LOADING AND EMINENCE DEVELOPMENT OF THE POSTNATAL HUMAN TEMPOROMANDIBULAR JOINT

by

Jeffrey Charles Nickel

A thesis
submitted to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Master of Science

Department of Preventive Dental Science

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ABSTRACT

A theoretical study was undertaken to determine whether there is a relationship between the development of the human temporomandibular joint (TMJ) eminence and the direction of condylar loading on the eminence.

The required data for this study were quantitative assessments of TMJ eminence slopes and the probable directions of condylar loads for individuals representative of the period of human TMJ development (from birth to approximately twenty (20) years of age). Suitable osteological collections provided data on forty (40) skulls ranging in ages from birth to twenty (20) years. Each skull provided three-dimensional metric coordinates of the skeleto-dental relationships and the origins and insertions of the masseter, temporalis, and lateral pterygoid muscles. The coordinates from each skull were used in a three-dimensional numerical model of isometric biting to estimate the TMJ load magnitude and direction. An elastomeric impression record was made of the temporal component of either the right or left TMJ eminence and fossa of each skull. Additional data were collected from nine (9) isolated temporal bones representing the ages of newborn to eighteen (18) months. An analysis of the sagittal morphology of the eminence was made and the velocity of shape changes with increasing age was recorded.

Analysis of the changes in the shape of the TMJ eminence indicates that the maximum velocity of change occurs prior to the age of three (3) years. It is hypothesized that early vertical loading of the condyle augments TMJ eminence development; development which occurs by means of a secondary cartilage. The secondary cartilage is a precursor of a chondroid type of bone which forms most of the newly developed eminence.

The results indicate that there may be a significant functional relationship between the timing of eminence development and the growth-related changes in the direction of condylar loading. It was found that the functional position of the mandible influenced the calculated direction of condylar loading. In the neonate, the mandible is protruded during suckling, which potentiates a predominantly vertical loading pattern of the condyle on the flat temporal component. Later, with the eruption of primary molars, posterior biting is possible. Biting on molars results in a change to a more anteriorly directed pattern of condylar loading on the newly developed eminence. The angle of condylar loading was found to be influenced by the anteroposterior position of the mandible and by changes in the relationships of the components of the biting apparatus, which result from growth. The early development of the TMJ eminence ensures perpendicular loading of the condyle on the eminence when molar biting occurs.

The TMJ is a synovial joint, and a common feature of such joints is the principle of minimization of loads per unit area. Perpendicular loading probably helps to minimize the magnitude of loading on the articulating surfaces and reduces the muscle forces necessary to maintain postural control of the mandible.

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Chapter 1

INTRODUCTION

The neophyte student researcher of the temporomandibular joint (TMJ) is in league with an unusual mix of company. Comparative zoologists and palaeontologists have looked to the development of the TMJ as the beginning of the phylogenetic order of mammalia, an order believed to have evolved from the order of reptilia. Physical anthropologists have looked at the temporomandibular joint and its mechanics as distinguishing features in the legacies of man's hominid ancestors. Anatomists and craniofacial biologists have long scrutinized joint anatomy and function in order to understand the basis of pathology and dysfunction of the human masticatory system.

A review of TMJ research indicates that the relationship between joint form and function is still a matter of considerable debate. The mechanisms by which alterations in joint form are produced have not been identified. Little is known about the orthopaedic characteristics of the TMJ design. The mechanisms of development of the TMJ eminence and the relationship between direction of condylar loading and eminence morphology have not been established.

A considerable amount of research has been performed on the growth and development of the TMJ condyle, but only recently has attention focused on the temporal component of the joint. Temporomandibular joint eminence development has been evaluated either histologically or from gross anatomical inspection. These accounts give only a qualitative evaluation of eminence development. Quantitative descriptions of eminence development from birth to maturity are not available.

A secondary cartilage has been described as the precursor of the osseous eminence. Researchers have begun to establish the influence of mechanical loading as a factor in the development of secondary cartilages. It is not known whether the immature TMJ is mechanically loaded during suckling or biting, but it has been established that the adult TMJ is a loaded joint. Theoretical modelling reported by Smith (1984) identified the various biting conditions under which the adult TMJ was loaded. _In vivo_ experimentation reported by several authors (reviewed by Hylander, 1985) has established condyle loading in adult animals for a few specified conditions.

This study examined the relationship between eminence development and direction of condylar loading. The joint loading was calculated by a numerical model similar to that used by Smith (1984) and Smith _et al_. (1986). For the purposes of the present study, a basic assumption was made that occlusal forces are present when children suckle, or participate in primary incisor and molar biting.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Since this study was concerned with the relationship between direction of joint loading and the development of the joint eminence, the literature review is divided into three main sections.

Section 2.2 provides a brief review of temporomandibular joint (TMJ) anatomy.

Section 2.3 examines the literature describing temporomandibular eminence development. This section briefly describes prenatal development (Section 2.3.1) and then focuses on qualitative and quantitative analyses of postnatal eminence development (Section 2.3.2). In order to contrast growth of the postnatal eminence with eminence remodelling, Section 2.3.3 briefly describes the current knowledge concerning remodelling of the mature eminence. A summary of the state of knowledge concerning eminence development is presented in Section 2.3.3.

Section 2.4 outlines the debate concerning whether or not the temporomandibular joint is loaded. Traditional experimental and more recent theoretical approaches are reviewed in Section 2.4.1. More recent *in vivo* experimental methods are described in Section 2.4.2. A summary of the state of knowledge concerning joint loading is presented in Section 2.4.3.

2.2 Review of the Anatomy of the Developing TMJ

An overview of the anatomy of the developing TMJ is presented in Figure 2.2.1. Of importance to note is the zone of maturing secondary cartilage (identified as "A."), which is a primary component of the developing eminence. The literature review will discuss the role of this secondary cartilage in the development of the TMJ eminence. An additional diagram has been taken from Humphreys' (1932) paper on age changes in the TMJ (Figure 2.2.2). The following review of the literature will examine the debate concerning the timing of the shape changes in the eminence that Humphreys has illustrated in this figure.

2.3 Development of the Temporomandibular Joint Eminence

This section of the literature review examines the current knowlege concerning the development of the TMJ eminence. A brief overview of prenatal development is followed by a more in-depth analysis of postnatal eminence development. A summary is presented in the conclusion of this section, to provide a synopsis of the state of knowledge concerning eminence development.

2.3.1 Prenatal Eminence Development

Several authors (Vinogradoff, 1910; Mundaca, 1948; Symons, 1952; Scott, 1954, 1955; Macalister, 1955; Moffett, 1966a; Moss, 1959a; Scott and Symons, 1961; Baume, 1962a, 1969; Furstman, 1963; Levy, 1964; Youdelis, 1966a, 1966b;

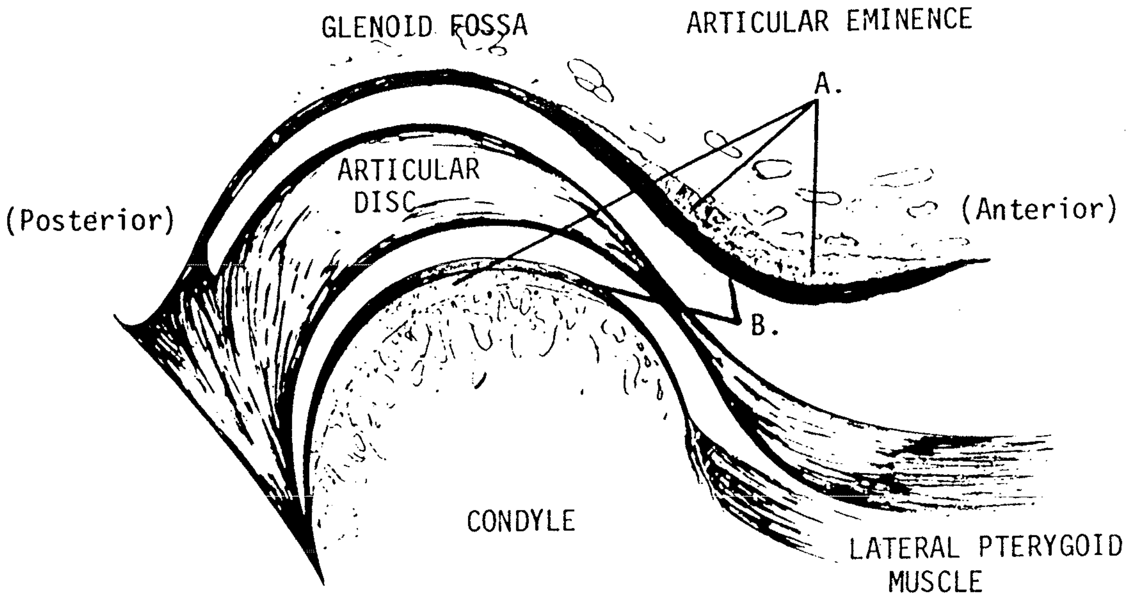


Figure 2.2.1 Lateral View of the Anatomy of the Developing Right TMJ

A. Subarticular Zone of Maturing Secondary Cartilage

B. Articular Zone of Fibrous Connective Tissue

(After Hinton and Carlson, 1983)

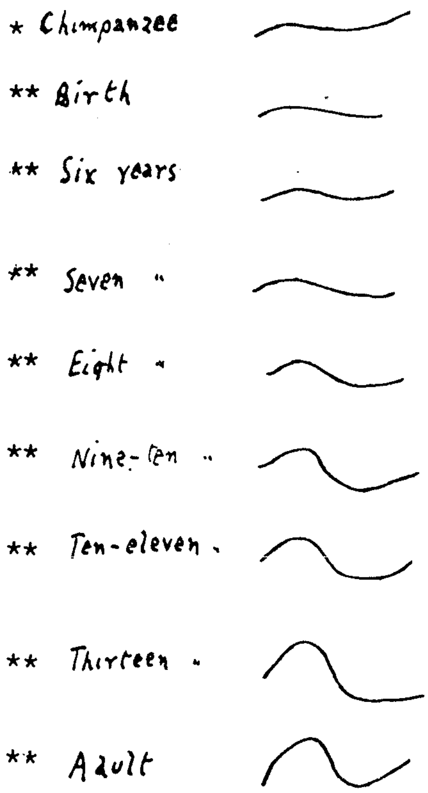


Figure 2.2.2 DEVELOPMENT OF THE TMJ EMINENCE

(After Humphreys, 1932)

* Adult Chimpanzee
** Human TMJ

Baume and Holz, 1970) have provided accounts of the histology of the <u>in utero</u> development of the temporal component of the temporomandibular joint. There is general agreement that a secondary cartilage (Beresford, 1981) appears <u>in utero</u> to form a rudimentary eminence. The timing of the appearance of this secondary cartilage continues to be a subject of debate. Symons (1952) claimed that the temporal secondary cartilage is well established by 16 weeks <u>in utero</u> (150 millimeter stage). He also reported that there was evidence that the cartilage begins to form at 13 weeks (95 millimeter stage). Reports by Scott (1954), Baume (1962a), and Baume and Holz (1970) indicate that the temporal component's secondary cartilage appears later than the secondary cartilages found in the developing condyle, coronoid process, and angular process of the mandible.

Scott (1954) and Baume (1962b) suggested that secondary chondrogenesis of the condyle, coronoid process, and angular process of the mandible may be related to <u>in utero</u> muscle activity which produces mechanical forces on the periosteum. The cartilage of the developing eminence, therefore, may be a result of <u>in utero</u> forces acting on the temporal component (Hall, 1967, 1970, 1979, 1983; Thorogood, 1979). Presumably, those forces would be a consequence of the developing condyle loading the developing temporal component of the joint (Kieffer, 1908; Hinton, 1979, 1985; Hinton and Carlson, 1979, 1983).

Most authors agree that the secondary cartilage of the mandibular condyle is still present at birth. Symons (1952) and Baume and Holz (1970) concluded that the transient cartilages of the temporal component, angular process of the mandible, and the coronoid process were required for the rapid growth of the biting apparatus of the developing fetus. The mechanisms which initiate the development of chondrocytes and the reasons the temporal, coronoid, and angular secondary cartilages do not persist through to term, as does the condylar cartilage, are not known.

2.3.2 Postnatal Eminence Development

2.3.2.1 Qualitative Assessment of Eminence Development

Descriptions of postnatal development of the temporomandibular joint eminence in humans (Baume, 1963; Wright, 1968; Oberg *et al.*, 1971; Wright and Moffett, 1974; Carlsson and Oberg, 1974; Thilander *et al.*, 1976; Ingerval *et al.*, 1976) and in monkeys (Zimmerman, 1971; Hinton and Carlson, 1983; Hinton, 1985) indicate that the eminence is rudimentary at birth and develops before and during the time of eruption of the primary dentition. This is supported in earlier literature presented by Langer (1860), Petrovits (1930), Humphreys (1932), Wallisch (1906), Kieffer (1908), Scott (1955), and Cousin (1960). It has been postulated that intermittent vertical pressure probably helps to stimulate eminence growth (Carlson *et al.*, 1978; Hinton, 1981a).

In man, during the period from birth to approximately eighteen years of age, extensive alterations occur in eminence morphology. Qualitative histological and radiographic observations prompted Wright (1968) to conclude that the developing eminence had achieved a mature "S" shape by the age of two and one-half years. Wright (1968) stated that there was a great variation in the developmental form of the eminence between children of similar occlusal maturity. It appeared that the child's age was the best indicator of eminence development and, at approximately two and one-half years of age, the eminence had a mature appearance. Wright's observation of very early maturation of the eminence is in contrast to reports of other authors. Oberg et al. (1971) described the eminence as being flat at birth and becoming well defined between the ages of five and eight years. Humphreys (1932) thought that the eminence remained rudimentary until the age of seven years, but assumed a mature appearance around twelve years of age (Figure 2.2.2)

Accounts of the histological growth of the eminence tissues are provided in reports by Zielinski (1965), Zimmerman (1971), Wright (1968), McNamara (1972), Wright and Moffett (1974), Carlsson and Oberg (1974), Thilander et al. (1976), Ingervall et al. (1976), Hinton and Carlson (1983). The neonatal human joint is characterized by the vascularity of the joint components. The temporal portion is quite rudimentary with a shallow fossa and absence of eminence. In the area of the glenoid fossa and anterior to the region where the eminence begins to form are regions of typical intramembranous bone formation (Figure 2.2.1).

Osteogenesis in the area of the eminence articulation, unlike intramembranous or endochondral ossification, is promoted by a secondary cartilage which produces a "chondroid bone" (Beresford, 1981).

Wright (1968) and Wright and Moffett (1974) offer a well- documented account of the histology of the immature temporal component of the growing human temporomandibular joint. They reported enlarged rounded cells in the lining articular tissues without presence of mitotic figures or isogenous groups (clones). There was an increase in basophilia of surrounding matrix which indicated an increase in matrix synthesis. Active resorption originated from the medulla of the chondroid bone and there was subsequent deposition of cortical bone which filled the bone resorption bays (Howship's lacunae). By the sixth to eighth week after birth, the enlarging tubercle displayed resorption lacunae and remodelling of the anterior slope. Between six months and two and one-half years of age, the height of the eminence increased and there was the development of the typical "S" shape in appearance. Nearing the age of two and one-half years there was a reduction of chondroid bone formation, but the temporal articular tissue remained thick and appositional bone continued to form at a slower pace. The histological evidence showed that growth declined during the mixed and permanent dentition years. During this period the articular slope steepened slightly until approximately eighteen (18) years of age. The articular tissues remained thick (Wright, 1968; Wright and Moffett, 1974; Thilander et al., 1976)

The chondroprogenitor layer of the temporal chondroid bone has been identified as the undifferentiated mesenchymal layer of the articular tissues (Dale et al., 1962; Blackwood, 1966; Folke and Stallard, 1966, 1967; Oberg, 1964; Hall, 1970, 1979, 1983; Thorogood, 1979; Beresford, 1981; Copray et al., 1985). Like the temporal secondary cartilage, undifferentiated mesenchyme is the progenitor layer of the chondrocytes of the secondary cartilage of the mandibular condyle. In ovo experiments done on chick embryos and in vitro experiments on neonatal rats (Hall, 1970, 1979, 1983; Thorogood, 1979; Copray et al., 1985) have indicated that mechanical loading is a potent mechanism for inducing secondary chondrogenesis from undifferentiated mesenchyme of periosteum on membrane bones (See Hall, 1970, 1983; Moss and Moss-Salentijn, 1983 for reviews). Hall and other reviewers have postulated that reduced oxygen potentials associated with decreased vascularity may be the control mechanism governing differentiation of the chondroprogenitor cells necessary for developing secondary cartilage.

The results of in vitro experimentation support Kieffer's (1908) hypothesis of functional stimulation (later reiterated by Carlson et al., 1980; Hinton, 1981a, 1985; Hinton and Carlson, 1983) as a mechanism for initiation and control of the eminence growth (Beresford, 1981). Condylar loading on the periosteum would probably produce results similar to those described in *in ovo* chick models and *in vitro* models, given Hinton's (1981b) postulate that the position of the condyle on the temporal component during early function may influence joint contour. The position of condylar loading may determine where the eminence begins to develop. Wright (1968) and Wright and Moffett (1974) reported that immature bone formation originated at the tip of the rudimentary eminence and that, by two and one-half years of age, the eminence was very mature in appearance (supported by Langer, 1860; Wallisch, 1906; Petrovits, 1930; Hjortsjo *et al*., 1953; Scott, 1955; Cousin, 1960). Thilander *et al*. (1976) and Ingerval *et al*. (1976) acknowledged the presence of a rudimentary eminence at the birth of a child. Thilander *et al*. (1976) described a transitory secondary cartilage at the future site of the eminence. Wright (1968), Zimmerman (1971), Stockli and Willert (1971), Wright and Moffett (1974), Carlsson and Oberg (1974), Hinton and Carlson (1983), Hinton and McNamara (1984) also described cartilage cells developing in the region of the growing eminence.

Hinton and Carlson (1983) noted that cartilage cells developed in the articular lining of the temporal component of the joint in infant monkeys. Neonate monkeys exhibited only solid layers of lamellar bone under a fibrous connective tissue articular layer. There was no evidence of cartilage cells in the fibrous connective tissue layer. Chondrocytes of the infant monkey were confined to the crest of the posterior slope of the area of eminence development. The tissue resembled a rapidly growing, newly deposited "chondroid bone" (Beresford, 1981).

Thilander et al. (1976) noted that the cartilage was missing from the fossa, but was a continuous thin layer in the developing tubercle. It was suggested that the cartilage layer increased in thickness during the pubertal growth spurt. However, Thilander et al. (1976) acknowledged that the histological techniques used were inadequate to verify increased mitotic rates of the chondrogenic zone of the undifferentiated mesenchyme. Hansson et al. (1977) noted that a difference was observed in the thickness of the undifferentiated mesenchymal layers of children and adults. Adults appeared to have decreased amounts of undifferentiated mesenchyme in the subarticular tissues. This is supported by the cell kinetic studies of Oberg (1964) and Kanouse et al.(1969).

Hinton and Carlson (1983) examined Rhesus monkeys representative of the age span of birth and adulthood. They described an increase in the thickness of the articular tissues in the neonate, infant, and juvenile stages of development. They interpreted the results as a response of articular tissues to forces delivered to the joint. Several authors (Zimmerman, 1971; McNamara, 1972; Carlson et al., 1978; Hinton, 1981b, 1985; Hinton and Carlson, 1979, 1983) have considered the variations in the anteroposterior topology of the TMJ to represent a response to functional stress.

Kieffer (1908), Petrovits (1930), Hinton (1979, 1981a) considered the position of the condyle along the crest of the slope of the developing eminence to be crucial in the determination of the manner by which alteration of contour (growth) takes place. Hinton (1979, 1981a) concluded that the developing topology of the eminence should follow Wolff's Laws of bone remodelling (further discussed by Currey, 1968; Bassett, 1971; Treharne, 1981). Carlson _et al_. (1978) and Hinton and Carlson (1983) concluded that the growing joint of macaques is loaded, and that in the neonate the direction of loading is vertical and, with increasing age, the direction of joint loading becoming more anteriorly directed due to the areas of attachment of the anterior temporalis becoming more anteriorly positioned. A number of authors (Todd, 1930; Mainland and Hiltz, 1934; Hellman, 1939; Angel, 1948; Herzberg and Sarnat, 1962; Dovitch and Herzberg, 1968; Strzalko _et al_., 1971; Hinton, 1979, 1981a, 1981b, 1985; Hinton and Carlson, 1979, 1983; Carlson _et al_., 1978) have postulated growth changes in muscle angulation to be a determinant in growth and remodelling of the postnatal joint.

In contrast, Steinhardt (1958) considered the mature joint to be load-bearing and that the young temporomandiblar joint was not loaded by the pressures of mastication.

2.3.2.2 Quantitative Assessment of Eminence Development

The majority of the authors cited in Section 2.3.2.1 have provided qualitative assessment of the growth and development of the temporomandibular joint eminence. Work reported by Angel (1948), Ricketts (1950), Hinton (1979, 1981a), Hylander (1972), Mongini (1972, 1975, 1977), Taylor et al. (1972), Ingervall (1974), and Dumas et al. (1986) provides quantitative evaluation of the postnatal development of the eminence of the temporomandibular joint. However, their work does not permit an accurate description of the growth of the eminence prior to the age of three years.

Investigations of the role of function in determining eminence development have not produced conclusive results. For example, Angel (1948) and Ricketts (1950) suggested that the development of the morphology of the joint is predominantly genetically determined. In contrast, Blackwood (1966), Seward (1976), Hinton (1979, 1981a), Hylander (1972), Hinton and Carlson (1979a) Mongini (1972, 1975, 1977), and Ingervall (1974) concluded that functional stresses play a significant role in defining joint morphology.

Angel (1948) concluded that genetic predisposition was the predominant determining factor in eminence development. Angel made his conclusions in consequence of being unable to find statistical correlation of relationships between eminence slope, specific anthropometric landmarks, and planes of muscle action. He surmised that eminence slope developed independantly of muscle and alveolar plane orientation. Angel believed that the eminence steepness is determined during youth, but that food and eating habits were probably only minor determinants of the slope. In the same report, Angel postulated that sliding pressure of the mandible down the eminence was an important factor, but that a wide latitude of "individual adjustment" accounted for the poor supporting evidence. Angel had hoped to use directions of muscle pull to explain the morphology of the eminence. Authors such as Hellman (1939), Todd (1930), and Mainland and Hiltz (1934) supported Angel's hypothesis. Angel's (1948) results did not support this collective opinion and he concluded:

> Separation of actual determinants will be possible only through mechanical and animal experiments combined with more exhaustive correlation of a larger mass of human data.

Ricketts (1950), like Angel (1948), concluded that genetics was the major factor determining joint form. Ricketts used cephalometric laminography to determine joint form in individuals from ages five to sixty years. He established that an increase in steepness of the eminence occurs with increasing age, until growth seems to stop in early adulthood. He calculated the average steepness of the eminence relative to Frankfort Horizontal, for individuals between the ages of five and ten years. Ricketts found that the eminence steepness was an average of 46.7 degrees, and he noted that it increased to 58 degrees for ages greater than twenty-two (22) years. It appears from Rickett's data that the slope of the eminence was stable after the age of twenty-two years. Ricketts did not comment on the large amount of growth which occurred prior to the age of five. Ricketts concluded that due to a lack of correlation of sizes of the condyle and temporal components, too much emphasis had been placed on the influence of forces in defining joint form. Ricketts felt that genetic predisposition was the predominant determinant in joint form.

Ingervall (1974) gave evidence of the possible relationship between craniofacial form and steepness of the eminence. Ingervall's conclusions are contrary to the conclusions of Angel (1948) and Ricketts (1950) Following the opinion of authors such as Mainland and Hiltz (1934), Angel (1948), Hjortsjo _et al_. (1953), and Taylor _et al_. (1972), Ingervall considered parameters such as the angle of occlusal plane relative to Frankfort Horizontal Plane, to be influential in determining eminence dimension and form. However, Ingervall's accounts of the amount of growth of the eminence during the mixed dentition are contrary to other published accounts of the histology (Wright and Moffett, 1974). Additionally, although statistical correlations were reported, Ingervall failed to establish a functional (mechanical) relation between the variables. He concluded:

> Whether the muscle function is decisive for the anatomy of the tubercle or whether other factors, such as more direct genetic influence, are the most

> important cannot, however, be decided on
> the basis of the present investigation.

2.3.3 Remodelling Changes of the Mature Eminence

The changes which occur in the morphology of the mature human TMJ have been reviewed by Angel (1948), Moffett *et al*. (1964), Blackwood (1966), Moffett (1966), Oberg *et al*. (1971), Carlsson and Oberg (1974), Seward (1976), Hansson and Nordstrom (1977), Hansson and Oberg (1977), Hansson *et al*. (1977), Hinton and Carlson (1979), Hinton (1981), and Solberg *et al*. (1985).

Moffett *et al*. (1964) classified the remodelling changes of the human TMJ into three categories: progressive, regressive, and circumferential remodelling. These adaptive processes of remodelling are in contrast with the process of primary growth of the TMJ eminence (Wright, 1968; Wright and Moffett, 1974). For example, Moffett *et al*. (1964) described the process of regressive remodelling as the primary mechanism of remodelling of the crest of the mature eminence. During regressive remodelling, osteoclastic activity resorbs the bone under the fibrous articular layer of the eminence. Vascular channels, originating from the medulla of the temporal bone, invade the resorbed areas and introduce mesenchymal tissue which differentiates into fibrous connective tissue. This increases the thickness of the fibrous connective tissue which forms the articular surface. The thickness is eventually reduced by attrition of the articular surface. The final slope of the eminence is flatter than the original eminence; which is opposite to the results produced by primary growth of the eminence (Wright, 1968; Wright and Moffett, 1974).

Moffett et al. (1964) have indicated that the remodelling of the adult TMJ shows no relationship with age, and appears to be dependant largely on the mechanical factors associated with function. Mongini (1972, 1975, 1977) and Seward (1976) reported that increased attrition rates of the dentition, and the loss of posterior dentition, seemed to be related to the amount of remodelling of the TMJ. With the loss of posterior tooth structure there was an increase in the osteodegenerative changes in the TMJ condyle and eminence. Similar results were reported by Carlsson and Oberg (1974). They concluded that the risk of changes in the TMJ appears to be greater in persons who have lost a large number of teeth. Carlson and Oberg indicated that biomechanical factors probably play an essential role in the course of remodelling and arthrosis of the mature TMJ.

2.3.4 Temporomandibular Joint Eminence Development: Summary

From the literature it is clear that the development of the eminence begins *in utero* and that the preponderance of growth occurs only in the earliest months of infancy. There is qualitative evidence that the majority of the development occurs prior to the complete eruption of the primary molars. However, there is a lack of quantitative data which describe the development of the eminence in humans from birth to three years of age.

The role of loading of the condyle in the development of the eminence is discussed in the literature, and is reviewed by Carlson _et_ _al_. (1980) and Hinton and Carlson (1983). It has been speculated that there are changes in the patterns of loading with normal changes in muscle growth and development. There is an absence of quantitative data to verify the suggestion that significant changes in muscle orientation occur and that such changes would result in alterations in loading patterns as predicted by Hinton (1981b, 1985) and Hinton and Carlson (1983).

Moffett _et_ _al_. (1964) noted that remodelling changes seem to bear no relationship to age and suggested that changes are the result of functional stresses, which remain within physiological limits. They state:

> However, the nature of these functional stresses which induce remodelling changes remain vaguely defined.

Hinton (1981b) provides an appropriate summation of our understanding of the development of the temporomandibular joint eminence. He concludes that the nature of morphological changes of the joint and of the mechanisms by which they are effected are poorly understood. The influence of changing bite points on the tooth row and muscle orientation on functional joint forces in the growing individual is a little understood topic, but one of great potential importance to the clinician. The reader may interpret Hinton to mean that the clinician is routinely faced with the problem of correcting dental and skeletal dysplasias. Correction of these dysplasias, in turn, influences the development of the temporomandibular joint.

2.4 Loading of the Postnatal Temporomandibular Joint

This section of the literature review examines the debate concerning whether the TMJ is loaded. The review starts with the traditional experimental approaches, and then follows with an examination of the more recent *in vivo* experimental methods. A closing summary is presented to provide an overview of the state of knowledge concerning TMJ loading.

2.4.1 Traditional Methods of Analysis

The early accounts of Lubosch (1906) and Kieffer (1908) described their evaluation of changes in joint form and their relationship to function. From these early reports to the most recent research endeavours (See Carlson *et al.*, 1980 for review) the underlying premise has been that joint loading initiates changes in histology and ultimately gross anatomical form. However, whether or not the temporomandibular joint is a functionally loaded joint has been a subject of considerable debate. Excellent reviews of this question have been compiled by Hylander (1972, 1975, 1979, 1985), Hinton (1979), Smith (1984), and Smith *et al.* (1986). There have been three approaches taken to determine whether the temporomandibular joint is a load-bearing joint. The first approach has been argument based on interpretation of the capacity of the joint's structural components to withstand loading. The second approach has been theoretical modelling of the mechanics of the biting apparatus. The objective of the theoretical modelling was to determine whether, during function, loading of the condyles was necessary in order to achieve static equilibrium. The third approach has involved direct *in vivo* measurement of condylar loading in an animal model.

2.4.1.1 Anatomical Evidence

Anatomists have described hyaline cartilage as the surface tissue lining stress-bearing articulations. Individuals such as Wilson (1920, 1921) and Robinson (1946) have inferred that, because the articular surfaces of the temporomandibular joint are covered by fibrous connective tissue, the joint is not stressed during function. Wilson (1921), Gingerich (1971), and Tattersall (1973) supported the argument, stating that a loaded condyle was a "wasteful use of energy" and evolutionary pressures would have precluded the development of such conditions. Hyaline cartilage was assumed to be the tissue of choice by the "Omnipotent Architect" (Wilson, 1921) to serve as a lining of loaded articulations. Moffett (1966) and Barbenel (1972) argued that the articular lining of the temporomandibular joint was different from that of other articulations due to the embryological origin of the tissues and not due to functional requirements. Moss (1959b, 1960), Thilander (1964), Griffin and Sharp (1960), Bloom and Fawcett (1968), and Jagger and Whittaker (1977) have commented that the fibrous connective tissue of the articular surface is well suited to withstand shear stress. Shear stress was postulated to predominate during joint function.

The neck of the condyle was also considered to be a weak structural feature that precluded loading of the temporomandibular joint (Tattersall, 1973). Hylander (1975) performed stress analysis experiments on the neck of the condyle of macaques to determine loading capacity. His conclusions were that the condylar neck was well suited for the magnitude of loading expected during maximum bite force.

2.4.1.2 Theoretical Modelling Approaches

Mathematical modelling has been a second general approach used to determine whether the temporomandibular joint is loaded during isometric biting. Until recently, mathematical modelling was limited to a two-dimensional sagittal analysis of mandibular mechanics. Hylander (1975, 1985), Hinton (1979), Smith (1984), and Smith *et al*. (1986) have reviewed the work of authors who have used this approach. Hylander (1975) identified a "Lever or Link" theme which is a common issue discussed in two-dimensional theoretical analyses of joint loading. The argument centres on the ability of the muscles of mastication to control a given bite force without producing a joint reaction force. "Link" hypothesis proponents (Wilson 1920, 1921; Robinson, 1946; Scott, 1955; Gingerich, 1971, 1979; Roberts, 1974) suggest that the muscle force vectors produce static equilibrium without the need for joint reaction force. "Lever" hypothesis proponents (Gysi, 1921; Roydhouse, 1955; Moss, 1959b; Barbenel, 1969, 1972, 1974; Hylander, 1972, 1975; Hekneby, 1974; Gosen, 1974; Hinton, 1979; Tradowsky and Dworkin, 1982; Tradowsky and Kubicek, 1981; Haskell et al., 1986) state that the mandible behaves as a Class II or Class III lever. Using a two-dimensional analysis of vector mechanics, these authors determined that for some conditions of biting, the condyle must produce a joint reaction force in order to produce static equilibrium.

The two-dimensional theoretical approach has an inherent drawback in that the craniomandibular apparatus is a three-dimensional mechanical system. Analysis of forces and moments in a three-dimensional system cannot be adequately addressed by a two-dimensional approach. Several authors (Mansour and Reynik, 1975a,b; Arvikar and Seireg, 1975; Smith, 1978; Walker, 1978; Druzinsky and Greaves, 1979; Pruim et al., 1980, Hylander, 1985; Throckmorton and Throckmorton, 1985; Throckmorton, 1985) have reported on the development of mathematical techniques to address the problem of three-dimensional temporomandibular joint loading.

Mansour and Reynik (1975a,b) calculated in vivo bite force moments around the condylar axis. The force transducer used in these experiments measured the vertical component of a bite force. The authors reported that bite force was reduced from molars to incisors. They found that the moment-to-force ratio was a positive linear function of the anteroposterior bite position from incisor to first molar. The function then became a negative linear function in the posterior molar region. The authors interpreted the change in function as a change from a class II lever system for bite forces anterior to the molars, to a class III lever system in the most posterior molars.

Smith's (1978) study examined two different two-dimensional views (sagittal and frontal) to determine condylar reaction forces during biting. His results suggested that large condylar reaction forces are present during mastication. Smith's calculations indicated that up to eighty percent of the condyle reaction force was borne by the contralateral balancing condyle. Smith limited his examination of forces to vertical bite force, vertical muscle forces, and vertical condyle reaction forces. This allowed Smith to limit his analysis to sagittal and frontal views, given that the moments would not occur around the vertical axis since he had assumed that transverse forces and anteroposterior forces were equal to zero.

Walker (1978) used the work of Gibbs, Møller, and Hylander to draw conclusions about muscle function. His conclusions concerning muscle function were derived from a three-dimensional analysis of muscle orientation. Walker's interpretation of muscle function was based on the assumption that muscle orientation was indicative of the function of a muscle. For example, Walker's observation of the orientation of the medial pterygoid muscle lead to his assumption that the mediolateral component of the medial pterygoid muscle is capable of stabilizing the mandible during conditions when there is a mediolateral component to a bite force

Druzinsky and Greaves (1979) evaluated the coronal view of the mandible of a turtle to determine the effect of vertical forces on jaw mechanics. Transverse and anteroposterior forces were not included in the calculations. Druzinsky and Greaves (1979) postulated tensile loading of the ipsilateral condyle rather than compressive loading during posterior unilateral molar biting.

Baron and Debussy (1979) analyzed muscle function of the biting apparatus by describing the three-dimensional nature of the orientation of the muscles of mastication. The authors described the origins and insertions of the muscles in the sagittal, frontal, and coronal planes. By this analysis of muscle vector orientation, they concluded that muscle function could be determined based on the capabilities of the muscles to produce moments. The authors noted that electromyography was required to confirm their conclusions.

Pruim et al. (1980) developed a mathematical model using integrated EMG forces to calculate muscle force. They concluded that loading of the temporomandibular joint was highest when the bite force was in the region of the premolars. This is contrary to in vivo findings of Hylander and Bays (1979) and Hylander (1979), namely, that temporomandibular joint loading was maximal during incisal biting. Pruim mentions that the mathematical model was based on three-dimensional geometries derived from frontal and lateral radiographs. Pruim assumed right and left symmetrical bilateral biting and limited his analysis to the sagittal projection. Imposing a bilateral biting condition eliminated the complications in theoretical calculations of the mechanics of unilateral molar biting. The EMG data required for the model were obtained during simultaneous recording of bite force. Bite force transducers were placed in occlusal splints to ensure accuracy of position on the dental arch. No comment was made on the influence of the bilateral splint on the neuromuscular control of the mandible. A splint may influence periodontal receptor input (Lund and Lamarre, 1973; van Steenberghe and De Vries, 1978) and alter joint position feedback due to change of vertical dimension (Butler, 1977). Pruim's use of a bilateral splint may have introduced a bias in the EMG of the muscles of mastication.

Previous researchers have used EMG data to calculate the muscle forces required by the various two-dimensional and three-dimensional mathematical modelling approaches. By assigning muscle force values, the mathematics of the system becomes simple and condyle reaction forces may be calculated. However, there is a problem in predetermining muscle force values. Research has not established that EMG values and muscle-cross sectional areas permit accurate calculation of muscle force values for given muscle lengths. The problem is compounded by the assumption that surface EMG recordings may be used to calculate force delivered by a multiplely pinnated muscle.

As an alternative to the previously mentioned approaches, Arvikar and Seireg (1975), Osborn and Baragar (1985), Smith (1984), and Smith et al. (1986) have used numerical modelling techniques to solve the mathematical indeterminancy of the mandibular mechanical system.

Arvikar and Seireg (1975) developed a three-dimensional model to evaluate the loading of the temporomandibular joint. The goal of the model was to minimize total muscle force and establish static equilibrium. Condylar loads were determined for three positions of jaw opening. The condyle was found to be loaded in each position of jaw opening.

Osborn and Baragar (1985) also developed a numerical model in which the objective was to minimize muscle energy expenditure while satisfying static equilibrium of the system. In their model, to provide a maximum bite force, muscle recruitment occurs in a "ripple" fashion. There is a single (most efficient) muscle recruitment pattern and the muscle begins to produce increasing force levels until a saturation of muscle force production is achieved. At the point of saturation, a second muscle is activated and the process continues until a maximum bite force is achieved.

Osborn and Barager (1985) limit the analysis to bilateral isometric biting. This effectively limited the analysis to a two-dimensional application of the model. Osborn and Barager (1985) claim that their results for maximum bite force are supported by the EMG results of Pruim *et al*. (1980). EMG studies reported by Møller (1966), Ahlgren (1966), Hylander and Johnson (1985), and McCall *et al*. (1986) do not support the model of Osborn and Barager (1985). The EMG data from the muscles of mastication do not exhibit the ripple effect described by Osborn and Barager and there is no substantiation for the suggestion that a specific muscle is activated to saturation before the activation of another muscle.

Smith (1984) and Smith *et al*. (1986) introduced a three-dimensional numerical model of temporomandibular joint loading to address the question, "Is it necessary for the condyle to be loaded for all conditions of isometric biting" (Smith, 1984). An iterative technique of altering muscle forces was used to determine the mix of muscle forces necessary to produce static equilibrium and minimize condyle loading under conditions of isometric biting. The results of Smith and co-workers indicated that the temporomandibular joint is loaded in compression in all positions of a unilateral vertical bite force except for biting on the third molar. Bite forces in the region of the third molar tended to distract the ipsilateral joint. Tensile loading of the ipsilateral joint had been postulated by Druzinsky and Greaves (1979). Hylander (1979) and Hylander and Bays

(1979) reported similar results from *in vivo* data on macaques biting on third molars. For non-vertical unilateral bite forces the numerical model of Smith and co-workers calculated asymmetrical condylar loading, and under certain conditions, the contralateral condyle was loaded more than the ipsilateral condyle. This is in support of Hylander's (1979) data but is contrary to the direct *in vivo* measurements of Boyd *et al*. (1982). On the other hand, muscle forces calculated by computer iteration were larger on the ipsilateral side in conditions of unilateral biting. Temporalis activity was calculated to be reduced when the bite force was moved anteriorly. Masseter activity was calculated to increase as the bite force was moved anteriorly. These theoretical calculations of muscle activities are similar to *in vivo* EMG data reported by Møller (1966), Ahlgren (1966), Hylander and Bays (1985), and McLachlan (personal communication).

Alternative methodologies in theoretical modelling have been presented by authors such as Ralph and Caputo (1975), Standlee *et al*. (1977, 1981), Tradowsky and Dworkin (1982), Tradowsky and Kubicek (1981), and Hatcher *et al*. (1986).

Ralph and Caputo (1975) and Standlee *et al.* (1977, 1981) developed a physical model of the mandible and muscle forces. The purpose of this physical model was to identify stress patterns during biting. The birefringent material used to construct the physical model enabled characterization of stress patterns in the condyle, ramus, and body of the mandible. The authors were able to describe the stress patterns of the condyle in all three anatomical planes and concluded that the condyle was loaded under the determined set of conditions tested.

Hatcher et al. (1986) constructed a physical model to study the relationship between unilateral occlusal bite force and temporomandibular reaction forces. Force transducers measured the right and left vertical condyle loads in response to a range of theoretically calculated muscle forces. Muscle forces were determined either by cross sectional area or a combination of cross sectional area and EMG values from the literature. Hatcher and co-workers identified a reduction of ipsilateral joint reaction force for bite positions progressing from the first molar to the third molar. Contralateral joint loading tended to remain constant for bite forces from the first molar to the third molar.

Tradowsky and co-workers (Tradowsky and Dworkin, 1982; Tradowsky and Kubicek, 1981) conducted in vivo experiments to test their hypothesis of a "physiological equilibrium point". This point represented an axis in the region of the molars where the mandible switched from a class II lever to a class III lever. Bite forces placed anterior to the axis would theoretically result in the mandible acting in the capacity of a class II lever. Bite forces posterior of the axis would result in a class III lever system. Utilizing pantographic clutches (Tradowsky and Dworkin, 1982) or electronic means (Tradowsky and Kubicek, 1981), Tradowsky and co-workers found that, when the mandible acted as a class II lever, the condyle was positioned superiorly. When acting as a class III lever, the condyle tended to be distracted from the temporal component of the joint. The results recorded by Tradowsky and co-workers are similar to those of the two-dimensional theoretical analysis reported by Mansour and Reynik (1975a).

2.4.2 *In vivo Experimental Approaches*

Recent *in vivo* experimental methods have been attempted to measure joint reaction force magnitude and direction. Findlay (1964) claimed to have placed a cannula into the superior joint space to measure articular pressure during function. He reported that opening, protruding, and contralateral movement produced negative pressure. Closing, retrusive, and ipsilateral mandibular movement produce positive pressure.

There are problems with this technique since the joint cavity is, in fact, a pseudospace and it is difficult to determine with confidence the position of the cannula and the origin of the pressures that were recorded. Complicating the interpretation of the data is the effect of the local anaesthesia of the joint capsule. Butler (1977) and Klineberg *et al*. (1971) reported that the TMJ has proprioceptive receptors. Other joints of the body exhibit proprioceptive, afferent influence on muscle activity (Appelberg *et al*., 1979; Baxendale and Ferrell, 1980).

Findlay's use of local anaesthesia may have inhibited the influence of the TMJ receptors on the muscles of mastication and may have altered the normal function of the mandible.

Hylander (1979) and Hylander and Bays (1979) placed strain gauges on the condyle necks of macaques which measured compression of the condyle neck during function. Hylander and his co-workers have established that the contralateral condyle was loaded more than the ipsilateral condyle during unilateral biting. Their results confirm Gysi's (1921) hypothesis and are supported by the calculations of Smith et al. (1986) for bite forces with an extreme mediolateral component. Smith's and co-workers' results indicated that there was very little asymmetry of forces between the condyles and very little distraction of the condyles when bite forces were on the tooth row, and within plus or minus twenty (+/- 20) degrees from vertical. Outside this range, a shift of bite force angle resulted in asymmetry of condylar loading and, in some cases, condylar distraction. Hylander also reported that there was an apparent unloading or perhaps tensile loading of the ipsilateral condyle when biting on the third molars. This is supported by the data reported by Smith and co-workers (1984, 1986), and Druzinsky and Greaves (1979).

Brehnan and Boyd (1979), Brehnan et al. (1981), Boyd et al. (1982) measured direct condylar loading in Macaca mulatta by implanting piezoelectric foil transducers over the temporal surface of the temporomandibular joint. Initial results (1979) indicated that the joint was not loaded. Later results (Brehnan _et al_., 1981; Boyd _et al_., 1982) indicated that the joint was loaded. Boyd _et al_. (1982) reported that it was the ipsilateral condyle which was loaded more heavily on unilateral mastication. This is contrary to reports of Hylander and co-workers (Hylander, 1979; Hylander and Bays, 1979). Hylander (1985) suggested that the differing results may be due to experimental design. Hylander studied isometric biting whereas Boyd's group studied mastication. Hylander (1985) has speculated that perhaps the lateral pterygoid may be responsible for increasing the loading of the ipsilateral condyle.

Hohl and Tucek (1982) inserted a transducer prosthesis in the neck of a baboon condyle to study joint loading during simulated mastication. Large condylar loads were recorded. It should be noted that the baboon in this experiment was under general anaesthesia and mastication was simulated by electrical stimulation of the trigeminal nerve.

2.4.3 Loading of the Postnatal Temporomandibular Joint: Summary

Evidence presented in the preceding sections supports the conclusion that the adult temporomandibular joint is loaded during isometric biting and mastication. It is not clear whether the immature temporomandibular joint is a loaded articulation. The conclusions of Smith and co-workers (Smith, 1984; Smith _et al_., 1986) are appropriate for mature adults but cannot be extrapolated to growing children. The calcified and muscular anatomical relationships of the adult human are significantly different from those of the immature human. The influence of these anatomical relationships on the magnitudes of joint loading or upon the direction of joint loading has not been established. Nor has it been established, as Hinton and Carlson (1983) propose, that growth-related changes in these anatomical relationships result in changes in directions of joint loading. The methodology of Smith (1984) and Smith *et al*. (1986) provides a means of establishing the magnitudes and directions of immature condylar loading, and the changes which occur in response to growth. The following chapter describing methods and materials will outline use of the numerical model.

Chapter 3

METHODS AND MATERIALS

3.1 Proposed Topic of Study

This study is focused on the question, "Is there a functional relationship between development of the immature temporomandibular joint (TMJ) eminence and direction of joint loading?"

To examine this functional relationship the following information is required:

1. Quantitative data describing eminence morphology for a given stage of development.
2. Quantitative data describing the directions of joint loading for a given stage of development.

3.2 Potential Sources of Data

3.2.1 Postnatal Eminence Development

Data on the postnatal development of the temporomandibular eminence can be collected by various means. An ideal technique would provide longitudinal three-dimensional data of the growth of the human temporomandibular joint eminence. A "longitudinally treated" population sample, examined by various modern radiographic techniques, might provide this type of information but radiation hazard precludes using this method on humans. Radiographic techniques could, of course, be used on an animal model such as Macaca mulatta which could provide both longitudinal and cross-sectional data for the study of the growth characteristics of the temporomandibular eminence. The difficulty of using such animal models is the high cost of maintaining an adequate number of animals, and the appropriate extrapolation of the results to humans.

Another option is a three-dimensional analysis of eminence development using human osteological remains as the primary source of data. This technique has the advantage of providing accurate three-dimensional data. The disadvantage is that cross-sectional data must be used to infer longitudinal growth changes. There is the additional problem of finding a number of very young children who were healthy until an acute bout of disease or trauma resulted in death.

3.2.2 Directions of Condylar Loading

In addition to data describing the development of the eminence, information is required concerning the probable directions and magnitudes of the loading of the condyle on the temporal component of the joint. The determination of the direction of condylar loading using an *in vivo* approach would require use of an animal model (Hylander, 1979). This is a very difficult and expensive method involving, in this case, operations on very immature animals.

The second method is a theoretical, three-dimensional numerical modelling technique (Smith, 1984; Smith *et al.*, 1986). The technique requires measurement of the spatial relationships between the components of the biting apparatus. The spatial relationships could be provided by human osteological material or existing longitudinal cephalometric radiograph collections. The disadvantages of using human osteological material are similar to those in Section 3.2.1.

It was noted in the literature review that there is an absence of data describing eminence development prior to the age of three years. Thus, the disadvantage of deriving longitudinal data from existing cephalometric radiographs is that most of the collections do not have records of very young children (ie. from birth to three years).

3.2.3 Account of Methods and Materials Used in this Study

Human osteological remains were used to provide the necessary data to quantify temporomandibular eminence development and to provide the metric data required for the calculation of the direction of joint loading. The numerical model described by Smith (1984) was used to compute the directions of joint loading. The Johns Hopkins and Hamann-Todd Osteological Collections provided a reasonable data base for evaluating the relationship between direction of condyle loading and temporomandibular eminence development.

Section 3.3 describes the osteological collections from which the primary data were acquired. Section 3.4 describes the techniques used to collect the data. Section 3.5 examines the several methods of data analysis that were used. Numerical calculations of various angles of condyle loading (RETRUDED LOADING ANGLE -F.C.r {force on condyle retruded}, PROTRUDED LOADING ANGLE- F.C.p {force on condyle protruded}) were used to derive the probable mean direction of condylar loading (MEAN CONDYLAR LOADING ANGLE- F.C.t {force on condyle total}). Section 3.5 also describes the EMINENCE DEVELOPMENT ANGLE, which characterizes the morphology of the growing eminence for this study. Various other analyses are presented in Section 3.5. The numerical model was used in these analyses to evaluate the effect of growth on the direction of condylar loading. Section 3.6 concludes the methods and materials chapter with an evaluation of the sources of error introduced by the various techniques employed in the study.

3.3 Description of the Sample

The osteological data required for this study were obtained from the Hamann-Todd Osteological Collection and the Johns Hopkins Infant and Foetal Skull Collection. Both collections are located in the Department of Physical Anthropology, Cleveland Museum of Natural History. A trip was made from Winnipeg to Cleveland, to collect the required data for this project.

The Johns Hopkins Collection is a sample of prenatal and postnatal skull specimens. The collection provided nine (9) specimens between ages of birth and ten (10) months. Of this sample, seven (7) were males and three (3) were females.

The collection's archival material recorded sex, ethnicity, chronological and maturational age. Information was not as complete concerning health history or cause of death. Nine (9) disarticulated temporal bones were gathered from this collection for analysis of eminence development.

The Hamann-Todd Osteological Collection is a unique assemblage of autopsied skeletal human remains. After autopsy each cadaver was macerated and the skeletal remains were catalogued and stored. Detailed medical and civic authority reports recorded the individual's maturational and chronologic age, sex, provenance, ethnicity, health history, and in many cases cause of death. The detailed archival information made it possible to maximize the quality of the data gathered from the collection. Forty (40) specimens were selected from the Hamann-Todd Collection. An effort was made to obtain as many specimens as possible from individuals who had reasonably good health until an acute bout of disease or a traumatic mishap resulted in death. An overview of racial origins and causes of death of the sample is presented below. Of this sample, nineteen (19) were female and eighteen (18) were male. An overview of the causes of death is presented below.

Cause of Death	Number of Individuals
Trauma	3
Acute Infection	15
Debilitating Disease	3
Not Determined	19

In cases where there was difficulty in determining cause of death an attempt was made to screen for gross malnutrition based on photographs, height and weight measurements of the cadavers, and notations of the pathologist performing the autopsy.

The combined sample from the Johns Hopkins Collection and the Hamann-Todd Collection provided individuals in the following age ranges.

Age Range (years)	Number of Individuals
Birth - 0.5	8
0.6 - 0.75	4
0.76 - 1.5	5
1.6 - 2.0	1
2.1 - 2.5	0
2.6 - 5.0	8
5.1 - 11.0	10
11.1 - 15.0	4
15.1 - 20.0	9

3.4 Data Collection Techniques

3.4.1 Three-Dimensional Anatomy of the Craniomandibular System

3.4.1.1 Specimen Preparation

In order to study the mechanics of the temporomandibular joint there was a need to obtain three-dimensional geometric coordinates of the muscles of mastication, dental structures, and mandible. To collect the required anatomical data it was necessary to assemble disarticulated or sectioned skulls of the Hamann-Todd sample. The assembly process reproduced a reasonably accurate intact skeletal anatomy. Accuracy of assembly was ensured by matching the transverse and anteroposterior dimensions of the skull to the dimensions of the intact mandible.

After assembly, the origins and insertions of the masseter, temporalis, and lateral pterygoid muscles were identified with coloured drafting tape. Only one side of the skull was marked. For the purposes of this project it was deemed reasonable to make the assumption of bilateral symmetry. The insertion of the masseter muscle was determined by examination of the bony scarring at the angle of the mandible and on the lateral cortical surface of the inferior one-half of the ramus (Sicher and Dubrul, 1975, p. 134). Individual variability was noted and this was reflected in the shape of the identified region of the origin. The most posterior point of origin of the masseter muscle into the inferior border and lateral cortex of the zygomatic arch was defined as being in the region of the zygomaticotemporal suture (Sicher and DuBrul, 1975, p.134). The origin was continued anteriorly as far as scarring could be identified on the zygomaticomaxillary process.

The insertion of the temporalis muscle was determined by the bony scarring on the lateral and medial cortical surface of the coronoid process. Anterior scarring of the origin of the temporalis muscle (superficial and deep tendons) continues anteriorly and inferiorly towards the external oblique ridge and retromolar region (Sicher and DuBrul, 1975, p.137). The origin of the temporalis muscle was determined by the inferior temporal line which extends across the parietal, temporal, and frontal bones (Sicher and DuBrul, 1975, p.136).

The insertion of the lateral pterygoid muscle was determined by the bony scarring found in the fovea of the neck of the condyle. The outline of the origin of the lateral pterygoid muscle consisted of the regions occupied by the inferior and superior heads of the lateral pterygoid muscle. This area encompassed the lateral cortical surface of the lateral pterygoid plate as well as the scarred surface of the greater wing of the sphenoid bone which forms part of the roof of the infratemporal fossa.

The occlusal plane was represented by a best-fit straight line through the intersecting cusps of the first molars (if present) and the primary molars and/or permanent bicuspids (Jacobson, 1976, p. 185). Some of the specimens were predentate. In these, a distance half way between alveolar ridges determined the predentate occlusal plane.

3.4.1.2 Photographic Technique

A photographic technique was developed to provide a means of recording and storing anatomical data. The specimen was supported in a holding device (a pan of Lima beans was used as a supporting medium, Figure 3.4.1) which allowed photographs to be taken of each specimen in the sagittal, frontal, and basal anatomical planes with a fixed camera. An identifiable focal plane was included for purposes of defining photographic perspective error in measurements of coordinates located behind the focal plane. The standardized technique maintained the camera lens at one-hundred centimeters (100 cm.) from the focal plane. Accurate photographic records were produced by a Minolta (registered trademark) thirty-five millimeter (35 mm.) single lens reflex camera using Ectachrome and Fujichrome ASA fifty (50) film (registered trademarks). The photographs produced by this technique were in the form of slide transparencies. This permitted reversal of the image, to ensure that the anatomical points of interest were always on the right side. This was done as a matter of convenience for the programming of the computer that was used to compile the anatomical geometries from the photographs.

Three sagittal photographs were taken of each specimen, from which a master tracing was made (Figures 3.4.2, 3.4.3, 3.4.4, 3.4.5). An initial view included the _in situ_ impression record of the temporomandibular joint (see Eminence Reproduction Technique, Section 3.4.2). A second view recorded the mandibular and maxillary dentitions in intercuspation. A third sagittal view recorded the sagittal aspects of the mandible alone. The holding device positioned the specimen with the occlusal plane horizontal and the parietal bone of the skull intersecting the focal plane. In the sagittal view of the mandible alone, the ipsilateral condyle intersected the focal plane and the occlusal plane was maintained horizontal.

Three frontal views and a master tracing recorded information of osseous and dental morphology and information necessary for analysis of muscle orientation (Figures 3.4.6, 3.4.7, 3.4.8, 3.4.9). In photographing the frontal plane of the skull the most anterior portion of the skull intersected the focal plane and the occlusal plane was maintained in a horizontal orientation. In the frontal views of the mandible alone, the occlusal plane was maintained horizontal and pogonion intersected the focal plane.

Two photographic views were taken of the basal aspects of the skull, from which a master basal tracing was made (Figures 3.4.10, 3.4.11, 3.4.13). One view was taken with the temporal impression record in place (see Eminence Reproduction Technique, Section 3.4.2). A second view was taken with the mandibular and maxillary dentitions in intercuspation. For photographs of the skull without the mandible, the most inferior point of the skull intersected the focal plane. In photographs of the skull with the mandible, the inferior border of the mandible intersected the focal plane. In the basal views the occlusal plane was kept parallel to the focal plane.

A final photograph (Figure 3.4.12) of the occlusal view of the mandible provided information concerning the anteroposterior and transverse dimensions of the dental arch. Either the condyles, or the coronoid processes intersected the focal plane. The condyle intersected the focal plane if it was longer than the coronoid process, and the coronoid process intersected the focal plane if it was longer than the condyle. The occlusal plane was maintained parallel to the focal plane.

3.4.1.3 Tracing Technique

The slide transparency records were projected at a suitable magnification onto a solid white screen and standardized tracings were made. The scaling of the photographic transparencies was dictated by a predetermined measurement on the specimen-holding device (Figure 3.4.1). A metal rod of one hundred and forty-nine millimeters (149 mm.) in length served as a marker for the front of the focal plane. Though for the purposes of this study only relative proportions were strictly necessary, the measured length of this marker provided a means of reproducing the actual dimensions of the specimens.

Sagittal photographs of the skull alone, skull and mandible, and mandible alone were superimposed to produce a master tracing of the sagittal aspect of the skull (Figure 3.4.5). Areas of the origins and insertions of the musculature were outlined and the dentition was traced. Additionally, the morphology of the eminence was reproduced on the master sagittal tracing (Section 3.4.2 Eminence Reproduction Technique).

Frontal photographs of the skull alone, skull and mandible, and mandible alone were superimposed to produce a master tracing of the frontal view of the skull and mandible (Figure 3.4.9). Areas of the origins and insertions of the musculature were outlined and the dentition was traced.

Basal photographic transparencies of the skull alone, skull and mandible, and the occlusal view of the mandible were superimposed to produce a master tracing of the basal aspect of the specimen (Figure 3.4.13). Areas of muscle attachment, condylar morphology, and the dentition were traced.

3.4.1.4 Digitizing Coordinates and Developing Geometries

The basal and sagittal master tracings provided the primary data for developing the three-dimensional geometries of the biting apparatus. A computer program was developed to digitize and store coordinates of the relevant components shown in the basal and sagittal master tracings. The coordinates were then combined to formulate the required three-dimensional geometries of the biting apparatus.

Before digitizing the master tracings it was necessary to orient the tracings on a digitizing pad (HiPad, registered trademark, Houston Instruments Inc.). A consistent orthogonal axis system was used throughout this study. This axis system was used for orientation of tracings as well as for identification of the three-dimensional coordinates of anatomical points. The anteroposterior axis was defined as the "X" axis, with the anterior direction being positive. The vertical axis was defined as the "Y" axis, and the superior or cephalic direction was defined as positive. The mediolateral or transverse axis was the "Z" axis, and the positive direction was determined to be on the ipsilateral side of the skull. For the sagittal master tracing, the horizontal (X) axis was defined by a line which was parallel to the occlusal plane and intersected the articulating surface of the condyle (Figure 3.4.5). The articulating surface of the condyle was considered to be the most anterosuperior aspect of the condyle. The vertical (Y) orientation axis was constructed in such a manner as to intersect the occlusal plane axis at right angles and intersect the articulating surface of the condyle. The primary data determined from the master sagittal tracing are presented in Table 3.4.1.

The horizontal (X) orientation axis of the master basal tracing was defined by the midsagittal plane of the specimen (Figure 3.4.13). A perpendicular transverse (Z) axis was identified as the best-fit line intersecting the centroids of the heads of the condyles (intercondylar axis). This study required the intercondylar axis to intersect the midsagittal plane at right angles. In some cases, asymmetry of the skull did not allow right angle intersection. In these circumstances the condyle on the "identified muscle" side was determined to be the point of origin of the vertical axis. The axis was made to intersect the midsagittal plane (horizontal axis) at a right angle. The primary data provided by the basal master tracing also is presented in Table 3.4.1.

3.4.2 Temporomandibular Eminence Reproduction Technique

A technique was developed to reproduce and analyze the development of sagittal morphology of the temporomandibular eminence.

3.4.2.1 Impression Technique

A polyvinylsiloxane (Reprosil, registered trademark) impression record was made of either the right or left temporomandibular joint fossa and eminence. In order to allow reorientation of the record, a wire was bent at approximate right angles in three planes and this wire was placed in the impression material before it had set in the fossa. The impression record and wire were left in place over the temporal component of the temporomandibular joint while the photographs of Figures 3.4.2, 3.4.6, and 3.4.10 were taken. In this manner the orientation wire was photographed from sagittal, basal, and frontal views. The three views made it possible to reorient the impression record to tracings of the photographic transparencies.

After photographing the eminence impression record, the record was removed from the skull and suitably identified and stored.

3.4.2.2 Reproducing Eminence Morphology

The impression record was used to make dental stone models of the eminence morphology. The stone models, when separated from the impression records, were a replica of the eminence morphology. The transverse axis of each eminence was assumed to be parallel to the transverse axis of the fossa (Figure 3.4.14). The depth of the fossa determined a point from which a perpendicular axis was made anteroposteriorly. This anteroposterior axis represented the sagittal plane of the temporomandibular eminence. The model was then sectioned along the sagittal plane and used as a template to trace the contour of the eminence.

3.4.2.3 The Eminence Model as a Template

To achieve correct placement of the sagittal morphology of the eminence in the master sagittal tracing, the sectioned stone model was first put back on the temporal impression record. The orientation wire then permitted superimposition of the impression record and stone model over a sagittal photographic projection. After orienting the complex, the impression record was removed. The model was used as a template and a sharp pencil was used to trace eminence morphology on the tracing of the sagittal photographic projection (Figure 3.4.15).

3.5 **Methods of Analysis**

3.5.1 Numerical Model of Temporomandibular Joint Loading

A rigorous description of the numerical model has been presented by Smith (1984). A brief overview is provided here to establish the terminology of the numerical model and the strategy adopted in this study for using the model as an analytical tool.

Loading of the temporomandibular joint was defined as a force which tends to move the condyle in any direction. The traditional view has been narrower in its definition. Loading traditionally has been defined as a force which tends to move the condyle towards the eminence. In the terminology of the numerical model, two types of loading are possible. Appositional (+) loading occurs when a force tends to translate the condyle towards the eminence. Distractive (-) loading occurs when a force tends to translate the condyle away from the eminence.

The term loading will be used synonymously with force and will have the characteristics of magnitude and direction. In a three-dimensional mechanical analysis, a force is represented by a unit vector (direction) multiplied by a scalar (force magnitude). Thus, the force vector has defining characteristics of magnitude, direction, and point of origin. The numerical model was used to calculate the direction of the force vector in response to a vertical bite force.

In the numerical model, bite-force direction, magnitude, and point of application are defined. The same orthogonal axis system used to define the three-dimensional anatomical coordinates was also used in the numerical model to define location of bite points and calculate directions and magnitudes of condylar loading.

For the purposes of this study, the points of origin and insertion of each muscle were defined by the centroid of each area of muscle origin and insertion. In this manner, the direction of action and points of application of the three muscle pairs (masseter, temporalis, lateral pterygoid) were specified. The magnitude of each muscle force was left to be determined by the modelling process. This yielded six unknowns. The points of force application on the condyles were defined but the direction and magnitude of the right and left condylar forces were not known and were determined by the modelling process. This resulted in another six unknowns for a total of twelve unknowns (Figure 3.5.1).

There were too many unknowns to arrive at a solution by an analytical means (See Smith (1984) for discussion). In order to solve for the unknowns the numerical model employed an iterative or "trial and error" method to calculate the six muscle and six condylar forces which restrained a defined bite force and produced static equilibrium. The iterative method varied each muscle force, in turn, to find the combination of muscle forces which would result in minimal condylar forces and would satisfy static equilibrium.

3.5.2 MEAN CONDYLAR LOADING ANGLE (F.C.t)

The direction of condylar loading was quantified by means of an angle termed the MEAN CONDYLAR LOADING ANGLE (F.C.t, force on condyle total). It was decided that the direction of condylar loading should reflect the influence of the anteroposterior position of the mandible during biting, and the relative amounts of time the mandible functioned in a particular position. Therefore, the MEAN CONDYLAR LOADING ANGLE (F.C.t) was defined as a composite of two different angles of loading. The two angles of loading were calculated by the numerical model. These two angles were the RETRUDED LOADING ANGLE (F.C.r) and PROTRUDED LOADING ANGLE (F.C.p).

3.5.2.1 RETRUDED LOADING ANGLE (F.C.r)

This angle was defined as the direction of condylar loading which would occur when the mandible was in a molar biting position. This position was dictated by occlusion of the posterior dentition and is representative of a centric occlusion position of biting. If the specimen lacked buccal dentition the position of the mandible was determined by the condyles in a "most superior and anterior" position in the glenoid fossa.

The numerical model used the photographed three-dimensional geometry of a specimen to determine the RETRUDED LOADING ANGLE (F.C.r). The angle was measured relative to the vertical (Y) axis (ie. perpendicular to occlusal plane).

3.5.2.2 PROTRUDED LOADING ANGLE (F.C.p)

This angle was defined as the direction of condylar loading which occurred when the mandible was translated forward to a position of incisal biting or suckling (Ardran *et al.*, 1958a,b).

To calculate the PROTRUDED LOADING ANGLE, a new geometry was derived to define the three-dimensional coordinates of the biting apparatus in a protrusive biting position. This was accomplished by measuring the amount of overjet present and arithmetically protruding the mandible to an edge-to-edge incisor relationship. In cases where an individual presented with a Class III incisal edge relationship, an assumption was made that during function on the anterior teeth, the mandible probably did not translate forward more than two millimeters (2 mm.). In all cases, the amount of inferior positioning of the mandible was dictated by the degree of overbite and the slope of the eminence. In cases of predentate specimens, the mandible was translated anteriorly by approximately three (3) millimeters (mm.) to reproduce the anteroposterior position of the mandible during suckling (Ardran _et al_., 1958a,b). The numerical model used the new geometry to calculate the PROTURUDED LOADING ANGLE (F.C.p). The measurement of the angle was made relative to the vertical (Y) axis.

The MEAN CONDYLAR LOADING ANGLE (F.C.t) was defined as a time-dependent mix of F.C.r and F.C.p. To determine the contribution of each category of angle, RATIO ACTIVITY CONSTANTS (K) were defined for each stage of dental development. RATIO ACTIVITY CONSTANTS (K) defined the amount of time the condyle was assumed to be loaded in either a protruded (incisor biting) or retruded (centric occlusion) position. For example, Ardran _et al_. (1958a,b) indicated that suckling occurred in a protrusive mandibular position. Therefore, based on the description of neonate function, the assignment of RATIO ACTIVITY CONSTANTS for a neonate was:

Protruded RATIO ACTIVITY CONSTANT (Kp)= 0.9 (90% of activity in the protruded mandibular position)
RetrudedRATIO ACTIVITY CONSTANT (Kr)= 0.1 (10% of activity in the retruded mandibular position)

By multiplying the appropriate RATIO ACTIVITY CONSTANT (Kp or Kr) with F.C.p and F.C.r, and summing the products, the MEAN CONDYLAR LOADING ANGLE (F.C.t) is obtained. This angle reflects the influence of anteroposterior mandibular activity. Table 3.5.1 lists categories of age groups, determinants of each group, and RATIO ACTIVITY CONSTANTS of each age group. Note that each pair of RATIO ACTIVITY CONSTANTS for each age group is only a rough estimation of the amount of time the mandible is found in a particular anteroposterior position during function. These estimates were based on the assumption that as teeth emerge, the mandible will change anteroposterior position during function to accommodate use of newly erupted teeth. Therefore, there will be an initial tendency to favour a more anterior or protruded mandibular position as the child develops anterior teeth. When the posterior teeth begin to erupt, the mandible will be shifted to a more retruded biting position and will be found in this functional position more often than in a protruded functional position.

3.5.3 EMINENCE DEVELOPMENT ANGLE

Quantitative evaluation of sagittal development of the temporomandibular eminence was accomplished by an angular measurement. The EMINENCE DEVELOPMENT ANGLE was constructed by intersecting the occlusal plane with a straight line drawn through the posterior slope of the temporomandibular eminence (Figure 3.5.2). The EMINENCE DEVELOPMENT ANGLE was constructed on the sagittal master tracing of each specimen.

3.5.4 Muscle Angle Analysis

An analysis of the angles of muscle action was made to determine whether growth changes in the angles of muscle pull could account for growth changes in the direction of condylar loading. The analysis was carried out in three anatomical planes. The line of muscle action was defined as a straight line joining the estimated centroids of the origin and insertion of a muscle. The reference planes were as follows: 1. Sagittal view- occlusal plane, 2. Frontal view- midsagittal plane, 3. Basal view- midsagittal plane (Figures 3.5.3, 3.5.4, 3.5.5).

3.5.5 Muscle Moment Potential Analysis

The ability of a muscle to produce a moment about an axis changes with growth and an investigation was carried out to quantify the changes.

The capacity of a muscle to produce a moment was determined for the basal and sagittal anatomical planes. The chosen points about which moments were taken in each plane are:

Sagittal- the intercondylar axis

Basal- intersection of the intercondylar axis and the midsagittal plane (figure 3.5.7).

Perpendicular linear measurements were made from the chosen points to the line of action of muscle pull. The linear measurements were defined as the muscle moment potential. However, it must be noted that, in this model, the potential for a muscle to produce a moment about any point is subordinate to the requirement of minimizing joint load. Therefore, although it may be helpful in some respects, this form of analysis can be misleading if the requirement of minimizing joint load is ignored.

3.5.6 Sensitivity Studies

Sensitivity study analyses were used extensively in this project. These studies were theoretical experiments which provided a means of quantifying the influence of specific variables, such as muscle angle and muscle moment potential, on the direction of condylar loading. In general, a sensitivity study required the creation of an "altered geometry" in which a variable (eg. ramus height) or variables were incremented to study the effect of the variable(s) on condylar loading patterns. The calculations of the numerical model enabled comparison of the normal loading angles (F.C.r, F.C.p, F.C.t) and angles of loading under the conditions predetermined in the "altered geometries". These altered geometries attempted to simulate growth or mandibular position changes to give an indication of their influences on the direction of condylar loading.

3.5.7 Statistical Method

Growth is typically non-linear and the polynomial regression technique is particularly useful in analyzing growth patterns. Polynomial regressions were used when scatter diagrams exhibited non-linear behaviour. Linear and polynomial regressions were calculated by a Hewlett-Packard Regression Analysis Program. The regression coefficient and the chosen degrees of freedom accompany each regression plot.

3.6 **Sources of Error**

3.6.1 Cross-Sectional Sample

It is not ideal to use cross-sectional sampling to investigate growth phenomena. As long as this is appreciated, then the various conclusions of this study may be judged accordingly. In the future, the conclusions of this study may be tested by examination of data provided by a longitudinal population sample.

3.6.2 Photographic Perspective Error

Measurement errors were noted in preliminary studies using the photographic technique. An analysis was undertaken to determine measurement errors due to photographic perspective. The study began with photographing a complicated three-dimensional object of known dimensions. Photographic transparencies of the object were projected and traced. The traced dimensions of the object were determined and analyzed for percentage error. The analysis determined that there was a photographic perspective error of 1 millimeter (mm.) for every 10 millimeters (mm.) behind the focal plane.

Photographic perspective error correction was accomplished through equations appropriate to each anatomical plane. These equations are as follows:

Sagittal Anatomic Plane: $Xa = Xm\ (1 + Zm/1000)$
$Ya = Ym\ (1 + Zm/1000)$

Basal Anatomic Plane: $Za = Zm\ (1 + Ym/1000)$
$Xa = Xm\ (1 + Ym/1000)$

Where: Xm, Ym, and Zm are the measured millimeter coordinates of an anatomical point. The X, Y, and Z indicate the axis on which each measurement was made (For a review of the orthogonal axis system used in this study, refer to Section 3.4.1.4). Xa, Ya, and Za are the corrected anatomical coordinates for each axis.

To determine whether the photographic perspective errors compromised the accuracy in determination of the various angles of condylar loading, preliminary work was undertaken to compare results calculated by the numerical model. The model used both "perspective corrected" and unaltered sample geometries of specimens #031 and #035. The results were compared for discrepancies in the computed loading angles. The mean differences in angles of loading of the condyle for "perspective corrected" and uncorrected geometries was one to two (1.0-2.0) degrees for both specimens. The amount of error was small, which indicated that unaltered geometries could be used in this study to give a close approximation of the direction of condylar loading.

3.6.3 Tracing Technique Error

Superimpositions of the tracings were quite easily accomplished, which indicated that tracing errors were not greater than one line thickness or approximately one-half of one millimeter (0.5 mm.).

3.6.4 Error in Determining EMINENCE DEVELOPMENT ANGLE

The error in determining the EMINENCE DEVELOPMENT ANGLE was found to be approximately plus or minus two and one-half (+/- 2.5) degrees. The posterior slope of the eminence is often curved and there is a degree of uncertainty in estimating the best straight line through the centre portion of the eminence. This was one source of error and accounts for some of the scatter seen in all plots involving EMINENCE DEVELOPMENT ANGLE. Errors may also have been introduced in the determination of the angle, given that sagittal sectioning of the stone model was not parallel to the focal plane of the photograph.

A special problem was encountered in the analysis of the temporal bones of the Johns Hopkins Collection. The temporal components of these specimens were disarticulated and it was not possible to analyze the eminence development with respect to the occlusal plane. To try to overcome this problem, a superimposition was made of the temporal component of the disarticulated specimen over the photographic projection of an articulated specimen of similar age. This introduced errors in determination of the development of the early eminence. However, the analysis of these very young specimens provides a best possible estimate of the degree of development of the early temporomandibular eminence. This method of analysis was conducted on the nine (9) isolated temporal bones acquired from the Johns Hopkins Collection.

3.6.5 Error in Determining Occlusal Plane

Occlusal plane was determined by a straight line through the molar/bicuspid or primary molar region (Jacobson, 1976, p. 185). Determination of the occlusal plane was more difficult in the predentate specimens. An approximation of an intermediate interalveolar distance helped in determination of the predentate occlusal plane.

Variation in determination of an occlusal plane for an individual was within plus or minus three (+/- 3) degrees. This range of error contributed to the scatter of the regression plots of EMINENCE DEVELOPMENT ANGLE.

3.6.6 Determination of Muscle Centroid

It has been disputed whether the centroid of muscle attachment represents the centre of muscle function. However, given that the muscle must work in a direction which is within the confines of its attachment, it is not unreasonable that the line of muscle action probably passes near the centroid of the areas of attachment. The centroid of each area of muscle origin and insertion was estimated, and a line of muscle action was defined to act through the estimated centroids of the muscle origin and insertion.

The identification of each centroid was difficult in younger specimens owing to problems of determining the regions of muscle scarring. The greatest error in determination of muscle scarring and centroid location was in the origin of temporalis and lateral pterygoid muscles. Estimating a centroid for the temporalis origin usually varied approximately plus or minus three millimeters (+/- 3 mm.) on the anteroposterior (X) and vertical (Y) axes. Lateral pterygoid centroid variation was predominantly on the vertical axis (Y) and was about plus or minus three millimeters (+/- 3 mm.).

Errors in determining the muscle centroids contributed to the scatter seen in the analyses involving the directions of condylar loading. It was noted that specimens 013, 028, 050, and 052 were at the extremes of the scatter of the plot of the EMINENCE DEVELOPMENT ANGLE vs. MEAN CONDYLE LOADING ANGLE. Changing the masseter or temporalis muscle angles of these specimens reduced the scatter (Table 4.3.2.5). It may be that the direction of action of the muscles of mastication was different for these specimens than for the rest of the sample. No explanation has been found to account for the differences that were exhibited by these specimens.

3.6.7 Digitizing Errors

Successive digitization of the same tracing determined that the error in digitizing was plus or minus one-half millimeter (+/- 0.5 mm.). This error was considerably less than the error in centroid determination. Given the results of other error studies, it was considered that this source of error had negligible influence on the results.

3.6.8 Error in RATIO ACTIVITY CONSTANTS

The assigned RATIO ACTIVITY CONSTANTS (Table 3.5.1) are an approximation based on the literature describing suckling and mastication of young children (Ardran *et al*., 1958a,b). It was assumed that, after completion of the eruption of primary molars, the mean anteroposterior positioning of the mandible during mastication became relatively constant.

For this study, the dentition status was the determinant in the assignment of the constants. Sensitivity tests were carried out to test the significance of an error in assignment of constants. Table 3.6.1 identifies the specimens and the results of the tests. The angles of loading were recalculated assuming that the specimens now functioned in the range of 40% retrusive(60% protrusive) to 60% retrusive(40% protrusive). The tests indicated that the youngest specimens would be most affected by changes in assignment in RATIO ACTIVITY CONSTANTS. However the maximum change in the direction of condylar loading was only 2.3 degrees, which indicated that errors in assignment of RATIO ACTIVITY CONSTANTS would not jeopardize the conclusions drawn from this study.

Table 3.4.1 Sources of Primary Data for the Coordinates of Anatomical Points

Axis Coordinate	Anatomical Point	Master Sagittal Tracing	Master Basal Tracing
Anteroposterior (X) Coordinate	Masseter Origin	X	
	Masseter Insertion	X	
	Temporalis Origin	X	
	Temporalis Insertion	X	
	Lat.Pterygoid Insert.		X
	Lat.Pterygoid Origin	X	
	Incisor position		X
	Cuspid position		X
	First molar position		X
	Condyle position	X	
Vertical (Y) Coordinate	Masseter Origin	Y	
	Masseter Insertion	Y	
	Temporalis Origin	Y	
	Temporalis Insertion	Y	
	Lat.Pterygoid Origin	Y	
	Lat.Pterygoid Insert.	Y	
	Incisor position	Y	
	Cuspid position	Y	
	First molar position	Y	
	Condyle position	Y	
Transverse (Z) Coordinate	Masseter Origin		Z
	Masseter Insertion		Z
	Temporalis Origin		Z
	Temporalis Insertion		Z
	Lat.Pterygoid Origin		Z
	Lat.Pterygoid Insert.		Z
	Incisor position		Z
	Cuspid position		Z
	First molar position		Z
	Condyle position		Z

Table 3.5.1 RATIO ACTIVITY CONSTANTS (K) for Specific Age Groups

Group	Age Range	RATIO ACTIVITY CONSTANT Kp*	Kr*	(Notes)
Neonate	Birth-5mo.	0.9	0.1	-predentate to the eruption of 31/41
Infant	6mo-12mo	0.8	0.2	-to eruption of 73/83
Toddler	13mo-18mo.	0.7	0.3	-to eruption of 74/84
Child	19mo-23mo.	0.7	0.3	-to eruption of 75/85
Preschool	2yrs-5yrs	0.4	0.6	-to eruption of 36/46
School	5.1yrs-10yrs.	0.3	0.7	-to eruption of 33/43
Junior	10.1yrs.-15yrs.	0.3	0.7	-to eruption of 17/27
Adolesc.	15.1yrs.-18yrs.	0.3	0.7	-permanent dentition
Adult	18.1yrs.-older	0.3	0.7	-permanent dentition

* Estimation (See Section 3.5.2.2)

Table 3.6.1: Sensitivity Study: Assignment of RATIO ACTIVITY CONSTANTS.

Specimen #001- age 3.0 years
Specimen #002- age 7.0 years
Specimen #004- age 1.3 years
Specimen #009- age 0.75 years

Spec. #	Normal Activity Constants		Test Activity Constants		Normal F.C.t (degrees)	Test F.C.t (degrees)	Change (degrees)
	Kr	Kp	Kr	Kp			
001	0.6	0.4	0.5	0.5	22.2	21.9	-0.3
			0.4	0.6	22.2	21.5	-0.7
002	0.7	0.3	0.6	0.4	17.0	16.6	-0.4
			0.5	0.5	17.0	16.2	-0.8
004	0.3	0.7	0.4	0.6	11.0	11.7	0.7
			0.5	0.5	11.0	12.4	1.4
009	0.2	0.8	0.4	0.6	8.1	10.4	2.3
			0.5	0.5	8.1	12.4	2.2

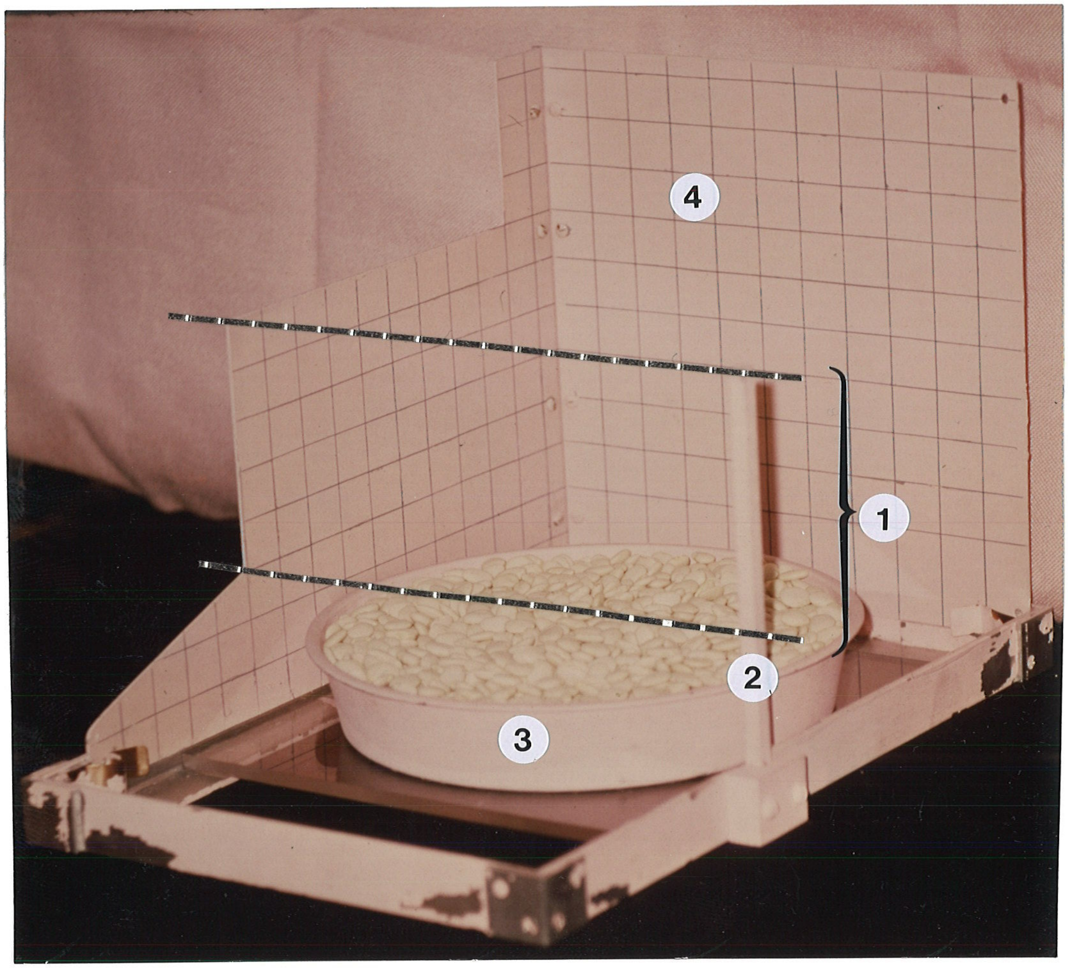
Kr- RATIO ACTIVITY CONSTANT for the retruded biting position

Kp- RATIO ACTIVITY CONSTANT for the protruded biting position

Normal F.C.t - previously calculated MEAN CONDYLAR LOADING ANGLE.

Test F.C.t - recalculated MEAN CONDYLAR LOADING ANGLE using different RATIO ACTIVITY CONSTANTS.

Figure 3.4.1 Photographic holding device



1. Photographic focal plane
2. Metal post used as a scaling reference (149 mm. in length)
3. Bean pan used to support the specimen
4. Backdrop (marked with a grid to aid orientation of the occlusal plane)

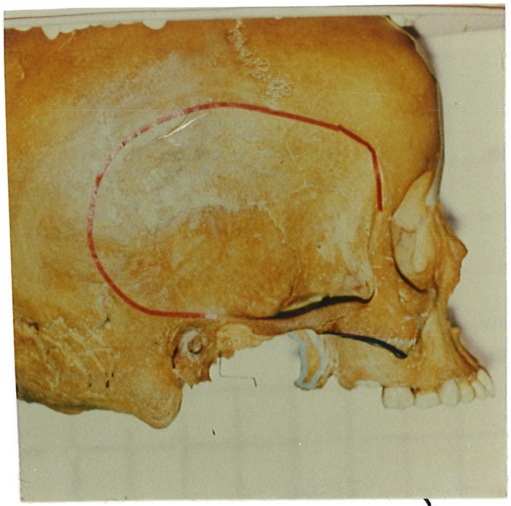


Figure 3.4.2 Sagittal photograph of skull

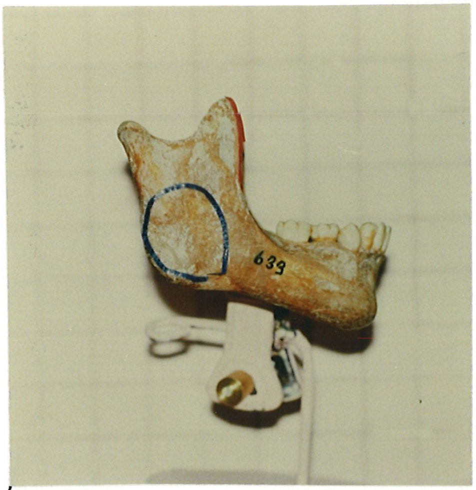


Figure 3.4.4 Sagittal photograph of mandible

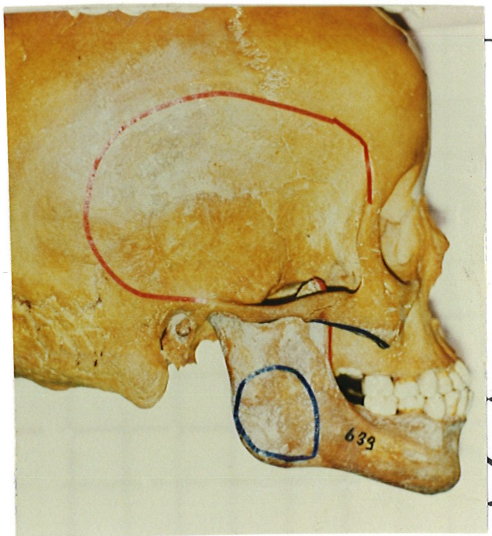


Figure 3.4.3 Sagittal photograph of skull and mandible

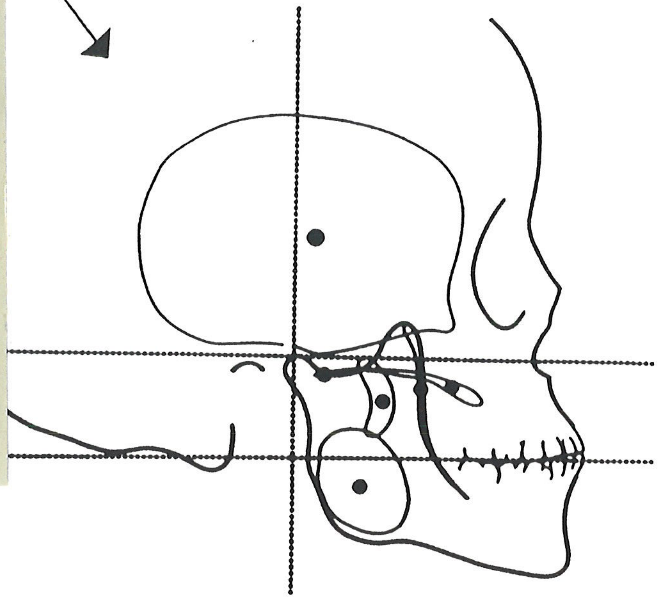


Figure 3.4.5 Master sagittal tracing

Figure 3.4.6 Frontal photograph of skull

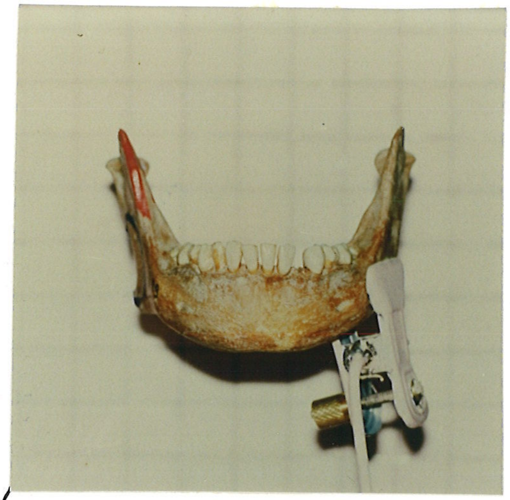


Figure 3.4.8 Frontal photograph of mandible

Figure 3.4.7 Frontal photograph of skull and mandible

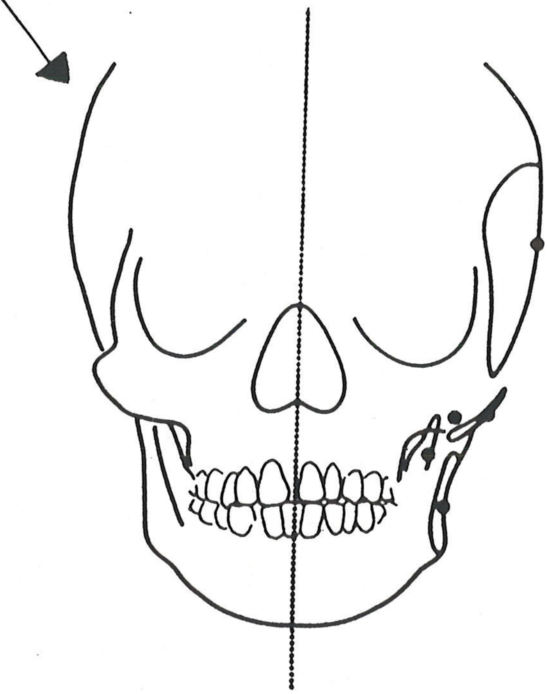


Figure 3.4.9 Master frontal tracing

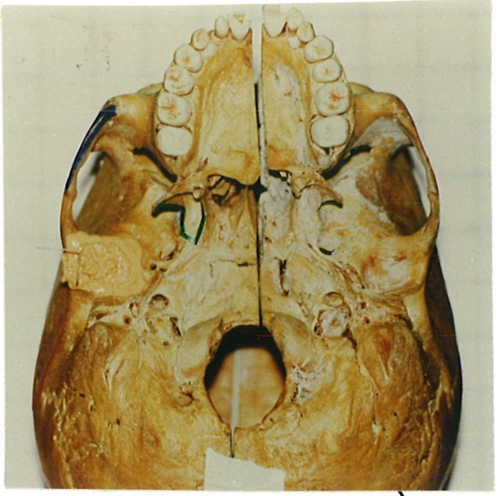


Figure 3.4.10 Basal photograph of skull

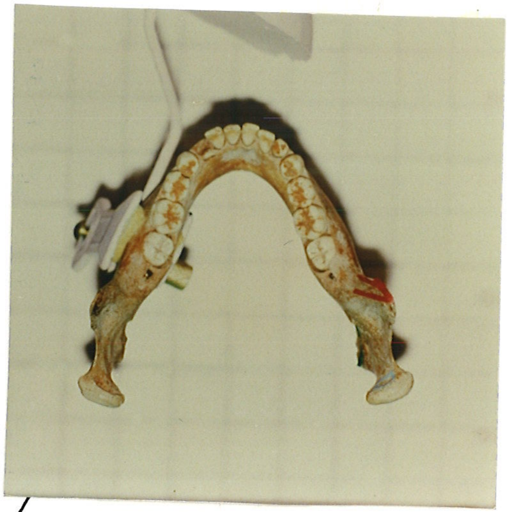


Figure 3.4.12 Occlusal photograph of mandible

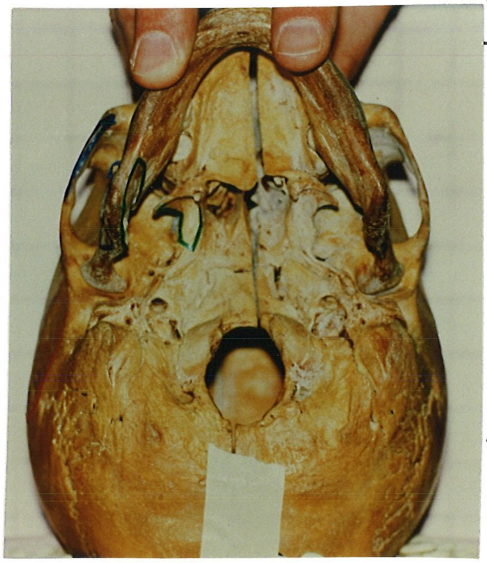


Figure 3.4.11 Basal photograph of skull and mandible

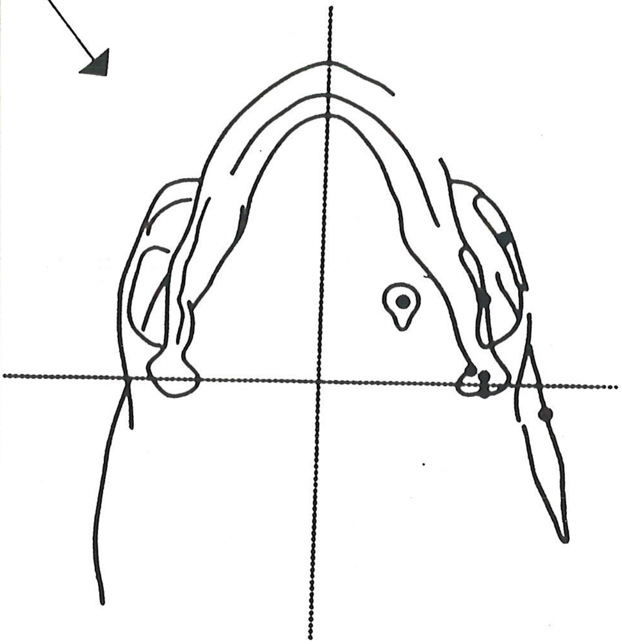


Figure 3.4.13 Master basal tracing

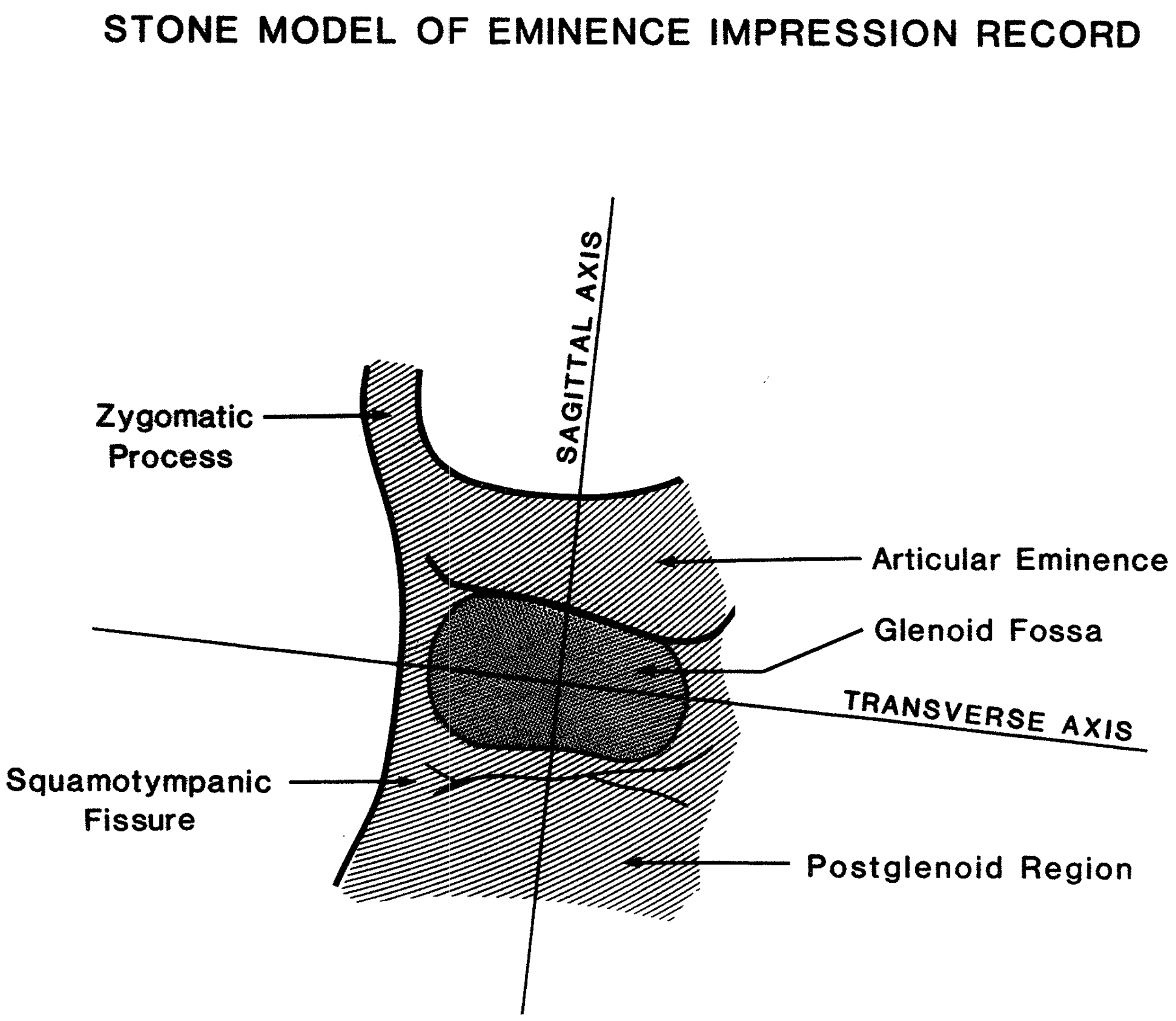


Figure 3.4.14 Model Record of the temporomandibular eminence

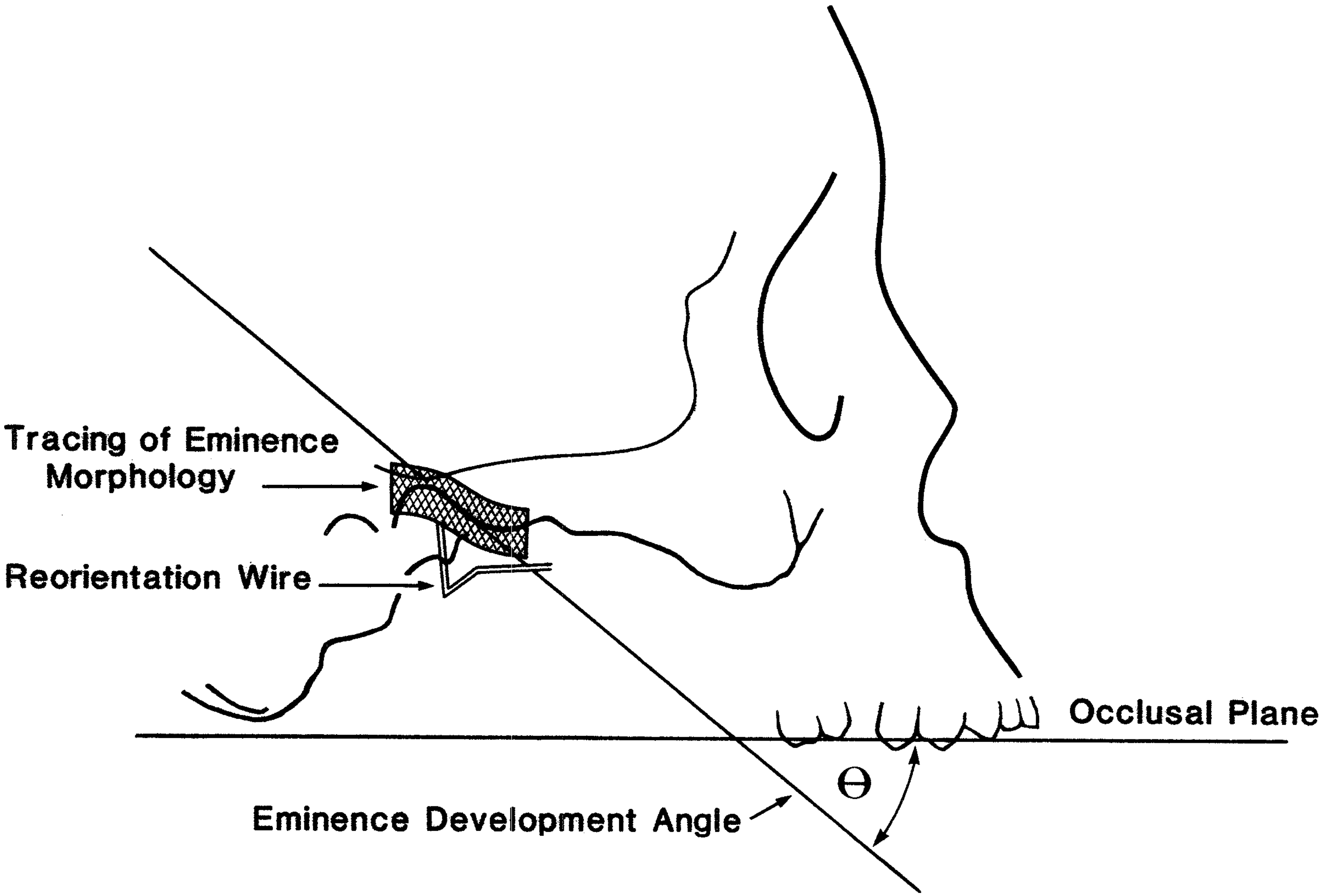
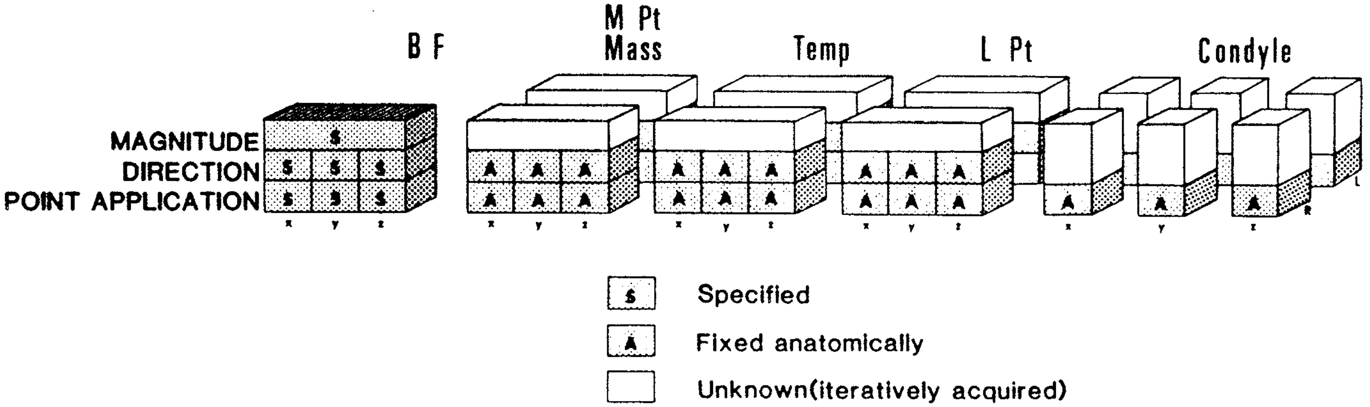


Figure 3.4.15 The impression record as a template

Figure 3.5.1 Information required to calculate static equilibrium



(From Smith (1984), with permission from the author)

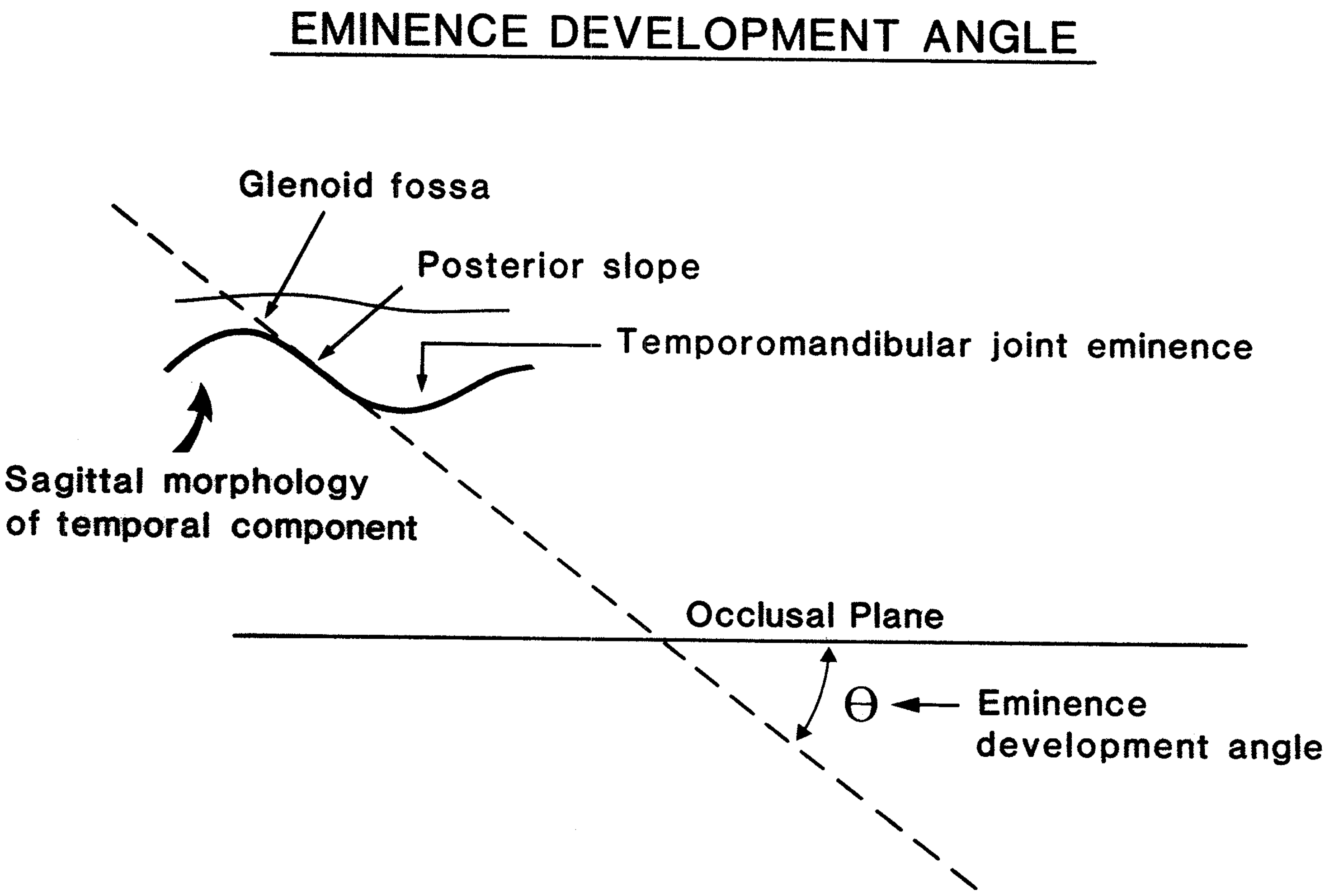


Figure 3.5.2 EMINENCE DEVELOPMENT ANGLE

SAGITTAL PLANE MUSCLE ANGLES

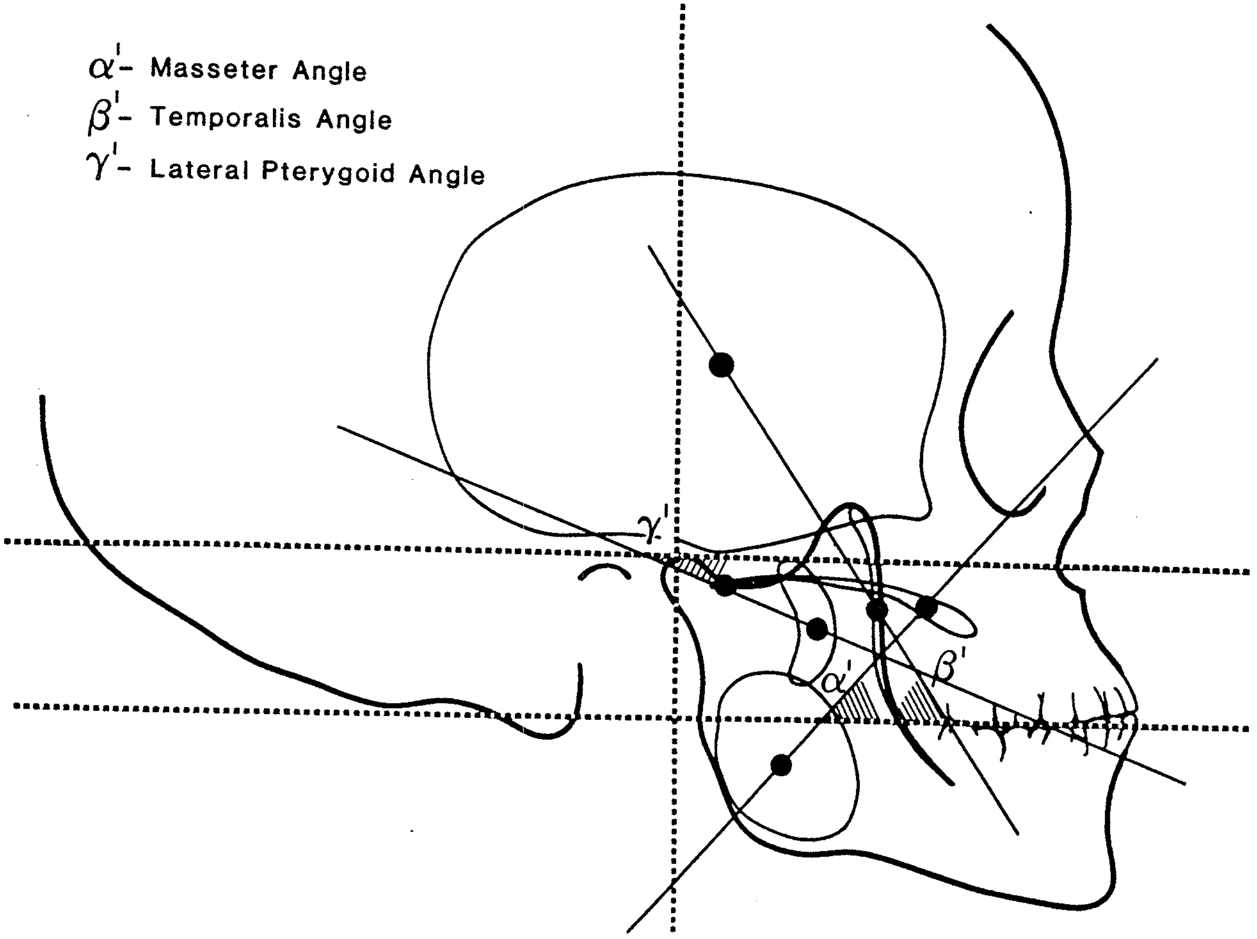
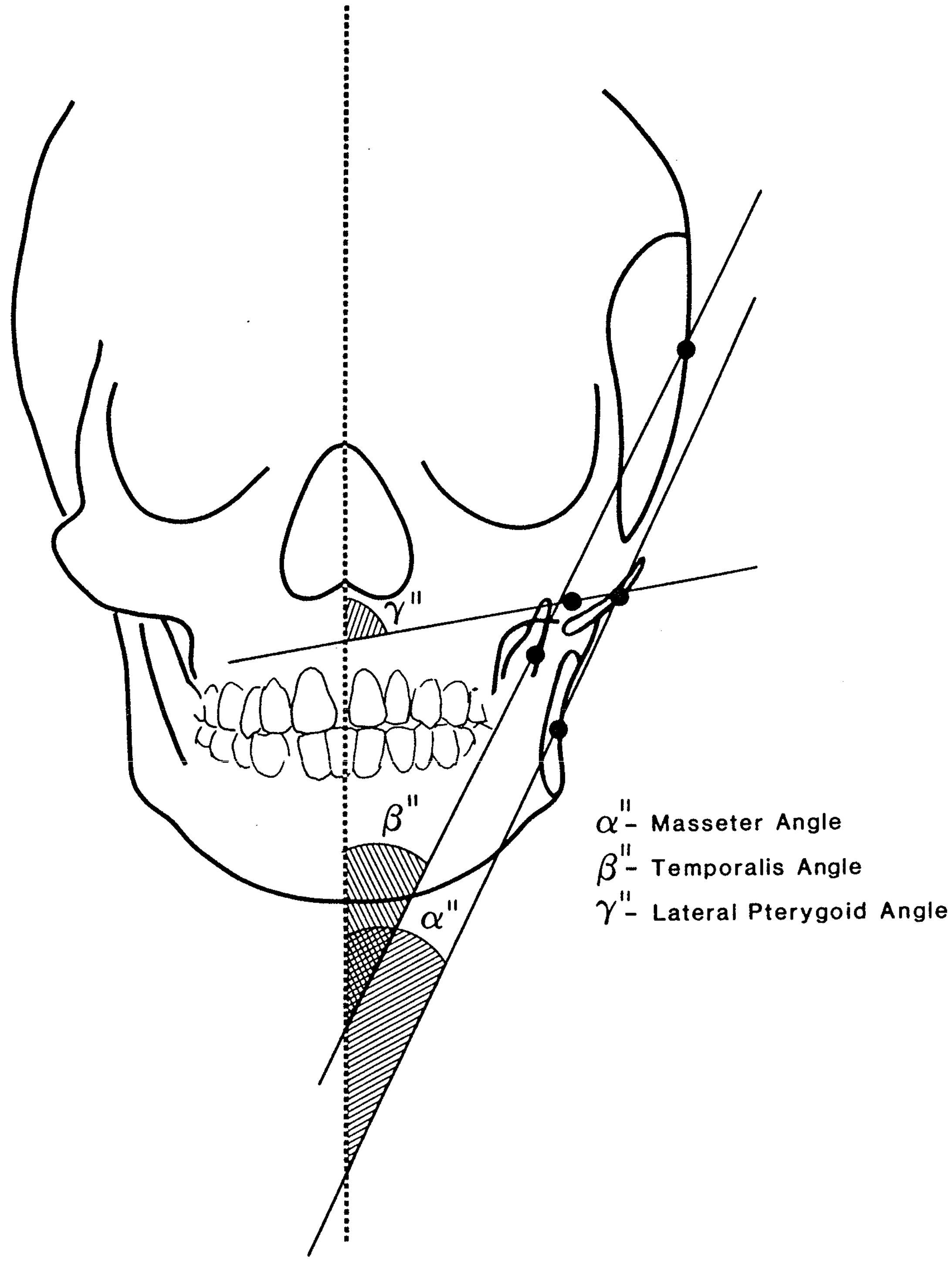


Figure 3.5.3 Sagittal plane muscle angles

Figure 3.5.4 Frontal plane muscle angles



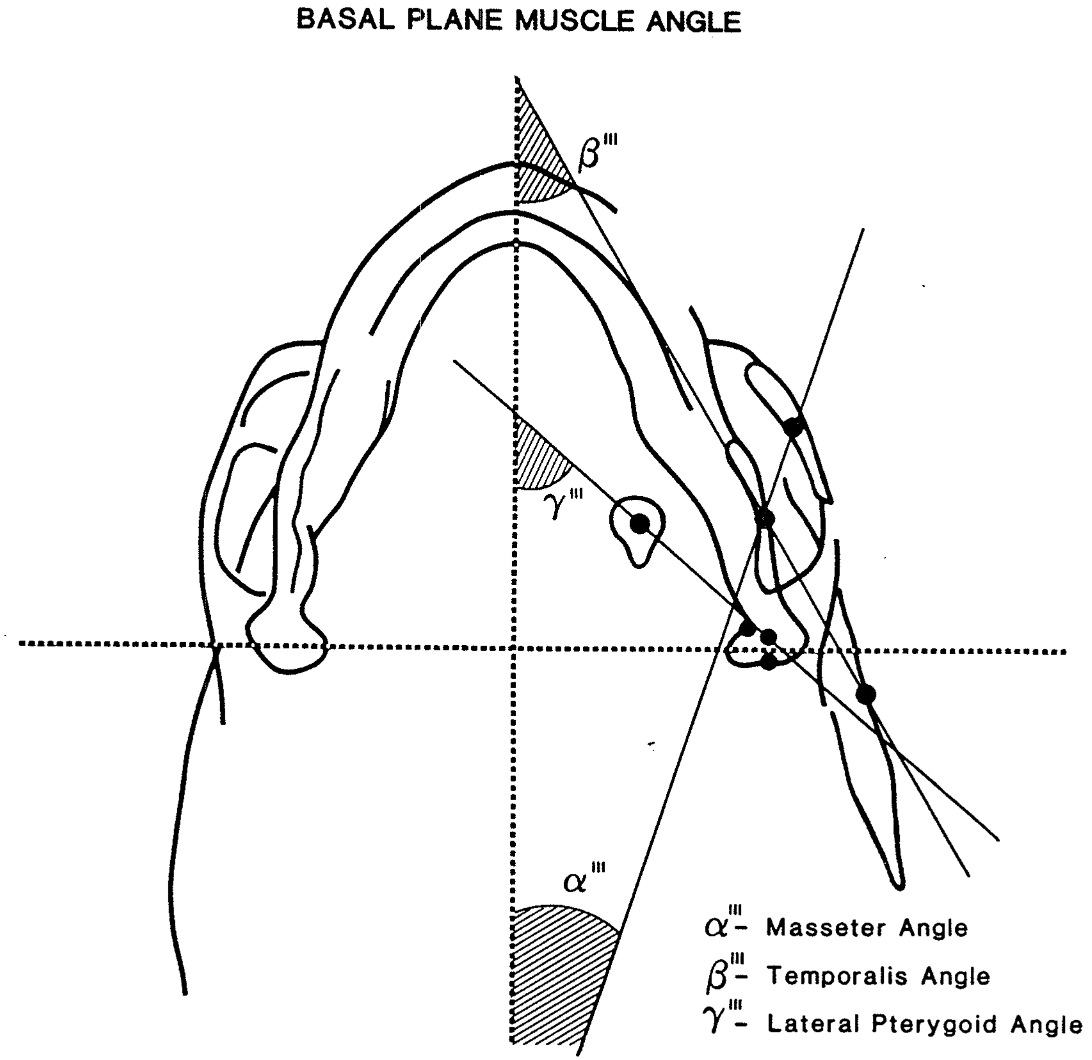


Figure 3.5.5 Basal plane muscle angles

SAGITTAL PLANE MUSCLE MOMENT POTENTIAL

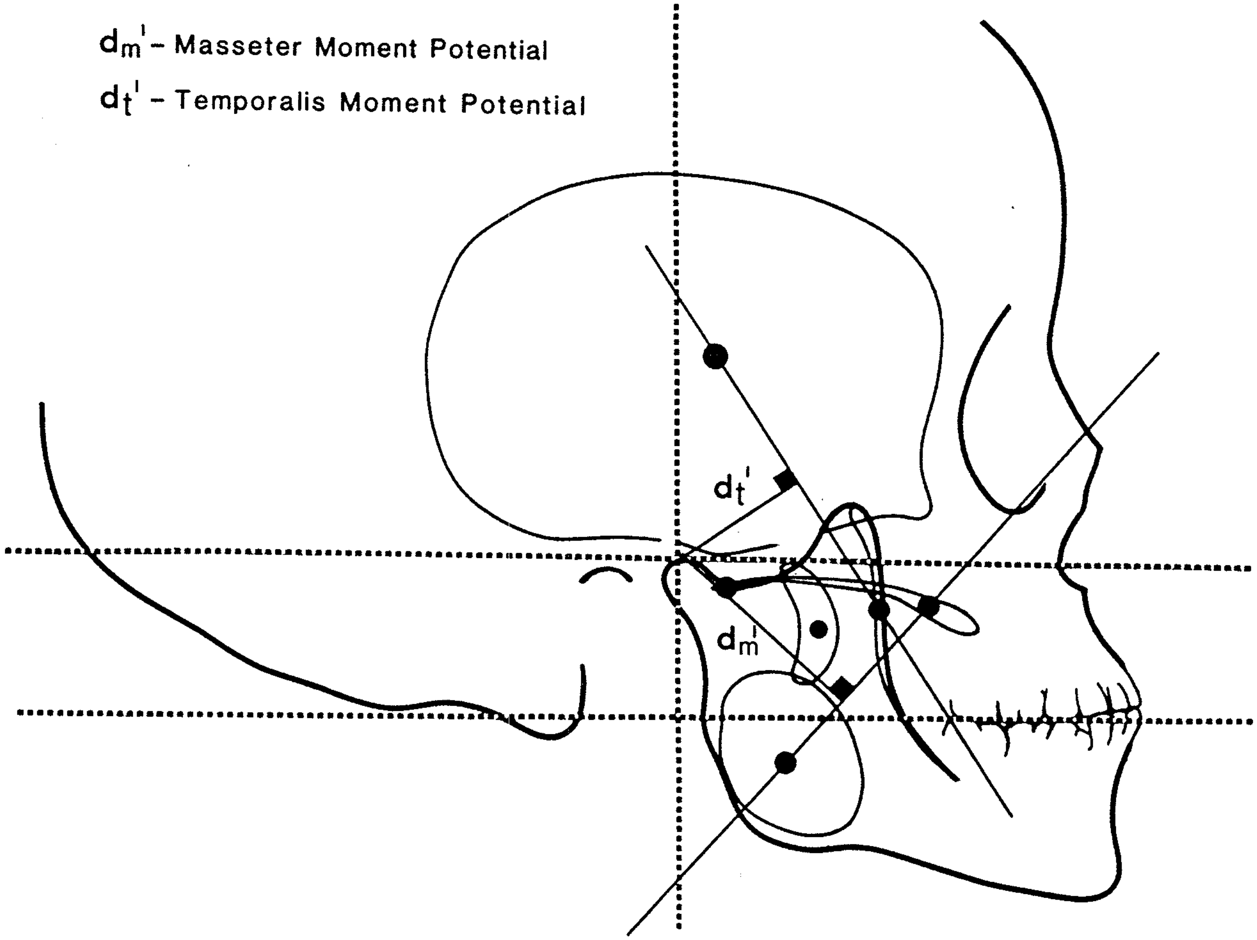


Figure 3.5.6 Sagittal plane moment potentials

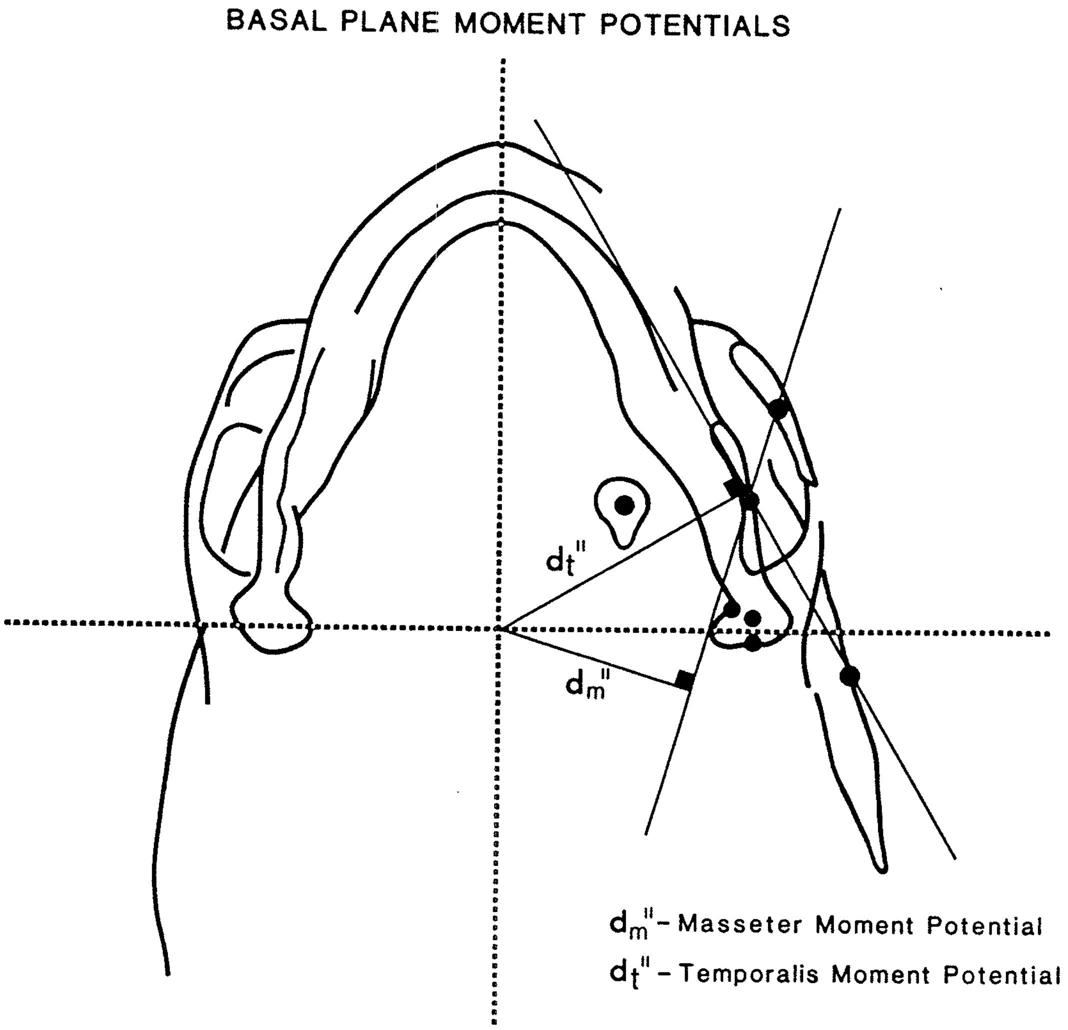


Figure 3.5.7 Basal plane moment potentials

Chapter 4

RESULTS

4.0 Introduction

From the literature review it became apparent that a quantitative analysis of growth changes in temporomandibular eminence morphology was warranted. The methods used to quantify the growth changes in the temporomandibular joint eminence were reported in Chapter Three. As well, Chapter Three describes how the numerical model was used as an analytical tool, to calculate the directions of condylar loading.

In this, the results chapter, Section 4.1 describes the age-related changes in eminence development. Section 4.2 examines the relationship between eminence development and the theoretical calculations of MEAN CONDYLAR LOADING ANGLE. The results of Section 4.2 prompted further examination of the variables affecting MEAN CONDYLAR LOADING ANGLE. The two variables examined were functional position of the mandible (Section 4.3.1) and growth changes in muscle geometries (Section 4.3.2).

4.1 Eminence Development

Eminence development was quantified by means of the EMINENCE DEVELOPMENT ANGLE. As shown in Figure 4.1.1 and discussed in Section 3.5.3, the angle was constucted by intersecting a line representing the posterior slope of the eminence, with the occlusal plane. Figure 4.1.2 (Table

4.1.1) shows the relationship between EMINENCE DEVELOPMENT ANGLE and Age. A plot of the best-fit polynomial to the data (two (2) degrees of freedom, r = 0.80) is also shown in Figure 4.1.2.. Maximum velocity of eminence development appeared to occur prior to three years of age. After three years of age development slowed until a plateau was reached at approximately fourteen (14) to fifteen (15) years of age.

4.2 Eminence Development and Direction of Condylar Loading

The fundamental question of this study was whether the immature TMJ is loaded. The results of this study indicated that regardless of age and biting conditions tested, the TMJ was loaded in compression . The numerical model calculated the directions of loading in each individual, and Figure 4.2.1 (MEAN CONDYLAR LOADING ANGLE vs. EMINENCE DEVELOPMENT ANGLE, Table 4.2.1) is presented to illustrate the relationship between EMINENCE DEVELOPMENT ANGLE and the MEAN CONDYLAR LOADING ANGLE (F.C.t). A best-fit straight line ($y = 0.5x - 2.5$, $r = 0.72$) describes a relatively linear relationship between the variables. It will be noted that the best-fit line intersects the abscissa at approximately five (5) degrees of eminence development. The slope of the best-fit straight line is approximately 0.5.

4.3 Variables Influencing MEAN CONDYLAR LOADING ANGLE (F.C.t)

4.3.1 Anteroposterior Position of the Mandible

The functional position (incisor biting, molar biting) of the mandible is a variable which influences the MEAN CONDYLAR LOADING ANGLE (F.C.t). Figure 4.3.1.1 (Table 4.3.1.1) shows that for all specimens, a change in functional position of the mandible results in a change in direction of the condylar loading. In all cases, the F.C.r was larger that the F.C.p. The plot also indicates that the effect of a change in anteroposterior position of the mandible was more significant in the younger individuals than in the more mature individuals. A larger change in loading angle was observed in individuals younger than the age of three (3) years.

In the very youngest of individuals, F.C.p was perpendicular to the temporal component, but F.C.r was not. As the eminence developed, F.C.r became perpendicular to the temporal component. This occurred prior to the age of two (2) years.

4.3.2 Growth Influence on Directions of Condylar Loading

Figure 4.3.1.1 indicates that the functional position of the mandible can cause a change in the direction of condylar loading. Therefore, the functional position of the mandible during biting will affect the MEAN CONDYLAR LOADING ANGLE (F.C.t). Functional position is one factor which affects direction of condylar loading. Figure 4.3.2.1 and Figure 4.3.2.2 are presented to give evidence of growth-related changes in the direction of condylar loading for both protruded and retruded biting positions. They show

RETRUDED LOADING ANGLE and PROTRUDED LOADING ANGLE vs. Age, respectively. Note that both angles of condylar loading increase with age.

Two variables affected by growth were examined to determine their significance in altering direction of condylar loading. The variables are:

1. Growth related changes in Muscle Angles.
2. Growth related changes in Muscle Moment Potentials.

4.3.2.1 Growth Changes in Muscle Angles

Figure 4.3.2.3 illustrates the constructions which define the various muscle angles. In the sagittal plane, muscle angles were determined by the intersection of the line of muscle pull with the occlusal plane. In the basal and frontal planes, muscle angles were determined by the line of muscle pull with the midsagittal plane. The view of the frontal plane was taken with the occlusal plane horizontal, whereas, in the basal view the occlusal plane is in the plane of the page.

Figures 4.3.2.4, 4.3.2.5, and 4.3.2.6 (Tables 4.3.2.1, 4.3.2.2, 4.3.2.3) are presented to depict growth-related changes in the angles of muscle pull. The changes seen in these muscle angles should be interpreted with caution, since a cross- sectional sample was used to try to establish the trends of longitudinal growth and there is a considerable amount of scatter on the plots. Figure 4.3.2.4 indicates that minimal growth changes occur in the sagittal plane muscle angles. The amount of change of these muscle angles is small. A larger increase in angle was noted for the lateral pterygoid.

Figure 4.3.2.5 plots the angle changes in the frontal anatomical plane. The most obvious change was in temporalis muscle angle (2 degrees of freedom, r = 0.75). There was a decrease of the temporalis muscle angle with increasing age. Lateral pterygoid and masseter muscles did not exhibit significant growth-related changes in frontal plane muscle angles.

Basal plane angles of the masseter and temporalis muscles (Figure 4.3.2.6) decreased with growth. There was only a small change in the lateral pterygoid muscle angle.

The plots of muscle angles vs. age established the growth changes in the direction of the pull of the muscles of mastication. Once the growth changes were quantified, sensitivity studies were conducted on randomly chosen specimens to evaluate the influence of changes in geometry on the direction of condylar loading. The changes that were tested were the types that occur during growth (Figure 4.3.2.4, 4.3.2.5, 4.3.2,6). Table 4.3.2.4 documents the variation of single muscle angles and multiple muscle angles and the effects on direction of condylar loading. The results indicate that change in the sagittal angle of the temporalis muscle (Column "C" of Table 4.3.2.4) was the most influential variable affecting the angle of condylar loading. This is verified by the large changes in RETRUDED LOADING ANGLE (F.C.r) in response to either an increase or decrease in sagittal angle of the temporalis muscle. These changes were noted to make the largest contribution to the change in loading angle described in column "F" (Multiple Variable Changes) of Table 4.3.2.4. The second most influential variable was the sagittal angle of the masseter muscle (Column "A" of Table 4.3.2.4). A change in this muscle angle tended to be more influential in the younger age specimens (# 009, #012). The muscle angles of other anatomical planes were not influential in altering the direction of condylar loading. Lateral pterygoid muscle angles were not evaluated, since the numerical model calculations indicated that lateral pterygoid muscle forces were not necessary in order to achieve static equilibrium and minimize condylar loading. The frontal muscle angle of the masseter muscle was not evaluated since Figure 4.3.2.5 showed that there was very little growth change in the direction of action of this muscle.

Reference to the sensitivity study of Table 4.3.2.4 will show that the changes in sagittal angles of the masseter and temporalis muscles affected the direction of condylar loading. However, previous results of Sagittal Muscle Angle vs. Age (Figure 4.3.2.4) indicated that the evidence for growth changes in the direction of action of these muscles was not strong. Therefore, it will be assumed that the growth changes in sagittal muscle angles made only a minor contribution to the changes which occurred in the directions of condylar loading.

It should be recognized that only vertical bite forces were examined. It is reasonable to assume that the other muscle angles may play a role in altering the directions of condylar loading as a result of a non-vertical bite force.

A special sensitivity study was conducted to examine the influence of muscle angles on the scatter of Figure 4.2.1 (MEAN CONDYLAR LOADING ANGLE vs. EMINENCE DEVELOPMENT ANGLE). The extremes of scatter are represented by specimens 052, 028, 050, and 013. The sensitivity study is presented in Table 4.3.2.5. Sagittal muscle angles of the temporalis (specimens 052, 050, and 028) and masseter (specimen 013) muscles were varied by predetermined amounts. The results indicated that significant changes in direction of condylar loading occurred when these muscle angles were altered. As a result of altering these muscle angles, the calculated angle of condylar loading more closely resembled the angles of loading of the majority of the sample. The experimental changes in temporalis (specimens 052, 050, 028) and masseter (specimen 013) sagittal muscle angles reduced the scatter of points in Figure 4.2.1 (MEAN CONDYLAR LOADING ANGLE vs. EMINENCE DEVELOPMENT ANGLE). It was noted previously (Section 3.6.6) that there was variability in the determination of the centroid of various muscle origins and insertions. This variability resulted in inter-individual variation of muscle angles and therefore may account for the scatter of the plot of MEAN CONDYLAR LOADING ANGLE vs. Age (Figure 4.2.1).

4.3.2.2 Growth Changes in Muscle Moment Potentials

The moment potential of a muscle was a second variable examined for possible growth changes and the influence of any changes on the theoretical direction of condylar loading. The method of determining the moment potential of a muscle is illustrated in Figure 4.3.2.7. In the sagittal view, moment potentials are defined as the perpendicular distance from the line of muscle pull, to the intercondylar axis. In the basal view, the perpendicular distance is measured from the line of muscle action to the point of intersection between the intercondylar axis and the midsagittal plane. The moment potential is a measure of the capacity of a muscle to produce a moment (rotation) about a defined axis.

Tables 4.3.2.6 and 4.3.2.7 document the moment potentials of the temporalis and masseter muscles for the sagittal and basal anatomical planes. This study did not include an analysis of moment potentials for the frontal anatomical plane. The basal plane analysis provided a reasonable first approximation of the transverse changes in the moment potential of each muscle. It was not necessary to duplicate these measurements from the frontal plane view. Figures 4.3.2.8 and 4.3.2.9 (Tables 4.3.2.6, 4.3.2.7) plot the growth changes of the moment potentials for the sagittal and basal anatomical planes. Figure 4.3.2.8 (Sagittal Muscle Moment Potentials vs. Age) illustrates that, with age, there was a significant increase in the moment potential of the masseter muscle. There is a hint that, prior to three (3) years of age, some change may have occurred in the moment potential of the temporalis muscle. However, the evidence is not strong. Plots of moment potentials in the basal anatomical plane (Figure 4.3.2.9) of the temporalis (3 degrees of freedom, r = 0.91) and masseter muscle (3 degrees of freedom, r = 0.73) illustrate that increases occurred in both muscle moment potentials. The most accelerated growth changes, in both cases, seem to have been before the age of three (3) years.

Figure 4.3.2.8 (Sagittal Muscle Moment Potentials vs. Age) and 4.3.2.9 (Basal Muscle Moment Potentials vs. Age) show that growth changes occurred in moment potentials of the masseter and temporalis muscle. Sensitivity studies were conducted to test the influence of these growth changes on the directions of condylar loading. These studies examined single and multiple variable changes. Table 4.3.2.8 presents the results of single variable changes. The results indicate that for the sagittal plane, moment potentials of the temporalis and masseter muscles were theoretically the most influential variables affecting the direction of condylar loading. However, caution should be exercised in concluding that moment potential of the temporalis muscle is an important variable. It was noted from Figure 4.3.2.8 that only small growth changes were evident for sagittal moment potential of the temporalis muscle.

Table 4.3.2.9 documents the results when combinations of growth changes occurred in the moment potentials of the temporalis and masseter muscles. Rows "A" and "B" list results which represent changes in direction of condylar loading in consequence of theoretical growth changes in moment potentials. Changes in the sagittal moment potential of the masseter muscle (Table 4.3.2.8) resulted in changes in direction of condylar loading that are very similar to the results in Column "A" and "B" of Table 4.3.2.9. The results give evidence that growth changes in the geometry of the masseter muscle (of which sagittal moment potential is one indicator) are influential in determining the RETRUDED LOADING ANGLE (F.C.r).

Table 4.1.1 Raw Data of EMINENCE DEVELOPMENT ANGLE and Age

Specimen #	Eminence Development Angle (degrees)	Age (years)
001	33	3.0
002	37	7.0
003	36	4.0
004	20	1.3
005	34	4.0
006	25	1.75
007	40	13
008	20	1.4
009	27	0.75
010	31	4.0
011	26	3.0
012	17	1.3
013	27	1.0
014	25	3.5
015	33	6.5
016	10	3.25
017	9.5*	0 **
018	9.5*	0 **
019	9.5*	0 **
020	39	10.0
021	37	10.0
022	35	6.0
023	30	8.5
024	42	9.0
025	37	4.5
026	48	6.5
027	32	9.0
028	35	12.0
029	42	11.0
030	49	10.0
031	50	14.0
032	33	14.0
033	44	14.0
034	52	17.5
035	41	17.5
036	9	0
037	4	0.5
038	19	0.25
039	17	0.7
040	9	0.25
041	10	0.2
042	13	0.8
043	11	0.3
044	10	0.3
050	48	19.0
051	44	19.0
052	41	20.0
053	52	19.0
054	46	18.0

*averaged from Johns Hopkins Collection
**averaged from Hamann-Todd Collection Archives

Table 4.2.1 CONDYLAR LOADING ANGLE AND EMINENCE DEVELOPMENT ANGLE

Sp#- specimen number
F.C.p- PROTRUDED LOADING ANGLE(degrees)
Kp- RATIO ACTIVITY CONSTANT for the protruded biting position
F.C.r- RETRUDED LOADING ANGLE(degrees)
Kr- RATIO ACTIVITY CONSTANT for the retruded biting position
F.C.t- MEAN CONDYLAR LOADING ANGLE- Sum of the products of FC.p(Kp) + FC.r(Kr)
E.D.A.- EMINENCE DEVELOPMENT ANGLE (degrees)

Sp.#	Product of: F.C.p (Kp)=	Product of: F.C.r (Kr)=	F.C.t	E.D.A.
001	20.2 (.4) = 8.1	23.5 (.6) = 14.1	22.2	33
002	14.1 (.3) = 4.2	18.3 (.7) = 12.8	17.0	37
003	14.1 (.4) = 5.6	24.3 (.6) = 14.6	20.2	36
004	8.8 (.7) = 6.2	16.0 (.3) = 4.8	11.0	20
005	12.5 (.4) = 5.0	14.5 (.6) = 8.7	13.7	34
006	3.9 (.4) = 1.6	9.2 (.6) = 5.9	7.5	25
007	16.7 (.3) = 5.0	20.4 (.7) = 14.3	19.3	40
008	4.2 (.7) = 2.9	11.6 (.3) = 3.5	6.4	20
009	6.6 (.8) = 5.3	14 (.2) = 2.8	8.1	27
010	8.8 (.4) = 3.5	12.4 (.6) = 7.4	10.9	31
011	9.3 (.4) = 3.7	16.8 (.6) = 10.1	13.8	26
012	5.6 (.7) = 3.9	12.2 (.3) = 3.7	7.6	17
013	0.3 (.7) = 0.2	5.9 (.3) = 1.8	2.0	27
014	12.5 (.4) = 5.0	16.3 (.6) = 9.8	14.8	25
015	9.5 (.3) = 2.9	12.7 (.7) = 8.9	11.8	33
016	5.2 (.4) = 2.1	7.1 (.6) = 4.3	6.4	10
017	1.9 (.9) = 1.7	6.8 (.1) = 0.7	2.4	9.5*
018	4.2 (.9) = 3.8	10.0 (.1) = 1.0	4.8	9.5*
019	1.9 (.9) = 1.7	6.4 (.1) = 0.6	2.3	9.5*
020	14.9 (.3) = 4.5	19.7 (.7) = 14.8	19.3	39
021	12.1 (.3) = 3.6	14.4 (.7) = 10.1	13.7	37
022	10.3 (.3) = 3.1	15.5 (.7) = 10.9	14.0	35
023	15.3 (.3) = 4.6	19.0 (.7) = 13.3	17.9	30
024	25.6 (.3) = 7.7	29.6 (.7) = 20.7	28.4	42
025	10.3 (.4) = 4.1	29.1 (.6) = 17.5	21.6	37
026	22.3 (.3) = 6.7	25.7 (.7) = 18.0	24.7	48
027	20.9 (.3) = 6.3	22.9 (.7) = 16.0	22.3	32
028	32.0 (.3) = 9.6	33.4 (.7) = 23.4	33.0	35
029	24.6 (.3) = 7.4	28.1 (.7) = 19.7	27.1	42
030	23.2 (.3) = 7.0	26.5 (.7) = 18.6	25.6	49
031	24.7 (.3) = 7.4	26.3 (.7) = 18.4	25.8	50
032	12.3 (.3) = 3.7	15.5 (.7) = 10.9	14.6	33
033	25.7 (.3) = 7.7	28.8 (.7) = 20.2	27.9	44
034	21.6 (.3) = 6.5	25.9 (.7) = 18.1	24.6	52
035	25.9 (.3) = 7.8	29.1 (.7) = 20.4	28.2	41
050	25.9 (.3) = 7.8	38.8 (.7) = 27.2	35.0	48

Table 4.2.1 (continued)

Sp.#	Product of: F.C.p (Kp)=	Product of: F.C.r (Kr)=	F.C.t	E.D.A.
051	29.7 (.3) = 8.9	32.4 (.7) = 22.7	31.6	44
052	28.6 (.3) = 8.6	32.7 (.7) = 22.9	31.5	41
053	24.9 (.3) = 7.5	29.4 (.7) = 20.6	28.1	52
054	29.4 (.3) = 8.8	31.8 (.7) = 22.3	31.1	46

*averaged from Johns Hopkins Collection

Table 4.3.1.1 Changes in Direction of Condylar Loading Due to Anteroposterior Change in Mandibular Position

F.C.r- (RETRUDED LOADING ANGLE) Angle of loading for retruded biting position
F.C.p- (PROTRUDED LOADING ANGLE) Angle of loading for protruded biting position

Specimen #	Age (yrs.)	FC.r (degrees)	FC.p (degrees)	Difference (degrees)
001	3.0	23.5	20.2	3.3
002	7.0	18.3	14.1	4.2
003	4.0	24.3	14.1	10.2
004	1.3	16	8.8	7.2
005	4.0	14.5	12.5	2.0
006	1.75	9.2	3.9	5.3
007	13.0	20.4	16.7	3.7
008	1.4	11.6	4.2	7.4
009	0.75	14	6.6	7.4
010	4.0	12.4	8.8	3.6
011	3.0	16.8	9.3	7.5
012	1.3	12.2	5.6	6.6
013	1.0	5.9	0.3	5.7
014	3.5	16.3	12.5	3.8
015	6.5	12.7	9.5	3.2
016	3.25	7.1	5.2	1.9
017	0*	6.8	1.9	4.9
018	0*	10.0	4.2	5.8
019	0*	6.4	1.9	4.5
020	10.0	19.7	14.9	4.8
021	10.0	14.4	12.1	2.3
022	6.0	15.5	10.3	5.2
023	8.5	19.0	15.3	3.7
024	9.0	29.6	25.6	4.0
025	4.5	29.1	10.3	18.8
026	6.5	25.7	22.3	3.4
027	9.0	22.3	20.9	1.4
028	12.0	33.4	32.0	1.4
029	11.0	28.1	24.6	3.5
030	10.0	26.5	23.2	3.3
031	14.0	26.3	24.7	1.6
032	14.0	15.5	12.3	3.2
033	14.0	28.8	25.7	3.1
034	17.5	25.9	21.6	4.3
035	17.5	29.1	25.9	3.2
050	19.0	38.8	25.9	12.9
051	19.0	32.4	29.7	2.7
052	20.0	32.7	28.6	4.1
053	19.0	29.4	24.9	4.5
054	18.0	31.8	29.4	2.4

*averaged from Hamann-Todd Collection Archives

Table 4.3.2.1 Raw Data of Sagittal Muscle Angles

Spec.#	Age (yrs.)	Masseter Angle** (degrees)	Temporalis Angle** (degrees)	Lat. Pterygoid Angle** (degrees)
001	3.0	57	57	7
002	7.0	46	52	6
003	4.0	59	51	0
004	1.3	60	57	6
005	4.0	71	48	4
006	1.75	60	48	0
007	13.0	49	55	13
008	1.4	51	52	1
009	0.75	52	57	4
010	4.0	51	55	3
011	3.0	45	60	0
012	1.3	60	44	1
013	1.0	54	48	0
014	3.5	60	63	7
015	6.5	58	50	0
016	3.25	59	31	0
017	0*	50	51	0
018	0*	60	50	6
019	0*	75	35	0
020	10.0	50	52	0
021	10.0	63	43	9
022	6.0	56	49	3
023	8.5	50	51	12
024	9.0	49	62	20
025	4.5	54	59	8
026	6.5	58	54	6
027	9.0	59	51	18
028	12.0	59	54	8
029	11.0	53	59	27
030	10.0	58	52	4
031	14.0	53	52	7
032	14.0	64	40	4
033	14.0	58	52	0
034	17.5	57	56	5
035	17.5	47	58	5
050	19.0	62	61	8
051	19.0	47	62	4
052	20.0	51	57	15
053	19.0	47	60	12
054	18.0	55	55	11

*averaged from Hamann-Todd Collection Archives
**determined by intersection of line of muscle pull with occlusal plane (Figure 4.3.2.3)

Table 4.3.2.2 Raw Data of Frontal Muscle Angles

Spec .#	Age (yrs.)	Masseter Angle** (degrees)	Temporalis Angle** (degrees)	Lat. Pterygoid Angle** (degrees)
001	3.0	15	30	85
002	7.0	18	25	80
003	4.0	11	28	84
004	1.3	22	38	85
005	4.0	12	23	88
006	1.75	21	35	90
007	13.0	21	24	63
008	1.4	14	34	83
009	0.75	19	41	88
010	4.0	19	32	80
011	3.0	16	32	87
012	1.3	14	38	86
013	1.0	10	41	88
014	3.5	14	23	69
015	6.5	12	25	89
016	3.25	20	40	89
017	0*	15	38	90
018	0*	17	39	89
019	0*	22	34	87
020	10.0	18	30	86
021	10.0	18	18	76
022	6.0	19	23	87
023	8.5	12	28	83
024	9.0	16	20	78
025	4.5	21	29	78
026	6.5	18	32	88
027	9.0	19	24	85
028	12.0	9	29	87
029	11.0	8	18	71
030	10.0	14	22	90
031	14.0	16	20	89
032	14.0	12	18	86
033	14.0	17	19	90
034	17.5	9	22	88
035	17.5	15	17	71
050	19.0	12	18	90
051	19.0	13	22	84
052	20.0	14	17	84
053	19.0	13	17	86
054	18.0	14	19	76

*averaged from Hamann-Todd Collection Archives

**determined by a line of muscle action intersecting the midsagittal plane (Figure 4.3.2.3)

Table 4.3.2.3 Raw Data of Basal Muscle Angles

Spec.#	Age (yrs.)	Masseter Angle** (degrees)	Temporalis Angle** (degrees)	Lat. Pterygoid Angle** (degrees)
001	3.0	10	35	45
002	7.0	6	28	55
003	4.0	16	31	45
004	1.3	29	49	50
005	4.0	30	30	46
006	1.75	43	42	44
007	13.0	12	32	50
008	1.4	14	39	48
009	0.75	18	41	55
010	4.0	19	38	50
011	3.0	17	45	54
012	1.3	27	40	40
013	1.0	12	40	49
014	3.5	19	25	52
015	6.5	12	33	40
016	3.25	20	28	44
017	0*	24	48	51
018	0*	54	29	61
019	0*	28	28	73
020	10.0	10	42	35
021	10.0	25	20	46
022	6.0	14	28	54
023	8.5	10	31	48
024	9.0	10	32	40
025	4.5	18	29	47
026	6.5	24	38	42
027	9.0	26	19	48
028	12.0	9	36	60
029	11.0	7	27	60
030	10.0	18	22	47
031	14.0	14	23	49
032	14.0	17	18	37
033	14.0	7	23	50
034	17.5	5	28	48
035	17.5	22	22	35
050	19.0	18	31	56
051	19.0	9	32	51
052	20.0	10	28	45
053	19.0	12	34	42
054	18.0	19	30	56

*averaged from Hamann-Todd Collection Archives
**determined by a line of muscle action intersecting the midsagittal plane (Figure 4.3.2.3)

Table 4.3.2.4 Sensitivity Study: Growth Simulated Muscle Angle Changes and Effect on RETRUDED LOADING ANGLE (F.C.r)

Specimen #052- age 20 years
Specimen #033- age 14 years
Specimen #012- age 1.3 years
Specimen #009- age 0.75 years

"A"- Sagittal Masseter Angle change of either + 10 or -10 degrees

"B"- Basal Masseter Angle change of either + 10 or - 10 degrees

"C"- Sagittal Temporalis Angle change of either + 10 or - 10 degrees

"D"- Basal Temporalis Angle change of either + 10 or - 10 degrees

"E"- Frontal Temporalis Angle change of either + 10 or - 10 degrees

"F"- Multiple Muscle Angle Changes.

Spec.#052-	Spec.#033-
"A"(+10 degrees)	"A"(+10 degrees)
"B"(+10 degrees)	"B"(+10 degrees)
"C"(-10 degrees)	"C"(-10 degrees)
"D"(+10 degrees)	"D"(+10 degrees)
"E"(+10 degrees)	"E"(+10 degrees)
"F"(Changes "A"-"E")	"F"(Changes "A"-"E")

Spec.#009-	Spec.#012-
"A"(-10 degrees)	"A"(-10 degrees)
"B"(-10 degrees)	"B"(-10 degrees)
"C"(+10 degrees)	"C"(+10 degrees)
"D"(-10 degrees)	"D"(-10 degrees)
"E"(-10 degrees)	"E"(-10 degrees)
"F"(Changes "A"-"E")	"F"(Changes "A"-"E")

Spec.#	F.C.r	------(Degrees Change in F.C.r)------					
		"A"	"B"	"C"	"D"	"E"	"F"
052	32.7	-0.1	-0.2	-8.8*	0	0.5	-10.5
033	28.8	-0.5	-0.2	-7.6*	0.2	0	-9.4
009	14	2.7**	0	7.5*	-0.1	-0.3	9.9
012	12.2	2.7**	-0.1	9.2*	0.1	0	11.1

* Largest Changes
** Moderate Changes

Table 4.3.2.5 Sensitivity Studies: Changes in Muscle Angles and the Effect on Scatter in Figure 4.2 (MEAN CONDYLAR LOADING ANGLE vs. EMINENCE DEVELOPMENT ANGLE)

Specimens 052,028,050- tested in the retruded biting position
- the variable tested was an increase in Sagittal Temporalis Angle of +10 degrees.

Specimen 013- tested in the protruded biting position
- the variable tested was a decrease in the Sagittal Masseter Angle of -10 degrees.

Specimen#	F.C.(initial) (degrees)	F.C.(altered) (degrees)	Difference (degrees)
052	32.7 (FC.r)	23.9 (FC.r)	-8.8*
028	33.4 (FC.r)	24.7 (FC.r)	-8.7*
050	39.3 (FC.r)	30.0 (FC.r)	-9.3*
013	0.3 (FC.p)	5.7 (FC.p)	+5.4*

* Change which theoretically reduces scatter in Figure 4.2.1

Table 4.3.2.6 Raw Data of Sagittal Muscle Moment Potential

Spec.#	Age (yrs.)	Masseter Moment Arm(mm.)**	Temporalis Moment Arm(mm.)**
001	3.0	23	14
002	7.0	28	18
003	4.0	25	12
004	1.3	20	14
005	4.0	30	16
006	1.75	22	14
007	13.0	35	20
008	1.4	20	15
009	0.75	20	14
010	4.0	25	18
011	3.0	23	19
012	1.3	22	14
013	1.0	21	15
014	3.5	25	15
015	6.5	29	19
016	3.25	24	13
017	0*	12	11
018	0*	13	11
019	0*	12	8
020	10.0	34	20
021	10.0	30	16
022	6.0	30	17
023	8.5	29	18
024	9.0	30	18
025	4.5	30	13
026	6.5	32	15
027	9.0	33	16
028	12.0	33	15
029	11.0	28	14
030	10.0	36	16
031	14.0	34	15
032	14.0	35	15
033	14.0	36	14
034	17.5	34	19
035	17.5	35	17
050	19.0	33	14
051	19.0	37	18
052	20.0	38	17
053	19.0	34	17
054	18.0	32	16

*averaged from Hamann-Todd Collection Archives
**determined by the perpendicular distance between line of muscle action and the intercondylar axis (Figure 4.3.2.7)

Table 4.3.2.7 Raw Data of Basal Muscle Moment Potential

Specimen #	Age (yrs.)	Masseter Moment Arm(mm.)**	Temporalis Moment Arm(mm.)**
001	3.0	29	39
002	7.0	38	47
003	4.0	30	39
004	1.3	21	33
005	4.0	20	43
006	1.75	16	37
007	13.0	39	50
008	1.4	29	35
009	0.75	26	33
010	4.0	29	43
011	3.0	29	39
012	1.2	22	35
013	1.0	27	32
014	3.5	29	40
015	6.5	35	45
016	3.25	22	38
017	0*	16	21
018	0*	12	26
019	0*	16	24
020	10.0	38	49
021	10.0	27	42
022	6.0	33	44
023	8.5	37	45
024	9.0	34	42
025	4.5	30	41
026	6.5	25	42
027	9.0	28	47
028	12.0	39	44
029	11.0	40	44
030	10.0	30	46
031	14.0	32	43
032	14.0	34	47
033	14.0	41	46
034	17.5	41	46
035	17.5	34	51
050	19.0	41	52
051	19.0	45	53
052	20.0	45	54
053	19.0	37	47
054	18.0	37	48

*averaged from Hamann-Todd Collection Archives
**determined by the perpendicular distance between the line of muscle action and the intersection of the intercondylar axis and the midsagittal plane (Figure 4.3.2.7)

Table 4.3.2.8 Sensitivity Study: Single Variable Simulated Growth Changes of Masseter and Temporalis Muscle Moment Potential and Effects on RETRUDED LOADING ANGLE (F.C.r)

A.- Increase of Sagittal muscle moment potential by 5 mm.
B.- Decrease of Sagittal muscle moment potential by 5 mm.

Spec#	Established RETRUDED LOADING ANGLE (F.C.r)	------(Degrees Change in F.C.r)------							
		Sagittal Masseter Potential		Basal Masseter Potential		Sagittal Temp. Potential		Basal Temp. Potential	
		A.*	B.*	A.	B.	A.*	B.*	A.	B.
052	32.7	3.6	-4.3	0.1	0.1	-8.0	7.4	0.2	0.4
033	28.8	2.7	-3.8	0.5	0.6	-8.5	8.7	0	0
009	14	6.9	-11.4	0.3	0	-11.1	13.2	0	0
012	12.2	5.6	-8.2	0.2	0.4	-7.8	11.7	0	0.1

*Increases or Decreases in Muscle Moment Potentials which significantly alter the RETRUDED LOADING ANGLE (F.C.r)

Table 4.3.2.9 Sensitivity Study: Combined Variable, Simulated Growth Changes, of Masseter and Temporalis Muscle Moment Potentials: Effect on RETRUDED LOADING ANGLE (F.C.r)

A. Increase in moment potentials of the adductor muscles (+ 5 mm. sagittal moment potential of the masseter. + 5 mm. basal moment potential of the masseter and temporalis)

B. Decrease in moment potenitals of the adductor muscles (- 5 mm. sagittal moment potential of the masseter. - 5mm. basal moment potential of the masseter and temporalis)

Specimen #	Normal Loading Angle (Degrees) (retruded biting position)	Multivariable Changes of Temporalis and Masseter Muscle Moment Potentials (loading angle change in degrees)	
		A.	B.
052	32.7	3.5	-4.4
033	28.8	2.7	-3.5
009	14.0	7.4	-6.2
012	12.2	5.6	-8.6

EMINENCE DEVELOPMENT ANGLE

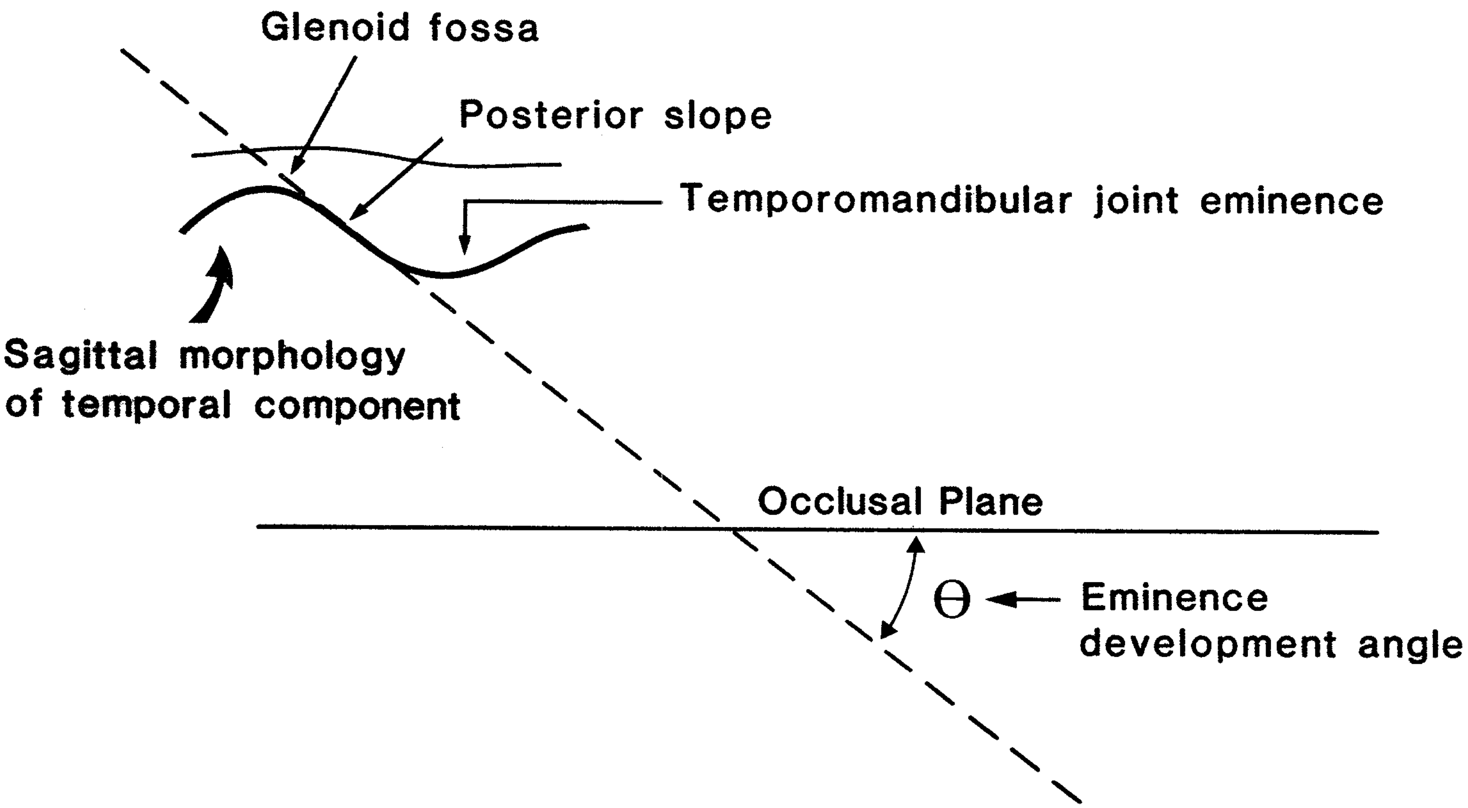


Figure 4.1.1 EMINENCE DEVELOPMENT ANGLE

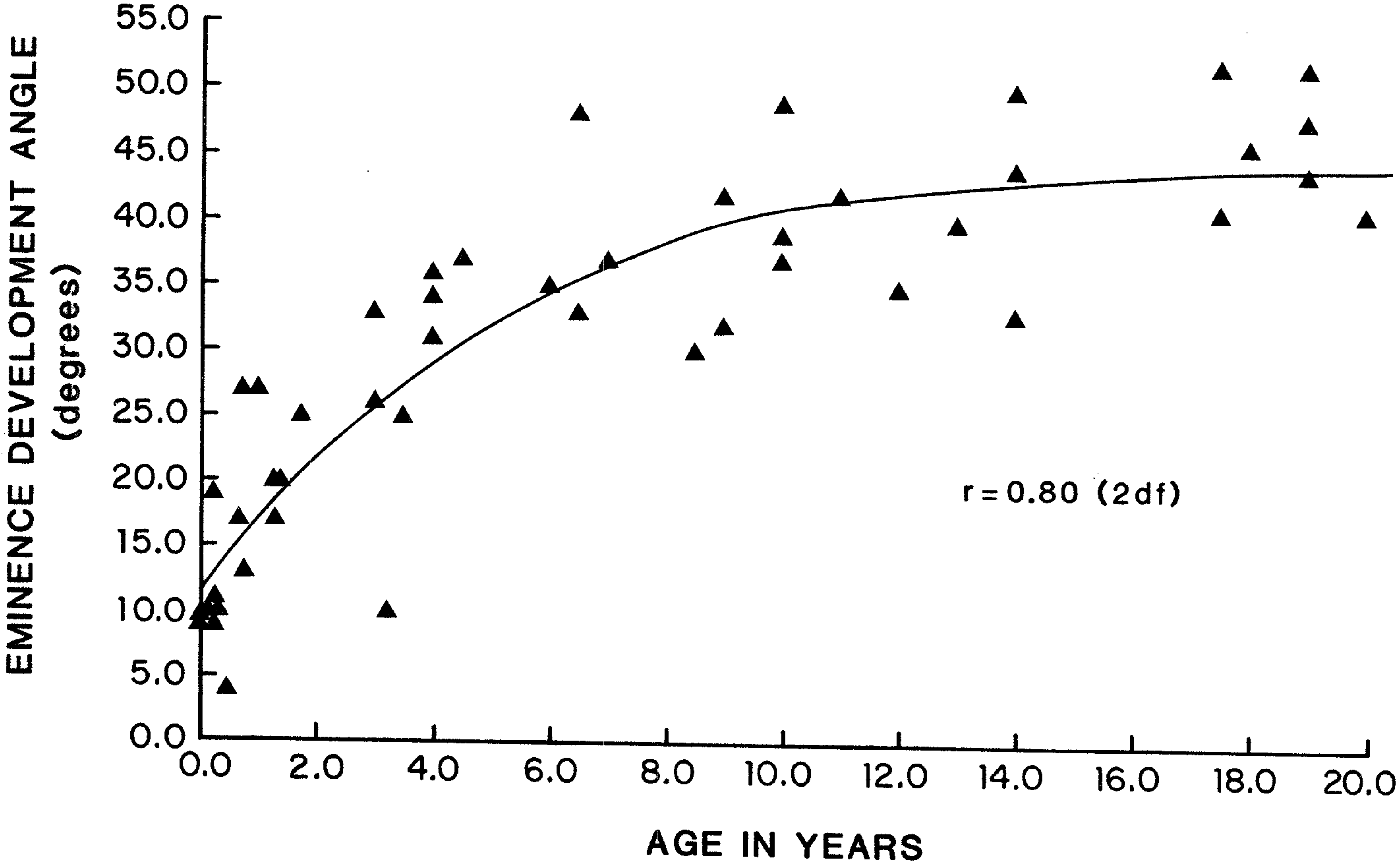


Figure 4.1.2 EMINENCE DEVELOPMENT ANGLE vs. age

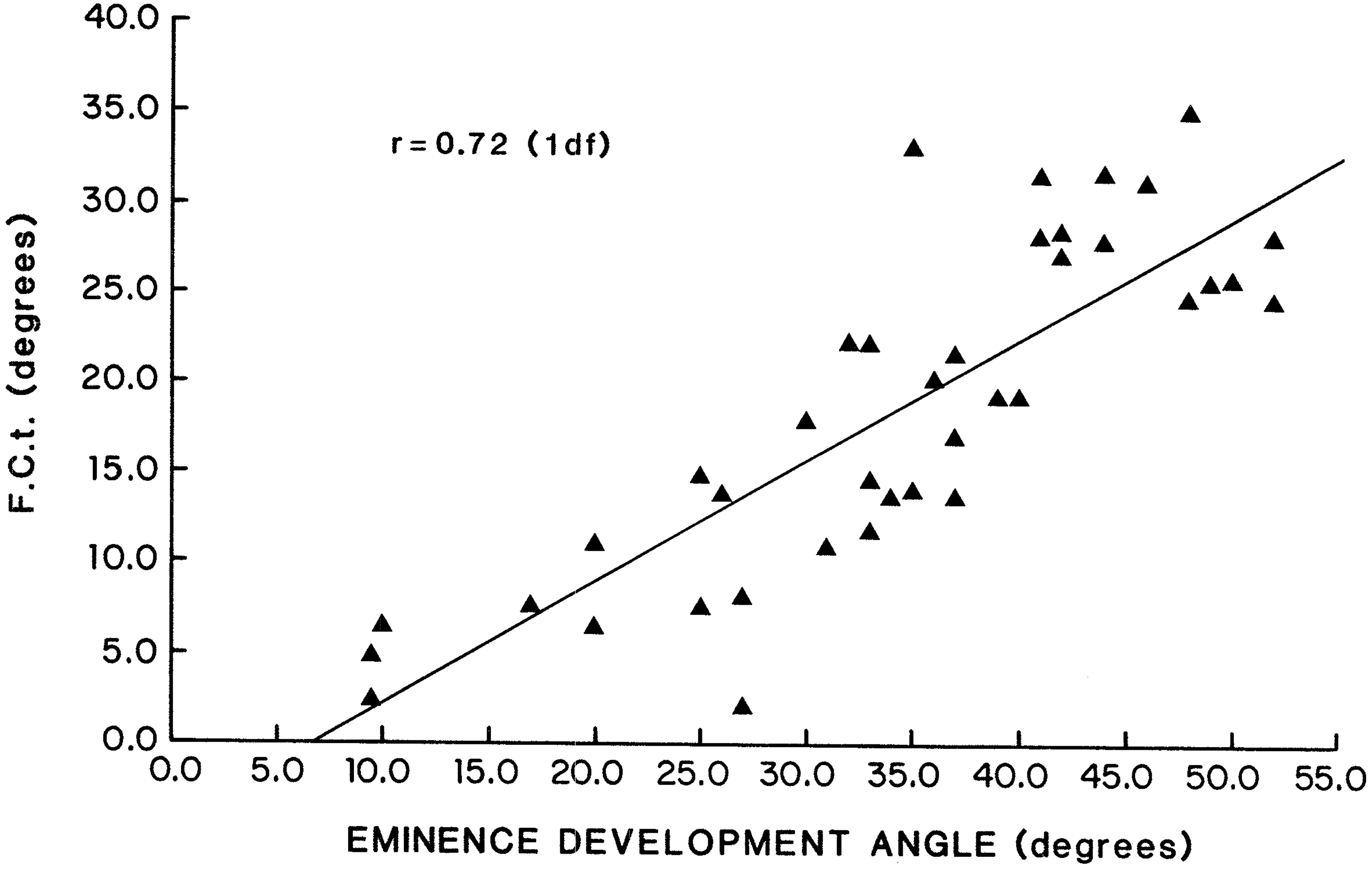


Figure 4.2.1 MEAN CONDYLAR LOADING ANGLE vs. EMINENCE DEVELOPMENT ANGLE

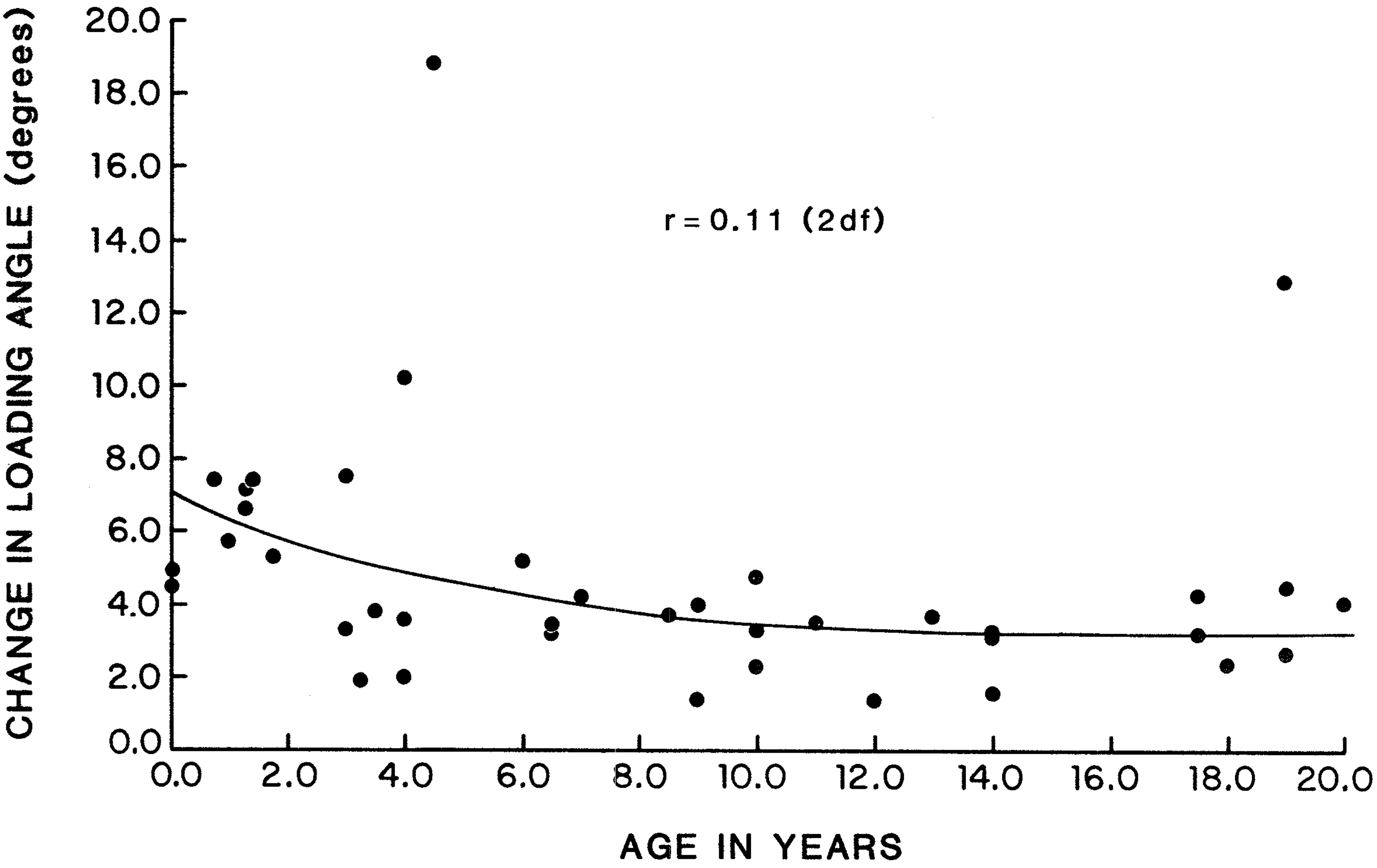


Figure 4.3.1.1 Loading angle change due to mandibular position change

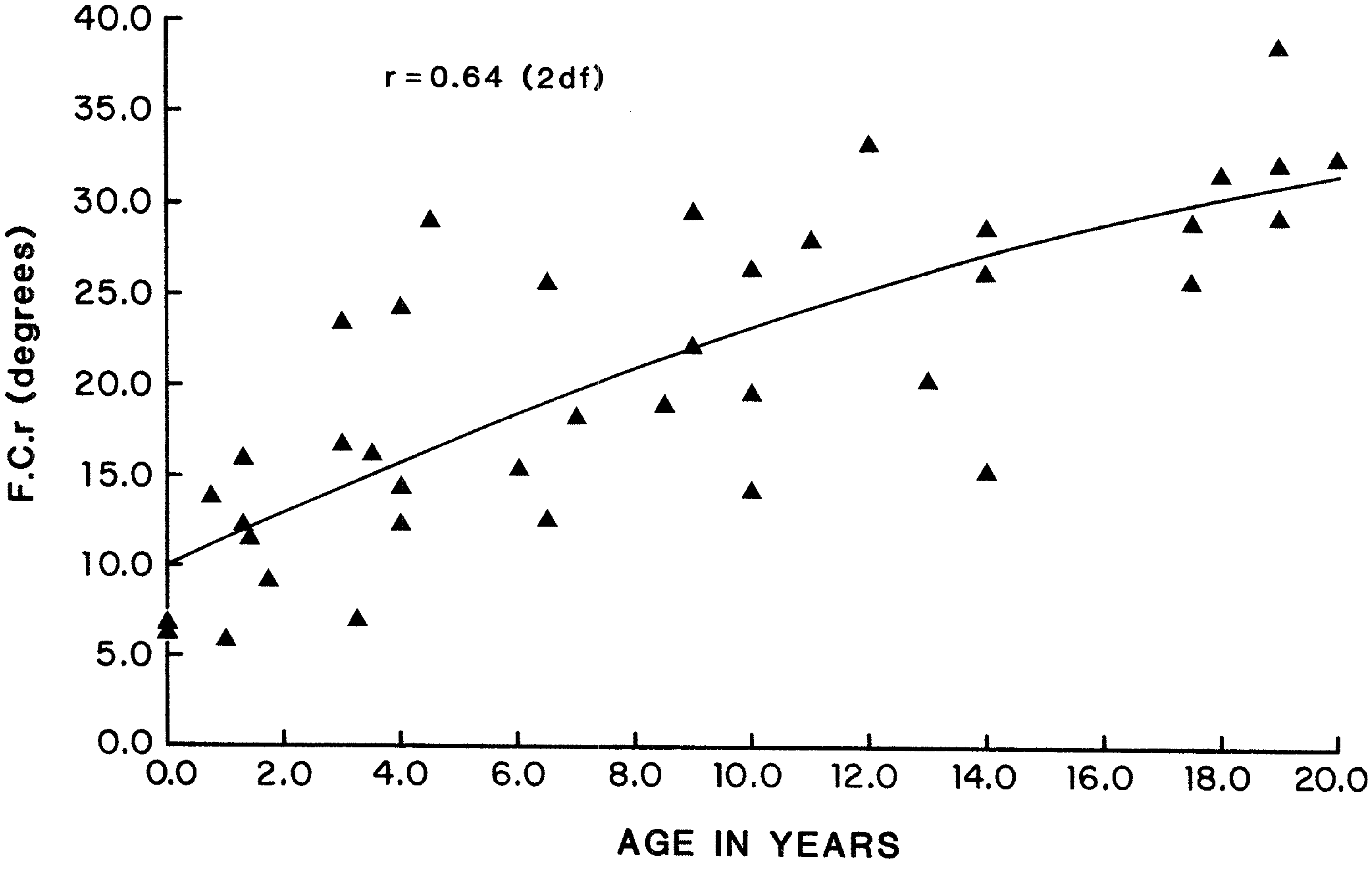


Figure 4.3.2.1 RETRUDED LOADING ANGLE vs. age

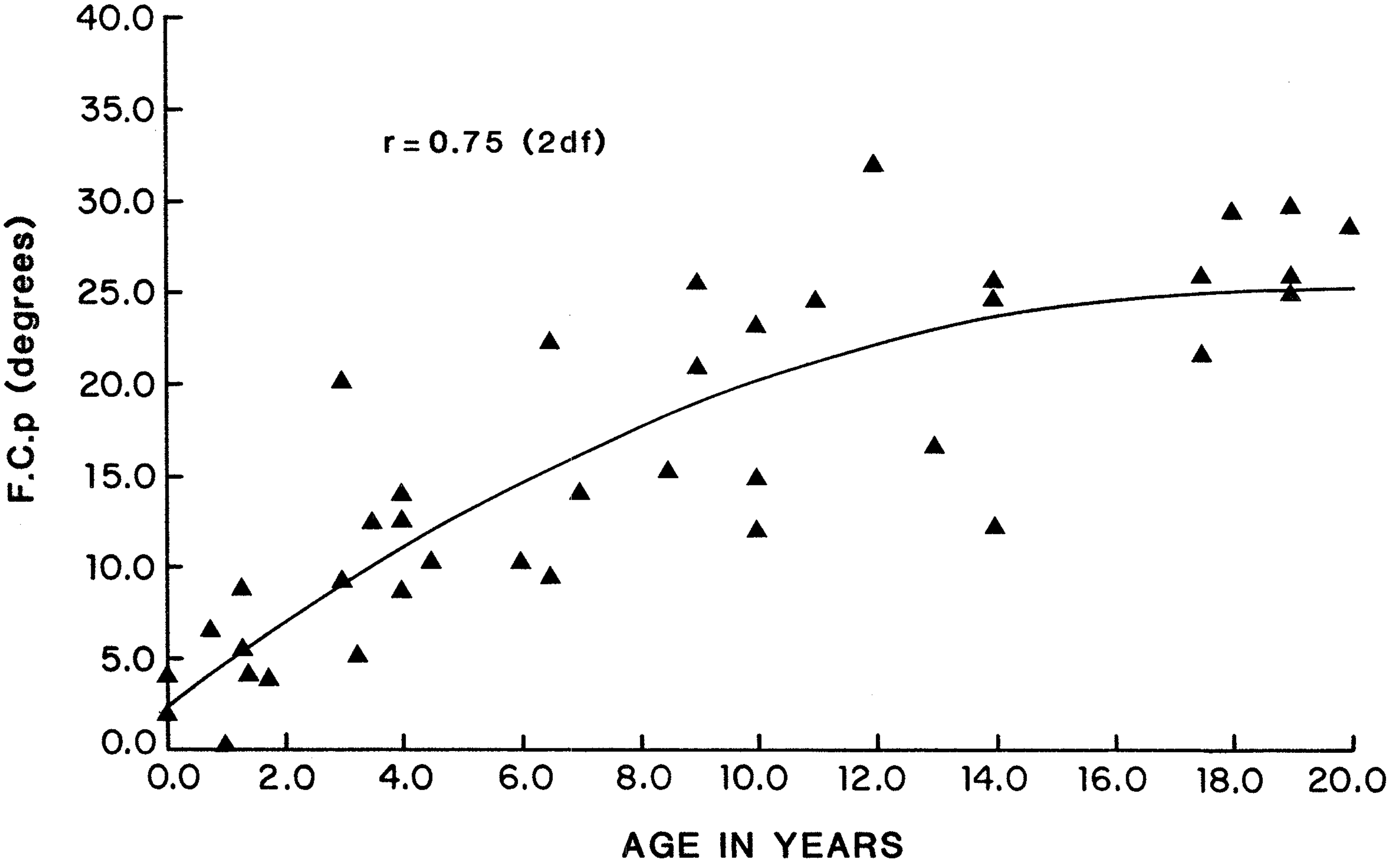


Figure 4.3.2.2 PROTRUDED LOADING ANGLE vs. age

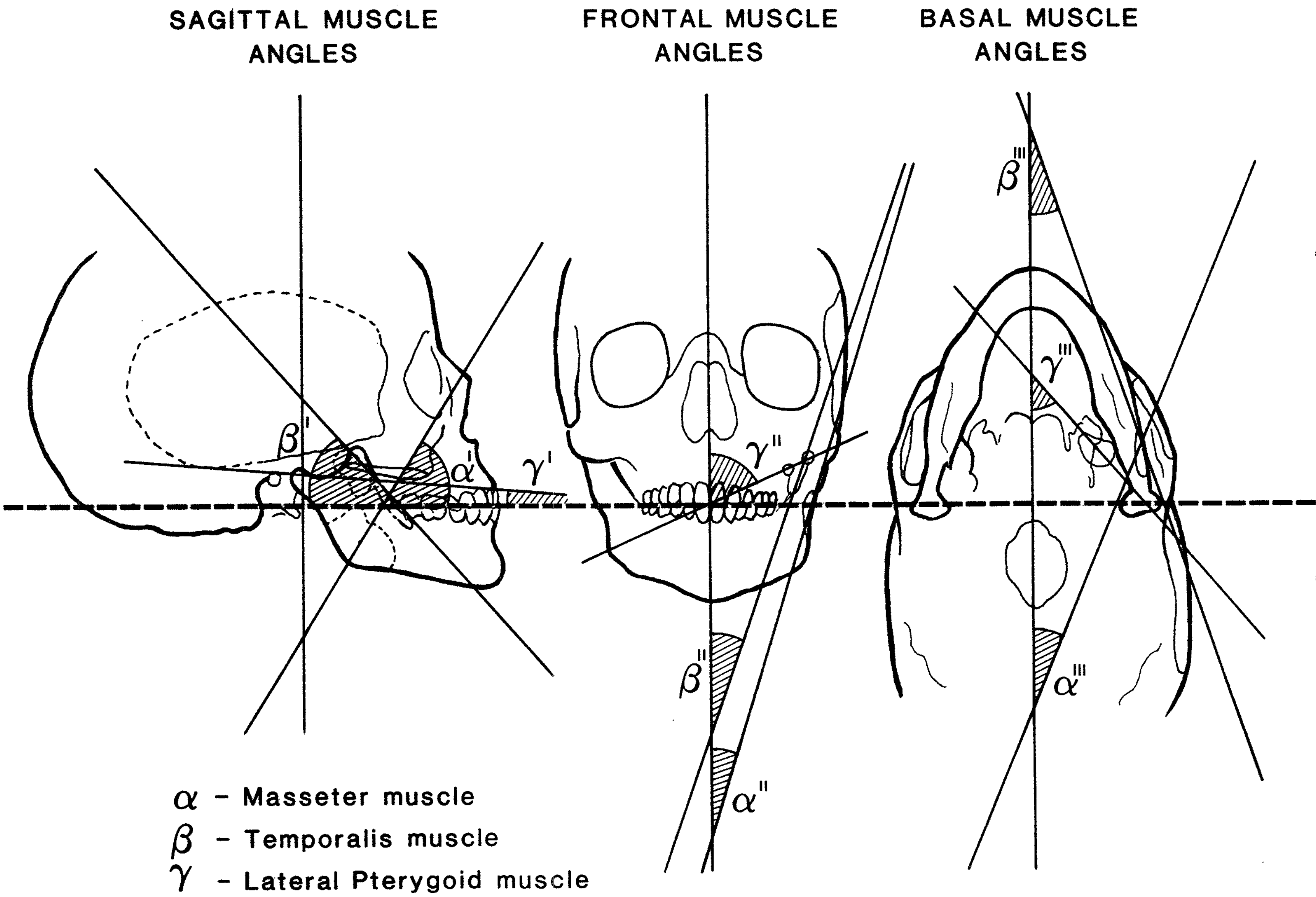


Figure 4.3.2.3 Muscle angles

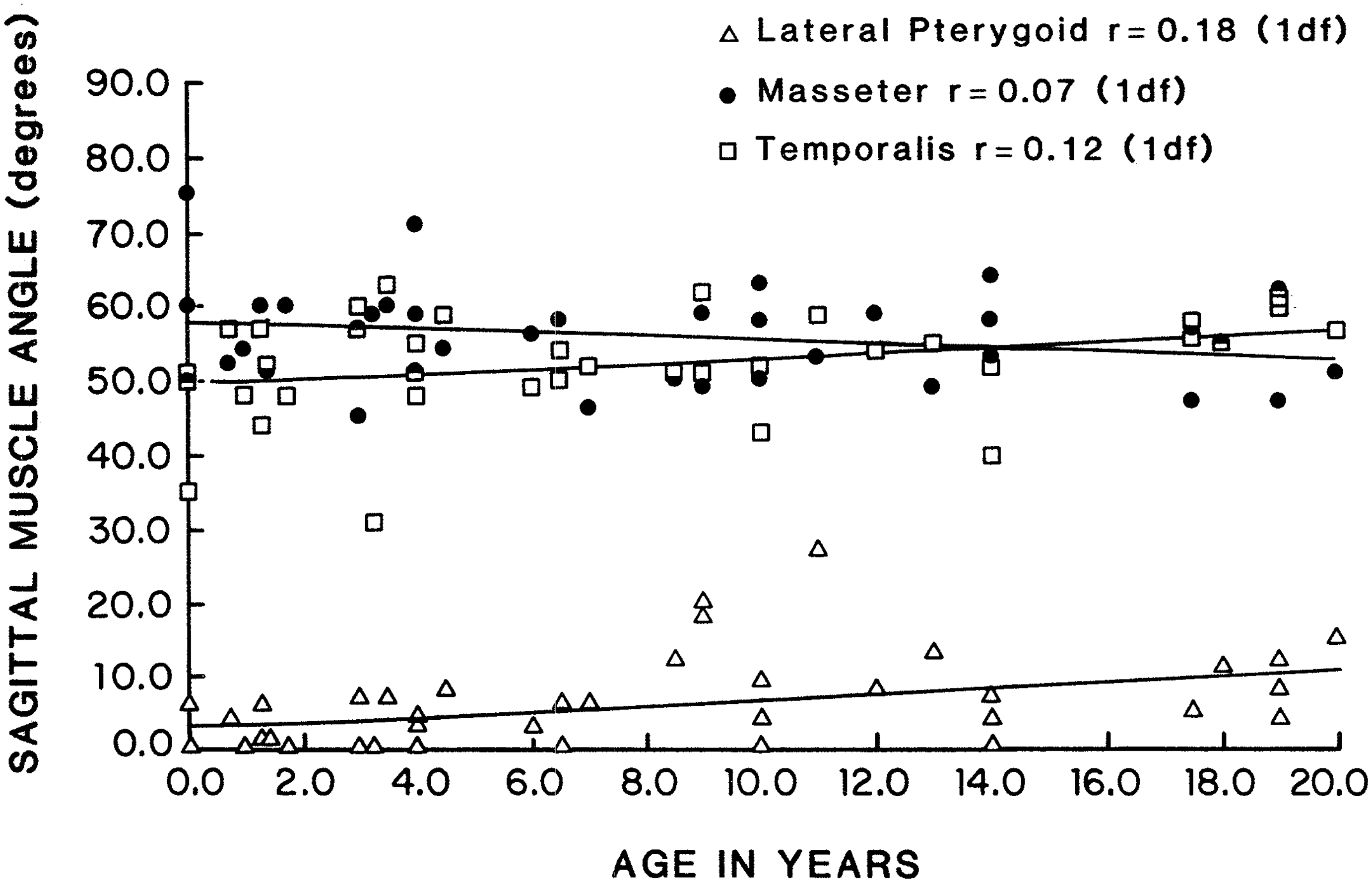


Figure 4.3.2.4 Sagittal muscle angle vs. age

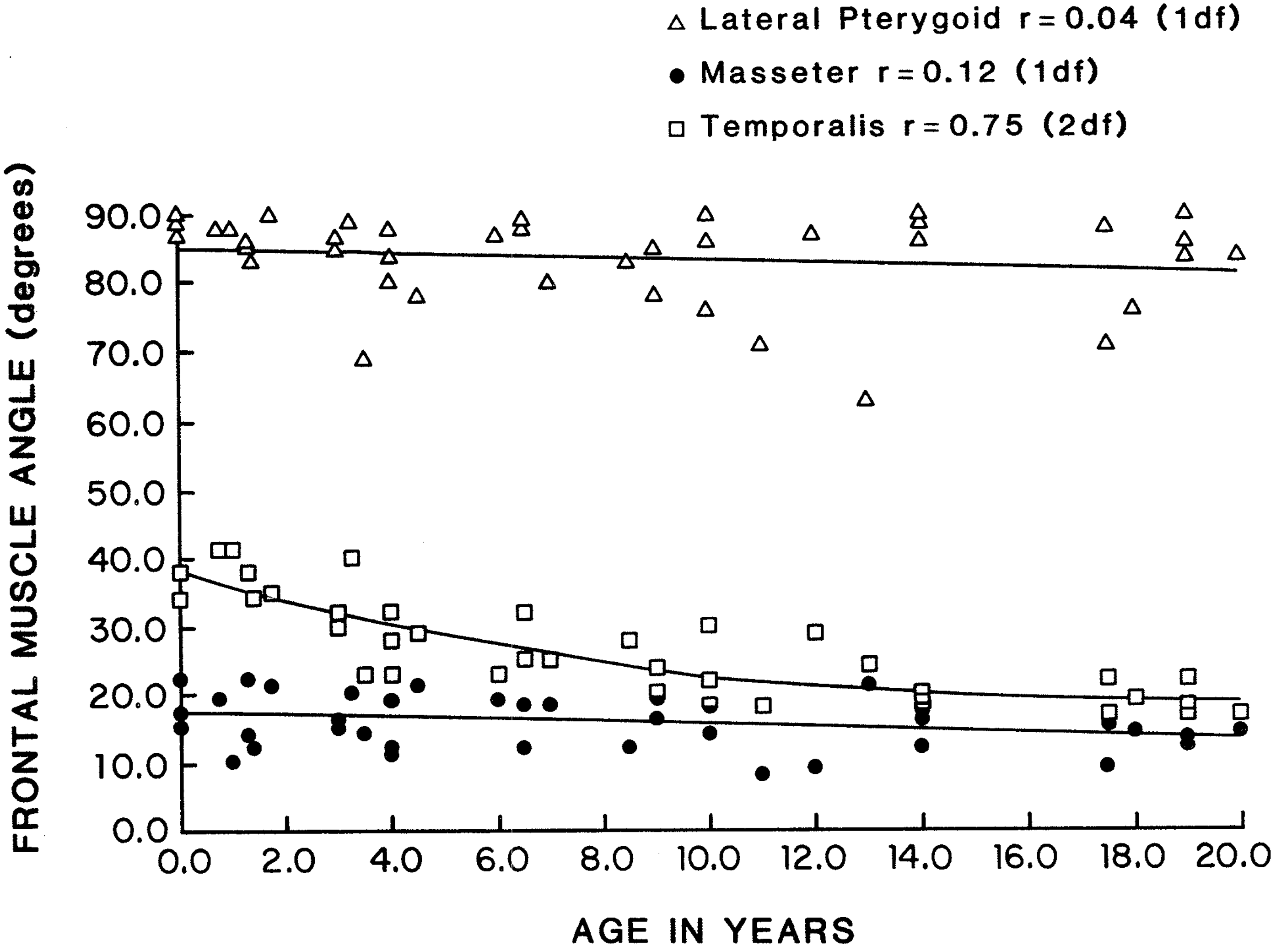


Figure 4.3.2.5 Frontal muscle angle vs. age

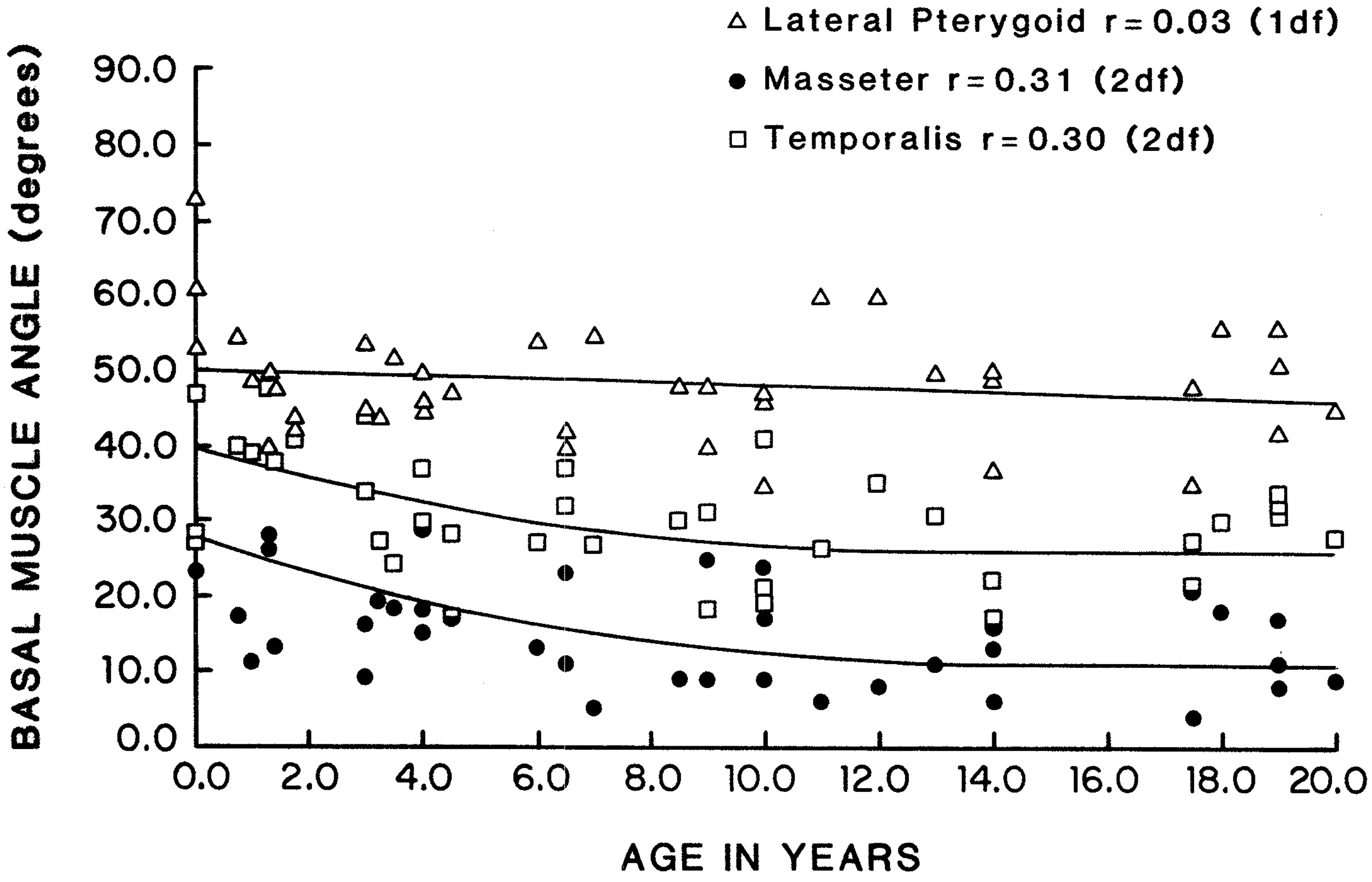


Figure 4.3.2.6 Basal muscle angle vs. age

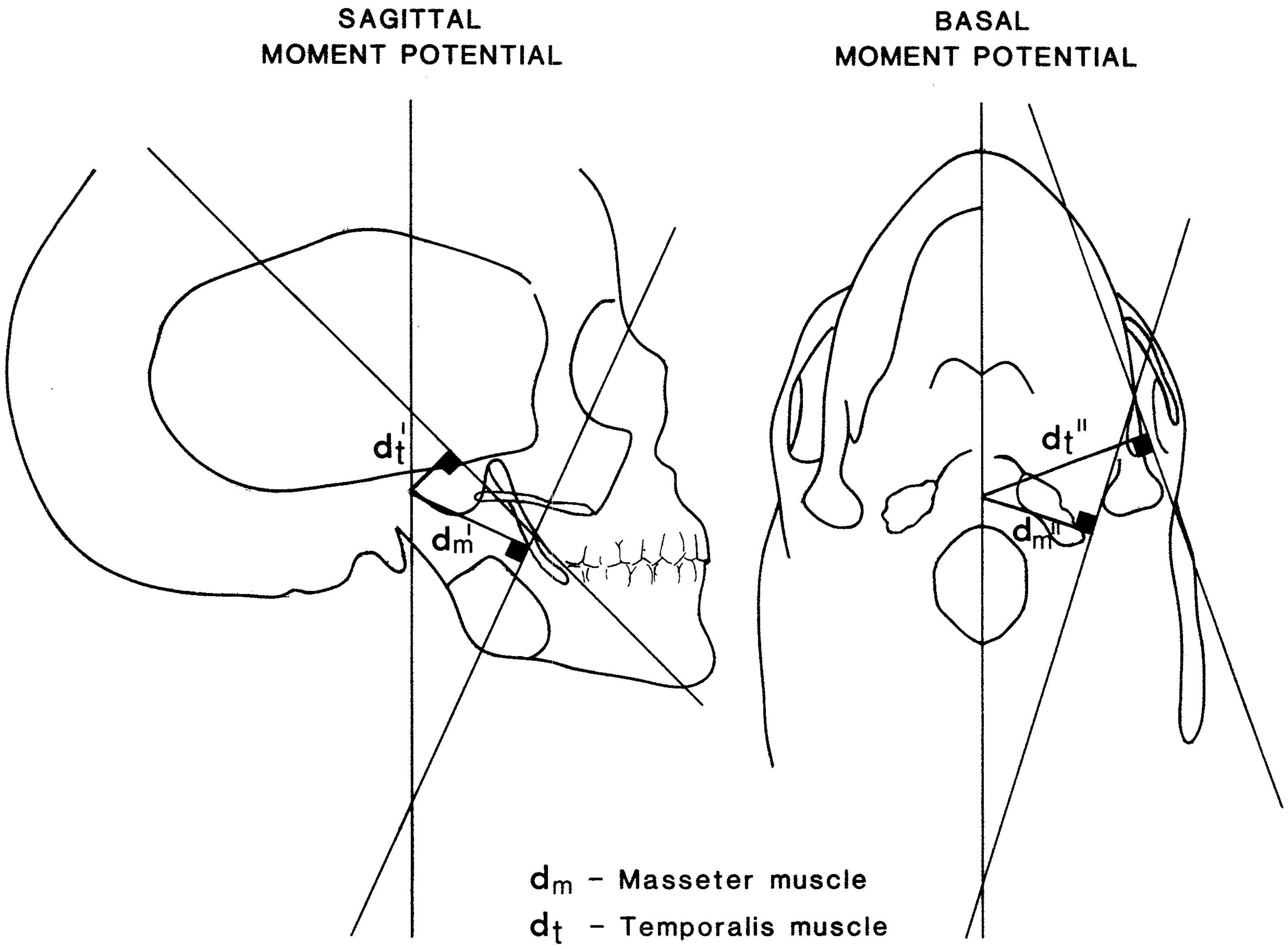


Figure 4.3.2.7 Muscle moment potentials

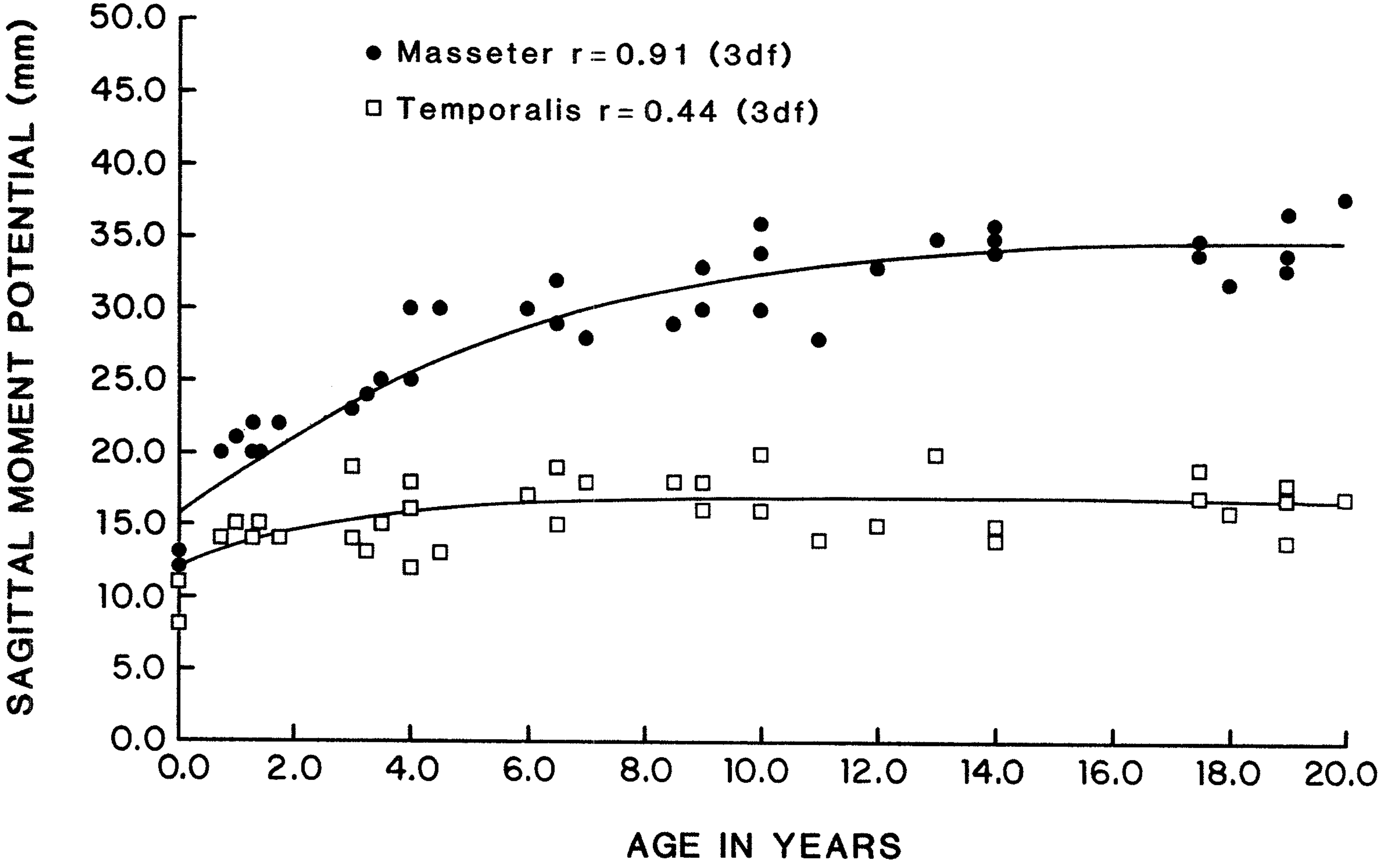


Figure 4.3.2.8 Sagittal muscle moment potential vs. age

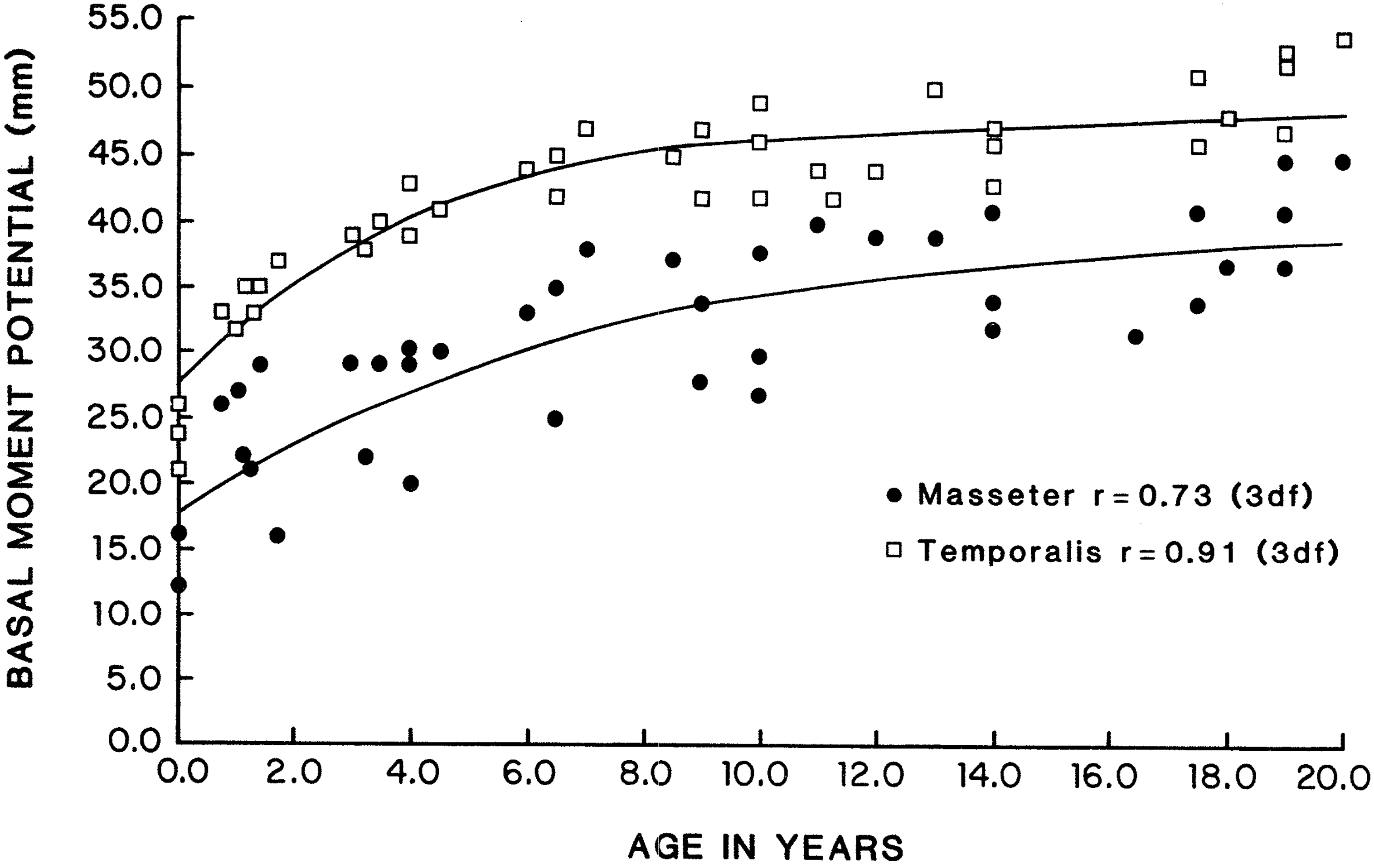


Figure 4.3.2.9 Basal muscle moment potential vs. age

Chapter 5

DISCUSSION

5.1 Introduction

The discussion has been divided into sections, with Section 5.2 beginning the discussion with comments concerning loading of the immature TMJ. Section 5.3 follows with a discussion of the significance of TMJ loading and the timing of eminence development, and presents a theoretical model of eminence development. This section also discusses the functional relationship between the direction of condylar loading and the angle of eminence development.

The numerical model used in this project had a primary objective of minimization of joint loading. Section 5.4 presents arguments to support the hypothesis that the neuromuscular system is designed to minimize joint loading. As well, this section raises some questions concerning the use of EMG data in determining the function of the muscles of mastication.

Section 5.5 concludes the discussion with an examination of the clinical implications of the results of the present work.

5.2 Loading of the Immature TMJ

Smith (1984) and Smith *et al*. (1986) established that, for most conditions of isometric biting, the adult TMJ was loaded. However, their results could not be extrapolated to determine whether the immature joint was loaded, since the geometry of the biting apparatus of the immature human is different from that of the adult. The results of the present study established that the immature TMJ must be loaded during isometric biting, in order to satisfy static equilibrium. It is important to note that, though the loads on the immature joint may be greater than those calculated, they cannot be less if the mandible is to be held in mechanical equilibrium. This conclusion is based on the calculations of the numerical model, in which the objective function was to attempt to satisfy static equilibrium without condylar loading. In no circumstances was it possible to solve static equilibrium without both condyles bearing some load.

Authors such as Steinhardt (1958) suggested that although it was likely that the mature TMJ was loaded, it was not possible for the immature TMJ to be loaded. His argument was based on the belief that mechanical loads on growing tissue would jeopardize normal development of the structure. The results of the present work indicated that under all the conditions tested, the immature joint was loaded. Later in the discussion (Section 5.3.2), it will be argued that the loading of the immature TMJ is essential for the development of normal joint morphology, and a theoretical model will be presented to offer an explanation of the relationship between immature joint loading and eminence development.

5.3 Development of the Immature TMJ Eminence

5.3.1 The Quantitative Evidence of Eminence Development

Evidence provided by this study indicates that eminence development begins before birth (the best-fit polynomial intersected the ordinate axis above the origin in Figure 4.1.1). The maximum velocity of eminence development occurred prior to three (3) years of age. Data from this study indicate that there is only a small degree of variability in the timing of growth and in the amount of eminence growth prior to three years of age. Previously cited authors (Angel, 1948; Ricketts, 1950; Taylor et al., 1972) reported inconclusive results concerning the relationship between craniofacial form and eminence development. For example, Ricketts (1950) attempted to determine the relationship between occlusal plane and eminence slope. However, Ricketts did not have the benefit of studying individuals younger than seven (7) years of age. In the present study it was possible to establish the velocity of eminence development primarily because the sample included individuals whose ages ranged from birth to eighteen (18) years.

The results of the present study indicated that the maximum variability in the development of the eminence (measured by the EMINENCE DEVELOPMENT ANGLE) was approximately twenty (20) degrees. It was noted in Section 3.6.4 that measurements of EMINENCE DEVELOPMENT ANGLE had an error of approximately plus or minus two and one-half (+/-

2.5) degrees. It may be that errors in determining EMINENCE DEVELOPMENT ANGLE might have contributed to the scatter of Figure 4.2.1. As well, the variability of EMINENCE DEVELOPMENT ANGLE between individuals may be due to differences in the anteroposterior position of the developing eminence. If the eminence develops slightly more anteriorly than usual, the final slope of the mature eminence would be reduced. It is suggested that the anteroposterior position of eminence development is dependent on the amount of protrusion a child must produce in order to accomplish tasks of suckling and anterior biting. The variability in the amount of mandibular protrusion during the period of eminence development may account for differences in the slopes of the eminence (Section 5.3.2 for more complete discussion).

The results of this study show that there was only a small amount of intersubject variability in eminence slope development when that development was referenced to the occlusal plane. In this investigation, analysis of eminence development was made relative to occlusal plane rather than to more traditional anthropomorphic planes. The biting apparatus is a mechanical system, and it is appropriate to establish the geometric relationship of the eminence relative to a reference plane which has functional significance. It does not seem appropriate to describe eminence development relative to a functionally unrelated reference plane such as the Frankfort Horizontal Plane. The results of the present study suggest that analysis of the mechanics of the biting apparatus should be made relative to occlusal plane, rather than the reference planes of Frankfort Horizontal or Sella-Nasion.

5.3.2 A Theoretical Model of Eminence Development

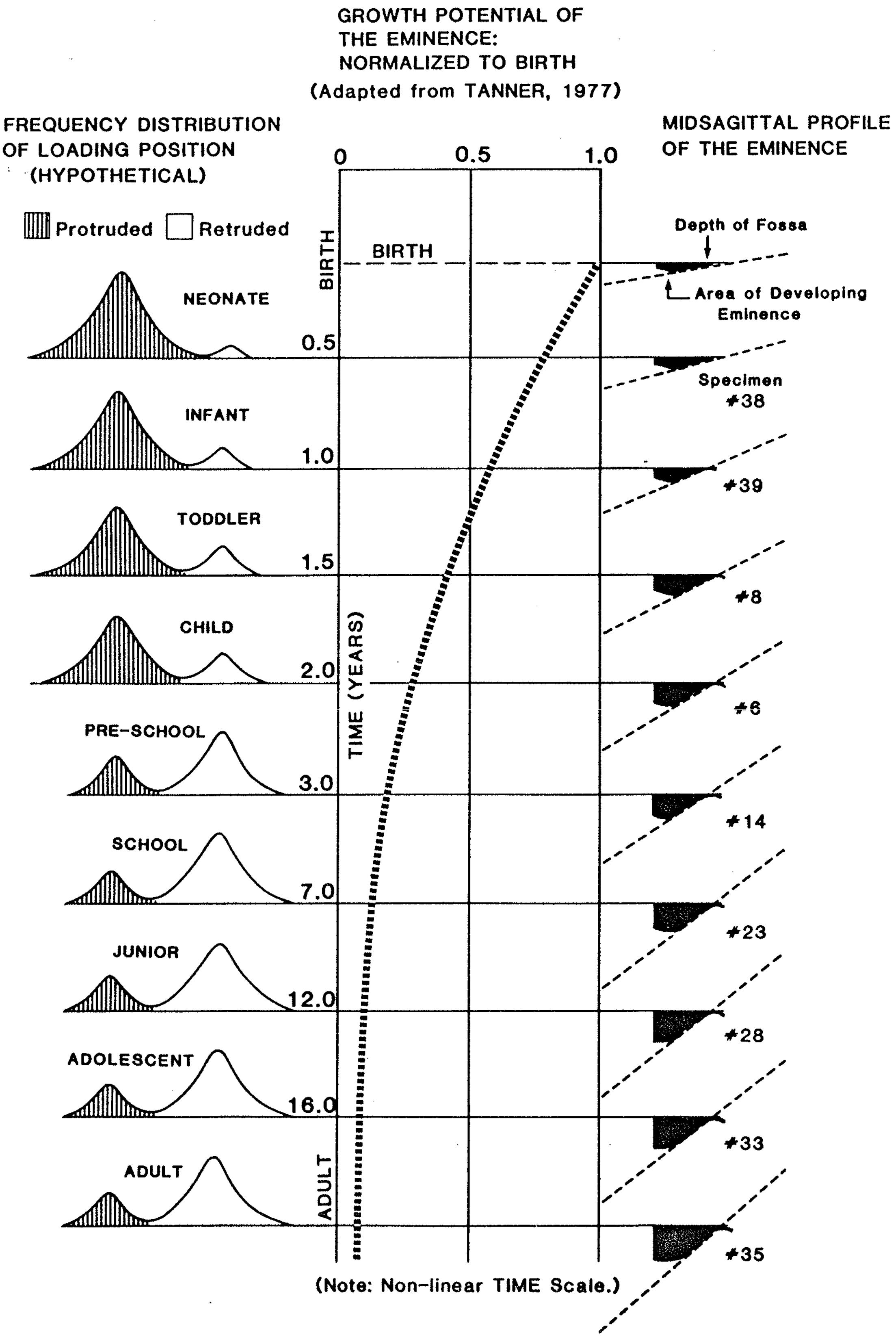
The loading of the immature TMJ occurs during a dramatic period of human development. This is a period of very rapid growth, the magnitude of which does not occur at any other time in the postnatal life of an individual (Tanner, 1977). During this period of intense growth, there is a large population of mesenchymal cells, which are sensitive to local environmental factors such as mechanical loading. The hypothesis is that strategic positioning of local mechanical loading of the condyle on the immature temporal component helps to orchestrate the development of the TMJ eminence from the mesenchymal cell population. The first step in validating this hypothesis was to show that the immature TMJ is loaded.

Figure 5.3.2.1 is presented to illustrate the suggested mechanism governing the relationship between early protrusive loading and the development of the TMJ eminence. It should be noted that the frequency distribution of loading in Figure 5.3.2.1 is hypothetical, but that the growth potential curve and the eminence profiles are factual. In the neonate, a protrusive position of condylar loading occurs when the growth potential of the eminence is high. The result is the early development of the secondary cartilage which forms the infant's eminence. Note that, in the adolescent, the frequency distribution of loading is predominantly in the retruded position. A significant growth response does not occur because the growth potential of the eminence has reduced. The potential for growth of the eminence is dependent on the mesenchymal cell population, which has been rapidly depleted during the early years of growth. This is why the eminence does not continue to grow throughout life.

Establishing that the immature joint is loaded, and that the loading occurs during a period of remarkable growth of the rest of the head, provides a basis for explaining why the TMJ eminence develops very rapidly after birth (Figure 4.1.1). The results of this study support the hypothesis that the mechanical force of condylar loading on the periosteum of membrane bone is a mechanism which initiates the development of the secondary cartilage that forms the eminence. The pressure of mechanical stress may not act directly, but more likely produces a temporary ischaemia which induces the chondrogenesis (Hall, 1970). The absence of condylar loading is the probable reason for the lack of eminence development in cases of congenital absence of condyles (Kazanjian, 1940), or as a result of surgical removal of the condyles (Sarnat, 1957; Sorensen and Laskin, 1975).

Ham (1930) described the osteogenic cell as having potential for either bone or cartilage formation, and low vascularity seemed to be a determining factor in the

Figure 5.3.2.1 The relationship between eminence growth and TMJ loading



initiation of chondrogenesis. Pritchard and Ruzicka (1950) indicated that adequate blood supply favoured differentiation of osteoblasts whereas certain types of mechanical stress favoured differentiation of chondroblasts. Their results support the hypothesis that the mechanical loading of the TMJ in the infant could initiate the differentiation of mesenchymal cells to a chondrogenic cell population. Once the cell line is differentiated, a secondary cartilage develops which ultimately gives rise to the joint eminence.

5.3.3 The Relationship Between Eminence Development and Direction of Condylar Loading

The directions of loading of the condyle were calculated using the numerical model. The relationship shown in Figure 4.2.1 (EMINENCE DEVELOPMENT ANGLE vs. MEAN CONDYLAR LOADING ANGLE, F.C.t) is supportive of the hypothesis that eminence development and direction of condylar loading are functionally related. However, the slope of the best fit straight line of Figure 4.2.1 is approximately 0.5, which superficially is less than might be expected. A slope of 1.0 would indicate that there is an equal increase in eminence development for every degree of increase in the direction of condylar loading, and the direction of condylar loading is perpendicular to the slope of the eminence. Further consideration, however, reveals that although EMINENCE DEVELOPMENT ANGLE and the MEAN CONDYLAR LOADING ANGLE were helpful in showing that a relationship exists between eminence development and direction of condylar loading, neither of these geometric quantities exist in the physiology of the TMJ. For example, it is most likely that the often loaded areas of the eminence are at the base of the eminence and the crest of the eminence. These regions are not represented well by the EMINENCE DEVELOPMENT ANGLE. Hence, it is inappropriate to draw a direct, physiological conclusion from the relationship between EMINENCE DEVELOPMENT ANGLE and MEAN CONDYLAR LOADING ANGLE. The fact that they do show a strong correlation justifies their inclusion here, in support of the general hypothesis of the effect of loading on eminence growth. The present correlation would suggest that EMINENCE DEVELOPMENT ANGLE increases more quickly than the MEAN CONDYLAR LOADING ANGLE.

Results from the model show that changes in the direction of condylar loading are influenced by the functional position of the mandible (Figure 4.3.1.1) and by growth changes in the dimensions of the biting apparatus (Figures 4.3.2.1, 4.3.2.2). It has been assumed that, in the very youngest individual, the functional position of the mandible is primarily one of protrusion. The calculations of the numerical model indicate that, in this protruded biting position, the direction of condylar loading remains primarily perpendicular to the developing eminence. As the child matures, the functional position of the mandible changes to accommodate molar biting. In this more retruded biting position, the direction of condylar loading is more oblique, but fortunately the developed eminence has adequately formed to ensure that perpendicular loading of the condyle on the eminence is possible. Thus, the results indicate that the loading of the eminence remains perpendicular to the eminence surface throughout the growth years.

The perpendicular loading of joint surfaces supports the hypothesis of minimization of joint loading. If non-perpendicular loading were to occur, there would be the necessity to adjust muscle forces to prevent the condyle from translating over the virtually frictionless articular surface. An adjustment in muscle forces would most likely increase condylar loading (The numerical model calculates minimal condylar load. Any change in mix of muscle forces will result in the condyles bearing a larger load, in order to satisfy static equilibrium). As a result, the higher condylar loads might exceed the capacity of the cartilage to maintain physiological integrity, and a condition conducive to osteoarthritis would be established. It would seem to be healthier for the articular surface to maintain minimal loading of the condyle by ensuring perpendicular loading. The results of this study indicate that this is the case, even during the dynamic years of growth and development.

The hypothesis of perpendicular loading of the TMJ structures is consistent with a fundamental orthopaedic principle of synovial joints, namely, the minimization of loading per unit area of articular surface. This principle is often quoted in the orthopaedic literature as an underlying theme in the design of synovial joints (Goodfellow and O'Conner, 1980; Goodfellow and Mitsou, 1977).

The final form of growing joints depends upon functional criteria of perpendicular loading; thus neuromuscular control is a potent determinant in ordered skeletal development. Goodfellow and co-workers have stated that there is evidence that the precise shapes of the articular surfaces are very dependent on the continued transmission of compressive stresses. Neuromuscular control of the muscles of mastication will determine the magnitude and frequency of compressive stresses in the joint. The argument of Goodfellow and co-workers suggests that the mechanism which controls the shapes of joint surfaces is pressure sensitive. In the TMJ, it is the ability to produce secondary cartilage under conditions of compressive load which determines the shape of the articulating surfaces. The ability to develop the shape of articulating surfaces enables the TMJ to maintain the orthopaedic principle of perpendicular loading during periods of extensive skeletal growth.

5.4 **Neuromuscular Control of Joint Loading**

5.4.1 Evidence for Minimization of Loading as an Objective for Neuromuscular Organization

Smith (1984) and Smith *et al.* (1986) suggest that minimization of joint loading may be the underlying objective of neuromuscular control during isometric biting. The numerical model calculations of muscle forces for given biting conditions compare favourably with in vivo data for the same biting conditions (McLachlan and McCall, personal communication). Unpublished results of their EMG experiments in adults suggest that organization of the neuromuscular system maintains minimal loading of the adult TMJ during isometric biting. As well, their data indicate that the muscle forces are remarkably linear for a wide range of bite force magnitudes. This is contrary to Hylander (1985), who reported that the working/balancing ratios of muscle EMG's can shift from 2.0 to 1.5 when macaques bite on one first molar. It was be noted that Hylander's conclusions are based on evidence from EMG data during isometric biting and motion (isotonic EMG). There should be caution in the use of motion EMG to interpret joint mechanics without the aid of a theoretical model to help analyze the components (motion and isometric force requirements) of an EMG signal.

It would be desirable to test whether TMJ loading control in children is similar to the loading control observed in adults. The numerical model used in this study examined isometric biting conditions for immature individuals. EMG data are required to test the numerical model calculations of muscle forces, but EMG data of isometric biting in young children have not been reported. Ahlgren (1966) reported the results an EMG study of mastication in children of ages nine (9) to fourteen (14) years. He indicated that ipsilateral EMG values were larger than contralateral values for the temporalis and masseter muscles, which is in general agreement with the numerical model. Differences in the relative amounts of ipsilateral and contralateral muscle activity measured by Ahlgren and from the calculations of the numerical model are probably due to the fact that this ratio is dependent upon the geometry of each individual subject.

The minimal loading hypothesis is supported by the current knowledge of the physiology of the articulating tissues. For example, a reduction of the magnitude of loading of the articular surfaces would reduce the likelihood of articular surface damage. This means that there would be less need for the articulating surface to maintain a significant repair potential. The cell kinetic studies of Folke and Stallard (1966) and Oberg (1964) indicate that there is limited capacity for repair of the surface layer of the articulating tissues. Thilander (1964) reported that the TMJ disc had reduced vascularity, which compromises the potential for repair of damage to the disc. The route of cartilage nutrition appears to be by fluid imbibition during the unloading of the tissues (Ekholm, 1955; Turek, 1984), and heavy loading over a long duration would compromise the nutrition of the articular tissues.

The phenomenon of fatigue failure of materials also supports the minimal loading hypothesis. Since cartilage is subject to cyclic loading, the tissue is capable of fatigue failure (Turek, 1984). By reducing the magnitude of condylar loading, the likelihood of fatigue failure is reduced. If the load during each cycle is sufficiently low and of brief duration there is elastic deformation of the cartilage with a short recovery period.

An increase in the magnitude of the load and the length of time under load introduces a time-dependent creep phase in cartilage. This phase is characterized by fluid flow out of the area of compression and is responsible for a slow recovery phase of cartilage during unloading (Myers and Mow, 1983; Turek, 1984). It is during this unloading phase that cartilage receives its nutrition by the reimbibition of fluid (Ekholm, 1955; Myers and Mow, 1983; Turek, 1984). However, reimbibition takes time, and more time is required when the magnitude of loading is increased. If a second load is applied before the cartilage matrix has fully reimbibed with fluid, it is possible for deformations of consecutive loadings to summate. The loss of matrix fluid reduces the ability of cartilage to distribute stress. Consequently, abnormal tensile stress is inflicted on the cartilage's collagen matrix and may lead to structural damage of collagen fibers.

There are indications that periodontal receptor input into the neuromuscular system is well suited for the control of condylar loading. The results of Lund and Lamarre (1973), and van Steenburghe and de Vries (1978) suggest that larger bite forces are enhanced in the molar region, and inhibited in the incisor region. It is possible, as well, that mechanoreceptors in the sutures of the premaxilla, may contribute information for neuromuscular control (Linden, 1978). These findings support the results calculated by the numerical model. The calculated root mean square value of condylar loading is less in cases of molar biting than in incisal biting for a given, constant bite force.

The control of condylar loading is also aided through periodontal and, possibly, suture receptor sensitivity to application of non-vertical forces on the teeth (Schaerer _et al._, 1967; Bowman and Nakfoor, 1968; Linden, 1975). The vertical bite forces used in this project tended to produce symmetrical condylar loads. The loads were reduced in magnitude as compared with condylar loads produced by non-vertical bite forces. However, the results of Smith (1984) and Smith _et al._ (1986) suggest that non-vertical bite forces can produce asymmetrical condylar loads and can significantly increase the magnitude of loading of the contralateral condyle. Given the clear potential of non-vertical bite forces to result in increased condylar loading, it is advantageous to have periodontal receptors more sensitive to tangential loading of teeth than to loading of the tooth in an axial direction (Bowman and Nakfoor, 1968). The sensitivity of these receptors enables critical control of non-vertical bite forces which could potentially compromise both joint health and periodontal health.

5.4.2 The Relationship Between Growth and Neuromuscular Control

Patterns of muscle activation calculated by means of the numerical model give evidence of continuity in neuromuscular control of joint loading from birth to maturity. The calculated patterns of muscle activation in children seem to be very similar to calculations for adults, as described by Smith (1984) and Smith *et al*. (1986). Remarkable changes occur in the human face from the time of birth to adulthood, yet it appears that the neuromuscular control of the mandible remains intact and in harmony with the growth changes of the biting apparatus.

This study has quantified the growth changes in the TMJ eminence and the geometries of the muscles of mastication. The sensitivity studies have identified moment potentials as one indicator of changes in the geometries of the major adductor muscles, which influence the direction of condylar loading (Tables 4.3.2.8, 4.3.2.9). Increases in moment potential of the masseter muscle, without muscle angulation changes, result in an increasing obliqueness of the loading of the condyle on the temporal component. These studied changes in the moment potential of the masseter muscle are similar to the established growth changes, which are evident in the plot of Sagittal Muscle Moment Potential vs. Age (Figure 4.3.2.8). These growth changes, in general terms, are an increase in the vertical height of the ramus, and an increase in the transverse width of the mandible. It is possible that, as the child matures, growth changes in the geometry of the masseter muscle contribute to the age-related changes in the direction of condylar loading (Figures 4.3.2.1 and 4.3.2.2). With these changes in the direction of condylar loading, there is the need to maintain the underlying control mechanism of perpendicular minimal joint loading. If the hypothesis of minimal joint loading is accepted, this objective is achieved by developing the TMJ eminence prior to age-related increases in the direction of TMJ loading. When these increases in the obliqueness of condylar loading finally occur, the osseous elements have adequately developed to help maintain the control mechanism of joint loading by ensuring perpendicular loading of the condyle on the temporal component.

As a reminder, this project limited analysis of condylar reaction forces to situations of vertical bite forces. Non-vertical bite forces will probably result in a complex interaction of muscle geometries. It is assumed that, in the normal function of the masticatory system, the potential for a muscle to produce a moment about a point is subordinate to the objective of minimization of joint load. Although a muscle may be capable of producing a moment about an axis, the muscle is activated only to that level which will contribute to minimal condylar load. Therefore, although it may be helpful in some respects, focusing strictly on the moment potential of a muscle can be misleading if the requirement of minimization of joint load is ignored.

5.4.3 Lateral Pterygoid Activity: Theoretical Calculations vs. EMG Studies

Smith (1984) and Smith *et al.* (1986) reported that numerical model calculations did not result in significant lateral pterygoid muscle force in order to achieve static equilibrium. Smith reported that lateral pterygoid muscle activity occurred only for isometric biting in the region of the third molar. In the present study, examination was limited to vertical biting conditions from the region of the incisors to the region of the first molar. The results support the conclusions of Smith and co-workers, but are contrary to those of McNamara (1973), who reported that there is significant lateral pterygoid muscle activity during biting in macaques. McNamara concluded that the superior and inferior heads of the lateral pterygoid muscle have different functions. The superior belly of the lateral pterygoid contributed as a positioning or stabilizing muscle during maximal biting, and the inferior belly contributed as an abductor muscle during translation and opening. Although it was stated by McNamara that both muscles function during the different stages of jaw activity, there is evidence (McNamara, 1973; Hylander *et al.*, 1987) of simultaneous activity.

The theoretical calculations indicate that the lateral pterygoid muscle contributes little force except in the case of biting in the third molar region. The results suggest that the lateral pterygoid muscle does not function as a stabilizing muscle as suggested by McNamara (1973).

McNamara studied motion EMG, whereas, the present study examined isometric biting conditions. The differences in the results between McNamara`s work and the present study suggest that lateral pterygoid muscle is active during jaw movement, but might not be necessary in order to produce a bite force.

The current theoretical model does not include motion control of the muscles, and research will have to continue to develop the model to include motion. This would help to determine the possible role of lateral pterygoid muscle activity during mastication.

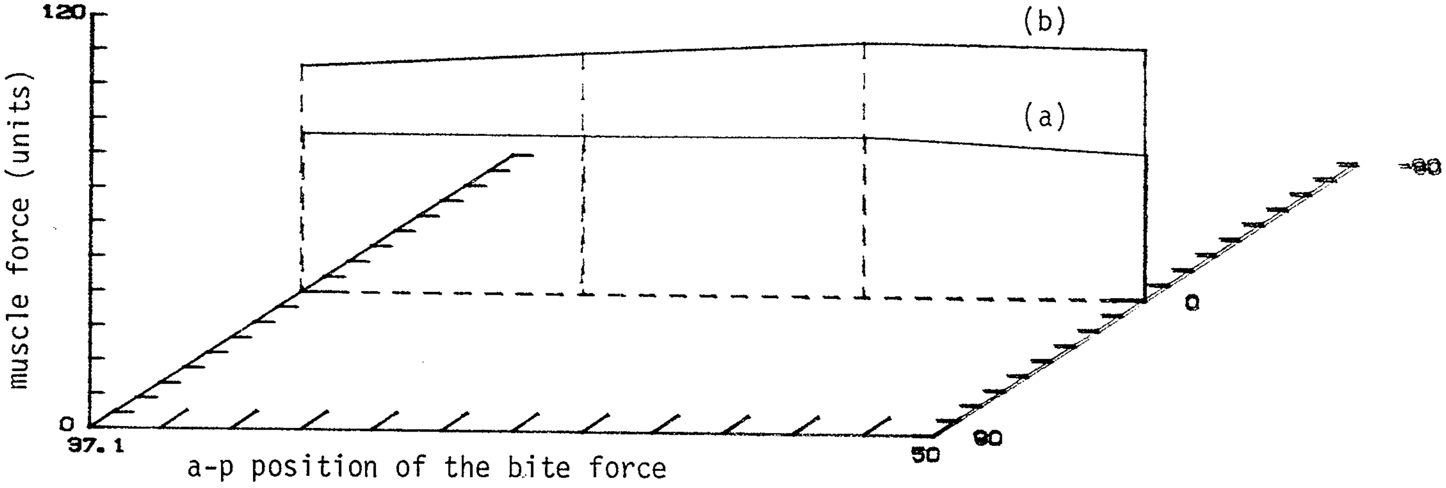
5.5 Clinical Implications of the Results

Functional appliances have been utilized in the correction of maxillomandibular skeletal dysplasias in growing patients. The premise of the therapy is that, if treatment is initiated early enough, manipulation of the developing skeletal units is possible and that correction of the dysplasias is achieved by inducing or modifying skeletal growth. Commonly, the earliest ages of functional appliance therapy are six to eight (6-8) years of age. Given the results of this study, early maturation of the TMJ eminence may indicate that major growth changes of the temporal component of the joint should not be expected as a consequence of functional appliance therapy. Metaxis (1983) demonstrated that monkeys had a reduced ability to remodel the temporal component of the TMJ during functional appliance therapy. Likewise, the results of this study indicate that maturation of the temporal component occurs very early, and it is possible that the eminence is not capable of significant growth changes after the age of three (3) years.

Another important clinical implication of the relationship between the direction of condylar loading and eminence development is the potential ramification of surgical orthognathic therapy for the correction of skeletal deformities. Significant changes in the mechanics of the biting apparatus may occur by surgical changes of the occlusal plane, and of the relationships of the origins and insertions of the major adductor muscles. The studies to determine the sensitivity of the chewing apparatus to imposed changes in geometry have demonstrated that surgical changes may well result in alteration of the direction of condylar loading. Consequently, post-surgical changes in direction of condylar loading may be severe enough to result in non-perpendicular loading of the condyle on the mature eminence. In this situation, altered patterns of muscle activation would be necessary to stabilize the mandible and prevent translation of the condyles during isometric biting. This altered muscle activity would ultimately increase the magnitude of load each condyle must bear, or dictate that the magnitude of the bite force be reduced to prevent the increase in loading of the condyle. If muscle activity must be increased in order to stabilize the condyles, the result is that muscles must work harder to accomplish specific tasks. If the muscles were required to sustain long periods of hyperactivity, an end result might be the clinical signs of Myofascial Pain Dysfunction Syndrome (Travell and Simons, 1983). Or, if the magnitude of loading of the condyle were to exceed the physiological capacity of the articulating tissues to adapt, a process of osteoarthritis might be initiated.

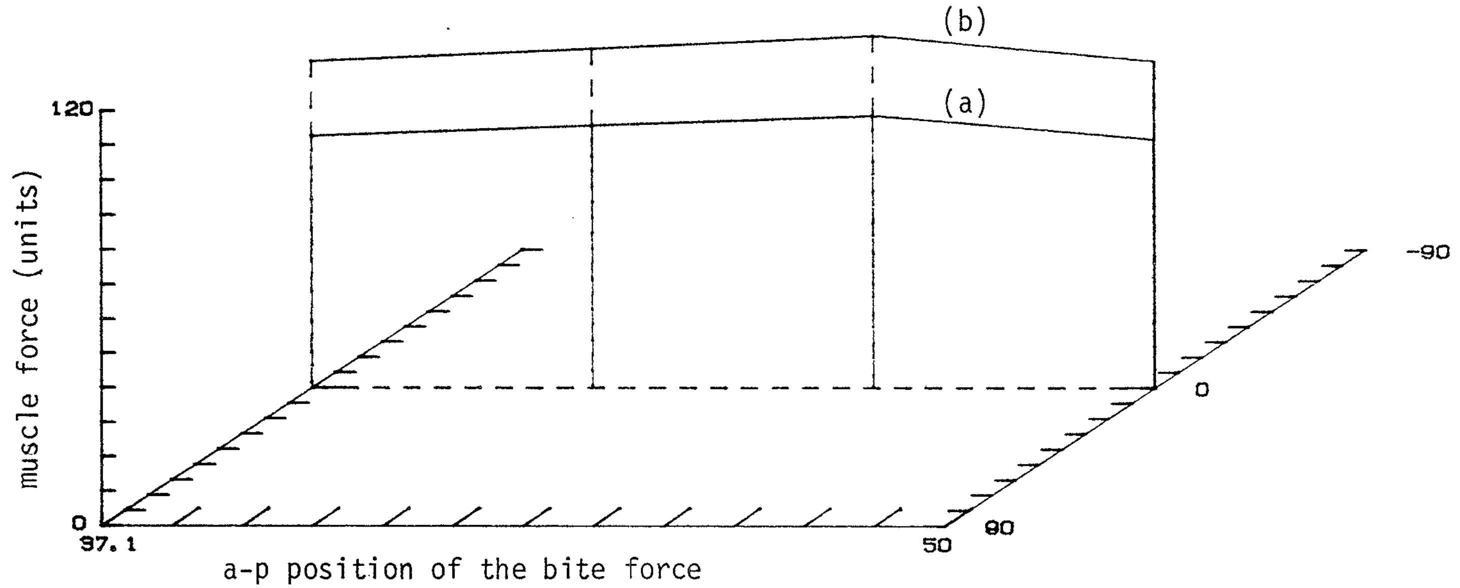
The neuromuscular control of TMJ loading has clinical implications in conditions such as juvenile rheumatoid arthritis or trauma to the young TMJ. These conditions have been shown to reduce the growth of the mandibular condyle. The theoretical results of this study have shown that altered growth results in changes in the mechanics of the biting apparatus. For example, reduction in the height of the condyle alone results in changes of the sagittal moment potentials of the masseter and temporalis muscles. In conditions such as this, the results of the numerical model indicate that there is a compensatory increase in masseter muscle force and temporalis muscle force in order to satisfy static equilibrium and minimize the loading of the joints (Figures 5.5.1, 5.5.2). Several authors (Sarnat, 1957; Sarnat and Muchnic, 1971; Sorensen and Laskin, 1975) have reported that in cases where posterior ramal height has been reduced, there is compensatory remodelling of the coronoid process and the gonial notch. These authors suggested that the remodelling is in response to alterations of the mechanics of the biting apparatus, a suggestion supported by the calculations of the model used in this study. Maintaining minimal condylar loading is the underlying theme governing these changes in muscle activities.

Figure 5.5.1 Temporalis muscle activity: Specimen 012



(a) Ipsilateral temporalis muscle activity: normal geometry
(b) Ipsilateral temporalis muscle activity: masseter muscle moment potential reduced by 5 mm.

Figure 5.5.2 Masseter muscle activity: Specimen 012



(a) Ipsilateral masseter muscle activity: normal geometry
(b) Ipsilateral masseter muscle activity: masseter muscle moment potential reduced by 5 mm.

Chapter 6

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

6.1 **Conclusions**

The results of this study support the following conclusions:

1. Static equilibrium cannot be satisfied unless the immature temporomandibular joint is loaded for the conditions examined. In the neonate, the direction of condylar loading is approximately vertical and directed perpendicular to the temporal component of the joint. The area of loading is in the region where the crest of the eminence develops, due to a protrusive mandibular position during suckling. As a child matures, the angle of condylar loading becomes more oblique, but remains approximately perpendicular to the developing eminence. The direction of condylar loading is influenced by the anteroposterior position of the mandible and by growth of the biting apparatus.

2. The temporomandibular joint eminence develops a mature shape prior to the age of three (3) years. After three years of age, eminence development slows until a plateau in growth is reached between the ages of fourteen (14) and sixteen (16) years.

3. Early loading of the immature TMJ provides the basis for

a theoretical model of eminence development. The early development of the eminence is consequent upon the stimulation of bone growth by the appropriate position and timing of loading of the immature condyle on the temporal component of the joint.

4. There is a linear relationship between the direction of condylar loading and one measure (slope) of the sagittal morphology of eminence development. The more oblique the direction of condylar loading, the steeper the temporomandibular joint eminence.

6.2 Suggestions for Further Work

The work presented in this thesis has been limited to the sagittal plane development of the TMJ eminence. It might be fruitful to consider extending this study to include a three-dimensional analysis of the development of the condyle and temporal component of the TMJ. In keeping with a three-dimensional analysis, loading of the immature TMJ might be examined in dimensions other than the sagittal plane, to establish the relationship between development of joint morphology and joint loading. The present study used a cross-sectional sample to determine growth changes in the biting apparatus. There are limitations in using this type of sample and the quality of some of the data might be improved by using a longitudinal radiographic sample.

The numerical model used in this study provides a means of predicting muscle function and control of condylar loads in growing individuals. In order to verify the accuracy of the neuromuscular calculations, EMG studies might be undertaken to examine muscle activities in young children. This would enable comparison of in vivo data with the theoretical results calculated by the model. This comparison would begin to examine the validity of minimization of loading as a basis of organization of neuromusuclar control.

Surgical orthognathic therapy is becoming a more common form of treatment of skeletal dysplasias, but there is evidence to suggest that this form of treatment results in alterations of the mechanics of the biting apparatus. The results of this project indicate that investigations might be undertaken to look at the possible changes in TMJ mechanics as a consequence of surgical intervention. Again, the validation of the theoretical calculations of the model would be possible by measuring EMG activities of individuals before and after orthognathic surgery.

The existing numerical model calculates condylar loads for conditions of static biting. In the future, the development of the model might include motion and asymmetries of the muscles and calcified structures. This extension of the model would enable further examination of the mechanisms of muscle function in the control of mandibular movement and condylar loading.

As discussed previously, it is hypothesized that joint loading is the mechanism initiating the development of the secondary cartilage, which changes the morphology of the newly developing joint. There are interesting evolutionary implications with respect to secondary cartilages. Reptiles do not produce secondary cartilages, in contrast to mammals (Irwin and Ferguson, 1986). Evolutionary trends (Crompton and Parker , 1978; Crompton, 1985) suggest that the mammalian temporomandibular joint evolved from mammal-like reptiles. The capacity of mammals to develop the unique anatomy of the temporomandibular joint is related to the ability of mammals to synthesize the secondary cartilage required to support the articular tissues. It might be possible to extend the use of the numerical model in comparative anatomical study of loading of the temporomandibular joints of other mammals and hominids. Animal models are used frequently in the fields of neuroscience and craniofacial biology to study the temporomandibular joint. The numerical model might prove useful in helping to understand the mechanics of mastication of mammals of interest to comparative zoologists. Finally, physical anthropologists have developed theories of the function of the biting apparatus in early hominids (Rak, 1983). The numerical model might be useful as an analytical tool, to aid in the reconstruction of mandibular function in man's early ancestors.

BIBLIOGRAPHY

Ahlgren, J. (1966) Mechanisms of Mastication: A quantitative cinematographic and electromyographic study of masticatory movements in children, with special reference to occlusion of the teeth. *Acta Odont. Scand.* 24 (Suppl. 44): 1-109.

Angel, J. L. (1948) Factors in temporomandibular joint form. *Am. J. Anat.* 83: 223-246.

Appelberg, B., Hulliger, M., Johansson, H., and Sojka, P. (1979) Excitation of dynamic fusimotor neurones of the cat triceps surae by contralateral joint afferents. *Brain Res.* 160: 529-532.

Ardran, G.M., Kemp, F.H., and Lind, J. (1958a) A cineradiographic study of bottle feeding. *Brit. J. Rad.* 31: 11-22.

Ardran, G.M., Kemp, F.H., and Lind, J. (1958b) A cineradiographic study of breast feeding. *Brit. J. Rad.* 31: 156-162.

Arvikar, R., and Seireg, A. (1975) A three-dimensional model for analysis of the human jaw during mastication. Proceedings of the 28th *Ann. Conf. Eng. Med.* and *Biol.* 28: 184.

Barbenel, J.C. (1969) Analysis of forces at the temporomandibular joint during function. *Dent. Pract.*

Dent. Rec. 19: 305-310.

Barbenel, J.C. (1972) The biomechanics of the temporomandibular joint: a theoretical study. *J. Biomech.* 5: 251.

Barbenel, J.C. (1974) The mechanics of the temporomandibular joint: a theoretical and electromyographical study. *J. Oral. Rehab.* 1: 19-27.

Baron, P., and Debussy, T. (1979) A biomechanical functional analysis of the masticatory muscles in man. *Arch. Oral Biol.* 24: 547-553.

Bassett, C.A.L. (1971) Effect of force on skeletal tissues. In *Physiological Basis of Rehabilitation Medicine*. J.A. Downey and R.C. Darling (Eds). Saunders and Company: Philadelphia, pp. 283-316.

Baume, L. J. (1962a) The prenatal and postnatal development of the human temporomandibular joint. *Trans. Europ. Ortho. Soc.* 38: 63-73.

Baume, L.J. (1962b) Ontogenesis of the human temporomandibular joint: 1. Development of the Condyles. *J. Dent. Res.* 41: 1327-1339.

Baume, L.J. (1963) Le developpment de l'articulation temporo-mandibulaire chez l'homme. *Rev. mens. Suisse Odonto-stomatol.* 73: 134-146.

Baume, L.J. (1969) Cephalo-facial growth patterns and functional adaption of temporomandibular joint structures. Trans. Europ. Ortho. Soc. 45: 79-98.

Baume, L.J., and Holz, J. (1970) Ontogenesis of the human temporomandibular joint: 2. Development of the temporal components. J. Dent. Res. 49: 864-875.

Baxendale, R.H., and Ferrell, W.R. (1980) Modulation of transmission in flexion reflex pathways by knee joint afferent discharge in the decerebrate cat. Brain Res. 202: 497-500.

Beresford, W.A. (1981) Chondroid Bone, Secondary Cartilage and Metaplasia. Urban and Schwarzenberg: Baltimore and Munich.

Blackwood, H.J.J. (1966) Adaptive changes in the mandibular joints with function. Dent. Clin. North Am. 10: 559-566.

Bloom, W., and Fawcett, D.W. (1968) A Textbook of Histology. Ninth edition. W.B. Saunders Co.: Philadelphia.

Bowman, D.C., and Nakfoor, P.M. (1968) Evaluation of the human subject’s ability to differentiate intensity of forces applied to the maxillary central incisors. J. Dent. Res. 47: 252-259.

Boyd, R.L., Gibbs, C.H., Richmond, A.F., Laskin, J.L., and Brehnan, K. (1982) TMJ forces in monkey measured with piezoelectric foil. *J. Dent. Res.* 61: 351.

Brehnan, K., and Boyd, R.L. (1979) Use of piezoelectric films to directly measure forces at the temporomandibular joint. *J. Dent. Res.* 58: 1243.

Brehnan, K., Boyd, R.L., Laskin, J., Gibbs, C.H., and Mahan, P. (1981) Direct measurement of loads at the temporomandibular joint in *Macaca arctoides*. *J. Dent. Res.* 60: 1820-1824.

Butler, W.B. (1977) An analysis of brain stem responses to temporomandibular joint rotation in the cat. M.S. Thesis. University of Michigan. Ann Arbor, Michigan.

Carlson, D.S., McNamara, J.A., Jr., and Jaul, D.H. (1978) Histological analysis of the growth of the mandibular condyle in the rhesus monkey (*Macaca mulatta*). *Am. J. Anat.* 151: 103-117.

Carlson, D.S., McNamara, J.A., Jr., Graber, L.W., and Hoffman, D.L. (1980) Experimental studies of growth and adaption of TMJ. Chapter 3 in *Current Advances in Oral Surgery*. W.B. Irby (Ed.). C.V. Mosby: St. Louis.

Carlsson, G.E., and Oberg, T. (1974) Remodelling of the temporomandibular joints. *Oral Sci. Rev.* 6: 53-86.

Copray, J.C.V.M., Jansen, H.W.B., and Duterloo, H.S. (1985) The role of biomechanical factors in mandibular condylar growth and remodelling *in vitro*. In *Developmental Aspects of Temporomandibular Joint Disorders*. D.S. Carlson, J.A. McNamara, Jr., K.A. Ribbens (Eds.). Monograph #16 of the Craniofacial Growth Series. Center for Human Growth and Development. University of Michigan. Ann Arbor. pp. 235-269.

Cousin, R.P. (1960) Embryologie et croissance de l'articulation temporo-mandibulaire. *Orthodont. Frac.* 31: 39-52.

Crompton, A.W. (1985) Development and adaption of the temporomandibular joint. In *Developmental Aspects of Temporomandibular Joint Disorders*. D.S. Carlson, J.A. McNamara, Jr., K.A. Ribbens (Eds.). Monograph #16 of the Cranifacial Growth Series. Center for Human Growth and Development. University of Michigan. Ann Arbor. pp. 1-18.

Crompton, A.W., and Parker, P. (1978) Evolution of the mammalian masticatory apparatus. *Am. Scien.* 66: 192-201.

Currey, J.D. (1968) The effect of protection on the impact strength of rabbits' bones. *Acta. Anat.* 71: 87-93.

Dale, J.G., Hunt, A.M., Purdy, G., and Wagner, D. (1963) Autoradiographic study of the developing temporomandibular joint. *J. Can. Dent. Assoc.* 29: 27.

Dovitch, V., and Herzberg, F. (1968) A radiographic study of the bony trabecular pattern in the mandibular rami of herbivores, carnivores, and omnivores. Angle Ortho 38: 205-210.

Druzinsky, R.E., and Greaves, W.S. (1979) A model to explain the posterior limit of the bite point in reptiles. J. Morph. 160: 165-168.

Dumas, A.L., Moaddab, M.B., Homayoun, N.H., and McDonough, J. (1986) A three-dimensional developmental measurement of the temporomandibular joint. J. Craniomand. Pract. 4: 23-35.

Ekholm, R. (1955) Nutrition of articular cartilage: a radioautographic study. Acta. Anat. 24: 329-338.

Findlay, I. (1964) Mandibular joint pressure. J. Dent. Res. 43: 140-148.

Folke, L.E.A., and Stallard, R.E. (1966) Condylar adaption to a change in intermaxillary relationship. J. Perio. Res. 1: 79-89.

Folke, L.E.A., and Stallard, R.E. (1967) Cellular kinetics within the mandibular joint. Acta Odont. Scand. 25: 437-469.

Furstman, L. (1963) Early development of the human temporomandibular joint. Am. J. Ortho. 49: 672-682.

Gingerich, P.D. (1971) Functional significance of mandibular translation in vertebrate jaw mechanics. Postilla 152: 1-10.

Gingerich, P.D. (1979) The human mandible: Lever, link, or both? Am. J. Phys. Anthrop. 51: 135-138.

Goodfellow, J., and Mitsou, A. (1977) Joint surface incongruity and its maintenance: an experimental study. J. Bone Joint Surg. 59: 446-451.

Goodfellow, J.W., and O'Connor, J.J. (1980) The design of synovial joints. In Scientific Foundations of Orthopaedics and Traumatology. R. Owen, J. Goodfellow, and P. Bullough (Eds.). W.B. Saunders Co.: Philadelphia. pp. 78-88.

Gosen, A.J. (1974) Mandibular leverage and occlusion. J. Prosth. Dent. 31: 369-376.

Griffin, C.J., and Sharpe, C.J. (1960) The structure of the adult temporomandibular meniscus. Aust. Dent. J. 5: 190-195.

Gysi, A. (1921) Studies on the leverage problem of the mandible. Dent. Digest 27: 74-84.

Hall, B.K. (1967) The formation of adventitious cartilage by membrane bones under the influence of mechanical stimulation applied in vitro. Life Sciences 6: 663-667.

Hall, B.K. (1970) Cellular differentiation in skeletal tissues. Biol. Rev. 45: 455-484.

Hall, B.K. (1979) Selective proliferation and accumulation of chrondroprogenitor cells as the mode of action of biomechanical factors during secondary chondrogenesis. Teratology 20: 81-92.

Hall, B.K. (1983) Tissue interactions and chondrogenesis. Chapter 5 in Volume 2 of Cartilage: Development, Differentiation, and Growth. B.K. Hall (Ed.). Academic Press: New York. pp. 187-222.

Ham, A.W. (1930) A histological study of the early phases of bone repair. J. Bone J. Surg. 12: 827-844.

Hansson, T., and Nordstom, B. (1977) Thickness of the soft tissue layers and articular disk in temporomandibular joints with deviations in form. Acta Odont. Scand. 35: 281-288.

Hansson, T., and Oberg, T. (1977) Arthrosis and deviation in form in the temporomandibular joint. Acta Odont. Scand. 38: 167-174.

Hansson, T., Oberg, T., Carlsson, G., and Kopp, S. (1977) Thickness of the soft tissue layers of the articular disk in the temporomandibular joint. Acta. Odont. Scand. 35: 77-83.

Haskell, B., Day, M., and Tetz, J. (1986) Computer-aided modelling in the assessment of the biomechanical determinants of diverse skeletal patterns. Am. J. Ortho. 89: 363-382.

Hatcher, D.C., Faulkner, M.G., and Hay, A. (1986) Development of mechanical and mathematical models to study temporomandibular joint loading. J. Prosthet. Dent. 55: 377-384.

Hekneby, M. (1974) The load of the temporomandibular joint: Physical calculations and analyses. J. Prosthet. Dent. 31: 303-312.

Hellman, M. (1939) Some facial features and their orthodontic implication. Am. J. Ortho. 25: 927-951.

Herzberg, F., and Sarnat, B.G. (1962) Radiographic changes in the bony trabecular pattern of the mandible of growing Macaca rhesus monkeys following condylar resection. Anat. Rec. 144: 129-134.

Hinton, R.J. (1979) Influence of dental function on the form of the human mandibular fossa. Ph.D. Thesis. University of Michigan. Ann Arbor, Michigan.

Hinton, R.J. (1981a) Changes in the articular eminence morphology with dental function. Am. J. Phys. Anthrop. 54: 439-455.

Hinton, R.J. (1981b) Form and function in the temporomandibular joint. In Craniofacial Biology. D.S. Carlson (Ed.). Monograph #10 of the Craniofacial Growth Series. Center for Human Growth and Development. University of Michigan. Ann Arbor. pp. 37-60.

Hinton, R.J. (1985) Adaptive response of the articular eminence and mandibular fossa to altered function of the lower jaw: an overview. In Developmental Aspects of Temporomandibular Disorders. D.S. Carlson, J.A. McNamara, Jr., and K.A. Ribbens (Eds.). Monograph #16 of the Craniofacial Growth Series. Center for Human Growth and Development. University of Michigan. Ann Arbor. pp. 207-234.

Hinton, R.J., and Carlson, D.S. (1979) Temporal changes in human temporomandibular joint size and shape. Am. J. Phys. Anthrop. 50: 325-334.

Hinton, R.J., and Carlson, D.S. (1983) Histological changes in the articular eminence and mandibular fossa during growth of the rhesus monkey (Macaca mulatta). Am. J. Anat. 66: 99-116.

Hinton, R.J., and McNamara, J.A., Jr., (1984) Temporal bone adaptations in response to protrusive function in juvenile and young rhesus monkeys (Macaca mulatta). Eur. J. Ortho. 6: 155-174.

Hjortsjo, C.-H., Persson, P.-I., and Sonesson, B. (1953)

Studies on the shape of the articular eminence with its relation to the mechanism in the temporomandibular joint. Odont. Rev. 4: 187-209.

Hohl, T.H., and Tucek, W.H. (1982) Measurement of condylar loading forces by instrumented prosthesis in the baboon. J. Maxillofac. Surg. 10: 1-7.

Humphreys, H. (1932) Age changes in the temporomandibular joint and their importance in orthodontics. Int. J. Ortho. Oral Surg. Rad. 18: 809-815.

Hylander, W.L. (1972) The adaptive significance of Eskimo craniofacial morphology. Ph.D. Thesis. University of Chicago. Chicago, Illinois.

Hylander, W.L. (1975) The human mandible: Lever or link? Am. J. Phys. Anthrop. 43: 227-242.

Hylander, W.L. (1979) An experimental analysis of temporomandibular joint reaction force in macaques. Am. J. Phys. Anthrop. 51: 433-456.

Hylander, W.L. (1985) Mandibular function and temporomandibular joint loading. In Developmental Aspects of Temporomandibular Joint Disorders. D.S. Carlson, J.A. McNamara, Jr., and K.A. Ribbens (Eds.). Monograph #16 of the Craniofacial Growth Series. Center for Human Growth and Development. University of Michigan. Ann Arbor. pp. 19-38.

Hylander, W.L., and Bays, R. (1979) An *in vivo* strain-guage analysis of the squamosal-dentary joint reaction force during mastication and incisal biting in *Macaca mulatta* and *Macaca fascicularis*. *Arch. Oral Biol.* 24: 689-697.

Hylander, W.L., and Johnson, K.R. (1985) Temporalis and masseter muscle function during incision in macaques and humans. *Int. J. Primat.* 6: 289-322.

Hylander, W.L., Johnson, K.R., and Crompton, A.W. (1987) Mastication in *Macaca fascicularis*. In Press.

Ingervall, B. (1974) Relation between height of the articular tubercle of the temporomandibular joint and facial morphology. *Angle Ortho.* 44: 15-24.

Ingervall, B., Carlsson, G.E., and Thilander, B. (1976) Postnatal development of the human temporomandibular joint: II. A microradiographic study. *Acta Odont. Scand.* 34: 133-139.

Irwin, C.R., and Ferguson, M.W.J. (1986) Fracture repair of reptilian dermal bones: can reptiles form secondary cartilage? *J. Anat.* 146: 53-64.

Iwasaki, L.R., McLachlan, K.R., and Smith, D.M. (1986) Facial Type: Is it functionally important? *J. Dent. Res.*65: 532.

Jacobson, A. (1976) Application of the "Wits" Appraisal.

Am. J. Ortho. 70: 179-189.

Jagger, R.G., and Whittaker, D.K. (1977) The surface structure of the human mandibular condyle in health and disease. *J. Oral Rehab.* 4: 377-385.

Joondeph, D.R. (1972) An autoradiographic study of the temporomandibular articulation in the growing *Saimiri sciureus* monkey. *Am. J. Ortho.* 62: 272-286.

Kanouse, M.C., Ramfjord, S.P., and Nasjleti, C.E. (1969) Condylar growth in rhesus monkeys. *J. Dent. Res.* 48: 1171-1176.

Kazanjian, V.H. (1940) Congenital absence of the ramus of the mandible. *Am. J. Ortho.* 26: 175-187.

Kieffer, J. (1908) Beitrage zur kenntnis der veranderung am unterkiefer und kiefergelenk durch alter und zahnverlust. *J. Morph. Anthrop.* 11: 1-82.

Klineberg, I.J., Greenfield, B.E., and Wyke, B.D. (1971) Afferent discharges from temporomandibular articular mechanoreceptors: an experimental analysis of the behavioural characteristics in the cat. *Arch. Oral Biol.* 16: 1463-1479.

Langer, K. (1860) Das kiefergelenk des menschen. Funter beitrag zur anatomie und mechanik der gelenke. *Sitz. Math. -Nat. Cl. Kais. Acad. Wiss.*(Wien) 39: 457-471.

Levy, B.M. (1964) Embryological development of the temporomandibular joint. In The Temporomandibular Joint. B.G. Sarnat (Ed.). Second edition. Charles C. Thomas: Sringfield, Illinois. pp. 59-76.

Linden, R.W.A. (1978) Properties of intraoral mechanoreceptors represented in the mesencephalic nucleus of the fifth nerve in the cat. J. Physiol. 279: 395-408.

Lubosch, W. (1906) Uber variationen am tuberculum articulare des kiefergelenkes des menschen und ihre mophologische bedeutung. Gegenbaurs Morphol. Jahrb. 35: 322-353.

Lund, J.P., and Lamarre, Y. (1973) The importance of positive feedback from periodontal pressoreceptors during voluntary isometric contraction of the jaw closing muscles in man. J. Biol. Bucc. 1: 345-351.

Macalister, A.D. (1955) The development of the human temporomandibular joint: a microscopic study. Aust. J. Dent. 59: 21-27.

Mainland, D., and Hiltz, J.E. (1934) Forces exerted on the mandible by the muscles of mastication. J. Dent. Res. 14: 107-123.

Mansour, R.M., and Reynik, R.J. (1975a) In vivo occlusal forces and moments: I. Forces measured in terminal hinge position and associated moments. J. Dent. Res.

54: 114-120.

Mansour, R.M., and Reynik, R.J. (1975b) _In vivo_ occlusal forces and moments: II. Mathematical analysis and recommendations for instrumentation specifications. _J. Dent. Res._ 54: 121-124.

McCall, W.D., Kull, R.S., McLachlan, K.R., and Smith, D.M. (1986) Linearity of jaw muscle EMG and bite force. Presentation to the _Society for Neuroscience_. November, 1986. Washington, D.C.

McNamara, J.A., Jr. (1972) Neuromuscular and skeletal adaptions to altered orofacial function. In Monograph #1 of the Craniofacial Growth Series. Center for Human Growth and Development. University of Michigan. Ann Arbor.

McNamara, J.A., Jr. (1973) The independant functions of the two heads of the lateral pterygoid muscle. _Am. J. Anat._ 138: 197-206.

Metaxis, A. (1983) Primate experiments in bone remodelling in the temporomandibular joint and facial complex using the Herbst appliance. M.Sc. Thesis. University of Toronto. Toronto, Canada.

Moffett, B.C. (1966a) The prenatal development of the human temporomandibular joint. _Contributions to Embryology_ 37: 19-28.

Moffett, B.C. (1966b) The morphogenesis of the temporomandibular joint. Am. J. Ortho. 52: 401-415.

Moffett, B.C., Johnson, L.C., McCabe, J.B., and Askew, H.C. (1964) Articular remodelling in the adult human temporomandibular joint. Am. J. Anat. 115: 119-142.

Møller, E. (1966) The chewing apparatus: an electromyographic study of the action of the muscles of mastication and its correlation to facial morphology. Acta Physiol. Scand. 69 (Suppl. 280): 1-226.

Mongini, F. (1972) Remodelling of the mandibular condyle in the adult and its relationship to the condition of the dental arches. Acta Anat. 82: 437-453.

Mongini, F. (1975) Dental abrasion as a factor in remodeling of the mandibular condyle. Acta Anat. 92: 292-300.

Mongini, F. (1977) Anatomic and clinical evaluation of the relationship between the temporomandibular joint and occlusion. J. Prosth. Dent. 38: 539-551.

Moss, M.L. (1959a) Embryology, growth, and malformation of the temporomandibular joint. In The Disorders of the Temporomandibular Joint. L. Schwartz (Ed.). W.B. Saunders Co.: Philadelphia. pp. 89-103.

Moss, M.L. (1959b) Functional anatomy of the TMJ. In The Disorders of the Temporomandibular Joint. L. Schwartz

(Ed.). W.B. Saunders Co.: Philadelphia. pp. 73-88.

Moss, M. (1960) Functional analysis of human mandibular growth. J. Prosth. Dent. 10: 1149-1159.

Moss, M.L., and Moss-Salentijn, L. (1983) Vertebrate cartilages. In Volume 1 of Cartilage: Structure, Function, and Biochemistry. B.K. Hall (Ed.). Academic Press: New York. pp. 1-30.

Mundaca, C.L. (1948) Contribucion a la histogenesis de la articulacion temporomaxilar ("Articulus mandibularis I.N.A.") en la especie humana. Arch. Esp. Morf. 6: 175-187.

Myers, E.L., and Mow, V.C. (1983) Biomechanics of cartilage and its response to biomechanical stimuli. Chapter 11 in Volume 1 of Cartilage: Structure, Function, and Biochemistry. B.K. Hall (Ed.). pp. 313-341.

Oberg, T. (1964) Morphology, growth, and matrix formation in the mandibular joint of the guinea pig. Trans. Royal Schools of Dentistry (Stockholm and Umea) 10: 1-161.

Oberg, T., Carlsson, G.E., Fajers, C.-M. (1971) The temporomandibular joint: a morphologic study on a human autopsy material. Acta Odont. Scand. 29: 349-384.

Osborn, J.W., and Baragar, F.A. (1985) Predicted pattern of human muscle activity during clenching derived from a computer assisted model: symmetrical bite forces. J. Biomech. 18: 599-612.

Petrovits, L. (1930) Die vebereinstimmung des kiefergelenkes des neugeborenen kindes mit dem kiefergelenk der anthropoiden. (mitt. aus dem Anat. Inst. Nr. II der Kon. Ungarischen Poznany-Peter Univ. in Budapest). Anat. Anz. 69: 136-145.

Pritchard, J.J., and Ruzicka, A.J. (1950) Comparison of fracture repair in the frog, lizard, and rat. J. Anat. 84: 236-61.

Pruim, G.J., De Jongh, H.J., and Ten Bosch, J.J. (1980) Forces acting on the mandible during bilateral static bite at different bite force levels. J. Biomech. 13: 755-763.

Rak, Y. (1983) The Australopithicine Face. Academic Press: New York.

Ralph, J.P., and Caputo, A.A. (1975) Analysis of stress patterns in the human mandible. J. Dent. Res. 54: 814-821.

Ricketts, R.M. (1950) Variations of the temporomandibular joint as revealed by cephalometric laminography. Am. J. Ortho. 36: 877-898.

Roberts, D. (1974) The etiology of the temporomandibular joint dysfunction syndrome. Am. J. Ortho. 66: 498-515.

Robinson, M. (1946) The temporomandibular joint: theory of reflex controlled nonlever action of the mandible. J. Am. Dent. Assoc. 33: 1260-1271.

Roydhouse, R.H. (1955) The temporomandibular joint: upward force of the condyles on the cranium. J. Am. Dent. Assoc. 50: 166-172.

Sarnat, B.G. (1957) Facial and neurocranial growth after removal of the mandibular condyle in the Macaca rhesus monkey. Am. J. Surg. 94: 19-30.

Sarnat, B.G., and Muchnic, H. (1971) Facial skeletal changes after mandibular condylectomy in the adult monkey. J. Anat. 108: 323-338.

Schaerer, P., Stallard, R., and Zander, H.A. (1967) Occlusal interference and mastication: an electromyographic study. J. Prosth. Dent. 17: 438-449.

Scott, J.H. (1954) The growth and function of the muscles of mastication in relation to the development of the facial skeleton and the dentition. Am. J. Ortho. 40: 429-449.

Scott, J.H. (1955) Growth changes in the glenoid fossa.

Dent. Prac. 6: 117-120.

Scott, J.H., and Symons, N.B.B. (Eds.) (1961) Introduction to Dental Anatomy. Third edition. E. & S. Livingstone Ltd.: Edinburgh and London. pp. 83-87.

Seward, F.S. (1976) Tooth attrition and the temporomandibular joint. Angle Ortho. 46: 162-170.

Sicher, H., and DuBrul, E.L. (Eds.) (1975) Oral Anatomy. Sixth edition. C.V. Mosby: St. Louis.

Smith, D.M. (1984) A numerical model of temporomandibular joint loading. M.S. Thesis. State University of New York at Buffalo. Buffalo, New York.

Smith, D.M., McLachlan, K.R., and McCall, W.D. (1986) A numerical model of temporomandibular joint loading. J. Dent. Res. 65: 1046-1052.

Smith, R.J. (1978) Mandibular biomechanics and TMJ function in primates. Am. J. Phys. Anthrop. 49: 341-350.

Solberg, W.K., Hansson, T.L., and Nordstrom, B. (1985) The temporomandibular joint in young adults at autopsy: a morphologic classification and evaluation. J. Oral Rehab. 12: 303-321.

Sorensen, D.C., and Laskin, D.M. (1975) Facial growth after condylectomy or ostectomy in the mandibular ramus. J. Oral Surg. 33: 746-756.

Standlee, J.P., Caputo, A.A., and Ralph, J.P. (1977) Stress trajectories within the mandible under occlusal loads. J. Dent. Res. 56: 1297-1302.

Standlee, J.P., Caputo, A.A., and Ralph, J.P. (1981) The condyle as a stress-distributing component of the temporomandibular joint. J. Oral Rehab. 8: 391-400.

Steinhardt, G. (1958) Anatomy and physiology of the temporomandibular joint: effect of function. Int. Dent. J. 8: 155-156.

Stockli, P.W., and Willert, H.G. (1971) Tissue reactions in the temporomandibular joint resulting from anterior displacement of the mandible in the monkey. Am. J. Ortho. 60: 142-155.

Strzalko, J., Ziemianski, A., and Malinowski, A. (1971) Functional variation of the structure of cancellous bone substance in the mandibular ramus in human ontogenesis. Pol. Przegl. Radiol. 35: 489-494.

Symons, N.B.B. (1952) The development of the human mandibular joint. J. Anat. 86: 326-332.

Tanner, J.M. (1977) Human growth and constitution. Part IV in the second edition of Human Biology: An introduction to human evolution, variation, growth, and ecology. G.A. Harrison, J.S. Weiner, J.M. Tanner, and N.A. Barnicot (Eds.). Oxford University Press. pp.

301-384.

Tattersall, I. (1973) Cranial anatomy of Archaeolemurinae (Lemuroidea primates). Anthrop. Pap. Amer. Mus. Nat. Hist. 52: 1-110.

Taylor, R.C., Ware, W.H., Fowler, D., and Kobayashi, J. (1972) A study of the temporomandibular joint morphology and its relationship to the dentition. Oral Surg. Oral Med. Oral Path. 33: 1002-1013.

Thilander, B. (1964) The structure of the collagen of the temporo-mandibular disc in man. Acta Odont. Scand. 22: 136-149.

Thilander, B., Carlsson, G., and Ingervall, B. (1976) Postnatal development of the human temporomandibular joint: I. A histological study. Acta Odont. Scand. 34: 117-126.

Thorogood, P. (1979) In vitro studies on skeletogenic potential of membrane bone periosteal cells. J. Embryol. Exp. Morph. 54: 185-207.

Throckmorton, G.S. (1985) Quantitative calculations of temporomandibular joint reaction forces: II. The importance of the direction of jaw muscle forces. J. Biomech. 18: 453-461.

Throckmorton, G.S., and Throckmorton, L.S. (1985) Quantitative calculations of temporomandibular joint reaction forces: I. The importance of the magnitude of the jaw muscles. J. Biomech. 18: 445-452.

Todd, T.W. (1930) Facial growth and mandibular adjustment. Int. J. Ortho. Oral Surg. Rad. 16: 1243-1267.

Tradowsky, M., and Dworkin, J.B. (1982) Determination of the physiologic equilibrium point of the mandible by electronic means. J. Prosth. Dent. 48: 89-101.

Tradowsky, M., and Kubicek, W.F. (1981) Method for determining the physiologic equilibrium point of the mandible. J. Prosth. Dent. 45: 558-563.

Travell, J.G., and Simons, D.G. (Eds.) (1983) Myofascial Pain and Dysfunction: The Trigger Point Manual. Williams and Wilkins: Baltimore.

Treharne, R.W. (1981) Review of Wolff's law and its proposed means of operation. Orthop. Rev. 10: 35-47.

Turek, S.L. (Ed.) (1984) Physiology of cartilage. Chapter Seven in Volume 1 of Orthopaedics: Principles and Their Application. J.B. Lippincott Co.: Philadelphia. pp. 191-215.

van Steenberghe, D., and de Vries, J.H. (1978) The influence of local anaesthesia and occlusal surface area on the forces developed during repetitive maximal clenching efforts. J. Perio. Res. 13: 270-274.

Vinogradoff, A. (1910) Development de l'articulation temporo-maxillaire chez l'homme dans la periode intrauterine. Internat. Monatsshr. f. Anat. u. Physiol. 27: 490-523.

Walker, A. (1978) Functional anatomy of oral tissues: mastication and deglutition. Chapter Eight in Textbook of Oral Biology. J.H. Shaw, E.A. Sweeney, C.C. Cappuccino, S.M. Meller (Eds.). W.B. Saunders Company: Philadelphia. pp. 277-296.

Wallisch, W. (1906) Das kiefergelenk. Arch. Anat. Entwick. (Liepzig). pp. 303-309.

Wilson, G. (1920) The anatomy and physics of the temporomandibular joint. J. Nat. Dent. Assoc. 7: 414-420.

Wilson, G. (1921) The anatomy and physics of the temporomandibular joint. J. Nat. Dent. Assoc. 8: 236-241.

Wright, D.M. (1968) The postnatal development of the human temporomandibular joint. M.S. Thesis. University of Washington. Seattle, Washington.

Wright, D.M., and Moffett, B.C., Jr. (1974) The postnatal human temporomandibular joint. Am. J. Anat. 141: 235-249.

Youdelis, R.A. (1966a) Ossification of the human temporomandibular joint. J. Dent. Res. 45: 192-198.

Youdelis, R.A. (1966b) The morphogenesis of the human temporomandibular joint and its associated structures. J. Dent. Res. 45: 182-191.

Zielinski, D.E. (1965) A study of the normal anatomy of the masticatory apparatus of *Macaca mulatta*. M.S. Thesis. Loyola University. Chicago, Illinois.

Zimmerman, H.I. (1971) The normal growth and remodelling of the temporomandibular joint of *Macaca mulatta*. M.S. Thesis. University of Washington. Seattle, Washington.