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Be so true to thyself, as thou be not false to others.

Francis Bacon (1561-1626)

University of Alberta

Condyle Angulation and Position Associated with Adolescent TMJ Disc Status

by

Philip C. Williamson ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfilment of the requirements for the degree of
Master of Science
in
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Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Condyle Angulation and Position Associated with Adolescent TMJ Disc Status** by Philip C. Williamson in partial fulfilment of the requirements for the degree of Master of Science in Orthodontics.

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Dedication

To my parents, sisters and brother, who have always supported and never doubted.

Abstract

The purpose of this research was twofold. Firstly, this study examined the identification error of certain submentovertex (SMV) landmarks and compared three different methods of determining a condylar long axis for horizontal condylar angulation determination. A random sampling of 12 SMV radiographs from pre-orthodontic patients between the ages of 10 and 17 were used to determine both intra- and inter-examiner landmark identification error. All landmarks studied demonstrated clinically acceptable levels of error, however several landmarks (pogonion, posterior condylar point, medial and lateral poles) demonstrated error of sufficient magnitude to warrant cautious consideration if used for research purposes. A computer-derived method representing the principal axis of minimum moment of inertia of the condyle demonstrated less variation than the interpolar axis method which is utilized most frequently in current practice.

Secondly, this research examined the relationship between condylar angulation and position and temporomandibular joint status in an adolescent population. SMV radiographs and MRI of 95 adolescent subjects (56 female and 39 male) were utilized. No significant differences were observed in condylar angulation or condyle position between male and female subjects. A statistically significant relationship was not observed between condylar angulation and TMJ status. A weak statistically significant correlation was observed between anterior disc displacement in medial and lateral portions of the condyle and transverse condyle position relative to the cranial base. Anterior-posterior and transverse condyle position was observed to be correlated with condylar angulation.

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Chapter One

Introduction
And
Literature Review

1.1 - Introduction

In orthodontics, it is important that irregularities of the temporomandibular joint or anatomical variations that may predispose to subsequent joint problems be identified as part of a routine diagnostic workup. Such information is valuable to the practitioner for several reasons. In the diagnosis and treatment planning process, such data aids in appropriate case selection and in the development of suitable treatment options and treatment mechanics for the individual patient. Also, this information is worthwhile from a medical-legal standpoint in terms of patient education and informed consent. Furthermore, such information might also be useful in elucidating possible factors of etiologic significance in the development of skeletal dysplasias and certain malocclusions. The literature suggests that temporomandibular disorders (TMD) may be related to deviant facial morphology, possibly resulting from growth disturbance.[1,2,3]

Diagnosis of TMD may be made through clinical assessment, or by a variety of available imaging modalities, including transcranial radiography,[4] tomography,[5,6] arthrograms,[7] computed tomography,[8] and magnetic resonance imaging.[9,10,11] Submentovertex radiographs (SMV's), though not utilized specifically in the diagnosis of temporomandibular joint irregularities, are commonly used for determination of the condylar long axis for corrected tomography of the temporomandibular joint.[12] Thus, SMV's are frequently taken as part of the routine diagnostic workup for patients suspected of having TMD. Research has suggested a possible relationship between horizontal condylar angulation as viewed axially, and variables such as facial form,[13] condylar dimensions,[14] certain malocclusions,[15] mandibular asymmetry,[16] and internal derangement of the temporomandibular joint.[17] If horizontal condylar angulation as viewed in a SMV radiograph can be shown to be closely associated with certain skeletal, occlusal and joint characteristics, then this radiographic view may prove to be useful as an orthodontic screening procedure to minimize the need for additional radiation exposure and expense. It may prove to be useful in the identification of certain patients who may be predisposed to temporomandibular disorders or growth patterns. As well, such imaging may also be significant in research which is directed at furthering our understanding of temporomandibular disorders and the possible contribution of certain skeletal factors in the etiology of such disorders.

The determination of the long axis of the condyle from SMV radiographs may be subject to variation, due in part to the irregularity in shape of the condyles in the axial view.[18,19] The great variability which exists in condylar shapes makes it difficult to accurately define a long axis with which to measure condylar angulation, regardless of what is used as a reference plane. Most studies on condylar angulation utilize points which represent the medial and lateral poles of the condyles, and have used a straight line connecting these poles to define a condylar long axis. However, limitations to this technique are obvious when one considers curved condyles with a pole to pole line deviating significantly from a mid-condylar point. Tapered condyles with medial or lateral deviations away from the long axis also contribute to the variability in defining an accurate condylar long axis. Furthermore, the condylar poles themselves can be difficult to identify, particularly the lateral pole due to superimposition of adjacent structures. This also may contribute to measurement variability when using this technique. The development of a method of condylar long axis determination which would not be sensitive to errors due to irregular condylar shapes and inconsistent pole identification would be beneficial, as it would allow a more reliable determination of condylar angulation. The development of such a tool might prove helpful in several applications. Firstly, it would be useful for a more accurate determination of an appropriate imaging axis for corrected imaging techniques of the temporomandibular joint. Also, if such a technique were to be shown to be more reliable than existing techniques for condylar long axis determination, it would have direct implications for any research which might involve condylar long axis measurements.

1.2 - Statement of the Problem

The goal of the diagnostic process is to develop a comprehensive problem list which should lead logically to treatment options specific to the individual. The identification of temporomandibular joint irregularities, whether such deviations comprise the presenting symptoms or are unknown to the patient and may predispose to certain conditions, is crucial in the diagnostic process. The collection of an adequate data base is fundamental to this process, and clinical, laboratory, photographic, and radiographic records are routinely utilized. Specific to the structures of the temporomandibular joint, several imaging modalities have been shown to be very useful in the identification of certain joint conditions, however these modalities are often only undertaken when clinical signs or symptoms are evident. It is possible that certain joint conditions, or certain anatomical features which might predispose to certain joint conditions, may elude detection by routine clinical and records examination. If further investigation can verify a significant relationship between certain skeletal characteristics and specific temporomandibular disorders, then this information, as derived by specific radiological imaging, would be useful to obtain as part of a routine diagnostic workup. Such information would not only be useful as a screening measure in diagnosis and in the development of appropriate treatment regimes, but may also contribute to an increased understanding of certain contributing factors in the development of TMD.

The means of determining condylar long axis currently described in the literature is subject to variability due to anatomical variations in condylar shape as well as difficulties encountered in the location of specific landmarks used in long axis determination. The development of a more reliable method of condylar long axis determination which would reduce the error associated with currently accepted techniques would be beneficial from a clinical as well as a research perspective.

1.3 - Purpose

The purpose of this retrospective research study is to examine the relationship between specific skeletal morphologic features (horizontal condylar angulation, sagittal and transverse condyle position) and the status of the temporomandibular joint (as determined by disc length and disc displacement measures) in adolescents. This will be accomplished by the examination of submentovertex (SMV) radiographs for skeletal data, and magnetic resonance imaging (MRI) for the determination of joint status. The determination of the relationship between several skeletal morphological features and joint status will provide useful information in two main areas. Firstly, it will allow clinicians and researchers to assess the usefulness of SMV radiographs in the identification and/or prediction of joint abnormalities. In addition, information derived from this may lead to an increased understanding of some of the contributing factors in the development of TMD.

It is also the intent of this research to investigate the reliability of several different methods of condylar long axis determination. If a method of long axis determination could be developed which overcomes some of the negative aspects of currently accepted methods, then this might prove advantageous from both a clinical as well as a research perspective.

1.4 - Research Questions

1. Is there a relationship between skeletal morphological features (horizontal condylar angulation, A-P and transverse condyle position) and joint status (disc length and disc displacement) in an adolescent population?

2. Is there a relationship between horizontal condylar angulation and condyle position (A-P and transverse) relative to cranial base landmarks?

3. Which is the most reliable of three different methods of condylar long axis determination?

4. What is the landmark identification error associated with specific landmarks utilized in SMV cephalometric analysis?

1.5 - Null Hypotheses

1. There is not a significant relationship between horizontal condylar angulation and joint status in an adolescent population.

2. There is not a significant relationship between A-P or transverse condyle position and joint status in an adolescent population.

3. There is not a significant relationship between A-P or transverse condyle position and horizontal condylar angulation in an adolescent population.

4. The interpolar method of determining a condylar long axis, as used in current literature, is the most reliable method of long axis determination.

1.6 - Literature Review

1.6.1 - Internal Derangement of the Temporomandibular Joint

A) Introduction

Internal derangement of the temporomandibular joint is an important cause of temporomandibular joint pain and dysfunction. Lownie and Lurie[20] defined internal or disc derangement as an abnormal relationship of the articular disc to the mandibular condyle, fossa and articular eminence. Disc derangements fall into the broad category of articular disorders, according to the International Headache Society's system of classifying temporomandibular joint disorders.[21] Derangements of the temporomandibular joint focus on a disturbance of condition, action, or function of the disc-condyle-fossa complex, and thus can be differentiated from destructive processes of the joint such as seen with degenerative diseases.[22] Also, myogenic disorders of the temporomandibular joint differ from internal derangements in many respects,[23] and belong to the masticatory muscle disorder classification of TMD.

B) Normal Anatomy

The temporomandibular joint is termed a *ginglymoarthrodial joint*, providing for both rotation and translation movements. The joint proper is comprised of the mandibular condyle fitting into the mandibular fossa of the temporal bone, separated by the articular disc. In a healthy state, the disc is composed of dense fibrous connective tissue devoid of any nerves or blood vessels. The articular surfaces of the glenoid fossa and the condyle are also lined by dense fibrous connective tissue, as opposed to hyaline cartilage. This dense connective tissue provides certain advantages, being less susceptible to the effects of aging and possessing a greater ability to repair compared to hyaline cartilage.[24]

The disc is normally biconcave with the disc being comprised of approximately equal thirds in an A-P dimension of a posterior band, an anterior band, and a thinned central portion. In the sagittal plane, the disc has a 'bow-tie' configuration, and in the coronal plane it demonstrates an arc shape,[25] with the medial extent of the disc being slightly thicker than the lateral extent. The precise shape of the disc is determined by condylar and fossa anatomy, as it is capable of adapting to the functional demands of the bony components in the healthy state. Destructive forces or structural changes within the joint are capable of causing morphological changes of the disc, resulting in disc pathology.

In the resting position, the disc lies superior to the condyle with the thicker posterior band of the disc lying superior to the condyle at approximately the 12 o'clock position relative to the condylar head. Prior to any movement, the thinned middle portion of the disc occupies an anterosuperior position between the condyle and the articular eminence. When the jaw opens, the condyle rotates and translates anteriorly toward the articular eminence, and the thin mid-portion of the disc remains interposed between the condyle and the eminence.[25] With anterior condylar movement, the thinned middle portion of the disc occupies a more superior position until it is at the 12 o'clock position at the crest of the eminence. As the condyle continues to move anteriorly and the mandible rotates open, the disc becomes positioned more posteriorly relative to the condyle.

The disc is attached posteriorly to the temporal bone and condyle by the posterior ligament or bilaminar zone. This zone is comprised of a *superior retrodiscal lamina* containing many elastic fibres and attaching to the tympanic plate, an *inferior retrodiscal lamina* composed of mainly collagenous, non-elastic fibres attaching to the posterior margin of the articular surface of the condyle, and *loose connective tissue (retrodiscal tissue)* lying between the superior and inferior laminae. This loose connective tissue is highly vascularized and innervated.

The superior and inferior attachments of the anterior region of the disc are to collagenous capsular ligaments. The *superior capsular ligament* attaches to the anterior margin of the articular surface of the temporal bone, and the *inferior capsular ligament* attaches to the anterior margin of the articular surface of the condyle. Between the superior and inferior capsular ligaments, the disc is generally considered to attach anteromedially to the upper belly of the *lateral pterygoid muscle*, however recent research has questioned the degree and significance of this attachment.[26] The lower belly of the *lateral pterygoid muscle* is a muscle of mastication, and attaches to the neck of condyle, and not to the disc per se.[25] The articular disc is also attached medially and laterally to the joint capsule *(medial and lateral capsular ligaments)* and to the poles of the condyle *(medial and lateral discal ligaments)*. These discal ligaments allow for hinging movement of the joint, and possess a vascular supply and nerve innervation, providing proprioceptive as well as nociceptive sensory information.

Other ligaments of the temporomandibular joint include the temporomandibular ligament, the sphenomandibular ligament, and the stylomandibular ligament, which are also referred to as 'accessory' ligaments. The *temporomandibular ligament* lies lateral to the capsular ligament and extends from the lateral aspect of the articular tubercle to the posterior lateral surface of the condylar neck. It functions to approximate the condyle to the articular eminence and limits the extent of pure rotational movement. As well, this ligament serves to prevent excessive posterior displacement of the condyle, and subsequent overstretching of the lateral pterygoid muscle.

The *sphenomandibular ligament* extends from the spine of the sphenoid bone to the lingula of the mandible, and the *stylomandibular ligament* extends from the styloid process to the posterior border of the ramus. Both running in a downward and forward direction, these ligaments help to prevent joint separation, limiting excessive protrusive movements.

The articular disc separates the inferior and superior noncommunicating joint spaces. The initial hinge action of opening occurs in the inferior joint space, and the second action of mouth opening occurs due to a deformation of the superior joint space during anterior translation of the condyle. In the healthy joint, there is a coordinated relationship among the disc, condyle and eminence, with the posterior band of the disc coming to rest posterior to the condyle with complete mouth opening. Synovial fluid fills both superior and inferior joint spaces, acting as both a source of nutrition, providing metabolic requirements to the joint tissues, and as a lubricant to decrease friction within the joint.

C) TMJ Dysfunction: Review of the Literature

Overview

Temporomandibular joint mechanical dysfunction occurs when natural disc position is altered. Internal derangement has been classically divided into three categories which represent increasing severity of conditions:[27]

1) *Anterior displacement with reduction* is considered the least severe of disc displacements. In this condition, the disc is commonly displaced anteriorly, but may be subluxed medially and laterally. Tasaki et al.[28] studied disc displacement in a group of 243 patients and 57 symptom-free volunteers using MRI, and identified eight different types of disc displacements, including rotational displacements. This supported the work of Matsuda and Yoshimura[29] who also found a proportion of rotational disc displacements by using MRI and a smaller patient population. Both groups found anterior and anterolateral displacements to be the most common displacements in their respective patient populations, although Matsuda and Yoshimura found a larger proportion of lateral displacements than Tasaki's group. This discrepancy may be explained by the different sampling methods used and possible inter-examiner differences. Disc displacement with reduction is often associated with joint noise with or without associated pain,[30,31] and a normal range of mouth opening is usually present. In this condition, abnormal disc position exists with the mouth in the closed position, and as the disc is recaptured on mouth opening a click is sometimes heard. This click is usually reciprocal in nature, often being louder upon opening, and is thought to be a result of friction between the posterior band of the disc and the condyle as they move in opposite directions. Williamson[22]

suggested that clicking is most frequently caused by the condyle hitting the disc and temporal component of the joint after having rapidly passed the posterior band of the disc. It is generally thought that the later the click during opening, the more severe is the internal derangement, as it represents a greater loss of elasticity in the bilaminar zone.[27]

2) *Disc displacement without reduction* is considered a more severe form of internal derangement, as it represents a condition in which the loss of elasticity of the bilaminar zone is so great that the disc is unable to return to its physiologic position and remains anterior to the condyle. In this condition, the disc represents a physical barrier to anterior translation of the condyle, and limited opening results. This is referred to as "closed lock". Because the disc is not recaptured, there is usually no click associated with this condition.

3) *Disc displacement with perforation* may occur as a result of chronic disc displacement without reduction. Prolonged loading of the bilaminar zone is the most frequent cause of disc perforation,[27] and is associated with pain and limitation of mouth opening. At times, however, excessive stretching of the bilaminar zone may allow for normal translatory movements. Osteoarthritis, or non-inflammatory degenerative joint disease, has been associated with disc displacement and perforation.[25,32-34]

Prevalence

There have been significant studies on the prevalence of TMD and internal derangement in the adult as well as in the adolescent population. In children and adolescents, signs and symptoms of mandibular dysfunction are a relatively frequent finding. Williamson[35] evaluated 304 pre-orthodontic children between 6-16 years of age and found that 35% complained of muscle or TMJ pain or else had detectable clicking. Hans et al.[36] investigated 51 juvenile orthodontic patients aged 8-15 years by MRI, clinical examination, and questionnaire, and found that 19.8% had a history of pain or clicking of the TMJ. Nilner and Lassing[37] found 71.6% of 440 Swedish children between 7-14 years of age demonstrated one or more signs of mandibular dysfunction. Keeling et al.[30] collected data on 3428 grade schoolchildren between the ages of 6 and 12 years, and found 10% to have temporomandibular joint sounds. Farrar and McCarty[38] suggested that 70% of patients with TMJ symptoms have some form of disc displacement and possible clicking.

Discrepancies exist, however, between subjective reports and clinical signs and symptoms, and definitive diagnosis of internal derangement by MRI or arthrography. One must be cautious when evaluating data which is based on subjective reports from children and comparing those results to those clinically-derived or obtained through the use of more definitive imaging modalities. Thilander[39] noted a difference in the reporting of subjective symptoms between children and adults, as children frequently do not report symptoms. Clinical signs of dysfunction in children appear to be relatively frequent, however the significance of clicking in this population is open to debate. Lieberman et al.[40] evaluated 32 pre-orthodontic children between 7 and 15 years of age and found that clinical examination tended to overstate the incidence of internal derangement when compared to MRI findings. Lieberman's group found a 59% incidence of mandibular dysfunction and/or internal derangement by clinical assessment alone, as compared to the

MRI results which detected disc displacement in only 5% of the joints imaged. The Hans study revealed 11.8% of his group of orthodontic patients had anterior disc displacement assessed by MRI as compared to almost 20% with a history of TMJ pain or clicking. The wide variation in results is likely a reflection of methodological variability that included both inter-examiner variation and subject selection.

In the adult population, Katzberg et al.[41] used sagittal and coronal MRI and found a prevalence of disc displacement of 33% in a sample of 76 asymptomatic volunteers and 77% in a sample of 102 symptomatic patients. Disc displacement without reduction was more prevalent in symptomatic subjects - 20% of symptomatic patients demonstrated non-reducing displaced discs, whereas only 4% of volunteers showed non-reducing discs in one or both joints. Ishigaki et al.[42] used arthrography to assess the joints of 247 symptomatic patients, and found 72% to have internal derangement. Of the patients with internal derangement, 47% had disc displacement with reduction, 32% had disc displacement without reduction, and 15.4% had disc displacement without reduction associated with disc perforation.

Paesani et al.[43] studied the prevalence of internal derangement in patients with TMD using both MRI and arthrographic means of assessment. Using a sample of 115 patients aged 10 to 73 years of age with signs and symptoms of TMD, 78% were found to have either unilateral or bilateral internal derangement and 22% demonstrated normal joints bilaterally. Of the 230 joints imaged, 60 (26%) showed disc displacement with reduction, 8 (3%) showed disc displacement without reduction, and 29 (13%) showed disc displacement without reduction associated with osteoarthritis. Interestingly, a portion of the patients (51) were examined with arthrography, whereas the remainder (64 patients) were examined using MRI. This may have influenced the findings and the conclusions derived from them, as MRI provides additional diagnostic information such as sideways and rotational displacements and evidence of joint effusion. Conclusions drawn from a sample using different means of assessment must be looked at critically.

Lundh and Westesson[44] investigated the frequency and distribution of clinical signs of internal derangement in an adult population of 403 non-TMD subjects. Clinical signs of internal derangement were found in 19% of the sample - 7% of the sample had reciprocal clicking and 12% had a history of clicking replaced by limitation of opening and deviation to the affected side (disc displacement without reduction). This study showed that clinical signs of TMJ internal derangement are present in nearly one fifth of non-TMD adult patients, and that those with clinical signs of internal derangement may also have subjective symptoms for which no treatment is sought.

Clinical signs of disc displacement are not 100% reliable. Lownie and Lurie[20] noted that up to 40% of the population have asymptomatic clicks during mandibular functioning. However, some clicking and limitation of opening might not necessarily represent internal derangement, and internal derangement might also be present in persons who do not present with clinical signs. Despite this, Lundh and Westesson[44] believed that clinical signs of joint sounds and mouth opening with observed deviations were probably adequate indicators of internal derangement for use in epidemiologic studies. A 59% accuracy in clinical diagnosis of disc position as compared to 73% accuracy using MRI has been reported in the literature.[45] Accurate diagnosis of disc displacement requires imaging studies such as arthrography or magnetic resonance imaging, which are not often practical for a non-patient population.

Sutton et al.[31] compared condyle/disc relationships on MRI between subjects with clinically silent TMJs and subjects with readily discernible TMJ sounds. The MRIs of the group with clinically discernible sounds tended to show a change in the relationship between the head of the condyle and the intermediate zone of the disc, whereas no condyle/disc change was found in the group with clinically silent joints. These authors pointed out that all joints create some sound during function depending on the recording device used, however different characteristics of the subclinical sounds versus the clinical sounds may indicate different sound origins.

Taken together, these studies seem to indicate that a high percentage of patients with clinical signs of TMD have imaging evidence of internal derangement. Thus, it may be likely that internal derangement is a contributing factor to TMJ signs and symptoms in a significant proportion of patients. It has been shown that internal derangement can be asymptomatic, however the prevalence of internal derangement has been shown to be much lower in persons without symptoms. Though evidence of internal derangement exists in symptomatic patients, this does not necessarily indicate that the source of the symptoms is internal derangement. The precise source of pain requires the results of additional tests in combination with imaging studies.[43] Disc displacement likely plays a role in the pain process, although the evidence provided shows that disc displacement may exist in the absence of symptoms. It follows, then, that change in disc position in isolation is not the sole factor in the development of pain. Disc displacement may represent part of the equation, however inflammation and disc dysfunction may also play a significant role. A biological response to the change in disc position may be the initiator of the pain process, such as capsulitis, impingement of the joint capsule, or impingement or pressure on the retrodiscal tissues. Sano and Westesson[46] in a MRI study reported an increased T2 signal in the retrodiscal tissue of painful joints, possibly indicating an increased vascularity of the joint tissue. This may represent an alteration of the tissue in the posterior disc attachment as a result of altered function.

Results of studies on internal derangement in asymptomatic volunteers are dependent upon accuracy of the clinical examination and patient cooperation. Self reporting is likely not a reliable indicator of TMJ sounds. Also, the age of the asymptomatic group may also be an important factor. Asymptomatic development of disc displacement is not uncommon, especially in elderly people. Also, older patients might not remember symptoms of previous joint problems.[47] Tasaki et al.[28] pointed out that abnormalities within articular tissues in asymptomatic individuals are not unique to the TMJ, as studies have shown similar incidence in knee joints as well as the cervical and lumbosacral spine. This evidence suggested the importance of basing treatment decisions upon patient symptoms and not solely on morphologic findings. A functional explanation for the finding of a relatively high incidence of disc displacement in asymptomatic subjects might lie in the following observation. When the disc is displaced so that the posterior lamina is sufficiently stretched it may function as a 'pseudodisc', allowing free movement of the disc anterior to the condyle without mechanical hindrance and without subjective symptoms that are normally consistent with dysfunction.

The absence of internal derangement in symptomatic patients may be due to contributions to joint etiology other than disc displacement, such as primary osteoarthritis without internal derangement or muscle dysfunction. In addition, subject selection criteria, interexaminer biases, and lack of strict criteria for the classification of displacements may influence the reported incidence of disc displacement. This may help to explain the variability in prevalence of internal derangements as well as the differences in the reported directions of disc displacements reported in different investigations.

Previous studies which have utilized different definitive diagnostic means for determination of disc displacement may under or overestimate the prevalence of this condition. Tasaki et al.[28] noted that lower joint space sagittal projection arthrography may not consistently identify sideways displacement of the disc. In addition, surgical assessment of disc displacement may lack precision since surgery does not provide a cross-sectional view of the joint. MRI is considered to be the current gold standard for disc identification purposes, however MRI of joints which fail to image in a corrected coronal view may lead to underdiagnosis of lateral displacements and overdiagnosis of medial displacements, since the laterally displaced disc may not be depicted in the same image as the condyle in this view. Recent evidence has suggested that disc displacements present as a spectrum of displacements in all directions, with rotational displacements making up a significant proportion of all disc displacements.[28,29]

Etiology

i) Craniofacial Morphology

Altered facial structure has been reported as a result of chronic synovitis as found in inflammatory conditions such as juvenile rheumatoid arthritis.[48] If destruction of the condylar head through an inflammatory process influences mandibular development and craniofacial structure, then any alteration in condylar anatomy and function may also have an effect on such structures. Brand et al.[45] used MRI and lateral cephalometric headfilms and investigated the relationship between skeletal pattern and internal derangement in a sample of 47 females between the ages of 18 and 63 years. Two groups, one representing female volunteers with normal TMJs, and the other a sample of 24 female patients with documented internal derangement were used. The findings of this study indicated that patients with internal derangement had significantly smaller lengths of maxillary and mandibular bodies, however other angular and linear measurements showed no significant differences. By use of the age range indicated, it is possible that internal derangement could have occurred in the patients following cessation of growth, thereby not demonstrating a significant effect on the patient's skeletal form in other dimensions.

Schellhas et al.[1] also investigated the relationship between internal derangement and facial development. Using MRI and radiographic records, 114 consecutive children aged less than 15 years with suspected TMD or skeletal abnormalities were retrospectively analyzed. 93% (56 of 60) of the retrognathic children were found to have internal derangement, generally bilaterally and often of an advanced stage. In cases of lower facial asymmetry, the chin was commonly deviated toward the smaller or more degenerated

TMJ. Of the 16 subjects with normal TMJs, most had a normal facial structure. With reference to these findings, the authors concluded that internal derangements are both common in children and may contribute to the development of retrognathia, with or without asymmetry in many cases. The authors suggested that internal derangement either arrests or retards condylar growth, resulting in decreased posterior vertical dimension and ultimately mandibular deficiency or asymmetry.

Dibbets and van der Weele[2] conducted a longitudinal study which investigated the relationship between signs and symptoms of TMD and craniofacial form as assessed by lateral cephalometric radiographs. Subjects averaged 12.5 years of age at the time of initial examination, and were reexamined at an average age of 26.4 years. These authors found a relationship between TMD signs and a sagitally shorter midface in adults. These same morphological features had been noted approximately 14 years earlier on initial examination. This suggests that not all TMD signs can be regarded as the exclusive result of some etiologic factor operating after the teenage period. Dibbets et al.[3] reported that children as young as 7 years of age can demonstrate clinical symptoms of TMJ dysfunction that point to a deviant facial morphology, in particular a smaller and retrognathic mandible. According to these authors, other features of children with dysfunction are shorter posterior face height, shorter ramus and smaller corpus, a larger gonial angle, and a steeper mandibular plane. These characteristics relate dysfunction to disturbed condylar growth.

On the other hand, Dahlberg et al.[49] did not find an association between disc displacement and the type of dentofacial anomaly in orthognathic surgery patients, although disc displacement was a common finding in patients who sought orthognathic surgery.

Artun et al.[50] evaluated the relationship between condylar position and signs and symptoms of internal derangement in a group of post-orthodontic female patients. They found a more posterior condyle location in tomographic sections of patients with clicking in comparison to patients without clicking. However, this does not answer whether or not posterior condyle position is a consequence of anterior disc displacement or a cause. Tallents et al.[51] also provided an account of more posteriorly positioned condyles in a TMD patient population. Westesson and Lundh[52] found that patients with pronounced joint pain and disturbed joint function, temporary locking, and a deep anterior recess of the lower joint compartment were more likely to progress to a closed lock from a reducible disc derangement condition than those without these features.

Ren et al.[53] used corrected tomograms and dual space arthrotomography and investigated the relationship between steepness of the articular eminence and disc displacement in 34 asymptomatic volunteers and 71 patients. Contrary to what was hypothesized, they found a steeper articular eminence in asymptomatic volunteers than in the patients, due mainly to remodelling or degenerative changes of the eminence in patients who demonstrated more advanced internal derangement. No differences were found in the steepness of the eminence between the volunteers and the patients with no signs of osseous changes. The remodelling process tended to flatten the articular eminence of deranged joints, particularly in the lateral section of the joints, to the point where they were more shallow than those of healthy volunteers. Hinton[54] also reported flattening of the mandibular fossa as an adaptive response to altered condylar positioning and function. Data from Galante et al.[55] supported the results of Ren's group, finding no angular or linear differences for depth of the articular fossa or angle of the articular eminence between symptomatic patients and asymptomatic volunteers.

ii) Occlusion

Various occlusal factors have been implicated as etiologic factors in internal derangement of the temporomandibular joint. Lownie and Lurie[20] suggested that Class II div 2 malocclusion, missing tooth support with posterior bite collapse, and occlusal contacts which deflect the condyles posteriorly, are all related to internal derangement. There have been several explanations given for the possible effects of occlusal variables on temporomandibular joint dysfunction. Ricketts[56] provides the following:

- Abnormal overjet, such as seen in typical Class II div 1 relationships, may cause the patient to move the mandible far forward in order to compensate for protruding teeth during function, and in forced occlusion the mandible would be forced posteriorly again in returning to its original position. This abnormal range of motion may cause trauma to the joint.

- Deflective occlusal contacts (ie: posterior inclines) which cause the condyle to be displaced posteriorly may lead to anterior disc displacement as the condyle becomes lodged behind the disc.

- Balancing side contacts due to lack of sufficient anterior or posterior guidance may upset the normal balance, increasing the stress on certain joint structures.

- Lack of posterior support due to missing teeth increases the loading on the joint, which may eventually lead to joint breakdown and degeneration.

Williamson[35] also supported the role of overjet and anterior guidance in the etiology of temporomandibular dysfunction. He found a strong predisposition for high mandibular planes and Class II div 1 malocclusions with open bites anteriorly, or else deep bite cases with excessive anterior guidance in a dysfunctional group. Williamson related much of these features to altered lateral pterygoid muscle function.

Pullinger and Seligman[57] looked at the relationship between overbite and overjet and different diagnostic groups of TMD. Incisal overbite tended towards the minimal and open bite ranges in the osteoarthritis group as compared to the controls. Open bite occurred in the osteoarthritis group, but not in symptom-free controls. Deep bite was found not to be more common in the disc displacement or osteoarthritic group. The study also demonstrated an increased overjet in the osteoarthritis group.

In general, results appear equivocal, and current literature does not appear to support a strong relationship between horizontal or vertical overlap and intracapsular disorders in the samples studied.

iii) Orthodontic Treatment

Reynders[58] provided a comprehensive review of literature and concluded that the sample studies available in the literature tend to indicate that orthodontic treatment should not be considered responsible for creating temporomandibular disorders. Sadowsky[59] provided another review of the literature pertaining to the possible relationship between orthodontic treatment and TMD, and also concluded that the overwhelming evidence supports the conclusion that orthodontic treatment on children and adolescents does not generally present a risk for the development of TMD in later years. Tallents et al.,[51] also in a review, concluded that it is appropriate to state that orthodontic therapy neither increases or decreases the "risk" of developing TMJ pain and dysfunction. However, due to the fact that more people receive orthodontic treatment today, it stands to reason that more people presenting for treatment of TMD will have had some type of orthodontic treatment.

Artun et al.[50] investigated whether or not maxillary anterior teeth retraction through orthodontic treatment would affect the anterior-posterior position of the mandible, and subsequently whether this had any relationship to signs and symptoms of internal derangement. Using 29 female Class II div 1 patients who underwent upper bicuspid extraction treatment and 34 female patients who had been treated non-extraction for Class I malocclusion, they noted that on certain tomographic sections (right central and medial) mean condylar position, as determined by distance from concentricity, was more posteriorly located in patients who were treated with extraction. The authors suggested that the differences which were seen were due to more anteriorly positioned condyles in the Class I non-extraction group, and not necessarily from condyles which had moved posteriorly as a result of treatment (pre and post tomographs were not done). However, no intergroup differences were found in the number of patients with clicking. Interestingly, the tomographs used in this study were not preceded by submentovertex views for the determination of the condylar long axis.

A longitudinal study by Kremenak et al.[60] did not find significant differences in TMD signs and symptoms between those treated with or without extractions, and further work could not support an etiologic role for orthodontic treatment in TMD in their sample.[61]. This was supported by Egermark and Thilander[62] who found that those who had experienced orthodontic treatment actually demonstrated a lower clinical dysfunction index than those who had not had a history of orthodontic treatment.

Katzberg et al.[63] looked at internal derangement using MRI in a group of 76 asymptomatic volunteers and 102 symptomatic patients. There was no association found between internal derangement and orthodontic treatment in symptomatic patients or in asymptomatic volunteers. Rendell et al.[64] followed a group of 451 patients who entered orthodontic treatment without signs or symptoms of TMJ disorders. After 18 months of treatment, none of this group had developed signs or symptoms of TMJ dysfunction.

iv) Trauma

Trauma has been cited as one of the main causes of internal derangement. Katzberg et al.[65] reported that 22 out of 89 patients with internal derangements proven arthrographically had a history of trauma immediately before the onset of their TMJ problems. According to Katzberg, trauma was reported as a cause of TMJ pain in 26% of pediatric TMD patients. Stack[66] stated that the greatest cause of TMJ disorders was trauma, especially if repetitive dental microtrauma was considered. Trauma is often categorized as being macrotrauma or microtrauma. Both types of trauma, in addition to possible mechanical disruption or alteration of the joint structure itself, are believed to influence the chondrogenic area of the condyle and are thus capable of having a deleterious effect on condylar growth. Macrotrauma may include a blow causing a condylar fracture or a joint infarction followed by healing and subsequent undergrowth. This is often the type of trauma that occurs in children's accidents in which condyles are fractured as a result of falling or by involvement in a sporting activity. Subsequent growth arrest may occur. Stack[66] reinforced the need for accurate history taking during initial examination, including specific inquiries about long forgotten birth and/or playground trauma, including falls from countertops, bassinets or changing tables, in addition to trauma in the toddler stage. Macrotrauma also includes insult by iatrogenic means, which includes general anesthetic administration, third molar surgery, endoscopy, tonsillectomy, and forced prolonged opening such as in long dental appointments.

Microtrauma may occur as a series of repeated small injuries or strains within the joint. Such causes may include occlusal trauma, loss of tooth support, or functional interferences. Trauma, whether it is of the micro or macro variety, may influence condylar anatomy, whether it be by its effect on the growth process in children, or the cause of degenerative and remodelling changes later in life.[56]

Goddard[67] followed a group of 130 orthodontic patients of which 6 asymptomatic patients subsequently were involved in a traumatic event (4 subjects in motor vehicle accidents, 1 involved in a fight, and 1 in a fall). All six of these subjects developed TMD signs and symptoms. Two of the subjects who were involved in motor vehicle accidents and the one involved in a fall were diagnosed with disc displacements (confirmed by MRI) after the traumatic episode.

Weinberg and LaPointe[68] have suggested that extension-flexion mechanics such as which may exist in whiplash-type injuries result in posterior movement of the mandible *less quickly* than the posterior movement of the head, resulting in downward and forward displacement of the disc-condyle complex relative to the cranial base. According to these authors, this leads to stretching and tearing of the posterior attachment and associated soft tissues, as well as the discal attachments to the medial and lateral condylar poles.

This is contradicted by both Goldberg[69] and Howard et al..[70] According to Goldberg, it is unlikely that a single traumatic episode would result in an anterior disc displacement if one were not already present to begin with. Blunt trauma to the mandible with teeth in occlusion would not cause a condylar displacement since the mandible is fixed by the clench. A direct blow to the masseter, temporalis, or directly to the TMJ with teeth in occlusion could however result in myofibrotic contraction with associated inflammation, but no disc displacement. A direct blow with teeth not in occlusion may cause a displacement of the condyle, and subsequent soft tissue injury with possible edema and hemorrhage may prevent closure of the mandible, however, according to Goldberg, this does not necessarily represent disc displacement due to the trauma. Goldberg notes that a secondary mechanism for derangement may be operational and relates this to the continued contraction of the superior lateral pterygoid muscle as a result of trauma. This may lead to a change of disc morphology , as the resulting muscle pull can result in a thinning of the posterior head of the disc due to the constant compressive load. One may theorize that functional movements may subsequently lead to an anteromedial displacement of the disc. Goldberg suggested that increased joint clicking as a result of extension-flexion injury is not necessarily a result of disc displacement, but rather due to a transient change in condylar position due to a change in posture (a more distal mandibular position due to altered head posture in response to contraction of anterior cervical muscles). Goldberg postulated that once the soft tissue problems (excessive muscle contraction as a result of the injury) are resolved, clicking will stop. Howard et al.[70] mechanically assessed the whiplash-type injury, and according to their mechanical analysis suggest that no significant tensile forces are generated across the temporomandibular joint in this type of injury. This contradicted the suggested mechanism of internal derangement (mechanical tearing of the joint attachments) as proposed by Weinberg and LaPointe.[68] Howard suggested that the forces in extension-flexion type injury are essentially compressive in nature rather than tensile, and that the force vector range associated with this type of injury is similar to that expected at the joint in normal chewing activity and mostly of lesser magnitude. Accordingly, they reasoned that such a mechanism would fail to produce forces of sufficient magnitude and direction to induce myospasm due to trauma to the superior head of lateral pterygoid muscle.

v) Muscle Dysfunction

Because of the hypothetical role of the superior lateral pterygoid muscle in coordinating disc movement during mandibular closure, there has been a considerable amount of controversy over the precise role of the lateral pterygoid muscle in TMJ dysfunction and disc displacement. Literature suggests that the superior lateral pterygoid muscle does not always attach to the TMJ disc in normal subjects, but rather under the disc or into the fovea in a significant percentage of cases. Bittar et al.[26] studied sections of 20 intact joints from autopsy specimens with an average age of 26.2 years. Specific examination of the histologic organization of the lateral pterygoid muscle interface with the temporomandibular joint revealed no consistent division of the lateral pterygoid muscle into separate anatomic muscle heads. Bittar's findings indicated that only 31% of the joint specimens demonstrated muscle attachment directly to the anterior portion of the articular disc. The most frequent configuration was observed to be a relatively parallel direction of muscle fibre orientation where fibres inserted primarily into the pterygoid fovea on the anteromedial surface of the condyle. In specimens with direct muscle to disc attachment, fibres inserting into the disc represented only 2.4 to 6.0% of the total superior-inferior length of the muscle insertion. In contrast, Lownie and Lurie[20] described two distinct heads of the lateral pterygoid muscle, each having distinct functions which are antagonistic in action, with the superior head being active in elevation of the mandible, and the inferior head being active in opening movements. According to these authors, disc displacement may result from a lack of coordination between the two heads. Discrepancies in anatomic descriptions of the muscle attachment to the disc may be due in part to different examination techniques used in assessment. Dissection alone may not accurately represent joint anatomy on a micro level. Histologic sections of sufficient magnification are required to differentiate muscle tissue from adjacent fibrous connective tissue of the disc, capsule and tendon.

Wongwatana et al.[71] studied the site of the superior lateral pterygoid muscle insertion into the temporomandibular joint disc and related this to disc displacement in a sample of cadavers (average age 77.6 years). Thirty of 42 joints where the superior lateral pterygoid muscle inserted directly into the disc demonstrated an anteriorly displaced disc. Only 19 of 36 discs without direct muscle attachment demonstrated disc displacement. Thus, a relationship between muscle insertion into the disc and disc displacement was found. The superior lateral pterygoid muscle, which contracts during closure, maintains the disc in an anterior position during closure. According to one theory, lateral pterygoid muscle contraction directly opposes the posteriorly - moving condyle which is directly influenced by the heavy pull exerted by posterior deep fibres of the masseter and posterior fibres of the temporalis, and can result in an anteromedial displacement of the disc. Goldberg[69] suggested that continued contraction of the superior lateral pterygoid muscle may lead to a gradual thinning of the posterior band of the disc, predisposing the disc to displacement. Also, Katzberg[41] noted a statistical association between bruxing and TMJ disc displacement. Whether these mechanisms represent a causal relationship between superior lateral pterygoid activity and internal derangement is open to debate since other factors are obviously involved, including the integrity of discal attachments to the lateral and medial condylar poles and the posterior attachment of the disc. The attachment site of the superior lateral pterygoid muscle may be significant only in situations where the other discal attachments are compromised, for example torn or stretched due to trauma. It seems plausible that a balance of soft tissue forces is at play, with each playing a specific role. The relative role of each individual factor is not defined, but the extent of muscle attachment to the disc may play a role. As noted earlier, Bittar et al.[26] found minimal muscle fibre insertion into the disc in the few cases which demonstrated muscle attachment at all. It seems implausible that such minimal attachment would be capable of exerting sufficient force to displace the disc anteriorly. This finding of a lack of distinct muscle heads of the lateral pterygoid muscle would oppose the theory put forth in which it is believed by some that hyperactivity and spasm of this muscle could contribute to anterior disc displacement due to opposing action of two distinct muscle heads. Likewise, this contradicts evidence of Zijun et al.[72] who used needle electrodes in 38 adult patients and found distinct EMG characteristics in patients with internal derangement by observing differences in superior versus inferior lateral pterygoid muscle activity during mandibular functioning. The accuracy of placing needle electrodes in specific heads of the lateral pterygoid muscle must be questioned in light of the evidence of Bittar and others. Also, relating muscle activity to anatomical features or patient symptoms does not prove a cause and effect relationship, as altered muscle function may result from a disc displacement rather than the reverse situation.

Despite the findings which appear to diminish the direct role of lateral pterygoid muscle pull on the disc itself in disc displacement, it does not necessarily disclude the role of this muscle in joint derangement entirely. The action of the lateral pterygoid muscle on the condyle itself may play a significant role in determining joint mechanics and subsequently the integrity of the discal attachments which are necessary for joint stability and function. It is possible that different angulations of the lateral pterygoid muscle, as seen in an axial view, may alter joint dynamics to the extent that it may contribute to deleterious joint loading patterns. Yamashiro,[73] in a 1984 Masters thesis, found that dolichocephalic facial patterns demonstrated smaller lateral pterygoid muscle angulations as assessed by axial computed tomography. Differing muscle angulations would directly influence force vectors acting within the joint, for example greater immediate sideshift with a greater transverse force component, and could possibly result in added stress on certain discal attachments, ultimately effecting disc position.[74]

vi) Osteoarthritis (OA) and Systemic Factors

Breakdown of temporomandibular joint tissues may occur due to increased mechanical stress and/or a decreased ability of the tissues to adapt to such stress.[75] Several authors have described the relationship between degenerative joint disease and internal derangement.[33,75,76]

DeBont and Stegenga[32] have provided a relevant review of the pathology of temporomandibular joint internal derangement and osteoarthritis. The TMJ is a synovial joint similar to other synovial joints in the body, however it contains fibrocartilage as articular cartilage as opposed to hyaline cartilage. Due to the fact that fibrocartilage receives nutrition from synovial fluid, synovial membrane changes have a likely effect on the articular disc as well as the articular fibrocartilage metabolism. DeBont and Stegenga point out that osteoarthritis may develop without disc displacement and disc displacement may be present without osteoarthritis, however internal derangement is highly correlated with TMJ osteoarthritis. Articular cartilage and disc breakdown due to OA mechanisms may effect the sliding properties of joint surfaces. Changes in the composition and quantity of synovial fluid may give rise to friction and adhesive wear which may impair movement of the disc and possibly lead to stretching of the disc attachments and subsequent displacement of the disc. It has been suggested that displacement of the articular disc may be a sign of TMJ osteoarthritis rather than its cause.[32] Stegenga et al.[76] reinforced the view that pre-existing osteoarthritis is often a primary factor which may subsequently lead to internal derangement. Cartilage and synovial membrane changes as a result of OA have been suggested to be responsible for a destructive process of cartilage breakdown and attempts at repair. Subsequent internal derangement may occur as a result of impaired gliding capacity of the articular disc as a result of the OA process. This, however, does not preclude the possibility of a pre-existing internal derangement due to trauma or inherent joint laxity playing an influential role in the onset and progression of OA.

If OA is considered a primary disease which subsequently influences further manifestation, what is the pathophysiology existing in OA? Stegenga et al.[76] has presented a detailed account of the pathophysiologic process operational in TMJ osteoarthritis. As Stegenga noted, articular cartilage of the TMJ and the underlying bone undergo changes in form by tissue remodelling in an attempt to maintain an equilibrium state. Increased joint loading can stimulate the remodelling process, which involves increased synthesis of proteoglycans and collagen fibrils. Absolute or relative overloading of the joint may disturb the equilibrium between form and function, giving rise to tissue breakdown. The osteoarthritic process is characterized early on as a structural failure of articular cartilage due to loss of proteoglycans, a change in the arrangement and size of collagen fibrils, and increased water content. Progression of cartilage changes may or may not occur, depending on tissue response and environmental factors. Cartilage breakdown is followed by attempts at repair, with proliferation of chondrocytes and increased synthesis of proteoglycans and matrix collagen, largely in the proliferative zone of the cartilage. The repair process may maintain the joint in a steady state of equilibrium, or the degradation process may dominate, resulting in further breakdown. The articular disc does not contain a proliferative zone, and thus is not capable of the same degree of repair as the articulating surfaces within the joint. Stegenga pointed out that progression of reducing disc displacement to non-reducing disc displacement may be due to cartilage breakdown (osteoarthritic process) which effects the sliding surfaces of the joint and synovial fluid alteration. The net effect of these changes is increased friction, adhesive wear, impaired disc translation, joint stiffness, and subsequent increased stretching of the disc attachments, ultimately resulting in a non-reducing disc. Katzberg[25] supported the concept of structural and ultrastructural changes in the cartilagenous tissues, and suggested there is growing evidence of significant changes in histopathology of the TMJ disc and posterior ligament in association with internal derangement. It is not unreasonable to suggest that metabolic and biochemical changes may occur in the TMJ disc just as occurs in diseases of the disc of the spine. This may represent a whole new vista of research using MR spectroscopic studies in evaluating these changes in the TMJ.

Ali and Sharawy[77] studied histopathological changes in rabbit craniomandibular joint with experimentally induced anterior disc displacement. The mechanical trauma associated with anterior disc displacement leads to a cascade of reparative and degenerative changes, including fibrillation of the disc, fibrosis of the bilaminar zone, chondrocytic cell clustering and subchondral hemorrhage and fibrosis of the cartilage of the condyle, chondrocytic cell clustering in the articular eminence, and marked synovial membrane hyperplasia. These changes were consistent with those changes described in osteoarthritis.

In anterior disc displacements, the bilaminar zone is subjected to increased loads, which may lead to an inflammatory process. Changes in the posterior band include thinning, fatty degeneration, and perforation. However, this region is also capable of certain adaptive changes, including decreased vascularity and elastin content and fibrosis of the anterior part of the bilaminar zone. Further cartilage breakdown may lead to disc perforation and denudation of the subchondral bone. Gross bony changes can be observed at this stage, and features such as osteophytic lipping, flattening of the condyle and eminence, and decreased height of the mandibular ramus can be observed.[76]

Systemic factors such as the influence of inflammatory mediators, aging, and other factors which influence the adaptive process are likely to be significant determinants of the progression of joint disease. Larheim et al.[78] provided an account of a woman with rheumatic disease who developed condylar destruction and anterior disc displacement over a 7 month period. It was theorized that the inflammatory changes existing with this disease played a significant role in destruction of the posterior attachment and subsequent condylar destruction. Thus, rheumatic disorders such as rheumatoid arthritis, ankylosing spondylitis, and psoriatic arthritis may involve the TMJ.

1.6.2 - Condylar Angulation

Condylar angulation, the angle which the medial - lateral long axis of the mandibular condyle makes relative to the frontal plane, may be an important feature of the temporomandibular joint. Laurell et al.[79] measured condylar angles directly from dried skulls, and found a positive correlation between intercondylar distance measured at the medial poles and condylar angulation. Results of this study also demonstrated a positive correlation between condylar angulation and the angle the inferior border of the mandible makes with the midsagittal plane (jaw taper). Lew and Tay[13] determined condylar angulation in a sample of 32 male Chinese subjects using submentovertex (SMV) radiographs and suggested a relationship between facial form and condylar angulation.

Tadej et al.,[14] using SMV's of 104 pre-orthodontic patients between the ages of 9 and 17 years, investigated the relationship between malocclusion and TMJ morphology. Their study revealed no significant differences in condylar angulation between groups with normal occlusion and those with malocclusion, however noted dimensional differences in the condyles between the groups. Medial-lateral condyle dimension in the normal group increased with age to approximately one half the anterior-posterior dimensions, a finding which supports the data of Taylor et al.,[80] however those with transverse occlusal anomalies were found to demonstrate less medial-lateral condylar width. Thus, a relationship was suggested between transverse malocclusion and abnormal TMJ morphology, with a possible link being an altered muscle influence on the condyle due to associated functional alteration. O'Byrn et al.[81] also found significant alterations due to transverse anomalies, having studied 60 adult patients with unilateral crossbites. These researchers found the condyle on the crossbite side to be positioned more posteriorly with the whole mandible being rotated in relation to the cranial floor. A posterior displacement of the glenoid fossa was inferred from the available data, and evidence for significant remodelling was shown as a result of the altered function within the joint.

Hackney et al.[82] and Carter et al.[83] studied changes in condylar angulation as a result of sagittal split osteotomy procedures. Hackney's group used SMV radiographs and determined that intercondylar angles from pre- to post- surgery varied depending on the data used, however the differences were not found to be of statistical or clinical significance. Carter et al. measured condylar angulation on dried mandibles and found increases in condylar angulation following sagittal split procedures performed on the mandibles in 82% of the cases. These cases included procedures involving both anterior and posterior movements of the distal segments.

Further research has evaluated the relationship between condylar angulation and malocclusion. Seren et al.[15] evaluated condylar position and angulation by computerized tomography in 21 untreated Class III adults and 18 normal controls, and found relative condylar protrusion and mediolateral condylar elongation within the glenoid fossa to be correlated with the Class III malocclusions. In addition, the Class III group demonstrated larger condylar angulation relative to a sagittal reference line, which essentially described a flatter or more perpendicular condylar angle in an axial view.

The relationship between condylar angulation and irregularities of the temporomandibular joint has also been investigated. Ebner et al.[84] studied condyle morphology and angulation in 18 human cadavers using SMV radiographs and related these findings to pathologic joint changes, both osseous and disc-related, seen on dissection. No statistically significant differences between the normal and abnormal joints were noted. Westesson and Liedberg[85] investigated the association between condylar angulation and temporomandibular joint pathology in a heterogeneous sample of 364 symptomatic TMD patients. SMV radiographs were used for condylar angle determination and arthrography was used to categorize disc position. These researchers were unable to find a significant statistical association between the angle of the condyle and the arthrographic diagnosis.

Westesson et al.[17] used a heterogenous sample of 30 normal volunteers and 200 TMD patients, and looked at the relationship between condylar angulation and joint irregularities using magnetic resonance imaging (MRI), both for condylar angle determination and for joint assessment. The temporomandibular joints, in both sagittal and coronal views, were categorized on a continuum as being normal, showing disc displacement with reduction, disc displacement without reduction, or degenerative joint disease. Findings showed that the more advanced pathologic changes were associated with greater (steeper) condylar angles.

Maxwell et al.[16] studied 52 patients who presented with clinical indicators of temporomandibular joint dysfunction, and did not report a significant correlation between condylar angulation and specific signs and symptoms of dysfunction. However, these researchers supported Weinberg[86] in noting the association between temporomandibular joint pain and internal derangement with TMJ asymmetry. Maxwell's group demonstrated greater condylar angulation on the side where the condyle was positioned more anteriorly in asymmetric subjects.

1.6.3 - Submentovertex Radiology

The submentovertex (SMV) projection is not as widely used in clinical practice as the lateral or postero-anterior cephalometric views. The main applications of submentovertex radiology have been for the determination of the condylar long axis for corrected tomography of the temporomandibular joint,[12] as well as for assessment of skeletal asymmetry.[87-89] Danforth et al.[90] investigated the use of SMV-determined condylar angulation and compared this method of determining the head position for TMJ tomography to other methods not requiring radiation exposure. They found no statistical difference between SMV-derived positioning and some of the alternative anatomic methods and concluded that proper alignment of the head for tomographic imaging could be obtained without the use of SMV radiographs. Evidence suggests that the determination of horizontal condylar angulation from SMV radiographs is subject to error.[91]

Condylar angulation may vary with subject head position. Generally, ideal positioning for SMV projections consists of the central ray being perpendicular to Frankfort horizontal plane. Lysell and Petersson[91] used SMV radiographs on dry skulls to study the effect of different head orientations about a transverse axis on condylar angulation. A significant linear correlation between beam direction and condylar angulation was found. Head orientation of ± 14 degrees from the Frankfort horizontal plane resulted in relatively minor changes in condylar angulation. Cranial rotation of 14 degrees resulted in a maximum decrease in measured angulation of 4 degrees, whereas caudal rotation of the skull of 14 degrees resulted in a maximum increase in condylar angulation of 3.5 degrees. Caudal rotation from the ideal projection is probably of more relevance clinically, as subjects with limitations in neck mobility may be restricted in their ability to extend their neck the amount necessary for ideal SMV alignment. The amount of error described for cranial rotation of 14 degrees is considered to be acceptable clinically in terms of joint imaging with tomography, since positioning of the condyle within 5 degrees of its true orientation appears to produce accurate images of the TMJ.[90]

The determination of the long axis of the condyle is also subject to variation. Numerous condylar shapes have been identified. Oberg et al.[18] described three main condylar shapes in the axial view: oblong, rounded to oval, and pear-shaped with either medial or lateral taper. Krenkel and Grunert[19] studied 126 SMV radiographs and found tremendous variation in condylar shape, both within and among individuals, and attribute the variation to functional patterns acquired during the course of development. The great variation which exists in condylar shape makes it extremely difficult to accurately define a long axis with which to measure angulation. Most studies have utilized points which represent the medial and lateral extent of the condyles, and have used a straight line connecting these poles to define a long axis. However, limitations to this technique are obvious when one considers curved condyles with a pole-to- pole line deviating significantly from a mid-condylar point. Tapered condyles with medial or lateral deviations away from the long axis also contribute to the variability in defining a long axis and thus in quantifying condylar angulation. As well, both condylar poles can be difficult to identify, particularly the lateral pole due to superimposition of adjacent structures, and this may also contribute to measurement variability.

For analysis of asymmetry or for determination of condylar angulation it is essential that a reference axis be established from which to base subsequent measurements. The literature reveals a variety of different axis which have been used for this purpose. Some studies utilize landmarks to identify sagittal planes from which to relate the condyles,[15] others have used frontal planes,[12,14,17,84,85] and still others have utilized intercondylar angulation[13,82] to describe the condylar long axis. The use of earrods for the determination of a reference plane from which to relate anatomical landmarks may be considered suspect due to both A-P and vertical asymmetry associated with the external auditory meatus.[92] The use of a sagittal reference plane derived from the foramen spinosum, which are used as passageways by the middle meningeal arteries, is considered to be a stable and valid reference. Forsberg et al.[89] studied possible SMV landmarks for reference line construction, noting the exceptional symmetry evident in the sphenoid bone, and supported the choice of foramen spinosum due to the stability and homogeneity of the location of basal foramina. Moss and Salentijn[93] also noted the stability of the basal foramina. Certain functions cannot be violated during normal growth and development, including the passage and location of the neurovascular bundle. Marmary et al.[94] used radiographs of 86 adult skulls and constructed a sagittal reference from a perpendicular bisector of an interspinosum line, and found average deviations to be within limits of measurement error. They noted that midlines which are determined by an interspinosum line are constant throughout cranial growth and development. The base of the skull, including the neural foramina, is generally not considered to be influenced strongly by environmental factors.[95] Arnold et al.[87] looked at the error associated with commonly used SMV landmarks, and found the foramen spinosum to be the most reproducible cranial base landmark.

Linear dimensions also vary with head angulation relative to the central beam. Linear distance between landmarks which lie on different planes will be most affected by head rotation.[96] Thus, linear measures in an A-P direction must be used with caution in assessing SMV radiographs due to possible elongation effects, especially if the landmarks representing the extent of measured segments lie on different planes relative to the source and film.

As with the consideration of any cephalometric analysis, it is important that landmark identification error and measurement reliability be established in order that results can be properly interpreted. A review of the literature regarding landmark identification error and condylar angulation determination in submentovertex cephalometrics revealed a paucity of literature specific to this subject. No articles were found which reported the landmark identification error in both horizontal and vertical directions. Error associated with the determination of condylar angulation in submentovertex radiographs was reported in only one article,[13] and a comparison of different methods of condylar angulation determination was not found in the literature. It is apparent that there has been only a small amount of research devoted to the SMV projection, and relatively few SMV analyses are presented in the medical or dental literature.

1.6.4 - Landmark Identification Error

According to Vincent and West,[97] measurement error may be categorized as projection error, landmark location error, or mechanical error inherent in the measurement tools. Projection errors arise due to the geometry of the radiographic setup[98] and is due primarily to the divergence of the x-ray beam as it moves away from the source. As a result, a radial displacement of points not lying on the principle axis occurs, in addition to a foreshortening of distances between points lying in different planes.[99] Distortion results as points lying closer to the film are less magnified than points lying a greater distance from the film.[100] Standardization of equipment and techniques may lead to a reduction in the effects of distortion and magnification.[101] Baumrind and Frantz[102] stated that the use of angular measures rather than linear measures reduces the impact of projection errors, as angular measures remain constant, regardless of the enlargement factor. This observation is theoretically legitimate under certain conditions. However, it does not account for the possible alteration of an apparent two-dimensional representation due to anatomical variation in another plane of space. In such instances, the orientation of an axis representative of a specific body may be altered relative to a reference axis due to positional change of the object relative to the x-ray source.

Landmark location errors represent another source of measurement error, and arise due to the uncertainty associated with locating specific anatomic landmarks on the radiograph.[98,100,103,104] Identification error has been described as the main source of error associated with cephalometric measurement.[101,103,105] Landmark identification error may be related to several features. According to Vincent and West,[97] such features include, 1) the curvature of the line upon which the landmark is positioned (a sharp curve of small radius provides improved delineation), 2) the contrast of the radiographic image (high contrast area provides for more accurate depiction), 3) "noise" (areas with greater superimposition of adjacent structures make point identification difficult),[106] and 4) description of the specific landmark (poor description allows for wider interpretation variability). As well, operator experience is an important factor since interpretive errors may be reduced by familiarity with radiographic landmark appearance and increased knowledge of anatomy.[98] Thus, inter-examiner variability represents a source of error due to difficulties encountered in examiner standardization, and variability within a single examiner would be expected to be less than variability observed between examiners.

The distribution of error for a given landmark has been shown to be characteristic for that landmark, and shows different distribution in different planes of space. Many landmarks have been shown to be associated with a characteristic noncircular envelope of error.[97,105] Thus, some landmarks may be easier to locate in a horizontal direction than in a vertical direction, and vice versa. Furthermore, identification of landmarks is more reliable than identification of planes, since a plane requires at least two points for its identification, whereas a specific landmark requires only a single point.[105]

Houston[99] provided a useful description of the terms validity and reproducibility as they apply to cephalometric measurement interpretation. Validity may be described as the extent to which the measured value represents the object of interest. Many cephalometric landmarks have been defined on the basis of identification convenience and reproducibility, rather than on grounds of anatomic validity.[99] Validity is frequently assumed, however is not assured unless comparisons of radiographic images are made to actual skull landmarks. Reliability is a necessary condition for validity.[105]

Reproducibility may be influenced by both systematic errors (bias) and random errors. Systematic errors are those in which measurements are consistently, or systematically, over- or under-recorded, and introduce a significant trend in data. Systematic errors may occur due to changes in projection geometry (alteration of magnification), inter-examiner differences, or bias associated with subconscious weighting of results within examiners.[99] Random errors may result from a number of different variables, including variation in patient positioning, film density, and in landmark identification. Some means of minimizing errors include the standardization of patient positioning and radiographic technique, using high quality and consistent radiographic supplies, optimal radiographic viewing and/or tracing conditions, standardized tracing technique, the utilization of experienced and calibrated examiners, as well as by appropriate and careful experimental design.[107]

Digitization offers several advantages over cephalometric measurements using a ruler and protractor. According to Broch et al.,[103] providing proper instrument operation and calibration, use of a digitizer should minimize measurement error and establish landmark identification error as the lone source of measurement error. The error associated with the digitizing procedure may be attributed to two sources, the operator/hardware component and/or the physical characteristics of the tablet itself. The operator/hardware component reflects the accuracy of the crosshair pointer and the precision by which the examiner can pinpoint the gridpoints.[108] The physical characteristics of the tablet itself reflect errors due to distortion of tablet coordinates, termed nonlinearity, which may be specific to the individual digitizer. Tourne[108] found the precision of digitization to be significantly greater than the accuracy by which anatomical landmarks could be located. Since the major component of recording error is that of point identification, there is little difference in accuracy between direct digitization and the use of an intermediate tracing stage.[107]

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Chapter Two

Research Paper #1

Landmark Identification Error in Submentovertex Cephalometrics - A Computerized Method for Determining the Condylar Long Axis

2.1 - Introduction

The submentovertex (axial) projection is uniquely valuable for the clear visualization of the anatomic structures of the cranial base. Despite its inherent benefits, this projection is not as widely used in clinical practice as the lateral or postero-anterior cephalometric views. The main applications of submentovertex radiology in the orthodontic literature have been for the determination of the condylar long axis for corrected tomography of the temporomandibular joint,[1] as well as for assessment of skeletal asymmetry.[2-4]

As with the consideration of any cephalometric analysis, it is important that landmark identification error and measurement reliability be established in order that information, whether intended for clinical or research applications, can be properly interpreted. Measurement error may be categorized as projection error, landmark identification error, or mechanical error inherent in the measurement tools.[5] Projection error results from the geometric features of the radiographic setup,[6] and is due primarily to the divergence of the x-ray beam as it moves away from its source. Standardization of equipment and techniques can lead to a reduction in the effects of distortion and magnification[7] which are due to projection effects.

Landmark identification error arises due to the uncertainty associated with locating specific anatomic landmarks on the radiograph.[6,8-10] Identification error has been described as the main source of error associated with cephalometric measurement.[7,9,11] Landmark identification error may be related to several features. According to Vincent and West,[5] such features include, 1) the curvature of the line upon which the landmark is positioned (a sharp curve of small radius provides improved delineation), 2) the contrast of the radiographic image (high contrast area provides for more accurate depiction), 3) "noise" (areas with greater superimposition of adjacent structures make point identification difficult),[12] and 4) description of the specific landmark (poor description allows for wider interpretation variability). As well, operator experience is an important factor, since interpretive errors may be reduced by familiarity with radiographic landmark appearance and increased knowledge of anatomy.[6] Thus, inter-examiner variability represents a source of error due to difficulties encountered in examiner standardization, and variability within a single examiner would be expected to be less than variability observed between examiners.

The distribution of error for a given landmark has been shown to be characteristic for that landmark, and shows different distribution in different planes of space. Many landmarks have been shown to be associated with a characteristic noncircular envelope of error. [5,11] Thus, some landmarks may be easier to locate in a horizontal direction than in a vertical direction, and vice versa. Furthermore, identification of landmarks is more reliable than identification of planes, since a plane requires at least two points for its identification, whereas a specific landmark requires only a single point.[11]

The determination of a condylar long axis, and thus measurement of horizontal condylar angulation in the submentovertex projection, is also subject to error. Oberg et al.[13] described three main condylar shapes in the axial view: oblong, rounded to oval, and pear-shaped with either medial or lateral taper. Krenkel and Grunert[14] studied 126 SMV radiographs and found tremendous variation in condylar shape, both within and among individuals, and attribute this in part to the variation in functional patterns acquired during the course of development. The great variation which exists in condylar shape makes it difficult to accurately define a long axis of the condyle. Some studies have utilized points which represent the medial and lateral extent of the condyles, and have used a straight line connecting these poles to define a long axis.[15-17] Others have arbitrarily defined a long axis by visual inspection of the shape of the condyle in the axial view.[18,19] However, limitations to these techniques are obvious when one considers curved condyles with a pole to pole line deviating significantly from a mid-condylar point, or tapered condyles with medial and lateral deviations away from the long axis. Condylar poles can be difficult to identify in SMV projections, particularly the lateral pole due to superimposition effects.

A review of the literature regarding landmark identification error and condylar angulation determination in submentovertex cephalometrics revealed a paucity of literature specific to this subject. No articles were found which reported landmark identification error along both 'x' and 'y' axes. Error associated with the determination of condylar angulation in submentovertex radiographs was reported in only one article[20] and no alternative methods of condylar long axis determination have been reported in the literature.

The purpose of this study was to examine the identification error of certain submentovertex landmarks and to compare three different methods of determining the condylar long axis, and thus condylar angulation, in submentovertex radiographs. Landmarks were chosen which were, 1) relevant in defining the sagittal, transverse, and angular position of the mandibular condyles in relation to the cranial base, 2) commonly used in the published literature,[3,18] and, 3) recognizable on the submentovertex radiographs.

2.2 - Materials and Methods

This study was approved by the human ethics committee of the combined faculties of Dentistry and Pharmacy of the University of Alberta.

Part I - Landmark Identification Error

A random sampling of 12 SMV radiographs was chosen from an original sample pool of 101 radiographs which were used as part of another study. Subjects consisted of pre-orthodontic patients between the ages of 10 and 17 who presented sequentially for orthodontic records. Consent was obtained for participation in the study from patients and their parent/guardian, so that the additional radiographic exposures and MRI could be obtained in addition to the usual survey required for the routine orthodontic workup. All radiographs were selected as part of the original sample pool on the basis of certain criteria which included exhibiting sufficient contrast and definition to enable identification of the foramen spinosum on initial inspection. All radiographs were exposed at the same private imaging facility using an AxialTome #5000 (AxialTome Corporation; San Carlos, California) x-ray machine exposure setting at 2 seconds, 15mA, and 80 kVp. Head positioning was established using standardized SMV protocol. Source-to-earrod distance was 102.9 cm and earrod-to-film distance was 24.1 cm.

All radiographs were viewed under standardized conditions and traced onto acetate overlays using a 0.3 mm diameter lead pencil. Landmarks were digitized from tracings made by a single operator using a Summasketch II (Summagraphics Corporation; Austin, Texas) digitizing tablet in conjunction with a 486 IBM-compatible personal computer. An individual coordinate system was established for each radiograph by including two pinholes as fiducial points placed in a standardized location in the upper left and right corners of each radiograph. The axis represented by a line connecting each fiducial point of each tracing represented the X-axis of a Cartesian coordinate system. The top left fiducial point was designated as the origin, with the Y-axis calculated as the line perpendicular to the line connecting the two fiducial points.

The following landmarks were identified on each radiograph (Figure 2-1, p. 92):

1. Foramen spinosum point - the geometric centre of each foramen spinosum. The location of this point was determined by estimating the centre point of the traced outline of each foramen spinosum.

2. Condylar lateral pole - the point representing the lateral pole of each condyle. This point was defined as the intersection of a 'visualized' condylar long axis with the lateral polar outlines of each condyle.

3. Condylar medial pole - the point representing the medial pole of each condyle. This point was defined as the intersection of a 'visualized' condylar long axis with the medial polar outline of each condyle.

4. Condylar centre point - the geometric centre of a circle which best fits the middle one third of each condyle medio-laterally. The location of this point was determined by estimating a centre point of a 'best fit' circle which was fit to the anterior

and posterior borders of the middle third of each condyle.

5. Posterior condylar point - the intersection of a line representing a longitudinal bisector of the proximal 15mm of the mandibular ramus toward the condyle and the posterior border of each condyle.

6. Pogonion point - the most anterior point on the mandibular symphysis relative to a line connecting the left and right foramen spinosum.

Intra-examiner landmark reliability was determined by the principal investigator tracing 10 radiographs five times in random order. Subsequent tracings of the same radiograph were separated by a minimum of 24 hours. All tracings were digitized consecutively by the same investigator. Identification error was determined for each landmark by first calculating the standard deviation of each landmark over the five tracings of each radiograph, and then calculating the average of the standard deviations over the ten radiographs.

Inter-examiner landmark reliability was determined by utilizing four examiners, each with graduate level training in cephalometrics and none of whom were the principal investigator. Each examiner attended an instructional session on submentovertex landmark identification and participated in practice exercises prior to participation in the study. Each was also provided with detailed written instructions on landmark identification. A balanced incomplete block design was utilized, with each of four examiners tracing six different radiographs twice. Using this design, each of 12 radiographs was traced twice by two different examiners (ie. four times in total). All radiographs were randomly allocated to examiners and coded with an identification number. Repeated tracings of radiographs by the same examiner were separated temporally by a minimum 24 hour period in order to avoid operator bias. All tracings were digitized by the principal investigator. Landmark identification error was determined by first calculating the standard deviation of each landmark across tracings and examiners for each radiograph, and then by calculating the average standard deviation over the 12 radiographs. A repeated measure analysis (ANOVA), with the examiners as a main factor and tracings as a repeated measure, was used to identify the specific effect of the examiner on the variability for each landmark.

The instrument error for point identification was established by repeated digitization by the principal investigator of a single point marked by a 0.2mm pen on tracing acetate. Twelve successive recordings were made without moving the cursor, and twelve additional recordings were made replacing the cursor between each recording.

Part II - Comparison of Methods of Condylar Angulation Determination

101 submentovertex radiographs from the sample described in Part I were selected in order to compare three different methods of determining a condylar long axis and thus horizontal condylar angulation. The tracing and digitization setup was as described previously. All tracings and subsequent digitizations were performed by the principal investigator.

The following methods for the determination of a condylar long axis were used:

1. Condylar principal axis - a computer-derived long axis which represents the principal axis of minimum moment of inertia of the two-dimensional condylar outline as viewed axially

2. Anterior condylar border - a computer-derived best-fit line of the anterior border of the condyle

3. Interpolar axis - a line connecting the visualized medial and lateral poles of the condyle

The digitization procedure for determination of the condylar principal axis (method 1) involved entering a maximum of 40 points representing the outline of the condyle. A computer program was developed which used these (x,y) values to fit cubic splines to the condylar outline, and area properties of the condyle were subsequently calculated. A centroid point (a point representing the centre of gravity of a 2-dimensional body) was identified, and the 'principal axis' of minimum moment of inertia (second moment of area) was distinguished based on the area distribution of the specific condyle. This computer-derived axis represents the theoretical axis which the condyle would rotate about most easily based on its 2-dimensional outline.

The digitization procedure for the anterior condylar border method (method 2) involved entering a maximum of 12 points representing the anterior border of the condyle. Points were selected which represented the middle 2/3 of the anterior border, and did not include the medial and lateral polar extremities. The computer program used this input to calculate a least squares best-fit line representative of the condylar long axis.

The interpolar axis method (method 3) involved the identification and digitization of the visualized medial and lateral poles of each condyle, as described in Part I. The line connecting these two points represented the condylar long axis.

All angular measurements were determined using the respective condylar long axes as described and calculating the angle formed by these axes and a mid-sagittal reference plane which represented the perpendicular bisector of a line connecting the geometric centre of each foramen spinosum (Figure 2-2, p.93).

Tracings of the 101 radiographs were repeated twice, and the means of each angular measurement were used to compare methods. Paired t-tests were used to test for differences in the variability between the three methods of condylar angulation determination. To quantify the differences between the methods, 10 randomly selected radiographs were traced 5 times each, and the average of the standard deviations for each method across the 10 radiographs was calculated for both left and right condyles. This represented the error involved in determining condylar angulation.

The error of the method for angular measurements was determined by digitizing one tracing 5 times and calculating the average standard deviation of the angular measures for each of the three methods used for condylar angulation determination.

2.3 - Results

Part I - Landmark Identification

A. Instrument Error

The magnitude of error associated with the digitization apparatus for landmark identification was extremely low. The standard deviation along the 'x' axis was calculated to be 0.00mm and the standard deviation along the 'y' axis was calculated to be 0.00mm when 12 successive digitizations of the same point were repeated without moving the cursor. With repeated digitizations of the same point with replacement of the cursor between each digitization, the standard deviation along the 'x' axis was calculated to be 0.00mm and the standard deviation along the 'y' axis was found to be 0.11mm.

B. Intra-examiner Reliability

The error associated with the identification of each of the eleven SMV landmarks is shown in Table 2-1 (p.84). The average standard deviation varied between specific landmarks, between the same landmarks bilaterally, and between the vertical and horizontal components of the same landmark. The average standard deviation averaged over 10 radiographs varied from 0.18mm to 0.82mm. The foramen spinosum landmarks demonstrated the lowest average standard deviation in both horizontal and vertical directions (SDx=0.18mm, SDy= 0.25mm), whereas the vertical component of the left lateral pole showed the highest average standard deviation (SDy=0.82mm). The vertical component of pogonion point demonstrated the highest single standard deviation among all radiographs (maximum SDy=3.79mm).

Table 2-2 (p.85) shows the intra-examiner landmark identification error of landmarks with left and right error values averaged. Foramen spinosum demonstrated the lowest average error in both vertical and horizontal directions (SDx=0.22mm, SDy=0.26), whereas the posterior condyle point demonstrated the greatest average error in both vertical and horizontal directions (SDx=0.74mm, SDy=0.68mm).

C. Inter-examiner Reliability

The average error for each landmark over all four examiners and 12 radiographs is presented in Table 2-4 (p.86). The vertical component of the right condylar centre point demonstrated the least identification error (SDy=0.25mm), whereas the vertical component of the left lateral pole showed the greatest average error (SDy=1.23mm). Overall, inter-examiner landmark identification error was greater than intra-examiner error, as seen by the mean standard deviation over all landmarks in both vertical and horizontal directions.

Table 2-3 (p. 85) shows the inter-examiner landmark identification error for landmarks with left and right error values averaged. The vertical component of the condylar lateral pole demonstrated the greatest average error (SDy=0.99mm), and the vertical component of the condylar centre point demonstrated the lowest average error (SDy=0.36mm).

Table 2-5 (p.87) shows the results of the ANOVA which was used to identify the specific effect of the examiner on the variability of each landmark. The vertical component of both left and right foramen spinosum points shows statistically significant examiner effects on landmark identification at a 5% level of significance.

Part II - Condylar Angulation

Mean angular values of the three different methods of condylar angulation determination derived from the mean of two tracings of each of 101 radiographs is presented in Table 2-6 (p.88). Right mean angular values vary from 66.3 degrees to 67.2 degrees, whereas left mean angular values vary from 67.9 to 68.2 degrees. The left condylar angular values demonstrate greater variance than the right condylar angular values. Also, all three methods demonstrate greater left mean angular values than right angular values.

Results of t-tests for pair-wise comparison of standard deviations of the three different methods of condylar angulation determination (taken over tracings) are presented in Table 2-7 (p.89). Paired t-tests comparing condylar principal axis (method 1) and interpolar axis (method 3) showed statistically significant differences ($p<.05$) between these methods for both left and right sides, with method 3 demonstrating more variability (greater standard deviation) than method 1. The observed mean differences in standard deviations between methods 1 and 3 was 0.42 degrees (right) and 0.60 degrees (left). A comparison of the anterior condylar border (method 2) and the interpolar axis (method 3) methods showed no statistically significant differences between these two methods for both left and right sides. The observed mean differences in standard deviations between methods 2 and 3 was 0.28 degrees (right) and 0.14 degrees (left). A comparison between the condylar principal axis (method 1) and the anterior condylar border (method 2) was not done.

Table 2-8 (p.90) presents the average error associated with the three methods of condylar angulation determination as calculated from 5 tracings of each of 10 radiographs. As well, the maximum error associated with single radiographs using the same data is presented. The condylar principal axis (method 1) demonstrated the smallest average standard deviations of all three methods (right average SD=1.08 degrees; left average SD=1.14 degrees), as well as the smallest maximum standard deviation seen on single radiographs. The interpolar axis (method 3) demonstrated the highest average standard deviations of all three methods (right mean SD=1.96 degrees; left mean SD=1.55 degrees).

The error of the method for angular measures was calculated from 5 repeated digitizations of a single tracing. Average standard deviations were very low, ranging from 0.12 degrees (right condylar principal axis) to 0.37 degrees (left interpolar axis), as presented in Table 2-9 (p.91).

2.4 - Discussion

It is evident from this data that each landmark demonstrates a characteristic pattern of error distribution, with differences found between x and y error components for most landmarks. The finding of a non-circular envelope of error associated with landmark identification supports the findings of others.[5,11] From Table 2-2, it can be seen that larger discrepancies exist between x values and y values for condylar centre points and pogonion point than for the other landmarks. This can be explained by the anatomical features and orientation of these landmarks relative to the Cartesian coordinate system used to locate these points. The condylar centre points show greater error in the horizontal direction, which stands to reason when one considers that this landmark requires the identification of a point at the midpoint along the medial-lateral condylar axis, which tends to be oriented horizontally relative to the coordinate system used. The vertical component of pogonion point demonstrates greater error than the horizontal component, and demonstrates the largest single standard deviation among radiographs (Table 2-1). This can be explained by the lack of clarity of this region and the tendency for superimposition of the inner and outer tables of the frontal bones and of the dentition over the anterior region of the mandibular symphysis. The amount of superimposition in this region is strongly influenced by head position, as head rotation about the transverse axis may project the pogonion point variously along the 'y' axis. Rotation about the transverse axis also affects linear measurements on the SMV, particularly those with a sagittal component.[21] Ideal head positioning for SMV projections consists of the central ray being perpendicular to Frankfort plane, however subjects with limitations in neck mobility may be restricted in their ability to extend their neck the amount necessary for ideal SMV alignment. Lysell and Petersson[16] suggest that minimal projection effects occur if the mandibular angle is projected immediately anterior to the condyle. Rotation about an anterior-posterior axis would be expected to be minimized by the use of cephalostat ear rods.

The foramen spinosum points show the smallest identification error in both vertical and horizontal directions. This may be explained by the fact that foramen spinosum is a relatively small circular landmark, and the geometric centre is easy to locate once the spinosum is identified. Another explanation for the low error associated with this landmark is that one of the selection criteria for the original sample pool of radiographs used for this study was that sufficient contrast and definition of the foramen spinosum was required upon initial inspection. This criteria was used so that a stable reference system could be established which was based on the position of the foramen spinosum,[4,14,22] however this resulted in selection bias.

The lateral and medial condylar poles demonstrate relatively high error in both vertical and horizontal directions. The finding of increased identification error in the lateral pole as compared to the medial pole supports the findings of others,[16] and may be influenced by the irregularity in condylar shapes in the axial view[13,14] and the superimposition of the lateral pole on adjacent structures.

In general, the intra-examiner data shows less landmark identification error (averaged standard deviations across all landmarks) in both vertical and horizontal directions than the inter-examiner data, however some exceptions are evident. Pogonion point demonstrated greater identification error along the 'y' axis in the intra-examiner data than in the inter-examiner data. The large maximum SD noted for the 'y' value of pogonion point in the intra-examiner data (3.79 mm, Table 2-1) is difficult to explain, however is likely related to superimposition effects which are commonly observed in this region. The landmarks which demonstrated greater identification error in the inter-examiner data could be explained by the inherent differences between the different examiners in landmark interpretation and experience, which leads to increased identification error. The inter-examiner data demonstrates some similarities with the intra-examiner data, including poor reliability of the condylar poles, especially in the vertical direction, and poor reliability of the posterior condylar point in the horizontal direction. The inter-examiner data was strongly influenced by some extreme values of foramen spinosum point in the vertical direction from one examiner. This was supported by the results of the ANOVA which found statistically significant examiner effects on landmark variability for these landmarks. This may have occurred as a result of poor landmark description or inexperience on the part of this examiner, which lead to the mistaken identification of other structures of the skull base as the foramen spinosum. This resulted in relatively high error to be reported for the vertical component of foramen spinosum in the inter-examiner data.

Since similar research reporting horizontal and vertical landmark identification error in submentovertex radiographs was not found, a comparison of results with other similar studies cannot be made. However, the error data reported here compares favourably to a study on posterior-anterior landmark identification error[6] which reported an intra-examiner range of error of 0.29mm to 1.03mm along the 'x' axis and 0.18mm to 1.36mm along the 'y' axis. A study by Vincent and West[5] reported landmark identification error for lateral cephalometric landmarks, and demonstrated SD values for such commonly used landmarks as porion (SDx=0.98), gnathion (SDx=1.0), condylion (SDy=1.03),and basion (SDy=1.34) to be greater than the error found for the SMV landmarks reported here. The relatively low landmark identification error (average standard deviation) found for the landmarks included in this study may indicate their usefulness for certain clinical or research applications, depending on the level of accuracy required. For research applications, landmarks demonstrating greater than 0.5mm of error in either direction might compromise the derived data. However, for clinical use, landmark identification errors of up to 1.5mm would appear to be acceptable.[5,6] The large maximum standard deviation values noted in this study for the vertical component of pogonion, the horizontal component of posterior condylar point, as well as the medial and lateral poles may indicate that certain caution should be exercised in interpreting measures utilizing these points. The error associated with the identification of the vertical component of the condylar lateral pole suggests that polar landmarks might provide an unreliable representation of the angulation of the condylar long axis. This is supported by the angulation data.

The results of the condylar angulation data suggest that the computer-derived condylar principal axis is a more reliable indicator of condylar long axis for the determination of condylar angulation than the interpolar axis, which is used most commonly. The observed mean differences in SD between methods 1 and 3 (0.42 degrees right and 0.60 degrees left) were shown to be significantly different statistically. These differences may also be significant when considering methods to be utilized for research purposes, however for general clinical usage are probably not significant.

A comparison between the condylar principal axis and the anterior condylar border method was not done, as the results of the first two comparisons revealed that significantly less variability existed in the condylar principal axis method (method 1) than in the currently-accepted interpolar axis method (method 3). This finding, along with the finding that the anterior condylar border method (method 2) was not significantly different than the interpolar method (method 3), revealed sufficient information regarding the usefulness of the condylar principal axis method for subsequent research.

The greatest differences in mean angular values between the methods was approximately 0.9 degrees for the right side, and 0.4 degrees for the left side, between the condylar principal axis method and the other methods tested. This difference is probably not of significance clinically,[15,16] however may have implications for research related to condylar angulation, depending on the accuracy required. The findings of greater mean angular values and greater variation in angular values of the left joints compared to the right joints are interesting, however are difficult to explain.

Most studies on condylar angulation, as well as tomographic imaging of the temporomandibular joint, rely on the interpolar method for the identification of a condylar long axis,[17,23-25] therefore this method may be considered the current standard. The computer-derived condylar principal axis is a more reliable measure of the condylar long axis since it is not strongly influenced by the lack of definition at the poles of the condyles (superimposition effects), or subject to interpretation effects in the case of significantly curved or irregularly shaped condyles. The findings of this study do not support or refute the validity of the computer-derived method in determination of a condylar long axis, however the closeness of the derived angular values to those of the current 'standard' would suggest that they represent similar measures. The validity of such a method for determination of a condylar long axis may not necessarily be derived from anatomical studies which compare angular values, but would involve a complex functional analysis of both centric and eccentric condylar movements in all three planes of space which would apply to the specific hypothesis being tested. Theoretically, the condylar principal axis as determined in this study represents the axis of minimum moment of inertia, and if the condyle was of uniform thickness in the plane of imaging then the condyle would rotate most easily about this one axis.

The apparent angulation of the condyle in the submentovertex view may be subject to variation due to projection error. Lysell and Petersson[16] found that head rotation about a transverse axis resulted in changes in horizontal condylar angulation, particularly in condyles with a marked mediolateral angulation in a frontal aspect. Any axis which is established based on a two-dimensional image of a three-dimensional object has limitations due to the missing information in the third dimension. Further research is needed to enable identification of a rotational axis based on information from all three planes of space.

The choice of reference system with which to measure condylar angulation may influence angular values. Some studies have utilized frontal planes[1,17,19] from which to relate the condyles, and others have described intercondylar angulation.[20,26] The use of earrods for the determination of a reference plane from which to relate anatomical landmarks may be suspect due to both anterior-posterior and vertical asymmetry associated with the external auditory meati.[26] The use of a sagittal reference plane derived from the foramen spinosum, which are passageways for the middle meningeal arteries, is considered to be a stable and valid reference.[2,22,27] Forsberg et al.[4] studied possible SMV landmarks for reference line construction, and supported the choice of foramen spinosum, due to the exceptional symmetry of the sphenoid bone and the stability and homogeneity of the location of the basal foramina, which are considered to be minimally influenced by environmental factors.

2.5 - Conclusions

Landmark identification error of certain submentovertex landmarks which are relevant for defining condylar position and angulation relative to the cranial base have been presented. In general, all landmarks which were studied demonstrated identification error which lies within the range of cephalometric error reported in the literature,[6] and thus all could be considered reasonable landmarks for clinical use, depending on the level of accuracy required. Inter-examiner landmark identification error tended to be greater than intra-examiner error on most of the landmarks tested. Individual landmarks demonstrated varying magnitudes of error and characteristic patterns of error which often varied between the horizontal and vertical components.

A comparison of three different methods of condylar angulation determination was presented. A computer-derived method representing the principal axis of minimum moment of inertia of the condyle demonstrated less variation than the interpolar axis method which is utilized in current literature and practice. The observed differences between these methods were found to be statistically significant, and may be considered significant for research applications where the required level of accuracy is great. However, for general clinical application, the observed differences are probably not of significance. The cost and time involved in a system capable of deriving a principal axis from the condylar outline would likely outweigh the benefits such a system could provide to the clinician.

Table 2 - 1 Intra-examiner Landmark Identification Error

Landmark	Average SD* ('x')	Max. SD** ('x')	Average SD* ('y')	Max. SD** ('y')
Left Foramen Spinosum Point	0.18 mm	0.50 mm	0.27 mm	0.55 mm
Right Foramen Spinosum Point	0.26 mm	0.43 mm	0.25 mm	0.44 mm
Left Condylar Medial Pole	0.31 mm	0.66 mm	0.54 mm	0.75 mm
Pogonion Point	0.44 mm	0.91 mm	0.61 mm	3.79 mm
Right Condylar Centre Point	0.50 mm	1.31 mm	0.36 mm	0.71 mm
Left Condylar Lateral Pole	0.54 mm	1.02 mm	0.82 mm	2.14 mm
Left Condylar Centre Point	0.59 mm	0.94 mm	0.41 mm	0.71 mm
Right Condylar Lateral Pole	0.63 mm	1.49 mm	0.50 mm	0.71 mm
Right Condylar Medial Pole	0.63 mm	2.05 mm	0.50 mm	0.83 mm
Left Posterior Condylar Point	0.68 mm	1.24 mm	0.45 mm	0.75 mm
Right Posterior Condylar Point	0.81 mm	1.48 mm	0.46 mm	1.05 mm
Mean	**0.51 mm**		**0.47 mm**	

* SD taken over 5 tracings of each radiograph, average SD taken over 10 radiographs

** maximum SD of any one radiograph

Table 2 - 2 Averaged Intra-examiner Landmark Identification Error (left and right values averaged, except midline landmark *)

Landmark	Average SD ('x')	Average SD ('y')
Foramen Spinosum Point	0.22 mm	0.26 mm
Condylar Medial Pole	0.47 mm	0.52 mm
Condylar Lateral Pole	0.58 mm	0.66 mm
Condylar Centre Point	0.55 mm	0.39 mm
Posterior Condylar Point	0.74 mm	0.68 mm
Pogonion Point*	0.44 mm	0.61 mm

Table 2 - 3 Averaged Inter-examiner Landmark Identification Error (left and right values averaged, except midline landmark *)

Landmark	Average SD ('x')	Average SD ('y')
Foramen Spinosum Point	0.45 mm	0.91 mm
Condylar Medial Pole	0.59 mm	0.53 mm
Condylar Lateral Pole	0.69 mm	0.99 mm
Condylar Centre Point	0.63 mm	0.36 mm
Posterior Condylar Point	0.81 mm	0.43 mm
Pogonion Point*	0.64 mm	0.45 mm

Table 2 - 4 Inter-examiner Landmark Identification Error

Landmark	**Average SD* ('x')**	**Max. SD** ('x')**	**Average SD* ('y')**	**Max. SD** ('y')**
Right Foramen Spinosum Point	0.42 mm	3.92 mm	1.00 mm	12.93mm
Left Foramen Spinosum Point	0.48 mm	2.68 mm	0.81 mm	13.21mm
Right Condylar Lateral Pole	0.50 mm	3.09 mm	0.76 mm	2.48 mm
Right Condylar Centre Point	0.50 mm	2.27 mm	0.25 mm	0.55 mm
Right Condylar Medial Pole	0.51 mm	2.06 mm	0.48 mm	1. 38 mm
Pogonion Point	0.64 mm	1.44 mm	0.45 mm	1.93 mm
Left Condylar Medial Pole	0.67 mm	4.54 mm	0.58 mm	3.30 mm
Right Posterior Condylar Point	0.73 mm	3.09 mm	0.36 mm	1.10 mm
Left Condylar Centre Point	0.75 mm	4.54 mm	0.48 mm	1.93 mm
Left Condylar Lateral Pole	0.88 mm	3.71 mm	1.23 mm	4.95 mm
Left Posterior Condylar Point	0.89 mm	2.89 mm	0.49 mm	2.48 mm
Mean	**0.63mm**		**0.63mm**	

* SD taken over tracings and examiners, average SD calculated over 12 radiographs

** maximum SD of any one radiograph

Table 2 - 5 Results of ANOVA on Effect of Examiner on Total Variance (four examiners)

Landmark	('x') p-value	('y') p-value
Left Foramen Spinosum Point	0.176	0.031*
Right Foramen Spinosum Point	0.501	0.038*
Left Condylar Lateral Pole	0.149	0.308
Left Condylar Centre Point	0.117	0.162
Left Condylar Medial Pole	0.050	0.267
Left Posterior Condylar Point	0.054	0.206
Right Condylar Lateral Pole	0.391	0.239
Right Condylar Centre Point	0.689	0.172
Right Condylar Medial Pole	0.693	0.42
Right Posterior Condylar Point	0.863	0.215
Pogonion Point	0.184	0.362

* significant at 5% level of significance

Table 2 - 6 Angular Values for Three Methods of Condylar Angulation Determination (values in degrees; n = 101)

Method	**Right Mean Angle (Range)**	**Left Mean Angle (Range)**
(1) Condylar Principal Axis	66.5 (46.1-96.2)	67.9 (37.8-108.5)
(2) Anterior Condylar Border	66.3 (46.6-104.1)	68.2 (37.1-120.2)
(3) Interpolar Axis	67.2 (47.7-93.5)	68.1 (38.2-94.2)

Table 2 - 7 Results of t-tests for Pair-wise Comparison of Standard Deviations of Three Methods of Angular Determination (n=101)

Methods	**p-value**	**observed mean difference (SD)**
(1) Right Condylar Principal Axis (3) Right Interpolar Axis	0.046*	0.42 degrees
(2) Right Anterior Condylar Border (3) Right Interpolar Axis	0.172	0.28 degrees
(1) Left Condylar Principal Axis (3) Left Interpolar Axis	0.0035*	0.60 degrees
(2) Left Anterior Condylar Border (3) Left Interpolar Axis	0.322	0.14 degrees

* significant at 5% level of significance

Table 2 - 8 Average Standard Deviation Associated with Methods of Angular Determination

Method	Average SD* (Right Angles)	Maximum SD** (Right Angles)	Average SD* (Left Angles)	Maximum SD** (Left Angles)
(1) Condylar Principal Axis	1.08 degrees	2.36 degrees	1.14 degrees	1.97 degrees
(2) Anterior Condylar Border	1.44 degrees	2.51 degrees	1.24 degrees	2.54 degrees
(3) Interpolar Axis	1.96 degrees	3.88 degrees	1.55 degrees	2.37 degrees

* SD taken over 5 tracings, average SD taken over 10 radiographs

** maximum SD of any one radiograph

Table 2 - 9 Average Standard Deviation Associated with Digitization Procedure for each Method of Angular Determination

Method	**Avg. SD*** **(Right Angles)**	**Avg. SD*** **(Left Angles)**
(1) Condylar Principal Axis	0.12 degrees	0.29 degrees
(2) Anterior Condylar Border	0.31 degrees	0.32 degrees
(3) Interpolar Axis	0.18 degrees	0.37 degrees

* taken over 5 tracings of a single radiograph

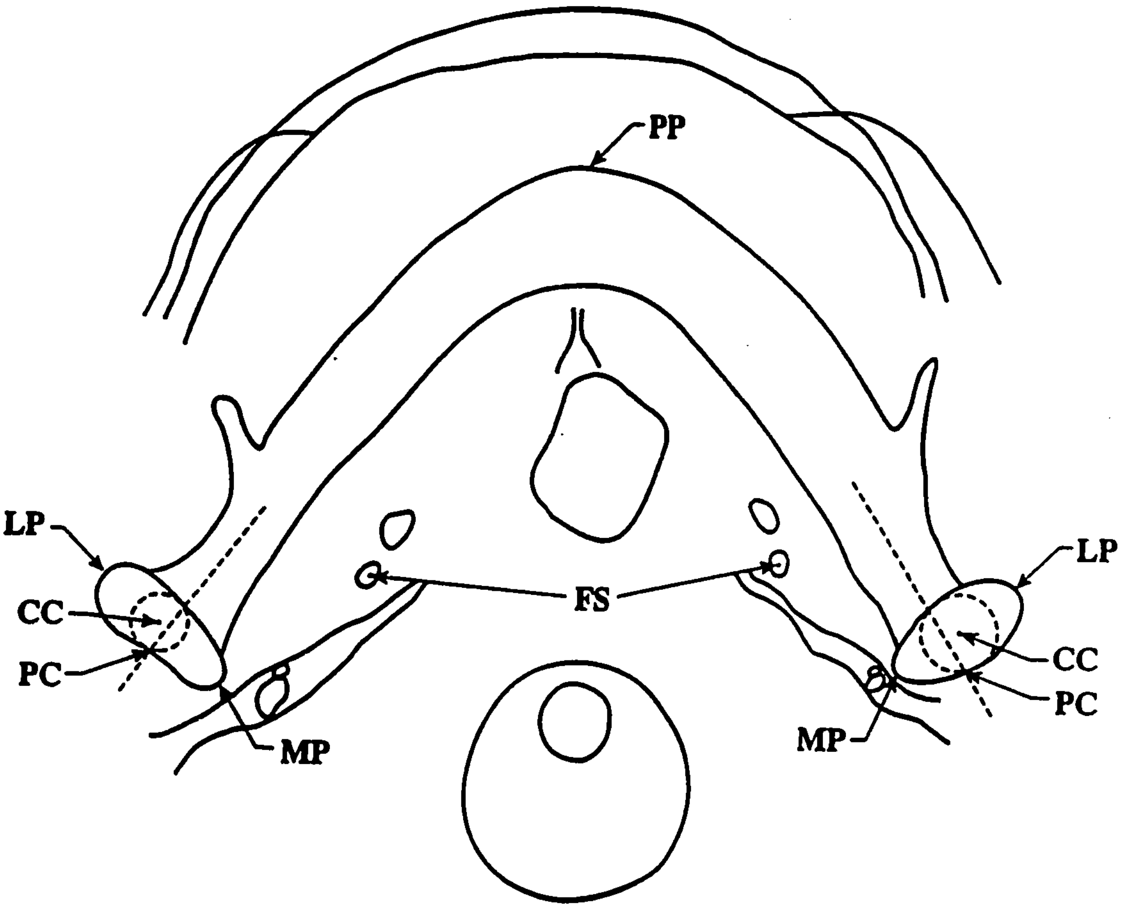

Figure 2 - 1 Submentovertex landmarks; Foramen Spinosum Points (FS), Condylar Lateral Poles (LP), Condylar Medial Poles (MP), Condylar Centre Points (CC), Posterior Condylar Points (PC), Pogonion Point (PP)

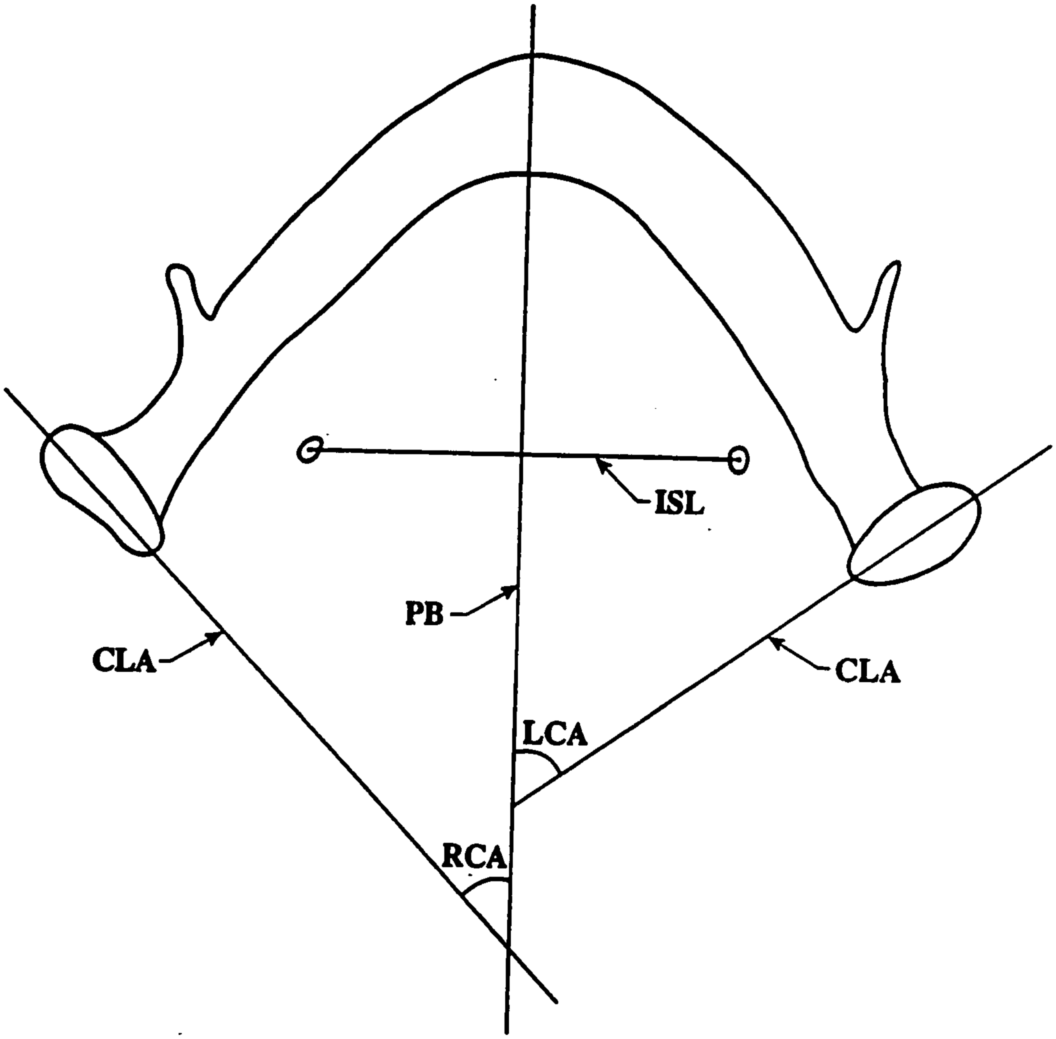

Figure 2 - 2 Horizontal condylar angulation measurement; Interspinosum Line (ISL), Perpendicular Bisector (PB), Condylar Long Axis (CLA), Left Condylar Angulation (LCA), Right Condylar Angulation (RCA)

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Chapter Three

Research Paper #2

Condyle Angulation and Position Associated with Adolescent TMJ Disc Status

3.1 - Introduction

In orthodontics, it is important that irregularities of the temporomandibular joint or anatomical variations that may predispose to subsequent joint problems be identified as part of a routine diagnostic work-up. In the diagnosis and treatment planning process, such data aids in appropriate case selection, the development of suitable treatment options, and the selection of specific treatment mechanics for the individual patient. Furthermore, this information is worthwhile in terms of patient education and from a medical-legal standpoint with regard to informed consent. Such information might also be useful in elucidating possible factors of etiologic significance in the development of skeletal dysplasias, certain malocclusions, and temporomandibular disorders (TMD).

Diagnosis of TMD may be made through clinical assessment or by a variety of available imaging modalities that include transcranial radiography,[1] tomography,[2,3] arthrography,[4] computed tomography,[5] and magnetic resonance imaging.[6,7,8] Submentovertex radiographs (SMV's), though not commonly utilized in the diagnosis of temporomandibular joint irregularities, are commonly used to determine the condylar long axis for corrected tomography of the temporomandibular joint.[9] SMV's are frequently taken as part of the diagnostic work-up for patients suspected of having TMD, and are useful for assessment of condylar angulation and position relative to cranial base landmarks.[10,11]

Research has suggested that condylar angulation, the angle which the mediolateral long axis of the mandibular condyle makes relative to either a frontal or sagittal plane as viewed axially, may represent a relevant feature of the temporomandibular joint. Lew and Tay[11] investigated condylar angulation in a sample of 32 male Chinese subjects using submentovertex (SMV) radiographs and suggested a relationship between facial form and condylar angulation. Ebner et al.[12] studied condyle morphology and angulation in 18 human cadavers and found no statistically significant differences between normal and abnormal joints. Westesson and Liedberg[13] investigated the association between condylar angulation and temporomandibular joint pathology in a heterogeneous sample of 364 symptomatic TMD patients. Using SMV radiographs for condylar angle determination and arthrography to categorize disk position, they were unable to find a significant statistical association between the angle of the condyle and the arthrographic diagnosis.

More recently, Westesson et al.,[14] using a heterogenous sample of 30 normal volunteers and 200 TMD patients, looked at the relationship between condylar angulation and joint irregularities using magnetic resonance imaging (MRI) for both condylar angle determination and joint assessment. The temporomandibular joints, in both sagittal and coronal views, were categorized on a continuum as: normal, showing disk displacement with reduction, disk displacement without reduction, or degenerative joint disease. Findings showed that the more advanced pathologic changes were associated with steeper condylar angulations.

Maxwell et al.[10] studied 52 patients who presented with clinical indicators of temporomandibular joint dysfunction, and did not report significant correlation between condylar angulation and specific signs and symptoms of dysfunction. However, Maxwell's group demonstrated steeper condylar angulations on sides where the condyle was positioned more anteriorly in asymmetric subjects.

The purpose of this retrospective research study is to examine the relationship between condylar angulation and position, as viewed in the submentovertex projection, and temporomandibular joint status in adolescents. By examining this relationship, the usefulness of SMV radiographs in the identification of joint abnormalities in an adolescent population can be assessed. Additionally, information derived from this may lead to an increased understanding of some of the contributing factors in the development of TMD in this age group.

3.2 - Materials and Methods

This study was approved by the human ethics committee of the combined faculties of Dentistry and Pharmacy of the University of Alberta.

Submentovertex radiographs and MRI of 95 subjects (56 female and 39 male) between the ages of 10 - 17 years (mean age 13.3 yrs), regardless of TMJ status, were used for this study. Mean male age was 13.2 years and mean female age was 13.4 years. Subjects consisted of individuals who presented sequentially to a private imaging facility for orthodontic records, regardless of TMJ status, and from whom consent was obtained for participation in the study. All radiographs were exposed at the same private imaging facility using an AxialTome #5000 (AxialTome Corporation, San Carlos, California) x-ray machine exposure setting at 2 seconds, 15 mA, and 80 kVp. Head positioning was established by alignment of Frankfort plane parallel to the plane of the film. Source to earrod distance was 102.9 cm and earrod-to-film distance was 24.1 cm.

All radiographs were viewed under standardized conditions and traced onto acetate overlays using a 0.3 mm diameter lead pencil. Each radiograph was traced by the principal investigator, and involved the identification of the geometric centre of each foramen spinosum and the outline of the mandibular condyles and body of the mandible. Each tracing was digitized by the same investigator using a Summasketch II (Summagraphics Corporation, Austin, Texas) digitizing tablet in conjunction with a 486 IBM-compatible personal computer. A computer program was written in Microsoft Visual Basic for Windows (Microsoft Corporation, Washington, DC) which interpreted all data entered and returned angular and distance measurements.

Determination of condyle position and angulation involved the digitization of a maximum of 40 points which represented the outline of each condyle. A computer program was developed which used this information to fit cubic splines to the condylar outline and calculate the area properties of each condyle. A condylar centroid point (a point representing the centre of gravity of the 2-dimensional condyle outline) was located by the computer program, and the 'principal axis' of minimum moment of inertia (second moment of area) was distinguished based on the area distribution of the specific condyle. This computer-derived axis represented the theoretical axis which the condyle would rotate about most easily based on its 2-dimensional outline as viewed axially. Angular measurements were determined for each joint by calculating the angle formed by the condylar long axis and a mid-sagittal reference plane represented by the perpendicular bisector of a line connecting the geometric centre of each foramen spinosum (Figure 3-1, p.122).

The following linear measurements were recorded:

1. A-P condyle position - distance parallel to the mid-sagittal reference plane between the centroid of the condyle and the corresponding foramen spinosum (Figure 3-2, p.123).

2. Transverse condyle position - distance perpendicular to the mid-sagittal reference plane between the centroid of the condyle and the corresponding foramen spinosum (Figure 3-2, p.123).

3. Intercondylar distance - distance between the centroid points of left and right condyles

4. Interspinosum distance - distance between the geometric centres of left and right foramen spinosa

All SMV tracings were repeated twice, and the means of each angular and linear measurement were used for subsequent statistical evaluation.

MRI of the TMJ's were performed without sedation using a 1.0 T magnet (Shimadzu Corporation 3, Kanda-Nishikicho 1-chrome, Chiyoda-Ku, Tokoyo 101, Japan) and a unilateral 3 inch surface receiver coil. Axial scout images were obtained to identify the condyles. Bilateral closed mouth sagittal sections were obtained perpendicular to the long axis of the condyle making use of polyvinylsiloxane (President Jet- Bite, Coltene / Whaledent Inc., Mahwah, New Jersey) centric occlusion bite registration. T1-weighted 500/20 (TR ms/ TE ms) pulse sequences were performed on all subjects using a 3mm slice thickness, 140 mm field of view, NEX of 2, and an image matrix of 204 x 204.

Sagittal images of the TMJ were produced from 3 mm thick volume slices of the joint and medial, central, and lateral slices were chosen which provided identification of both soft tissue and osseous components on each slice. One of the investigators (B.N.) traced the outline of the articular structures as well as the articular disc of each image. Disc displacement and disc length values were determined for each of the three slices of each joint by establishing a standardized eminence reference plane (ERP), which represented the longest posterior slope of the articular eminence, as previously described by Nebbe et al.[15] The ERP is defined as being 50 degrees to Frankfort Horizontal at a point 10.0 mm anterior to the maximum height of the glenoid fossa (Figure 3-3, p.124). Three points were defined on the articular disc and one point was defined on the condylar head. These points consisted of the midpoints of the anterior and posterior bands, the midpoint of the disc, and a point on the head of the condyle termed the condylar load point (CLP). The CLP represented the closest joint space between the head of the condyle and the posterior slope of the articular eminence. All four points were projected onto the eminence reference plane by making use of perpendicular lines from the identified points to the ERP. This allowed for disc displacement and disc length measurements.

Disc displacement was measured as the distance from the midpoint of the disc to the condylar load point along the eminence reference plane, and disc length was measured as the distance between the midpoints of the anterior and posterior bands, also measured along the eminence reference plane (Figure 3-4, p.125).[15]

3.3 - Analysis of Data

I - Method Error

To determine the error of measurement of angular and linear SMV values, ten radiographs were randomly traced five times each, and then each tracing was subsequently digitized by a single investigator. The standard deviation of each angular and linear measure was determined over the five tracings of each radiograph. Subsequently, the average SD for each angular and linear measure was determined by calculating the average SD value over all ten radiographs (Table 3-1, p.116).

The reliability of obtaining the eminence reference plane on MR images was determined by randomly selecting twenty-five MRI's and retracing the required landmarks. Dahlberg's formula[16] for determination of the standard error was applied for double determinations, and the standard error was expressed in degrees (Table 3-2, p.116).

Determination of reliability in measurement of disc length and disc displacement was determined by selecting ten MRI's representative of normal disc position, and ten representative of disc displacement. These twenty MRI's were randomly traced five times each on consecutive days to determine measurement error. Multivariate ANOVA procedure with MRI's and tracings as factors were utilized to generate a F-statistic and determine the coefficient of intra-rater reliability ($R=1-1/F$) for disc length and disc displacement[17] (Table 3-3, p.117).

II - Joint Assessment

Anterior disc displacement values and disc length values were obtained through measurement of MRI slices of lateral, central, and medial aspects of each joint. This provided three disc length and three disc displacement measurements for each joint. A principal component analysis was used to synthesize this data to a single disc length variable and a single disc displacement variable for each joint. Thereafter, a single TMJ internal derangement (I.D.) variable was computed for each joint by making use of the same principal component analysis, entering both the disc length variable and the disc displacement variable for each joint. A total of nine variables, including the six measured values (disc length and disc displacement values for each of three slices) and the three additional variables derived through principal component analysis (disc length variable, disc displacement variable, and TMJ internal derangement variable),[15] were thus established for each joint. These variables represented joint status.

III - Statistical Analysis

Of the 95 subjects which were imaged, all but four (two male and two female) had complete bilateral data sets available. For these four patients, only data from one joint each was used. Thus, 186 joints (110 female joints and 76 male joints) were used for statistical analysis. Each joint was considered as a separate case, with left or right joint MRI data matched with the corresponding SMV angular and linear data from the same side. For the purpose of statistical analysis, independence of joints was assumed.

Independent sample t-tests were used to assess whether or not differences in angular and linear SMV measurements existed between genders. Pearson correlation coefficients were calculated to assess the relationship between age and all angular and linear SMV measurements.

Correlation coefficients were computed to assess the relationship between joint status and condylar angulation and position. As well, a linear regression analysis was used to assess the predictability of joint status from condylar angulation and position variables. In this instance, joint status variables represented the dependent variables. Independent variables were represented by condylar angulation as well as by A-P and transverse condyle position values. Each of the nine dependent variables were entered separately against all angular and linear independent variables.

Correlation coefficients were computed to assess the relationship between A-P and transverse condyle position, and condylar angulation. A linear regression analysis was used to further assess the relationship between these variables, with condylar angulation entered as the dependent variable and condyle position (A-P and transverse) entered as independent variables.

3.4 - Results

Table 3-4 (p.117) shows the means and standard deviations of all linear and angular measurements acquired from the SMV radiographs categorized by gender. Females generally demonstrated slightly smaller values on all linear measurements, however a comparison of group means between the male and female subjects showed no statistically significant differences (5% level of significance) between gender on any of the measurements. Observed mean differences between genders for angular data were 1.35 degrees for left condylar angles and 3.28 degrees for right condylar angles. Observed mean differences for linear data ranged from 0.19 mm for left transverse condylar position to 1.20 mm for intercondylar distance. Correlations run on all condylar angulation and position data showed non-significant age effects on these variables, with correlation coefficients ranging from 0.02 to 0.18, and the corresponding p-values ≥ 0.077 (Table 3-5, p.118).

The relationship between joint status and condylar angulation was not statistically significant at the 5% level of significance (Table 3-6, p.118). Correlation coefficients were low ($r = -0.02$ to -0.14). Linear regression analysis failed to show a significant association between these variables, indicating that condylar angulation was not adequate in explaining the variability observed in joint status.

Table 3-7 (p.119) displays the data used to assess the relationship between joint status and condyle position. Anterior disc displacement values from medial and central slices, the disc displacement variable and the TMJ internal derangement variable all show statistically significant but relatively weak correlations with the transverse condyle position. The strongest relationship is between anterior disc displacement on the medial aspect of the joint and the transverse condyle position ($r=0.219$). The correlations are positive, indicating that as the transverse distance between the condyle and the cranial base reference increases, greater anterior displacement of the disc is observed, particularly in the medial and central aspects of the joint. Statistically significant associations determined by linear regression analysis are reported in Table 3-8 (p.120).

The relationship between condylar angulation and condyle position is demonstrated in Table 3-9 (p.120). Both A-P and transverse condyle position show a statistically significant relationship (p-values$\leq$ 0.01) to condylar angulation, with correlation coefficients of 0.25 and -0.22 respectively. These values indicate that as the condyle is located more posteriorly and more medially relative to the foramen spinosum, the angulation of the condyle is greater in relation to the sagittal reference plane (flatter condylar angulation). Significant values derived from linear regression are shown in Table 3-10 (p.121).

3.5 - Discussion

The finding of no significant differences in condylar angulation between male and female subjects concurs with a study by Christiansen et al.[18] who measured condylar angulation, intercondylar (inter-medial pole), extracondylar (inter-lateral pole), and transverse condylar dimensions (lateral pole to medial pole) in a group of adults using axial computed tomography (CT). The Christiansen study reported gender differences in transverse condylar dimension and extracondylar distance with males demonstrating greater linear measures. No gender differences were found in intercondylar dimensions. The discrepancy with the data obtained in this study may be due in part to the age sample differences between the two studies, as the present study utilized only adolescent subjects. It is possible that a relatively greater increase in mediolateral condylar dimension, which would be expressed as increased extra-condylar distance, may be experienced more in the male population than in the female population during the transition period from adolescence to adult. An increased intercondylar distance during the transition from mixed to permanent dentition has been reported by others.[19,20]

The condylar angulation values reported here are reasonably similar to those reported by others for normal joints,[11-13,18] however vary from those reported by Sato et al.,[21] who reported flatter condylar angulations in a Japanese sample. Reported condylar angulation values must consider the specific reference plane which is used. Other studies have utilized a frontal plane represented by either the transporionic axis,[11] posterior aspect of the condyles,[14] a transmeatal line,[12] or an external reference such as the earrods of the cephalostat.[13] The present study utilized a sagittal reference plane with which to measure condylar angulation, as reported by Seren et al..[22] The use of the foramen spinosum to establish a reference plane, as used in the present study, is supported in the literature.[23-25]

Direct comparisons of condylar angulation values between studies which utilize different imaging techniques for data collection cannot be made. Imaging modalities such as CT and MRI utilize transverse sections which may give different results depending on the plane of the acquired slice.[21] This makes direct comparisons with SMV-derived measurements difficult.

The variability in angular measurements observed in this study is relatively large, supporting the findings of others of the large variation which exists in condylar angulation in the general population.[9,19]

The lack of a significant correlation between age and condylar angulation contrasts to the findings of Christiansen et al.,[26] who reported significant age effects on diseased joints in a sample which ranged in age from 15 to 73 years. It is possible that the age range used in the present study was too narrow (range= 9.6-17.1 yrs, mean= 13.3 yrs) to detect any age effects. Certain processes which might influence condylar remodelling and, potentially, changes in condylar angulation may typically occur in an older population than that which is represented by the present sample.

The lack of a statistically significant association between condylar angulation and joint status variables is supported by some studies. Sato et al.[21] compared morphologically 'normal' condyles to morphologically 'abnormal' condyles as determined by lateral and frontal tomographs, and found no differences in condylar angulation between the two groups. A study by Westesson and Liedberg[13] also failed to show significant associations between condylar angulation and joint status. Joint status was determined by arthrography, and assessed based on stages of internal derangement and on osseous changes within the joint. Both studies utilized SMV radiographs for the determination of condylar angulation. Samples in both studies consisted of TMD subjects encompassing a broad age range.

Some evidence exists which supports a relationship between condylar angulation and joint status. Christiansen et al.[26] found a statistically significant correlation between severity of radiographic changes in temporomandibular joints as determined by sagittal, coronal, and axial CT scans, and CT - derived condylar angulation. His study used a mostly adult sample with a broad age range (range=15-73 yrs, mean=37 yrs), all of whom had some degree of osseous degenerative changes in the temporomandibular joints.

A more recent study by Westesson et al. (1991)[14] demonstrated statistically significant differences in condylar angulation among different categories of joint status. Joint status included: normal, disc displacement with and without reduction, and degenerative joint disease. Both joint status and condylar angulation were determined by use of MRI. The sample used in his study consisted of a control group of normal adult volunteers in addition to a symptomatic patient sample with a broad age range (range=23-43 yrs, mean=28.6 yrs).

The disparity in results between the present study and some of the previously noted studies may be explained in part by the samples utilized as well as by the particular methods used to assess both condylar angulation and joint status. Since degenerative joint disease tends to be more prevalent in an adult population,[20,27] regressive remodelling which may accompany degenerative conditions and which might possibly contribute to changes in condylar angulation may not occur to the same degree in the adolescent population. Condylar angle changes with aging have been noted in diseased joints in a predominantly adult population.[26] Also, studies which utilize only TMD patients and fail to include a control group may not detect differences between normal and diseased joints, since joint changes which may not be detected by conventional means may be more prevalent in a patient population than in a non-patient group.[6,21] Joint status as determined by MRI yields different information than that provided by arthrography, conventional radiography, or CT.[1,4,5,7,13] Specific limitations exist with any imaging modality, however, changes in soft tissue components would be expected to occur at a different rate and to different degrees than bony changes which might be reflected in alterations to condylar angulation. Also, differences in condylar angulation may be found between different imaging techniques, as methods which utilize image slices such as MRI and CT may demonstrate different values depending on the superior-inferior level of slice.[21]

Poor correlation was found between joint status and A-P condyle position. Although the relationship between condyle position and TMD has been investigated by several researchers,[1,28,29] the existing evidence does not appear to support A-P condyle position as a dependable predictor of joint abnormality.[30] Other studies have used such means as tomography[28] or transcranial radiography[29] to assess condyle position. The present study assesses condyle position relative to a cranial base reference which differs from the previously noted studies.

The data found a weak but statistically significant correlation between transverse condyle position and anterior disc displacement on medial and central slices, as well as for the disc displacement variable and TMJ internal derangement variable. This suggests that the greater the transverse distance between the cranial base reference point (foramen spinosum) and the condyle centroid, the greater the anterior displacement of the disc on the medial and central aspects of the joint. One explanation for this observation may be the possible influence of the transverse distance between the cranial base and the condyle on the angulation of the lateral pterygoid muscle. The angle formed between the lateral pterygoid muscle (represented by a line from the muscle origin on the roof of the infratemporal fossa and lateral pterygoid plate and inserting postero-laterally into the capsule, disc and pterygoid fovea) and an inter-meatal reference line would be expected to decrease with a condyle position located more laterally. It is possible that this decreased muscle angulation may alter the distribution of forces on the condylar and discal attachments as the force vector would consist of a greater medial component.[31] Theoretically, this could stress the medial discal attachment and predispose or initiate disc displacement at the medial aspect of the condyle.[32] Whether or not the force generated by the lateral pterygoid muscle or the degree or distribution of muscle fibre insertion into the disc would be adequate to cause disc displacement is controversial.[33-35]

The finding of a statistically significant association between condylar angulation and condyle position in this population alludes to the possibility that functional influences during normal growth and development may contribute to the determination of condylar angulation. The positive correlation between the A-P condyle position and the condylar angulation indicates that the further posterior the condyle is positioned relative to the foramen spinosum, the flatter the condylar angulation (greater the angulation relative to the mid-sagittal reference plane). The negative correlation found between the transverse condyle position and the condylar angulation suggests that a greater transverse distance between the foramen spinosum and condyle is associated with a steeper condylar angulation.

Unique force vectors associated with different angulations of the lateral pterygoid muscle might also influence condylar angulation. Yamashiro[36] found lateral pterygoid muscle angulation to be related to facial type as determined by axial CT. This would lend support to the notion that relative A-P and transverse condyle position may play a role in describing the direction of forces exerted at the condylar region. The finding of a statistically significant relationship between condyle position and condylar angulation in this sample does not preclude the contribution of other factors such as joint abnormalities in the determination of the condylar angle, as both A-P and transverse condyle position together explain only a relatively small portion of the angle (r^2=.126). Future studies should be directed at investigating the relationship between these variables in adults to see if degenerative processes and subsequent regressive changes which may result from internal derangement of the joint might play a larger role in the determination of condylar angulation in an older population.

3.6 - Conclusions

1. No statistically significant differences were observed in condylar angulation or condyle position between male and female subjects

2. No statistically significant relationship was observed between condylar angulation and joint status.

3. A weak statistically significant correlation was observed between anterior disc displacement in medial and central portions of the condyle and transverse condyle position.

4. A statistically significant correlation was observed between condylar angulation and A-P and transverse condyle position.

The results of this study suggest that condylar angulation and condyle position information derived from SMV radiographs does not provide adequate diagnostic information for the assessment of joint status in an adolescent population. This does not diminish the value of SMV's for other diagnostic purposes, including the assessment of condylar angulation for the purposes of corrected tomography of the TMJ.

Table 3 - 1 Average, Maximum and Minimum SD Values for SMV Linear and Angular Measurements

Variable	Average SD *	Maximum SD	Minimum SD
left condylar angle	1.14 degrees	1.97 degrees	0.52 degrees
right condylar angle	1.08 degrees	2.37 degrees	0.19 degrees
left condyle A-P	0.32 mm	0.66 mm	0.16 mm
right condyle A-P	0.33 mm	0.57 mm	0.19 mm
left condyle transverse	0.35 mm	0.59 mm	0.16 mm
right condyle transverse	0.34 mm	0.46 mm	0.22 mm
intercondylar distance	0.38 mm	0.70 mm	0.16 mm
interspinosum distance	0.26 mm	0.48 mm	0.13 mm

* SD for each radiograph determined over five tracings of each radiograph - average SD represents mean of SD's over ten radiographs

Table 3 - 2 Error of Method in Determination of Reference Plane (MRI)

Variable Tested	Standard Error
MRI eminence reference plane	1.165 degrees

Table 3 - 3 Reliability of Repeated Measures for Disc Displacement and Disc Length Determination (MRI)

Test Variable	Rel = 1 - 1/F	Maximum SD	Minimum SD
disc displacement (mm)	1.00	0.33 mm	0.05 mm
disc length (mm)	0.98	0.47 mm	0.07 mm

Table 3 - 4 Angular and Linear SMV Measurements - Comparison of Male (n=39) and Female (n=56) Means (measurements in mm. except where noted)

Measurement	Males Mean (SD)	Females Mean (SD)	Observed Mean Diffs.	p-value
Left Condylar Angle*	66.4 (12.2)	67.8 (8.7)	1.35 deg	0.531
Right Condylar Angle*	64.1 (7.8)	67.4 (8.8)	3.28 deg	0.065
Left A-P Condyle	5.5 (2.8)	5.2 (2.7)	0.37 mm	0.519
Right A-P Condyle	5.4 (1.9)	4.8 (2.4)	0.51 mm	0.209
Left Transverse Condyle	21.3 (2.2)	21.1 (2.2)	0.19 mm	0.673
Right Transverse Condyle	21.9 (1.9)	21.2 (2.3)	0.62 mm	0.177
Interspinosum Distance	72.6 (4.5)	72.3 (3.4)	0.39 mm	0.632
Intercondylar Distance	115.8 (6.3)	114.6(5.6)	1.20 mm	0.332

* measurements in degrees

Table 3 - 5 Correlation Coefficients of Age vs SMV Variables

Age - SMV Variables	**r**	**p-value**
Age - left condylar angle	-.027	.795
Age - right condylar angle	-.022	.834
Age - left A-P condyle position	.085	.411
Age - right A-P condyle position	.017	.869
Age - left transverse condyle pos'n	.168	.104
Age - right transverse condyle pos'n	.182	.077

Table 3 - 6 Relationship Between Joint Status and Condylar Angulation

Condylar Angulation - Joint Status Variables	**r**	**p-value**
Condylar Angulation - Anterior Disc Displacement (Lateral)	-.02	.803
Condylar Angulation - Anterior Disc Displacement (Central)	-.03	.686
Condylar Angulation - Anterior Disc Displacement (Medial)	-.09	.209
Condylar Angulation - Disc Length (Lateral)	.02	.754
Condylar Angulation - Disc Length (Central)	-.09	.223
Condylar Angulation - Disc Length (Medial)	-.14	.054
Condylar Angulation - Disc Displacement Variable	-.11	.144
Condylar Angulation - Disc Length Variable	-.11	.148
Condylar Angulation - TMJ Internal Derangement Variable	-.12	.110

Table 3 - 7 Relationship Between Joint Status and Condyle Position

Condyle Position - Joint Status Variables	r	p-value
A-P Condyle Position - Ant. Disc Displ. (Lateral)	.078	.289
A-P Condyle Position - Ant. Disc Displ. (Central)	.097	.190
A-P Condyle Position - Ant. Disc Displ. (Medial)	.058	.429
A-P Condyle Position - Disc Length (Lateral)	.061	.404
A-P Condyle Position - Disc Length (Central)	.002	.975
A-P Condyle Position - Disc Length (Medial)	.017	.815
A-P Condyle Position - Disc Displacement Variable	.129	.080
A-P Condyle Position - Disc Length Variable	.038	.603
A-P Condyle Position - TMJ I.D. Variable	.093	.207
Transverse Condyle Position - Ant. Disc Displ. (Lateral)	.021	.772
Transverse Condyle Position - Ant. Disc Displ. (Central)	.149	.041*
Transverse Condyle Position - Ant. Disc Displ. (Medial)	.219	.003*
Transverse Condyle Position - Disc Length (Lateral)	.062	.400
Transverse Condyle Position - Disc Length (Central)	.029	.692
Transverse Condyle Position - Disc Length (Medial)	.017	.822
Transverse Condyle Position - Disc Displc't Variable	.194	.008*
Transverse Condyle Position - Disc Length Variable	.069	.351
Transverse Condyle Position - TMJ I.D. Variable	.145	.049*

*statistical significance at 5% level

Table 3 - 8 Results of Linear Regression on Joint Status/Condyle Position Variables

Joint Status (Dependent)	**Condyle Position (Independent)**	**R^2**	**Regression Coefficient**
disc displacement (medial)	transverse condyle position	.048	.212
disc displacement variable	transverse condyle position	.037	.089
disc displacement (central)	transverse condyle position	.022	.165
TMJ internal derangement variable	transverse condyle position	.021	.067

Table 3 - 9 Correlation Coefficients of Condylar Angulation/Position Variables

Condylar Angulation - Condyle Position Variables	**r**	**p-value**
Condylar Angulation - A-P Condyle Position	.25	.0006
Condylar Angulation - Transverse Condyle Position	-.22	.0022

Table 3 - 10 Results of Linear Regression for Condyle Angulation/Position Variables

Condylar Angulation (Dependent)	**Condyle Position (Independent)**	**R^2**	**Regression Coefficient**
Condylar Angulation	A-P condyle position	.063	.9574
Condylar Angulation	Transverse condyle position	.050	-.9716

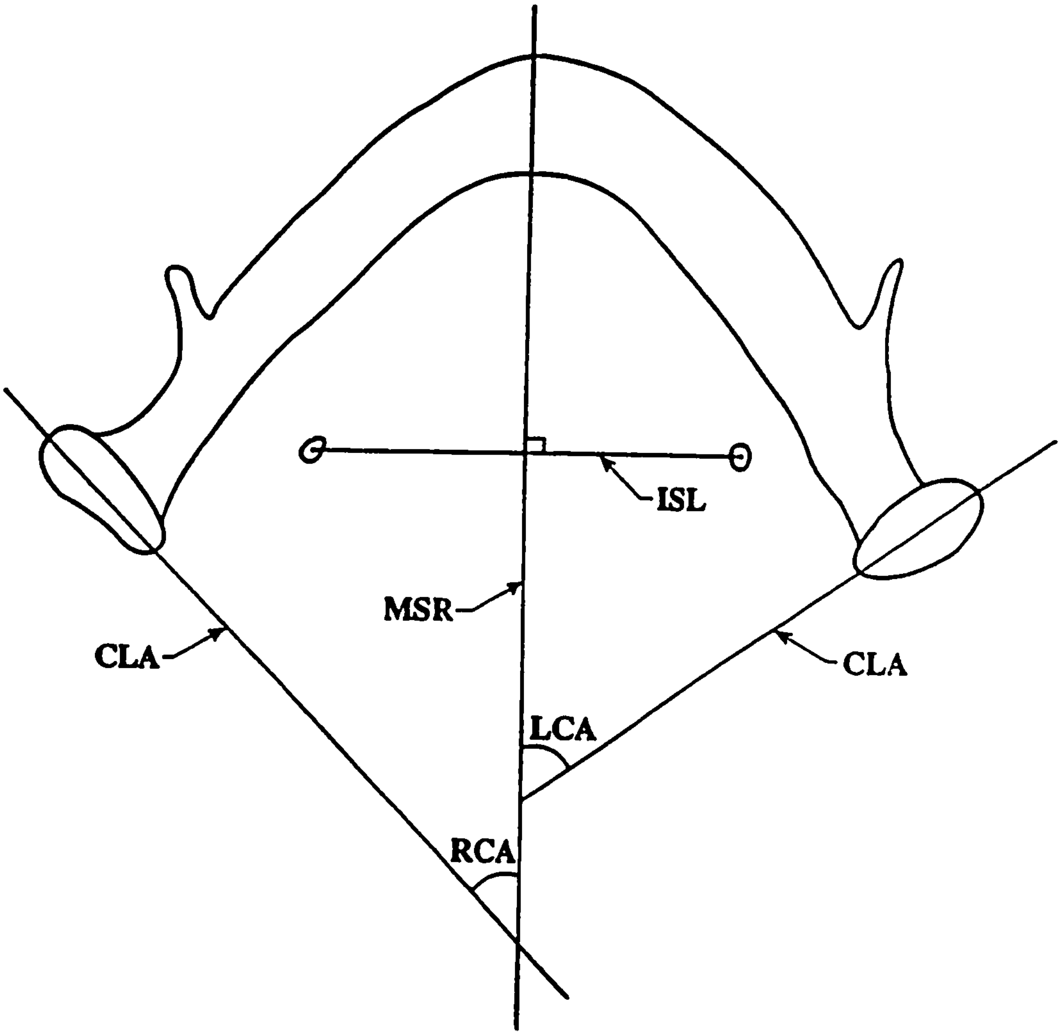

Figure 3 - 1 Condylar Angulation Determination: ISL - interspinosum line; MSR - mid-sagittal reference line; CLA - condylar long axis; LCA - left condylar angle; RCA - right condylar angle

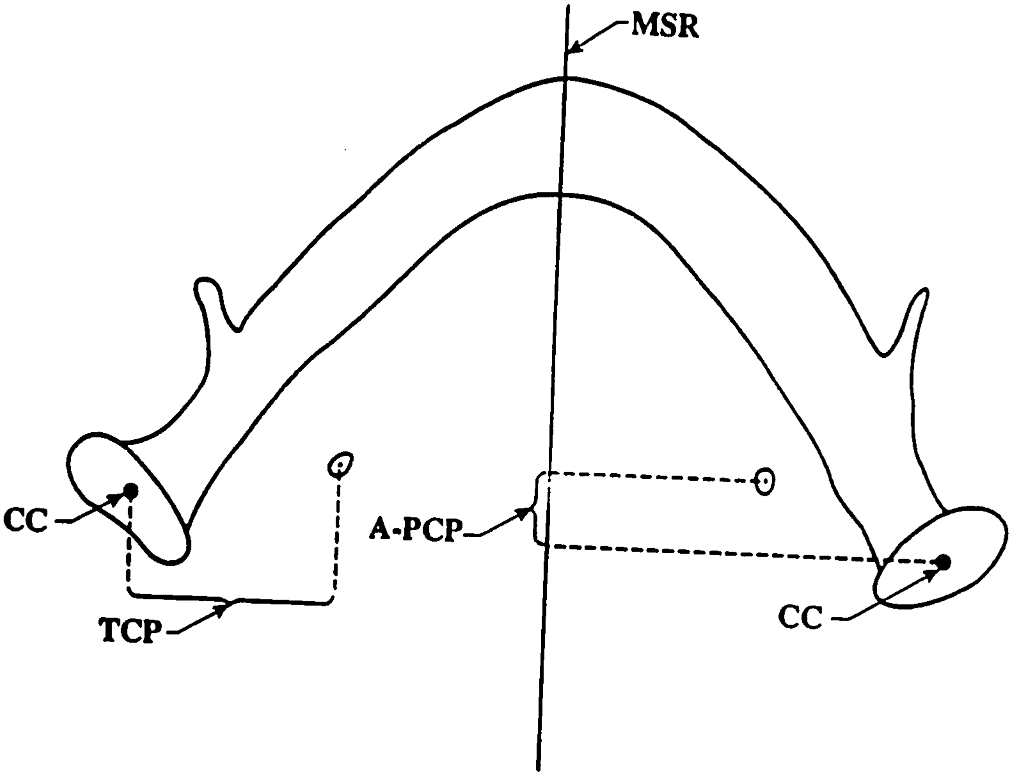

Figure 3 - 2 Condyle Position Determination: MSR - mid sagittal reference line; CC - condylar centroid point; TCP - transverse condyle position; A-PCP - anterior-posterior condyle position

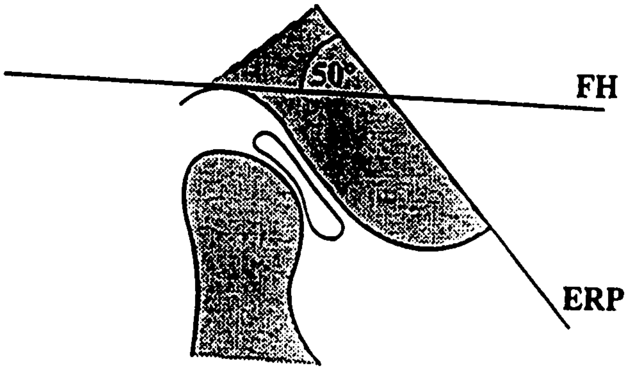

Figure 3 - 3 Establishment of Plane for Quantitative Assessment; FH - Frankfort horizontal; ERP - eminence reference plane

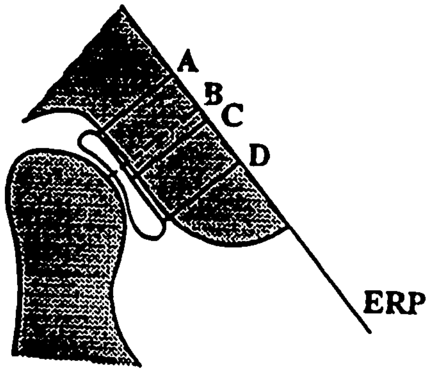

Figure 3 - 4 Reference Points for Disc Length and Disc Displacement Determination:

A - posterior band; B - condylar load point; C - midpoint of disc;

D - anterior band

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Chapter Four

Discussion

and

Recommendations

4.1 - General Discussion

Identification of factors which might suggest a predisposition to temporomandibular disorders (TMD) would be beneficial for the orthodontic clinician in the diagnosis and treatment planning process. In contemporary practice, there exists several diagnostic modalities with which to investigate the presence of temporomandibular disorders. However, the multitude of theories which have been put forth to explain TMD make it difficult to identify those patients which, though non-symptomatic upon clinical presentation, may subsequently be more at risk for the development of this condition during or following treatment. The problem is exacerbated by the fact that, although much has been written about TMD, no single unifying theory exists to explain this condition. Indeed, a multifactorial explanation, though nondescript in nature and disconcerting for the scientist who seeks a distinct and rational answer to this question, seems most plausible. Perhaps our role should be rather directed at seeking the relative contribution of various factors to this condition, and then applying these factors to the individual circumstance. The tremendous variation which exists in the biologic constitution of living beings makes this a challenging endeavour for those who seek a definitive answer to this significant question.

The purpose of this research project was to investigate the contribution of condylar angulation and condylar position to joint status in the temporomandibular joints of adolescents. Current literature demonstrates that variants to this question have been addressed in the adult population by several researchers, most notably by Christiansen et al.,[1] Westesson and Liedberg,[2] Westesson et al.,[3] Maxwell et al.,[4] and Sato et al..[5] However, to this date, this question has not been investigated in the adolescent population. Since active condylar growth ceases by the mid to late teen years,[6,7] the study of subjects who have not completed condylar growth may elucidate contributing factors which may differ from factors operational in an adult population, and contribute further to our understanding of TMD. Another purpose for this research lies in the potential use of the SMV radiograph in the identification of those patients who may be predisposed to TMD. Although there presently exists numerous means to identify joint abnormalities, many of these modalities are costly and inconvenient to perform on a routine basis in the absence of patient symptoms. The SMV radiograph, if shown to be useful for the identification of contributing or predisposing factors to TMD, might prove to be a useful screening tool for routine patient examination, without the expense, accessibility challenge, and inconvenience as some other imaging modalities currently available. As such, it may guide the clinician in the selection of appropriate treatment protocols, and may alert the practitioner to potential problems which may arise during orthodontic treatment.

The first part of this study examined the identification error of certain SMV landmarks and compared three different methods of identifying a condylar long axis, and thus condylar angulation. Though the current literature contains a number of references to SMV analyses,[4,5,8-13] it was the intent of this study to establish the identification error of specific landmarks which would be relevant in defining the sagittal, transverse, and angular position of the mandibular condyles. The use of the foramen spinosa has been well established in the literature as a valid cranial base reference system,[11,14,15] and was used as such in this research. The use of intercondylar angulation as a measure of the angulation of the condyles has been used by some researchers[12] and has an advantage when one considers that no external reference system is required, however it does not allow for correlative study with individual joint status. Since the purpose of the main part of this research project was to investigate condylar position and angulation, it was essential that the reliability of the foramen spinosum points, the condylar long axis as well as a point representing the condyle itself be established. This is especially relevant when one considers the tremendous variation encountered in condylar shapes,[13] and the difficulties in identifying polar anatomy due to superimposition effects.

Results from the first part of the study revealed that each landmark demonstrated a characteristic non-circular envelope of error, supporting the findings of others regarding cephalometric landmarks.[16,17] As noted, these can be explained by the orientation of these landmarks relative to the coordinate system used to locate these points. Pogonion point demonstrated a relatively large amount of error in the vertical direction, and was not included in the second part of this research project. Pogonion point has been used in other studies using SMV radiographs[4,12,18,19] and is a useful landmark for evaluation of mandibular asymmetry. Had this landmark been easier to locate with certainty in our preliminary sample and demonstrated less identification error, useful information may have been derived in relating mandibular asymmetry to joint status. The explanation for the poor consistency in locating this landmark likely has to do with patient positioning effects and superimposition of the inner and outer tables of the frontal bones and of the dentition over the anterior region of the mandibular symphysis. Head rotation about the transverse axis directly influences where pogonion point is projected relative to adjacent structures, and failure to position the head correctly may lead to poor visualization of structures in this region.

Foramen spinosum landmarks demonstrated the lowest identification error, except for in the inter-examiner portion where one examiner consistently mis-located this landmark, resulting in poor inter-examiner reliability. This was attributed to inexperience on the part of this examiner and/or poor description of the landmark during the instructional and preparation sessions. The fact that radiographs were selected randomly from a sample which was initially chosen on the basis of ease of identification of the foramen spinosa contributed to bias regarding the reported identification error of this landmark. In this respect, numerous radiographs were excluded from this study based on the initial selection criteria including being of sufficient contrast and definition to enable identification of specific landmarks (101 radiographs were chosen from an original sample of 187). Reasons for poor definition might include inaccurate equipment settings and/or poor film developing procedures, however it is doubtful that these would have made a significant contribution to poor quality films as these were generally standardized at the same private imaging facility for all radiographs. A more likely explanation might involve poor patient positioning or patient movement during film exposure. Although a cephalostat was used to establish proper head positioning, it is still possible to get some A-P head rotation around the transverse axis which would alter head position from the desired position of the central ray orientation perpendicular to Frankfort Horizontal. Minimal projection effects occur if the mandibular angle is projected immediately anterior to the condyle.[10] Patients with restricted neck mobility who might be unable to extend their neck sufficiently may be compromised in achieving proper position for SMV imaging, however this might be expected to be a more significant problem in an older population than that used in this research. Deleterious projection effects as a result of poor patient positioning could also be manifest in poor definition of the foramen spinosa, altered superimposition patterns, and compromised clarity and contrast of other cranial base landmarks. These parameters were assessed subjectively, and resulted in the exclusion of a large number of radiographs from this study.

Analysis of landmark identification error revealed that certain condylar points demonstrated poor reliability. The condylar lateral and medial poles demonstrated relatively large identification errors, and were likely influenced by the irregularity in condylar shapes as viewed axially[13,20] as well as superimposition effects. Most studies which have assessed condylar angulation have utilized condylar medial and lateral poles to establish a condylar long axis,[2,10,21] however due to the relatively high degree of error associated with the identification of these points it would follow that the angular measures subsequently derived may also be subject to variation. It was this reasoning which subsequently led to a search for an alternative method for describing a condylar long axis. Results from the condylar angulation data suggest that a computer-derived long axis which is calculated based on the condylar outline is a more reliable method than the two alternative methods tested, including the interpolar method which is most commonly cited. A likely explanation for this is that the computer-derived method is not as dependent on the identification of specific points, in this instance the two polar points which are difficult to locate with precision. Since the calculation of the condylar long axis involved the entry of up to 40 points representing the outline of each condyle, a slight locating error involving one or several points along the outline would have only minor affects on the resultant long axis, as compared to the more extreme influence which might result from error in locating only one of the two polar points. As well, obliteration of the polar extremities, which was noted on several radiographs and was likely a result of superimposition effects, does not necessarily preclude determination of a long axis as it would with the interpolar method. If one were to use the interpolar method in this instance, location of the polar point would be merely an arbitrary exercise, whereas relatively less information would be lost if the visualized condyle outline were to be entered.

The point used to describe condyle position in the main part of this project was the condyle centroid point, which was defined mathematically from the entered condylar outline. This was assumed to be a more accurate point for assessment of both A-P and transverse condylar position using the same rationale as noted previously. The location of one specific point along the condylar outline with which to assess condylar position, for example the posterior condyle point,[4] is subject to a relatively large amount of identification error as demonstrated in this study. The computer-derived centroid is subject to less identification error, since slight deviation of one or several points from the true condylar outline will have a less significant effect on the derived point which is calculated from up to 40 entered data points. Repeated A-P and transverse measurements utilizing these derived points demonstrated a high degree of repeatability in defining the condylar centroid. Current literature does not reference a derived centroid point in defining condylar position.

Despite the finding of less variation in angular measurements with the computer-derived method, the actual difference found was relatively small, with the mean difference being approximately one half of a degree between condylar principle axis and interpolar axis measurements. Though statistically significant differences in variability were reported between the two methods noted above, these differences are probably of little significance in practical terms, except for possible research applications where a high degree of precision is required. The decision as to which method to use might be reasonably established based on practicality. The range observed in angular values of all three methods tested is quite large, which has been found elsewhere in the literature.[9,22] Angular values may vary due to a number of reasons which might include anatomical variation, plane of slice as in CT and MRI studies,[5] relative head position,[10] and poor visualization of condylar anatomy or reference structures.

This study was aimed at addressing the issue of reliability of condylar long axis determination and thus condylar angulation, however the question of the relative validity of such measures remains unanswered. The computer-derived principal axis represents the axis of minimum moment of inertia, which essentially describes the axis which the condyle would rotate around most easily given the 2-dimensional outline of the condyle represented in the SMV radiographs. Condylar outline varies with relative head position due to projection effects,[10] thus influencing the derived condylar long axis, however this is not dissimilar to the other methods which have been used. If we consider the interpolar axis method as the current gold standard for defining a condylar long axis, then an assumption could be made that we are essentially measuring the same entity, since the difference between the resultant mean angles is relatively small (0.5 degrees). To more directly address the validity of the described long axis, it is essential to be cognizant of what is to be measured. The definition of a long axis can be reduced to a mathematical entity, and the computer program developed for this project determines this to a high level of accuracy given the condylar outline. However, is this what we really want? Regarding the mandibular condyle, this may best be answered from a functional perspective specific to the hypothesis being tested. In the present instance, the question may lend itself to a complex functional analysis of condylar movement in all three planes of space, which might require a 3-D reconstruction of the condyle through CT or MRI modalities. Subsequently, functional analysis of both centric and eccentric condylar movement over and above simple condylar rotation might better describe the role of specific anatomical features of the condyle (specifically angular measurement) and soft tissue structures (capsular and muscle tissues) and the possible role they play in influencing joint status. Such an undertaking represents a new vista of research which is well beyond the scope of this project. In the present study, an assumption has been made regarding the validity of the derived condylar long axis and the accuracy of the mathematical model used to identify it.

The second paper represents the main focus of this project, that being to investigate the relationship between condylar angulation and position, and joint status. In addition, the relationship between condylar angulation and condylar position was also studied. The original intention of this portion of the study was to divide the joints categorically into those joints with no abnormalities, and those joints with extreme abnormalities in order to compare angular means of the two extremes of joint status. Unfortunately, by using only extreme measures a great deal of information was lost, and the sample size was reduced significantly. Because of this, it was decided that a continuous data base might be better utilized in order to maximize the use of all available data.

To our knowledge, this study represents the first of its kind to use a continuous data set in the assessment of joint status to describe relationships with condyle angulation and position. This enables utilization of a greater amount of information from a given sample. MRI offers several advantages over other imaging modalities,[23] including being noninvasive, free from ionizing radiation, and pain free. MRI also allows quantification of information, and has been proven very useful in identifying condyle disc relationships.[24,25] The method of quantification of disc displacement and disc length used for this study was developed by Nebbe et al.,[26] and the MRI data was utilized unaltered from the work of these researchers.

The finding of no statistically significant differences between males and females in condylar angulation or condylar position relative to a cranial base reference is interesting. Mean male distances appear to be marginally larger than female values on all linear measures, however the differences are not statistically significant. Other literature describing similar measurements was sparse, and thus direct comparison of values with other studies was difficult. It is evident by other research that racial differences may exist in condylar angulation, as Sato et al.[5] found significant differences in condylar angulation in their Japanese sample. The present study did not control for racial variability, and it is possible this may have influenced results involving angular measures.

In the age group represented by our sample, no statistically significant relationships were found between joint status variables and condylar angulation. Disparate findings in the literature may be explained by numerous variables, including the specific imaging modalities used, the means of evaluating joint status, and the age range of the sample. A review of the existing literature demonstrates that only one of the studies[3] referenced herein utilized a control group, rather than a sample of solely symptomatic patients or confirmed abnormal joints. The Westesson study[3] was also the only study found which utilized MRI for assessment of joint status, rather than tomography, clinical assessment, or arthrography. The Westesson study[3], therefore, might be considered the gold standard with which to compare results in terms of the relationship between joint status and condylar angulation. Differences, however, do exist between the Westesson study and the present work. Westesson utilized categorical data derived from both coronal and sagittal MRI, and used axial MRI to assess condylar angulation. Perhaps the most significant difference between the two studies is the different age range of the samples which have been utilized, as Westesson used a mainly adult sample versus the adolescent sample utilized herein. On this basis, a plausible explanation has been presented for the disparity in findings regarding the relationship between condylar angulation and joint status. Condylar angulation changes resulting from joint abnormalities may be manifest mainly in adult samples as a product of regressive remodelling associated with degenerative joint disease. Degenerative joint disease is more prevalent in the adult population,[27] and it follows that changes in condylar angulation might be observed more frequently in adults, possibly as a consequence of an abnormality within the joint leading to altered stress distribution or functional loading. It is possible that derangement of the temporomandibular joint in adolescence may not result in angulation changes, whereas such changes may be more readily observed in adults. Histologic differences have been observed in the condyle of growing persons in comparison to adults, including a decreased thickness of the proliferative zone and a general decrease in cellularity.[28-31] It has also been observed that the reaction of the mandibular condyle to altered functional loading varies according to the growth potential which exists.[28] That is, a growing condyle is better able to adapt to imposed stresses than one which has a reduced adaptive capacity. It is possible that increased functional stress on a joint which doesn't possess adequate adaptive potential may result in changes in condylar angulation which are not seen in younger condyles which are better able to adapt.

No significant differences were found between A-P condylar position and joint status. However, it must be noted that the measurement of A-P condylar position is made relative to the foramen spinosa landmarks, rather then conventional means as determined in lateral cephalometric or tomographic images, which may result in different findings compared to other studies. Remodelling of the temporal component does not directly influence A-P values as obtained in this study, as condylar position has not been assessed based on the relative position within the glenoid fossa. In addition, it must also be noted that all SMV radiographs were taken in maximum intercuspation rather than in a centric relation position. If a significant A-P shift occurred between the two positions, then the recorded condylar position would not represent a physiologic condylar position.

A statistically significant correlation was found between anterior disc displacement at the central and medial aspects of the condyle and transverse condylar position. This can be explained on the basis of the geometric orientation of the lateral pterygoid muscle as determined by the transverse position of the condyle relative to the muscle insertion at the cranial base. An assumption has been made that the transverse distance between the foramen spinosum and the condyle is related to the transverse distance between the muscle insertions of the lateral pterygoid (the roof of the infratemporal fossa and the lateral aspect of the lateral pterygoid plate) and the condyle. This assumption is based on the fact that the foramen spinosa as well as the muscle origins noted are constituents of the sphenoid bone. The literature suggests that the basal foramina are stable structures[15] and that the cranial base is influenced minimally by environmental factors.[14] Existing literature, however, does little to further validate this assumption. Due to the fact that visualization of the muscle origins was not possible in the SMV view, the foramen spinosum landmarks were used as a compromise. Other axial imaging such as CT or MRI would be required for more accurate location of muscle origin relative to insertion, or for direct visualization of muscle angulation.

As noted, the explanation of disc displacement on the basis of relative muscle orientation could be argued by those who question whether the degree of muscle attachment to the disc would be great enough to effect disc displacement,[32] however this concept is at least plausible in theory. The low correlation between disc displacement and transverse condyle position suggests that there are also other variables which play a role in disc displacement, and inter-individual variation in the degree of muscle attachment to the discal structures may contribute to the variability in the data. This theory is also supported by the findings of Yamashiro[33] who found a relationship between lateral pterygoid muscle angulation and facial type and reported a decreased muscle angle in a dolichofacial group. This suggests that a relatively narrow cranial base in comparison to transverse condylar position might be associated with decreased muscle angulation. However, the relevant literature does not report a higher incidence of disc displacement in dolichofacials. It would have been an interesting adjunct to this study to compare facial type to individual joint status, however this was not done as joints were considered as individual entities and joint status was not assigned on a whole patient basis.

As discussed, muscle orientation may be hypothesized to influence the relative stress directed at discal attachments. In a similar manner, muscle orientation might also play a role in determination of condylar angulation. With normal growth and development, functional influences are instrumental in determining both shape and inner architecture of bone as dictated by Wolff's law.[31] This is not incompatible with the theory that degenerative disease might play a role in determining condylar angulation in an older population group. It would be interesting to see how early in life condylar angulation is determined, and what age changes if any might occur with normal development in the absence of disease. Perhaps, as was observed in this study, condylar angulation is established early (prior to age 7) based on normal functional influences and facial pattern determinants, and is constant until such time as increased joint stresses overcome the adaptive potential of the joint and result in condylar angulation alteration concomitant with degenerative changes. Longitudinal studies are necessary to address these questions.

In conclusion, the present research investigated: 1) the identification error of specific SMV landmarks and a comparison of three different methods of determining a condylar long axis and, 2) the relationship between joint status and condylar angulation/position. Through this research a better appreciation has been gained for the usefulness and limitations inherent in the SMV projection. An increased awareness of the importance of proper patient positioning in SMV projections, and a better understanding of the identification error associated with specific, commonly-used SMV landmarks has been gained. In addition, a computer-derived method of determining a condylar long axis which demonstrates less variability than methods which are currently used has been developed. The clinical usefulness of this method, in light of the small but statistically significant differences observed, is probably of minor significance, however depending on the accuracy required for a specific application (ie: research) it may be a useful tool for SMV analysis.

The second part of this project has provided more information with which to better understand the relationship between joint status and condyle position and angulation. Obviously, there are many factors which influence the status of the temporomandibular joint. This study has observed that joint status as determined by disc displacement and disc length is unrelated to condylar angulation in an adolescent population. Disc displacement noted on medial and central MRI slices appears to be related to the transverse relationship of the condyle to the cranial base. In addition, it appears that condylar angulation may be determined more by condylar position relative to the cranial base than by joint status in the adolescent population. The clinical usefulness of these findings is not directly evident, however a theory has been postulated which may help explain these findings relative to other observations noted in the literature. The information gained from this research represents a contribution to the present knowledge base regarding temporomandibular disorders in the adolescent population, however additional research is required to further elucidate the factors, both predisposing and initiating, which are operational in TMD.

4.2 - Recommendations for Future Studies

As with any study, there are inherent weaknesses in this study which may be addressed in future studies. The following are areas of consideration:

1. The elimination of a large number of SMV radiographs due to poor definition of structures and/or improper patient positioning indicates a need for better standardization of imaging procedures and head position. Due to the fact that a certain degree of A-P head movement is allowed about a transverse axis with the current system, an alteration to the present system may be suggested which would eliminate any head movement after setup and prior to imaging. Proper head position and lack of movement during imaging would allow for better definition of anatomical structures, and may help eliminate the superimposition of pogonion point which would be useful for symmetry studies.

2. An anatomical study to test both the currently-used interpolar method and the computer-derived method of long axis determination against metal-implanted condylar poles in dry skulls would be useful to see how these two methods compare.

3. Longitudinal studies, though often impractical and ethically questionable, would provide answers that cannot be answered by cross-sectional data alone. Longitudinal data would provide information regarding changes in condylar angulation with normal growth

and development, and changes that occur over time as a result of joint abnormality. It may better answer whether steep condylar angulation predisposes to subsequent internal derangement, or whether an existing internal derangement ultimately results in an increased condylar angulation, and at what stage of development this may occur.

4. The creation of a 3-D reconstruction of each mandibular condyle would allow for a 'true' long axis determination which may be more relevant functionally than a long axis derived from information acquired from a 2-D image. This would require use of different imaging modalities such as CT or MRI.

5. Axial imaging with MRI would allow for more precise condylar angulation determination, and would allow for visualization of muscle orientation to more accurately assess the role of the lateral pterygoid muscle in disc displacements and in determination of condylar angulation.

6. Due to race-specific condylar angulation variation noted in the literature, it would be useful to clean up the data set so as to eliminate racial variability as a possible confounding variable. To do this, one would limit the sample to one racial group, or gather a large enough sample size so as to maintain statistical power while grouping subjects by race.

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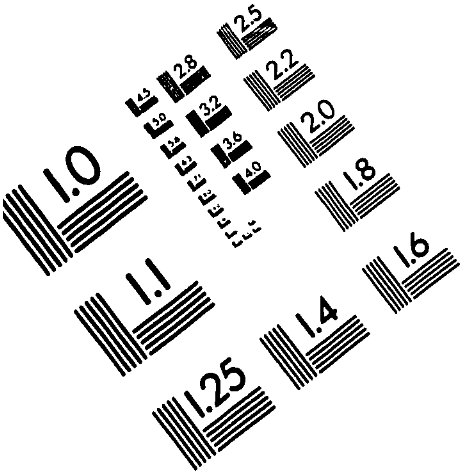
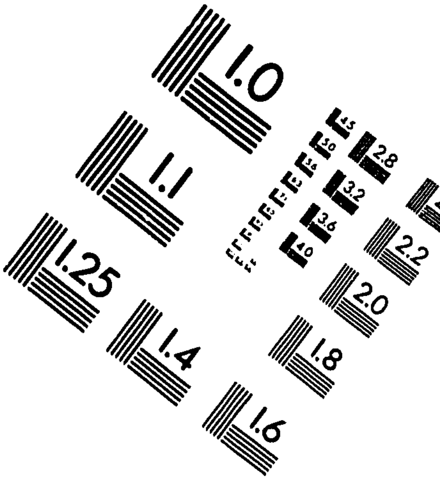
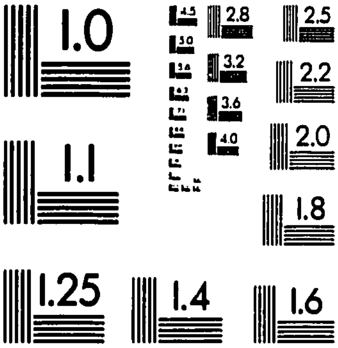
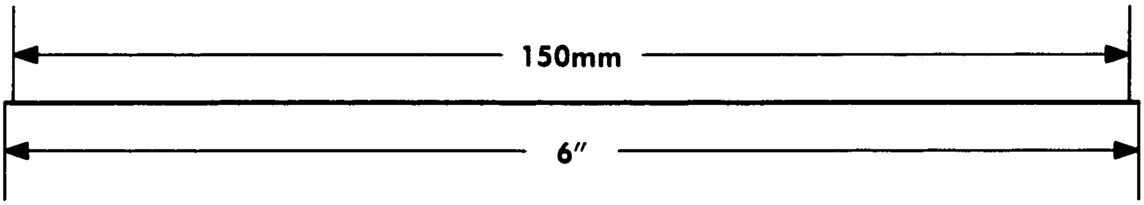
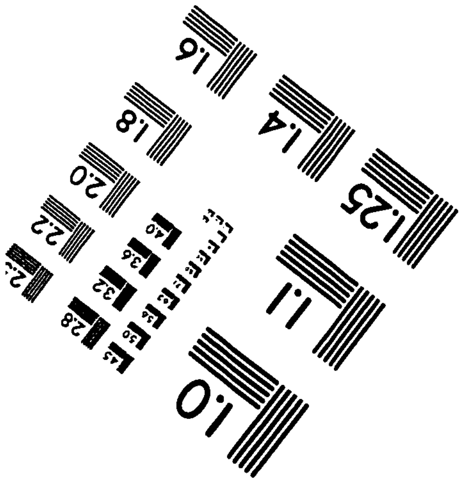
IMAGE EVALUATION TEST TARGET (QA-3)

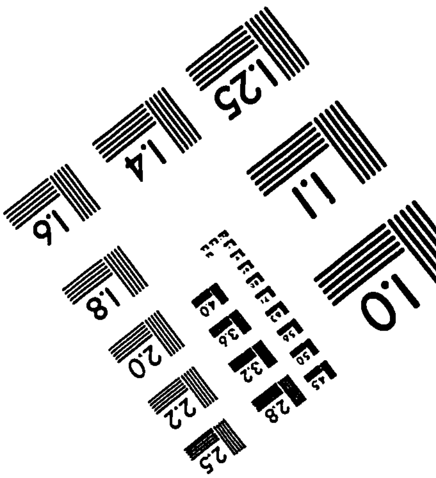












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