin cup loading was calibrated as a percentage of muscle activity during posterior biting. Figure 5.12 shows that for opening angles the masseter muscle never exceeded 54% of the muscle activity associated with posterior biting (subject HP). When closing angles were tested, the masseter muscle activity stayed below 22% of muscle activity during posterior biting. During opening moments, digastric muscle activity induced by chin cup loading, represented approximately 60% of muscle activity of posterior biting. Digastric activity increased up to 119% when jaw-closing moments were generated. Temporalis muscle was 77% less active than for normal molar biting. These figures were comparable to the averaged percentage of the sample group. When a force of 900gr was applied on the chin, masseter muscle activity on average, never surpassed 54% of muscle activity during posterior biting. Digastric muscle remained under 137%, while temporalis muscle was never more than 27% of muscle activity during biting.

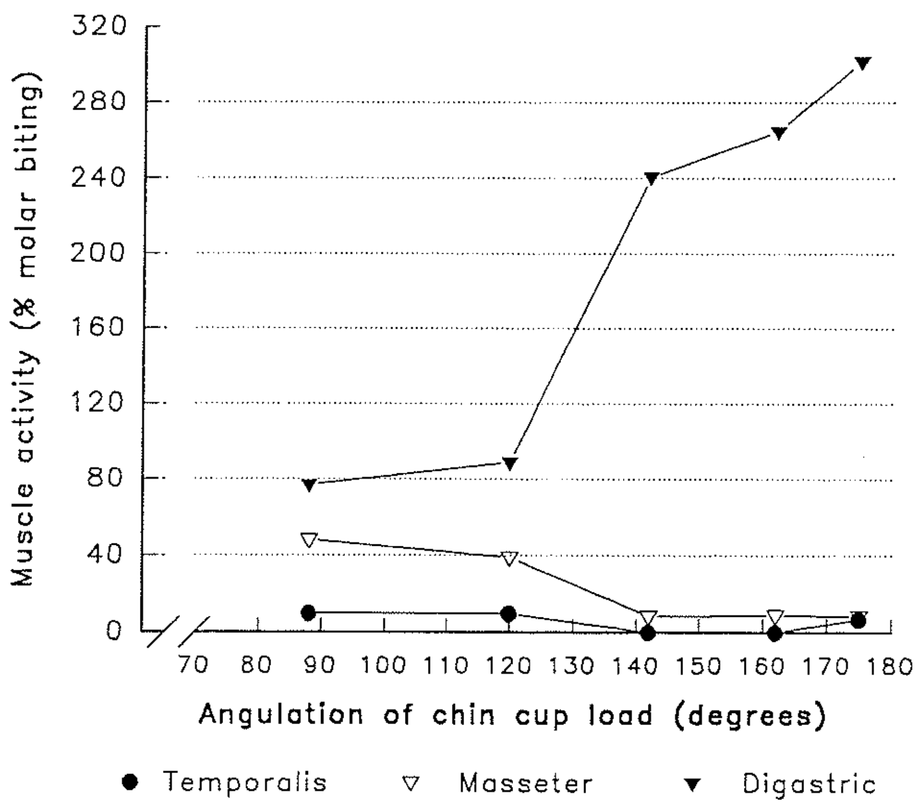


Figure 5.12. Plot representing each muscle effort relative to normal molar biting for the different chin cup loading angles. Results are from subject HP. In this experiment, the head was supported. Chin cup activation was 900 grams (8.82N) in magnitude.

Figure 5.13 shows the proportion of energy used by the muscles during a given chin cup load when compared to the muscle activity of normal posterior biting. For closing angles between 120 and 180 degrees, the muscle activity never exceeded 28% of muscle activity during normal biting. However, when a chin cup load was applied at 88 degrees from the vertical reference plane, the muscle activity was much higher (113% of muscle activity during molar biting).

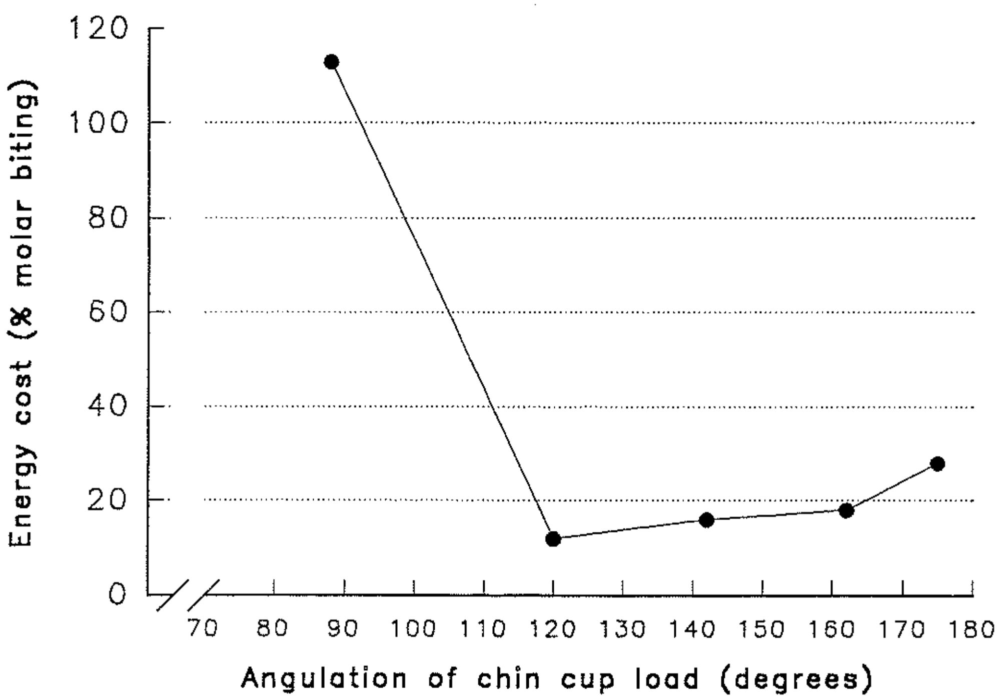


Figure 5.13. This graph represents the energy used by the jaw system for a given chin cup load. It is expressed as a percentage of the energy cost for normal molar biting.

5.5. RELATIVE IMPORTANCE OF JOINT LOADS INDUCED BY CHIN CUP FORCES

Joint loads during chin cup therapy can only be meaningful if a comparison is undertaken with joint loads produced during normal function such as molar biting. Figure 5.14 presents the relationship between non-physiologic and physiologic loads. When a jaw-opening load was applied on the chin, there was 35% higher joint loads than for normal biting. However, results showed that during jaw-closing angles, joint loads remained below the loads associated with molar biting, varying between 35% to 77%. A chin force directed towards the condyles appears to produce the least load on the joints.

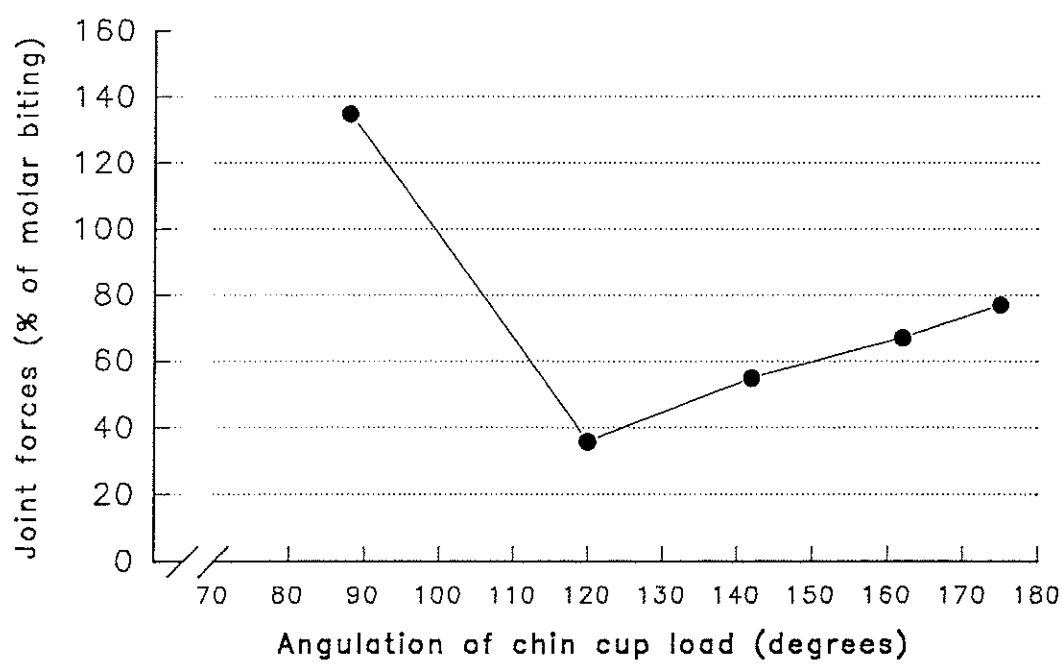


Figure 5.14. Graph representing the percentage of joint forces during a given chin cup load relative to joint loads from molar biting. The direction of the force application to the chin was varied. Numerical model predictions were used to calculate joint loads during molar biting. (Subject HP).

5.6. COMPARISON OF OBJECTIVE FUNCTIONS IN OPTIMIZATION

It is unknown if the neuromuscular system controlling mandibular posture is organized to minimize joint load. Thus, a comparison was made between the predicted muscle forces and joint loads for the objective of minimization of joint load, and minimization of the square of muscle forces (muscle energy). Using the geometry of subject HP, the numerical model calculated joint loads and muscle forces for minimization of the sum of the squares of muscle forces, which were then compared with model calculations of muscles forces and joint loads associated with minimization of joint load.

Muscle forces and joint loads were virtually identical for both situations, whether the objective was to minimize joint loads or muscle forces squared.

CHAPTER 6 - DISCUSSION

6.1. INTRODUCTION

For growing patients with various skeletal deformities, orthopedic therapy has been advocated for controlling and/or redirecting craniofacial growth. The findings of Kloehn (1947) about cervical headgear enhanced the idea that growth could be manipulated. From this consideration, it has been assumed for a long time by clinicians that mandibular growth could be retarded by applying a force on the chin in line with the condyles. Cephalometric studies have suggested remodelling changes in the ramus, body and mandibular symphysis in response to chin cup forces. However, it was also postulated from animal studies that compressive loads at the mandibular condyles could produce changes in chondrocyte proliferation and matrix synthesis resulting in the inhibition of mandibular growth. However, it is not known whether joint loads are actually augmented upon application of chin cup forces in humans. Thus, a knowledge of joint loads during chin loading and normal biting, and how they compare was needed to examine the effects of chin cup therapy on mandibular growth in humans.

6.2 VALIDATION OF PREDICTED MUSCLE RECRUITMENTS.

The direct measurements of joint loads have been attempted only in animal studies (Brehnan and Boyd, 1979; Brehnan et al, 1981; Boyd et al, 1982; Boyd et al, 1990). Direct measurement of these loads is impossible in humans without using totally unacceptable, invasive techniques. Moreover, the proprioceptive receptor response due to the pressure of a force transducer could complicate the interpretation of the data.

The use of a three-dimensional numerical model represented an acceptable indirect method to test non-invasively, different hypotheses about functional behaviour of the system under consideration, and its relevant anatomical variables. However, in order to justify its use, the theoretical model employed had first to be validated by a series of *in vivo* experiments in which individual muscle recruitments, as indicated by EMG signals, would be compared with the model predictions of muscle activity. Other investigators have supported this approach (Faulkner *et al.*, 1987; Koolstra *et al.*, 1988; Van Eijden *et al.*, 1988; Dixon *et al.*, 1990; Koolstra and van Eijden, 1992, Trainor, 1992). For reasons similar to those mentioned for joint loads, muscle forces cannot be measured *in vivo*. Thus, *in vivo* muscle forces could not be directly compared with modelled muscle forces. However, the pattern of muscle recruitment can be determined *in vivo* because of the linear relationship between E.M.G. activity and muscle force generation in isometric contraction. Thus, the model would not have any valididity if its pattern of muscle activity was different in form from that given by the EMG activity of the modelled subject. Conversely, if these patterns are similar, it is reasonable to use the model's results for those force magnitudes and directions that cannot be assessed *in vivo*. Moreover, inter-individual comparisons of EMG muscle forces would have been meaningless since it is impossible to evenly control all the parameters affecting the individual signal magnitudes. Thus, incorporating the anatomy of a living subject into the model, which involved collection of anatomical data *in vivo*, allowed validation on an individual basis. Thereafter, a search for trends could be undertaken between each subject's muscular recruitment pattern.

Consequently, the *in vivo* and model comparisons were needed in order to have reasonable confidence in assessing joint load predictions of the model. The objective function was the minimization of joint load. The assumption was that the function of the neuromuscular system could find the pattern of muscle forces which minimizes the load on the joints.

It is not certain whether minimization of joint load is the operating neuromuscular objective since a method of detecting joint load is not evident. Nevertheless, the evidence suggests that the typical morphological development of the joint is produced by a process involving minimization of joint load (Nickel, 1987). Trainor (1992) stated that if the system was designed to minimize some function of muscle effort, a much greater range of sagittal joint load angulations would have to be allowed which morphologically is unlikely. The minimal loading hypothesis is also supported by current knowledge of the physiology of the articulating tissues. Thus, the mechanism of cartilage nutrition appears to be by fluid movement during loading and unloading of the tissues (Turek, 1984). Heavy loading over a long duration would compromise the nutrition of the articular tissues which may reduce the ability of cartilage to distribute stress and consequently, accelerate joint breakdown.

The equilibrium of the mandible under chin cup loading is such that an analysis of mandibular loading can be undertaken using the principles of rigid body mechanics. When a force is applied to the chin, muscle forces are necessary to prevent linear movement and/or mandibular rotation around any axis in order to satisfy static equilibrium. In fact, to totally satisfy static equilibrium, the force exerted on the mandible by the chin cup, and the reactive joint force, must be resisted by muscle forces so that the resultant force and the resultant moment on the mandible is zero. If muscle forces were non-existent, condyles would have to take all the reactive load from the chin cup force and static equilibrium could only be satisfied by constraining forces of the joint capsule. This situation is structurally and functionally unrealistic.

The understanding of Newton's third law can explain that when a force not in line with the condyle, is applied to the chin, a moment about the condylar axis is induced. A moment can also be described by an action of one body upon another which creates a propensity to rotate. A moment is defined as the product of the force and the moment arm which is the perpendicular distance between the point at which rotation might occur and the vector of the force. Masticatory muscles are the elements capable of producing counter moments necessary to obtain static equilibrium of the mandible upon chin cup loading. Thus, it was from the analysis of these muscular recruitments that comparisons of patterns could be made to provide essential information about joint loads.

The results obtained in this investigation displayed reasonable similarity between the predicted and the EMG muscle recruitment patterns. At extreme angles, the model successfully predicted qualitatively the same maximal discharge for the masseter and digastric as was found in the EMG experiments. However, in the *in vivo* experiments there was a tendency for the activities of the masseter and digastric muscles to overlap for the range of loading angles (100 to 140 degrees), whereas the model had predicted an activity switch over between 120 and 130 degrees.

It is difficult to certify what was happening within that range because of the absence of loading angles tested in the range between 115 and 130 which could hide detailed information with respect to the muscle behaviour. Consequently, it is possible that the overlapping zone of loading angles associated with the EMG experiment could include the predicted switch over point. However, the explanation may be that there was a need for the masseter and digastric muscles to be coactivated in order to produce stiffness of the lower jaw. In contrast, the model could not have predicted the activity overlap since it is a force equilibrium model and, hence, does not include any stiffness components. Thus, it is unlikely that muscle EMG activity would switch sharply from one muscle to the other as the model has predicted. For the present study, it is important to note that the form of relationship between the muscle EMG activity and the model prediction is similar and that the predicted crossover angle between masseter and digastric muscle activities is similar to that shown experimentally. In addition, the gravity force and the weight of the chin cup device may have contributed to some extent to the coactivation of the masseter muscle, even though they were designed to be as light as possible. Miles and Wilkinson (1982) stated that digastric muscles tended to co-contract with masseter muscles when resistance between the teeth is expected to yield. However, it is unlikely that the observed co-contraction during the overlap zone was a result of such a reflex mechanism. In the experiments reported here, jaw-opening angles had the greatest potential for inducing a co-contraction response, however, only masseter was demonstrated to be active.

The pattern of muscle recruitment for loading angles between 100 and 140 degrees showed a minimal activity in the masseter and digastric muscles. This pattern suggest a significant involvement of the lateral pterygoid muscle in producing stiffening of the mandible as well as minimizing joint loads when the chin cup loading angle approximated the condylar region. The work of Janzen and Bluher (1965) bears the evidence that the lateral pterygoid muscle plays an important function for chin cup loads directed toward the condyles. They observed a definite hypertrophy of the lateral pterygoid muscle as a result of a mandibular retractive force in line with the condyles.

For two subjects (CS, VO), slight temporalis activity together with masseter muscle was observed for jaw-opening angles. It is most likely that the temporalis muscle was recruited minimally to keep the joint load angle correct for the particular morphology of the masticatory system of these two subjects. The possibility of muscular fatigue for the *in vivo* experiments is not be considered in light of the results. As presented in Figure 5.12, the maximal masseter muscle effort during chin cup loading for an jaw-opening angle was less than 50 per cent of the required biting effort (biting on a tongue blade). Clark *et al* (1988) showed that normal subjects could sustain a maximum contraction of 50 per cent (unilateral clench) for 115 seconds. Therefore, it appears unlikely that a muscle effort of 5 seconds would produce fatigue of the masseter muscle.

This investigation showed linearity in the EMG signal-force relationship, which was in correspondence with the evidence presented previously by numerous authors (Scherrer and Bourguignon, 1959; Moritani and De Vries, 1978; Basmajian and De Luca, 1985; McCall *et al*, 1986; Kull *et al*, 1988). Therefore, variations in the force magnitude from the chin cup, would not have affected the muscle recruitment pattern itself.

In summary, both the numerical model predictions and the EMG experiments showed a similar trend, which was characterized by a relative inactivity of the temporalis muscle through the range of loading angles, a maximum activation of the masseter muscles when jaw-opening moments were produced and, a maximum activity of the digastric muscles associated with jaw-closing moments. These muscular patterns may play a significant role in the objective function of minimization of joint loads. As a result, it appeared to be reasonable to use the numerical model to predict joint loads in response to forces applied symmetrically to the chin.

6.3. JOINT LOADS WITH CHIN CUP THERAPY

The analysis of the predicted joint loads has revealed that these loads were perpendicular to the articulating surfaces with significant variations in magnitude over the range of chin cup loading angles for a constant chin cup force magnitude (900 grams / 8.82N). The plot for all subjects represented a sharp trough with its minimum associated with applied force angles in line with the condyle area. Chin cup loading angles ranging between 120 and 180 degrees produced joint loads not exceeding 44 per cent of the chin load. In addition, angles approximating the mandibular condyles, with respect to their line of application (120-135 degrees), indicated least loading of the joints (15-35%). The reactive condylar forces became significantly higher for loading angles producing jaw-opening moments (54-94% of the chin load). These loads were predicted to be almost 4 times the loads associated with a chin cup force in line with the condyles. However, because of the design of commercialized chin cup appliances, it becomes practically impossible to produce jaw-opening activations. Therefore, it is unlikely that joint loads could exceed 55% of chin cup loads.

By examining joint loads associated with molar biting, it was possible to establish a relationship between joint loads during chin cup therapy and normal function. This was essential in order to verify the main hypothesis that chin cup forces affect joint loads in such a way that condylar growth can be impeded. With chin cup loads applied vertically or towards the condyles, joint loads were calculated to represent 35% to 77% of the joint loads associated with normal molar biting (Figure 5.14). When the chin was pulled downward (90 degrees), the condylar forces reached 135% of the normal biting conditions. It appeared that conventionally directed chin cup forces loaded the condyles to a lesser degree than those produced during normal biting. Consequently, the evidence suggests that the neuromuscular system has succeeded in minimizing the joint loads upon chin loading.

When the model objective involved a sagittal constraint of the joint load angle, based on jaw position and a calculated eminence morphology, the joint load angulation was maintained approximately at 25 degrees for the chin cup loading conditions. These angulations allow the condyle to be braced against the posterior slope of the articular eminence in order to maintain good congruity of the articular surfaces. If the joints are not loaded perpendicular to the articulation surfaces for any given antero-posterior position of the mandible, additional muscle effort is needed to produce perpendicular forces and hence, increased joint load. In addition, joint congruity is presumed to have a major impact on the health of the joint structures by distributing the mechanical stresses on a large surface (Nickel, 1991).

6.4. BIOMECHANICAL EFFECTS OF CHIN CUP FORCES.

Estimated joint loads from the numerical model are concentric (point) loads. The articular disc was proposed as a structure capable of transmitting loads over a large area of the articular surfaces, thus reducing stress concentration. This brings about the concept of general stress, which can be defined by the equation:

$$\text{Stress (MPa)} = \frac{\text{Load (N)}}{\text{Area (mm}^2\text{)}}$$

The work of Copray *et al.* (1985a) and Takano-Yamamoto *et al.* (1991) has shown that a static compressive force of a high magnitude may inhibit glycosaminoglycans synthesis and chondrocyte mitosis. The inhibition of cartilage growth from assumed increased joint loading will depend however, on the distribution of stresses on the articular tissues. Thus, in the temporomandibular joint, like other synovial joints, the magnitude of the mechanical stress is proportional to the magnitude of the load which pushes the articulating surfaces together, but inversely proportional to the area of the load bearing surfaces. Therefore, in order to evaluate the impact of these loads on condylar cartilage and the chondrocytes, it is important to determine how these loads are distributed on the articular surface of the condyle.

An estimation of the general stresses produced from each chin cup loading condition, was obtained by dividing the predicted joint loads resulting from chin cup forces, by an averaged loading area of the articular surfaces.

In determining the general loading area, the anteroposterior and mediolateral dimensions were estimated from osteological data reported by Nickel (1991). The general loading area was calculated for two age groups. Eight specimens with age ranging from 10 to 15 years demonstrated an average general loading area for the mandibular condyle of 53.6mm^2 and the eighteen specimens in the age group of 16-25 years showed on average a loading area of 66.8mm^2. These calculations were done under the assumption that the proportions of the superior surface of the condyle under load represent 66 percent of the anteroposterior dimension and 80 per cent of the mediolateral dimension.

The results of this study showed general stresses, for chin cup loading angles between 120 and 175 degrees, varying from .024 to .052 MPa for the age group 10-15 years, and from .019 to .042 MPa for age group between 16-25 years (Figure 6.1). It was estimated from the work of Copray *et al.* (1985c)) on continuous compressive forces for condylar cartilage, and of Carvalho (1990) about rat condyles that the threshold for inhibition of condylar growth was 0.16 MPa. Jones and associates (1982) reported a 50% decrease in GAG synthesis in articular cartilage using static compressive stresses of 2-3 MPa. Stresses up to 1 MPa did not alter GAG synthesis compared to unloaded controls. It is difficult to be certain that the compressive stresses used in animal studies would induce an identical response in humans. However, it may be reasonable to assume that a threshold for inhibition of matrix synthesis also exists in humans and could be anywhere between 0.16 and 2MPa.

There is no question that in the living body, load or muscular activity serves as an extracellular stimulus that is transmitted to cells and modulates their genetic growth and differentiation. Copray *et al.* (1985a; 1985b; 1985c; 1988) and Takano-Yamamoto *et al.* (1991) suggested that heavy loads producing compressive stresses on the condylar cartilage could inhibit chondrocyte proliferation and DNA synthesis and thus, condylar growth. The evidence presented in this investigation shows that it is unlikely that chin cup forces are sufficiently large to inhibit growth of the condyles. In fact, joint loads during normal molar biting were even predicted to be larger than those during chin cup loading.

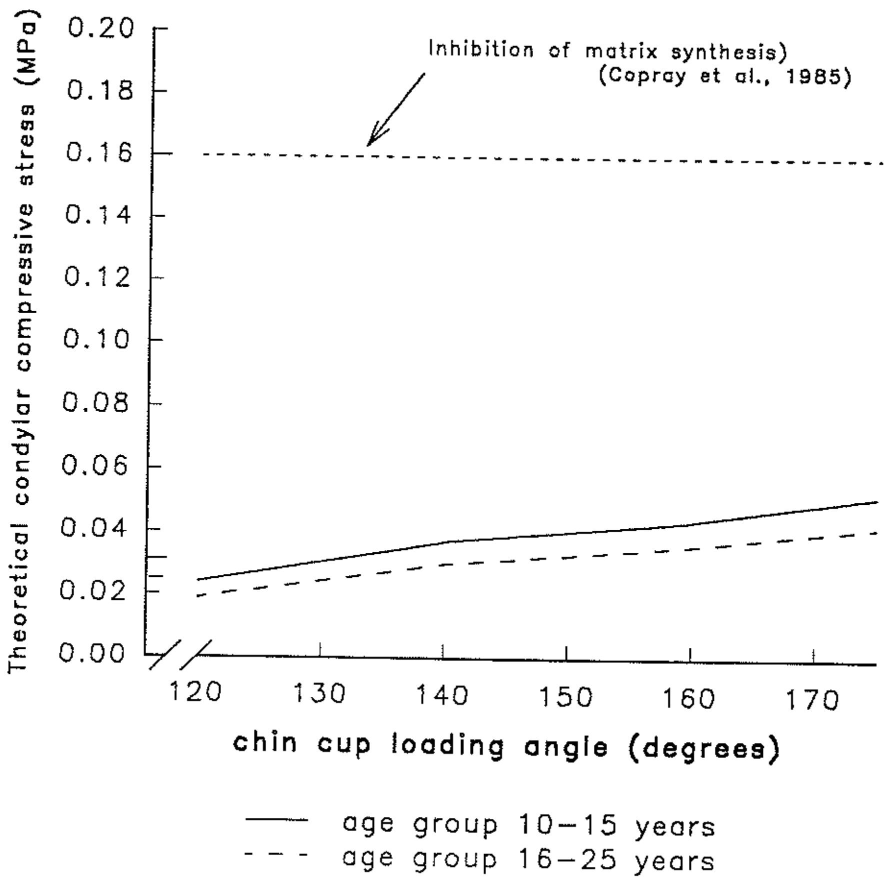


Figure 6.1. Plot presenting general stresses on condylar cartilage in response to a chin cup load of 900 grams. The results were calculated for loading angles between 120 and 175 degrees for two age groups since the general loading area changes with age. Compressive condylar stresses were found to be smaller to the magnitude threshold suggested by Copray *et al* (1985c).

The experimental protocol used in the work of Copray *et al* (1985c) had a significant impact on the results regarding condylar growth. Indeed, the condylar cartilage cells were extirpated from their "natural" environment" which normally includes articular disc, ligaments and muscles. Consequently, it is likely that these structures play a role in protecting the joint by keeping the joint load angle perpendicular and minimizing the stresses on the articular surfaces.

There is evidence that varying the duration of joint loads may not have made any difference assuming that the neuromuscular system minimized the joint loads. Copray *et al.* (1985a) showed that the growth of the condylar cartilage of rats during the application of a small continuous force almost equaled the growth of the uncompressed controls. Therefore, a minimization of the joint loads by the muscles could allow growth to continue its normal course. Kantomaa and Hall (1991) stated that with minimal functional stimulation, condylar cartilage cells develop into osteoblasts. Mitani and Fukazawa (1986) observed some increments of growth for each mandibular measurement during use of the chin cap in all growth phases. They concluded that complete inhibition of mandibular growth is difficult, if not impossible, to achieve with "conventional" chin cup therapy in human subjects. In addition, joint loads were predicted to be apposition. Therefore, assuming that these loads may have an effect on the growth of the condyles, the effect would likely be in the wrong direction if antero-posterior changes are desired

It was reported for long bones that mechanical strains from static loads played a role in altering the shape of bones (Hassler *et al.*, 1980; Meade *et al.*, 1983; Hart *et al.*, 1983; Lanyon and Rubin, 1984). Recent biomechanical studies have ascribed remodelling of the alveolar and craniofacial bones incident to functional and orthopedic forces to principal stresses (Tanne, 1990; Hart *et al.*, 1991; Tanne and Sakuda, 1991; Tanne *et al.*, 1993). Consequently, remodelling of the mandible may be the key to the understanding the effects upon the mandible caused by orthopedic chin cup forces. Yamada (1973) showed that with a chin cup force, the mandible was compressed along the axis of the chin to the condyle. The findings of Tanne *et al.* (1993) showed uniform tensile and compressive stresses at the outer and inner borders respectively of the mandible resulting from chin cup forces directed towards the condyles. Compressive stresses were prominent at the angle of the mandible (junction of the body with the ramus) and at the symphysis where the force was applied. These bending stresses, which appear similar to those experienced for long bones with loading, could be associated with a mechanism of remodelling the mandibular shape.

Furthermore, piezoelectric changes produced by mechanical stresses were shown to be related to bone remodelling (Cochran *et al.*, 1967; Gross and Williams, 1982; Iguchi, 1989).

With respect to the association between bone remodelling and stresses, the following sequence may be postulated. Compressive and tensile stresses generate different electrical potentials, which further activate osteoclasts and osteoblasts in the stressed areas. Consequently, cellular activity may orchestrate the remodelling of the mandibular bone involving resorption and deposition.

6.5. CHIN CUP THERAPY WITH TEETH TOGETHER.

The *in vivo* experiment involved investigating the muscular response with the teeth brought together. A significant change was observed with regard to the pattern of muscle recruitment (Figure 5.4 and 5.5). The finding was that every muscle showed a minimal discharge for chin loading angles in line with the condyles or more vertically. It can be assumed that the opposing forces were provided by the maxilla and the upper dentition, and headrest (or potentially by neck muscles for the unsupported head condition). The effects are likely felt in the maxilla rather than in the joint. Haas (1965) and, Majourau and Nanda (1994) demonstrated that molar extrusion and increased vertical dimension caused by rapid palatal expansion could be prevented by vertical chin cup forces (500g).

This provides some evidence that a dentoalveolar effect was expressed on the maxilla and the upper dentition from the chin cup forces.

It was not possible to determine joint loads when the teeth were together since this represents an indeterminate system. However, because no muscles were recruited, it may be postulated that the joint loads were similar to those associated with the mandible at rest. Nikolai (1985) acknowledged the absence of jaw muscle activity when the teeth were brought together by chin cup forces superior to the condyles. He suggested the responsive force comes from the maxillary teeth and not from the TMJ. Consequently, it is unlikely that a chin cup worn with an activation that keeps the teeth together may have any inhibiting effect on condylar growth due to increased joint loads.

6.6 NECK MUSCLES AND HEAD POSTURE.

By testing chin loads without any head support, the intention was to obtain some insight into the muscular involvement of the neck muscles in head stabilization and to assess the effects of such involvement on the activity of the muscles required for jaw positioning in the presence of an externally applied chin cup load.

It was demonstrated that the SCM muscle was minimally recruited for the head supported condition. The headrest of the dental chair provided a reciprocal response to chin cup forces comparable to the headcap of the chin cup appliance. Therefore, it is likely that the SCM and presumably other neck muscles have a negligible effect during chin cup therapy.

The removal of the head support clearly demonstrated the direct involvement of neck muscles in head posture. All subjects were found to have

SCM muscle activity in association with jaw-closing moments. However, some variations were observed among the subjects with respect to the sternocleidomastoid response to chin cup load. This could be explained by the work of Keshner *et al* (1989) on isometric head stabilization where a load was horizontally applied at the top of the head using a motorcycle helmet. They found on average, a minimal response of SCM and three other neck muscles to a load of 900 grams, 1400 grams being necessary to obtain significant reading of the four muscles.

The SCM muscle tended to follow the same activity pattern as the digastric muscle without changing the general muscular recruitment pattern observed in the head supported condition. Trainor (1992) observed a premature activation of the digastric muscle upon external loading of the chin relative to model predictions. An association was proposed with the neck muscles as a need for increased head stiffness. He suggested that this reflex mechanism would disappear with head support. The analysis of the *in vivo* results demonstrated the presence of a premature digastric activation in three of the seven subjects (43%) which disappeared when the head was supported. None of these subjects demonstrated a SCM coactivation with the digastric premature response. Therefore, it was not possible to validate the postulate suggesting an association between digastric and neck muscles (SCM) for head stiffness purposes. However, considering the unstable head posture, the premature digastric activation may have represented a protective mechanism for the dento-skeletal structures of the masticatory system. Miles and Wilkinson (1982) suggested stiffening of the jaw-opening muscles when expecting a sudden unloading of the jaw. Consequently, it should be recognized that changes in research protocols associated with EMG studies of head posture may affect muscle recruitments and complicate interpretation of the results.

CHAPTER 7 - CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

7.1. INTRODUCTION

It has been has shown that the neuromuscular system was effective in minimizing condylar loads in reaction to chin cup forces. Joint loads were at least 23 percent less than those of normal molar biting. Therefore, the evidence presented in this study rejects the hypothesis that chin cup therapy has an effect on joint loads such as to inhibit growth at the mandibular condyles. In addition, general stresses on the condylar surface were estimated to be below the inhibition threshold for chondrocyte mitosis and matrix synthesis. Consequently, it was postulated that bending stresses produced by the force of the appliance could initiate remodeling changes and modification in the growth direction throughout the mandible which may account for the results observed clinically. This study supports the findings by Asano (1986) who stated that the growth retardation is likely the result of adapting to the orthopedic force and that the mandible remodels its form and structure to accommodate the force and the altered environment.

7.2. CONCLUSIONS

The results presented in this study are supportive of the following conclusions:

1. Reasonable similarity was found between *in vivo* muscular recruitment patterns and those predicted by the numerical model. Consequently, the

numerical model employed in the present study was found to represent a reasonable means for the determination of joint loads in response to the application of chin cup forces.

2. The masseter was recruited maximally when jaw-opening moments were produced upon chin cup loading. Digastric activity rose significantly for jaw-closing moments. Temporalis revealed minimal EMG activity throughout the range of loading angles.

3. Minimal muscular activity was found for the masseter and digastric muscles when the force was applied in line with the condyles. It may be postulated that the lateral pterygoid muscle plays a major role in maintaining condylar loading perpendicular and in minimizing the joint loads in presence of chin cup forces directed towards the condyles. This is strongly supported by the model predictions.

4. Joint loads associated with chin cup forces in line with the condyles were found to be the lowest. In addition, these loads were revealed to be one third of those in relation to normal molar biting.

5. Chin cup forces are calculated to produce compressive stresses on the articular surface of the condyle that are estimated to be below the threshold for inhibition of matrix synthesis and chondrocyte mitosis. Consequently, chin cup therapy is likely to have minimal effect on condylar growth. Furthermore, the clinical efficacy of chin cup therapy with respect to growth modification of the condyle is questionable.

6. Bending stresses associated with chin cup therapy could be related to growth modification in the mandible.

7.3. SUGGESTIONS FOR FUTURE WORK

7.3.1. Class III sample group.

In this project, joint loads were numerically determined from EMG validation of subjects with a normal growth pattern and a dento-skeletal Class I. It was reported that Angle Class III malocclusion patients have an abnormal muscle function related to the jaw form. Therefore, a sample group of Class III individuals could be used to test the hypothesis that chin cup forces can produce larger joint loads than for Class I individuals. In addition, considerations should be given to age when selecting a sample group.

7.3.2. Force magnitude

Linearity in the EMG signal and force magnitude relationship has been reported by several authors namely McCall *et al* (1986) and Kull *et al* (1988). However, some variation was observed in this study for the digastric muscle between 800 and 900 grams when a maximum jaw-closing moment was produced as demonstrated on figure 5.9. A similar muscular response was noticed for subjects HP, CL, and CS. Therefore, it might be advisable to avoid using a force magnitude beyond 800 grams when testing digastric muscle until further investigations in this regard are performed.

7.3.3. Increase of chin cup angles.

Some concerns were initially expressed with respect to subject and operator fatigue. Therefore, a large number of chin loading angles were not tested as was possible with the model. The decision to divide the external surface of the chin cup into five equidistant points was a reasonable one. However, it created a lack of information which could have been useful to provide irrefutable evidence for the model validation. Thus, it may be suggested that more chin loading angles could be tested with a greater number of these angles in the region approximating the condyles. Furthermore, it could be possible to limit the number of angles to five but, these angles should be in the range between 110 and 150 degrees with an interval of 10 degrees. The initial concern would then be addressed while adding supplemental information.

7.3.4. Joint loads with jaw-opening moments.

It was interesting to find that joint loads were the highest when jaw-opening moments were produced. When the line of force application was below the occlusal plane, these loads even exceeded the ones associated with normal molar biting by 35 percent. It appeared more difficult for the subjects to maintain their mandible in a stable position since the total muscle effort with jaw-opening loading was 13 percent higher than that for molar biting. Therefore, it may be revealing to investigate muscle recruitments and joint loads with devices such as low-pull headgear and orthopedic facemask. It would be mandatory to determine the force vectors involved with the facemask therapy and the direction of the resulting force on the chin. Muscle recruitments could be compared with numerical model predictions for validation. It was reported that the forces acting at the chin as a result of facemask do not pass exactly through the condylar hinge axis, and that the resulting moment was balanced by the masticatory muscles (Grandori *et al.*, 1992).

A research protocol involving low-pull headgear would likely raise more objections since it should potentially involve banding lower molars in non orthodontically treated subjects. However, a project of that nature could provide information of the reactive condylar forces. Nevertheless, special attention should be given to jaw position because of its influence on the reactive forces.

7.3.5. Numerical model.

The existing model has revealed itself as a valuable tool in determining reasonably well condylar loads from externally applied loads. However, it was dependent on anatomical data generated from both direct and indirect measurements. From the evidence presented in this study, it appeared adequate to use an indirect method to obtain anatomical coordinates. The sensitivity study showed that the muscle recruitment pattern was not affected by a 3mm variation in the x and y axes of the lateral pterygoid and anterior digastric origin coordinates. Consequently, it is suggested that a larger osteological sample should be used to create a data base for an indirect method in determining muscle coordinates. This should minimize the margin of error by limiting the variations within 3mm.

In addition, the numerical model used in the study did not take into account any stiffness requirement especially for chin cup loading angles approximating the condylar region. A modification of the theoretical force model may be suggested in this regard.

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APPENDIX A

INFORMED CONSENT FORM

Neuromuscular mechanisms and joint loads in presence of chin cup forces.

I .... agree to be part of the above mentioned study. I understand that some muscular activity tests will be done following pressures applied on my chin. This will help understand more about the way jaws are functioning. I understand that examination records, radiographs, photographs, and impressions for dental models will be taken as part of the regular orthodontic records which will also be used for this study. The records will become the property of the University of Manitoba, and may be used for research and presentation purposes.

I understand that more than one session may be necessary to collect the required data, and that I will have fifty dollars ($ 50.00) per session attended deducted from the total fees for my orthodontic treatment.

I also understand that there may be some discomfort with the testing but, the risks associated with the procedure are extremely small.

I understand that the study is for the purposes of research with no immediate benefit to myself. I understand that my participation in this study is voluntary and that I can withdraw at any time without penalty.

SUBJECT

Name;
(please print)...

Signature ....

INVESTIGATOR

Dr. Guy M. Lacoste

Signature ....

APPENDIX B

MANITOBA ANALYSIS FORM

PATIENT'S NAME ______________________________ BIRTHDATE ______________
Surname Given Name Initials Day Month Year

DATE	D M Y	D M Y	D M Y	D M Y	D M Y
AGE	Y M	Y M	Y M	Y M	Y M
CODE					

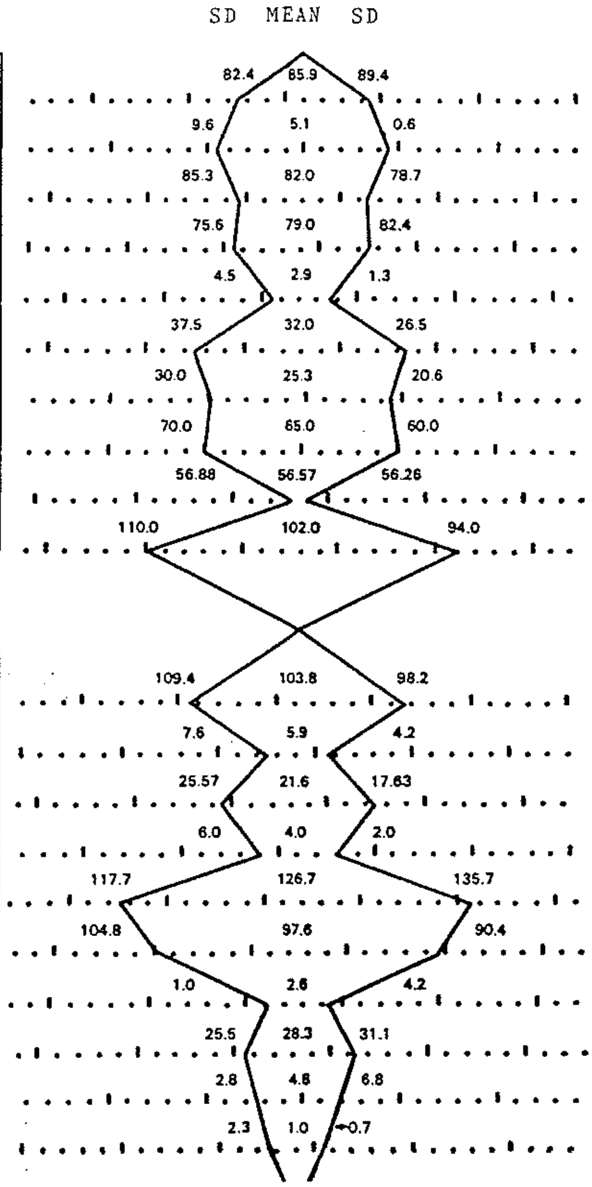
PRE-TREATMENT
DURING TREATMENT
POST TREATMENT
POST RETENTION
LONG RANGE RETENTION

SKELETAL PATTERN

NP-FH (°)					
NAP (°)					
SNA (°)					
SNB (°)					
ANB (°)					
MP-SN (°)					
MP-FH (°)					
ANS-Me (mm)					
ANS-Me / N-Me (%)					
NASO-LABIAL (°)					

DENTAL PATTERN

UI-SN (°)					
UI-AP (mm)					
UI-NA (°)					
UI-NA (mm)					
UI-LI (°)					
LI-MP (°)					
LI-AP (mm)					
LI-NB (°)					
LI-NB (mm)					
P-NB (mm)					



APPENDIX C

COMPENDIUM OF RESULTS

The present section displays results for each subject involved in the study. The data present the information in three areas of interest;

C.1.1. Muscle recruitment generated from 900 grams (8.82N) of chin cup loading with the head supported (S) and unsupported (US). No interocclusal contacts.

C.1.2. Muscle recruitment generated from 900 grams (8.82N) of chin cup loading with the head supported (S) and unsupported (US). Teeth together without biting.

C.2 Muscle recruitment pattern generated from model predictions using subject anatomical data.

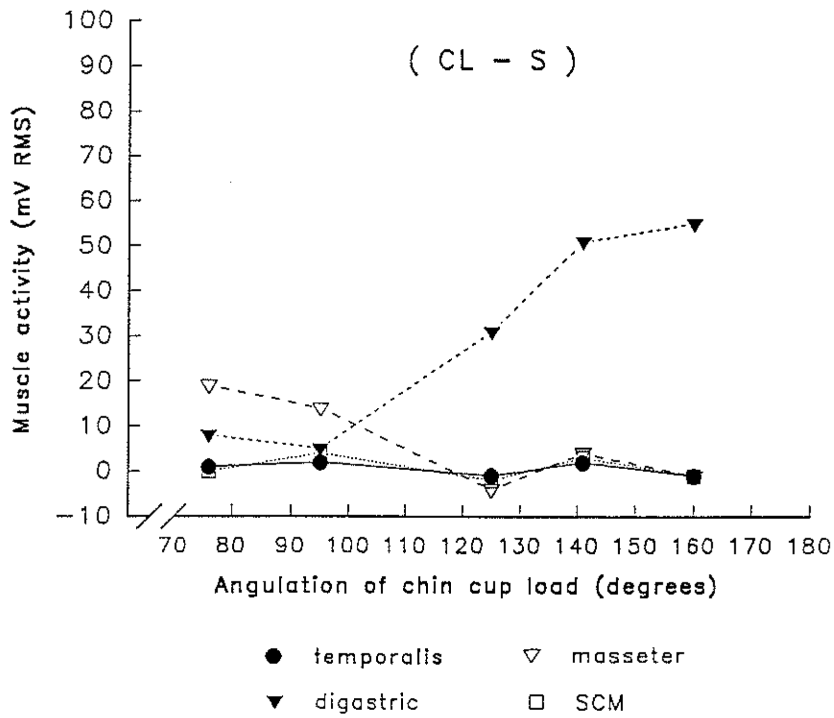
C.3 Model predictions of joint forces during chin cup loading in relation to chin cup loading angles.

Subjects involved in the study were CL, CS, DB, HP, HR, IY, KH, and VO.

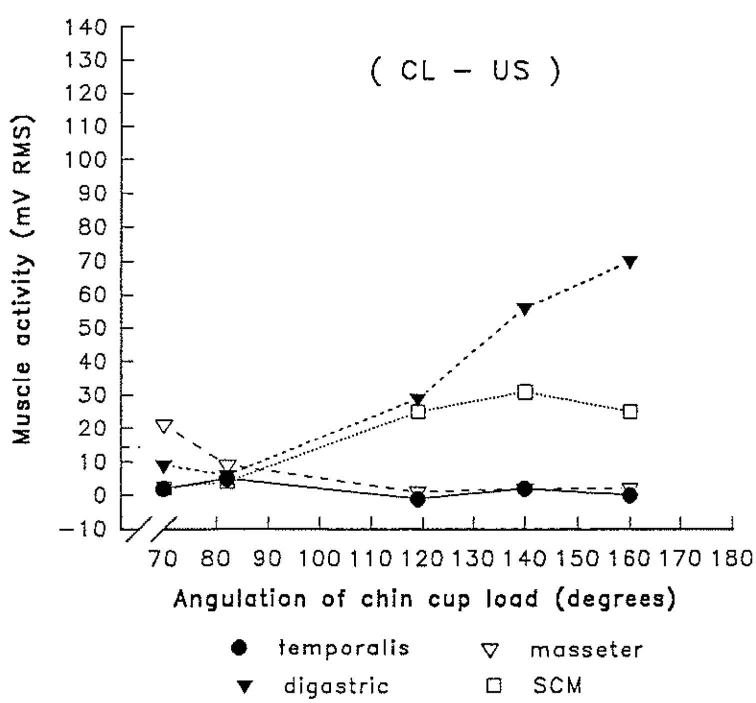
SECTION C.1.1.

Muscle recruitments generated from 900 grams (8.82N) of chin cup loading with the head supported (S) and unsupported (US). No interocclusal contacts.

SUBJECT CL

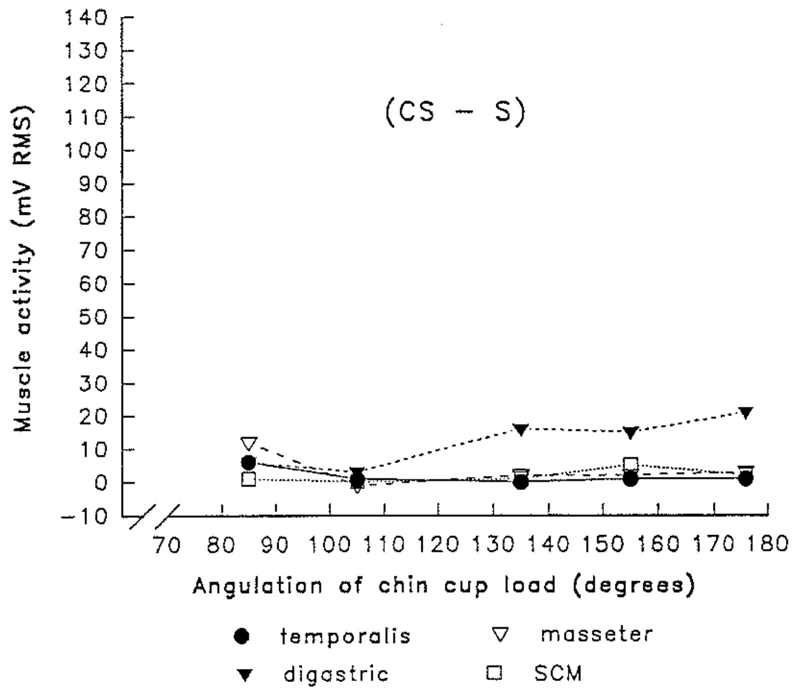


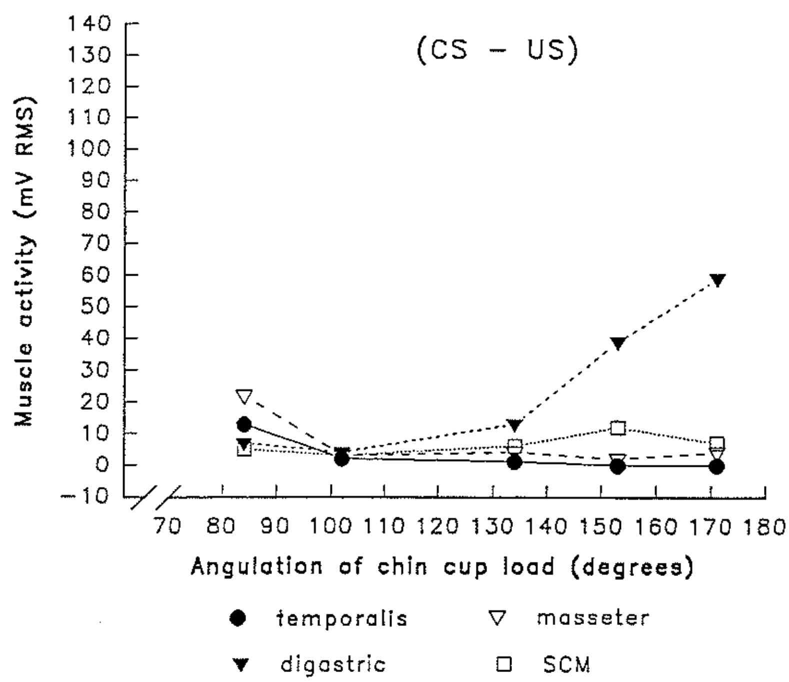
(CL - S)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM



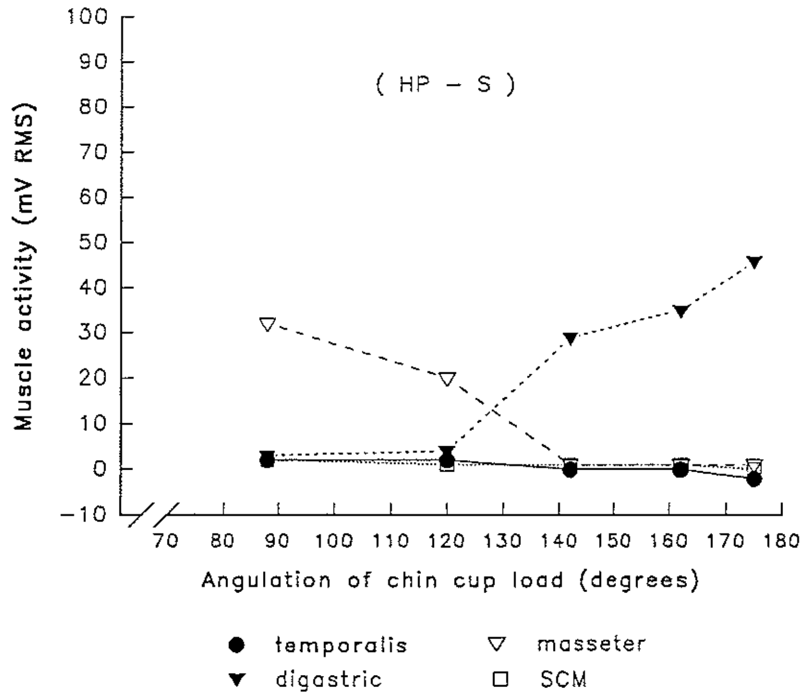
(CL - US)
Muscle activity (mV RMS)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

SUBJECT CS

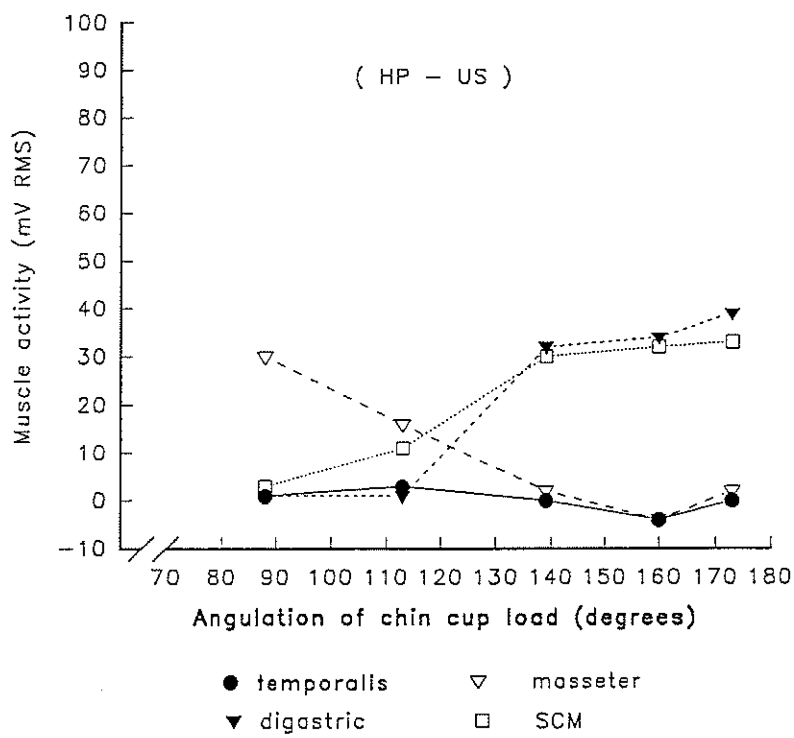

(CS – S)
Muscle activity (mV RMS)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM


(CS – US)
Muscle activity (mV RMS)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

SUBJECT HP

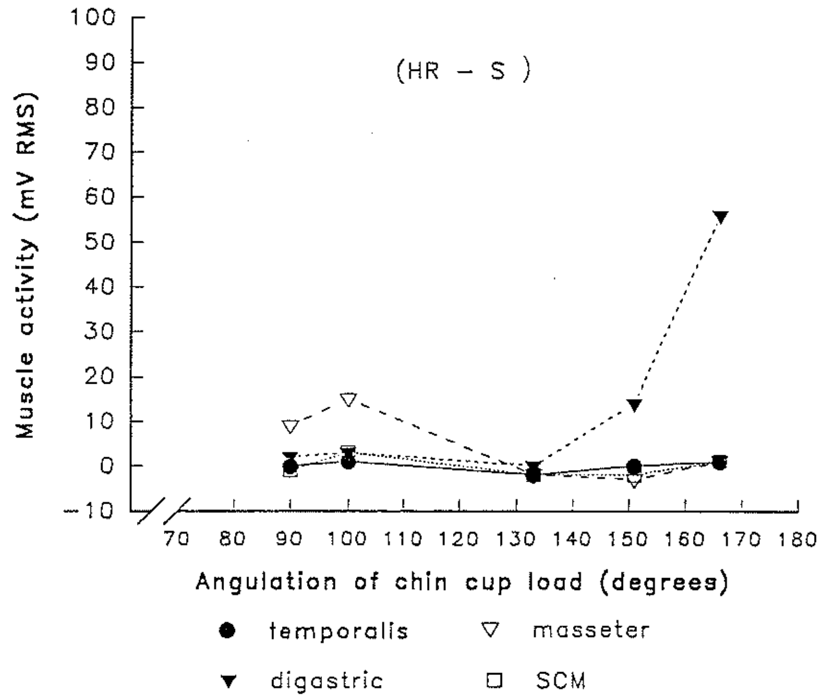


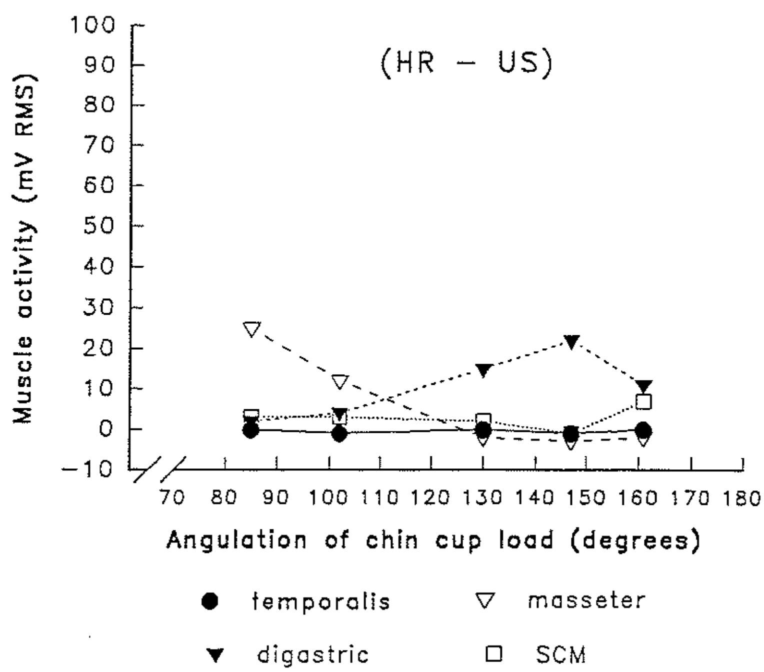
100
90
80
70
60
50
40
30
20
10
0
-10
Muscle activity (mV RMS)
(HP - S)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM



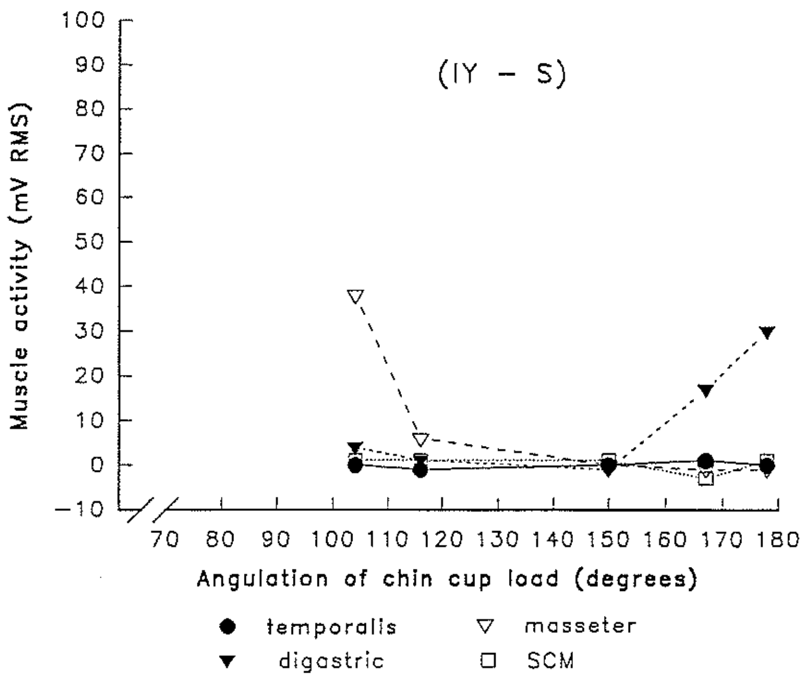
100
90
80
70
60
50
40
30
20
10
0
-10
Muscle activity (mV RMS)
(HP - US)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

SUBJECT HR

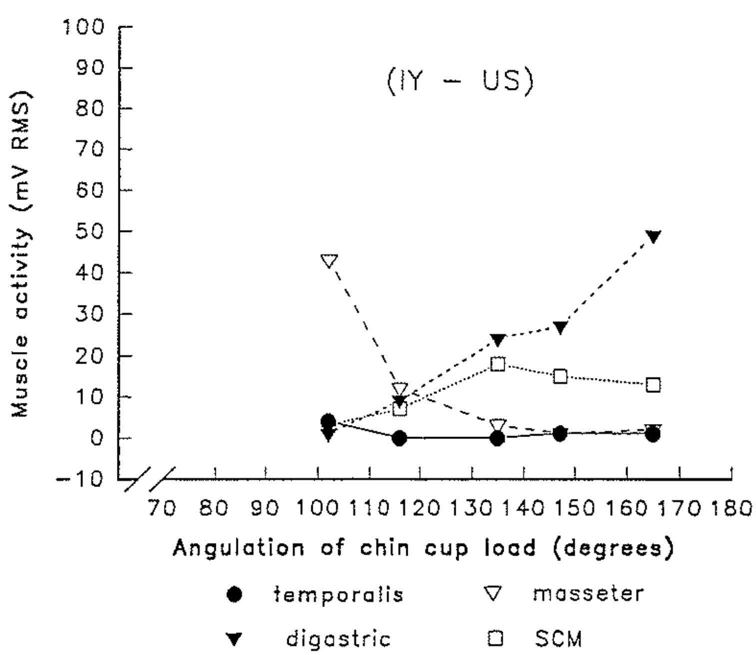

(HR – S)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
–10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM


(HR – US)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
–10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

SUBJECT IY

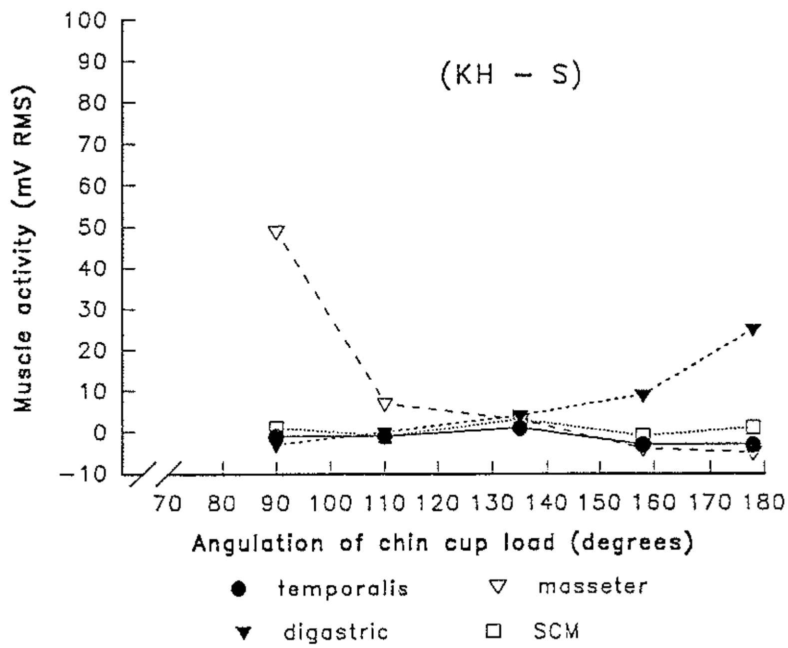


(IY - S)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

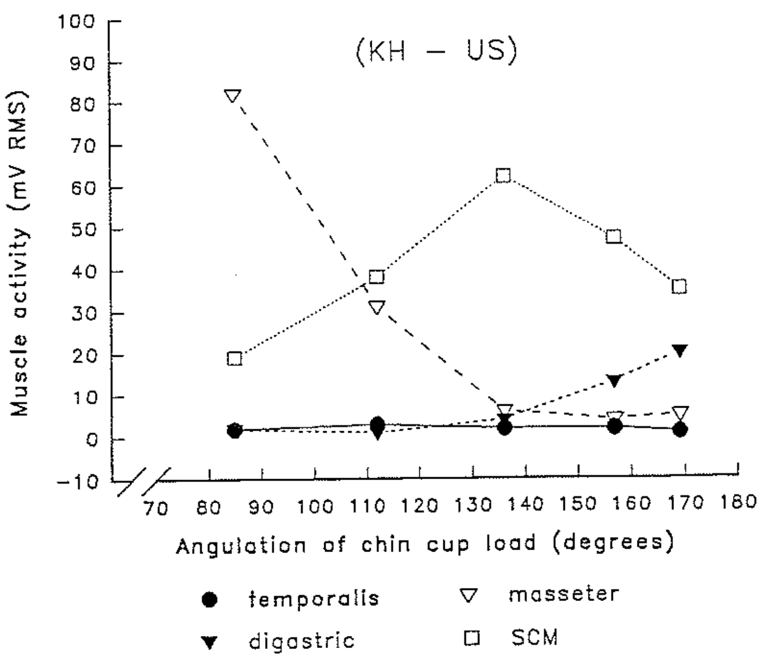


(IY - US)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

SUBJECT KH

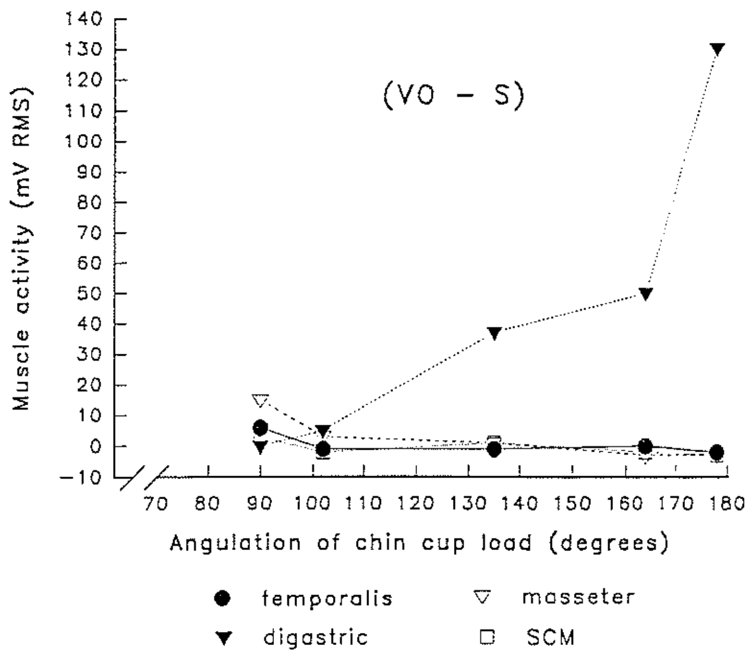


(KH – S)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
−10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

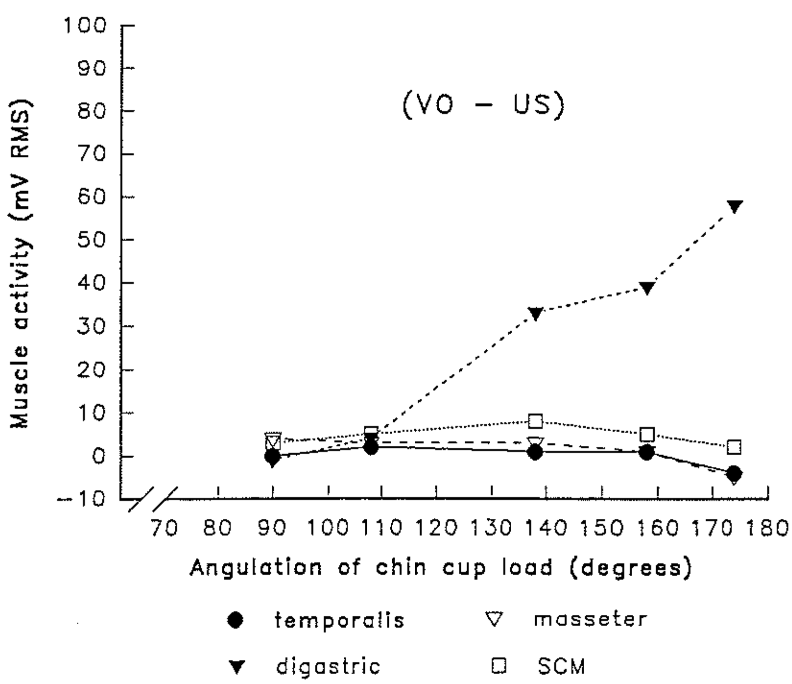


(KH – US)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
−10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

SUBJECT VO



(VO - S)
Muscle activity (mV RMS)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

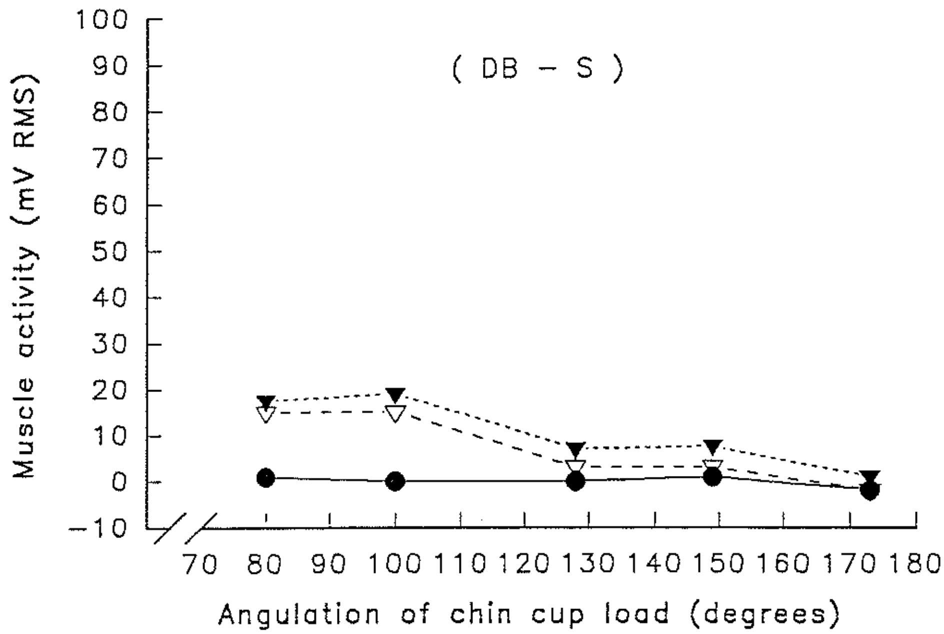


(VO - US)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
SCM

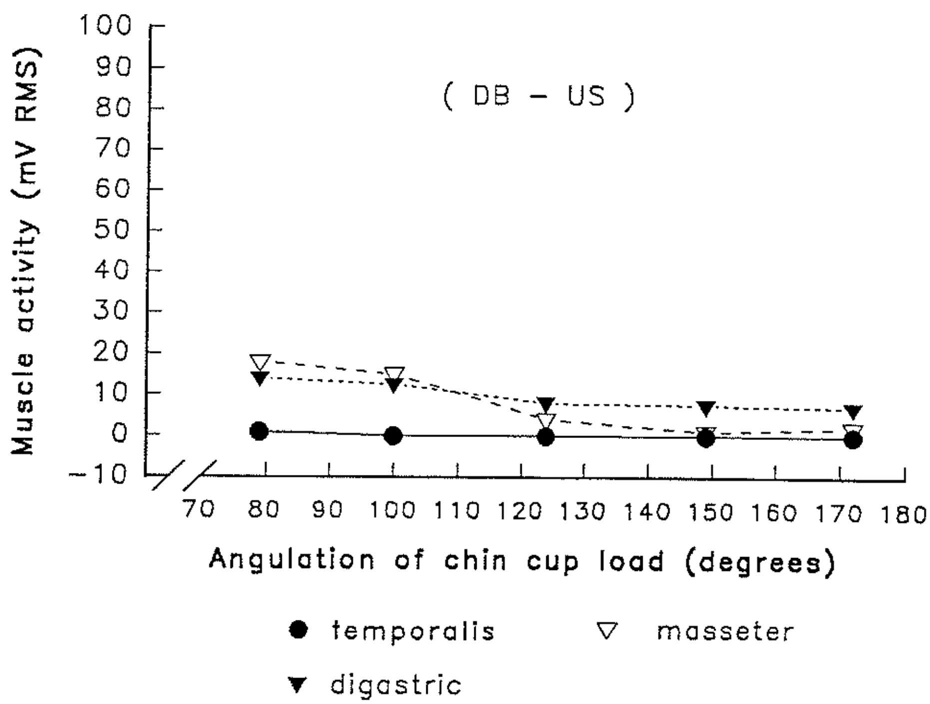
SECTION C.1.2.

Muscle recruitment patterns produced from 900 grams (8.82N) of chin cup loading with head supported (S) and unsupported (US). Teeth together without biting.

SUBJECT DB

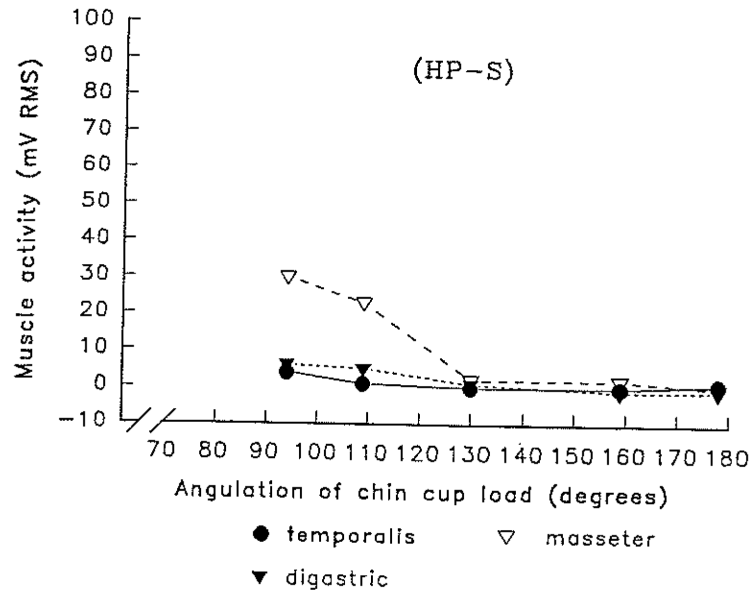


(DB – S)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
–10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)

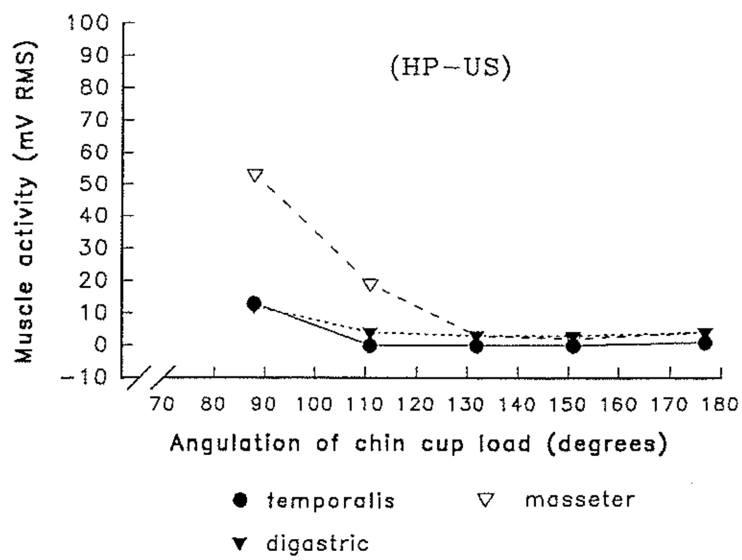


(DB – US)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
–10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric

SUBJECT HP

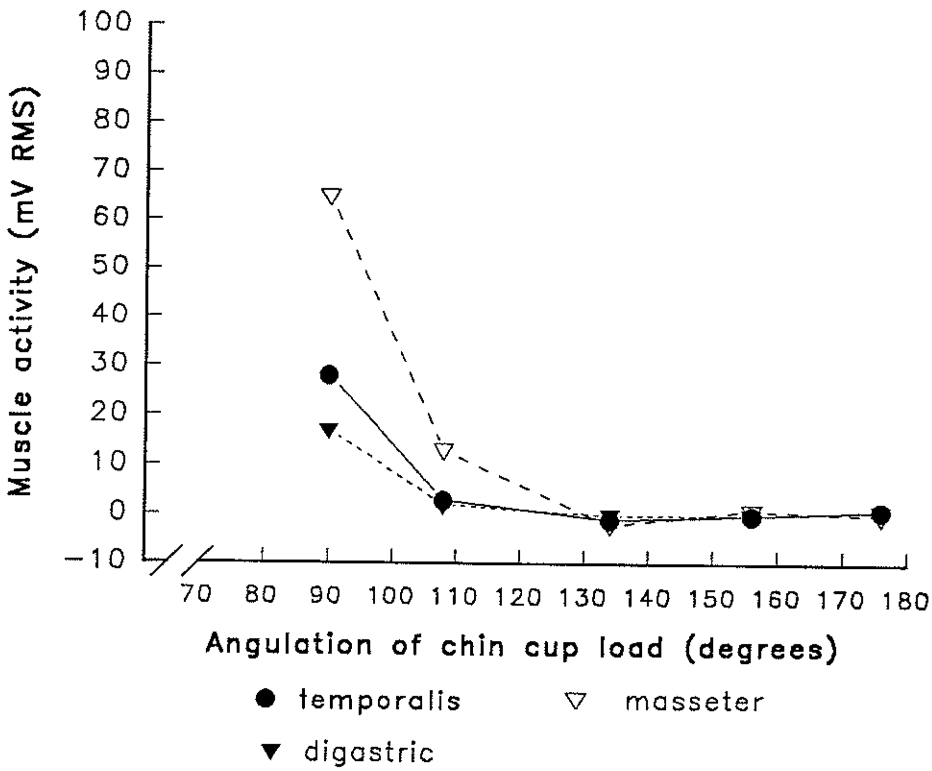


(HP-S)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric



(HP-US)
Muscle activity (mV RMS)
100
90
80
70
60
50
40
30
20
10
0
-10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric

SUBJECT IY

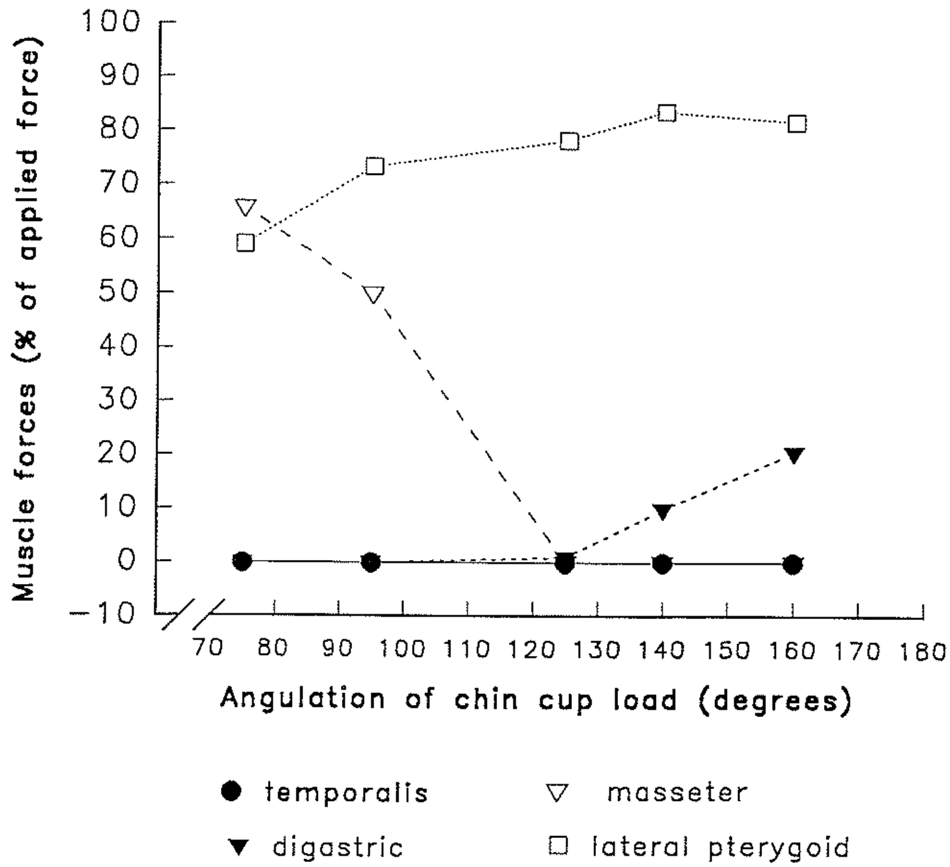


100
90
80
70
60
50
40
30
20
10
0
-10
Muscle activity (mV RMS)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric

SECTION C.2

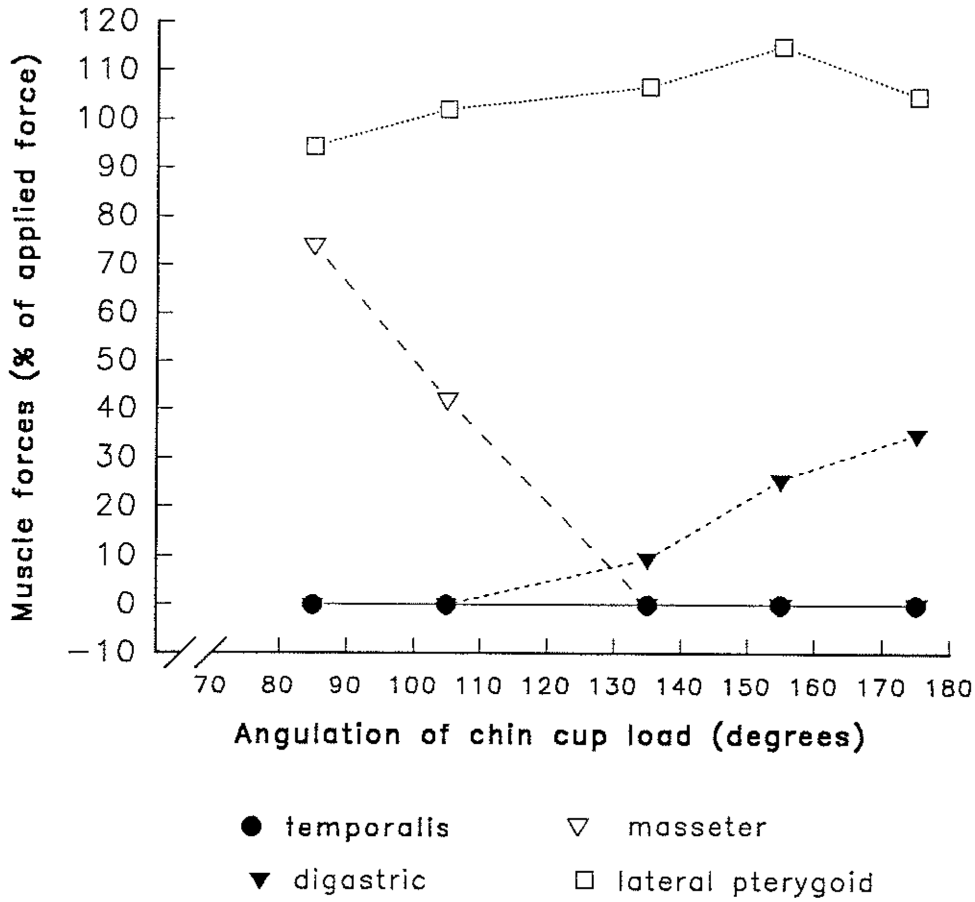
Muscle recruitment patterns generated from model predictions using subject anatomical data.

SUBJECT CL

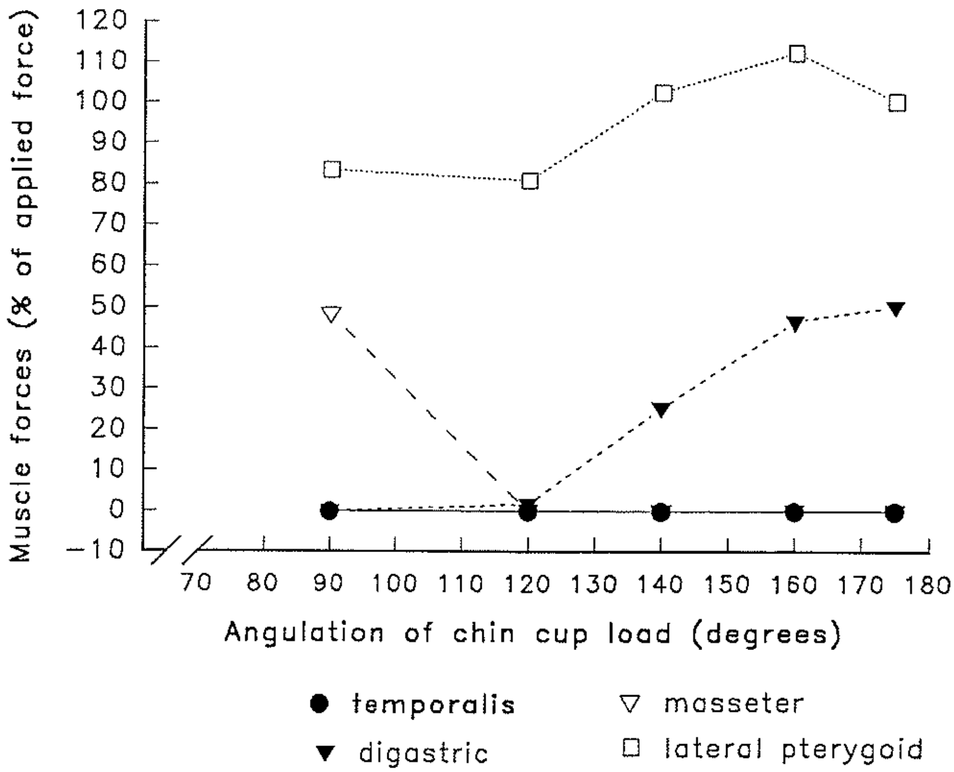


100
90
80
70
60
50
40
30
20
10
0
−10
Muscle forces (% of applied force)
70
80
90
100
110
120
130
140
150
160
170
180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
lateral pterygoid

SUBJECT CS

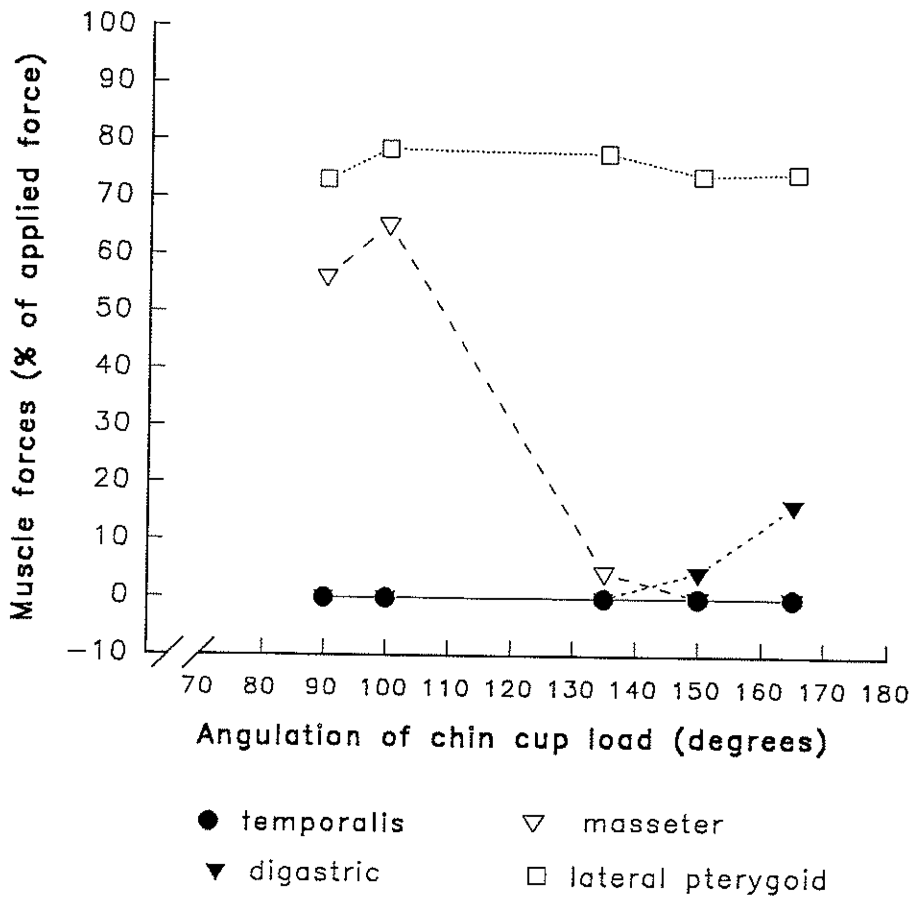

120
110
100
90
80
70
60
50
40
30
20
10
0
−10
Muscle forces (% of applied force)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
lateral pterygoid

SUBJECT HP



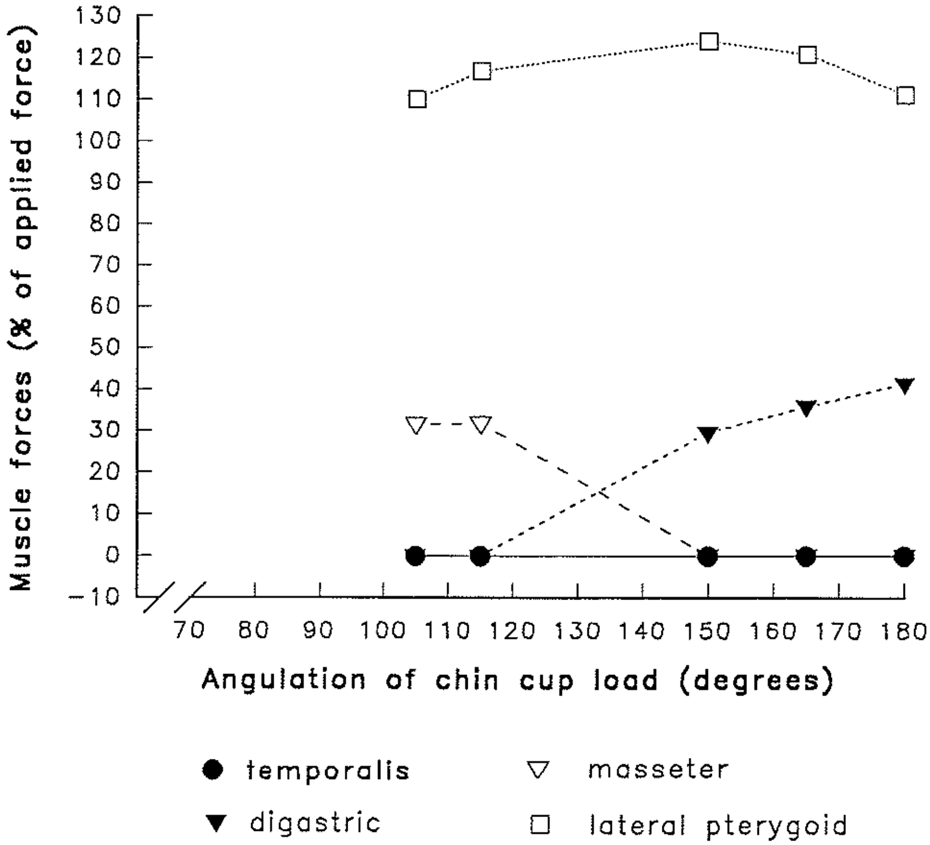
Muscle forces (% of applied force)
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
lateral pterygoid

SUBJECT HR



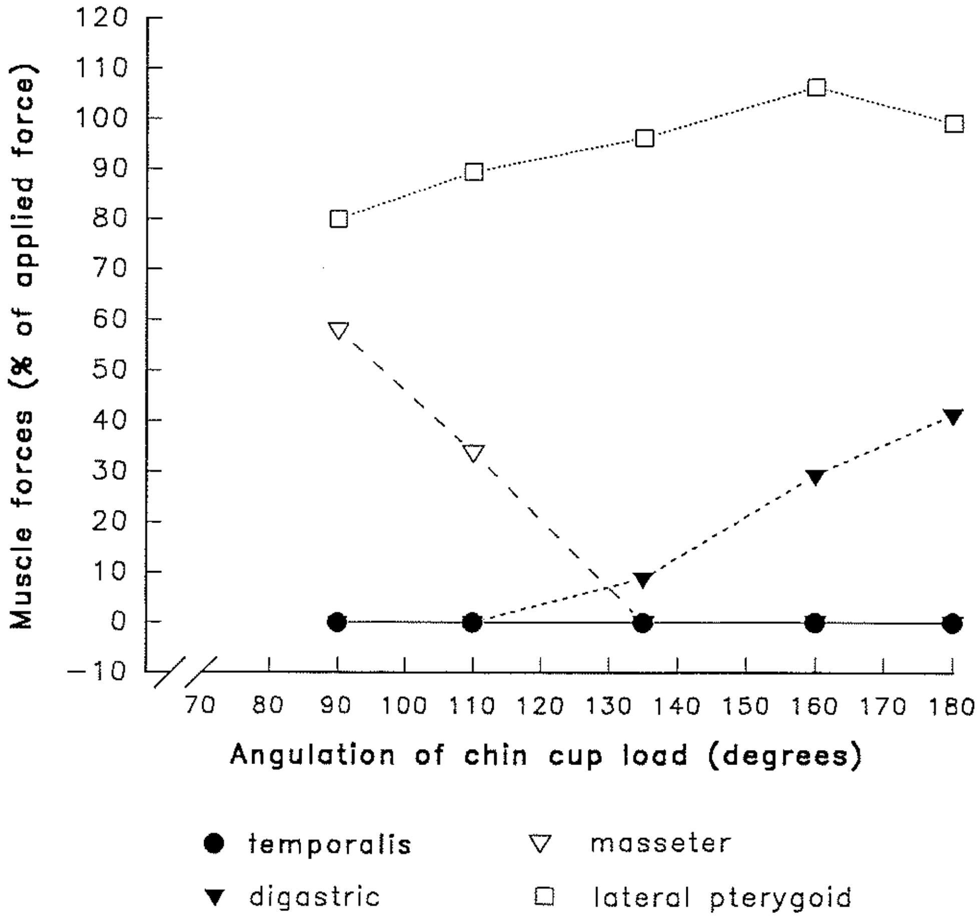
100
90
80
70
60
50
40
30
20
10
0
−10
Muscle forces (% of applied force)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
lateral pterygoid

SUBJECT IY



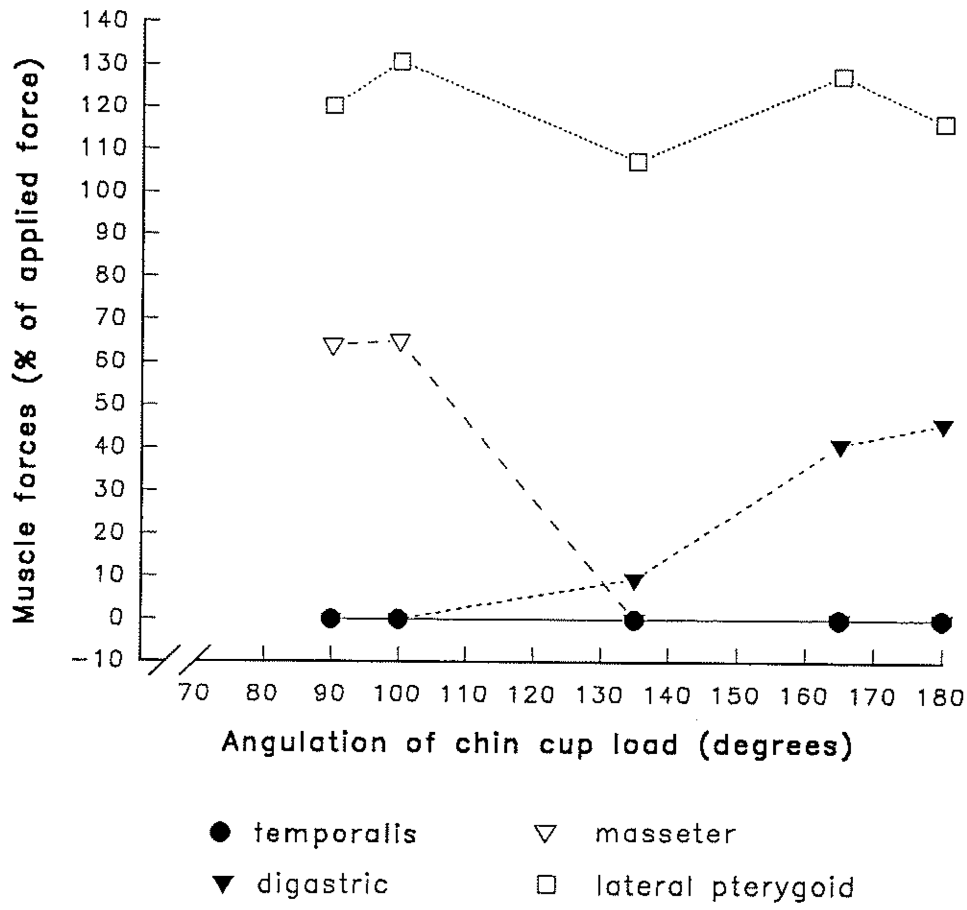
Muscle forces (% of applied force)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
lateral pterygoid

SUBJECT KH



120
110
100
90
80
70
60
50
40
30
20
10
0
−10
Muscle forces (% of applied force)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
lateral pterygoid

SUBJECT VO

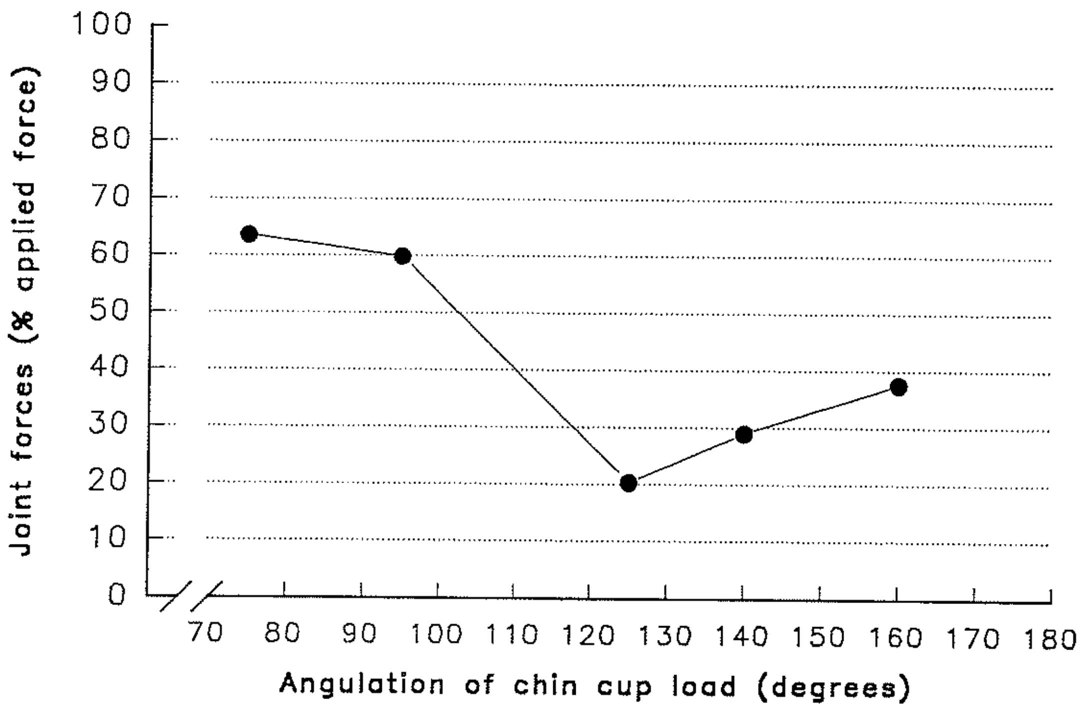


Muscle forces (% of applied force)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)
temporalis
masseter
digastric
lateral pterygoid

SECTION C.3

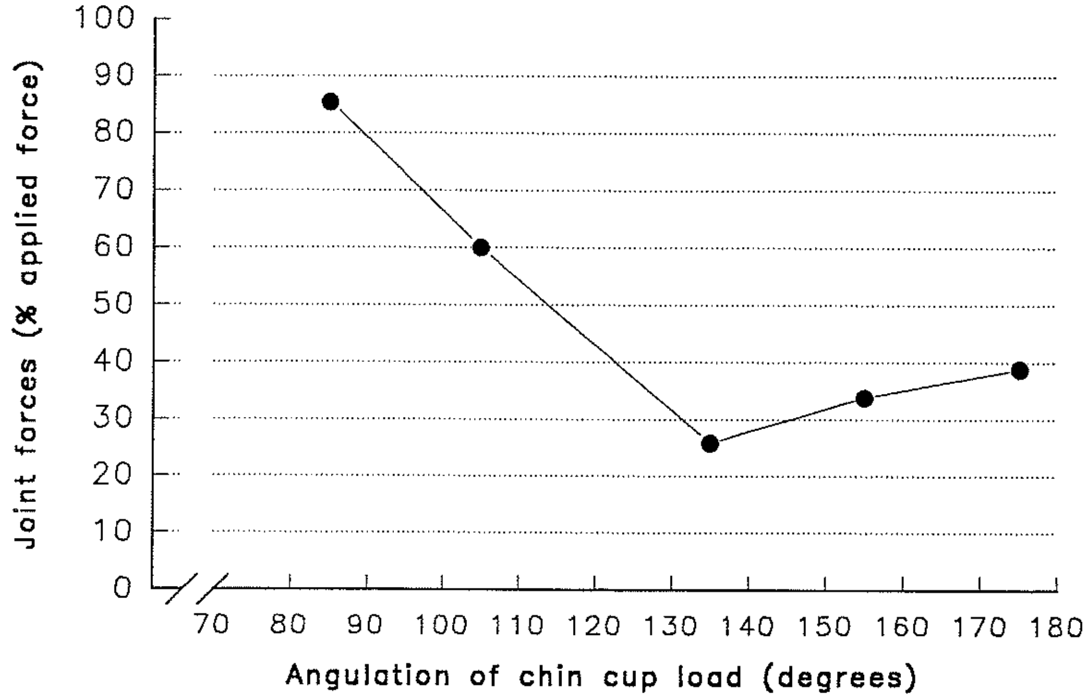
Model predictions of joint forces upon chin cup loading in relation to chin cup loading angles.

SUBJECT CL



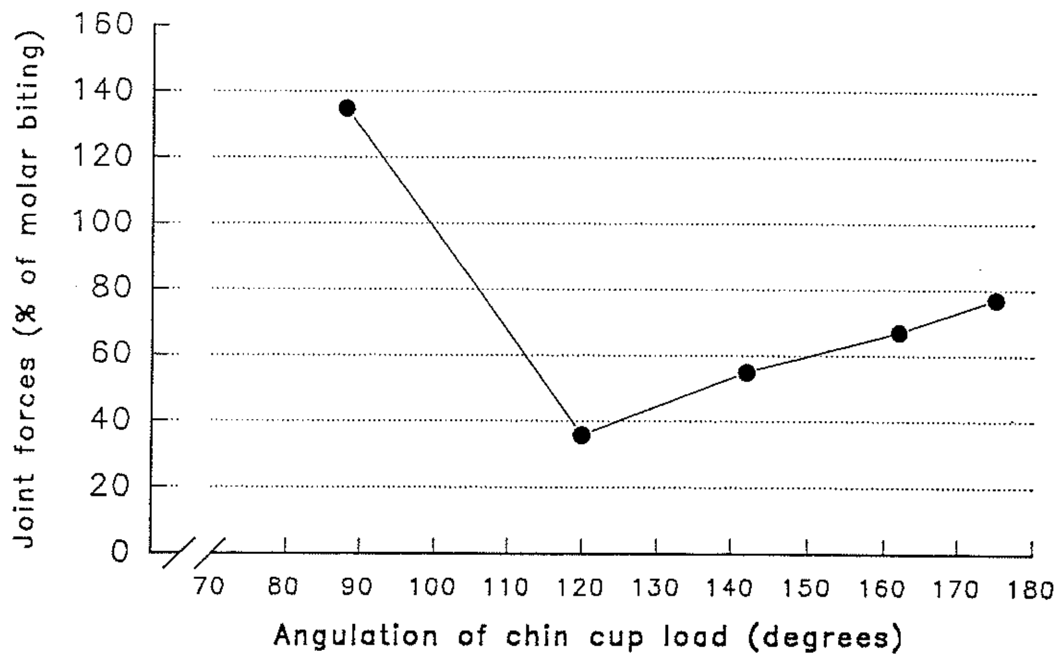
100
90
80
70
60
50
40
30
20
10
0
Joint forces (% applied force)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)

SUBJECT CS



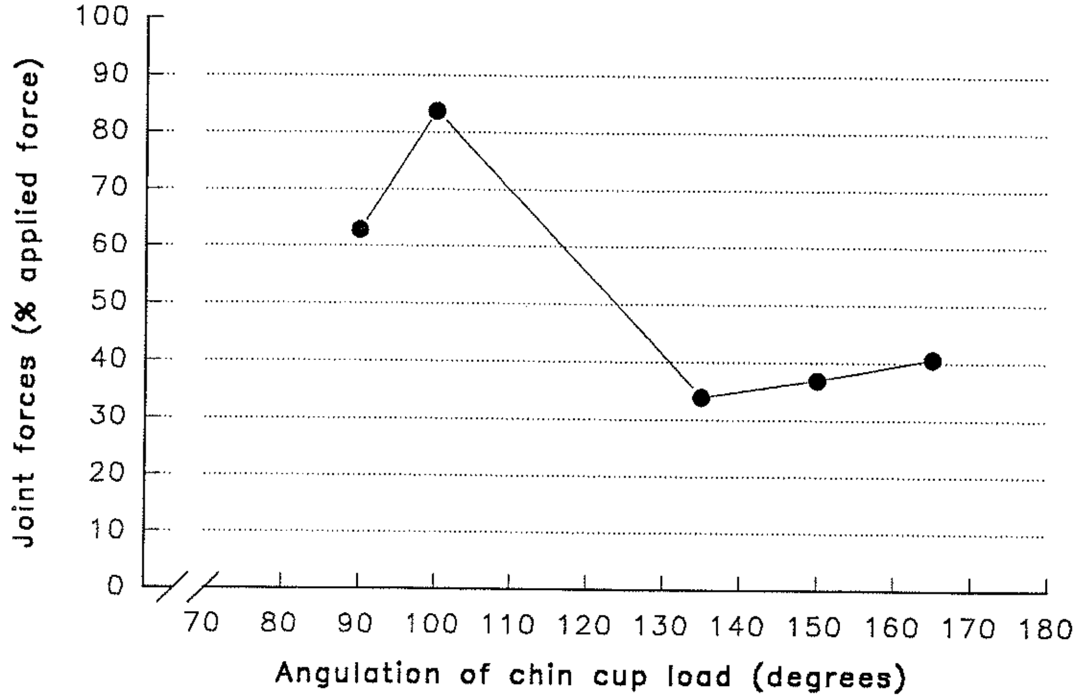
100
90
80
70
60
50
40
30
20
10
0
Joint forces (% applied force)
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)

SUBJECT HP

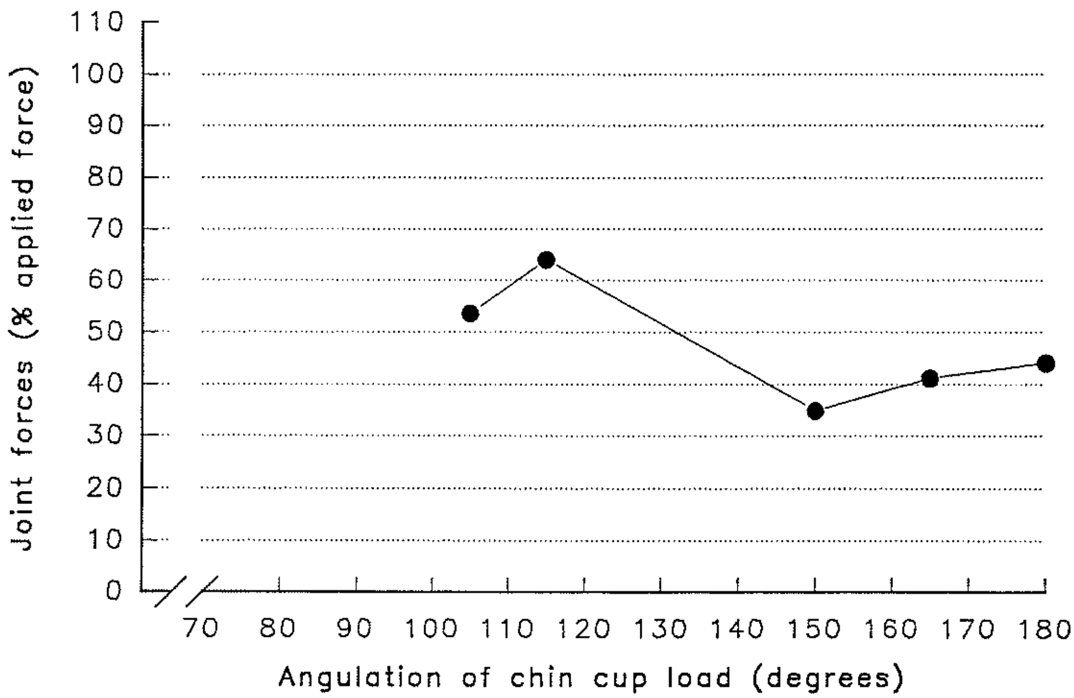


Joint forces (% of molar biting)
160
140
120
100
80
60
40
20
0
70
80
90
100
110
120
130
140
150
160
170
180
Angulation of chin cup load (degrees)

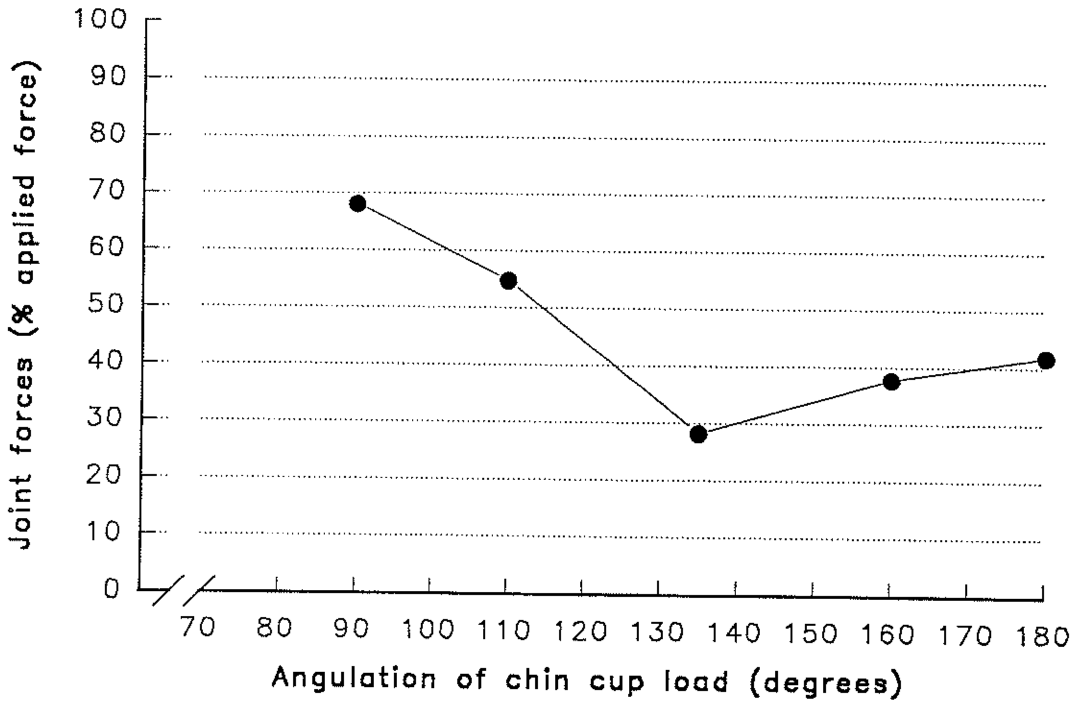
SUBJECT HR


100
90
80
70
60
50
40
30
20
10
0
Joint forces (% applied force)
70
80
90
100
110
120
130
140
150
160
170
180
Angulation of chin cup load (degrees)

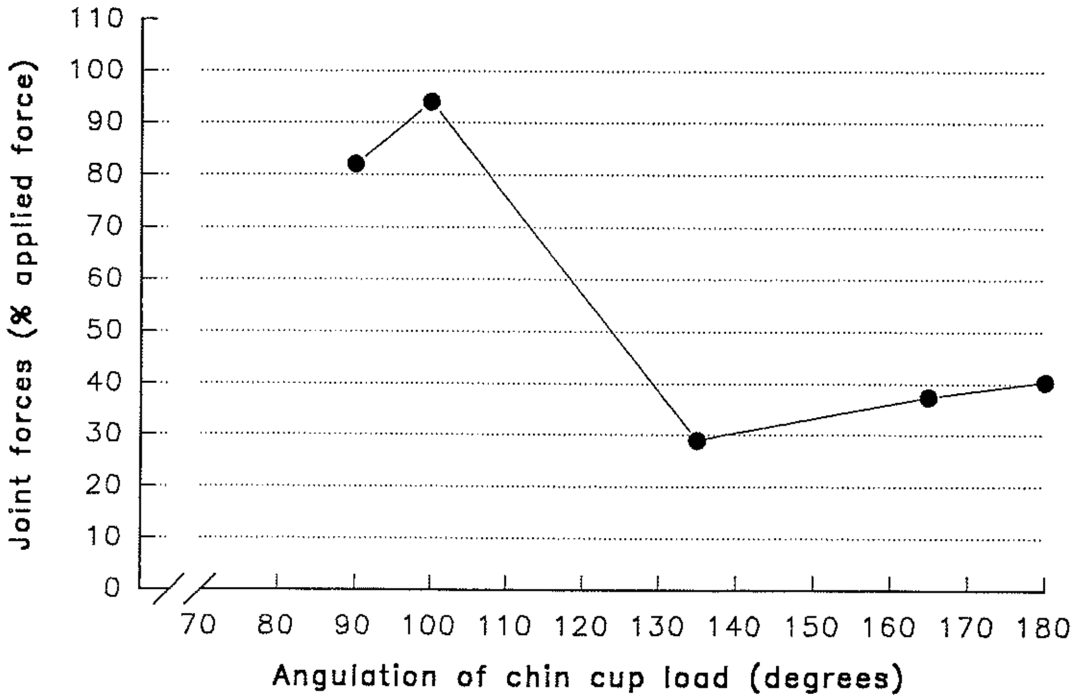
SUBJECT IY


Joint forces (% applied force)
110
100
90
80
70
60
50
40
30
20
10
0
70 80 90 100 110 120 130 140 150 160 170 180
Angulation of chin cup load (degrees)

SUBJECT KH


Joint forces (% applied force)
100
90
80
70
60
50
40
30
20
10
0
70
80
90
100
110
120
130
140
150
160
170
180
Angulation of chin cup load (degrees)

SUBJECT VO



Joint forces (% applied force)
110
100
90
80
70
60
50
40
30
20
10
0
70
80
90
100
110
120
130
140
150
160
170
180
Angulation of chin cup load (degrees)

APPENDIX D

MANDIBULAR PROGNATHISM.

Mandibular prognathism was defined by the British Standards Institution (1983), as "a marked forward projection of the mandible beyond the normal distance from the cranial base". Approximately 5 per cent of the caucasian population of North America exhibits mandibular prognathsim (Graber, 1975). The incidence is even greater in Japan, Central America and some Scandinavian countries (Scott, 1993). There is confusion related to this expression since the terms "mandibular prognathism" and "Class III malocclusion" have been used synonymously in the dental literature to describe both occlusal and skeletal relationships. However, individuals who exhibit a Class III malocclusion as described by Angle (1907), may present with any number of combinations of skeletal and dental variations within the facial skeleton.

Several authors have found that a high percentage of their Class III patients have a prognathic mandible with normal maxilla (Sanborn, 1955; Jacobson *et al.*, 1974; Mackay *et al.*, 1992). Ellis and McNamara (1984) and Guyer *et al.* (1986) reported a larger number of patients with a combination of maxillary retrusion and mandibular prognathism, than with any other combination. Other clinicians registered a high incidence of retrusive maxilla with normal mandible within sample groups of individuals with Class III dental malocclusion (Dietrich, 1970; Ishii *et al*, 1987). Major and Elbadrawy(1993) proposed the term Class III skeletal malocclusion which would encompass all the different skeletal variations.

Horowitz *et al.* (1969) examined 52 adult individuals with mandibular prognathism and explained from their findings that the prognathism was not primarily a matter of size discrepancy, but rather the result of a complex disturbance of craniofacial relationships. However, the relative position and form of the mandible was a contributing feature to the deformity.

Characteristic dento-skeletal features have been attributed to mandibular prognathism. Guyer *et al.* (1986) reported that class III patients consistently exhibited longer posterior cranial bases than average, larger mandibular plane angles, larger gonial angles, longer mandibles, maxillary incisor protrusion, and mandibular incisor retrusion. However, the opening of the gonial angle as a common finding in Class III cases, is still a matter of some discussion (Cole, 1988).

Bimler (1970) has related mandibular prognathism to an abnormality of the temporal and occipital regions of the base of the skull resulting in a "pathological" forward position of the temporomandibular joints.

Increased angular flexure of the cranial base (Bjork, 1947) and a raised natural head position (Solow and Tallgren, 1976; Cole, 1988) have also been reported to be associated with mandibular prognathism.

In an electromyographic study of 12 Class III malocclusion cases, Ahlgren (1970) associated abnormal muscle contraction patterns with the characteristic Class III jaw form. This was confirmed by Moss and Chalmers (1974) who also found that patients with Class III malocclusion had a distinctive pattern of muscle activity.

A multitude of different cephalometric criteria have been suggested to determine the anteroposterior position of the mandible. Some of the criteria included the relative position of B point to the cranial base (Riedel, 1952; Steiner, 1954), angular measurement of A and B points relative to Nasion (Ahlgren, 1970), unit length standards of mandible (Harvold, 1974), the linear difference between a projection of point A and point B to the functional occlusal plane (Jacobson, 1975), the anteroposterior molar relationship (Horowitz *et al.*, 1969; Guyer *et al*, 1986), or the angular measurement between point A and B relative to a craniofacial centre (Johnson and Eid, 1980). Sollow and Tallgren (1976) and Lundström and Lundström (1989), stressed the importance of measuring prognathism from a true horizontal line instead of sella-nasion line.

The use of a particular cephalometric analysis as a radiological method may be misleading in describing skeletal prognathism. Sue *et al.* (1987) reported that when SNA and SNB angles were used to determine the antero-posterior jaw discrepancy, the mandible was implicated as the major contributor, but, when linear measurements of A point to facial plane and Nasion perpendicular to A point were used, the majority of cases were classified as maxillary retrusion.

There appears to be a definite familial and racial tendency to mandibular prognathism. The majority of individuals with Class III skeletal relationship appears to have inherited their jaw proportions (Litton *et al.*, 1970; Jacobson *et al.*, 1974; Mew, 1986). Sugawara *et al.* (1990) postulated that facial profiles were predetermined morphogenetically and were difficult to change. Guyer *et al* (1986) pointed out that most of the characteristics associated with adult Class III malocclusion are already present at an early age. Dietrich (1970) and Proffitt (1986) claimed that the incidence of mandibular prognathism tended to increase with age because of a longer-lasting mandibular growth.

APPENDIX E

E. ERROR CONSIDERATIONS

E.1. Analysis of angular variations of the loads on the chin.

It was reported in section 4.9.2. that there was on average, -1.0 ± .85 degree (SD) error in the force direction with a range varying between +1.0 degree and -1.5 degree. Therefore, the numerical model was used to evaluate the effects of a load applied on the chin which deviates in direction from the desired mid-sagittal plane. Lateral deviations (θ_{XZ} angle) of the loading angle by 1, 2, 3, 4, and 5 degrees (see figure E.1) were tested and muscle forces and joint loads were calculated for subject HP. The results were compared with the results of symmetrical chin loading.

At 175 degrees θ_y, joint loads remained exactly the same and for θ_{XZ} angles of 3, 4 and 5 degrees. Only the digastric muscle showed a difference in muscle force varying up to 1.2 per cent increase in the ipsilateral muscle. A deviation 1 and 2 degree from a symmetrical loading angle induced changes in the muscle forces of less than to 0.5 per cent.

For a 160 degree θ_y closing angle, no differences were found for all muscles except the digastric muscle which exhibited an increase in muscle force ranging between 0.9 to 5 per cent. Joint loads did not exceed 1 per cent for θ_{XZ} angle of 1 to 5 degrees. When the θ_y chin cup loading angle was 140 degrees, digastric muscle force increased from 2 to 10 per cent for 1-5 degree difference in θ_{XZ} angle.

A different response was observed at 120 degrees. The lateral pterygoid muscle on the opposite side of the chin load generated 4 to 13 per cent more force for a 2-to-5 degree range of θ_{XZ} angles. The digastric response was maintained below 2 per cent of augmentation, while joint loads varied from 0.3 to 2.6 percent for the same range of θ_{XZ} angles.

Jaw-opening forces in a θ_y direction of 90 degrees in combination with small θ_{XZ} forces of chin cup load, induced asymmetrical forces in the contralateral masseter, lateral pterygoid and medial pterygoid muscles, showing an increase from 4 to 14 per cent for θ_{XZ} angles larger than 3 degrees. Up to twenty per cent more load was produced to the ipsilateral joint.

It can be assumed that for the different closing angle loads, the source of error induced by the operator was not of great significance for θ_{XZ} angles less than 3 degrees. The numerical model predicted a decrease in the ipsilateral digastric muscle force of less than 4 per cent on the side. Therefore, it is reasonable to suppose that the effect on the muscle recruitment pattern would be minimal. For the jaw-opening loads, an asymmetrical pattern in the muscle forces and the joint loads was determined by the numerical model for a θ_{XZ} angle as small as 1 degree. Assuming that the deviation in the mid-sagittal plane did not exceed 3 degrees, the left masseter muscle might have shown a decrease of 3 to 9 per cent. The digastric muscle activity was not affected by any deviation at this loading angle. However, joint loads could increase up to 12 per cent.

Consequently, there is evidence that the effect of the deviation errors in the mid-sagittal plane on the assessment of muscle activity pattern was likely to be minimal. Nevertheless, a conscious effort should be made to keep the load on the chin cup as symmetrical as possible in order to allow an adequate validation of the model predictions.

E.2. SENSITIVITY STUDY

It was desirable that the indirect approach of measurement used in this project had provided a reasonable estimate of the subject muscle coordinates essential for the numerical model. Thus, similar muscular recruitment patterns were found between the EMG results and the model predictions. However, it was decided to explore the effects of coordinate variations on muscle and joint responses using the model. The sensitivity study required the creation of an "altered" anatomical geometry in which a variable such as the insertion of the lateral pterygoid muscle, was moved antero-posteriorly or supero-inferiorly by 3mm to study the effects on the muscle recruitment pattern and on the condylar loading. The calculations of the numerical model enabled comparisons between the indirectly derived geometry file and its altered versions. These were determined for a chin cup loading angle of 90 degrees.

The analysis showed that the "altered" geometries produced little change in the muscular recruitment patterns obtained from the unaltered geometry file. Temporalis and anterior digastric muscles remained inactive or minimally active independently of the "altered" geometry's. The masseter muscle showed less than 1 per cent variation in the muscle force. The numerical model predicted an increase of 8 per cent in muscle forces of the lateral pterygoid muscle when the origin was moved posteriorly by 3mm, but a decrease between 3 and 5 per cent if the origin was displaced 3mm anterior, superior of inferior. Also, the model predicted a variation in joint loads of ± 8 per cent.

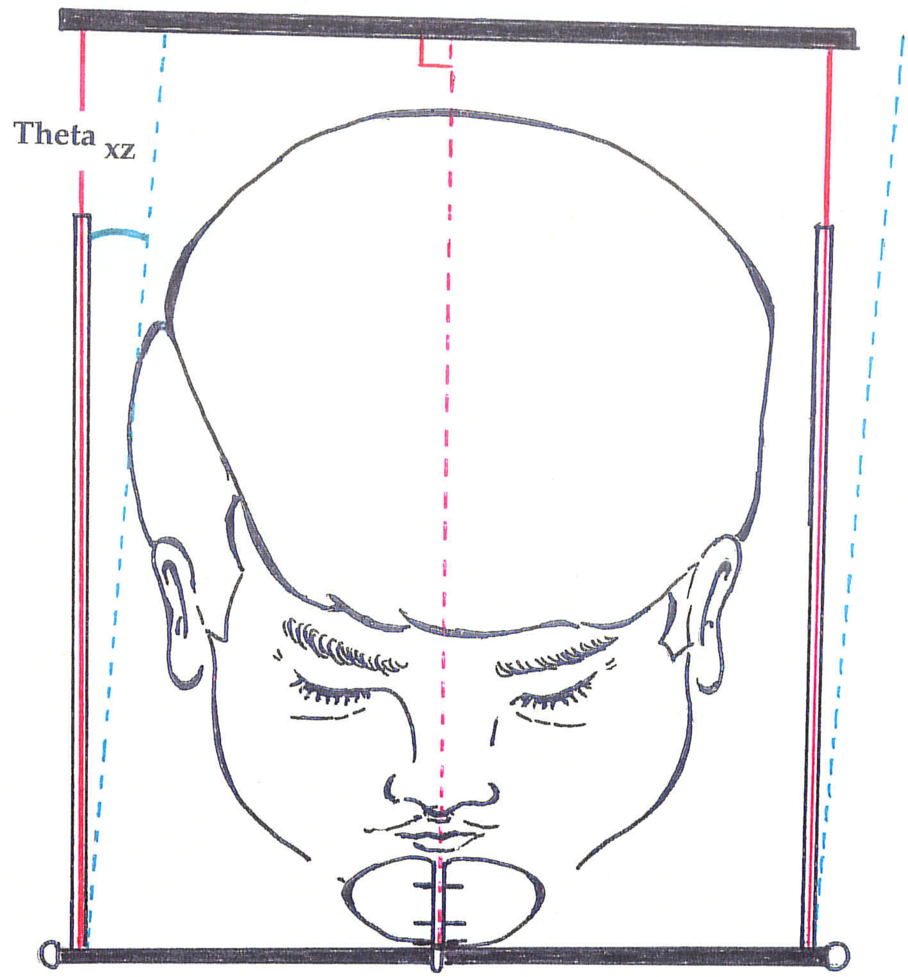


Figure E.1 Lateral deviation of the chin cup loading angle from the desired mid-sagittal plane is expressed by θ_{XZ} angle. The tendency was for the chin cup load to be applied with a 1.0 degree deviation from right to left .