AN INVESTIGATION OF GROWTH ROTATIONS OF THE JAWS

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DECLARATION.

I, Stephen David Springate, confirm that the work presented in this thesis is my own and that this thesis is the one on which I expect to be examined. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

ABSTRACT

This thesis describes an investigation into the origin and mechanism of growth rotations of the jaws. The materials comprised serial lateral, frontal and oblique cephalometric radiographs of 11 untreated children (5 males and 6 females) with tantalum markers in the mandible and both maxillae. The radiographs were recorded annually over an average period of 9.6 years (mean age at initial records 7.21 years) and were drawn from the archives of the Mathews Longitudinal Growth Study of the University of California, USA.

The investigation comprised two separate but related studies: (i) an initial survey examining the correlations between growth rotations of the jaws and growth changes at sites throughout the face; and (ii) an in-depth investigation of the patterning of the sequences of annual increments of growth employing time-series analysis to detect intra-individual co-ordination of growth.

The initial survey revealed a series of associations that matched those found in previous implant studies but some exceptions. The main study extended these results and indicated that the vertical growth displacements of the ramus and anterior maxilla combined to produce growth rotation of the mandible while the horizontal to vertical distribution of maxillary growth displacement produced growth rotation of the maxilla. Growth rotations of the jaws were found to be co-ordinated with: vertical growth displacement of the ramus ($p=0.030$) and anterior maxilla ($p=0.009$); horizontal growth displacement of the mandible ($p<<0.001$) and maxilla ($p=0.015$); horizontal migration of the maxillary molars ($p=0.034$); changes in angulation of the maxillary molars ($p=0.009$); and changes in the postural height of the tongue ($p=0.048$).

The patterning of the co-ordination between rotational and translational growth displacements of the jaws and growth related changes in the dentition suggests a linkage to postural changes in the mandible and tongue. Based on these findings an explanatory model is proposed for the origin and control of growth rotations of the jaws.

IMPACT STATEMENT

During normal growth the stable cores of the upper and lower jaws gradually rotate in an anti-clockwise direction when viewed from the patient's right hand side. On average the lower jaw rotates by about 15 degrees and the upper jaw rotates by half this amount. However, in a small proportion of the population there is a much more marked forward rotation (-20 degrees) or, less commonly, a marked backward rotation (+15 degrees). These extreme forms of growth rotation are disproportionately associated with some of the most difficult orthodontic treatment problems often necessitating surgical correction in adult life.

The present research examined the co-ordination between growth rotations of the jaws and growth changes throughout the facial bones and dentition to locate possible causal factors. This required the accurate measurement of the intra-individual patterns of sequential growth increments which has not generally been possible previously because of two confounding effects: 1) the doubling of the random error in locating the end points of the increments; and 2) the negative serial correlation between adjacent increments. A new method of radiographic analysis was developed to suppress the serial correlation and to reduce the random error thereby allowing intra-individual patterns of incremental growth to be accurately recorded without the introduction of artifacts induced by the standard curve-fitting and smoothing procedures.

As a result of the study evidence was found that contradicts the prevailing theories of the causation of growth rotation and which, instead, points strongly to the postural relationship of the mandible to the cranium as being the primary underlying cause. This suggests the possibility of developing orthodontic treatments to intercept and reduce the most severe forms of growth rotation by influencing cranio-mandibular posture during childhood and adolescence. If this could be achieved it should avoid the need for complex surgery to correct the effects of the most severe forms of growth rotations of the jaws.

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CONVENTIONS OF NOTATION, SYMBOLS AND ABBREVIATIONS

In this section the conventions of notation, abbreviations and symbols are described.

Footnotes

The symbol ¶ indicates an accompanying footnote, which appears at the bottom of the same page. Where two footnotes appear on the same page the symbol § is also used. Footnotes generally contain additional information relevant but not essential to points raised in the main body of the text.

Mathematical and statistical conventions

The notation used for statistics follows current convention. However, where it is necessary to indicate probabilities that have been adjusted for multiple inference (and dependency) this is signified by a circumflex overmark, ^. For example, $\hat{p} = 0.02$, indicates the *Bonferroni-corrected probability (p-value) adjusted for dependency between the variables.*

Abbreviations

The abbreviations used to indicate standard cephalometric reference points (landmarks), and cephalometric lines or planes together with the cephalometric variables examined in this study, are given together with appropriate definitions in Chapter 5 (Material, Subjects and Methods).

The following non-cephalometric abbreviations are used:

Abbreviation	**Meaning**
2-D	two-dimensional
ACB	anterior cranial base
ANOVA	analysis of variance
CI	confidence interval
COR	centre of rotation
DEP	dependency (between variables or statistical tests)
degs	degrees
dep	dependency
df	degrees of freedom
HOR	horizontal
MC	mathematical coupling
MGR	mandibular (displacement) growth rotation (Not to be confused with the variable *MGR*)
MxGR	maxillary (displacement) growth rotation (Not to be confused with the variable *MxGR*)
PCB	posterior cranial base
PDF	probability density function
PFMME	post-functional mandibular molar eruption
PHV	peak height velocity
PSD	power spectral density (*see* Glossary)
TMJ	temporo-mandibular joint
SD	(sample) standard deviation
VERT	vertical
yrs	years

Symbols

The following conventional symbols are used:

Symbol	Meaning
α	false-positive error rate
β	false-negative error rate
H_0:	null hypothesis
ln	natural logarithm ($\log_e$)
mm	millimetres
n	number in a sample
ns	not statistically significant
$\boldsymbol{p}$	probability
$\hat{\boldsymbol{p}}$	multiple inference and dependency adjusted probability
r_{xy}	correlation coefficient between samples x and y
$r_{(n=11)}$	correlation coefficient of a sample of size 11
r	correlation coefficient (of a sample)
$\lvert r \rvert$	absolute correlation
$\lvert \mathbf{r} \rvert_{dep}$	dependency
$\boldsymbol{r}$	Pearson's product-moment correlation coefficient
$\boldsymbol{r}_{\mathbf{s}}$	Spearman's rank correlation coefficient
S	error standard deviation
S_x and S_y	standard deviation for differences of double determination
χ^2	Chi-squared (statistical test)
W	Shapiro-Wilk's statistic

GLOSSARY OF TERMS

Several terms are used in this thesis that are either unusual or uncommon in the dental and orthodontic literature. The terms are usually defined where they first appear in the text. The following terms are used:

Word or Term	**Meaning**
Autocorrelation	Self-correlation (within a time-series) where values measured close together in time are more alike than those measured further apart in time (Eklund and Nichols, 2017).
Beurling-Landau instability	The situation where a small error in the measurement of the value at a sample-point does *not* lead to a correspondingly small error in the reconstructed (growth) curve because the original continuous function was sampled below the *Nyquist rate*.
Change variable	A variable describing differences in position or orientation of reference points or lines relative to a site of superimposition.
Discrete time-series	A collection of observations ordered sequentially in time where the observations are not made continuously but at discrete *sample-points* in time (usually with the same time interval between recordings).
Fourier transform	The decomposition of a function or signal into the sum of a set of sine or cosine (oscillatory) functions. An alternative method of describing a function.
Growth Track	The 2-D path of a stable anatomical point on the crown of a tooth or implant defined point in or on a bone.
Implant centre	See ‘single implant point’ A reference point at the geometric centre of the body of an implant (avoiding its tapering tip.

Glossary of Terms Continued …

Word or Term	**Meaning**
Intra-osseous eruption	The phase of tooth eruption before the crown perforates the alveolar ridge.
Median implant point	A nominal mid-sagittal point constructed by bisecting a straight line joining the images of implants in matching anatomical sites in the right and left maxillae.
Non-linear Time-series analysis	Mathematical analysis of a time-series not relying on the assumptions of linearity or Normality of the distribution of the observational values.
Nyquist frequency	The minimum rate at which a signal can be sampled without automatically introducing errors (twice the highest frequency present in the signal).
Nyquist rate	The sampling rate (of a discrete signal processing system) at twice the maximum component frequency of the function being sampled.
Observational noise	Random measurement error.
Orthogonal	In the present context this refers to an *orthogonal projection* where two planes are at 90 degrees to each other.
Permutation	A random re-arrangement of a sequence of values (‘shuffling’ without replacement).
Power spectral density	Describes the ‘power’ present in a signal as a function of frequency. It depends on the amplitudes of the frequency components of the function and is calculated as the squared magnitude of the Fourier Transform.
Radiogrammetry	The high precision analysis of radiographic images (the radiographic equivalent of photogrammetry).
Rigid body	A concept in mathematical physics whereby the dimensions (and shape) of a ‘body’ remain unchanged as its location or orientation is altered.
Rotation variable	A variable describing angular differences in orientation of lines or planes relative to a site of superimposition.

Glossary of Terms Continued …

Word or Term	**Meaning**
Sample-point	The point in time where an observational measurement is made and which forms part of a time-series.
Sampling Theorem	A mathematical theorem concerning the problem of reconstructing an analytic function from its sampled values.
Serial correlation	Describes the dependency (correlation) between the values of a sequence or time-series. See ‘Autocorrelation’.
Single implant point	A reference point at the geometric centre of the body of an implant (avoiding its tapering tip).
Signal	A function that conveys information about the behaviour or attributes of some phenomenon (Priemer, 1991).
Supra-osseous eruption	The phase of tooth eruption after the crown perforates the alveolar ridge.
Synchronous	Two or more systems or processes are said to be ‘synchronous’ if their rhythms or the pattern of their oscillations coincide.
Time-series	A collection of observations ordered sequentially in time.
Translation variable	A variable describing linear differences in position of reference points relative to a site of superimposition.
Translocation	The total linear displacement of a tooth relative to the anterior cranial base. Combining the effects of migration and eruption of a tooth, and displacement of the bone to which the root of the tooth is attached.

CHAPTER
1

INTRODUCTION

1.1 BACKGROUND TO THE STUDY

The publication of the classic cephalometric growth studies by Brodie (1941, 1949) ‘confirmed’ the prevailing concept that craniofacial growth was linear with the cranium growing concentrically and the facial bones following a simple downward and forward growth pattern.

Although the findings from vital staining studies in growing primates cast doubt on the validity of these concepts (Brodie, 1949) it was the early implant studies of Björk (1955, 1963) which confirmed that jaw growth in humans was not simply linear but involved a rotational component in the sagittal plane. Subsequent implant studies by Björk and co-workers (Björk and Skieller, 1974, 1976, Björk *et al.*, 1995) and by Rune *et al.*, (1980) have shown that the maxillae undergo growth rotations both in the sagittal and transverse planes.

The more extreme forms of growth rotation of the jaws are frequently associated with severe forms of malocclusion that are generally difficult to treat by orthodontics alone (Björk, 1969; Wang, 2007). Despite many studies into growth rotation and the development of several theoretical models to explain this phenomenon, the cause or causes of growth rotation of the jaws remain unknown.

1.2 OUTLINE OF THE THESIS

The research which led to the writing of this thesis began because of perceived inconsistencies in the reported associations between mandibular growth rotation and other features of facial growth. These inconsistencies appeared to arise from flaws in some of the methods employed by Björk and co-workers in the analysis and interpretation of the Copenhagen (implant) growth study (Björk, 1968).

In an attempt to resolve these inconsistencies it was decided to re-examine the relationships between growth rotations of the jaws and other features of growth displacement of the jaws, tooth eruption and tooth migration in a different sample of untreated children with tantalum implant markers observed longitudinally during a period of growth.

In the time since the original analyses were performed (the early 1950's through to the 1980's), there have been major advances in the methods for gathering and analysing radiographic data. It was hoped that these advances (in visual enhancement and image signal processing) and associated advances in statistical analysis of dynamical systems would permit a deeper insight into the possible causes of growth rotations of the jaws. The description of the investigations employing these updated methods forms the substance of this thesis.

The thesis is laid out in a series of 9 chapters, each of which describes a separate aspect of the study.

Chapter 2 provides a review of the literature relevant to the subject of the thesis. It is divided into 11 sections. The first 10 sections describe a separate aspect of growth rotations of the jaws and the final section presents a summary of the literature review.

Chapter 3 describes the aims and objectives of the study and examines the nature of the problem investigated in this thesis.

Chapter 4 lays out the general approach to the design of the study and the difficulties likely to be encountered in this type of investigation. The implications of the mathematical 'sampling theorem' for the longitudinal study of *any* continuous phenomenon recorded by periodic sampling are explained together with potential solutions.

Chapter 5 describes the subjects, materials and methods used in the study together with the methods of handling data in the form of digital images.

Chapter 6 is divided into three sections. The first section outlines the statistical methods employed in the analysis of the data from the initial correlation survey. The problems in assessing the statistical significance of multiple correlation coefficients, particularly where the correlations are inter-correlated, are explained. The use of a correction for multiple-inference and the use of the dependence (covariance) structure of the data to adjust the critical values for statistical significance are explained together with the segmentation of the correlations into statistical families. The second section describes the methods used to assess the degree of synchrony between discrete time-series representing the patterns of angular and linear growth velocities throughout the jaws and dentition. The final section examines and assesses the technical errors of the method and provides estimates of the errors of precision for the measurement of growth and growth related changes of the teeth and jaws.

Chapter 7 describes the results of the separate investigations and examines the statistically significant findings.

Chapter 8 is divided into two sections. The first section discusses the limitations of the study and the potential pitfalls in the interpretation of the results. In the second section the results of the study are discussed and possible explanations for the findings are outlined together with possible alternative explanations. The findings are compared with those from previous investigations. The standard explanations of the inter-relationship between growth rotations of the jaws and growth changes throughout the face are critically examined in the light of the findings of the present study. New insights into the patterns of facial growth are described together with a re-appraisal of the current concepts relating to the association between growth in different parts of the face. As a consequence of the findings, a theoretical explanation for the origin of growth rotation of the jaws is proposed and developed.

Chapter 9 concludes the body of the thesis with some general considerations on the consequences of this study and provides a summary of the important findings together with suggestions for further study.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 INTRODUCTION

Growth rotations of the jaws were first identified by Björk (1955) in his classic metallic implant study of facial growth. This study confirmed earlier suspicions (Björk, 1948) that jaw growth was not simply linear and translatory in nature, as had been previously thought (Brodie, 1941), but contained a rotational component when viewed in the lateral projection.

The use of metallic markers implanted in the cortices of the mandible and maxillae as fixed reference points made it possible for the first time in human subjects to locate sites of apposition and resorption in the individual jaws and to examine individual variations in direction and intensity of growth displacement in the two-dimensional projections of frontal and lateral cephalometric films. Moreover, as Björk later remarked, *"The marker technique has also proved useful in the analysis of the mechanisms underlying changes in the intermaxillary relationship during growth, an analysis that has led to a radical modification of previous views."* (Björk 1969).

One of the main findings of Björk's initial study (Björk 1955) was that the mandible rotated during growth relative to the floor of the anterior cranial fossa (the 'anterior cranial base'). The immediate cause of the rotation was differential growth in the anterior and posterior facial heights; and the degree of rotation appeared to be closely related to the direction of condylar growth.

In two of the five subjects in the sample there was also evidence of rotation of the maxilla in the sagittal plane. It was later confirmed that sagittal growth rotation of the maxilla occurs to some degree in most, if not all, actively growing subjects (Björk and Skieller, 1972, 1976; Björk, 1977).

There appear to have been two reasons for the difficulty in observing maxillary rotations in the remaining three subjects in the sample: (i) because of the much lower levels of growth rotation of the maxilla compared to that of the mandible; and (ii) because implant markers were only inserted in the right maxilla and not bilaterally, which makes it especially difficult to accurately define the motion of the upper jaw (Björk and Skieller, 1976).

The growth rotations observed in the subjects of Björk's 1955 study were all in a clockwise direction when viewed from subject's left side. As these rotational changes occurred, the inferior outline of the mandible and palate, and the superior outline of the nasal floor remodelled in the opposite direction to the rotation, which masked much of the rotation of the bony cores of the mandible and maxilla.

As Björk's investigations continued (Björk, 1963, 1964, 1969) it became clear that growth rotation could occur in the opposite direction (anti-clockwise with the patient facing to the left) with different patterns of resorption and deposition to those observed in clockwise rotating subjects (Björk, 1963, 1969). In addition, it was found that the two maxillae also rotated in the transverse plane (Björk, 1964) and it became clear that many of the more difficult orthodontic treatment problems occurred in children exhibiting extreme patterns of rotational growth (Björk, 1969).

More recently, it has been observed that growth rotations occur in the frontal bone of human subjects (Björk *et al.,* 1985) and experimental investigations in the rat have revealed growth rotations in the parietal, interparietal and supraoccipital bones (Vilmann 1968, 1972). It appears likely that similar rotations occur in the bones of the human cranial vault (Rune *et al.,* 1979) although there is no direct evidence of this in untreated subjects. Nevertheless, as Rune *et al.,* (1987) pointed out *"…with differential articular growth in the craniofacial complex the absence of rotatory displacement of bones would be inconceivable."*

2.2 THE CONCEPT AND GENERAL NATURE OF GROWTH ROTATIONS OF THE JAWS

Enlow (1975) defined two ways in which a bone can rotate during growth: as a *remodelling rotation* or as a *displacement rotation.*

2.2.1 Remodelling Rotation

A remodelling rotation occurs when the outline or external contour of the bone is altered by resorptive and depository growth processes along its surface to produce angular as well as dimensional changes of the bone as it is progressively relocated. This definition of rotation is widely employed in human evolutionary studies and paleoprimatology (Bromage 1989; McColumn, 2008) and was later employed by Björk and Skieller, (1983) in their concepts of matrix and intramatrix rotations (Section 2.3).

This use of the term 'rotation' for this form of angular change in surface contours has, however, been criticised by Rune *et al.,* (1987) who commented that the concept of growth rotation is only valid in the context of bone displacement (because the bony corpus can be regarded as a 'rigid body') but not where the position and inclination of bone contours are altered by remodelling. Interestingly, Rune and Sevik (two of the three authors of the paper, Rune, *et al.,* 1987) softened their stance regarding what could, and what could not, be considered a rotation when they later co-authored a paper with Björk on matrix-rotation of the frontal bone (Björk *et al.,* 1995).

2.2.2 Displacement Rotation

A displacement rotation describes the relocation of the corpus of a bone. In the sense of a displacement (rotational or otherwise) the 'corpus' is those parts of the bone that have not undergone detectable remodelling growth (Rune *et al.,* 1987) and are therefore macroscopically invariant. In practical terms this is primarily the bony cortex, the dense layer of bone that defines the outline of the bone and which can be considered, in terms of mathematical physics, as a 'rigid body'. Displacement rotation was the most widely used meaning of the term 'growth rotation' until Björk and Skieller, (1983) described and defined two additional forms: matrix and intramatrix rotation.

2.3 TERMINOLOGY AND NOMENCLATURE OF GROWTH ROTATIONS

Björk (1955) used the term '*mandibular rotation*' which clearly referred to the rotation of the mandibular corpus – the invariant parts of the mandible (Solow and Houston, 1988). The terms '*mandibular growth rotation* ', '*forward rotation of the mandible*' and '*backward rotation of the mandible* ' first appear in Björk's paper on the prediction of mandibular growth rotation in which he also discussed the relationship of these rotations to mandibular form (Björk, 1969). *Forward rotation* and *backward rotation* were used to describe clockwise and anticlockwise rotations respectively, with the subject facing to the left of the observer [¶].

[¶] When (Shudy, 1965) used the terms 'clockwise' and 'anticlockwise' (or counterclockwise) to described growth rotations they were defined with the subject facing to the right of the observer.

Ødegaard (1970b) described two growth induced angular changes in the mandibles of subjects with metallic implants. He used the terms *angle alpha* and *angle gamma* to describe rotation of the mandibular lower border to the mandibular core and the rotation of the core to the anterior cranial base respectively. These terms have not been subsequently employed in any major study but these concepts were developed by Lavergne and Gasson (1977) who used the term *'positional rotation'* to describe changes in the orientation of the mandible relative to the anterior cranial base, and *'morphogenetic rotation'*, for changes in the shape of the mandible resulting from growth.

In a study on the implications for orthodontic treatment of growth rotation of the mandible, Schudy (1965) employed the terms *clockwise rotation* and *counterclockwise rotation* for backward and forward rotations respectively. In the USA the convention was for the left side of the subject's face to be closest to the film cassette such that the patient would be viewed from their *right* side. In Björk's implant studies the subjects were seated with the right side of the face closest to the film cassette (Björk 1968) such that when viewed from the subjects *left* side a clockwise rotation of the jaws would be a forward rotation. Nevertheless, despite the differences in notation, forward rotation is by convention designated as negative and backward rotation as positive.

New concepts and a new terminology were introduced by Björk and Skieller (1983) in which the rotation of invariant structures in the mandible relative to the anterior cranial base was termed '*total rotation*'. Rotation of the lower border of the mandible relative to the cranial base was designated as '*matrix rotation*', and the change in the orientation of invariant structures in the mandible relative to the lower border was termed '*intramatrix rotation*'. Dibbets (1985), however, used the term '*counterbalancing rotation*' to describe intramatrix rotation.

Solow and Houston (1988) described this terminology as *"internally consistent"*, but that it had*"… given rise to confusion"*. Rune *et al.,* (1987) have been more blunt, remarking that intramatrix rotation *"…seems to have no relation to the general concepts of craniofacial bone growth"*. The confusion over the terminology of growth rotations prompted Solow and Houston (1988) to propose a new terminology for describing the growth rotation of the mandible. They followed the concepts of Rune *et al.,* (1987) whereby a distinction is made between rotation (of a rigid body) and angular change (of a reference line). They defined the following terms: *true mandibular rotation* - rotation, relative to the anterior cranial base, of the mandibular body when registered on implants or stable natural structures; *apparent mandibular rotation* which is the angular change in the orientation of the mandibular line relative to the cranial base; and *angular remodelling* of the mandibular border as the angular change in the mandibular line when the mandible is registered on implants or stable natural structures.

Unfortunately, this new terminology has not been fully accepted and Profitt *et al.,* (1999) have proposed additional and potentially even more confusing terms for these rotational and angular growth changes.

The terminology of growth rotations of the maxillae has not been subject to the same degree of confusion. The only major distinction is between sagittal growth displacement rotation and the mutual displacement rotations of the two maxillae in the transverse plane. Björk used the terms ‘*rotation of the maxilla’* and *‘rotation of the maxilla in the sagittal plane’* for sagittal rotation (Björk, 1964). It was not until a decade later that Björk and Skieller (1974) first described the rotation in the transverse plane calling it the ‘*transverse rotation of the two maxillae*’. Iseri and Solow (1990) and Solow and Iseri (1996a) used the terms ‘*transverse mutual rotation’* and ‘*transversal maxillary rotation’* for the growth rotations of the two maxillae relative to one another in the transverse plane.

The present study will use the terminology originally given by Björk (1969) for displacement rotations of the mandible and by Björk (1964) and Solow and Iseri (1990) for displacement rotations of the maxillae. The abbreviations MGR and MxGR are used for the displacement rotations in the sagittal plane of the mandible and maxilla respectively. A list of the various alternative terms used for growth rotations and angular growth changes is given in Table 2.1.

2.4 METHODS OF DESCRIPTION OF DISPLACEMENT ROTATIONS OF THE JAWS

Bones undergo rotational growth displacement by differential articular growth in synchrondroses, sutures or articular joints (Rune *et al.,* 1987). The displacement of bones occurs in all three dimensions of space and can be described in terms of rotations about and translations along the three cardinal axes (Selvik, 1974). However, growth displacements of the jaws have usually been recorded radiographically as 2-D projections (at least historically). Consequently, the displacement of the mandible or maxilla has generally been described in terms of a rotation around a centre determined by the observer together with a translation relative to a fixed 2-D frame of reference (Solow, 1980).

Where multiple sequential movements are to be described Solow (1980) indicated that there are two alternative but equivalent methods: one with the rotational centre fixed relative to the bony corpus plus a series of translations; the other where the rotational centre is not fixed but is essentially arbitrary plus a series of translations.

Table 2.1 Terms used to Describe Growth Rotations of the Jaws

Reference	Rotation relative to the intra-bony implants	Remodelling relative to the Anterior Cranial Base	Rotation relative to the Anterior Cranial Base
Mandible:			
Björk (1955)	-	-	mandibular rotation
Schudy (1965)	-	-	clockwise / counterclockwise rotation
Björk (1969)	-	Forward / Backward rotation	-
Ødegaard (1970b)	Angle alpha	Angle epsilon	Angle gamma
Lavergne & Gasson (1977)	-	morphogenetic rotation	positional rotation
Björk and Skieller (1983)	Matrix rotation	intrmatrix rotation	Total rotation
Dibbets (1985)	-	counterbalancing rotation	-
Solow & Houston (1988)		Angular remodelling	True rotation
Profitt et al., (1999)	Total rotation	External rotation	Internal rotation
Maxilla:			
Björk (1964)	-	-	rotation of the maxilla rotation of the maxilla in the sagittal plane
	------------------- *(rotation between the two maxillae)* ----------------------		
Björk and Skieller (1974)	transverse rotation of the two maxillae'	-	-
Iseri & Solow (1990)	transverse maxillary rotation transverse mutual rotation	-	-

2.4.1 Centres of Rotation.

The construction of centres of rotation of the jaws became an important topic in the decade following the publication by Björk of methods to predict mandibular rotation (Björk, 1969). This was probably because of the assumption that knowledge of the centre about which the rotation occurred (or from which the rotation arose) would provide greater insight into the mechanism and effects of the rotation (Isaacson *et al.,* (1981).

The centre from which a rotation appears to arise has usually been assessed for two-dimensional displacements in the plane of the lateral cephalometric radiograph. In this case the change in orientation of the jaws (usually the mandible) is simplified to an interpretation of the displacement as a pure rotation about an axis perpendicular to the plane of the radiograph, and the intersection of this axis with the film plane is denoted as the centre of rotation (COR). In this case, the COR can be constructed as the intersection of the perpendiculars from the midpoint of the translation vectors for two invariant points in the bone (Rune *et al.,* 1987).

This method of determining the COR uses no other information than that contained in the radiographic images and is geometrically valid for the 2-D representation of the axis of rotation. Isaacson *et al.,* (1981) found that these 'instantaneous centres of rotation' were generally situated superiorly and anteriorly to the mandible in forward rotating subjects and inferiorly and posteriorly in backward rotating subjects. The location of the COR was specific to the change that occurred between two points in time (the times at which the two radiographs were recorded).

This was not the case with Björk's construction of the COR for the mandible which, as Solow (1980) describes was *"… a centre which is fixed relative to the mandible, namely the fulcrum in the dental arch around which the mandible revolves."* This description by Solow (1980) is, however, not strictly correct. The rotational centre used in Björk's descriptive system was not fixed but moved relative to the corpus (as defined by stable implants) with continued alveolar growth and post-functional eruption of the teeth.

Björk's method of description was doubtless influenced by his concept of the *anatomical* point (or axis) rather than the *material* point about which the rotation occurred (Moss *et al.,* 1981). In addition, there is no evidence that Björk ever formally described the translational component necessary for a full description of the rigid-body growth displacements of the mandible as described by Selvik (1974), Rune *et al.,* (1987) and Solow (1980). Instead, Björk and co-workers measured only the rotational component of growth displacement relative to stable structures in the anterior cranial base (Björk and Skieller, 1983).

Björk described four rotational centres of the mandible – at the head of the condyle or at one of three main sites along the line of the occlusion – and provided a broad classification for mandibular growth rotation based on them and on the direction of the rotational motion.

2.4.2 Björk's Classification of Mandibular Growth Rotation

Björk (1969) defined three types of forward rotation and two types of backward rotation (Figure 2.1) and in each case he included a brief note on possible causative factors. The following classification and descriptions are taken from Björk (1969).

2.4.2.1 Forward rotation

Type I: The COR is located at the temporomandibular joints. Individuals with this pattern of MGR tend to have an increased anterior overbite as a result of the lower dental arch pressing into the upper arch. This in turn leads to a reduced lower anterior face height. Possible causes include an occlusal imbalance due to loss of buccal segment teeth and powerful closing musculature. This type of rotation occurs mainly in non-growing adults although it is possible to occur at any age.

Type II: The COR is located at the incisal edges of lower anterior teeth. This class of rotation arises from marked vertical growth of the posterior face height while the anterior face height remains at normal levels. This results in the posterior part of the mandible rotating away from the maxilla giving rise to an increase in vertical eruption of the mandibular molars to maintain contact with the maxillary molars. The cause of the marked increase in posterior face height potentially results from the lowering of the middle cranial fossa relative to the anterior cranial base with a concomitant lowering of the articular (glenoid or condylar) fossa. Alternatively, vertically directed condylar growth elongating the mandibular ramus could produce this class of MGR. Type II rotation also leads to an increase in mandibular prognathism with a more prominent (anterior) location of the chin. This is the most common form of forward rotations pattern.

Type III: The COR is in the premolars area rather than at the incisors. This class of MGR is likely to occur where there is a markedly increased overjet that prevents unstrained contact between upper and lower incisors. Individuals with Type III rotational pattern

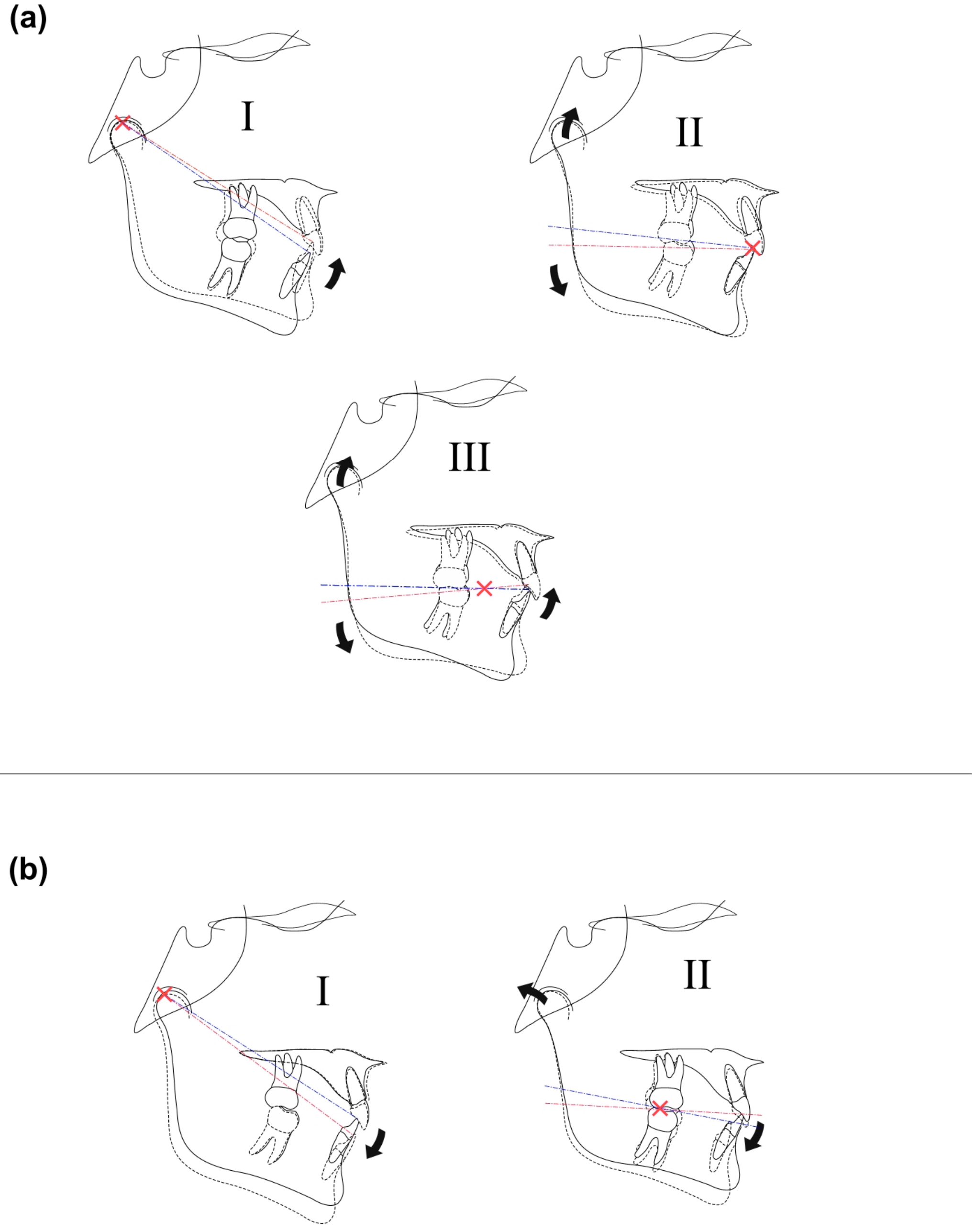

Figure 2.1 **Diagrammatic representation of Björk's classification of growth rotations of the mandible defined by the centre of rotation (COR).**

(a) The three classes of forward growth rotation of the mandible: I, COR at the temporomandibular joint; II, COR at the incisal edges; III, COR at the premolars or the most mesial (anterior) stable occlusal contact. **(b)** The two classes of backward growth rotation of the mandible: I, COR at the temporomandibular joint; II, COR at the most distal occlusal contact. The COR is indicated by ✕ . An initial arbitrary line and its post-rotational location are indicated by -·-·- and -·-·- respectively. The CORs used by Björk to classify growth rotations are not mathematically based in the sense defined by Rune *et al.,* (1987) but reflect the anatomical point about which the rotation *appears* to occur in a clinical setting. Forward rotation is also known as anterior, or counterclockwise rotation. Backward rotation is also known as posterior or clockwise rotation.

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will generally have a reduced anterior face height and potentially deep basal overbite. The prominence of the chin is more pronounced than in Type II rotation.

The forward rotation of mandible is thought to directly affect the inclination of the teeth. It leads to an increase in alveolar prognathism and mesial displacement of the path of eruption of teeth. In addition, inter-premolar and inter-molars angle increase as the lower posterior teeth tend to be more upright compared to the upper posterior teeth (Björk, 1969).

2.4.2.2 Backward rotation

Type I: The COR is located at the temporomandibular joint. This type of rotation occurs where the posterior face height is shortened or reduced relative to the anterior face height particularly where condylar growth is deficient or where there is flattened cranial base angle raising the middle cranial fossa relative to the anterior cranial fossa. It can also occur as a consequence of treatment to ‘raise the bite’ or to extrude the buccal segment teeth.

Type II: The COR is located at the most distal occluding molar. This rotation is associated with the upward and backward directed growth of the condyle. A Basal open bite may occur as a consequence of this type of rotation.

It is worth emphasising that the condylar head and the mandibular dental arch both grow vertically away from the core of the mandible and, consequently, the rotational centres chosen by Björk were was not fixed in relation to the rigid body to which they were referenced (the core of the mandible) and probably cannot be considered to be rotational centres in the geometric sense. From a clinical perspective, however, they serve a useful function in defining the site from which a particular rotation originates.

2.5 THE QUANTITATIVE MEASUREMENT OF ROTATIONAL PATTERNS OF JAW GROWTH

2.5.1 Implanted Markers

The detection of growth rotation of the jaws was made possible by the use of metallic implant markers inserted into the cortices of the mandible and right maxilla (Björk, 1955). The stability of the implants could be tested in the two-dimensional frame of reference provided by the plane of the film by examining the distance between a pair of implants inserted in the same bone. If this distance remained the same in the interval between the recording of the radiographs then the implants were deemed to be stable.

The high radiopacity of the implant markers allowed them to be uniquely identified in each serial radiograph. Growth rotation of each jaw was measured as the change in angulation of an imaginary line joining a pair of implants in the same jaw when the radiographs (or their tracings) were superimposed on the contours of the anterior cranial base.

The detection of displacement rotations requires (i) highly reproducible projection geometry for the radiographic exposures; and (ii) that the sites of superimposition are stable (invariant) over the interval between the films (Björk, 1968).

The standard cephalostat does not hold the head in a fully reproducible position and slight variations of projection geometry inevitably occur between the recording of consecutive films. These variations can be overcome to some extent by averaging measurements from the two sides of the mandible or from both maxillae (assuming implants have been inserted bilaterally). Nevertheless, this limits the accuracy of the measurement of rotations. The precision of measurement with the standard cephalometric technique has a standard deviation of between 0.5 and 0.7 degrees for the lateral projection (Rune *et al.,* 1979; Solow and Iseri 1996b).

At the beginning of Björk's implant study the implants were made from a cobalt chromium alloy ('Vitalium') which was not sufficiently inert to avoid reaction with the bone and often led to movement or loss of the implants (Björk, 1963). Later implants were made from chemically hardened tantalum which caused far less irritation in the bone and after a settling in period of around two months (Rune, 1980; Alberius, 1983a) the implants generally remained stable unless uncovered by remodelling or displaced by erupting teeth.

The co-ordintate system for the measurement of rotation was established relative to the endocranial contours of the anterior cranial base. The primary contours of which are generally believed to be stable after 6 years of age (Björk and Skieller, 1983).

The measurement of maxillary rotation in the sagittal plane poses additional technical problems to those encountered with mandibular rotation because of the mutual rotation of the maxillae in the transverse plane (Björk and Skieller, 1976, 1977). This requires a compensation to be applied to the measurement of growth to account for the foreshortening of the implant line in the lateral projection (Solow and Iseri, 1995). A related problem occurs with the measurement of the rotation of the maxillae in the transverse plane because of the *reduction* of magnification of the transosseous implant line (the line joining matching implants in the two maxillae) with facial growth (Iseri and Solow, 2000).

2.5.2 Natural Reference Structures

As a result of his investigations in subjects with metallic implants, Björk (1963, 1969) suggested four anatomical structures in the mandible, which might usefully act as natural reference markers (NRS) when implanted markers were not available. Later, Björk and Skieller (1983) added a fifth structure to the list.

Although the short-term stability of Björk's original structures has been corroborated by the independent implant study of Julius (1972), other researchers have questioned their usefulness because of the difficulty in locating, tracing, and superimposing them, especially where bilateral images occur (Feasby, 1981; Cook and Gravely, 1988; Isaacson, 1996). Springate (2010) identified a further nine NRS which could be used to supplement, or substitute for, Björk's mandibular reference structures where they were either not present or not easily identifiable.

Björk and Skieller (1976, 1977) also suggested two possible NRS in the maxilla which could be used to reliably analyse maxillary growth: the anterior contour of the zygomatic process of the maxilla (ACZ); and the tooth buds prior to root development. These latter structures are, however, only available for a short time, which does not generally coincide with the time of orthodontic treatment. In a more recent study, Springate (2015) identified a further six NRS in the maxilla that might assist in the measurement of MxGR where implants are not available.

The technical measurement of growth rotations using NRS requires high quality radiographic images to identify the fine trabecular details forming the NRS. In addition, greater precision is likely to be achieved by avoiding the use of intervening tracings and using direct superimposition of the original radiographs or image enhanced transparent copies (Björk, 1968; Springate, 2010, 2015). Nevertheless, the achievable precision is likely to fall short of that obtained with implanted markers. In addition, the magnitude of rotation of the maxilla in most clinical studies is likely to be of the same order as the precision of the method, which itself is likely to be significantly worse than the precision of measurement of inter-implant angulation: SD = 1.03 degrees (Springate, 2015).

2.6 RATES OF GROWTH ROTATION

The rates at which displacement rotations occur is highly variable and appears to depend on many factors: the age of the subjects, the maturational stage of the dentition, the direction of rotation (forward or backward) and the skeletal unit being examined (mandible or maxilla). However, few studies have ever reported statistically significant sex differences (Buschang and Jacob, 2014).

Most studies have used natural reference structures (NRS) rather than implanted markers and have restricted their measurements to mandibular rotations. Such NRS have been lacking for the maxilla and those that have been proposed (Moss and Greenberg, 1967; Mew, 1974; and Springate, 2015) have either been shown to be unstable relative to the maxillary core or are only available for short periods during development. Where maxillary implants have been available the rate of maxillary rotation in the sagittal plane is reported to be only about half that of the mandible (Björk and Skieller, 1972 and Björk, 1964).

Quantitatively, displacement rotations of the jaws are generally quoted as annualised rates (degrees per year). Table 2.2 shows that range of values for mandibular and maxillary rotations in previous implant studies. The average rate for the mandible is around 0.7 degrees per year during childhood and adolescence but there is some evidence that the rate is higher in subjects with a low mandibular plane angle (Karlsen, 1995). Studies that have used implanted markers also indicate a higher rate around the pubertal growth spurt as measured by peak height velocity (Skieller *et al.,* 1984; Björk and Skieller, 1983).

For the maxilla, the available multi-subject group data indicate that the average (forward) rotation of the maxilla is 0.4° per year but this is based on only two implant studies both of which used subjects from Björk’s Copenhagen growth study (Björk and Skieller, 1972; Solow and Iseri, 1996).

2.7 THEORIES OF THE ORIGIN AND MECHANISM OF GROWTH ROTATIONS OF THE JAWS

Growth rotations of the jaws result from differences in anterior and posterior facial heights and consequently, as Solow (1980) and Houston (1988) have pointed out, the origin of growth rotations must be sought in the factors that cause this discrepancy. In general, the theories that have been advanced to explain growth rotations of the jaws have attributed the main role to variations in either the anterior or the posterior facial height. However, as pointed out by Houston (1988) no comprehensive explanation has yet been offered of their origin. Nevertheless, several broad theoretical explanations have been offered.

Table 2.2 Annualised Rates of Growth (Displacement) Rotations of the Jaws in Previous Implant Studies

Reference	*Number of subjects*	*Age range* (yrs)	*Rotation rate* (degs/yr)
Mandible:			
Ødegaard (1970b)	25	7-14	-0.8
Lavergne & Gasson (1977)	30	7-19	-0.9
Skieller et al., (1984)	21	PHV + 3 yrs	-1.0
Björk and Skieller (1972)	21	PHV + 3 yrs	-1.0
Maxilla:			
Björk and Skieller (1972)	19	PHV + 3 yrs	-0.42
Solow and Iseri (1996)	14 (Females)	8.5-12.5	-0.38

2.7.1 Theories Attributing the Primary Cause to Variations in Posterior Face Height.

2.7.1.1 Björk and co-workers

Although Björk and co-workers have not explicitly indicated the reason(s) for the variation in growth rotations from subject to subject their attention has focussed on the magnitude or "intensity" of condylar growth (Björk, 1963; Björk and Skieller, 1972, 1983) together with the vertical component of relocation of the articular fossa resulting from growth of the posterior cranial base (Björk, 1955b) and the remodelling of the articular fossa itself (Björk and Skieller, 1972). However, the strong correlations between mandibular growth rotation and both the intensity and direction of condylar growth (Björk and Skieller, 1972) has led to speculation that mandibular growth rotation may be part of a genetically determined growth pattern in the development of the bone and muscle systems (Björk and Skieller, 1983).

2.7.1.2 Lavergne and Gasson

A more elaborate hypothesis was formulated by Lavergne and Gasson (1977a) who suggested that forward growth rotation of the mandible (resulting from an upward and forward direction of condylar growth) is a biological mechanism that dissipates excessive growth of the mandible relative to the maxilla. In this way, the mandibular dental arch is forced to keep pace with the maxillary dental arch despite much greater growth of the condyles than displacement of the maxilla.

This view appears to have arisen from a consideration of the classical view of mandibular growth (Enlow, 1975) whereby posteriorly directed condylar growth produces a horizontal advancement of the mandible. Consequently, by re-directing condylar growth upwards and forwards it contributes less to the prognathism of the mandible than if the growth were directed posteriorly. In support of their hypothesis Lavergne and Gasson (1977a) found a strong correlation between the degree of MGR and the difference in growth rates between the two jaws. However, this view is at odds with the observationally determined relationship between mandibular growth rotation and mandibular prognathism found by Björk and Skieller (1972). Namely, that the greater levels of MGR the greater is the level of mandibular prognathism.

Nevertheless, Lavergne and Gasson (1977b, 1977c) in a second longitudinal implant study of maxillary rotation (in the sagittal plane) found variations in both the direction and intensity from year to year and suggested that maxillary rotation and mandibular rotation interact to establish and maintain vertical as well as horizontal relationships between the two jaws. They concluded that during normal growth the rotations of maxilla and mandible harmonise to achieve a more favourable development of the face. This appears to presuppose the existence of a strong environmental influence on growth rotations of the jaws.

2.7.1.3 Dibbets

In a theoretical paper, Dibbets (1985) developed a simple model relating the magnitude and path of condylar growth to the increase in mandibular length. He postulated that the direction and curvature of the path of condylar growth was part of a mechanism by which selective enlargement of the mandible could occur in response to increments of condylar growth. Rotation of the mandible was a consequence of this mechanism. This mechanism becomes operative when it is necessary to offset the effects of condylar growth that would otherwise move the mandible and mandibular dental arch out of alignment with the maxillary arch. During this process the periosteal matrix of the mandible leads to a remodelling of the cortex as the mandible rotates due to the curving ("circular") path of condylar growth. This he termed a "counterbalancing rotation" (cf: intramatrix rotation).

In a second paper, Dibbets (1990) described a study examining the enlargement of the mandible as a percentage of condylar growth in the 21 subjects in the implant study by Björk and Skieller (1972). He reported that the proportion by which counterbalancing rotation neutralised condylar growth was strongly associated with facial structure, as expressed by the Angle classification. He concluded that counterbalancing rotation is a mechanism capable of preventing condylar growth from contributing to an increase in mandibular length. He did not however, discuss the factors that determine (or might potentially determine) the direction or curvature of the path of condylar growth.

2.7.2 Theories Attributing the Primary Cause to Variations in Anterior Face Height.

2.7.2.1 Houston

Houston (1988) developed a theoretical model for the causation of MGR in which the main focus was on variations in the vertical growth of the cervical column (which he claimed to be the primary factor determining growth in anterior face height) and the associated stretch of the craniocervical fascia and musculature. Superimposed on this are the effects of variations in head and mandibular posture.

This theory has direct implications for the causation and stability of rotations induced by orthodontic treatment and on their avoidance. It is widely cited in general orthodontic texts and although observational evidence appears to support this theory formal confirmation is lacking. Such confirmation may, in fact, not be possible as experimental evidence from animal studies (for example, non-human primates) is unlikely to be able to take into account the effects of cranio-cervical posture which differs from that in humans.

2.7.2.2 Buschang and co-workers

In a study examining the maturity gradients of craniofacial growth Buschang *et al.,* (1983) found a reduction in the ratio of lower anterior face height to total face height during the transition from deciduous to mixed dentition stages. Buschang and co-workers (Wang *et al.,* 2009 and Ueno *et al.,* 2013) have shown an increase in forward mandibular rotation associated with this reduction in facial height.

At the time of the transition of the anterior teeth it is known to take 19 months on average for the permanent incisors to reach 90% of their ultimate adult height (Giles *et al.*, 1963). This prompted Buschang and co-workers (Buschang et al., 2011; Buschang and Jacob, 2014) to suggest that it is the additional vertical space anteriorly in the jaws during the transition from deciduous to mixed dentition stages which causes an increase in forward rotation of the mandible.

Buschang and Jacob (2014) also claim that such an increase in MGR is responsible for the anterior positioning of the chin and, consequently, it is MGR that should be targeted in the treatment of Class II subjects possibly by intrusion of the maxillary posterior teeth.

2.7.3 Other Theories of the Causation and Mechanism of Growth Rotations of the Jaws

Moss and co-workers (Moss and Salentijn, 1970, 1971; Salentijn and Moss, 1971) and later Ricketts (1972) have put forward a different view for the origin of growth rotation of the mandible.

2.7.3.1 Moss and Salentijn

Moss and Salentijn (1970, 1971) formulated the view that the signals controlling growth are derived from the nerves that innervate the ‘capsular matrices’ of the craniofacial complex. This ‘neurotrophic’ view contends that the main nerve trunks of the fifth cranial nerve maintain the same pathway during growth. Moss speculated that the path of the inferior alveolar nerve followed a logarithmic spiral perfectly aligned on foramen ovale, the mandibular foramen and the mental foramen and that during growth the mandible moves downwards and along this spiral resulting in the rotation of the mandible relative to the cranium (Moss and Salentijn, 1970). Moss and Salentijn (1971) have extended this concept to cover growth throughout the craniofacial complex in the human, prenatally as well as postnatally. Björk and Skieller (1983), however, found no evidence that the mandible followed a logarithmic spiral postnatally.

2.7.3.2 Ricketts

Ricketts formulated a similar view of facial growth whereby the mandible followed an arcial course when viewed in the lateral projection. The arc was not a logarithmic spiral but a segment of a circle whose radius was determined by the distance from the cephalometric point *protuberance menti* to point *Eva* on the medial side of the ramus (Ricketts, 1972). Thus the arc differed between individuals and will differ over time within the same individual. The causes of the archial path of mandibular growth are unclear but Ranley (1980) has speculated that the pivot points of the arc are related to the ‘neurotrophic bundle’ that supplies the mandible thereby providing a link to the logarithmic spiral of Moss.

As was the case with the postulated logarithmic spiral pattern of growth, Björk and Skieller (1983) found no evidence that the mandible followed an arcial course of growth as described by Ricketts (1972).

2.8 RELATIONSHIPS BETWEEN GROWTH ROTATIONS AND OTHER GROWTH RELATED CHANGES

2.8.1 Growth Rotation and Skeletal Growth

2.8.3.1 Mandibular Rotation

Mandibular growth rotation is generally believed to play an important role in determining the growth changes of the face. Several studies have suggested that the shape and morphology of the mandible is influenced by mandibular growth rotation, particularly the gonial angle, ramus, and condyle. The antero-posterior and vertical relationships between the two jaws and chin position also appear to be strongly influenced by mandibular rotation.

Björk and Skieller (1972) examined the relationship between MGR and mandibular morphology noting that in forward rotating subjects there was a marked bony apposition below the symphysis and resorption at the posterior of the mandibular lower border with a decrease in the gonial angle. In backward rotating subjects, there was remodelling in the opposite direction, with slight apposition below the symphysis and posterior remodelling of the posterior ramus with an increase in the gonial angle.

Schudy (1965) quantified ‘apparent mandibular rotation’ and emphasised its implications for orthodontic treatment. He studied 62 untreated subjects and 50 orthodontic subjects who had been treated over an average period of 18 months. Mandibular rotation was classified as forward if there was more horizontal condylar growth than vertical maxillary growth. The average total vertical facial growth was 6.3 mm in untreated subjects and 7.1 mm in treated subjects. The average total horizontal growth was 7.2 mm and 6.7 mm, respectively in untreated and treated subjects. The untreated group showed more forward mandibular rotation, more horizontal change of the chin and less increase in anterior facial height. The differences were statistically significant at the $p < 0.05$ level. The author reasoned that when vertical maxillary growth was greater than vertical condylar growth the mandible rotated backward resulting in greater anterior facial height and less anterior movement of the chin.

Buschang and Gandini (2002) examined the associations between MGR, mandibular skeletal growth, and mandibular remodelling in 186 untreated French-Canadian children (79 females, 107 males) between the ages of 10 and 15 years. The subjects were evaluated cephalometrically using natural reference markers as substitutes for metallic implants. Over the five-year period, they found an average of 2.7 degrees of true forward rotation of the mandible, 11.2 mm of inferior and 2.3 mm of anterior displacement of the mandible. They reported that subjects with forward mandibular rotation tended to show greater superior and more anteriorly directed condylar growth. Most growth and remodelling changes were significantly correlated with MGR. Subjects with the most vertical growth and greatest posterior remodelling of the ramus had the greatest levels of forward rotation.

Lavergne and Gasson (1977a) reported on the relationship between MGR and mandibular morphology in a sample of 30 patients with metal implants in both jaws. They found that individuals who underwent true forward rotation showed an average annual decrease of 1.2 degrees in the gonial angle. Those patients who underwent true backward rotation showed an average annual increase of 0.3 degrees in the gonial angle. The direction of condylar growth was reported to be weakly related to MGR.

Sinclair and Little (1985) studied the relationship between MGR and growth changes of the face in 65 subjects between 9 and 20 years of age and who were considered to be representative of orthodontic “normals.” MGR was correlated with a decrease in the mandibular plane angle, y-axis, and gonial angle. SNA slightly increased, SNB increased, and ANB showed a small but statistically significant ($p<0.05$) decrease in the subjects with forward rotation. Posterior facial height increased and was correlated ($p<0.05$) with a decrease in SNB, mandibular plane to SN, and vertical development of anterior facial height. Increases in lower anterior facial height were correlated ($p<0.05$) to changes in ramus height and mandibular molar eruption. Forward MGR was associated with a rotation of the mandibular plane, occlusal plane and ANB angle. They also found a statistically significant degree of sexual dimorphism. Males had larger facial proportions than females. Males also had a statistically significant amount of late condylar growth, which was correlated ($p<0.05$) with vertical facial development.

Buschang and Santos-Pinto (1998) examined the relationship between condylar growth and displacement of the glenoid fossa in a longitudinal study of 118 children and 155 adolescents. Male subjects were measured at 7 and 11 years of age and female subjects at 10 and 14 years of age. They found a mean of 1.1 mm of posterior condylar growth, a mean of 9.9 mm posterior condylar growth, 1.95 mm of posterior and 1.4 mm of inferior fossa displacement respectively of over 4 years. They argued that if posterior fossa displacement is greater than posterior condylar growth, posterior displacement of the chin might be expected. Because this type of change does not normally occur, they suggested that true mandibular rotation might play a more fundamental role in determining the horizontal position of the chin than condylar growth.

Buschang, Santos-Pinto, and Demirjian (1999) carried out a cephalometric study into the growth components that determine the antero-posterior position of the chin at pogonion. Two-hundred and thirty subjects were followed during childhood and adolescence using serial lateral cephalometric radiographs to quantify condylar growth, MGR, and changes in location of pogonion and of the glenoid fossa. During the period of the study there was 2.1 to 3.3 mm anterior movement of pogonion, 9.0 to 10.7 mm superior and posterior growth of the condyles, and 2.0 to 3.5 degrees of forward mandibular rotation together with a posterior and inferior relocation of the glenoid fossa. Multiple regression analysis showed that MGR explained most of the variation in the horizontal positional changes of pogonion followed by horizontal condylar growth and horizontal positional changes of the glenoid fossa. Interestingly, the relationships between MGR and: (i) the antero-posterior position of pogonion; and (ii) the horizontal component of condylar growth were stronger during childhood than in adolescence. They concluded that methods of treatment which control true mandibular rotation might show the greater improvements in patients with antero-posterior skeletal discrepancies than methods that attempt to control the direction of condylar growth (such as functional appliances).

Karlsen (1995) investigated craniofacial growth in two groups of untreated males with high and low mandibular plane to sella-nasion (MP-SN) angles to discover whether differences in MP-SN were associated with differences in MGR. Lateral cephalometric radiographs were recorded at 6, 12 and 15 years of age. All subjects underwent forward growth rotation but the low angle group showed approximately 3.5 degrees more forward rotation than the high angle group between the ages of 6 to 12 years and a 5 mm greater increase in anterior facial height than posterior facial height in the high angle group. There was an overall significant correlation between matrix rotation and the change in change in the angulation of the mandibular plane.

In a second related study, Karlsen (1996) examined the associations between vertical craniofacial growth and mandibular growth rotation in two groups of children with high and low (n=29, for each group) MP-SN angles. Increases in posterior facial height and increases in ramus height were consistently correlated with forward matrix rotation regardless of the MP-SN angle. Increases in anterior facial height were not correlated with MGR. He concluded that overdevelopment of the lower anterior face height in high angle cases occurred because the steep mandibular plane directed corpus growth more downward than normal *not* because of a backward rotation of the mandible.

Chung and Wong (2002) studied the lateral cephalometric radiographs of 85 untreated skeletal Class II subjects (45 male and 40 female) drawn from the Bolton-Brush and the Burlington Growth Studies. The subjects were divided into three groups: high; average; and low mandibular plane angles. They found that the low-angle group had greater SNA and SNB angles, a longer posterior cranial base, a larger mandibular body, a higher ramus height, and a greater posterior facial height than the other two groups. The low angle group had more facial flattening and more apparent forward rotation than the high-angle group.

Kim and Nielsen (2002) examined the association between the intensity of condylar growth and MGR in a longitudinal study of 32 untreated subjects with class II malocclusion. Serial lateral cephalometric radiographs were recorded annually between 8 and 13 years of age. Analysis revealed that the intensity of condylar growth was on average greater in males but varied little between males and females. Forward MGR was observed in 95% of the subjects but no clear relationship was observed between the amount of condylar growth and MGR. This finding contrasts with those of Björk (1963, 1969), Ødegaard (1970), and Björk and Skieller (1972).

Björk (1963, 1969) suggested that a marked degree of (vertical) condylar growth increases posterior face height and generally leads to forward MGR with the centre of rotation located at the tips of the lower incisors. Ødegaard (1970) also found that MGR was associated with the direction and the magnitude of condylar growth and that the greater the degree of vertical condylar growth the greater the rate of forward MGR.

Björk and Skieller (1972) in their classic implant study of 21 untreated subjects found a significant relationship between the magnitude of condylar growth and MGR but their findings have been criticised because of the inclusion of subjects with extremes of facial growth including extreme patterns of MGR.

Sinclair and Little (2002) in a study of untreated subjects between the ages of 9 and 20 years found that the amount of condylar growth was strongly correlated with the amount of vertical facial development and that the direction of condylar growth was related to the change in antero-posterior position of the mandible.

The majority of studies have indicated a strong positive association between skeletal growth and MGR and while cross-sectional studies have revealed greater amounts of condylar growth in forward rotating subjects than in subjects with backward rotation this was not a consistent finding in longitudinal studies (Kim and Nielsen, 2002). Subjects with a forward MGR tended to have lower mandibular plane angles that those with a backward rotation.

Additionally forward rotation is generally associated with greater relative posterior facial heights while the anterior facial height either remains the same or decreases as a proportion of total anterior facial height. This results in a more anterior positioning of the chin, and a general improvement of the inter-arch relationship in class II subjects. Forward MGR is also found to be associated with greater bone deposition at the posterior ramus, increased resorption at the posterior lower border of the corpus, and increased deposition on the anterior lower border.

2.8.1.2 Maxillary Rotation

The majority of studies and theoretical papers deal with mandibular rotation alone. No mention is generally made of the effect of, or on the growth rotation of the maxilla (MxGR). This is probably because of the much smaller magnitude of MxGR compared to MGR in untreated subjects. It appears that the maxilla simply follows the rotational pattern of the mandible and this is the cause of the similar patterns of associations that exist between MxGR and skeletal change and MGR and the same skeletal changes.

2.8.2 Growth Rotation and Changes in the Dentition

2.8.2.1 Mandibular Rotation

Several studies have reported strong associations between MGR and effects on the dentition. Björk and Skieller (1972) reported that subjects with Type I forward rotation display underdevelopment of the anterior facial height because their lower dental arch is “pressed” into the upper, giving rise to a deep anterior overbite. In Type II forward rotation the posterior part of the mandible is lowered and molar eruption keeps pace, resulting in greater post-functional eruption of the molars that the incisors. As a result the occlusal plane tips down posteriorly but with no increase in overbite.

Sinclair and Little (1985) examined the relationship between true mandibular rotation and dental development in 65 untreated subjects between 9 and 20 years of age. Forward MGR was accompanied by mesial tipping of the mandibular molars and anterior movement of the mandibular incisors, especially in male subjects. In agreement with Björk and Skieller (1972) they found that mandibular molar eruption was greater than incisor eruption in forward rotating subjects and that changes in tooth position were found to be closely correlated with changes in the amount and direction of MGR.

Nanda (1990) investigated differences between subjects with open bite and those with a deep overbite. He suggested that in open bite subjects the maxillary molars act as a fulcrum around which the mandible rotates resulting in backward rotation of the mandible and increased lower anterior facial height. In these cases, dentoalveolar compensation leads to the molars erupting less than the incisors. Solow and Iseri (1996) reported similar findings in backward rotation subjects and Björk (1975) has reported intrusion of the molars resulting from backward rotations of the mandible.

The general view appears to be that MGR induces dentoalveolar compensation but that extremes of MGR often exceed the ability of compensatory mechanisms to achieve and maintain normal occlusal relationships (Solow, 1980). In Type II forward rotation, both dental arches shift forward as a unit, maintaining normal Class I occlusal relationships. Björk and Skieller (1972) have pointed out this forward shift of the dentition in both arches is the normal response to forward MGR. Other types of rotational pattern do not allow the maintenance of a normal occlusion and malocclusion is the likely result.

Despite the widespread view that MGR *causes* changes in the dentition there is some evidence that the post-functional development of the dentition, specifically the vertical eruption of the teeth and associated alveolar bone, affects or modifies MGR.

In an interesting study examining mandibular growth in subjects with infraoccluded deciduous molars Leonardi *et al.,* (2005) analysed the growth characteristics of 28 subjects with infraoccluded deciduous molars in comparison to a control group matched for dental maturity and gender. They found that infraocclusion of the deciduous molars was associated with anterior rotation of the mandible. Drawing on the work of Petrovic and co-workers (Stutzmann and Petrovic, 1984; Petrovic and Stutzmann, 1986) they suggested that this might be related to greater rates of alveolar bone turnover which leads to anterior (forward) MGR and infraocclusion.

Spady *et al.,* (1992), Buschang and Santos-Pinto (1998), and Liu and Buschang (2011) have all implicated the reduction in anterior alveolar height that occurs at the transition from deciduous to early mixed dentition as a cause of an increase in the rate of forward MGR. Buschang and Jacob (2014) have suggested that molar intrusion could also lead to an increase in forward MGR and Houston (1988) has argued that molar extrusion from whatever cause will lead to backward MGR.

2.8.2.2 Maxillary Rotation

A similar situation exists with regard to the relationship between MxGR and the dentition as was indicated above for skeletal growth. That is, the majority of studies and theoretical papers deal with the relationship between the dentition and mandibular rotation alone. In addition to MxGR generally being much smaller than MGR the lack of suitable natural reference structures in the maxilla makes studies of dental changes in the maxilla especially difficult. Consequently, the majority of studies reporting changes associated with or resulting from rotation of the maxilla have been conducted on subjects with metallic implants in one or both maxillae.

Björk and Skieller (1972, 1977, 1983) have described post-functional eruption and migration of the maxillary dentition related to maxillary rotation but the close association between MxGR with MGR prevents these effect on the dentition from being uniquely related or associated with MxGR.

Solow and Iseri (1996) and Solow (1996) examined the longitudinal records between 9 and 25 years of 14 females drawn from the archives of Björk’s implant study (Björk, 1968). They found differences in the eruptive paths of the maxillary molars and incisors between forward and backward rotating subjects. That is, the eruptive paths tended to be directed vertically in backward rotating subjects and directed more horizontally (mesially) in forward rotating subjects.

Siersbæk-Nielsen (1971) reported the individual rates of eruption of the central incisors in eight boys in the 6 years around puberty. She reported a prominent peak in eruption coincident with the peak in standing height for 6 boys but this peak in eruption occurred in the year *preceding* the peak in standing height in two of the boys. A similar peak was not found by Solow and Iseri (1996a, 1996b) who reported a gradual reduction of eruption velocity from 10 years of age onwards despite claiming that their results and those of Siersbæk-Nielsen (1971) showed a similar relation to the rate of growth in height. (Solow and Iseri, 1996b)

Interestingly, in the study by Siersbæk-Nielsen (1971) the eruptive tracks of both upper and lower incisors followed a sigmoidal pattern moving alternately anteriorly and posteriorly relative to the anterior implant marker(s) in the maxilla. Whether this is related to annual variations in MxGR or MGR is unknown. However, in the transverse plane Björk and Skieller (1977) found no association between increasing distance between the implants in the infra-zygomatic buttress of the maxilla on right and left sides and the lateral movement of the maxillary first molars. Given that the expansion of the distance between these implants is the main feature of the mutual transverse rotation of the maxillae, it seems reasonable to assume that there is no association between the rate of widening of the maxillary dental arch at the level of the first molars and the rate of mutual transverse rotation of the maxillae.

2.8.4 Postural Associations with Growth Rotations of the Jaws

In the absence of implanted markers it is difficult to detect less obvious features that are strongly associated with a particular direction or intensity of growth rotations. However, some associations between growth rotations of the jaws and elements of posture have been detected.

Solow and Siersbæk-Nielsen (1986) examined the cephalometric relationships between head posture and subsequent facial growth in a group of 43 untreated children over a mean observation interval of 2.7 years starting at a mean age of 9.5 years. They found the most conspicuous cluster of associations to be between growth rotation of the mandible and the change in the craniocervical posture. They reported that increasing flexion of the head was associated with a more pronounced forward growth rotation of the mandible, whereas increasing extension of the head was accompanied by a reduced forward rotation or even backward rotation of the mandible.

Huggare and Cooke (1994) in a similar study examined the relationship between head posture in a group of 36 untreated children followed longitudinally over intervals between 2 and 5 years. They found a statistically significant correlation ($r = 0.59$; $p < 0.01$) between initial craniocervical posture and “*a measure of mandibular growth rotation*” (which was, the direction of subsequent mandibular growth measured at prognathion). When their data were analysed by sex the correlation was, however, only significant for males.

Springate (2012) in a correlation study of 59 untreated children followed longitudinally for a mean period of 3.5 years (mean age at initial observation, 11.8 years) found a statistically significant correlation between the change in craniocervical posture and the *rate* of growth rotation of the mandible ($r = 0.60$; $p < 0.001$). This finding supported the earlier findings of Solow and Siersbæk-Nielsen (1986) and agreed with them that this and other associations indicated that growth co-ordination exists between changes in craniofacial morphology and postural changes, and that the co-ordination appears to be centred on the development of the mandible.

None of the studies examining cranial and craniocervical posture have examined subjects with implanted Björk-type markers. Consequently, it has not been possible to examine the relationships between maxillary rotation and posture. Nevertheless, the known association between maxillary sagittal rotation and growth direction (Björk and Skieller, 1974) strongly suggests that changes in maxillary rotation might also accompany changes in craniocervical posture.

2.8.5 Anatomical Associations with Pre-existing Growth Rotations of the Jaws

From the forgoing Section it is clear that pre-existing growth rotations of the jaws will have led to specific morphological, structural and possibly postural features of the craniofacial complex dependent on the direction and intensity of the rotation(s). Björk (1969) and Björk and Skieller (1972) identified several anatomical features associated with rotations of the mandible and maxilla. The most prominent features occurred with the growth rotation of the mandible rather than the maxilla.

2.8.4.1 Forward Mandibular Rotation

1. Forward rotational remodelling of the lower border.
2. Resorption at the inferior border in the gonial angle.
3. Bone apposition at the posterior surface of the symphysis.
4. Forward curving path of condylar growth relative to the posterior border of the ramus.
5. Resorption at the anterior border of the ramus
6. Apposition at the lower part of the posterior border of the ramus.
7. Proclination of lower incisors.
8. Obtuse intermolar and inter premolar angles.

2.8.4.2 Backward mandibular rotation

1. Resorption at the inferior surface of the symphysis.
2. Apposition below the gonial angle,
3. Apposition at the posterior border of the ramus
4. Posteriorly directed condylar growth.

5. Narrowing of the symphysis antero-posteriorly.
6. Soft tissue bunching beneath the mandible (‘double chin’).
7. Retroclination of the lower incisors
8. Acute intermolar and interpremolar angles

2.8.4.3 Growth rotations of the maxilla

Because growth rotation of the maxilla in the sagittal plane is much less than that of the mandible there are no obvious associations with minor variations of MxGR that are visible in the lateral cephalometric view. The main associations that are visible are only detectable at the extremes of rotation. These are: the inclination of the incisors; molars and premolars to the nasal floor; and, potentially, the upper anterior face height as a proportion of total face height. The anterior border of the zygomatic buttress has also been shown to tilt anteriorly accompanying extreme forward rotation induced by treatment (Björk and Skieller, 1974; Mandall *et al.,* 2010).

Maxillary rotation in the transverse plane is associated with the width of the maxillary arch. Again this is only detectable at the extremes of the range of transverse rotation with a very narrow maxillary arch accompanying backward rotation. However, a narrow maxillary dental arch can occur in the absence of posterior growth rotation (Björk, 1976).

2.9 PREDICTION OF GROWTH ROTATIONS OF THE JAWS

2.9.1 Mandibular Rotation

Björk (1969) identified certain morphological features visible on the lateral cephalometric radiograph that indicated the presence and direction of MGR. On the assumption that previous growth experience is a good predictor of future growth performance, Björk claimed that these features could be used to predict the future direction of MGR. The more of these features that could be identified the greater the likelihood of a correct prediction.

The seven structural features are:

(i) Inclination of condylar head

(ii) Curvature of the mandibular canal

(iii) Shape of the lower mandibular border (antegonial notch)

(iv) Inclination of the mandibular symphysis

(v) Interpremolar and Intermolar angles

(vi) Interincisal angles

(vii)Lower anterior facial height

This *structural method,* as Björk described it, is based on information concerning the remodeling processes of the mandible during growth, gained from his implant studies. He claimed that using this information in the form of his seven structural signs it is possible to predict mandibular growth rotation from a single lateral cephalometric radiograph. The principle is to recognise specific structural features that develop as a result of the remodeling in a particular type of mandibular rotation. In subjects with a forward growth rotation; the condylar head is inclined forwards; the contour of the mandibular canal is more curved than the mandible itself; the contour of the lower border of the mandible is convex at the angle; the symphysis is tilted posteriorly; the interpremolar; intermolar and interincisal angles are increased and the anterior facial height is decreased.

In subjects with a backward growth rotation; the condylar head is inclined backwards; the contour of the mandibular canal is straight; there is a prominent antegonial notch; the mandibular symphysis faces forwards; the interpremolar; intermolar and interincisal angles are all decreased and the anterior facial height is increased.

The structural method of prediction was applied by Skieller *et al.,* (1984) to 'predict' MGR in the 21 subjects from the earlier implant study by Björk and Skieller (1972). The results showed a high degree of predictive ability from this method. The results of this study have, however, been criticised because of the extreme growth patterns of several of the subjects by Baumrind *et al.,* (1984) who tested the ability of five experienced clinicians to predict MGR using Björk's method. They concluded that it was not possible to differentiate forward from backward rotators nor was it possible to accurately predict MGR in subjects with an average degree of MGR.

Several other studies have applied Björk' Structural method (or elements of the method) to the prediction of mandibular growth direction (rather than as a measure of MGR). Some of studies reported the method to be clinically useful (Balbach 1969; Singer, 1986; Aki *et al.,* 1994) while others reported the method to be unreliable (Ari-Viro and Wisth, 1983; Halazonetis *et al.,* 1991; Mair and Hunter, 1991; Leslie *et al.,* 1998; Kolodziej *et al.,* 2002; von Bremen and Pancherz, 2005).

These studies assessed MGR using natural reference markers or using mandibular growth direction as a surrogate indicator of MGR. They cannot therefore provide the most reliable test of Björk's structural method of prediction. Only the study by Lee *et al.,* (1987) has used an independent sample of growing subjects with implanted tantalum markers to test Björk’s method. Lee *et al.,* (1987) used a sample of 25 subjects from the Mathews growth study of the University of California. The sample lacked the extremes of MGR found in the sample by Skieller *et al.,* (1984) and Björk’s method was found to be unreliable as a predictor of MGR. However, the sample used by Lee *et al.,* (1987) included treated as well as untreated subjects.

The development of an alternative method of prediction of MGR was undertaken by Steinberg (1977). He used the records of 31 females and 35 males from the Denver Growth Study and attempted to develop an individualised two year prediction of mandibular growth rotation and horizontal growth changes. He performed a multiple regression analysis of MGR and the distance from articulare to pogonion versus eight craniofacial variables that describe mandibular morphology. Although several patterns emerged none were clinically useful. He did, however, find that the symphyseal angle “improved” as a predictor of growth rotation at the time of the peak growth velocity of mandibular length.

Another interesting, if slightly bizarre study was conducted by Schmuth and Madre (1979) who assessed a different method of prediction of growth rotation of the mandible. The method used Björk's Sum of Angles and Jarabak's Facial Height Ratio. The method was applied to a sample of 447 patients and the predicted direction of growth was compared to the actual direction. They found no correlation between the predictions and what actually occurred. However, the definition of growth rotation of the mandible used in this study did not correspond to Björk’s descriptions but was instead the ratio of vertical proportions of the face growth measured from conventional cephalometric landmarks at anterior and posterior regions of the mandible.

2.9.2 Maxillary Rotation

Similar structural features have not been identified in the lateral view of the maxilla but it is generally assumed that the maxilla will rotate during growth in the same direction as the mandible but with much smaller magnitude. Nevertheless, in a recent longitudinal study the change in inclination of the anterior contour of the zygomatic buttress of the maxilla has been used to identify maxillary growth rotation (MxGR) resulting from treatment with extra-oral forces to the maxilla (Mandall *et al.,* 2010).

2.10 CLINICAL IMPLICATIONS OF GROWTH ROTATIONS OF THE JAWS

Early cephalometric studies by Broadbent (1937) and by Brodie (1941) indicated that orthodontic treatment did not influence the growth of the jaws and that changes in dental base relationships were minor and usually of little occlusal importance (Houston, 1979). In those children where the skeletal proportions altered markedly it was found that the occlusal changes were much less than anticipated due to the effects of dento-alveolar adaptation (Björk and Palling, 1955; Solow, 1980). This led to a general approach to the planning and execution of orthodontic treatment where no consideration was given to the growth changes that might occur during or after completion of the active treatment.

However, as Houston (1988) has pointed out although avoiding considerations of facial growth simplifies treatment planning there are, nevertheless, serious objections to ignoring growth or assuming that it does not matter. A favourable growth pattern may facilitate treatment and allow a better result to be obtained with less difficulty than expected; alternatively an adverse growth pattern could make treatment difficult or, at times, impossible.

On average, there are approximately 15° of forward rotation of the mandible during the period between childhood and adulthood or about 0.7° per year (Björk and Skieller, 1972). However, in a small proportion of the population forward rotation of 25° may occur or for a similarly small proportion of the population there may be up to 15° of posterior growth rotation. It is in these groups at either end of the spectrum of rotation that growth rotations of the jaw are of most clinical relevance.

2.10.1 Treatment Planning and Active Treatment

Accompanying marked forward rotation there is generally a deep anterior overbite and in Type II MGR the overbite often continues to increase during the period of orthodontic treatment or be particularly difficult to reduce as growth rotation continues to cause the lower anterior teeth to press up into the maxillary dental arch. Early interception of the overbite has been suggested as a way to overcome this by using a removable bite plane to hinder the effect of MGR. In addition, as the mandible rotates forwards the deepening overbite causes the lower incisors to be held behind the corresponding upper anterior teeth leading to overcrowding and irregularity of the lower incisors.

However, as the mandible rotates forward the prognathism of the mandible increases which can be particularly helpful in patients with a Class II skeletal pattern (Buschang and Jacob, 2015).

In individuals with a marked posterior or backward growth rotation of the mandible the ‘normal’ levels of dentoalveolar compensation may be inadequate to maintain active contact between the anterior teeth resulting in a skeletal anterior open bite. Additionally, the prognathism of the mandible may be reduced leading to marked retrusion of the chin in severe cases.

Backward rotation of the mandible does not appear to be part of the normal pattern of jaw growth and usually results from pathology in or around the temporomandibular joints (Houston, 1988). For example, in juvenile rheumatoid arthritis of the joints or fibrous ankylosis of the temporomandibular joints.

2.10.2 Implications for Post-treatment Stability

At the extremes of the range of MGR there are changes in anterior face height during growth. If these changes are interrupted or modified by treatment the induced changes in anterior face height are generally unstable unless they are accompanied by adaptive changes in head posture or in the muscular balance of the mandible (Houston, 1988).

Orthodontic treatment using Class II inter-arch traction, anterior bite planes or anchorage bends can contribute to a transient backward rotation of the mandible and an increase in anterior face height. In growing subjects these effects generally reverse after the cessation of treatment and in forward rotating subjects the long-term effect on the position of the mandible (relative to the cranium) is usually minimal.

In forward rotating subjects with a marked reduction in anterior facial height the treatment induced backward rotation of the mandible is likely to be followed by a forward rotation resulting in intrusion of the occluding teeth under the influence of occlusal forces. In such cases, the incisors are generally unable to prevent the worsening of overbite as the posterior teeth intrude (Houston, 1988).

However, in patients with a backward rotation of the mandible and increased lower anterior face height prior to treatment (the so-called, ‘long face syndrome’) such treatments will generally lead to an increase in posterior rotation that is not subsequently corrected by post-treatment growth (Kreiborg, *et al.,* 1978; Houston, 1988).

The intrusion of posterior teeth (Altuna and Woodside, 1985) and the surgical impaction of the maxilla (Wessberg et al., 1982) generally cause a forward rotational effect on the mandible. These ‘autorotations’ are only stable if there is a lasting change in craniocervial posture or adaptation in the muscles and fasciae of the mandible.

2.0 SUMMARY OF THE LITERATURE REVIEW

Growth rotations of the mandible and maxilla in the sagittal plane were first identified by Björk (1955). Similar growth rotations were identified in primates and in other mammalian species (Nielsen, *et al.,* 1989; Schneiderman, 1992) as well as rotations of the maxillae in the transverse plane and rotations of other cranial bones (Moss, 1958; Vilmann, 1972; Alberius, 1983b). Enlow (1975) in his classic descriptions of facial growth defined two different forms of growth rotation: remodelling rotation and displacement rotation. In clinical orthodontic usage growth rotation of the jaws was initially taken to mean displacement rotation where it is the invariant structures within each jaw that define the structure that is rotating in relation to stable structures in the floor of the anterior cranial fossa or ‘anterior cranial base’.

However, Ødegaard (1970), Lavergne and Gasson (1977), Björk and Skieller, (1983) and Dibbets (1985), all later defined other forms of rotation (primarily for the mandible) in which bony outlines or contours of the jaws rotated in relation to invariant structures either within the jaw or anterior cranial base. These additional forms of growth rotation were essentially remodelling rotations and led to the development of a confusing collection of terms for both displacement and remodelling rotations. This prompted Solow and Houston (1988) to propose a new terminology for describing the growth rotations of the mandible (but not the maxilla) which is now widely but not universally accepted. For pure displacement rotation some additional terms that describe the direction of the rotation have come into widespread use. These are ‘backward’ or ‘posterior’ and ‘forward’ or ‘anterior’ rotations, which are clockwise and anticlockwise rotations respectively with the subject facing to the left of the observer.

As part of a fuller description of displacement rotations Björk (1964) and later Isaacson *et al.,* (1981) established the notion of the ‘centre of rotation’ (COR) – the point about which the rotation appeared to occur without an additional translational component. On the basis of these CORs Björk (1969) defined three types of forward rotation and two types of backward rotation for the mandible. However, the CORs were anatomically defined sites that were not fixed in relation to the core of the mandible.

The measurement of the direction and intensity of displacement growth rotations of the jaws is most easily made with the aid of implanted tantalum markers that are stable in the bone and are visible radiographically. In the absence of implanted markers Björk

(1963, 1969) and later Björk and Skieller (1983) suggested several natural reference structures which could be used as substitutes for implants. These structures are often difficult to detect and trace and are not always stable. This complicates the measurement of growth rotations in the majority of cases.

Growth rotations of the jaws, in particular the displacement rotation of the mandible is associated with several morphological features of the mandible and maxilla and their associated dentitions that are visible on the lateral cephalometric radiograph. This led Björk (1969) to propose his structure based method of growth prediction.

Prediction of mandibular growth rotation would be useful in clinical orthodontics to alert the clinician to a favourable growth pattern that might facilitate treatment or to forewarn of an adverse growth pattern that could make treatment more difficult than anticipated. This would be especially useful for the planning of treatment in those patients where surgical correction would ultimately be required. The association between mandibular growth rotation and relapse following treatment is also an important area where prediction of growth rotation would be helpful.

Björk’s structural method has, however, been found to be unreliable except for subjects with extreme growth patterns and although other methods of prediction have been proposed none have proved to be useful clinically.

The ability to predict growth rotations would almost certainly be aided by detailed understanding of their origin and ultimate cause or causes. Several theoretical explanations have been proposed with the primary focus on the displacement rotations of the mandible. However, as pointed out thirty years ago by Houston (1988), no comprehensive explanation has yet been offered for their origin. Disappointingly, this is still true today.

CHAPTER

3

THE NATURE OF THE PROBLEM; AIMS AND OBJECTIVES OF THE STUDY

3.1 THE NATURE OF THE PROBLEM

Although the cause or causes of MGR remain unknown attention has focussed on the potentially causal role of condylar growth. The primary evidence for this comes from the classic implant studies of Björk and Skieller (1972, 1983) who reported strong correlations both within and between subjects for MGR and the: direction; magnitude; and curvature of condylar growth.

While such correlations cannot establish a cause-and-effect relationship between variations in the growth of the condyle and MGR, they have, nevertheless, been taken as highly persuasive evidence of the key role played by condylar growth in determining the direction and intensity of MGR.

3.1.1 Deficiencies and Potential Flaws in the Interpretation of Björk's Implant Studies

Björk's implant studies are rightly considered landmarks in our understanding of human dento-facial growth. Nevertheless, although stable metallic implants provide a uniquely reliable means of orientating serial cephalometric images, it appears that some of the methods used by Björk and co-workers for data extraction and statistical analysis were flawed. In particular, there is now good evidence that Björk and Skieller's (Björk and Skieller, 1972 and 1983) numerical and statistical documentation of condylar growth were incorrect (Buschang and Santos-Pinto, 1998; Springate, 2009) and, consequently, the reported associations between the condylar growth variables and MGR are potentially misleading. This raises the possibility that condylar growth may not be the main determinant of MGR nor, indeed, the primary factor controlling mandibular form during normal growth.

3.1.2 Possible Determinants of Growth Rotations of the Jaws

By definition, growth rotation of the mandible will only occur where there is a difference in the amounts of lowering of the posterior (condylar) and anterior (tooth-bearing) parts of the mandible (Solow, 1980). Consequently, if the variation in condylar growth is not the primary determinant of MGR then it seems reasonable to assume that one or more of the other growth sites contributing to the vertical decent of the mandible (relocation of the articular fossa, sutural lowering of the maxilla, or eruption of the occluding teeth) must be responsible.

However, because the mandible is hinged at the articular joint, the effect of tooth eruption on MGR will be modified or modulated by the associated mesial migration of the dentition. Thus, the investigation of MGR will require an examination of: the magnitude and direction of condylar growth; the vertical relocation of the articular fossa; the sutural lowering of the maxilla; and the vertical eruption and migration of the occluding teeth in both jaws.

3.2 AIMS AND OBJECTIVES OF THE STUDY

The study will examine in detail the longitudinal inter-relationships between the growth at these sites and growth rotations of the jaws.

The longitudinal documentation of the amounts and two-dimensional (sagittal, coronal and transverse) directions of displacement of the craniofacial bones can only be carried out reliably where no treatment has been performed and where stable implanted markers are available. There have only ever been two human growth studies where these two fundamental requirements have been met – Björk’s Copenhagen study; and the smaller and less well known Mathews’ UCSF study (Mathews and Ware, 1978).

The records from Björk’s study are not available for independent study (Hunter *et al.*, 1993) but even if they were the deficiencies of Björk’s material would still exist. However, many of the deficiencies have been overcome or at least mitigated in the Mathews’ UCSF study.

A primary precondition and requirement of the present research was to obtain access to the high resolution radiographic records of untreated subjects from the Mathews' UCSF growth study which amounts to several hundred serial radiographs. After two decades of trying, full privileged access to these records has now been obtained.

3.2 AIMS

To undertake longitudinal study of the relationships between rotational and translational displacement growth of the jaws and the eruption and migration of the teeth during a period of observation in a sample of children from the time of the juvenile growth spurt (7-8 years of age) up to and beyond the adolescent (or pubertal) growth spurt.

To undertake this study using appropriate methods and safeguards during the collection and analysis of the data and thereby avoid (or at least, mitigate) the pitfalls inherent in this type of radiographic growth study particularly with regard to the problems of serial dependency in incremental data, as explained in Section 4.3.2.

To resolve the uncertainties outlined in Section 3.1.1 (above) and hopefully gain a deeper insight into the mechanism(s) responsible for growth rotations of the jaws and to gain an understanding of the interplay between growth of the jaws and the natural movements of the teeth.

3.3.2 Specific Objectives:

- To examine the strengths of the relationships between growth rotations of the jaws and growth changes at sites throughout the jaws and dentition.

- To locate the anatomical sites (or combinations of sites) providing the most conspicuous associations with the growth rotations of the jaws

- To reconstruct the annual incremental patterning of displacement growth and growth related changes at sites throughout the jaws and dentition; and to test these patterns for synchrony with the annual incremental pattern(s) of growth rotation(s) of the jaws.

- Finally, using the results of these investigations, to provide a plausible, testable explanatory hypothesis or hypotheses identifying and explaining the causal factors leading to growth rotations of the jaws.

CHAPTER
4

DESIGN OF THE STUDY: PROBLEMS AND LIMITATIONS IN THE STUDY OF GROWTH

4.1 THE CONCEPTS UNDERLYING THE DESIGN OF THE STUDY

Underlying the design of the study is the concept that the rotational growth of the jaws, the growth displacements of the jaws and the natural movements of the teeth are separate but inter-dependent (interacting) sub-systems. This inter-dependence of jaw growth (both rotational and translational) and post-functional tooth eruption and migration suggests that it may be possible to detect the interaction and co-ordination between them by comparing the patterns of growth (intensity and direction) of the individual sub-systems. That is, by examining and comparing the patterning of the direction and intensity of the growth of the mandible and maxillae with each other and with the eruption and migration of the teeth over corresponding time intervals it was hoped to reveal more about the mechanisms generating and controlling growth rotations of the jaws.

4.2 THE DESIGN OF THE STUDY

The study was designed as a longitudinal investigation of the associations between growth rotations of the jaws and: the translational growth displacements of each jaw; and the natural movements of the teeth in a group of children with tantalum markers implanted in both jaws. Measurements were gathered from lateral, frontal and 45° oblique cephalometric radiographs recorded approximately annually throughout a period of observation averaging nine years during which no orthodontic treatment was performed.

The changes between the ‘annual’ observations (the *growth increments*) for each variable were scaled with respect to the exact time intervals over which the changes had occurred to provide a sequence of mean annual growth velocities. The growth velocities were ordered chronologically into a discrete time-series for each variable[¶]. These time-series were assumed to represent the temporal patterns of growth activity at the different sites throughout the face.

The associations between the time-series were investigated using non-linear time-series analysis to characterise the patterns of growth and to detect meaningful (statistically significant) correspondences between growth rotations of the jaws and growth displacements of the mandible and maxillae and the natural movements of the teeth.

Prior to the analysis of the time-series an exploratory survey was carried out employing correlation analysis of the growth changes over a single extended observation interval of six years focussing on the relationships between the growth changes throughout the face and growth rotations of the jaws. This initial survey was undertaken for three reasons: first, to allow comparison with the findings of previous studies, in particular the classic implant studies of Björk and Skieller (1972, 1976, 1983); secondly, to provide broad general summaries of the relationships between these variables (by lessening the obscuring effect of measurement errors on the overall relationship between the variables); and thirdly, to locate anatomical sites and growth variables that might usefully be investigated in more detail and at higher temporal resolution in the main time-series study.

The initial survey was conducted at the level of the whole sample to provide a group analysis examining total growth changes. For the main study the analysis of the time-series was conducted first at the level of the individual subject. That is, each individual’s data were analysed separately because the timing of peaks and troughs in the annual incremental growth records would not be expected to coincide precisely from child to child, thereby preventing the detection of possible synchronous patterning of growth. The individual analyses were then combined by statistical meta-analysis to form a multi-subject, group analysis.

Consequently, this investigation comprised two longitudinal observational studies involving descriptive, exploratory and inferential analyses.

[¶] The reason for using growth velocities rather than the actual measured increments was to avoid the detection of apparently real but otherwise spurious associations between the growth at different sites caused by their joint dependence on variations in the lengths of the observation intervals.

4.3 THE FUNDAMENTAL LIMITATIONS IN THE STUDY OF GROWTH

The longitudinal measurement of growth processes within an individual child suffers from one fundamental limitation and two associated major analytical challenges.

Conceptually, growth can be viewed as a continuous function of time even if there are periods where no actual growth occurs and the function remains ‘flat’. However, we can never observe growth continuously, at least, not at a clinical level. What we do instead is to take periodic samples of the cumulative growth experience and use these to reconstruct the continuous trajectory of growth. For reasons of analytical convenience this is usually done by fitting a mathematically defined curve to the sampled data points. The growth ‘velocity’ and growth ‘acceleration’ at different times (the incremental growth per unit time; and the change in incremental growth per unit time) are obtained by taking first and second mathematical derivatives respectively of this curve.

However, while these procedures can be useful in constructing average growth curves and associated percentiles for populations or subject groups, the true continuous trajectory of growth for an individual child can never be accurately recovered, in this or in any other way, no matter how we attempt to represent and interpolate the growth trajectory between the sample points. This is a fundamental mathematical limitation in the study of *any* continuous phenomenon recorded by periodic sampling. This limitation is known in applied mathematics as the ‘sampling problem’ and it arises as a consequence of the ‘sampling theorem’ (Whittaker, 1915; Shannon, 1948; Gensun, 1996).

4.3.1 The Sampling Theorem

The sampling theorem concerns the problem of reconstructing an analytic function from its sampled values. It is formally stated as follows:

A function $\boldsymbol{f}$ *that is continuous, square integrable on* $\mathbf{R}$ *and whose Fourier transform* $\mathbf{F} \in \mathbf{L}_2(\mathbf{R})$ *has support contained in* $[-\pi \mathbf{W}, \pi \mathbf{W}]$ *for some* $\mathbf{W} > 0$ *can be completely reconstructed from its sample values* $\boldsymbol{f}(\mathbf{k}/\mathbf{W})$*, taken at nodes* $\mathbf{k}/\mathbf{W}$*,* $\mathbf{k} \in \mathbf{Z}$*, equally spaced apart on* $\mathbf{R}$*.*

Less formally stated, the Sampling Theorem says that: *a continuous mathematical function can be completely reconstructed from regularly spaced samples provided that the Fourier transform of the function contains no terms with a period less than twice the sampling interval* (Landau, 1967).

In the context of human growth studies where measurements are made at annual or semi-annual intervals there will inevitably be frequency components with periods less than twice the sampling interval (Wales and Gibson, 1994). This appears to imply that the information conveyed by, or contained in, these higher frequency components is irretrievably lost as a result of sampling. This is indeed the case but it is not the worst of it. While meaningful information cannot be retrieved from these higher frequency components the higher frequencies themselves are *not lost* but appear as spurious lower frequency distortions in the reconstructed function.

The nature of the distortions depends on whether or not the samples are taken at exactly equally spaced intervals. If they are then a problem known as "aliasing" occurs (Chatfield, 1984). If they are not (as is almost always the case in human growth studies) then the distortions will appear as unpredictable (random) fluctuations in the reconstructed growth curve above and below the true value.

The degree to which these distortions are a problem is determined by the ratio of what are known as the *power spectral densities* (PSDs) of the Fourier components of the original continuous function above and below the Nyquist frequency (the frequency whose period is twice the sampling interval). The PSD of a frequency component is proportional to the square of its amplitude so that even quite small but rapid changes or fluctuations in growth rate can lead to disproportionately large distortions in the reconstructed function.

In practice this is compounded by a related mathematical problem, *Beurling-Landau instability,* which results from inaccuracies in the measurement of the sample values. Beurling-Landau instability refers to the situation where a small error in the measurement of the value at a sample point will only lead to a correspondingly small error in the reconstructed (growth) curve if the original continuous function has no frequency components above the Nyquist frequency (Beurling and Malliavin, 1962; Landau, 1967). As indicated above, this condition is unlikely to be met in a human growth study and as a consequence, small errors of measurement will potentially lead to much larger errors in the reconstructed growth curve.

These problems could be overcome by increasing the rate of sampling until the PSD of the resulting time-series approached zero (Chatfield, 1984). For the analysis of a pre-existing growth study (as in the present case) this is clearly not possible.

The only realistic alternative is to completely avoid reconstructing the continuous trajectory of growth and rely instead on the measured increments of growth. That is, on the actual growth changes that occur in the time intervals *between* the sampling points. In the absence of measurement error this will provide a record of the actual incremental pattern of growth in the form of a series of isolated (discrete) values. In practice, of course, the increments cannot be recorded without measurement error.

4.3.2 The Reconstruction and Analysis of Incremental Data Series

Reconstructing an incremental pattern of growth presents a major analytical challenge because of the way in which the values of the increments are obtained: by subtracting the measurement at the beginning from that at the end of each observation interval. This not only leads to a *doubling* of the errors of measurement it also introduces a *negative serial correlation* into the resulting incremental data series, which makes it impossible to reliably detect all but the largest differences in growth from year to year (van der Linden, 1970; Lampl, 1998).

The cause of this problem is that adjacent increments are affected by the same random measurement error. That is to say, a random error in locating the end point of one increment will also affect the location of the starting point of the next increment. It is not usually possible to overcome this problem and the best that can be done is to reduce the effect by keeping the random errors of measurement as small as possible. Even so, the effect of the negative serial correlation means that to establish a true *difference* between adjacent increments at $p \leq 0.05$ their (measured) values must differ by at least (±) 4.97σ where σ is the standard deviation of the random error of measurement of the end points (van der Linden, 1970).

This poses a problem for the analysis of any growth study relying on incremental data but it poses a particular problem for this type of study where the increments of growth (in facial structures) are expected to be small in relation to the errors of measurement.

In most human growth studies it is not possible to overcome this because the growth increments cannot be measured independently. However, because the fundamental growth records in this case are radiographic projections of the skull rather than direct measurements of the tissues it should be possible to make measurements of adjacent increments that are essentially independent in terms of the random errors of measurement. This is achieved by making two series of measurements of each growth variable and selecting the values for adjacent increments from different (alternate) series. The two measurements must of course be made at widely spaced points in time to avoid the statistical dependence that accompanies measurements made close together in time (Houston, 1983).

This procedure should remove the negative dependence between adjacent increments due to random error of landmark location and measurement. The remaining potential sources of error leading to the negative serial correlation will be geometric errors resulting from variations in the projection and recording of the skull from film to film – the so-called errors of ‘position and pose’. These can be made negligible in relation to the spatial resolution of the radiographs by employing precise points of measurement that are only in planes parallel or approximately to the film plane. This will limit the geometric errors to rotational differences (from film to film) around cranio-caudal and antero-posterior axes[§]. The resulting geometric errors will vary as the cosine of the angular difference and with rotational errors less than 4° (the general limit imposed by the cephalostat (Baumrind *et al.,* 1992)) the resulting linear error (the change in linear distance) should be no greater than ~0.24%. Because the limiting spatial resolution of the radiographic screen-film system is between ~0.05mm and ~0.1mm (Barrett and Swindell, 1981; Ishizuka, 1981) this degree of linear error would only be detectable where the distance being measured was greater than ~30mm. Very few of the distances (and none of the annual increments) likely to be encountered in the present study will exceed this value.

4.4 SPECIAL CONSIDERATIONS IN THE OBSERVATIONAL DESIGN

In addition to these fundamental problems of reconstructing the pattern of growth there are other potential problems and sources of error in recording and analysing the data in this type of observational investigation where none of the variables are under direct experimental control.

4.4.1 Assessing the degree of association between growth variables.

Correlation analysis is the method of choice for the assessing the degree of association between biological variables that are examined *observationally* (Sokal and Rohlf, 1995). This form of analysis was used in the initial exploratory survey where the variables were examined in pairs. Classical correlation analysis, however, suffers from several problems that complicate the interpretation of the findings. These are:

[§] Translational errors in the film plane have no effect on measurements. Only translations in the plane perpendicular to the film induce an error but because the head is constrained by the cephalostat and because of the long object-focus distance the effect of translation perpendicular to the film should have an effect which is smaller than the spatial resolution of the screen-film system.

1) The problem of spurious correlation where the variables (whose correlation is to be established) share a common point, line or reference base; or where both variables are calculated arithmetically from another measured variable. The causes of this problem are the effects known as *mathematical coupling* and *regression to the mean effect* (RTM effect). These effects result primarily from the inclusion of identical random errors in the variables to be correlated and, unlike the usual situation where random errors reduce the likelihood of obtaining a statistically significant result, in the case of correlation, they can lead to large but otherwise entirely spurious correlations (Moreno *et al.*, 1986).

2) The problems of establishing the compliance of the measured variables with the assumptions underlying the standard measure of correlation – the *Pearson product-moment correlation* - and the effect of failure to meet these assumptions. Particularly the inflation of the apparent correlation coefficient by non-Normal distributions of the variables.

3) The uncertainties associated with multiple comparisons and simultaneous inference. The problem is, that even where no correlation truly exists, on average, 5% of the correlations will appear to be statistically significant at the $p \leq 0.05$ by chance alone.

4) The difficulties in comparing and testing correlations derived from repeated measurements on the same individuals. This is a particularly difficult area for statistical analysis because of the *dependence* between the correlations (that is, the correlations are correlated among themselves). This dependence affects the critical values used to decide statistical significance in a complex and highly non-linear way (Krishnamoorthy and Xia, 2007).

5) The problems of statistical inference caused by *over-determination* (having many more observational variables than original measured points). Although only 16 linear distances and 9 angles were measured in the initial study, they were used in various combinations to form 49 growth variables. Consequently, much of the information will be duplicated within the variables. This duplication leads to increased dependence between the variables, over and above that which would be expected from repeated

measurements of the same individuals. This is then a further potential cause of spuriously high correlation between the variables.

6) Although correlation analysis is the method of choice for assessing the degree of association between the variables examined in the initial study it is not suited to the analysis of the associations between time-series, as required for the main study. If the degree of match between two time-series is assessed by the standard (Pearson) correlation this requires not only that the variables are Normally distributed but also that the sampling intervals are the same throughout each time-series. However, even where these requirements are met the Pearson correlation coefficient does not take into account the temporal order of the sample values and consequently does not provide an accurate representation of the similarity or synchrony between time-series (Möller-Levet *et al.,* 2003).

1) The other standard measures for assessing the similarity or synchrony between time-series (for example, Euclidean distance) are unable to deal effectively with the varying lengths of sampling intervals within each time-series and they too fail to take into account the temporal order of the sample values (Möller-Levet *et al.,* 2003; Wang *et al.,* 2012). These measures and methods of analysis also generally require many hundreds of data points to allow curve fitting to assess the degree of similarity (Liao 2005; Klawonn *et al.,* 2012). None of these requirements could be met by the time-series in the present investigation.

The investigative methods for the initial survey and main (time-series) study were designed, planned and executed to take account of and, as far as possible, overcome each of these potential problems and sources of error.

CHAPTER
5

MATERIALS, SUBJECTS AND METHODS

5.1 MATERIALS

The materials comprised serial lateral, frontal (postero-anterior) and 45° left oblique cephalometric radiographs recorded approximately annually for 14 children (5 males, 9 females). The radiographs were recorded between 1967 and 1978 as part of the research records of the Mathews Longitudinal Growth Study of the University of California, San Francisco, USA.

At the time of admission to the growth study each child had between 3 and 5 Björk-type tantalum markers implanted in the left side of the mandible (the side nearest the radiograph) and between 3 and 5 tantalum markers both in right and left maxillae. The markers, in the form of 99.9% pure tantalum pins (0.64mm diameter; 1.69 mm in length) were implanted under general anaesthesia using a modified Björk pin setter (Mathews and Ware, 1978). They were inserted via an intra-oral approach with the exception of the ramal marker which was placed extra-orally through the masseter in the approximate centre of the ascending ramus (Mathews and Ware, 1978). The locations of the implant markers are shown in Figure 5.1.

All radiographs were recorded on Kodak dual emulsion Safety Film (Eastman Kodak Corporation, Weatherfield, Oklahoma, USA) using DuPont Detail intensifying screens (E. I. du Pont de Nemours and Company, Brevard, North Carolina, USA.) and a scatter reducing stationary grid with fine lead slats set 0.1 mm apart. The radiographs were exposed with the head held in a cephalostat with nasal bridge locator and aluminium

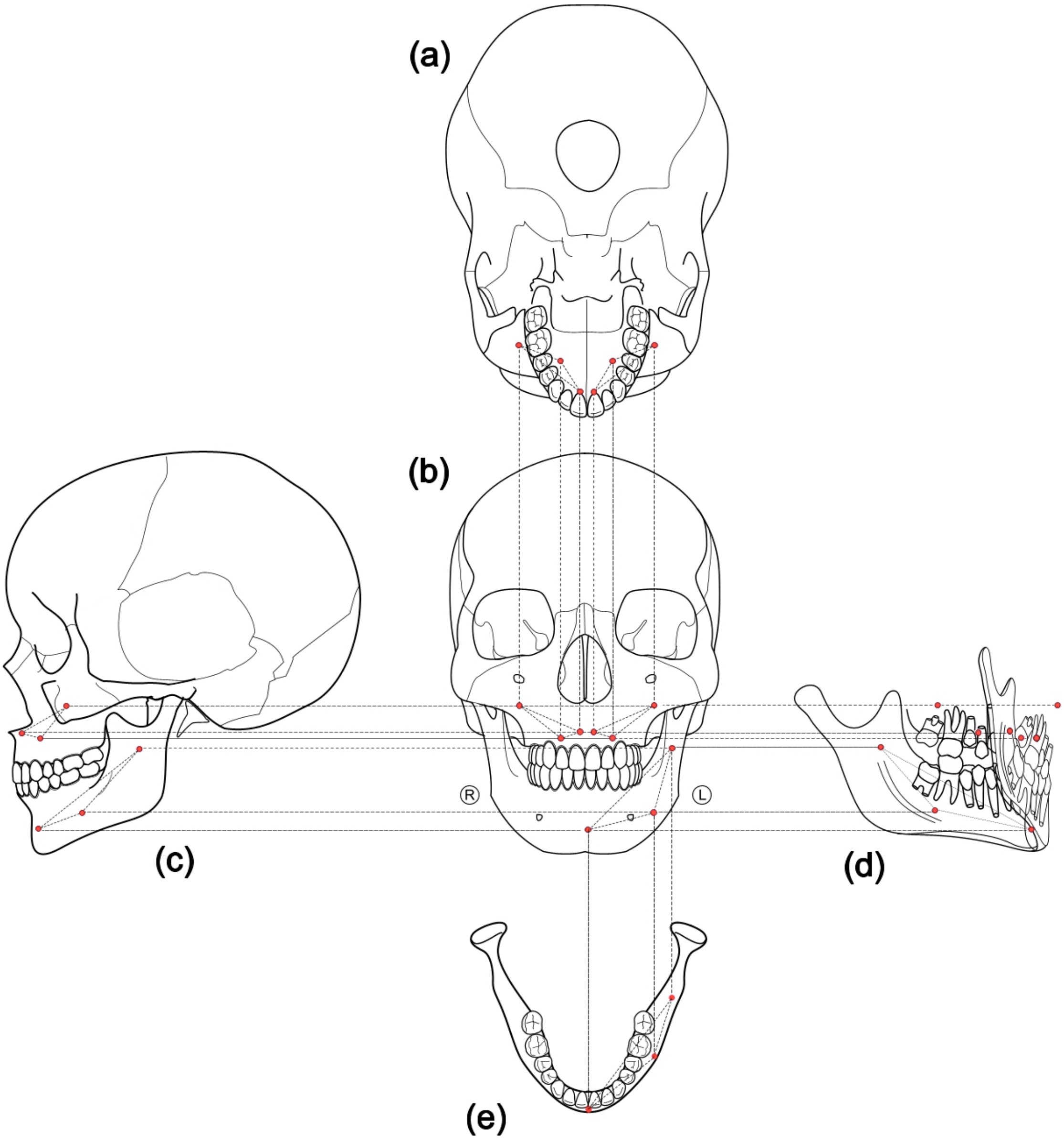

Figure 5.1 Locations of the tantalum implant markers.

The diagram indicates the positions of the intra-cortical tantalum marker pins (indicated by ●) used as fixed reference points in the mandible, right and left maxillae. (**b**), **(c),** and (**d**) show the positions of the pins as they would be viewed in the frontal, lateral and 45° left oblique cephalometric projections respectively. (**a**) and (**e**) show the positions of the pins as if they were viewed in the transverse plane (basal cephalometric projections were not part of the records of the Mathews UCSF Growth Study from which the subjects in this investigation were drawn).

wedge to enhance the recording of the soft tissues over the anterior contour of the face.

The x-ray tube target was set at 60 inches (1518mm) from the mid-sagittal plane of the cephalostat for lateral radiographs and at the same distance from the ear-rod to ear-rod plane for the frontal radiographs; and the central vertical axis of the cephalostat for the oblique radiographs. The x-ray tube to radiograph distance was fixed at 66 inches (1669.8 mm). For each child, each annual set of three radiographs was recorded on the same day but *not* simultaneously. Examples of the radiographs and radiographic series are shown in Figure 5.2.

All the radiographs were recorded by the same radiographer, using the same cephalostat, x-ray tube and screen-radiograph combination throughout the growth study. No modifications were made to the equipment, imaging technique or radiograph processing method for the duration of the study (Baumrind and Korn, 1992).

To permit computer based processing and analysis the original radiographs were duplicated in high resolution digital format by technical staff at the Craniofacial Research Instrumentation Laboratory of the University of the Pacific, San Fransisco, USA. The digital radiographs were supplied for this study at a spatial resolution of 600 dpi and a densitometric resolution of 16-bits which provide a limiting spatial resolution of 0.042mm and grey-scale quantization of 512 levels. Each radiographic image was stored in a computer readable file (generally TIF format) of approximately 80 Mb per radiograph.

5.2 SUBJECTS

The subjects were drawn from an original group of 38 apparently healthy children with no facial deformity who were enrolled in the Mathews longitudinal growth study of the University of California, San Francisco, USA. All children in the mixed dentition who were seen by the dental examiner of the University of California School of Dentistry during the period June 1967 and February 1972 were invited to participate in the study. The risks and benefits were explained to the parents of each child and all those for whom appropriate consent could be obtained were enrolled in the study (Mathews and Ware, 1978; Baumrind and Korn, 1992). Ethical approval for the study including the insertion of tantalum implant markers was granted by the Committee on Human Experimentation at the University of California, San Francisco (Mathews and Ware, 1978).

From the original 38 subjects 2 were lost to recall and long-term annual records were not available. The samples for this investigation were selected from the remaining 36 subjects.

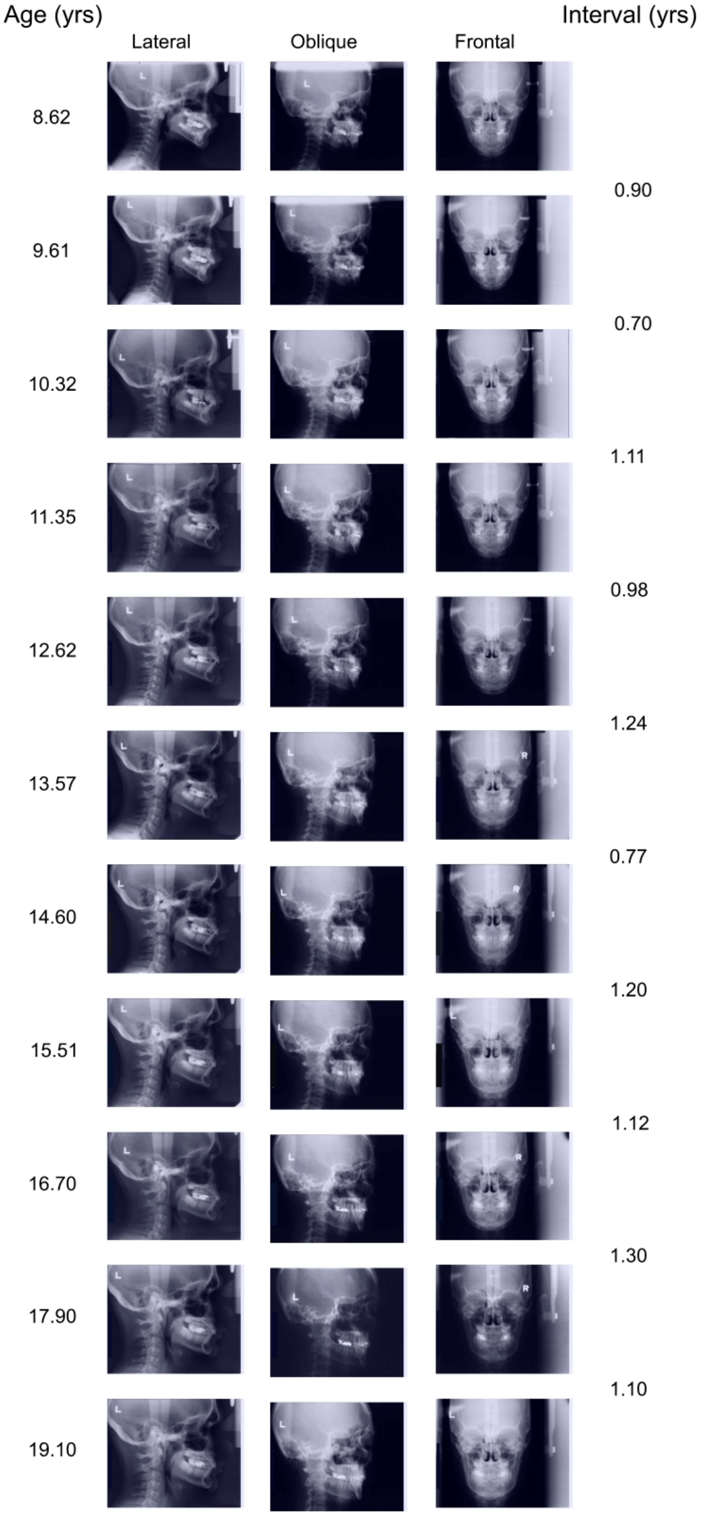

Figure 5.2 Examples of the serial cephalometric radiographs used in the study.

The frontal, lateral and left 45°oblique cephalometric radiographs were recorded approximately annually as part of the physical records of the Mathews UCSF Growth Study which began in 1967 (Mathews and Ware, 1978). The original radiographs were scanned at high spatial and densitometric resolution at the Cephalometric Research Instrumentation Laboratory (CRIL) of the Department of Growth and Development, University of California, San Francisco. The radiographs in this example are those of subject 5.

5.2.1 Selection of the Sample

The sample was selected on the basis that each child had: 1) a complete annual radiographic series covering the period from before the peak of the juvenile growth spurt and extending beyond the peak of the pubertal growth spurt; 2) that no treatment had been performed during or prior to this period; and 3) that a minimum of 2 tantalum markers had remained stable in each bone (mandible and in *both* maxillae) throughout the period of observation. This provided a sample of 11 subjects (5 males and 6 females) with a mean age at initial radiographs of 7.22 (SD=1.05) years and mean age at final radiographs 16.01 (SD =1.42) years.

The serial radiographic records of the 11 subjects were used to perform two studies: an exploratory investigation of associations across the sample ('the initial survey'); and (ii) a time-series analysis with the aim of detecting intra-individual co-ordination of growth ('the main study').

For the time-series study the full annual radiographic series of each subject was used. However, for the initial survey it was necessary to ensure uniformity of the physical maturity of the subjects for the between-subject comparisons to be valid. This was achieved by selecting an observation period of 6 years aligned on the maximum pubertal vertebral growth of each subject. The observation period began 5 years prior to the annual record immediately following the pubertal maximum of cervical vertebral growth and continued for one year following this maximum. The age distributions of the radiographs for the two studies are shown in Figure 5.3

All children were of Caucasian racial type of Northern European ancestry living in the San Francisco Bay area of California, USA. Although not deliberately selected, the sample nevertheless included the full range of antero-posterior skeletal discrepancies (skeletal Class I, Class II and *mild* Class III) and high and low mandibular angles. The details of the sample are given in Table 5.1.

5.2.2 Ethical Considerations

The materials used in this study were drawn from the research files of a historical growth study. As indicated above, the Committee on Human Experimentation at the University of California, San Francisco had given ethical approval for the original study

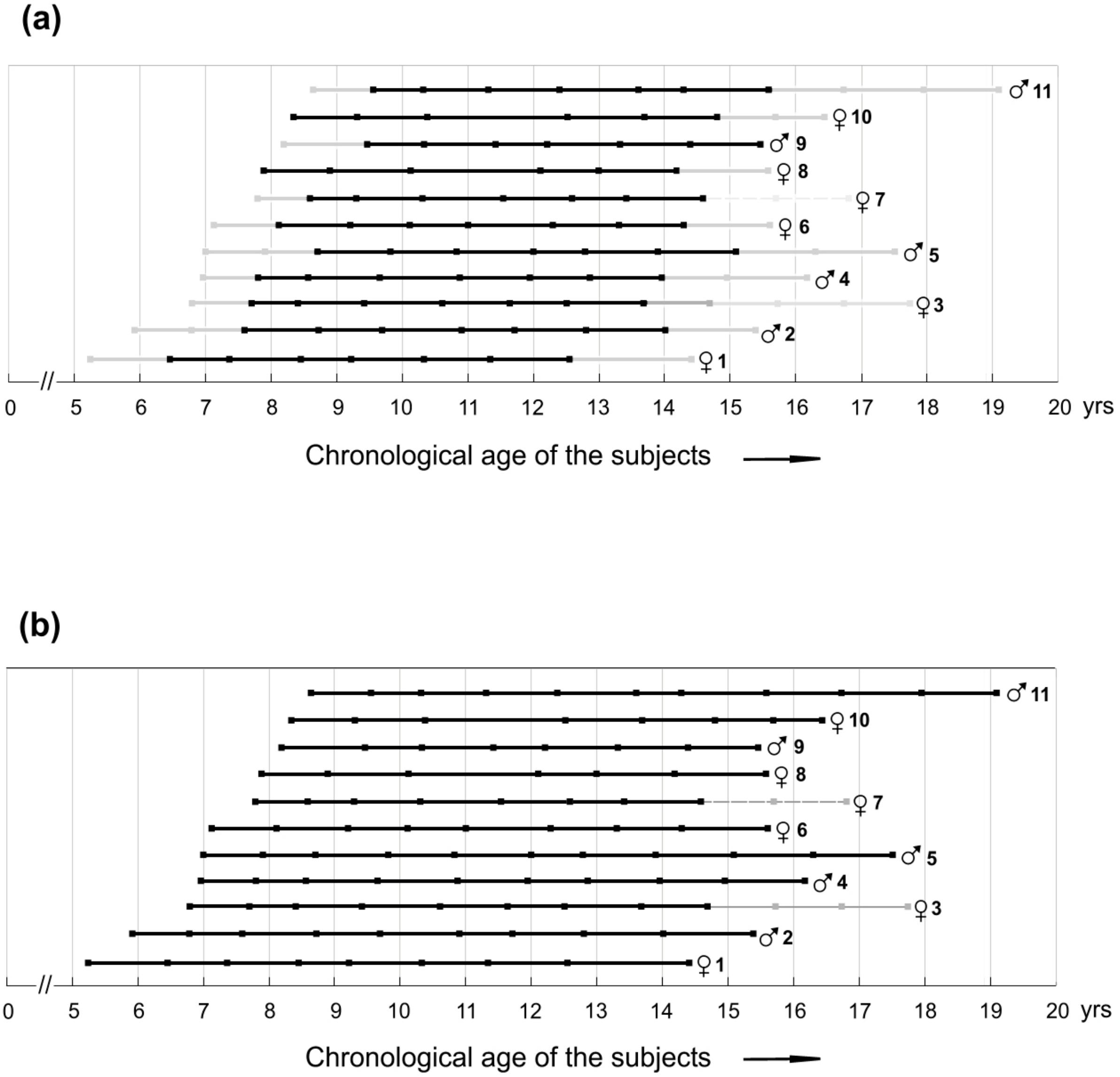

Figure 5.3 The age distribution of the radiographs for (a) the Initial Survey and (b) the Time-Series study.

Solid black lines indicate the observation periods examined in this research. Dashed lines indicate periods where treatment was carried out (data from these periods were not used). The marks (-▪-) indicate the ages at which growth records were made and cephalometric radiographs were recorded. **(a)** The observation periods for the Initial Survey were matched as closely as possible for all subjects (mean = 6.21 yrs, SD = 0.21 yrs). To ensure uniformity of physical maturity the observation period began 5 years prior to the maximum pubertal vertebral growth for all subjects. **(b)** The observation periods for the main (time-series) study encompassed either the whole period for which records were available or, for subjects No 3 and No 7, the period prior to treatment. The subject number and gender are indicated to the right of each line.

Table 5. Details of the Subjects in the Sample.

Subject No.	*sex*	*Skeletal Pattern*				*Age (years)*		*Age Range (years)*	*Annual Record sets*
		Ant-post	Vertical (MMPA) *(Initial*	*Final*	*Diff')*	*Initial film*	*Final film*		
1	F	Class I	21.1	22.4	-1.3	5.10	14.40	9.30	9
2	M	Class I	29.1	29.1	0	5.90	16.40	10.50	11
3	F	Class II	38.7	32.2	6.5	6.70	16.80	10.10	12
4	M	Class I	29.2	30.3	-1.1	6.90	16.10	9.20	10
5	M	Class I	30.9	17.8	13.1	7.10	17.50	10.40	11
6	F	Class II	38.9	41.8	-2.9	7.00	15.50	8.50	9
7	F	Class II	32.1	34.5	-2.4	7.80	16.80	9.00	10
8	F	Class I	27.2	19	8.2	7.90	15.50	7.60	6
9	M	Class II	25.0	24.2	0.8	8.10	15.50	7.40	8
10	F	Class II	20.9	19.9	1	8.20	16.40	8.20	8
11	M	Class I	28.8	16.4	12.4	8.60	19.00	10.40	11

and formal consent was obtained from the parents of each child enrolled in the study (Mathews and Ware, 1978; Korn and Baumrind, 1990).

Permission for the use of the radiographic records in the present investigation was given by the lead researcher, the late Dr J R Mathews (Department of Growth and Development, University of California, San Francisco) and separately by the present custodian of the records, Professor Dr S Baumrind (The Craniofacial Research Instrumentation Laboratory (CRIL), Dugoni Dental School, University of the Pacific, San Francisco, USA) who provided the materials in high resolution digital format. The digital radiographs were provided in an anonymised form. That is, all personal identifying details had been deleted thereby preventing the identification of the individual subjects in the study.

5.3 METHODS

Throughout this investigation the viewing, manipulation, measurement and analysis of the radiographic images were carried out on a desktop computer linked to a calibrated image display monitor (Sony SDM-X72. Sony Electronics Inc. 680 Kinderkamack Road, Oradell, NJ 07649, USA) capable of displaying images with a densitometric (grey-scale) resolution of 24 bits. During viewing of the radiographic images the background lighting of the room was dimmed and a short period of visual adjustment was observed prior to performing any analysis or manipulation of the images.

5.3.1 Preliminary Examination and Processing of the Images Prior to Formal Analysis

5.3.1.1 Confirming the scale and geometric accuracy of the digital images

Because the radiographs were provided in digital format (rather than as the original radiographs) it was necessary to confirm that they were dimensionally accurate copies of the original radiographs and that all the radiographs for each subject were displayed at the same, known scale. It was particularly important to ensure the geometric accuracy for their use in this type of radiogrammetric investigation. Because the original radiographs were not available for comparison an alternative method was used.

Prior to the conversion of the original radiographs to digital format a series of fine pin holes 0.5 mm in diameter were punched in the surface of each radiograph to act as reference marks. These reference or ‘fiducial’ marks were placed away from the main anatomical image using a rigid template with fine projecting metal pinpoints which perforated the radiograph base (Baumrind, 1991). A constant known coordinate relationship exists between the pins marks. Consequently, by measuring the relative positions of the fiducial marks it was possible to determine the scale of the images and to check that the scale was constant in both planes of space for all radiographs for each subject.

As a secondary check on the scale of the images and to check for geometric distortion, the fine lines imprinted on the radiographs by the scatter reducing grid were compared across each radiographic series for each subject using the method of ‘image subtraction’ (Dunn *et al.,* 1993).

5.3.1.2 Identification and correct coupling of implant markers in the three radiographic projections.

The identification of the same implant in all three radiographic views is an important prerequisite to the checking of implant stability (see Section 5.3.1.3) as well as establishing the correct reference plane and implant lines in the lateral and oblique views (see Section 5.3.2.2).

The identification of the same implant in the frontal and oblique views was generally uncomplicated, as was the identification and matching of the mandibular implants across all three views except in those cases where double implants had been inserted close together at the same anatomical site. The unambiguous identification of the implants in the lateral view and matching these with the same implants in the frontal and oblique views of the maxillae posed the greatest difficulties because of the superimposition of right and left sides of the upper jaw in the lateral view.

Correct coupling of the implant images across the different perspective projections was undertaken in seven stages as shown in Fig. 5.4.

5.3.1.3 Confirming the stability of the implanted tantalum markers

The valid measurement of growth changes requires stability of the implanted tantalum markers. It is known that tantalum implants may become unstable or lost due to fibrous reaction in the bone, inadequate depth of placement resulting in periosteal drag or by uncovering during periods of rapid remodelling (Björk, 1963; Rune, 1980; Alberius, 1983a). This is a particular problem in the fine bony cortices of the maxillae (Björk and Skieller, 1976) and in the posterior body of the mandible (Kuroda *et al.*, 1979). It was therefore essential to confirm the stability of the implants before they could be used as valid reference markers.

Two methods were used to test the stability of the implants for each subject: the method of Korn and Baumrind (1990); and that of Springate (2015). The method of Korn and Baumrind (1990) required plotting of the inter-implant distances and examining these for systematic variation with age of the subject as an indication of instability. The method of Springate (2015) required the comparison of inter-implant angulations between serial radiographs for significant differences by reference to the random errors of measurement.

5.3.1.4 Image enhancement of hard tissue contours

To improve the visibility of fine bony details for superimposition on the anterior cranial base and for the consistent location of implant centres and anatomical landmarks, the images were enhanced by computer processing. First, the contrast and brightness were equalised while maintaining the densitometric range; secondly, the tonal range was reversed (bone and teeth appear dark) and a false-colour was added to give a mid-blue tone to the middle and maximum optical densities (as shown in Fig 5.4). This tonal alteration maximises the psychometric perceptibility of fine details of the teeth and bone (Pratt, 2003). It is important to note, however, that these visual enhancements and the tonal reversal *do not* alter the *spatial* characteristics of the images.

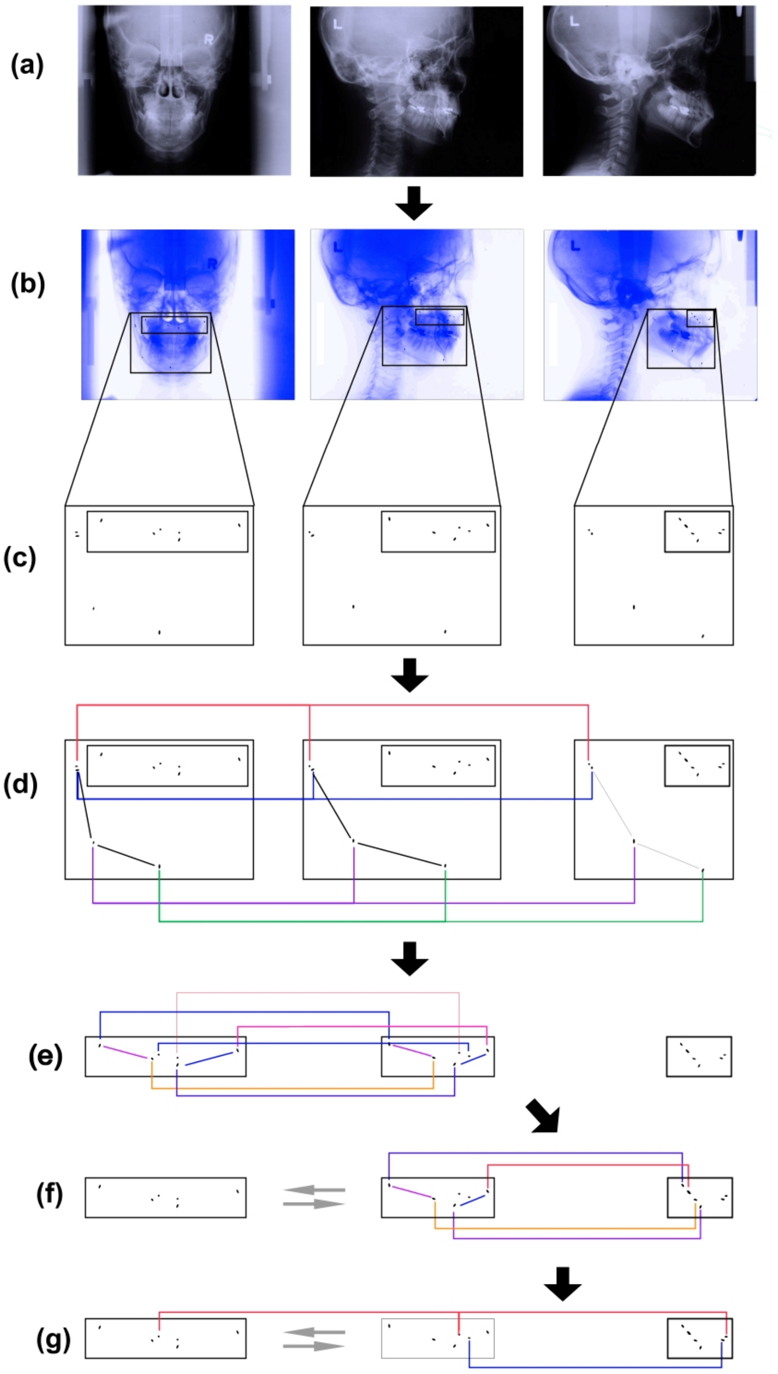

Figure 5.4 **Diagrammatic representation of the processes used to locate the correct coupling of the implant images across the three radiographic projections.**

(a) The three original digital radiographic images recorded at each time point are digitally enhanced and tonally reversed to allow the implants to be more easily identified as shown in **(b). (c)** The implants in the mandible and maxillae are identified in all three views. **(d)** The mandibular implants are matched first and eliminated from further consideration. **(e)** The most anterior and most posterior (lateral) implants in the maxillae are matched between the frontal and oblique views. **(f)** The most superior and most inferior maxillary implants are then matched between oblique and lateral views. These are generally the canine (palatal) and infra-zygomatic crest implants. However, confusion can occur between the anterior and canine implants in the lateral view. Where this occurs, the vertical height and horizontal parallax between oblique and lateral views are used to decide on the correct couplings. **(g)** The remaining unmatched implants are usually the anterior implants seen below the nasal spine in the lateral and oblique views. The correct coupling of these images is often the most difficult to determine. The decision is generally made by first identifying the right hand anterior implant (indicated by the fine blue line in **(g)**) then matching its vertical position in all three views to leave only the left hand anterior implant to be coupled.

5.3.1.5 Correction of Magnification and Geometric Distortion

5.3.1.5.1 Magnification. In general, correction of magnification is only practicable for midline structures and for the mean of bilateral structures projected onto the mid-sagittal plane in the lateral view. In the present study the majority of structures examined were set away from the midline and closer to the radiograph. This makes correction of magnification difficult to achieve. However, methods have been developed for the correction of magnification at points away from the midline but these require a minimum of two projections of the skull and they rely on the assumption that the projections are truly orthogonal. They also rely on the ability to precisely locate the same point in both projections (Buck and Hodge, 1975; Baumrind *et al.,* 1983). These requirements are unlikely to be met in practice except where the images are exposed simultaneously as in the original Broadbent-Bolton cephalometric system (Broadbent, 1931).

In the present study the primary measurements of interest were the annual increments of growth. For the structures examined the magnitude of change was below 3 mm in 91.5% of the measured changes (58.5% < 1.00 mm) and even applying the standard correction for magnification, this amounts to just under 0.3 mm at the midline (it will be less for structures closer to the radiograph). However, although this is not negligible the analysis of the increments relied *not* on their actual values but on the relationships between the magnitudes of adjacent increments. Consequently, the correction for magnification would only have relevance if adjacent increments were subject to markedly different levels of magnification. While the difference in magnification of structures between the first and last radiographs might differ in this way due to growth moving the structure of interest closer to (or further away from) the film, the difference in magnification for adjacent *annual* increments was felt to be too small to have any influence on the results.

That is to say, the limiting spatial resolution of the cephalometric screen-film system is ~ 0.05 mm (Barrett and Swindell, 1981; Ishizuka,1981). Thus, for the change in magnification to have any detectable effect it must cause the measured value of any increment to vary by at least ±0.05 mm. The largest (uncorrected) linear increment recorded in the study was 8.45 mm (growth of the cervical spine for Subject number 5).

To alter this by 0.05 mm the structure of interest would need to move 7.59 mm further away from the radiograph or 10.1 closer to the radiograph between annual measurements. This degree of movement is 3 times greater than the maximum annual horizontal change (0.25 mm mandible; 2.14 mm maxilla) required to affect measurements on the frontal radiograph or 5.4 times greater than the maximum annual lateral change (1.03 mm) required to affect measurements on the lateral radiograph.

5.3.1.5.2 Geometric distortion. Geometric distortion is an inevitable consequence of the projection of any three-dimensional object on to a two-dimensional plane. This source of distortion was kept to a minimum by employing structures in planes parallel to the screen-film plane and using a registration point at the same distance from the film as the structure of interest, as explained in Section 4.3.2.

This was not possible, however, for the measurement of the growth displacement and growth rotation of the mandible as recorded from the lateral radiograph. The reason is that the radiographs were superimposed and registered on midline structures in the anterior cranial base but the tantalum markers were implanted only on one side of the mandible (left side) in a plane oblique to the radiograph. Consequently, small rotational changes of the head between annual recordings would distort the projected location of the implants thereby biasing the calculation of mandibular changes - particularly growth rotation in the sagittal plane. To correct for this effect the method described by Björk and Skieller (1972) for subjects with unilateral mandibular implants was used.

In this method corrections are made separately for small rotational changes affecting the horizontal location of a unilateral posterior implant and those affecting its vertical location. For the horizontal correction a line is constructed joining anterior and (left) posterior implants. This line is then kept at a constant length throughout the radiographic series while registering the line on the anterior implant. For the vertical correction the position of the posterior implant is adjusted by one half the difference in the vertical divergence from the average distance between the lower borders of the mandible in the successive radiographs.

5.3.2 Analysis of the Longitudinal Radiographic Series

5.3.2.1 Terminology and conventions of spatial position and orientation

Although standard cephalometric terminology has been used in some of the descriptions that follow, the high precision radiogrammetric nature of this study required additional terms to describe features and processes not generally found in cephalometric analyses. New or uncommon terms are defined where they first appear in the text but for quick reference as well further guidance on terminology please see the Glossary (p. 19).

Throughout the study the primary plane of orientation was the *occlusal plane* defined on the occluding surfaces of the left hand posterior teeth without involving the teeth anterior to the primary molars or premolars. This was done to allow similar orientations to be achieved in both the lateral and oblique radiographs[¶].

Changes in the location and orientation of structures of interest during the study were defined in relation to the three cardinal axes as shown in Figure 5.5. The x-y and y-z planes correspond to the planes of the lateral and frontal radiographic projections respectively. The plane of the oblique projection shares the same vertical dimension (the 'y' axis) as the other two projections but its horizontal axis is orientated at approximately 45° to both the frontal and lateral ('y-z' and 'x-y') planes. Consequently, the horizontal component of motion or change seen in the oblique views does not correspond to the horizontal component seen in either of the other two projections.

5.3.2.2 Reference points, lines and planes

Three types of reference points were used in this research: conventional anatomical points, implant defined points and control points. In addition to reference points, reference lines were used to establish a common coordinate space (parallel to the screen-film plane) that was consistent from radiograph to radiograph within each specific radiographic series.

5.3.2.2.1 Implant defined points. The tantalum implants were used to define two types of reference points: *implant centres (single implant points)*; and *median implant points.* These points were used in the registration of the serial radiographs; as surrogate points for the measurement of translation; as end-points of the lines for the measurement of rotation of the mandible and maxillae relative to the anterior cranial base; and for the assessment of transverse changes in the maxillae.

Implant centres (single implant points). The geometric centre of the body of an implant was used to provide a precise and consistent point of reference both as a sole reference and in defining implant lines and implant configurations. That is, when an implant was viewed perpendicular to its long axis the tapering tip was disregarded and the centre of the remaining cylindrical part of the implant was located and used as the reference. This was done to standardise the location of the reference within the body of the implant in those (few) cases where the tip had been deformed during insertion in the bone.

[¶] The anterior teeth were not included in the definition because the images of these teeth in the oblique radiographic projection are highly variable and difficult to interpret.

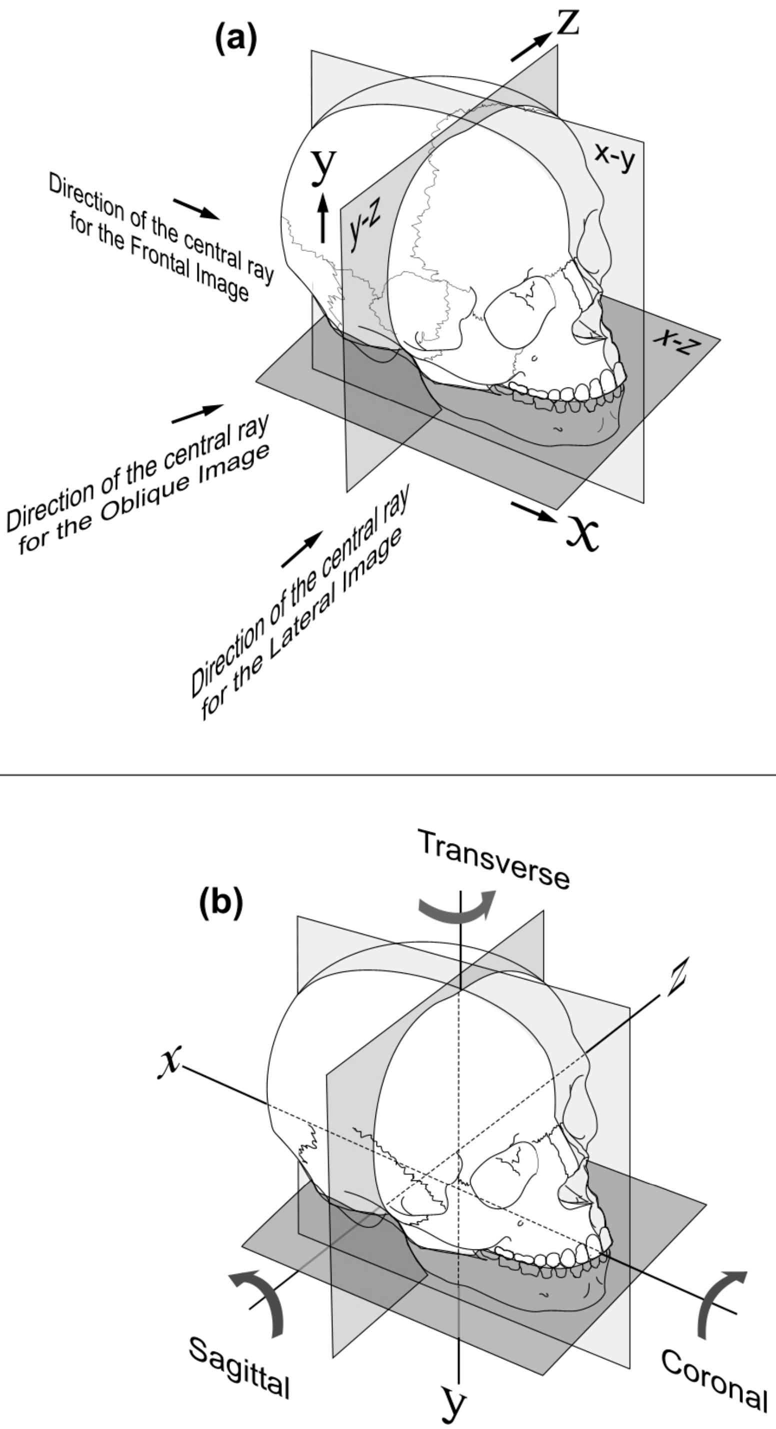

Figure 5.5 The cardinal axes used in the orientation of the head and in the descriptions of growth displacements and tooth migrations.

(a) Shows the three planes of space and their relationships to the central ray of the x-ray beam during the exposures. **(b)** Shows the rotational (angular) directions relative to the three planes of space. It is important to note that the 45° oblique radiograph shares the same vertical (Y) axis as the frontal and lateral radiographs but is orientated horizontally half way between the Z and X axes. Consequently, horizontal measurements on the oblique image do not correspond to those made in either of the other two views.

Median implant point. When superimposing lateral views of the maxillae minor variations in head position from radiograph to radiograph lead to marked differences in the relative location of implants on the right and left sides of the head (Bjork and Skieller, 1976). To mitigate this effect the mid-point between right and left implants at matching anatomical sites was used to define a '*median implant point*'. The median implant points representing the lateral, canine (or 'palatal') and anterior implants were used to define the nominal mid-sagittal reference of the maxillae as viewed in the lateral projection (Bjork and Skieller, 1972; 1976).

5.3.2.2.2 Anatomical points. The majority of reference points or landmarks used in this investigation were either on, or defined in relation to, the images of tantalum implant markers. The exceptions to this were anatomical reference points on the teeth, mandibular condyle, articular (glenoid) fossa, tongue, hyoid and cervical spine. These anatomical points are defined in Table 5.2.

5.3.2.2.3 Control points. Control points were used in the detection of incorrect superimposition on the anterior cranial base in the sequence of lateral radiographs using the 'debugging method' described by Solow and Iseri (1996). The control points were located on the endocranial outline at well defined irregularities in the occipital and frontal bones.

When all the lateral radiographs within the series are superimposed on the reference radiograph, the track of each control point is expected to follow an orderly path. If, however, the tracks of all the control points showed an identical inconsistent irregularity during the same observation period this was taken to indicate faulty superimposition (Solow and Iseri, 1996). The superimposition procedure was then repeated for the radiograph where the fault was identified *and* for the radiographs immediately preceding and immediately following. By repeating the superimposition for three radiographs the potential for bias was reduced in the re-superimposition.

5.3.2.2.3 Reference lines and planes of orientation.

Reference lines. The primary reference lines employed in the study are the implant lines that define the stable core of each skeletal unit (the mandible and the two maxillae). Implant lines in the mandible were established between two of the three implant centres. The precise choice of which depended on the radiographic view and on the location of the structure of interest. Implant lines in the maxillae were defined differently in the three radiographic views.

Table 5.2 Reference points and lines on the cephalometric radiographs

Symbol	*Definition*
Anatomical Reference Points:	
n	Nasion. The most anterior point of the fronto-nasal suture.
s	Sella. The centre of the sella turcica with mid-point of the diameter is taken with the upper limit defined as the line joining the tuberculum and dorsum sellae.)
ba	Basion. The posterior inferior point on the occipital bone at the anterior margin of the foramen magnum.
cs	Condylar summit. The most superior point on the outline of the mandibular condyle relative to the occlusal plane (OP Ref).
gs	Glenoid summit. The most superior point on the inferior contour of the roof of the glenoid fossa relative to the occlusal plane (OP Ref).
pm	Pterygomaxillare. The intersection between the nasal floor and the posterior contour of the maxilla.
tp1	The point on the outline of the dorsum of the tongue where it is intersected by a perpendicular from pm.
ra	Ramus anterior. The intersection between the occlusal plane and the anterior contour of the ramus.
hy	Hyoid. The most superior, anterior point on the body of the hyoid bone.
is	Incision Superius. The incisal tip of the most prominent upper central incisor.
ii	Incision Inferius. The incisal tip of the most prominent lower central incisor.
C1	Control point 1. Located at a distinct irregularity on the endocortical outline of the occipital bone.
C2	Control point 2. Located at a distinct irregularity on the endocortical outline of the frontal bone.
$\mathbf{CV2^{ap}}$	The apex of the body of the second cervical vertebra.
$\mathbf{CV2^{mip}}$	The mid point of the inferior surface of the body of the second cervical vertebra.
$\mathbf{CV3^{mip}}$	The mid point of the inferior surface of the body of the third cervical vertebra.
$\mathbf{CV4^{mip}}$	The mid point of the inferior surface of the body of the fourth cervical vertebra.
$\mathbf{CV5^{mip}}$	The mid point of the inferior surface of the body of the fifth cervical vertebra.
$\mathbf{CV6^{mip}}$	The mid point of the inferior surface of the body of the sixth cervical vertebra.
Implant Defined Reference Points:	
MxA	Anterior Maxillary Point. The *median implant point* on the line joining the two anterior implants in the maxillae. Surrogate point for the anterior maxilla.
MxP	Palatal Maxillary Point. The *median implant point* on the line joining the two palatal (canine) implants in the maxillae.
MxL	Lateral Maxillary Point. The *median implant point* on the line joining the two anterior implants in the maxillae. Surrogate point for the posterior maxilla.
i **1**	Anterior Mandibular Point. The implant centre of the anterior mandibular implant. Surrogate point for the anterior mandible.
i **2**	Mandibular Body Point. The implant centre of the (LEFT) mandibular body implant.
i **3**	Mandibular Ramus Point. The implant centre of the (LEFT) mandibular ramus implant.
Reference Lines:	
OPRef	The reference functional occlusal plane. A line lying at the level of "best fit" between the occlusding cusps of the first permanent molars and premolar teeth (or primary molar teeth) transferred via implants markers.
OPRef	The occlusal plane transferred from the reference film via implant markers in the mandible.
ACB	Anterior cranial base represented by stable structural details in the lateral projection of the anterior cranial fossa as defined by Bjork and Skieller (1983).
SNL	Sella-Nasion Line.The line joining the landmarks sella point and nasion.
Uma	Long axis of the upper incisor
Uia	Long axis of the upper 1st molar
Lma	Long axis of the lower 1st molar
Lia	Long axis of the lower incisor

In the lateral view they were generally established between the lateral and anterior median implant points. However, if one or both anterior implants became unstable or were lost late in a longitudinal series the palatal (canine) median implant point was used instead. In the oblique view the implant line was established between the left lateral and left palatal implant centres without reference to the anterior implants. In the frontal view the implant lines were established *across* the median suture between the centres of right and left lateral implants. It is important to note that these were *inter-osseous* implant lines joining the two maxillae. They were used primarily for measuring the width and change in width of the maxillary skeletal base in the transverse plane; and as the plane of orientation for the measurement of tooth eruption in the coronal (frontal) plane.

Planes of orientation. As explained above (Section 5.3.2.1) the primary plane of orientation was the occlusal plane defined on the occluding surfaces of the left hand posterior teeth. Because the occlusal plane is defined in relation to the teeth its orientation during growth varies in relation to the stable cores of the mandible and maxillae as well as to the more usual frame of reference - the stable structures in the anterior cranial base. For this reason the orientation of the occlusal plane was defined in relation to the stable structures in the anterior cranial base on the nominal 11 year lateral radiograph. This orientation was then transferred to earlier and later lateral radiographs by direct superimposition as described by Björk and Skieller (1983) and Solow and Iseri (1996).

For the sequence of oblique radiographs the occlusal plane on the nominal 11 year radiograph was transferred to earlier and later radiographs by superimposition separately on the implant line of each jaw for the measurement of changes within the respective jaws. This procedure leads to slight differences in the orientation of the coordinate axes between lateral and oblique radiographs other than the nominal 11 year radiographs.

Due to growth rotation of the jaws these differences in orientation will generally increase with increasing time interval between the 11 year radiograph and earlier and later radiographs. This was felt to be of importance only for the construction of curves representing the trajectories of structures over the entire observation period. That is, for the graphical depiction of velocity curves; growth tracks; and paths of eruption, migration and translocation. The direct linear measurement of the annual changes within each jaw and within each sequence of radiographs will not be effected by this. Where, however, positional changes are resolved into horizontal and vertical components slight differences will occur in the partitioning between the two coordinate axes in the earlier and later radiographs of the lateral and oblique series. The magnitude of the differences could potentially affect the detection of otherwise matching temporal patterns of growth between the two radiographic views.

For the frontal radiograph it was not possible to use the occlusal line for orientation. Instead, the plane of orientation was provided by the inter-osseous implant line between the lateral implants on the nominal 11 year radiograph. In those cases where a lateral implant was lost or became unstable the inter-osseous implant line between the palatal (canine) implants was used instead.

5.3.2.3 Data extraction and the method of measurement.

The radiographic analysis utilised several methods that were common to all three radiographic projections. There were, however, important differences in the ways data were extracted from the different radiographic views as well as the anatomical sites at which growth was examined. For these reasons a general outline of the methods is provided first followed by descriptions specific to each of the three radiographic projections and their associated longitudinal series.

5.3.2.3.1 The methods of data extraction. For each subject, the growth changes that occurred over the observation period of six years provided the data for the initial survey. For the main study the growth changes were recorded as a series of increments, one for each annual observation interval. Although the radiographs were recorded approximately annually the exact observation intervals between consecutive radiographs were calculated by subtracting the date of the radiograph at the beginning of the interval from date of the next radiograph in the sequence.

Growth data were extracted from the radiographic sequences by first identifying and marking the location of each reference point, whose growth or positional change was to be measured, in each radiograph. Where the measurement of a rotational (angular) difference was required the structure of interest was represented by a single straight line drawn through two points representing the structure. To achieve consistency in locating the same points in each radiograph of the same series, they were marked concurrently on all the radiographs of that series (lateral, frontal or oblique).

In any radiographic growth study the information of interest is contained in the *differences* between earlier and later radiographs. In the present investigation, these differences were determined by the method of superimposition in which the images of the radiographs were superimposed and the data read directly from the superimposed images. No intervening tracings were used.

The three radiographic projections were analysed separately. For the lateral radiographs a mid-sequence radiograph was used as the reference image – usually the nominal 11year radiograph. That is, the images of all earlier and later lateral radiographs were superimposed directly on the 11year lateral radiograph. This process was repeated for the 45° oblique radiographs again using a mid-sequence radiograph as the reference image matched in age to the reference image for the lateral projection. The frontal radiographs were also analysed by superimposition but the analysis was limited to the examination of changes between the two maxillae and between the maxillae and the maxillary dentition using an *inter*-osseous rather than an *intra*-osseous reference as defined above (Section 5.3.2.2.3.).

The differences in position (location) of the reference points between sequential pairs of radiographs were measured directly on the superimposed radiographs both as simple linear distances and as differences in the two co-ordinate axes. The co-ordinate axes were established on the lateral and oblique radiographs with the occlusal plane of the reference radiograph as the horizontal axis and its perpendicular as the vertical axis. For the frontal radiographs the inter-osseous implant line joining the two lateral implants on the reference radiograph was used as the horizontal axis and its perpendicular as the vertical axis.

It is important to note that it was not necessary to establish an origin for these axes as the measurements of interest (the growth changes) were the *differences* in location and/or direction relative to the site of superimposition. Not by their location or orientation or by changes in location or orientation relative to a fixed origin.

Replication of the processes of measurement. This entire process of locating the reference points, superimposing the radiographs and measuring the differences in location or orientation was then repeated without reference to the earlier data. The delay between the two occasions of measurement was a minimum of three months. The differences at each time point *between* the two series of measurements were stored and used in the assessment of the method errors. The difference between the two series of measurements at *consecutive* time points *within* each radiographic series were used in the construction of the time-series representing serial growth increments and annual growth velocities as explained in Section 4.3.2.

5.3.2.3.2 Analysis of the lateral radiographic series. The lateral radiographs were employed to examine: the growth rotations and linear growth displacements of the mandible and maxillae in the sagittal plane relative to the anterior cranial base; the translocations of the buccal teeth (represented by the first permanent molars) and incisors; the eruption, migration and angular changes of the incisors in both jaws; the growth in height of the cervical column; and the changes in the postural height of the tongue between first and last radiographs in the series.

Reference points on the lateral radiograph. In addition to the implant points on the images of the mandible and maxilla 14 anatomical reference points and a variable number of control points were located and marked on the image of each lateral radiograph as shown in Figure 5.6. The anatomical reference points are defined in Table 5.2

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Superimposition and registration of the lateral radiographs. The growth changes (or growth related changes) of interest between consecutive serial images were measured relative to superimposition on one of three anatomical sites: the anterior cranial base (ACB); the median implant line of the maxillae; and the mandibular implant line.

5.3.2.3.3 Analysis of the left oblique radiographic series. The sequence of 45° left oblique radiographs were employed to examine the pattern of growth of the mandibular condyle and the detailed patterns of eruption and migration of the buccal teeth. It should be possible to gain an accurate indication of the precise mesio-distal and vertical movements of the molars and premolars because of the largely unimpeded view of one side (left hand) of the mandible. The mandibular canines (primary and permanent) were not clearly visible in most cases and were excluded from the analysis.

Superimposition and registration of the oblique radiograph. The assessment of growth changes was based on the method of superimposition on the lateral-canine implant line of the left maxilla to examine changes in the location and orientation of the molars and premolars. In the mandible superimposition was on the body-anterior implant line for the teeth and on the ramus-body implant line for growth changes in the mandibular condyle. The regions analysed from the oblique radiographic series are shown in Figures 5.7 and 5.8.

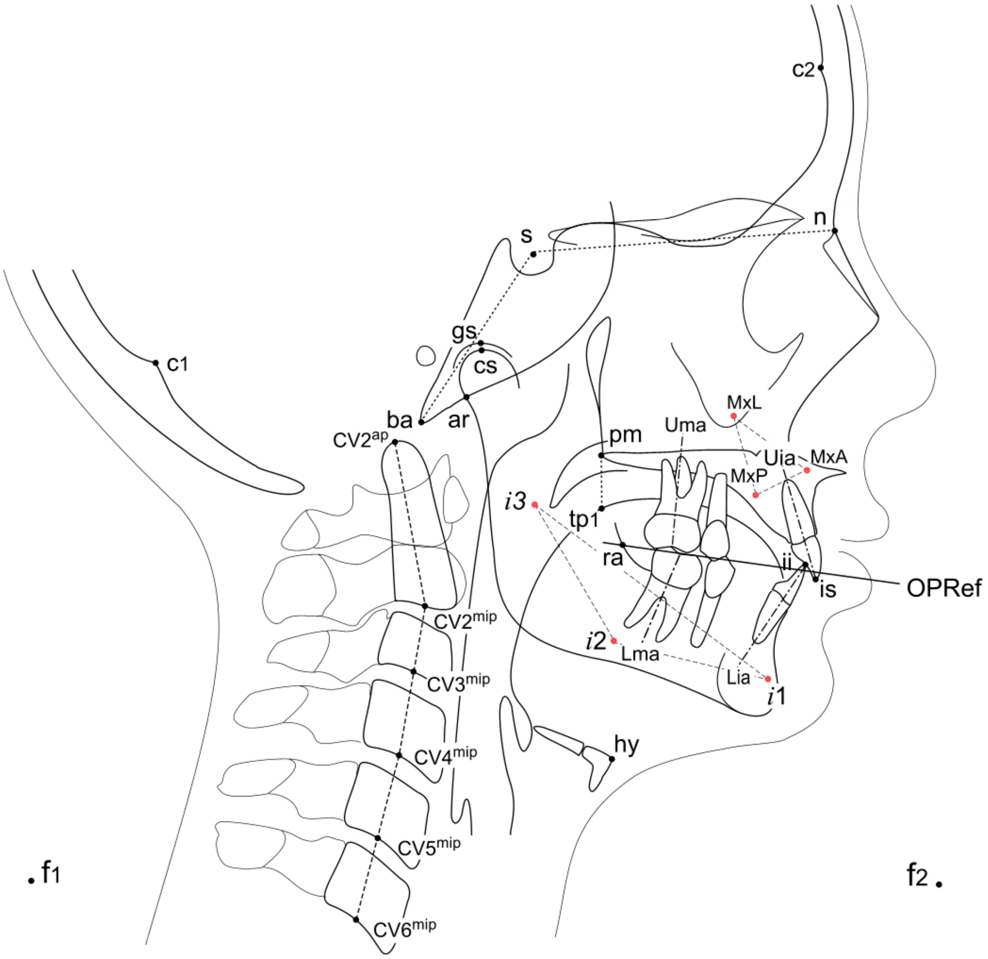

Figure 5.6 The points, lines and planes in the lateral cephalometric radiograph.

Definitions of the anatomical points, lines and planes are given in Table 5.2. The points C1 and C2, and f1 and f2 are the control points and fiducial points respectively (as defined in the text). The implant points (i2, i3), anatomical lines Uma and Lma, and the points gs and cs were also used in the analysis of the oblique radiographs.

Reference points on the oblique radiographs. In addition to the implant points anatomical points on the condylar head and glenoid fossa were identified in each image. A further series of anatomical reference points were identified on the images of the buccal teeth to provide precise location and orientation of the crown and to establish the long axis of each tooth that was consistent from radiograph to radiograph.

This posed a particular problem for the analysis of the permanent teeth in the early stages of development where the crowns were incompletely formed or where root development was only at a rudimentary stage. To overcome this the later images showing complete or more advanced development of the teeth were used to establish the long axis which was then transferred to the earlier images of each tooth by direct superimposition of the images of the crown.

A similar problem was faced in the later stages of some primary molars where the roots had undergone extensive resorption or where extensive restorations had been placed in the crowns of the teeth. As with the early developmental stages of the permanent teeth the assessment of change was carried out on the best fit of structures identifiable in successive radiographs. Consequently, the structures used to identify the crowns of the teeth often varied through the radiographic sequence. The locations of the main identifiable anatomical regions on the teeth are shown in Figure 5.8.

5.3.2.3.4 Analysis of the frontal radiographic series. The sequence of frontal radiographs were used to examine: the changes in the width of the maxillary skeletal base in the transverse plane; the mutual transverse rotation of the maxillae; and the pattern of eruption of the first maxillary molars in the coronal plane.

Reference points on the frontal radiograph. Implant points in the maxillae and were located and marked on all radiographs of the series. However, the consistent identification of anatomical points on the crowns of the teeth was not easily possible in the frontal view. Consequently, changes in the location and orientation of the crowns of the teeth were determined by direct superimposition of the images of the crowns from radiograph to radiograph. Where the internal structure of the crowns was obscured the outlines of the crowns were marked and used instead. The points, lines and measurements made are shown in Figure 5.9.

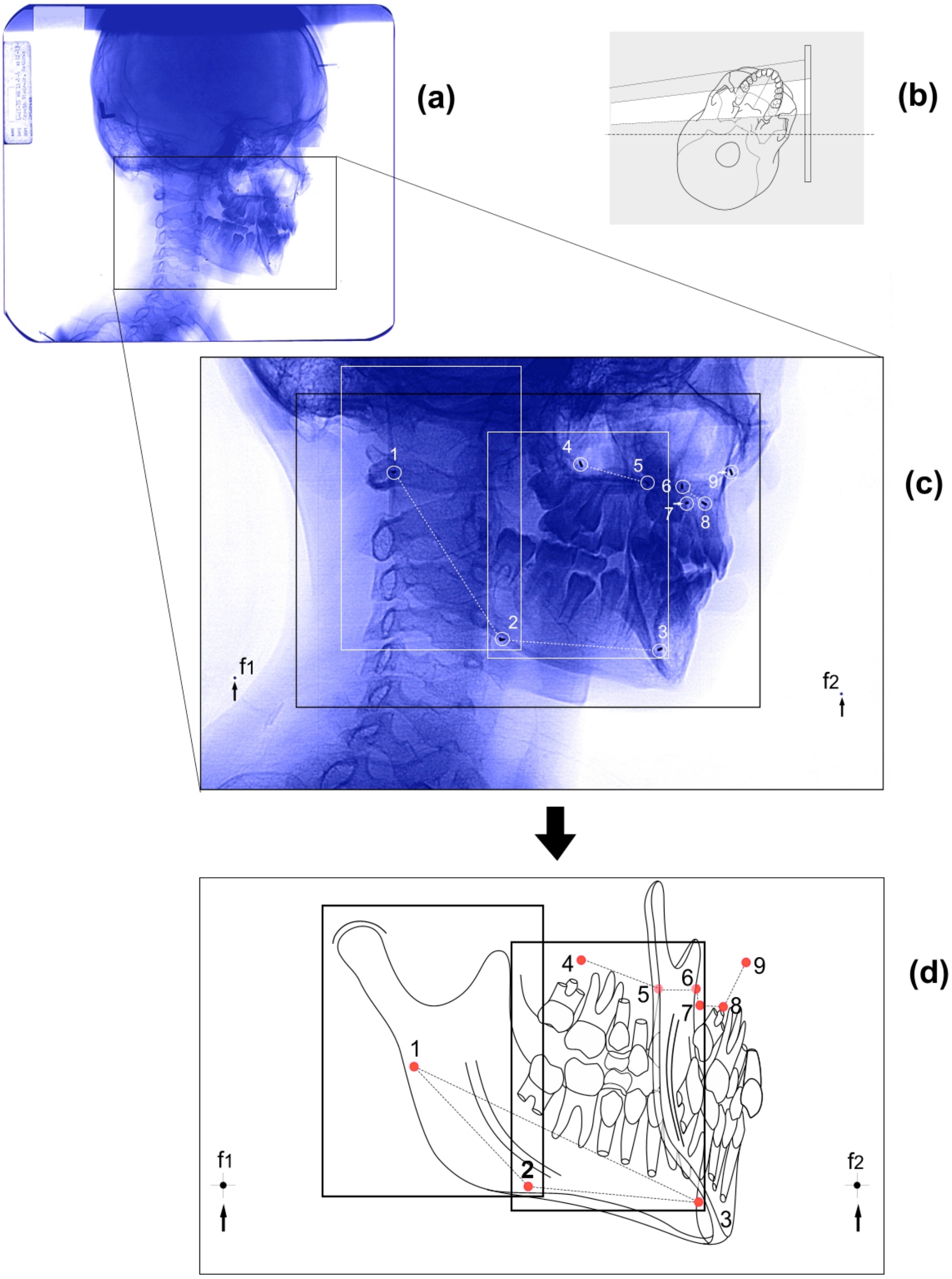

Figure 5.7 The regions analysed on the oblique cephalometric radiograph.

(a) Full 45° left oblique cephalometric radiograph. **(b)** The orientation of the head during the x-ray exposure. **(c)** Enlarged section of the film showing the regions examined in this study. The tantalum implants are numbered 1-3 in the mandible; 4-6 in the left maxilla; and 7-9 in the right maxilla; f1 and f2 are the fiducial points punched into the acetate film base. **(d)** Diagrammatic representation of the overlapping anatomical regions studied together with the implants used in the orientation.

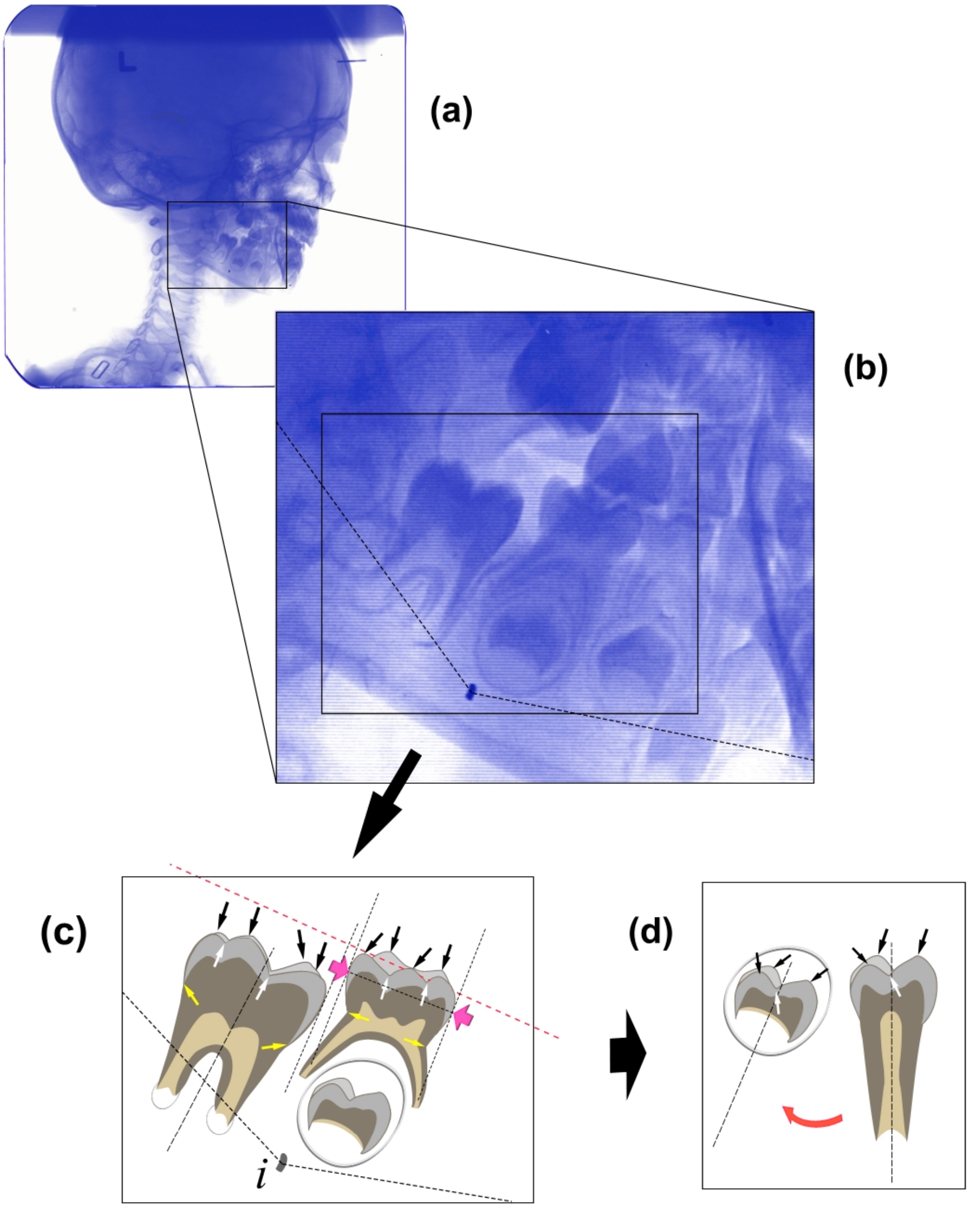

Figure 5.8 Analysis of the eruption and migration of the buccal teeth from the oblique cephalometric radiograph.

The sequence of 45° left oblique radiographs were employed to determine patterns of eruption, migration and angulation of the buccal teeth. **(a)** 45° left oblique radiograph. **(b)** An enlarged section of the radiographic image showing the mandibular buccal teeth. To provide precise locations and orientations of the crowns of the teeth (relative to the implant lines) a series of reference points were identified on the enamel outlines of each tooth. Examples of these reference points are shown diagrammatically in **(c)**. To establish the long axis of each tooth that was consistent from radiograph to radiograph it was often necessary to transfer the long axis from images showing advanced stages of dental growth to the earlier images of each tooth by direct superimposition of the images of the crown. This is shown diagrammatically in **(d)**. The black arrows indicate the tips of the identifiable cusps; and the white arrows, the inflexion of the curvature at the base of the fissures. The yellow arrows point to the mesial and distal crown-root junctions at the cementum-enamel junction. The occlusal plane is represented by the red dashed line (-----). The letter *i* indicates the mid mandibular implant (*i*2).

Superimposition and registration of the frontal radiographs. The increase in width of the maxillary arch and the movements of the maxillary buccal teeth between consecutive serial images were measured relative to superimposition on the inter-osseous implant line joining the lateral implants in the two maxillae. The point of registration was on the lateral implant for measurements of the teeth on the same (ipsilateral) side.

5.3.2.4 The variables

The variables used in this study were *change variables* describing differences in position or orientation of reference points or lines relative to a site of superimposition. Two catagories of change variables were used in this investigation: *translation variables*; and *rotation variables*. The variables used in the study are defined in Tables 5.3 and 5.4

***5.3.2.4.1 Translation variables*.** These describe the translation of a reference point usually identified by a tantalum implant relative to a reference region defined by a site of superimposition. These variables were of two types defined as either a simple linear distance between the two locations of a reference point; or as horizontal (X) and vertical (Y) displacements, where the horizontal plane is defined parallel to the occlusal plane on the reference radiograph, and the vertical plane defined as perpendicular to the horizontal plane. The partitioning of resultant vectors of displacement or growth into horizontal and vertical components allows a more meaningful comparison of changes at different sites throughout the jaws and dentition and provides for easy manipulation and statistical analysis of the variables (Schneiderman, 1992).

Horizontal displacements were designated as positive when the change was directed mesially or anteriorly and as negative when they were directed distally or posteriorly (depending on the radiographic projection). Vertical displacements were designated as positive (+ve) when the change was towards the occlusal reference plane or negative (-ve) when it was directed away for the occlusal reference plane.

***5.3.2.4.2 Rotation variables*.** Rotational variables were used to describe the angular relationship between reference lines relative to regions defined by sites of superimposition. They are expressed in degrees counted in an anti-clockwise direction with the subject facing to the right. It should be noted that for growth rotations of the jaws in the sagittal plane that this designates a forward rotation as *positive* (+ve) rather than the usual or conventional designation of negative (-ve).

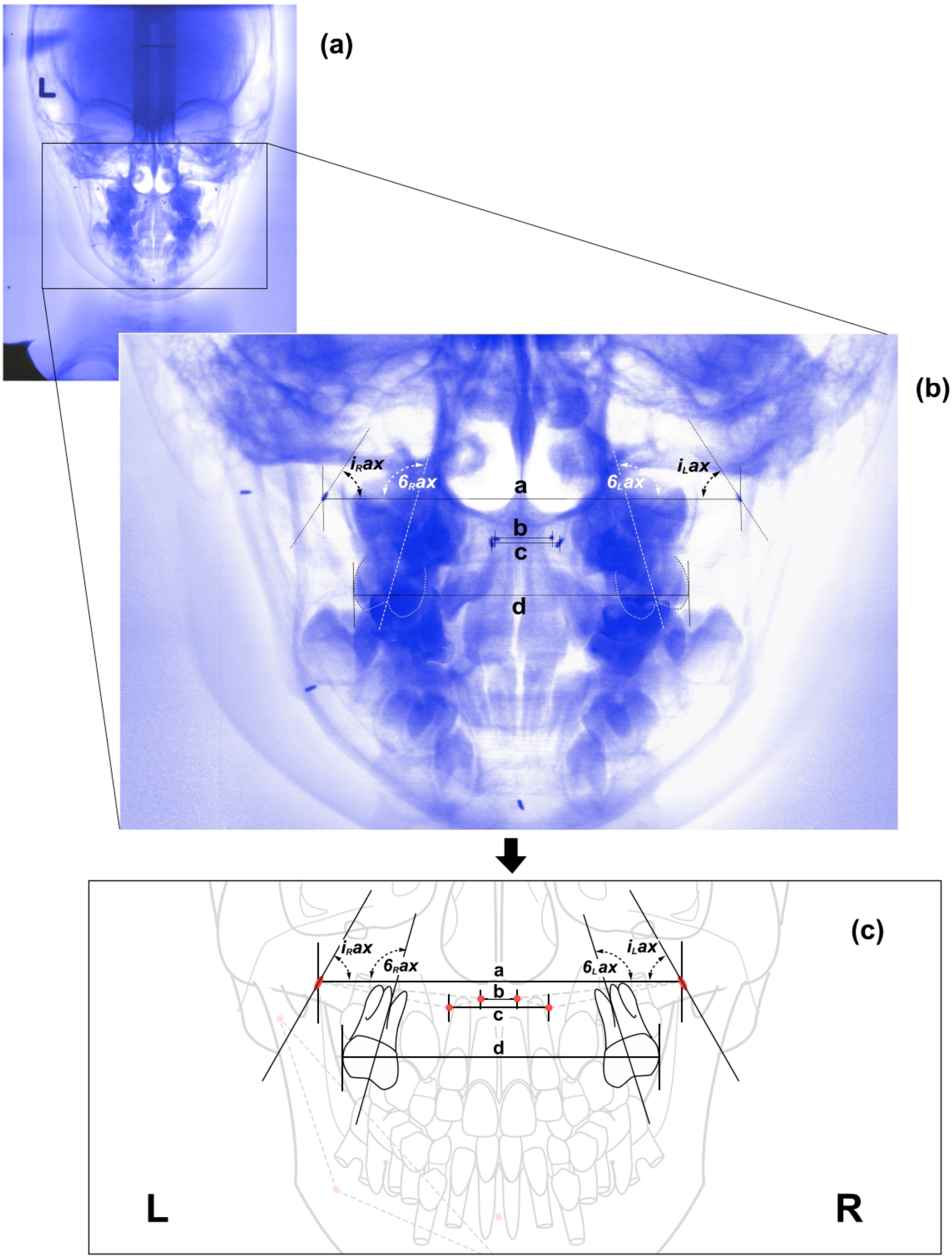

Figure 5.9 **The regions analysed and measurements made on the frontal cephalometric radiograph.**

(a) The frontal (antero-posterior) cephalometric radiograph. **(b)** Enlarged section of the film showing the regions examined in this study, which were limited to the two maxillae. **(c)** Shows a digrammatic representation of **(b)**. The lettters **a** to **d** show the trans-osseous widths between: **a**, lateral implants; **b**, anterior implants; **c**, canine (palatal) implants; and **d**, the buccal surfaces of the erupting first adult molar. The long axes of the right and left molars relative to the implant line **a**, are indicated by 6_Rax and 6_Lax resepectively. The angualtion of the long axes of the lateral implants relative to the implant line **a**, are indicated by i_Rax and i_Lax respectively.

Table 5.3 Variables examined in the Initial Survey

Code No.	*Symbol*	*Description /Designation*
01	**MGR**	Mandibular growth rotation.
02	**MxGR**	Maxillary growth rotation (in the sagittal plane).
03	**MAnt-Dir**	Mandibular growth direction (relative to ACB) measured at i1.
04	**MAnt-T**	Total mandibular growth displacement (relative to ACB) measured at i1.
05	**MAnt-V**	Vertical mandibular growth displacement (relative to ACB) measured at i1.
06	**MAnt-H**	Horizontal mandibular growth displacement (relative to ACB) measured at i1.
07	**MRamus-V**	Vertical mandibular growth displacement (relative to ACB) measured at i3.
08	**MRamus-H**	Horizontal mandibular growth displacement (relative to ACB) measured at i3.
09	**MRamus-T**	Total mandibular growth displacement (relative to ACB) measured at i3.
10	**RamusRet**	Horizontal retraction of the mandibular ramus measured at the occlusal level.
11	**MxAnt-Dir**	Maxillary growth direction (relative to ACB) measured at MxA.
12	**MxAnt-T**	Total maxillary growth displacement (relative to ACB) measured at MxA.
13	**MxAnt-H**	Horizontal maxillary growth displacement (relative to ACB) measured at MxA.
14	**MxAnt-V**	Vertical maxillary growth displacement (relative to ACB) measured at MxA.
15	**MxPost-T**	Total maxillary growth displacement (relative to ACB) measured at MxL.
16	**MxPos-H**	Horizontal maxillary growth displacement (relative to ACB) measured at MxL
17	**MxPos -V**	Vertical maxillary growth displacement (relative to ACB) measured at MxL
18	**MxMol-Ax**	Change in the inclincation of the Maxillary 1st molar axis relative to the maxilla.
19	**MxMol-T**	Total change in location of the maxillary 1st molar relative to the maxilla.
20	**MxMol-V**	Vertical change in location of the maxillary 1st molar relative to the maxilla.
21	**MxMol-H**	Horizontal change in location of the maxillary 1st molar relative to the maxilla.
22	**MxInc-ACB**	Change in the inclination of the maxillary incisor relative to the ACB.
23	**MxInc-Ax**	Change in the inclination of the maxillary incisor axis rleative to the maxilla.
24	**MxInc-T**	Total change in location of the maxillary incisor relative to the maxilla.
25	**MxInc-V**	Vertical change in location of the maxillary incisor relative to the maxilla.
26	**MxInc-H**	Horizontal change in location of the maxillary incisor relative to the maxilla.
27	**MMol-Ax**	Change in the inclination of the mandibular 1st molar axis relative to the mandible.
28	**MMol-T**	Total change in location of the mandibular 1st molar relative to the mandible.
29	**MMol-V**	Vertical change in location of the mandibular 1st molar relative to the mandible.
30	**MMol-H**	Horizontal change in location of the mandibular 1st molar relative to the mandible.
31	**M-MxMol-V**	Combined vertical changes of the maxillary and mandibular 1st molars.
32	**MInc-Ax**	Change in the inclination of the mandibular incisor axis rleative to the mandible.
33	**MInc-T**	Total change in location of the mandibular incisor relative to the mandible.
34	**MInc-V**	Vertical change in location of the mandibular incisor relative to the mandible.
35	**MInc-H**	Horizontal change in location of the mandibular incisor relative to the mandible.
36	**Cond-Dir**	Direction of growth of the mandibular condyle relative to the mandible.
37	**Cond-Mag**	Condylar growth magnitude measured as the change in location of the point cs.
38	**Glenoid-T**	Total relocation of the glenoid fossa relative to the ACB.
39	**Glen-Ang**	Direction of relocation of the glenoid fossa relative to the ACB.
40	**MxLat-T**	Change in maxillary width measured between the lateral implants.
41	**TRN-MxMol**	Horizontal change in location of the maxillary 1st molar relative to the ACB.
42	**TRN-MMol**	Horizontal change in location of the mandibular 1st molar relative to the ACB.
43	**TRN-MxInc**	Horizontal change in location of the maxillary incisor relative to the ACB.
44	**TRN-Minc**	Horizontal change in location of the mandibular incisor relative to the ACB.
45	**Hy-V**	Vertical change in location of the hyoid bone relative to the anterior cranial base.
46	**Hy-H**	Horizontal change in location of the hyoid bone relative to the anterior cranial base.
47	**Hy-T**	Total change in location of the hyoid bone relative to the anterior cranial base.
48	**Tng-V**	Vertical change in the height of the dorsum of the tongue measured at Tp1.
49	**CervSp**	Growth of the cervical spine measured as the change from CV2^{ip} to CV5(or 6)$^{mip.}$

Notes: ACB refers to the stable structures in the anterior cranial base as viewed in the lateral radiograph as defined by Björk and Skieller (1983). The 'mandible' and 'maxilla' are defined by their respective implant configurations.

Table 5.4 Variables examined in the main study

Code No.	*Symbol*	*Description /Definition/designation*
Variables expressing (mean annual) rates of change between consecutive time points		
54	**r-MGR**	Rate of mandibular growth rotation.
55	**r-MxGR**	Rate of sagittal maxillary growth rotation.
56	**r-Cond-Dir**	Rate of change in condylar growth direction.
57	**r-Cond-Mag**	Rate of condylar growth.
59	**r-MRamus-V**	Rate of vertical displacement of the mandibular ramal implant relative to ACB.
60	**r-MRamus-H**	Rate of horizontal displacement of the mandibular ramal implant relative to ACB.
61	**r-MRamus-T**	Rate of (total) displacement of the mandibular ramal implant relative to ACB.
62	**r-MAnt-T**	Rate of (total) mandibular displacement (relative to ACB) measured at the Anterior implant.
63	**r-MAnt-V**	Rate of vertical mandibular displacement (relative to ACB) measured at the Anterior implant.
64	**r-MAnt-H**	Rate of horizontal mandibular displacement (relative to ACB) measured at the Anterior implant.
65	**r-MxPos-T**	Rate of (total) displacement of the maxillae (relative to ACB) measured at MxL.
66	**r-MxPos-H**	Rate of horizontal displacement of the maxillae (relative to ACB) measured at MxL.
67	**r-MxPos -V**	Rate of vertical displacement of the maxillae (relative to ACB) measured at MxL.
68	**r-MxAnt-T**	Rate of (total) displacement of the maxillae (relative to ACB) measured at MxA.
69	**r-MxAnt-H**	Rate of horizontal displacement of the maxillae (relative to ACB) measured at MxA.
70	**r-MxAnt-V**	Rate of vertical displacement of the maxillae (relative to ACB) measured at MxA.
71	**r-MxMol-Ax**	Rate of change in the angulation of the maxilla.ry 1st molar axis relative to the maxilla.
72	**r-MxMol-T**	Rate of change in location of the maxilla.ry 1st molar relative to the maxilla.
73	**r-MxMol-V**	Rate of vertical change in location of the maxillary 1st molar relative to the maxilla.
74	**r-MxMol-H**	Rate of horizontal change in location of the maxillary 1st molar relative to the maxilla.
75	**r-MxInc-Ax**	Rate of change in the inclination of the maxillary incisor axis rleative to the maxilla.
76	**r-MxInc-T**	Rate of change in location of the maxillary incisor relative to the maxilla.
77	**r-MxInc-V**	Rate of vertical change in location of the maxillary incisor relative to the maxilla.
78	**r-MxInc-H**	Rate of horizontal change in location of the maxillary incisor relative to the maxilla.
79	**r-MMol-Ax**	Rate of change in the angulation of the mandibular 1st molar axis relative to the mandible.
80	**r-MMol-T**	Rate of change in location of the mandibular 1st molar relative to the mandible.
81	**r-MMol-V**	Rate of vertical change in location of the mandibular 1st molar relative to the mandible.
82	**r-MMol-H**	Rate of horizontal change in location of the mandibular 1st molar relative to the mandible.
83	**r-MInc-Ax**	Rate of change in the inclination of the mandibular incisor axis rleative to the mandible.
84	**r-MInc-T**	Rate of change in location of the mandibular incisor relative to the mandible.
85	**r-MInc-V**	Rate of vertical change in location of the mandibular incisor relative to the mandible.
86	**r-MInc-H**	Rate of horizontal change in location of the mandibular incisor relative to the mandible.
87	**r-M-MxMol-V**	Rate of vertical changes of the maxillary and mandibular 1st molars combined.
89	**r-MxTRA-Lat**	Rate of change in maxillary width measured between the lateral implants.
90	**r-MxTRot**	Rate of transverse maxillary growth rotation.
91	**r-TRN-MxMol**	Rate of change in location of the maxillary 1st molar relative to the ACB.
92	**r-TRN-MMol**	Rate of change in location of the mandibular 1st molar relative to the ACB.
93	**r-CervSp**	Rate of vertical growth of the cervical spine measured from CV2^{ip} to CV5(or 6)$^{mip.}$

Notes: ACB refers to the stable structures in the anterior cranial base as viewed in the lateral radiograph as defined by Björk and Skieller (1983). The 'mandible' and 'maxilla' are defined by their respective implant configurations.

5.3.2.5 Variable Transformations

Although the radiographic records of the Mathews UCSF Growth Study were collected annually the actual time interval between successive radiographs varied within and between the individual children enrolled in the study. It was necessary therefore to standardise the change variables to ones expressing the rate of change per unit time (annualised change variables). In transforming the variables in this way, the behaviour of each variable was assumed to be approximately linear over the time interval between the films. This is almost certainly wrong for many, possibly all variables examined in the study. As a consequence some information will inevitably be lost by standardising the data in this way, but it permits the observations to be grouped in a manner that allows statistical comparisons between the patternings of the data series. The transformation of the *change variables* (translation and rotation variables) to variables expressing standardised rates of change is described in Chapter 6.

5.3.2.6 Data Verification

A number of procedures were used to verify the accuracy and quantify the amount of error in the data sets. These procedures, designed to maximise the reliability of these data, were performed at various stages in the collection and subsequent processing of the raw measurements.

***5.3.2.6.1 Data acquisition**.* The coordinate data from the radiographic images were plotted and related points on the same radiograph were connected using colour-coded lines. Composite plots of the data were used to visualise serial changes in the structures of interest relative to the various sites of superimposition. For each individual subject the plots indicate graphically the 2-dimentional direction and amount of change that had occurred.

These composite plots serve two functions: first, they allow a comprehensive picture of morphological change within and among the various regions of the craniofacial complex to be gained – a ‘picture’ that would not be available when dealing just with numerical data; secondly, they provide a guide to the accuracy of the quantitative data by highlighting biologically impossible or implausible changes. Examples of the composite plots are shown in Figure 5.10.

When biologically impossible or implausible changes were identified the data points were relocated (*without* reference to the suspect data) and the radiographs were resuperimposed. This procedure allowed the identification and correction of gross blunders. More subtle errors were identified and corrected using the *control points* located at the periphery of the skull as described in Section 5.3.2.2.3. This form of "debugging procedure" originally developed by Solow and Iseri (1995) is primarily aimed at detecting errors or inconsistencies of superimposition but also allows the detection of errors and inconsistencies of landmark location.

5.3.2.6.2 Verification of numerical data. The numerical values of each variable were plotted graphically as a simple scatterplot for visual examination to identify values possibly read or calculated incorrectly. Where extreme values or 'outliers' were detected the original calculations were repeated and checked. In the case of the raw data from the main study (in which duplicate measurements were made of all variables) the differences *between* duplicate measures were also examined to detect deviant values (Pritchard, 2001). Where obvious gross blunders had occurred or where doubt existed a *single* new measurement was made. This was then paired with the value from the two original duplicate values to which it was most similar to form a new duplicate pair.

5.3.3. The Practical Measurement Procedure

Throughout this investigation the location and marking of the points and lines and the superimposition of the radiographic images were carried out on desktop computer using the computer graphics program *CorelXara* (Corel Corporation, Ontario, Canada).

The landmark and superimposition data were transferred to *Image Tool version 3* (University of Texas Health Sciences Center, San Antonio, Texas, USA) where all linear and angular measurements were made. The resulting metric data were transferred to the various statistical analysis programs and to *Microsoft Excel* (Microsoft Corporation, Redmont, USA) for tabulation.

To prevent spurious correlations induced by mathematical coupling (Archie, 1981) or regression-to-the-mean (Blomqvist, 1977; Andersen, 1990), and to avoid topographical correlations, all reference points and landmarks were located, recorded and measured separately and, as far as possible, independently on each occasion that a measurement was to be made involving that reference point or landmark. In addition, separate superimpositions of the images were performed for the duplicate measurements of each variable for the reasons outlined in Section 4.3.2. To this extent, the random errors involved in location and measurement were not shared by any of the variables.

For each radiographic projection there were multiple, often quite similar, radiographs for each subject. The potential for confusion and misidentification of the radiographic images and their position in the temporal sequence was reduced during superimposition and measurement by attaching a colour-coded marker to each radiographic image. Identical colour markers were used for lateral, frontal and oblique radiographs that were recorded on the same date. The various points, lines and planes were also marked on the images with the colour specific to the date of that image. This colour coding allowed the correct sequence of growth changes to be identified more easily and permitted the visual tracking of changes throughout the radiographic sequences. Examples of the colour coding are shown in Figure 5.10.

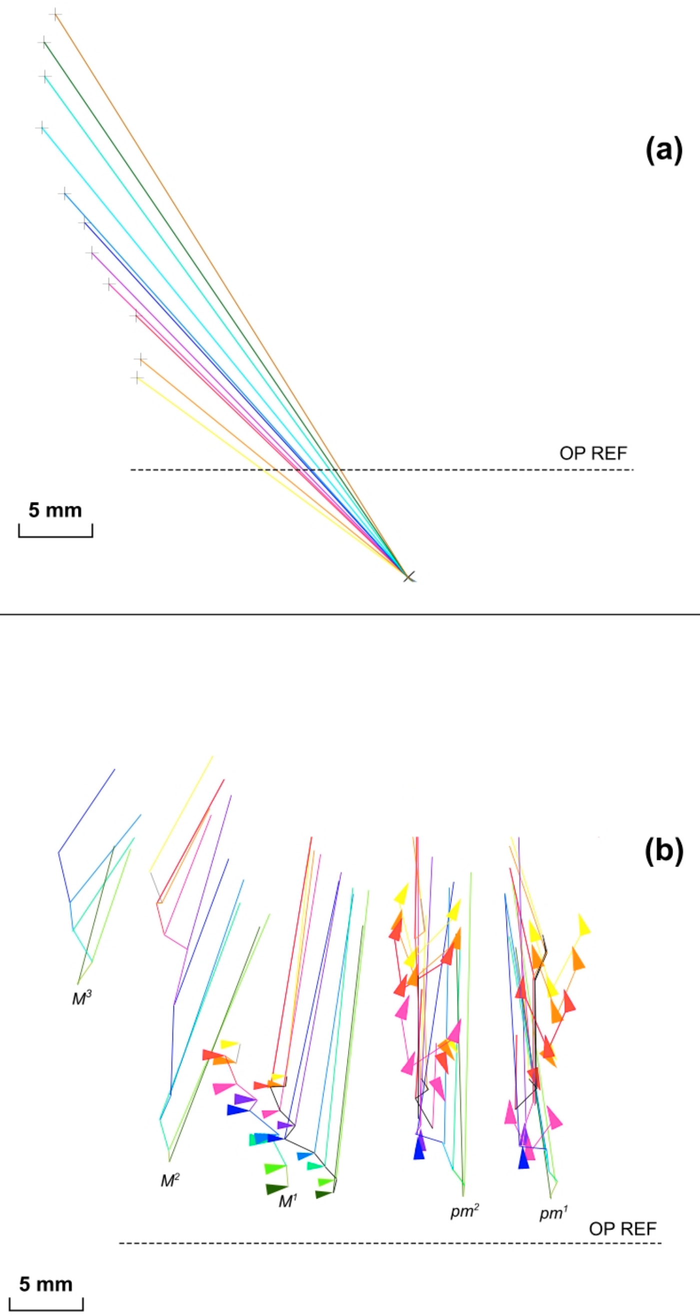

Figure 5.10 Examples of the composite plots and colour coding used in the analysis of the radiographic growth sequences.

(a) Shows the colour-coded lines between the ramal implant and the condylar summit relative to superimposition on the mid-body to ramal implant line used in the measurement of the growth track of the condyle. **(b)** Shows a composite plot of the intra- and supra-osseous eruption of the maxillary buccal teeth. The colour-coded lines are the long axes of the teeth; the arrow-heads mark the location of anatomical reference points on the crowns of the teeth. The colours are specific to points and lines measured on radiographs recorded on the same date for that subject and follow a specific sequence. OP REF is the occlusal plane reference.

CHAPTER
6

DATA ANALYSIS: STATISTICAL METHODS AND ERROR ANALYSIS

6.1 STATISTICAL METHODS

6.1.1 The Initial Survey: Exploratory Correlation Analysis

6.1.1.1 Descriptive Statistics

Standard descriptive statistics for the whole sample were calculated for each variable at the two time-points (initial and final radiographs) and for the changes in those variables variable during the observation period. For data that followed a normal (Gaussian) distribution standard descriptive statistics of sample mean, standard deviation, variance, standard error of the mean, and 95% confidence interval were used. Where data were not normally distributed the median, inter-quartile range and 90-percentile confidence intervals were used.

6.1.1.2 Correlation Analysis

Correlation analysis was used to examine and assess the strength of the relationships between variables of interest. The analysis was not aimed at producing a classical correlation matrix containing all possible correlations for all variables. It was instead designed to assess the correlations between an *index* variable and variables expressing: linear (translational) growth displacement of the jaws; tooth eruption; tooth migration; and tooth translocation. Two index variables were selected, one to represent rotational growth of the jaws (*MGR*) and the other to represent general somatic growth (*CervSp*).

All variables were examined for normality using the Shapiro-Wilks test and the bivariate relationships between the index variables and each of the other variables were plotted graphically and examined for approximate linearity. However, because one of the primary reasons for assessing these correlations was to allow comparison with the findings of the classic studies of Björk and Skieller (1972, 1983) the Pearson correlation was used even where the underlying assumptions (normality and linearity) were not met. In this respect it is important to note that data were presented and analysed without adjustment. That is, outliers were not removed before the calculation of the Pearson correlation (***r***) and in some cases this will have spuriously inflated the correlation. Where this was suspected the Spearman Rank correlation was also calculated.

6.1.1.3 Correction for Multiple Comparisons and Simultaneous Inference

The level of statistical significance (*p*-values) associated with each correlation is valid only for single inference. Where correlations are calculated between many different variables, on average, 5% of the correlations will have associated *p*-values *less* than 0.05 by chance alone even where no correlation truly exists. A common way to account for this is to apply a *Bonferroni correction* where the critical *p*-value for the acceptance of statistical significance is set in relation to the number of tests – in this case, the number of correlations – to give an overall false-positive probability ($\hat{p}$) of 0.05. The equivalent process is to adjust the original, raw *p*-values by multiplying each one by the number of tests to give the *Bonferroni-corrected p-values* which are then compared to the conventional $p \leq 0.05$ threshold (or ≤ 0.01; ≤ 0.001 as the case may be).

The Bonferroni correction, however, is extremely conservative because it does not take into account the dependence structure of the data. That is, it assumes that all the tests are statistically independent, which is not the case in this study - because the correlations were calculated using the same set of measurement data.

6.1.1.4 Correction for the dependence structure of the data

To take account of the dependence structure of the data the Bonferroni correction can be modified using the effective number of *independent* tests rather than the overall number of tests. This makes the Bonferroni correction less conservative and at the same time reduces the false-negative error rate. The effective number of independent tests was estimated from the average absolute correlation between the analysed variables (Garcia 2004). This was implemented using the statistical program SISA (Garcia, 2004; Uitenbroek, 1997).

6.1.1.5 Statistical Families and the levels of inference.

A set of hypotheses to be considered jointly is referred to as a 'family'. Although a family will often include all hypotheses to be tested in a given study, hypotheses tested in large studies (such as the present study) and are usually divided into subsets of separate families for separate error control.

Family 1. This family comprised the tests of the correlations between the mandibular growth rotation and all other anatomical variables. These tests were considered jointly and the threshold for statistical significance was set at the level for multiple inference.

H0=0, there is no correlation between the variable expressing mandibular growth rotation and the variables expressing growth and positional change at anatomical sites throughout the face and dentition (48 tests).

Family 2. This family comprised the tests of the correlations between general somatic growth (as expressed by the vertical growth of the cervical spine) and all other anatomical variables. These tests were considered jointly and the threshold for statistical significance was set at the level for multiple inference.

H0=0, there is no correlation between the variable expressing between general somatic growth and the variables expressing growth and positional change at anatomical sites throughout the face and dentition (48 tests).

In testing these null hypotheses it is important to keep in mind that the Pearson Correlation (***r***) only assesses the strength of the *linear* relationship between the variables while the Spearman's rank correlation coefficient (r_S) assesses the more general *monotonic* relationship between the variables.

6.1.2 The Main (Time-Series) Study

6.1.2.1 *Preliminary Analysis*

The measured values of the annual growth increments bear an uncertain relationship to the true values because they are contaminated with random measurement errors[¶] that obscure the true values of the increments. The major challenge posed by these errors is the induced negative serial correlation between neighbouring increments (van der Linden *et al.*, 1970; Lampl, 2002). This has been dealt with by the way in which the raw data have been compiled into the incremental sequences (Section 4.3.2). There remains, however, the uncertainly associated with the value of each individual increment and the way in which this affects the reconstructed temporal patterning of growth. That is to say, the way in which the measurement errors influence the shape of the growth velocity 'curve', which is the main target for later analysis.

6.1.2.1.1 Assessing the Statistical Significance of the Measured Increments of Growth. To ensure that the temporal pattern of growth reflects reality as far as possible account must be taken of the uncertainty ('errors') involved in the recording of the increments of growth. There are two questions that arise. First, is each measured increment significantly different from zero? That is, has any growth actually occurred during each annual observation interval? Secondly, does this increment differ significantly from the adjacent increments – is growth rate increasing, decreasing or remaining flat?

Questions about the rate of growth cannot be answered by examining only the magnitude of the increments but must also take into account the actual length of each observation interval, which differs slightly from year to year. However, if the measured increments of growth are first standardised or 'scaled' in relation to the observation interval the effect of the random measurement errors cannot be easily assessed or addressed (Taylor, 1997). Consequently, the former question must be addressed first. This was done using the method described by van der Linden *et al.,* (1970) and modified for the detection of discrete growth events by Lampl (2002). In this method, each measured increment for each growth variable is subjected to statistical analysis to establish with

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[¶] Only the random component of error is considered here because any systematic measurement error is assumed to be the same (that is, provide a constant measurement bias) for all measurements of the same growth variable. Even though such a bias might be different for different variables.

a high level of probability that it represents a change due to growth rather than an error of measurement.

This is an incremental analysis of each *individual's* data designed to identify significant differences from zero only when those differences exceed an *a priori* level (Lampl and Johnson, 1998; Lampl, 2002). If this threshold level is not exceeded the value of the increment is deemed to be zero (that is, no growth had occurred during this observation interval). This level was set at the 90% confidence limits calculated using the SD of the random errors of measurement (σ_{ie}) and employing the *t*-statistic (two-tailed $p \leq 0.1$) as opposed to the more usual *z*-statistic and thereby accounting for the small sample size. Consequently, where the measured magnitude of an increment lies outside these confidence limits it will have a probability of approximately 1 in 10 (or less) that it represents a chance event rather than a real (significant) growth change.

The 90% confidence limits were calculated by the following formula:

$$90\%\ \textit{confidence limits} = \pm\, t_{(P=0.1;\ df=n-1)}(\sigma_{ie})$$

Where: $t_{(P=0.1;\ df=n-1)}$ is the *t*-statistic for p=0.1 with n-1 degrees of freedom;
n is the sample size;
σ_{ie} is the random error of measurement of the growth increment.

The same procedure was applied to identify significant differences between adjacent increments. This was done by examining sequential increments in pairs, again setting the threshold for acceptance of a real difference at the 90% confidence limits calculated from the SD of the random errors of measurement (σ_{ie}). If this threshold level was not exceeded the value of the later increment was deemed to be the same as that of the preceding increment. That is, the increments of growth were deemed to be the same during the two adjacent observation intervals and the mean of the two increments was used as the value for both.

Remarks. First, it is important to note that for several variables a 'growth change' could be either negative or positive. This 'test' is therefore two-tailed. Secondly, as Lampl (2002) and Lampl and Johnson (1995) indicate, this type of approach to the analysis makes no assumptions about the underlying temporal processes of growth, and is relatively robust to non-normal data.

6.1.2.1.2 The temporal patterning of growth: construction of the discrete time-series. The preliminary analysis described in the previous Section focuses on establishing a reliable statistical estimate of the individual increments of growth. However, variations in the length of the sampling interval (the time between the recording of the radiographs) complicates the analysis of the resulting sequence of validated increments. This is because the growth velocities between the recordings of the increments and the slopes of the transitions between increments depend on the lengths of the observation intervals. To avoid this problem the measured increments of growth were averaged over the time intervals during which they had occurred to provide a sequence of mean (annualised) growth velocities. For each variable, the chronological sequence of growth velocities formed a discrete time-series representing the temporal pattern of growth activity at each site.

The sequence of stages in the construction of the discrete time-series beginning with the raw (measured) increments of growth are shown diagrammatically in Figure 6.1.

6.1.2.2 *Growth Pattern Analysis*

The *within-subject* associations between these discrete time-series were investigated using methods drawn from statistical pattern analysis and non-linear time-series analysis to characterise the patterns of growth and to detect the presence of synchrony between the patterning of growth changes at the different sites.

6.1.2.2.1 Detecting synchrony between the discrete time-series. The fundamental assumption underlying the analysis of the main study is that the co-ordination of growth between the different (hard tissue) regions of the face will be reflected in the synchronous patterning of growth between those regions. In its classical sense, the term ‘synchronous’ refers to the coincidence of the rhythms or oscillations of two or more systems or processes (Varela *et al.,* 2001). The presence of synchrony between two systems (in this case, the anatomical units of the craniofacial complex) is indicated by the closeness of the match between the time-series representing observations on those systems (Rosenblum, *et al.*, 2001). This is formally assessed by a task specific ‘similarity measure’ or ‘distance metric’ (Lee *et al.,* 2002).

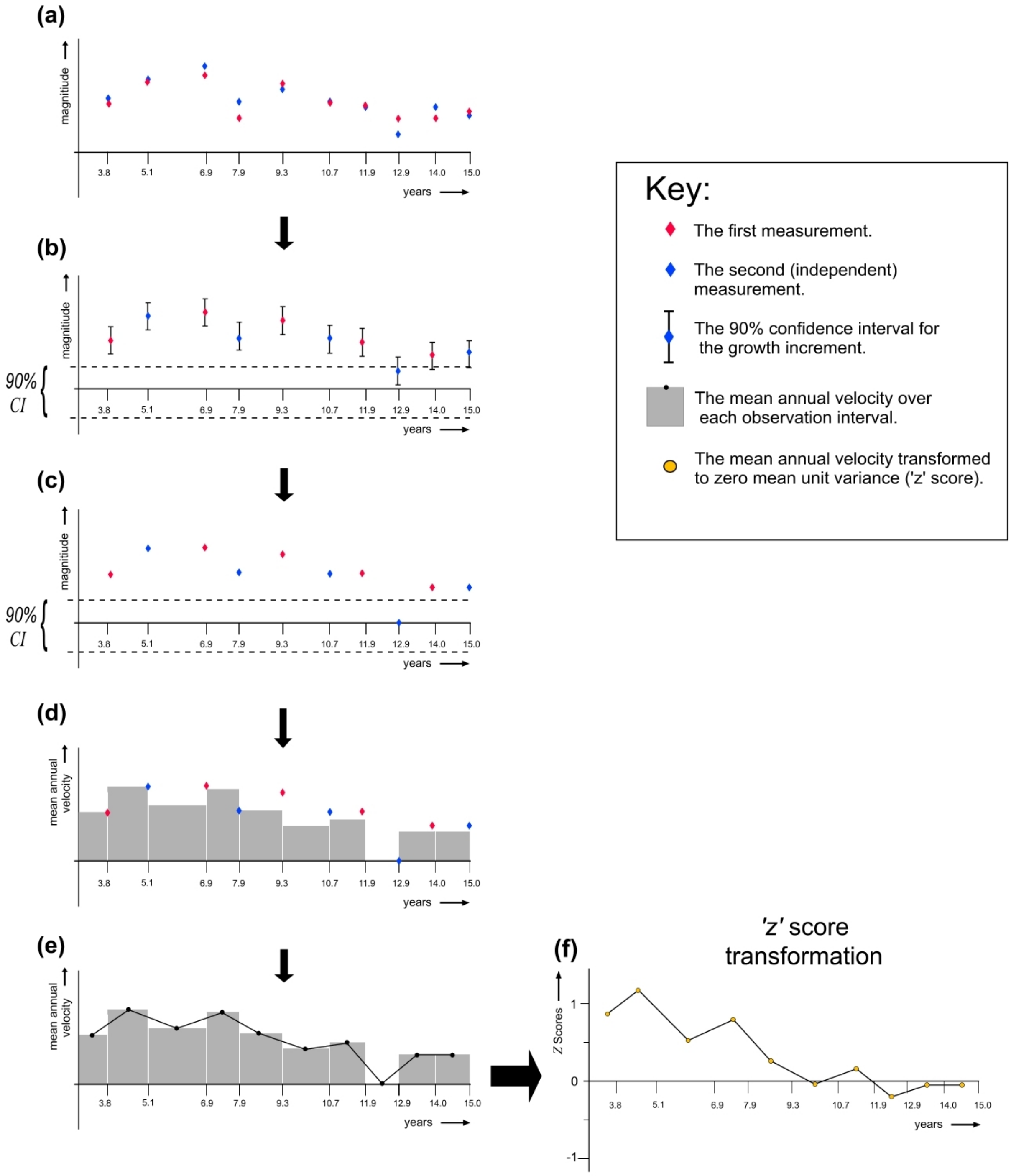


Figure 6.1 The sequence of the stages in the construction of the discrete time-series.

The figure shows a graphical representation of stages in the construction of the discrete time-series of a growth variable for a typical subject. The horizontal axis of each graph indicates the chronological age of the subject at the recording of each radiograph (the beginning and end of the intervals over which the increments were measured). **(a)** The two independent series of measurements of the increments of growth at each time-point. **(b)** At each consecutive time-point the value of the increment is selected from a different (alternate) series of measurements. **(c)** The values of adjacent increments are assessed in relation to the 90% CI based on the 'random' measurement error. **(d)** Calculation of the mean (annual) growth velocity for each observation period (the time between the recording of consecutive radiographs). **(e)** The mean velocity is re-plotted at the mid-point of each observation interval and transitions between adjacent data points are defined as straight lines. **(f)** To test for synchrony between growth displacements at different sites the sequences of mean velocities are transformed to zero mean and unit variance ('z' scores).

Traditionally, Euclidean distance or the Pearson correlation coefficient are used as the measure of similarity between time-series (Lee *et al.,* 2002; Floratou *et al.,* 2010). However, these measures are unable to take into account the temporal order of the samples forming the time-series or the variations in the length of the sampling intervals, and they generally require many hundreds or thousands of data points (Moller-Levet *et al.*, 2003; Lee *et al.,* 2002). These features make the traditional measures unsuitable for the detection of synchrony in the present study.

In the present application there were six primary requirements of the similarity measure and the match it produces.

1). It must be insensitive to the absolute values and to different scales.
2). It must be insensitive to variations in the sampling interval.
3). It must be sensitive to the relative values or variations within each time-series.
4). It must be sensitive to the temporal order of the data points.
5). It must be tolerant of measurement error (observational noise).
6). The match must be amenable to statistical validation with the ability to account for autocorrelation within the series.

Based on these requirements the short time-series distance (STSD) was selected as the similarity measure (Moller-Levet *et al.*, 2003). This is given by the following equation:

$$d^2_{\mathrm{STS}}(x,v) = \sum_{k=0}^{n_t-1} \left(\frac{v_{(k-1)} - v_k}{t_{(k+1)} - t_k} - \frac{x_{(k-1)} - x_k}{t_{(k+1)} - t_k} \right)^2$$

where $d^2_{STS}\ (x,v)$ is the STSD score between two time-series x and v; n_t is the number of time points; $t_{(k-1)} - t_k$ is the time interval between two successive time points; $v_{(k-1)} - v_k$ and $x_{(k-1)} - x_k$ are the corresponding changes over the time interval for the respective time-series. In the present application, the expression in parentheses is the difference in growth velocity between the two variables forming the time-series over the time interval.

The STSD allows the identification of matching patterns in the time-series by the relative linear changes in growth and growth related activity between time points as well as their temporal order. This measure is, however, highly sensitive to the absolute values of the data. To remove this sensitivity a z-score standardisation or normalisation of each series (to zero mean and unit variance) is required prior to identifying synchronous patterns (Everitt, *et al.*, 2011). This standardisation was achieved using the following equation:

$$z_i = \frac{(x_i - \bar{x})}{s_x}$$

where z_i is the z-score of the ith time point (x_i) of the time-series x, and where $\bar{x}$ is the mean and s_x is the standard deviation of all time points $x_1 ,\ldots\ldots, x_n$ in the time-series.

6.1.2.2.2. *Identifying sites with synchronous patterns of growth.* The STSD measure was applied separately to each individual's data (in the form of standardised growth variables) to identify those variables whose time-series exhibited synchrony *within* each individual subject. Although the primary purpose of the growth pattern analysis was to identify anatomical sites whose growth patterns were synchronous with that of growth rotation of the jaws, the analysis also sought to identify sites where the pattern of growth was synchronous with general somatic growth as had been done in the initial survey.

6.1.2.2.3 *Growth pattern index variables.* To identify significant growth patterns it was necessary to select representative growth variables as 'growth pattern indices' (index variables) against which synchrony of other growth variables could be comparably measured for all subjects. Two indices were required: one expressing growth rotation of the jaws; the other expressing general somatic growth. The time-series variables corresponding to the index variables in the initial correlation survey were selected as the growth pattern indices for the main study (*r-MGR*; and *r-CervSp*)

6.1.2.2.4 Assessing the statistical significance of the similarity scores as an indication of synchrony. While similarity measures or distance metrics provide an assessment of the match between 'data objects' they do not generally allow a test of the statistical significance of the match. Traditionally, the main difficulty with deriving formal significance tests is determining the sampling distribution of the similarity measure used (Everitt, 1979). Recently, however, permutation based tests have become widely available that allow the sampling distribution to be determined by resampling or permuting the original data (Davidson and Hinkley, 1997; Sham and Purcell, 2014). This type of computationally intensive method was used to provide a statistical test of the degree of similarity between the time-series representing growth patterns within each subject.

The permutation method used was the *resampling permutation* (Berry *et al.*, 2016) sometimes also known as a 'bootstrap permutation' (Good, 2005) in which the data points within each time-series are randomly permuted ('shuffled') multiple times and the similarity measure calculated between each permuted series and the index variable. Although this procedure is highly effective in determining the statistical significance with conventional samples where the data values are independent it fails to produce valid significance levels where there is *dependence* between the values (Lahiri, 2003).

The reason for this dependence is the autocorrelation ('self-correlation') within each series where values measured close together in time are more alike than those measured further apart in time (Houston, 1983). Randomly permuting or 'shuffling' the data points within each series destroys the autocorrelation of the original series leading to spuriously inflated levels of statistical significance.

To overcome this problem it is necessary to randomise the data points within each time-series in blocks of contiguous values (Belmonte and Yurgelun-Todd, 2001; Kreiss and Lahiri, 2012). A *moving block* resampling procedure (Bühlmann and Künsch, 1995) using overlapping blocks of two consecutive data points (Hall *et al*., 1995; Bühlmann and Künsch, 1999) was used to provide the (single inference) statistical significance of the STSD scores.

For each variable 20,000 random block permutations of the time-series were carried out and the STSD score between the growth pattern index and each permuted time-series was calculated using a histogram of the frequency distribution of the scores. The histogram was plotted using a bin width of 0.5 between zero and the maximum value (~50) of the STSD scores. The empirical probability for the (unpermuted) STSD scores was then determined by comparison to this reference distribution (the sampling distribution under the null hypothesis). This procedure was repeated for each variable with both indices to provide the probabilities *(p)* under the null-hypothesis of no similarity between each index and the other time-series measured in pairs (Good, 2006).

This procedure is designed to detect synchronous patterning of growth between the time-series of the index variable and the time-series of other variables. The results of the Initial Survey, however, indicated several variables were likely to have patterns of growth that were inverted relative to the index variables.

The challenge in detecting synchronicity between the index variables and inverted temporal patterns of growth was to avoid doubling the number of tests and thereby raising the critical threshold for the acceptance statistical significance. This was overcome by plotting and viewing the time-series and by examining the unadjusted probabilities of the STSD scores. For those variables where there was a high *a priori* likelihood of an inverted growth pattern the test was run with the signs (+ or -) of the differences reversed. For other variables (without any prior expectation of an inverted pattern of growth) the detection of an inverted temporal pattern of growth was based on the *p*-value of the STSD score. Where $p \geq 0.975$ the growth was deemed to be inverted relative to the index and the STSD score was recalculated with the signs of the differences reversed and the new *p*-value assigned to the match.

The resulting *p*-values (for all variables) were used in the calculation of the adjusted $\hat{p}$-values within each subject prior to the multi-subject group analysis of synchrony as indicated in the next section.

Correction for multiple testing under dependency. The single inference probabilities do not take into account the simultaneous inference from multiple tests nor the degree of dependence between those tests. It was necessary therefore to adjust the single inference probabilities to account for multiple testing under dependency. This was carried out using a variation of the permutation method known as a '*Step down minP-adjusted P-value procedure'* (North, *et al.*, 2002; Becker and Knapp, 2004; Zhu, 2005).

In this method, the data values of all time-series to be tested simultaneously are shuffled (permuted) within each time-series and the tests recalculated on the shuffled data set. This procedure is repeated many times and on each occasion the *minimum p*-value in the set of simultaneous tests is recorded. An empirical frequency distribution of these minimum *p*-values is then constructed and the *p*-values calculated for single inference (as detailed above) are compared to this distribution to determine the empirically adjusted *p*-values. For each of the original tests, the adjusted p-values ($\hat{\boldsymbol{p}}$) is determined from the proportion of minimum *p*-values in the distribution that are *smaller* than the *p*-value from the actual data set using the following formula (North *et al.*, 2002, 2003; Davison and Hinkley, 1997):

$$\hat{p} = (r + 1)(n + 1)^{-1}$$

Where *r* is the number of minimum p-values that are *smaller* than the single inference *p*-value; and n is the total number of permutations used to construct the empirical frequency distribution (North *et al.*, 2002, 2003; Davison and Hinkley, 1997). In the present study 20,000 permutations were used in the construction of the empirical frequency distribution for the calculation of the $\hat{p}$-values with each growth pattern index.

Minimising the number of simultaneous tests. The adjusted p-value ($\hat{p}$) for a given STSD score is inversely related to the number of simultaneous tests. Large numbers of tests reduce the likelihood of detecting statistically significant matches among those tests. It was therefore important to keep to a minimum the number of variables whose time-series were examined for statistical significance. This was achieved in two ways: 1) by removing variables where the analytical uncertainty measured as the standard deviation of the random error was of the same order as the mean annual increment in the initial study. This led to the removal of the hyoid, glenoid fossa and tongue posture variables; 2) The removal of redundant or potentially redundant variables and those formed as ratios or differences with high *a priori* dependence. Horizontal and vertical variables were retained for all sites but the growth directions at the same anatomical sites were removed with the exception of the directional change of the mandibular condyle. In these ways the number of variables to be tested against the index variables was reduced from a total of 48 to 38. The variables used in the growth analyses are shown in Tables 5.2 and 5.3.

6.1.2.3 *Accounting for incomplete and missing data*

The STSD scores and their associated probabilities vary with the number of time points in each time-series. Where data points are missing from one series but not from others the global threshold for statistical significance as well as the *p*-value assigned to the match will be altered. There are broadly three statistical approaches to handling incomplete or missing data: (i) eliminate bands or samples with missing data; (ii) assign values to missing data; or (iii) ignore the problem if the missing data constitute less than an arbitrarily chosen proportion of the data set. (Schlüter and Harris, 2006). The approach taken in the present study was a combination of all three methods depending on the nature of the missing data.

There were two primary reasons for incompleteness of a data series: implant loss or instability; and, in the case of tooth eruption and migration, that the tooth was pre-functional (that is, it had not yet reached the point of occlusal contact) and was not therefore included in the comparisons with other variables.

6.1.2.3.1 Missing data due to implant loss or instability. Early implant instability or loss (in sites where only a single implant was placed or where no alternative implant existed) will have led to the rejection of that particular subject from inclusion in the study. Consequently, only loss of an implant late in the series has been tolerated. However, this made it impossible to accurately determine the mutual transverse rotation of the two maxillae in the final observation intervals of 9 of the 11 subjects in the sample.

6.1.2.3.2 Missing data due to pre-functional positions of the teeth. Missing data due to the pre-functional positions of the teeth affected only a few teeth in subjects number 1 and 3. Because this affected only one data point in two series and two data points in one series respectively, the missing data were ignored and the analysis of synchrony was based on a slightly shorter time-series in each case. The affect this has on the analysis will depend on whether or not synchrony actually existed between growth at the anatomical sites represented by the time-series. If it did not exist the absence of the data points will not have altered the result (the true negative level will be the same). However, if synchrony did exist, the missing data (in the absence of measurement error) will have reduced the likelihood of detecting that synchrony (increased the false-negative level). While both effects will influence the intra-individual analyses their influence on the global (multi-subject) analysis was felt to be of minor importance and unlikely to affect the detection of meaningful synchrony across the multi-subject group.

6.1.2.4 Combining the data from individual subjects: meta-analysis

The adjusted probability values were calculated at the level of the individual subject rather than the more usual multi-subject, group level. While these *within-subject* probability values are of interest in establishing the synchrony of growth within each subject it is the more general multi-subject patterns of synchrony (*between-subject* probabilities) that are ultimately of greater interest. It was necessary, therefore, to combine the data from all subjects to gain insight into the general patterns of growth co-ordination.

The numerical value of the STSD scores depends heavily on the number of data points within the time-series and because this varied from subject to subject it was not possible to validly combine the scores to provide an overall score for the sample. However, the null-hypotheses to which the adjusted probability values ($\hat{\boldsymbol{p}}$-values) relate were common to all subjects in the study but were tested independently for each subject. These factors (independent tests with common null-hypotheses) permit the null-hypotheses from each subject to be combined into a series of global (multi-subject) null-hypotheses that could be tested by combining the individual $\hat{\boldsymbol{p}}$-values using an appropriate meta-analytical procedure.

Fisher's combined probability test (Fisher, 1932; Loughin, 2004) was used to combine the $\hat{\boldsymbol{p}}$-values from the independent tests of synchrony of all subjects in the study. The test is based on the χ^2 form of the null-distribution of the inverse of the natural logarithm of the combination of the probabilities. That is, if all null hypotheses of the m tests are true, then the null-distribution will be a χ^2 distribution with $2m$ degrees of freedom. The threshold for acceptance of statistical significance of the resulting probability values from the Fisher’s tests was set at p = 0.05.

6.1.2.5 Statistical Families

Two statistical families were defined in the main study. The within-subject families for the tests of synchrony with each of the two growth pattern index variables. The primary statistical analysis of the main study was, however, conducted as a group analysis (at the level of the whole sample).

The null hypotheses, $H_0 = 0$: within each subject there is no synchrony between the time-series representing the growth pattern indices and the time-series of any other growth variable (38x 2 = 76 tests for each subject). For the group analysis, the null hypothesis was simply an extension of this: within the group there is no synchrony between the time-series representing the growth pattern indices and the time-series of any other growth variable.

6.1.2.6 Statistical Software and Computation

The observational data accumulated during the study were analysed using three computer programs:

> *SPSS System for Statistical Analysis* (SPSS Inc. 444 North Michigan Avenue, Chicago, Illinois, USA);
>
> *Resampling Stats* (Resampling Stats Inc. 612 N. Jackson Street, Arlington, Virginia 22201, USA);
>
> *Lumenaut* (Lumenaut Ltd 7th floor, Po Hing Court, 10-18 Po Hing Fong, Sheung Wan, Hong Kong);
>
> *Statgraphics Centurion XV* (Statpoint Technologies Inc., 560 Broadview Avenue, Warrenton, Virginia 20186, USA).

In addition to these standard statistical programs an additional statistical software resource was used to determine the modifying effect of dependency between the variables on the critical values used for the Bonferroni modified thresholds ($\hat{\boldsymbol{p}} \leq 0.05$; ≤ 0.01; ≤ 0.001) in the Initial Survey. These were calculated with using *SISA* statistical analysis program, which is the standard implementation of the procedure due to Sankoh *et al.*, (1997) and is available for direct use or download in Javascript at http://home.clara.net/bonfer.htm.

6.2 ERROR OF THE METHOD

Method errors refer to sources of uncertainty in the analytical method brought about primarily by inaccuracies of measurement. For reasons of conceptual and mathematical convenience method errors are usually broken down into systematic and random errors (Springate, 2011). Without knowing the true value of the quantity being measured, it is not possible to determine the magnitude of any systematic error. However, while detecting systematic error is important in ensuring the absolute accuracy of the linear and angular measurements it is the random errors that affect the outcome of standard (comparative) statistical tests.

There are two broad approaches to estimating random error and both require the replication of the measurements made in the original study. One approach then uses these replicated measurements to perform an analysis of variance. The second approach is to calculate a measure of the spread of the differences between the replicated measurements where the spread is assumed to be symmetrical around a mean value of zero (van der Linden *et al*, 1970; Jaech, 1985; Houston, 1983). This second approach is the one taken in the present study.

In studies involving cephalometric radiographs it has been customary to assess the errors from two sources: landmark location; and those resulting from radiographic superimposition. However, the quantification of these errors does not provide a clear indication of the uncertainty in the assessment of growth or growth related changes resulting from the entire observational method. This is because of the complex interaction of the three sources of error – the two end points of the vector of growth and the method of superimposition (van der Linden *et al.*, 1970; Baumrind *et al.*, 1976). To provide a more meaningful appraisal of the (technical) errors involved in the present study the error analysis was focussed directly on the growth changes themselves rather than on the intermediate sources of error.

6.2.1 The Method of Estimation of Errors in the Measurement of Growth

The radiographic images of all 11 subjects were used to assess the errors in the measurement of growth changes. This was done by replicating the procedures used in the two studies. For the initial survey the measurements were then combined with the original measurements from the same radiographs to form duplicate pairs. For those landmarks where the growth change was partitioned into horizontal and vertical components these were measured separately after locating the horizontal reference and transferring it from the first (reference) film by direct superimposition.

The error was assessed as the standard deviation of the differences between the duplicate pairs of measurements using the method described by Jeach (1985). In addition, the replicate data were examined for the presence of bias between replicates using a single-sample Student's *t*-test.

The random errors involved in the main study, however, were assessed as an integral part of that study and used to detect non-zero growth increments and to identify significant differences between adjacent increments as reported in Section 6.1.2.1.1.

Table 6.1 Technical Errors for Distances Measured Between Implant Markers

Direction	*Mean diff. (mm.)*	*Error: SD*	
Horizontal	-0.0198	0.0359	*n* =32
Vertical	0.0045	0.0166	*n* =32

The technical (method) errors were derived from 32 double determinations.

Table 6.2 Method Errors for the Initial Survey

Code No.	*Variable*	*Mean diff.*	*Error: SD*	
		(degrees or mm.)		
01	**MGR**	0.04	0.42	
02	**MxGR**	0.00	0.34	
03	**MAnt-Dir**	-0.10	2.20	
04	**MAnt-T**	-0.30	0.40	
05	**MAnt-V**	0.00	0.35	
06	**MAnt-H**	0.00	0.71	
07	**MRamus-V**	0.20	0.60	
08	**MRamus-H**	0.10	0.60	
09	**MRamus-T**	0.00	0.73	
10	**RamusRet**	-0.50 *	0.80	
11	**MxAnt-Dir**	-0.08	2.30	
12	**MxAnt-T**	0.20	0.40	
13	**MxAnt-H**	0.20	0.72	
14	**MxAnt-V**	0.10	0.60	
15	**MxPos-T**	0.00	0.54	
16	**MxPos-H**	-0.20	0.54	
17	**MxPos -V**	-0.10	0.38	
18	**MxMol-Ax**	0.10	1.43	
19	**MxMol-T**	0.00	0.70	
20	**MxMol-V**	-0.20	0.60	
21	**MxMol-H**	0.10	0.40	
22	**MxInc-ACB**	0.20	2.13	
23	**MxInc-Ax**	0.00	1.60	
24	**MxInc-T**	0.10	0.07	
25	**MxInc-V**	0.00	0.40	
26	**MxInc-H**	0.00	0.60	
27	**MMol-Ax**	-0.20	1.80	
28	**MMol-T**	0.10	0.70	
29	**MMol-V**	0.10	0.40	
30	**MMol-H**	-0.30	0.70	
31	**M-MxMol-V**	-0.50 *	1.10	
32	**MInc-Ax**	-0.07	2.68	
34	**MInc-V**	0.10	0.40	
35	**MInc-H**	-0.10	0.50	
36	**Cond-Dir**	0.10	2.10	
37	**Cond-Mag**	0.20	0.80	
38	**Glen-T**	-0.11	0.43	
39	**Glen-Ang**	0.40 *	3.35	
40	**MxLat-T**	0.03	0.13	
41	**TRN-MxMol**	0.00	0.70	
42	**TRN-MMol**	0.20	0.90	
43	**TRN-MxInc**	-0.07	1.20	
44	**TRN-Minc**	0.00	1.80	
45	**Hy-V**	-0.16	0.83	
46	**Hy-H**	0.13	0.74	
47	**Hy-T**	0.08	0.79	
48	**Tng-V**	-0.20	1.33	[0.66][$]
49	**CervSp**	0.20	1.12	

* signficant at $p < 0.05$

[$] The value of 1.33 mm for *change* in vertical height of the tongue is calculated from the linear error SD of 0.67mm.

Table 6.3 Method Errors for the Main Study

Code No.	Variable	Mean diff. (degrees or mm.)	Error: SD
Combined for all subjects			
53	**r-MGR**	0.03	0.31
54	**r-MxGR**	0.07	0.22
55	**r-Cond-Dir**	0.06	1.92
56	**r-Cond-Mag**	-0.09	0.33
57	**r-MRamus-V**	-0.04	0.28
58	**r-MRamus-H**	-0.05	0.32
59	**r-MRamus-T**	0.03	0.37
60	**r-MAnt-T**	0.09	0.08
61	**r-MAnt-V**	0.12 *	0.14
62	**r-MAnt-H**	0.02	0.16
63	**r-MxPos-T**	0.00	0.12
64	**r-MxPos-H**	0.07	0.30
65	**r-MxPos -V**	-0.04	0.22
66	**r-MxAnt-T**	0.06	0.18
67	**r-MxAnt-H**	0.01	0.21
68	**r-MxAnt-V**	-0.01	0.24
69	**r-MxMol-Ax**	0.01	0.26
70	**r-MxMol-T**	-0.06	0.17
71	**r-MxMol-V**	-0.08	0.23
72	**r-MxMol-H**	0.01	0.22
73	**r-MxInc-Ax**	0.01	0.24
74	**r-MxInc-T**	-0.03	0.32
75	**r-MxInc-V**	-0.02	0.37
76	**r-MxInc-H**	0.00	0.32
77	**r-MMol-Ax**	-0.01	0.33
78	**r-MMol-T**	-0.02	0.18
79	**r-MMol-V**	0.02	0.22
80	**r-MMol-H**	0.00	0.24
81	**r-MInc-Ax**	0.00	0.25
82	**r-MInc-T**	0.04	0.22
83	**r-MInc-V**	0.00	0.03
84	**r-MInc-H**	0.00	0.02
85	**r-M-MxMol-V**	0.01	0.27
87	**r-MxTRA-Lat**	0.03	0.41
88	**r-MxTRot**	0.04	0.62
89	**r-TRN-MxMol**	0.01	0.24
90	**r-TRN-MMol**	-0.01	0.38
91	**r-CerSp**	-0.10 *	0.36

The statistical estimates of the measurment errors are based on the assumption that the samples are drawn from the same Gaussian (Normal) distribution for all subjects.

* signficant at $p < 0.05$

6.2.2 Results of the Error Study

The results for the errors are shown in Table 6.1- 6.3.

6.2.2.1 The random errors

The random components of the error were generally small for all variables examined but was generally greater for angular measurements as a proportion of the total measured changed. Interestingly, changes in the intermaxillary width (in the transverse plane) had the smallest error SD - a value that was close to the spatial resolution of the original radiographs. This almost certainly reflects the high precision achievable when the points of measurement are the centres of small, highly radiopaque objects – the tantalum pins – as opposed to landmarks defined on anatomical contours.

Perhaps the most surprising result of the error study was the finding that the location of a single implant point was significantly more precise vertically than horizontally (Table 6.1). It is tempting to speculate that this is the result of the orientation of the implant pins where the centre of the longitudinal axis is located with less precision than that of the transverse axis. This was, however, not the case. Whether this tendency for greater precision in the vertical as opposed to the horizontal plane is universal or the result of a specific perceptual problem with the observer in this study is unknown.

The analysis of the random errors relied on replicating the observational (measurement) process on the same radiographic images as those used in the study. As such, it is incomplete and almost certainly underestimates the total random error, which could be evaluated more accurately using replicated radiographs. Sadly, no replicated (same day) radiographs were available for such an analysis.

6.3.1.2 Systematic Errors between replicate measurements

The only statistically significant mean differences between replicate measurements were for the variables *RamusRet*, *M-MxMol-V* and *Glen-Ang* for the Initial Survey and *r-MAnt-V* for the Main Study (Tables 6.2 and 6.3). Each of these systematic errors between replicate measurements were significant at the $p < 0.05$ level and the number of errors (5) is close to that which would be expected by chance alone. Thus, these may simply be chance findings or they may reflect a small but real systematic difference between replicate measurements possibly resulting from ‘drift’ or alteration in the method of recording these variables. Two of the variables (*RamusRet* and

Glen-Ang) required the location of cephalometric points on anatomical outlines alone (not involving implant markers) while the other two variables were partitioned components of displacement growth. These partitioned components clearly involved a greater possibility of error (due to relocating the horizontal reference and transferring it from the reference film via direct superimposition).

CHAPTER
7

RESULTS

7.1 PRESENTATION AND LAYOUT OF THE RESULTS

The results of this investigation focus primarily on the outcomes of the correlation analyses in the initial survey and on the corresponding short time-series distance (STSD) scores in the main growth pattern study. That is, the associations between mandibular growth rotation and the growth changes throughout the face during an observation period of approximately 6 years where the subjects were maturationally matched - the initial survey; and the intra-individual synchrony between the time-series representing the annual incremental patterning of a reduced set of growth changes over the total observation period - the main study.

In presenting the results, no attempt has been made to distinguish between the results for boys and girls nor to subdivide the data to provide age-specific descriptions of growth or morphological change in relation to mandibular growth rotation.

7.1.1 The Initial Survey: Presentation of the Correlation Analyses

The results for the correlation analyses are presented graphically as a correlation matrix in Figure 7.1. The Figure is not a correlation matrix in the classical sense of a square matrix, symmetrical about its principal diagonal and that contains the correlations for all possible pairings of the variables. Rather, it is a rectangular matrix where each row represents a growth or displacement variable and the columns represent the variables expressing: 1) growth rotation of the mandible (MGR); and 2) general somatic growth (GSG) as represented by vertical growth of the cervical spine. To simplify interpretation, the matrix has been segmented horizontally into anatomical regions and into classes of variables within each region (angular or directional; and vertical, horizontal, and total change) to allow patterns of significant associations to be visualised more easily.

Only those correlations that were statistically significant are indicated. Within the matrix the critical values for statistical significance differ between the elements (cells) depending on: the sample sizes for the two variables; and the type of correlation used (Pearson, $\boldsymbol{r}$ or Spearman, $\boldsymbol{r}_s$).

The data used in the construction of the Figure 7.1 are presented in Table 7.1 and as scatterplots in Appendix A1. The classes of the variables that were statistically significantly correlated with either of the two index variables are shown in Figure 7.2. The associations between growth variables and rotation of the jaws are illustrated with mean facial diagrams for subjects drawn from the extremes of the range of growth rotation in Figures 7.3 and 7.4.

7.1.2 The Main Study: Presentation of the Time-Series Analyses

The results of the main study are presented in a similar format to the initial survey but with the correlation variables replaced by the corresponding time-series variables. The nature of the results differ, however, from those of the initial survey because not all variables in the initial survey are represented by corresponding time-series variables for the reasons indicated in Section 6.1.2.2.4.

7.2 ASSOCIATIONS BETWEEN GROWTH ROTATION OF THE JAWS AND GROWTH CHANGES THROUGHOUT THE FACE: THE INITIAL SURVEY

7.2.1 Correlations Between Growth Rotation of the Mandible and Displacement Growth of the Jaws and Movements of the Teeth

As can be seen Table 7.2 and graphically in Figure 7.1, many of the correlations have associated probabilities above the significance level ($\hat{\boldsymbol{p}} \leq 0.05$). For most, but not all, variables the absolute magnitude of the correlation was greater with MGR than with general somatic growth (GSG).

For the comparisons with MGR, there were 16 significant correlations (at $\hat{\boldsymbol{p}} < 0.05$) and for those with GSG there were only 9. This difference is statistically significant ($\chi^2 = 4.174$; 1 *df*; $p = 0.041$). Only one growth variable reached statistical significance with both MGR and GSG: *MRamus-T* (total growth displacement measured at the ramal implant). Although the correlation was higher with MGR than with GSG (**r** = 0.716 and **r** = 0.698 respectively) they were not significantly different ($\hat{\boldsymbol{p}} > 0.05$).

Although the significant correlations for MGR and for GSG were widely spread across the anatomical regions, there were, however, clear differences in the locations of the significant associations between those with MGR and those with GSG. In the main the significant associations for MGR were with variables expressing: growth directions of the jaws; changes in the angulation of the molars; and the horizontal components of jaw displacement and molar migration. Whereas, for GSG the significant associations were with variables expressing the total magnitudes and vertical components of growth displacements of the jaws, eruption and migration of the molars.

The highest absolute correlations with MGR were for the horizontal component of maxillary growth measured at the anterior implant point ($\boldsymbol{r} = 0.940$); for the horizontal component of mandibular growth measured at the anterior implant point ($\boldsymbol{r} = 0.928$); and for the translocation of the maxillary molar ($\boldsymbol{r}$ = 0.937) relative to the anterior cranial base. For GSG the highest absolute correlations were with the magnitude of condylar growth ($\boldsymbol{r}$ = 0.898); the vertical growth of the mandibular ramus ($\boldsymbol{r}$ =0.820); and for the combined vertical eruption of the maxillary and mandibular molars ($\boldsymbol{r}$ =0.787).

While the numerical values and associated levels of statistical significance of the correlations provide some insight into the associations between growth rotation and growth displacements of the jaws and natural movements of the teeth, these relationships can be more easily appreciated graphically as scatterplots (Figure A.1) and visually as facial diagrams. Figure 7.3 depicts the growth changes over the total observation period between subjects drawn from the two extremes of the range of MGR. The instantaneous centres of rotation (COR) for mandible and maxilla between these two extremes are shown in Figure 7.4.

As can be seen the general pattern of growth differs quite markedly between the two extremes. The subjects with the greatest forward growth rotation had marked prognathism of the jaws as well as a total anterior shift of the dentition in both jaws. In those with the least forward rotation the direction of growth was more vertical with a much lower prognathism of the jaws and a much smaller degree of translocation of the mandibular teeth and mesial migration of the maxillary molar.

A particularly interesting feature of these diagrams is the orientation of the head and cervical spine, which are as they appear in the initial radiographs relative to the environmental vertical established by the frame of the cephalostat. Despite the positioning of the head via the nasal bridge indicator during the exposure the s-n plane is angulated upwards in the low MGR subjects while it is almost horizontal in the high MGR subjects. Similarly, the orientation and antero-posterior location of the cervical spine differs between the two extremes of MGR and the change in orientation over the mean observation intervals also differs.

Another point of note is the general difference in morphology between the two extremes of MGR at the time of the initial radiographs. Although the first radiographs were recorded at an overall mean age of 7.63 years there were some clear differences in cranial form between the subjects that later experienced high or low levels MGR, as shown in Figure 7.3c This strongly suggests that the growth changes observed during this study were simply a continuation of the previously existing patterns of growth.

TABLE 7.1 Initial Survey: Growth and Growth Related Changes During the Observation Period

Code No.	*Variable*					*Subject Number:*							**Mean*	**SD*
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	*(degrees or mm per year)*	
	Difference between Initial and Final radiographs													
	Observation period	6.2	6.4	6.0	6.1	6.4	6.3	6.1	6.3	6.1	6.6	6.0	6.21	0.20
01	**MGR**	9.0	5.5	6.2	8.5	3.9	1.9	-1.3	5.6	2.1	5.0	12.7	5.4	3.8
02	**MxGR**	11.3	1.7	3.6	3.0	2.5	0.6	-1.6	2.7	1.2	3.6	6.2	3.2	3.3
03	**MAnt-Dir**	44.8	76.1	59.0	49.6	57.8	74.5	85.5	38.2	73.1	57.0	29.4	58.6	17.4
04	**MAnt-T**	19.9	25.8	22.9	21.4	15.4	18.7	20.7	20.1	11.3	13.1	18.5	18.9	4.2
05	**MAnt-V**	11.3	20.7	14.9	16.0	11.1	17.0	18.4	17.8	10.8	7.9	4.6	13.7	4.9
06	**MAnt-H**	14.5	4.7	7.7	13.2	7.1	4.7	1.2	6.2	2.1	8.5	15.8	7.8	4.9
07	**MRamus-V**	23.5	21.2	22.0	26.1	16.8	19.6	16.2	13.2	13.3	18.0	23.1	19.4	4.2
08	**MRamus-H**	10.8	5.5	6.4	7.4	3.0	6.4	2.4	5.9	1.6	6.4	7.8	5.8	2.7
09	**MRamus-T**	26.7	22.9	24.9	27.1	18.2	20.6	16.8	23.9	13.8	14.7	24.7	21.3	4.8
10	**RamusRet**	7.5	10.0	7.1	6.2	7.0	3.9	4.0	3.2	5.5	5.3	7.0	6.1	2.0
11	**MxAnt-Dir**	20.2	61.3	53.4	20.6	39.8	75.9	64.0	57.4	34.4	46.7	14.4	44.4	20.2
12	* **MxAnt-T**	9.3	9.4	7.9	9.2	6.5	8.4	6.2	8.7	2.8	4.8	9.4	8.4	2.9
13	**MxAnt-H**	8.1	3.9	6.3	7.6	5.1	1.8	1.0	5.1	1.5	4.3	8.6	4.8	2.7
14	**MxAnt-V**	3.4	7.0	4.3	4.7	5.7	6.9	8.6	5.6	3.1	6.2	3.2	5.3	1.8
15	**MxPost-T**	9.5	9.4	8.2	9.2	8.3	7.3	5.6	8.8	5.3	6.0	9.8	7.9	1.7
16	**MxPos-H**	8.2	5.3	4.3	7.4	6.5	2.3	2.9	4.8	2.7	2.1	8.9	5.0	2.4
17	* **MxPos -V**	4.4	6.0	5.7	5.2	5.8	6.2	5.3	5.8	2.3	4.8	3.5	5.3	1.2
18	$ **MxMol-Ax**	10.5	7.2	7.5	11.8	6.4	3.5	0.8	7.4	3.8	16.9	13.1	8.2	5.0
19	**MxMol-T**	10.2	12.7	14.9	10.9	9.8	8.7	12.6	13.8	6.8	9.6	10.6	11.0	2.4
20	**MxMol-V**	9.1	11.9	9.6	10.2	7.5	6.7	11.0	10.7	5.7	6.6	5.1	8.5	2.3
21	**MxMol-H**	4.6	2.5	2.7	3.9	4.4	2.1	0.8	2.6	0.7	5.7	8.1	3.5	2.2
22	**MxInc-ACB**	4.9	-3.1	2.9	5.5	-1.1	-10.2	-13.3	-0.1	-4.4	-9.2	4.3	-2.2	6.5
23	**MxInc-Ax**	-7.9	4.8	-4.0	-4.2	-4.1	-8.3	-4.4	0.4	9.3	-11.1	-14.1	-4.0	6.8
24	**MxInc-T**	12.9	19.7	8.7	12.2	7.4	11.9	28.6	14.2	6.3	9.1	13.6	13.1	6.3
25	* **MxInc-V**	9.1	16.7	5.5	10.5	6.9	8.5	15.4	11.1	6.3	7.0	7.7	8.5	3.9
26	* **MxInc-H**	0.5	6.6	2.0	3.2	-0.3	-2.2	23.4	4.3	0.4	3.7	-2.2	2.0	3.9
27	**MMol-Ax**	-7.4	2.2	-5.2	3.2	1.8	4.2	0.7	1.1	3.5	1.6	3.3	0.8	3.7
28	**MMol-T**	9.1	7.3	6.4	7.7	6.1	5.6	5.8	3.7	8.3	3.3	8.4	6.5	1.9
29	**MMol-V**	8.6	4.5	3.8	6.8	2.8	4.3	2.8	4.2	4.2	4.2	5.3	4.7	1.7
30	**MMol-H**	3.1	3.6	3.1	3.6	5.7	2.5	0.5	1.8	2.2	1.0	5.9	3.0	1.7
31	**M-MxMol-V**	13.1	15.7	15.0	13.1	8.7	10.0	11.2	7.6	9.7	8.9	11.2	11.3	2.7
32	**MInc-Ax**	10.4	9.2	9.8	7.8	4.2	-2.0	2.5	3.9	3.9	-1.5	11.3	5.1	4.6
33	**MInc-T**	0.4	11.7	8.0	3.0	4.0	7.3	5.2	5.9	3.2	4.7	4.0	5.2	3.0
34	**MInc-V**	0.7	4.3	0.4	0.5	1.1	3.5	4.9	2.1	1.6	2.1	1.3	2.0	1.5
35	* **MInc-H**	6.6	2.8	2.8	11.7	2.5	-1.2	-0.3	1.4	2.8	-2.2	1.4	2.5	2.3
36	**Cond-Dir**	107.3	110.1	108.9	106.0	103.2	123.7	115.2	104.3	115.8	103.7	92.8	108.3	8.2
37	**Cond-Mag**	19.0	22.1	22.5	22.2	16.8	21.3	16.9	14.2	14.9	18.6	23.2	19.2	3.2
38	**Glenoid-T**	4.3	-0.5	0.4	4.3	0.4	0.9	2.5	0.7	-1.0	-0.2	0.9	1.2	1.8
39	**Glen-Ang**	-1.2	-0.4	-1.0	-1.2	-0.5	-0.3	-0.8	-1.0	-0.7	-0.9	-2.0	-0.9	0.5
40	* **MxLat-T**	3.0	3.0	5.1	2.0	3.4	1.6	2.0	4.0	2.3	1.7	2.0	2.3	1.2
41	**TRN-MxMol**	12.7	6.4	9.0	11.6	9.5	3.9	1.9	7.7	2.2	10.0	16.7	8.3	4.6
42	**TRN-MMol**	17.6	8.3	11.9	16.8	12.8	7.1	1.7	4.1	4.3	9.4	21.8	10.5	6.3
43	**TRN-MxInc**	15.0	11.2	14.8	16.4	6.8	2.5	24.6	5.6	2.5	12.2	13.7	11.4	6.7
44	**TRN-Minc**	21.1	7.5	12.2	24.9	9.6	3.5	0.9	3.7	4.9	6.2	17.2	10.2	7.8
45	**Hy-V**	22.0	26.5	25.3	31.5	30.8	11.3	14.0	17.2	23.7	15.4	28.5	22.4	7.0
46	**Hy-H**	12.0	5.2	6.5	3.6	9.7	-5.6	0.9	3.3	9.3	2.4	20.2	6.1	6.7
47	**Hy-T**	25.0	27.0	26.1	31.7	32.3	12.6	14.0	20.7	25.6	15.6	34.9	24.1	7.6
48	**Tng-V**	-0.9	0.5	-0.4	-1.1	-0.8	3.8	5.3	-1.4	1.1	2.2	-0.8	0.7	2.2
49	**CervSp**	21.0	27.4	25.7	22.8	16.6	18.3	16.3	13.5	11.5	14.7	28.5	19.7	5.8

* The mean and standard deviation for the variables marked with an asterix are replaced by the median and inter-quartile range.

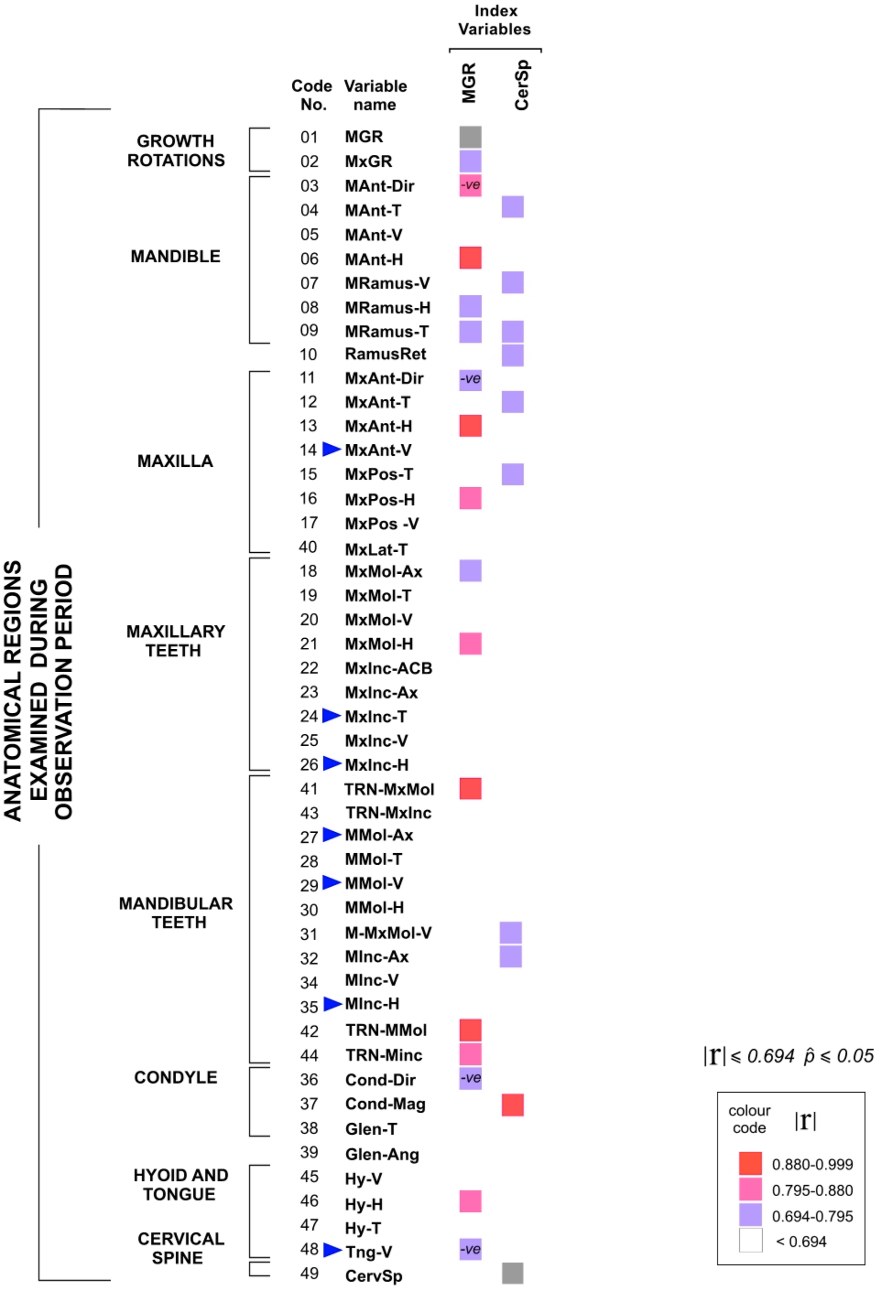
$ Sample size for this variable was n=10. For all other variables, n=11.

TABLE 7.2 Correlations between the Index Variables and Variables Expressing Growth, Eruption and Migration of the teeth

Code No.	*Variable*	**Index of Growth Rotation (MGR)**	**Index of Somatic Growth (CervSp)**
01	**MGR**	1.00	0.65
02	**MxGR**	0.78	0.35
03	**MAnt-Dir**	-0.86	-0.26
04	**MAnt-T**	0.21	0.70
05	**MAnt-V**	-0.49	0.00
06	**MAnt-H**	0.93	0.54
07	**MRamus-V**	0.67	0.82
08	**MRamus-H**	0.76	0.52
09	**MRamus-T**	0.72	0.70
10	**RamusRet**	0.47	0.71
11	**MxAnt-Dir**	-0.74	-0.25
12	**MxAnt-T**	0.60	0.73
13	**MxAnt-H**	0.94	0.60
14	**MxAnt-V**	-0.68	-0.19
15	**MxPost-T**	0.60	0.72
16	**MxPos-H**	0.83	0.60
17	* **MxPos -V**	-0.34	0.16
18	$ **MxMol-Ax**	0.75	0.63
19	**MxMol-T**	0.13	0.42
20	**MxMol-V**	-0.16	0.19
21	**MxMol-H**	0.81	0.44
22	**MxInc-ACB**	0.85	0.53
23	**MxInc-Ax**	-0.42	-0.30
24	* **MxInc-T**	-0.14	0.17
25	**MxInc-V**	-0.24	0.17
26	* **MxInc-H**	-0.12	-0.17
27	* **MMol-Ax**	-0.23	-0.19
28	**MMol-T**	0.42	0.49
29	* **MMol-V**	0.67	0.34
30	**MMol-H**	0.63	0.58
31	**M-MxMol-V**	0.29	0.79
32	**MInc-Ax**	0.74	0.74
33	**MInc-T**	-0.25	0.34
34	**MInc-V**	-0.63	-0.13
35	* **MInc-H**	0.52	0.32
36	**Cond-Dir**	-0.77	-0.36
37	**Cond-Mag**	0.53	0.90
38	**Glenoid-T**	0.28	0.19
39	**Glen-Ang**	-0.78	-0.42
40	* **MxLat-T**	0.13	0.17
41	**TRN-MxMol**	0.94	0.56
42	**TRN-MMol**	0.89	0.66
43	**TRN-MxInc**	0.10	0.38
44	**TRN-Minc**	0.81	0.57
45	**Hy-V**	0.58	0.51
46	**Hy-H**	0.69	0.39
47	**Hy-T**	0.69	0.52
48	* **Tng-V**	-0.73	-0.33
49	**CervSp**	0.65	1.00

* The variables marked with an asterix were not normally distributed and The Pearson correlation (r) is replaced with Spearman's rho.

$ Sample size for this variable was n=10. For all other variables, n=11.



ANATOMICAL REGIONS EXAMINED DURING OBSERVATION PERIOD	Code No.	Variable name	Index Variables	
			MGR	CerSp
GROWTH ROTATIONS	01	MGR	◼	
	02	MxGR	🟪	
MANDIBLE	03	MAnt-Dir	▩ -ve	
	04	MAnt-T		🟪
	05	MAnt-V		
	06	MAnt-H	🟥	
	07	MRamus-V		🟪
	08	MRamus-H	🟪	
	09	MRamus-T	🟪	🟪
	10	RamusRet		🟪
MAXILLA	11	MxAnt-Dir	🟪 -ve	
	12	MxAnt-T		🟪
	13	MxAnt-H	🟥	
	14 ►	MxAnt-V		
	15	MxPos-T		🟪
	16	MxPos-H	▩	
	17	MxPos -V		
	40	MxLat-T		
MAXILLARY TEETH	18	MxMol-Ax	🟪	
	19	MxMol-T		
	20	MxMol-V		
	21	MxMol-H	▩	
	22	MxInc-ACB		
	23	MxInc-Ax		
	24 ►	MxInc-T		
	25	MxInc-V		
	26 ►	MxInc-H		
MANDIBULAR TEETH	41	TRN-MxMol	🟥	
	43	TRN-MxInc		
	27 ►	MMol-Ax		
	28	MMol-T		
	29 ►	MMol-V		
	30	MMol-H		
	31	M-MxMol-V		🟪
	32	MInc-Ax		🟪
	34	MInc-V		
	35 ►	MInc-H		
	42	TRN-MMol	🟥	
	44	TRN-MInc	▩	
CONDYLE	36	Cond-Dir	🟪 -ve	
	37	Cond-Mag		🟥
	38	Glen-T		
	39	Glen-Ang		
HYOID AND TONGUE	45	Hy-V		
	46	Hy-H	▩	
	47	Hy-T		
	48 ►	Tng-V	🟪 -ve	
CERVICAL SPINE	49	CervSp		◼

$|r| \leqslant 0.694$ $\hat{p} \leqslant 0.05$

colour code	$|r|$
🟥	0.880-0.999
▩	0.795-0.880
🟪	0.694-0.795
⬜	< 0.694

Figure 7.1 The correlations for the Initial Survey showing the locations of significant associations after correction for multiple inference.

The Figure has been segmented horizontally into 8 anatomical sites or regions to allow significant associations to be visualised more easily. Each element is represented by a square cell which is colour-coded to indicate the absolute magnitude of correlation coefficients greater than, $|r|_{(n=11)} = 0.694$ (the critical level for statistical significance at $\hat{p} \leqslant 0.05$). The figure was constructed using Pearson's product-moment correlation coefficients except for those variables with non-normal distributions (indicated by a blue arrow ►). In these cases, the Spearman correlation coefficient was used, which has a critical value of $|r_s|_{(n=11)} = 0.702$ at $\hat{p} \leqslant 0.05$). *MGR* is the index for growth rotation and *CervSp* is the index for general somatic growth.

Figure 7.2 Initial Survey: comparison of the nature and location of growth changes statistically significantly correlated with the indices of growth.

The Figure shows the variables whose correlations with either or both of the two growth indices (*MGR*; *CervSp*) reached or exceeded the threshold for statistical significance at $\hat{p} = 0.05$. The variables are colour-coded to indicate the nature of the growth or growth related change expressed by each variable. As can be seen, with very few exceptions *MGR* is associated with directional (angular and axial) and horizontal growth displacements while *CervSp* is associated with the total magnitudes and vertical growth displacements.

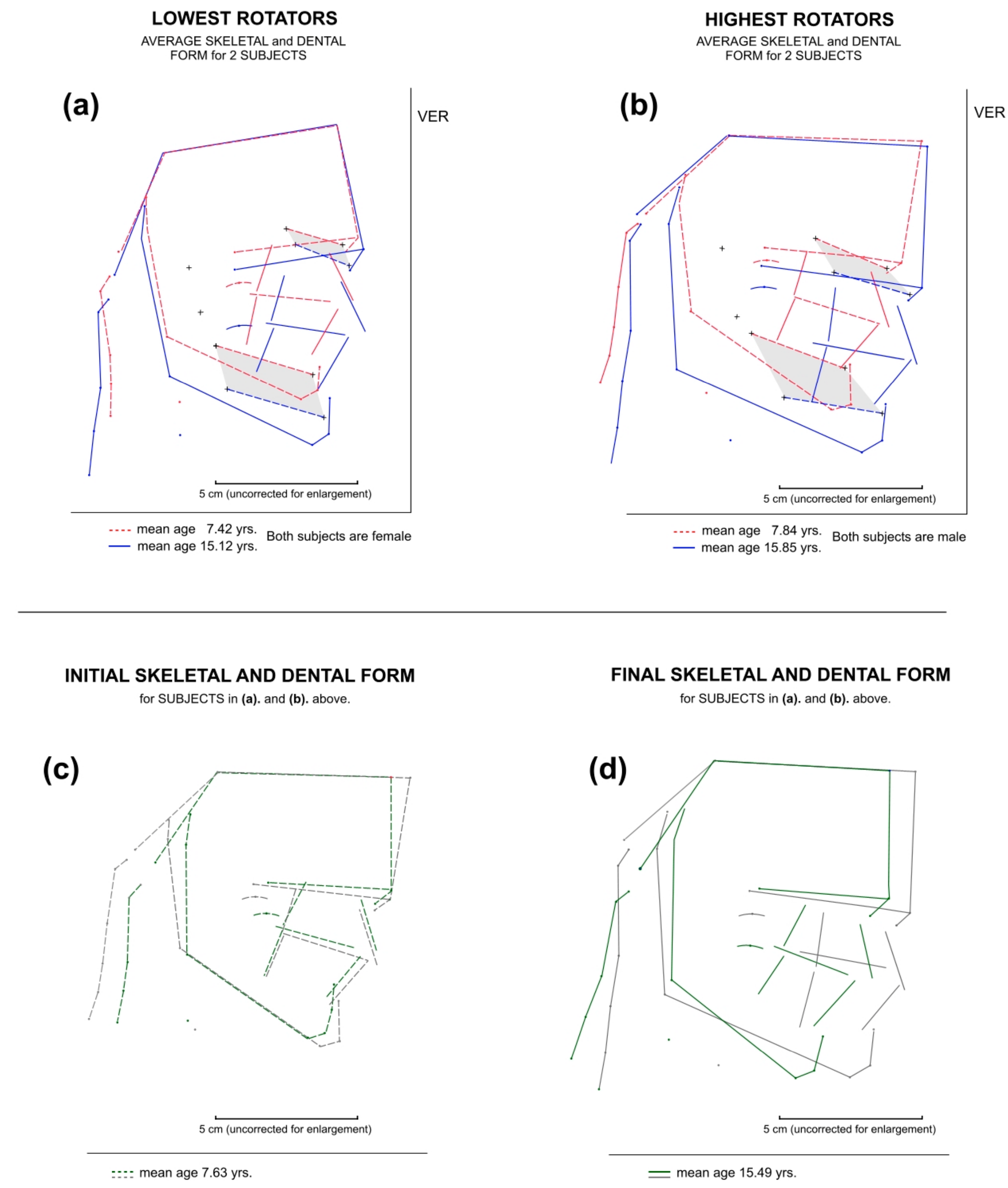


Figure 7.3 Mean facial diagrams for subjects at the extremes of the range of mandibular growth rotation.

Mean facial diagrams illustrating the average sagittal changes at 25 skeletal and dental landmarks for the 2 subjects with **(a)** the largest (forward) mandibular growth rotation (mean = 11.6 degs); **(b)** the smallest mandibular growth rotation (mean = 0.0 degs). Note particularly the direction of growth of the maxilla, the positions of the teeth, orientation of the occlusal plane and the postural position of the tongue, hyoid bone and cervical spine (the positions of the head and neck were not specifically 'posed' during exposure of the films). Note also the mandibular rotation evident in the shaded areas between the two positions of the corpus reference lines between the implant markers. The diagrams **(c)** and **(d)** show the average initial and final skeletal (and postural) form of the subjects in diagrams **(a)** and **(b)**. A divergence in skeletal form during the observation period is evident horizontally in the maxilla, vertically and horizontally in the mandible, hyoid bone, locations of the teeth in both dental arches and in the orientation of the posterior cranial base, cervical spine and tongue. The diagrams **(a)** and **(b)** are orientated at the average cranio-vertical angulation recorded at the initial observation of the 2 subjects used in each illustration with the illustrations registered at *sella* point.

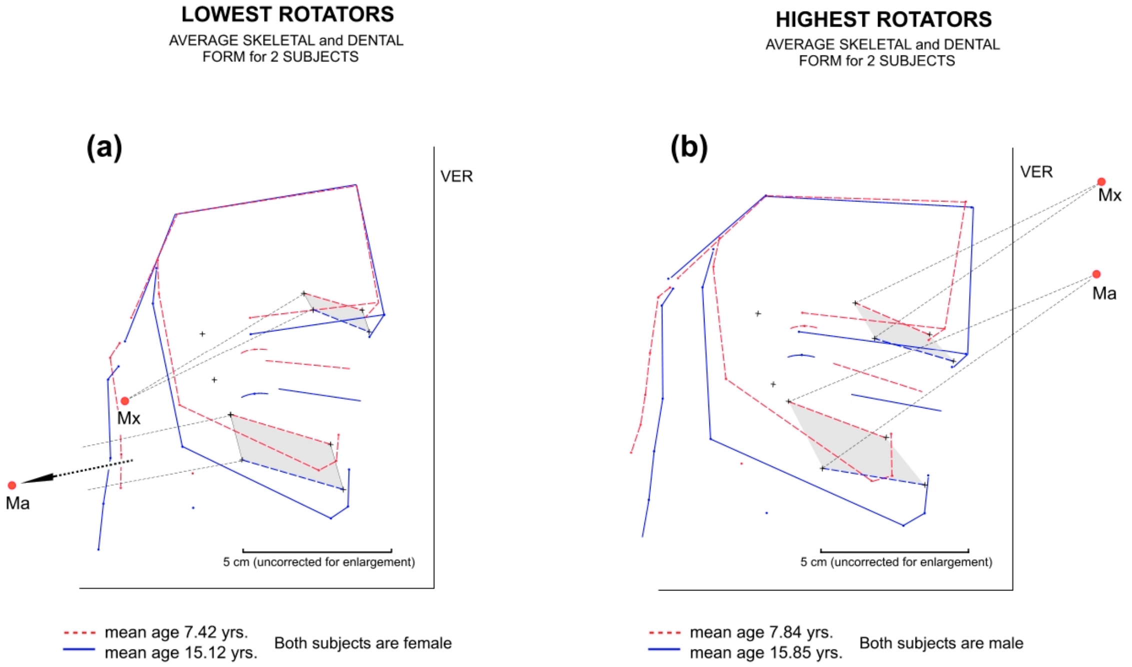


Figure 7.4 Centres of growth rotations of the jaws in subjects from the extremes of the range of mandibular rotation: (a) lowest rotators; and (b) highest rotators.

Each diagram shows the mean anatomical form and the locations of the instantaneous centres of rotation (COR) over the total observation period of the study. Ma is the COR of the mandible; Mx is the COR of the maxillae. **(a)** lowest rotators: the mean of these female subjects produced CORs that were located postero-inferiorly. **(b)** the highest rotators: the mean of these male subjects produced CORs that were located antero-superiorly. These positional differences in the locations of the CORs are probably not gender specific in general but instead appear to be determined by the magnitude and direction of jaw rotation (backward or forward).

7.3 THE MAIN GROWTH PATTERN STUDY: TIME SERIES ANALYSIS OF THE TEMPORAL PATTERNING OF GROWTH

The results of the main study are presented schematically showing the degree of synchrony between time-series variables for sites throughout the jaws and dentition and the two index variables expressing: growth rotation of the mandible; and general somatic growth (as represented by the vertical growth of the cervical spine). The results are presented in Figures 7.5 – 7.9 and full numerical data are given in Appendix A2).

Figure 7.5 shows those time series variables that reached or exceeded statistical significance at the $\hat{p} = 0.05$ threshold for the whole sample after correction for multiple inference and dependency within each subject and after combining the results for all subjects by meta-analysis using Fisher's combined probability test. The classes of variables whose time-series were synchronous with either of the two index variables are shown in Figure 7.6.

As can be seen, the results broadly mirror the findings of the initial survey in that significant synchrony with *r-MGR* and with *r-CervSp* is widely spread across the anatomical regions but with clear differences in the locations of the time-series variables with which they matched. The temporal pattern of *r-MGR* was matched by those time-series variables expressing: growth directions of the jaws; changes in the angulation of the maxillary molar; and the horizontal components of jaw displacement and molar migration. Whereas, the temporal pattern of *r-CervSp* was shared by variables expressing the total magnitudes of the growth displacements of the jaws and teeth and by those expressing the vertical components of growth. However, the degree of intra-individual synchrony with *r-MGR* and *r-CervSp* varied widely across the sample.

7.3.1 Growth Variables in Synchrony with the Pattern of Mandibular Growth Rotation

The time-series variables that strongly expressed patterns synchronous to *r-MGR* were: the vertical displacement of the ramus (*r-MRamus-V*); the total growth displacement of the anterior mandible (*r-MAnt-T*); the horizontal component growth displacement of the maxilla *(r-MxPos-H*, *r-MxAnt-H*); the axial change of the maxillary molar (*r-MxMol-Ax*); the horizontal translocation of the mandibular molar (*r-TRN-MMol*);

and the vertical growth displacement of the anterior and posterior maxilla (*r-MxPos-V and r-MxAnt-V)* for which the patterns of synchrony were *inverted* relative to that for *r-MGR*..

Interestingly, the transverse mutual rotation of the maxillae was not strongly nor significantly synchronous with the pattern of sagittal rotation of the mandible for the whole sample ($\hat{p} = 0.091$). There was, however, some evidence of an association in the individuals at the extremes of the range of MGR.

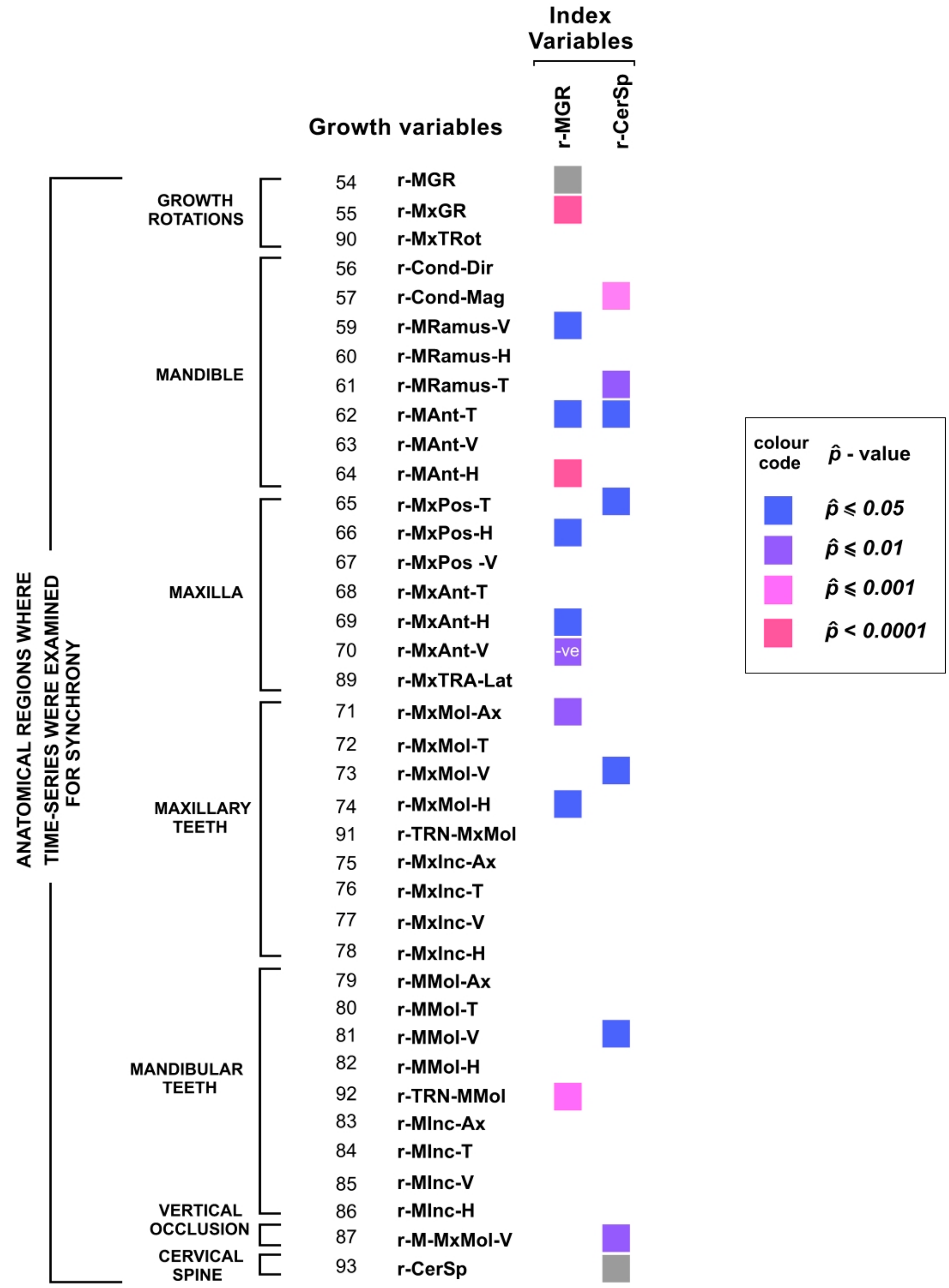
Time-series plots of the 10 variables in statistically significant synchrony with the temporal patterning of *r-MGR* are shown in Figure 7.7 for subjects with the: maximum; median; and minimum cumulative growth rotation of the mandible.

7.3.2 Growth Variables Not in Synchrony with the Pattern of Mandibular Growth Rotation

Although the primary focus of this part of the study was to establish the sites where displacement growth was in synchrony with *r-MGR* some of the variables that failed to reach statistical significance may also have a bearing on the origin and mechanism of MGR. This is particularly so for the variables in synchrony with GSG. Time-series plots of *r-CervSp* (GSG) versus *r-MGR* for the subjects in the study are shown in Figure 7.8. Time-series plots of other variables of interest but which were not statistically significantly synchronous with the temporal patterning of *r-MGR* are shown in Figure 7.9.

As can be seen, the pattern of general somatic growth did not generally match that of growth rotation of the mandible although, as was seen previously with *r-MGR*, there was a substantial amount of variability. Nevertheless, as was the case with *r-MGR* there are several variables whose pattern is consistently closely synchronous with that of *r-CervSp*. These variables are mainly the time-series equivalents of the variables in the initial survey that were either significantly correlated with *CervSp* or that just fell short of significance. That is, they are those variables expressing total growth displacement at the various skeletal sites and vertical (post-functional) eruption of the maxillary and mandibular molars.

There were three variables expressing moderate or strong synchrony with general somatic growth (as represented by the growth in height of the cervical spine (*r-CervSp*)). These were: the magnitude of condylar growth (*r-Cond-Mag*); the total displacement growth of the mandibular ramus, and the combined continued vertical eruption of maxillary and mandibular molars (*r-M-MxMol-V*).



ANATOMICAL REGIONS WHERE TIME-SERIES WERE EXAMINED FOR SYNCHRONY		Growth variables	Index Variables r-MGR	Index Variables r-CerSp
GROWTH ROTATIONS	54	r-MGR	▩	
	55	r-MxGR	🟥	
	90	r-MxTRot		
MANDIBLE	56	r-Cond-Dir		
	57	r-Cond-Mag		▣
	59	r-MRamus-V	🟦	
	60	r-MRamus-H		
	61	r-MRamus-T		🟪
	62	r-MAnt-T	🟦	🟦
	63	r-MAnt-V		
	64	r-MAnt-H	🟥	
MAXILLA	65	r-MxPos-T		🟦
	66	r-MxPos-H	🟦	
	67	r-MxPos -V		
	68	r-MxAnt-T		
	69	r-MxAnt-H	🟦	
	70	r-MxAnt-V	🟪 -ve	
	89	r-MxTRA-Lat		
MAXILLARY TEETH	71	r-MxMol-Ax	🟪	
	72	r-MxMol-T		
	73	r-MxMol-V		🟦
	74	r-MxMol-H	🟦	
	91	r-TRN-MxMol		
	75	r-MxInc-Ax		
	76	r-MxInc-T		
	77	r-MxInc-V		
	78	r-MxInc-H		
MANDIBULAR TEETH	79	r-MMol-Ax		
	80	r-MMol-T		
	81	r-MMol-V		🟦
	82	r-MMol-H		
	92	r-TRN-MMol	▣	
	83	r-MInc-Ax		
	84	r-MInc-T		
	85	r-MInc-V		
	86	r-MInc-H		
VERTICAL OCCLUSION	87	r-M-MxMol-V		🟪
CERVICAL SPINE	93	r-CerSp		▩

colour code	$\hat{p}$ - value
🟦	$\hat{p} \leqslant 0.05$
🟪	$\hat{p} \leqslant 0.01$
▣	$\hat{p} \leqslant 0.001$
🟥	$\hat{p} < 0.0001$

Figure 7.5 Time-series study: the growth variables whose time-series were in statistically sigificant synchrony with the indices of growth.

The Figure shows the variables whose time-series (representing the temporal patterns of growth) were in statistically significant synchrony with either or both of the two growth indices (*r-MGR*; *r-CervSp*) at the $\hat{p} \leqslant 0.05$ level. The variables are colour-coded to indicate the degree of synchrony between the time-series as represented by the statistical significance of the short time-series distance (STSD) scores. It is important to note that the STSD scores themselves are not uniquely associated with a specific degree of synchrony between time-series.

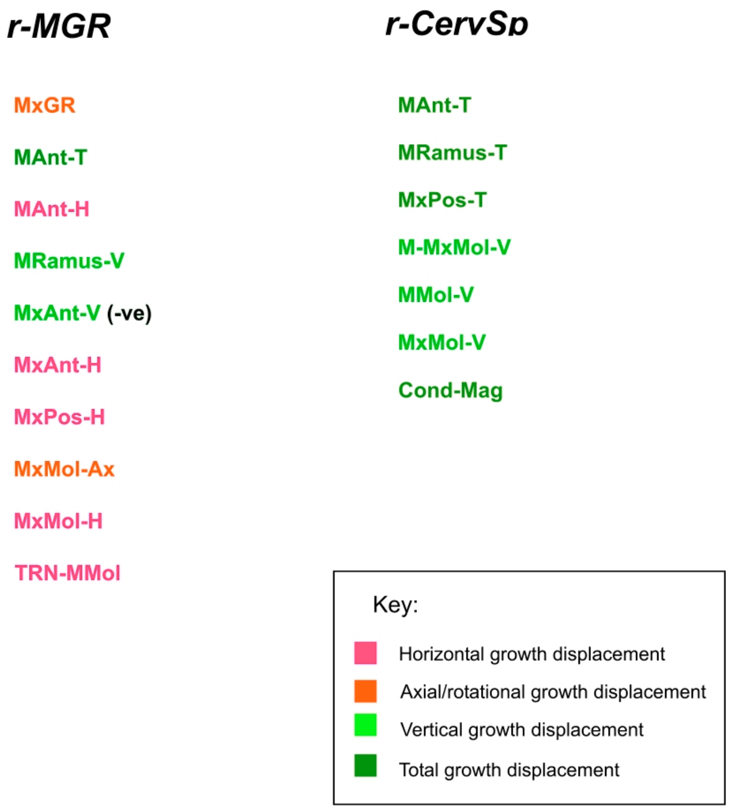


Figure 7.6 Time-series study: comparison of the nature and location of growth changes in statistically significant synchrony with the indices of growth.

The Figure shows the variables whose time-series (representing the temporal patterns of growth) were in statistically significant synchrony with either or both of the two growth indices (*r-MGR*; *r-CervSp*) at the $\hat{p} \leqslant 0.05$ level. The variables are colour-coded to indicate the nature of the growth or growth related change expressed by each variable (cf Fig. 7.2). There is more variability than in the Initial Survey but as can be seen *r-MGR* is mainly synchronous with variables expressing angular (axial) and horizontal growth displacements while *r-CervSp* is synchronous with variables expressing vertical and total magnitudes of growth displacements.

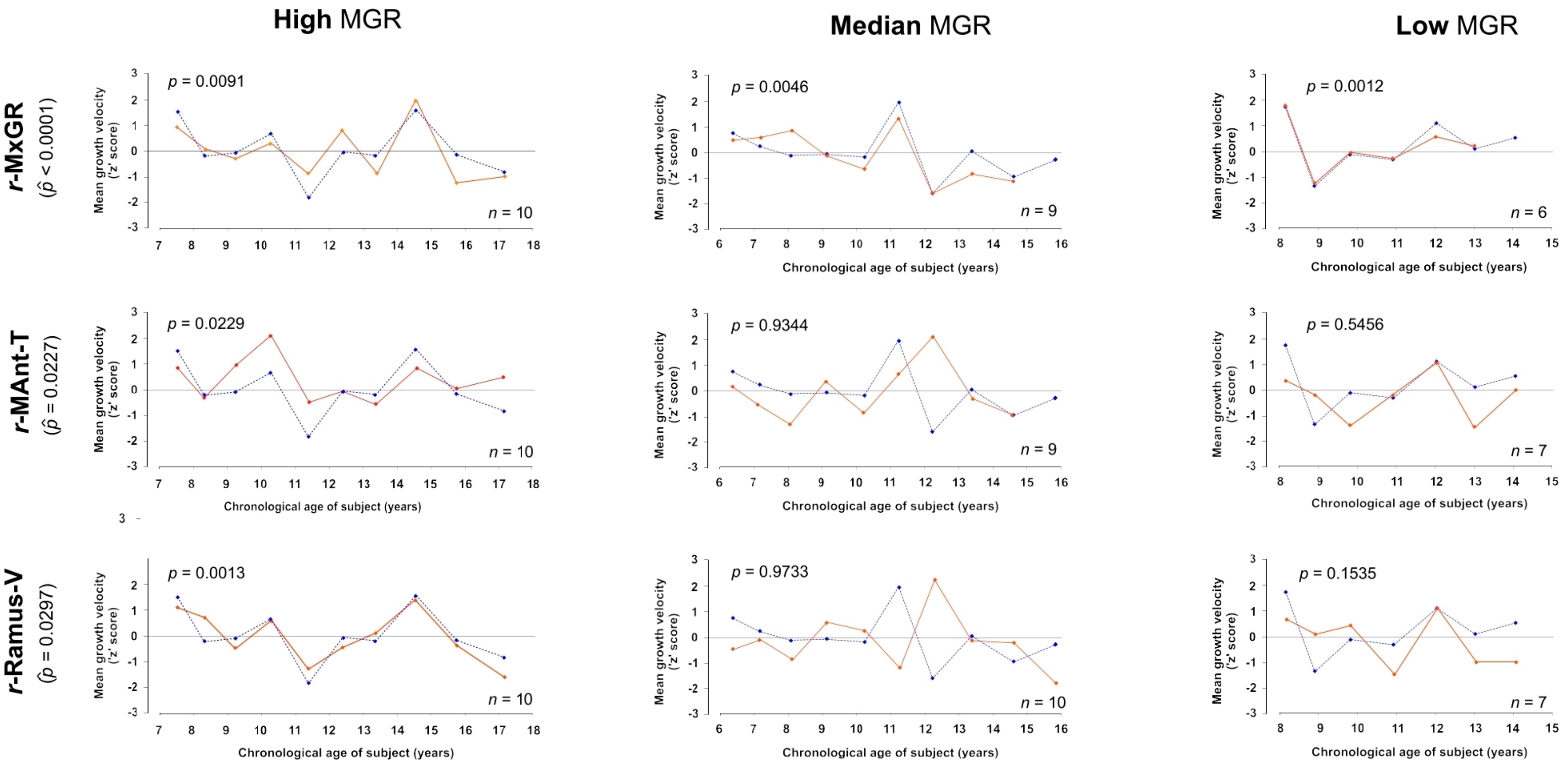


Figure 7.7 **Time series plots of the 10 variables in statistically significant synchrony with the temporal patterning of mandibular growth rotation (*r-MGR*) for subjects with the: maximum; median; and minimum cumulative growth rotation of the mandible.**

The time-series variables in each plot have been standardised to zero mean and unit variance ('z-scores') to allow valid comparisons between the time series For each subject the variable of interest (—◆—) is shown together with the corresponding plot for the *r-MGR* variable for that subject (‐‐‐◆‐‐‐) (N.B. forward rotation is designated as +ve). The degree of synchrony is indicated only by the statistical significance of the match between the two time series. The *p*-value given for each plot is the probability adjusted for both multiple inference and dependency and is specific to that subject. The *p*-value for the multi-subject group analysis ($\hat{p}$) is given to the left of each line against the name of the variable. The data are plotted at the mid-point of each observation interval. The High; Median; and Low MGR subjects in the Figure are numbers 5♂; 2♂ and 7♀respectively.

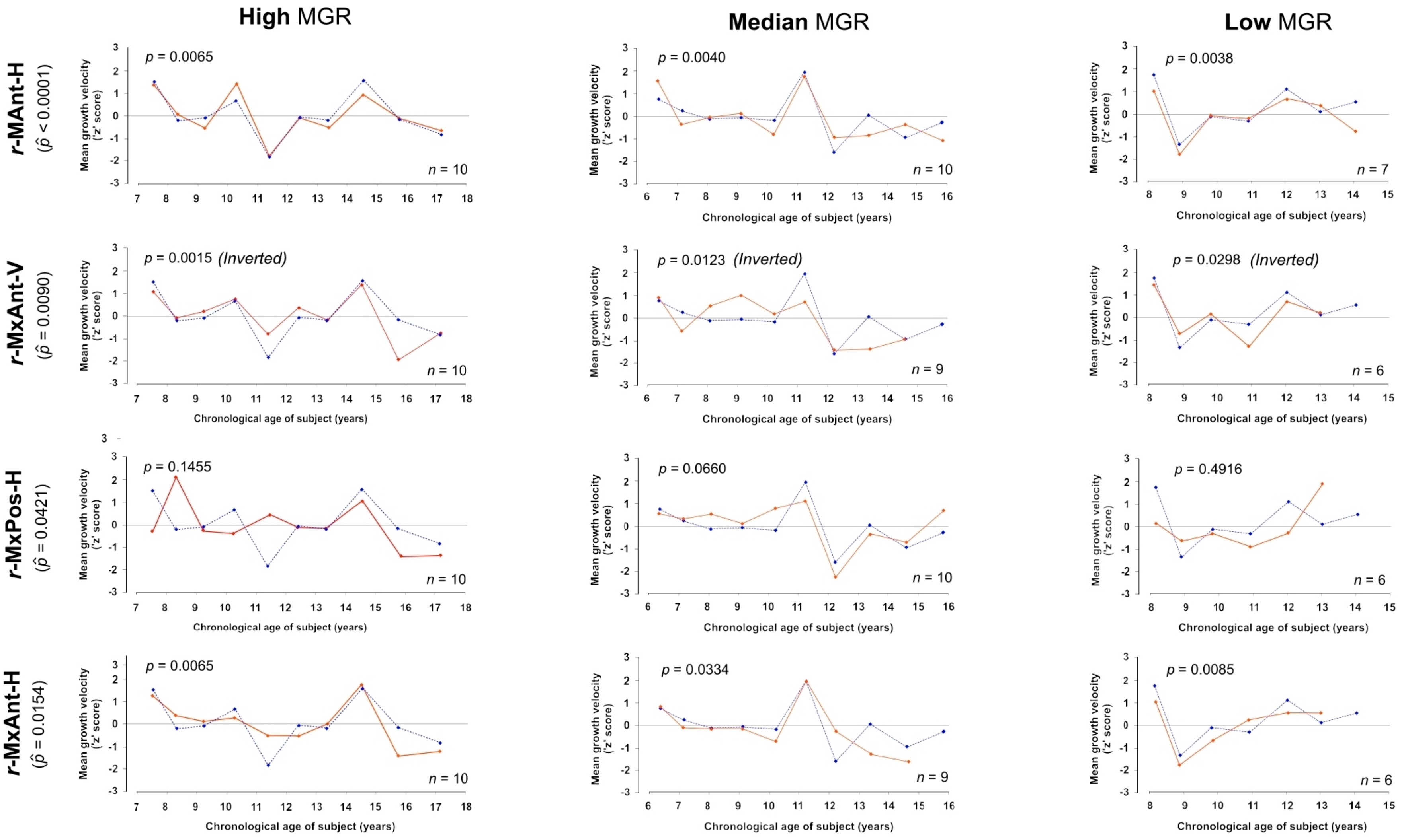


Figure 7.7 *Continued (2) ...*

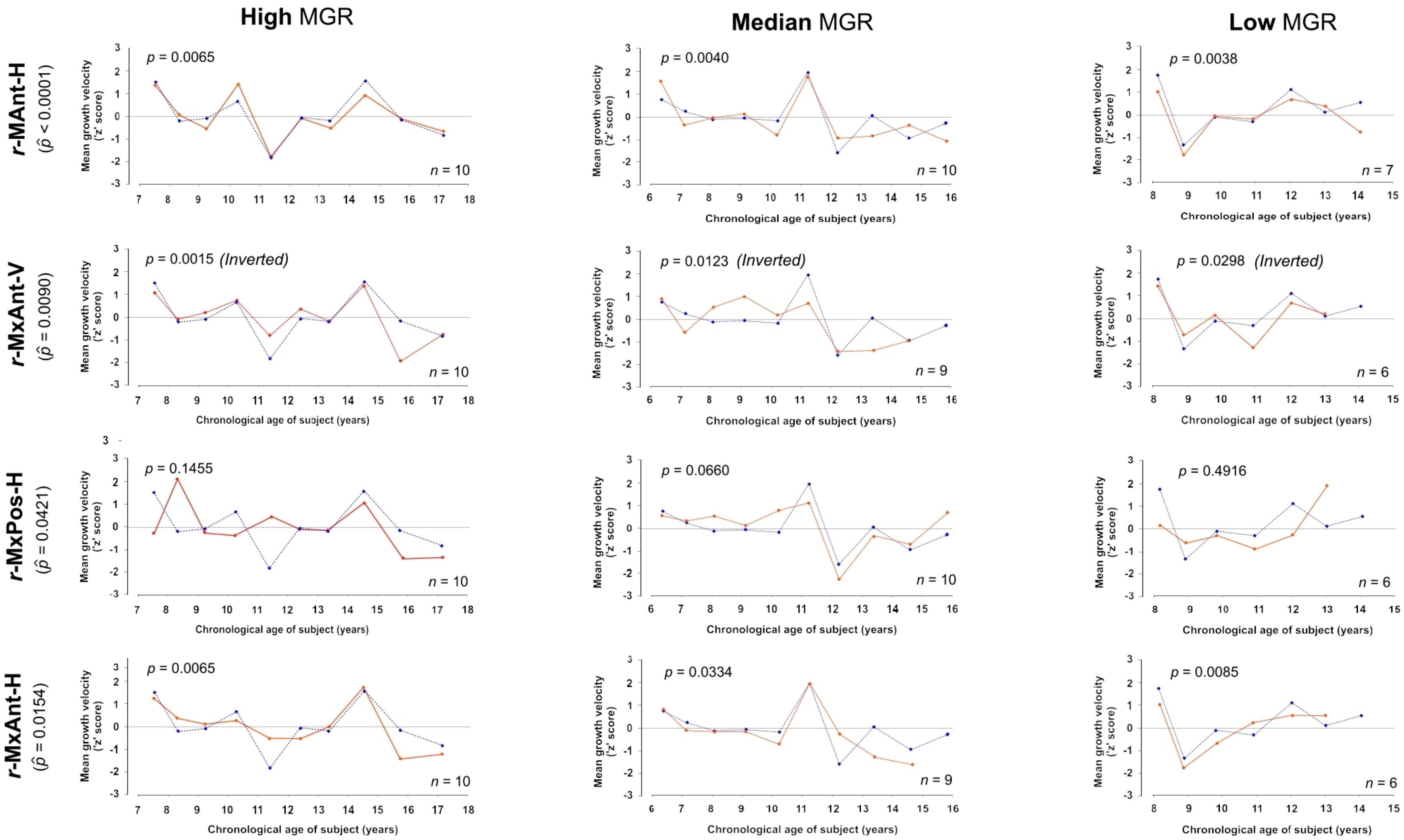


Figure 7.7 *Continued (2) ...*

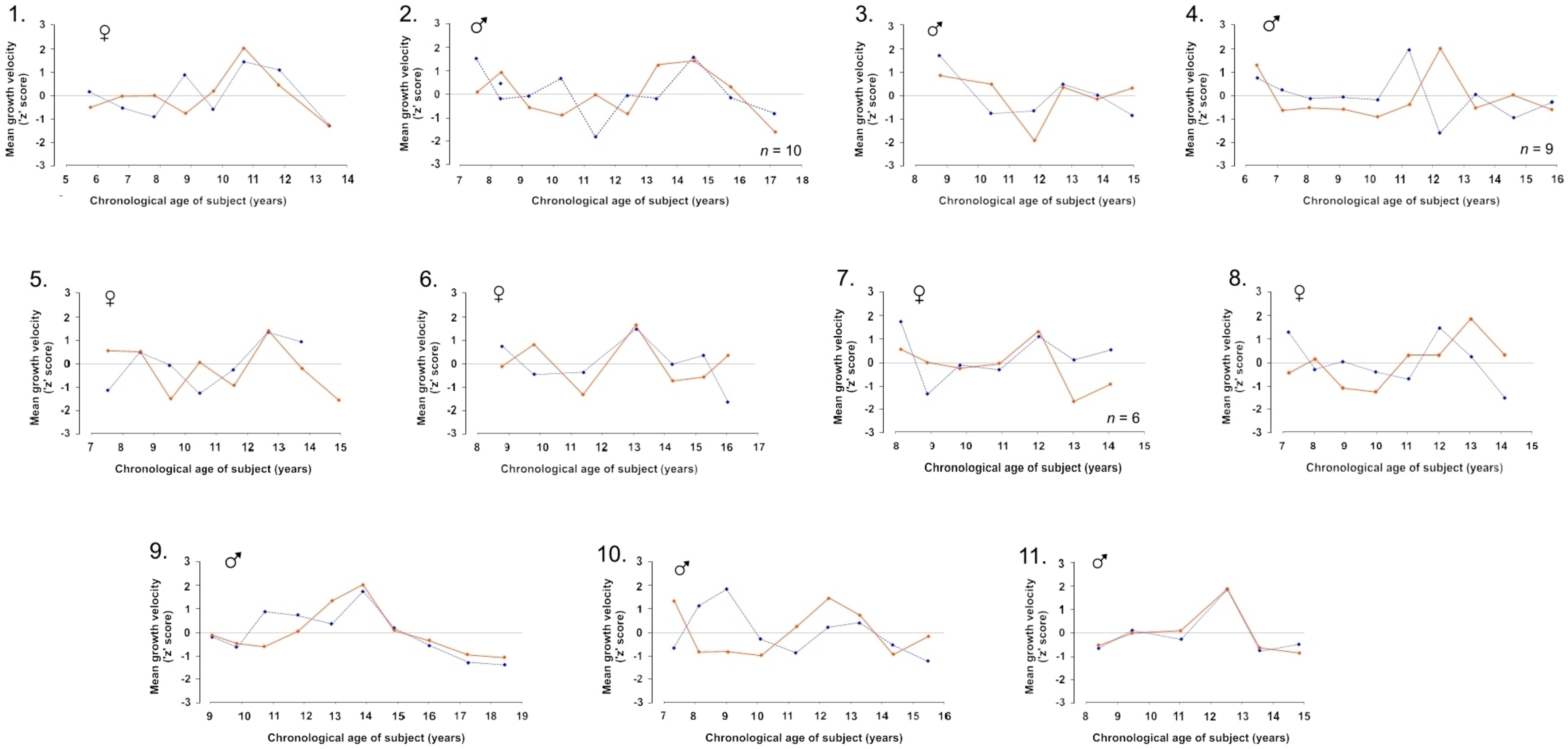


Figure 7.8 **Time-series plots of the pattern of general somatic growth (*r-CervSp*) *versus* the pattern of mandibular growth rotation (*r-MGR)* for all subjects in the study.**

For each subject the plot of *r-CervSp* (◆—◆—◆) is shown together with the corresponding plot for *r-MGR* for that subject (◆----◆----◆). As can be seen, the patterns of the two index variables are generally quite different but in 9 of the 11 subjects the pubertal peaks coincide. The data are plotted at the mid-point of each observation interval. The subject number and gender are indicated against each plot.

Weaker expressions of synchrony with *r-CervSp* were found for: the total growth displacements of the anterior mandible, and posterior maxilla; and for the continued vertical eruption of the mandibular and maxillary molars (*r-MxMol-V, r-Mmol-V*). Of interest in this regard is that *separately* the vertical eruption of the molars in the two jaws were each only weakly synchronous with *r-CervSp* but the *combined* vertical eruption of the molars, which effectively represents the growth in inter-maxillary height, was strongly synchronous with the pattern of somatic growth (*r-CervSp*).

Other time-series variables that were not synchronous with *r-MGR* in the group analysis but are of interest were: the mutual transverse rotations of the maxillae; the translocation of the maxillary molars; and horizontal migration of the maxillary and mandibular incisors. As can be seen in Figure 7.9, the migration of the incisors and the translocation of the maxillary molars do appear to be closely synchronous in the subjects with the: maximum; median; and minimum cumulative growth rotation of the mandible. However, for the group as a whole they failed to reach statistical significance. This again emphasises the marked variability of the relationships between MGR and skeletal displacement and tooth migration across the sample.

Perhaps the most unexpected failure to detect synchrony with MGR was for the variable representing the transverse rotations of the maxillae. From the limited evidence available the temporal pattern of this variable (*r-MxTRot*) appears to follow more closely general somatic growth than mandibular rotation, although this was not the case for all subjects.

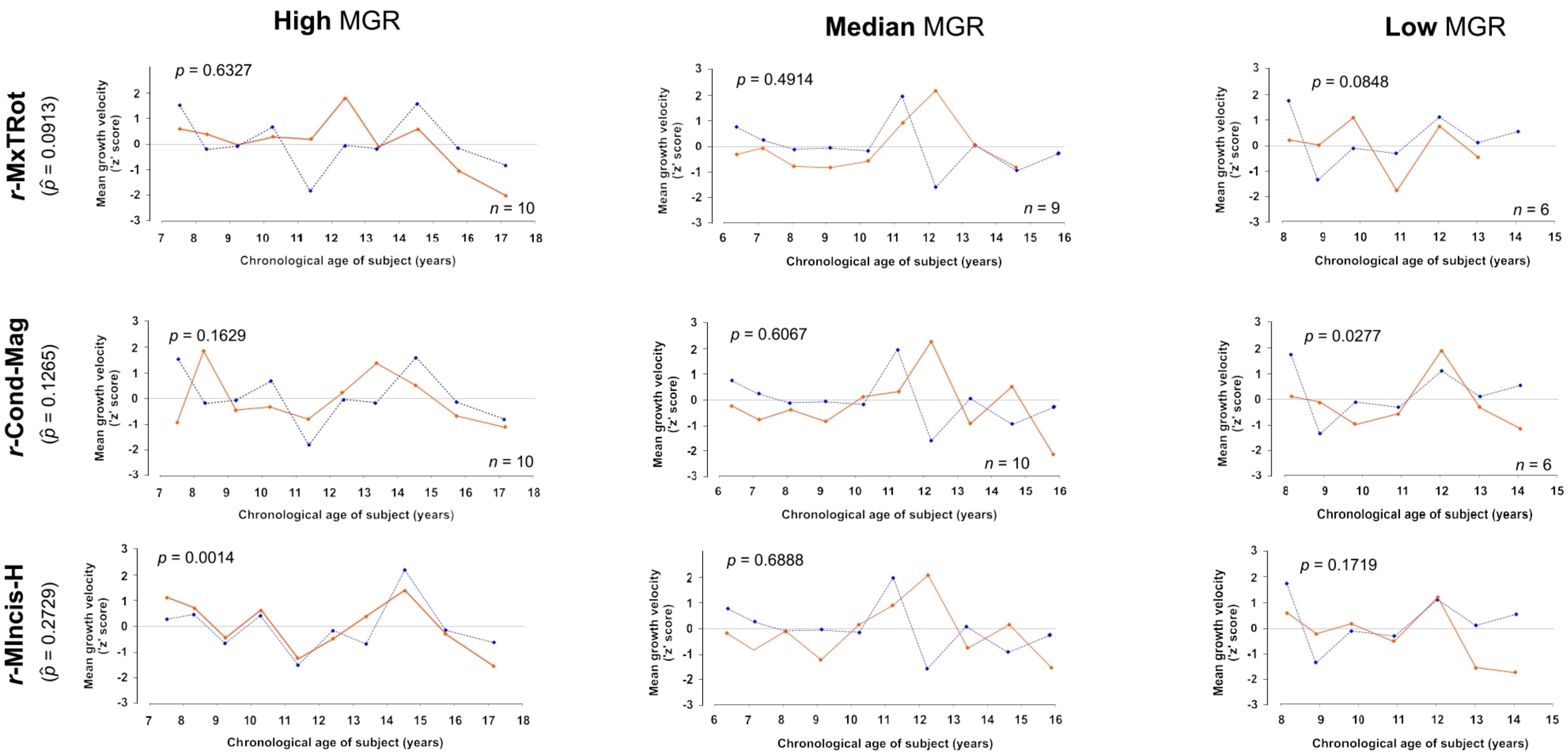


Figure 7.9 **Time series plots of additional selected variables *without* statistically significant synchrony with the temporal patterning of mandibular growth rotation (*r*-MGR) for subjects with: maximum; median; and minimum cumulative growth rotation of the mandible.**

The time series variables in each plot have been standardised to zero mean and unit variance ('z-scores') to allow valid comparisons between the time series For each subject the variable of interest (●——●——●) is shown together with the corresponding plot for the *r*-MGR variable for that subject (●------●------●) (N.B. forward rotation is designated as +ve). The degree of synchrony is indicated only by the statistical significance of the match between the two time series. The p-value given for each plot is the probability adjusted for both multiple inference and dependency and is specific to that subject. The p-value for the multi-subject group analysis ($\hat{p}$) is given to the left of each line against the name of the variable. The data are plotted at the mid-point of each observation interval. The High; Median; and Low MGR subjects in the Figure are numbers 5♂; 2♂ and 7♀respectively.

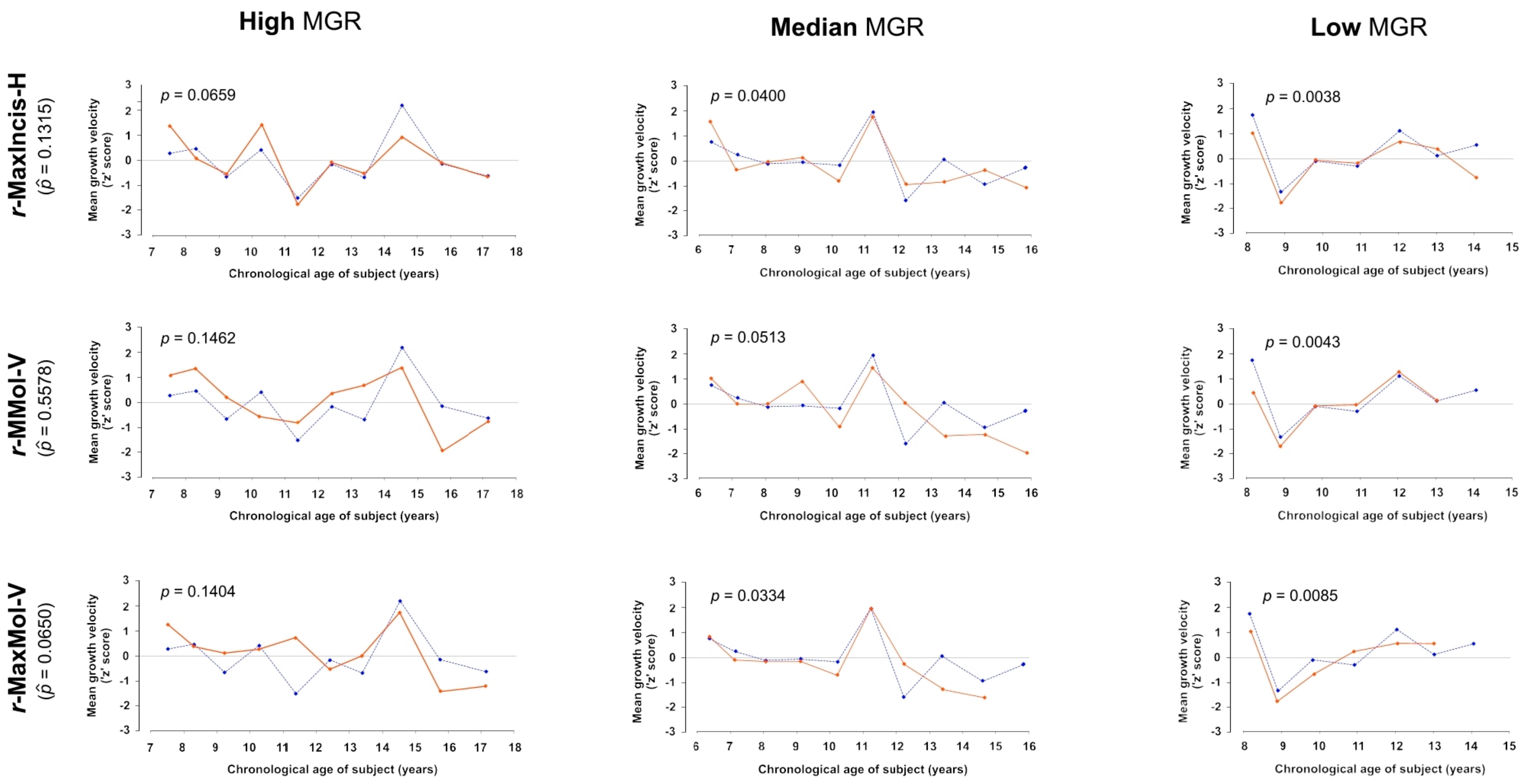


Figure 7.9 *Continued ...*

7.4 SUMMARY OF THE RESULTS

7.4.1 The Initial Survey of Associations

The Initial Survey of associations between the index variables and the changes in the variables expressing growth and growth related changes throughout the face and dentition revealed distinctly different patterns of associations for the two index variables. Growth rotation of the mandible was generally associated with the variables expressing angular (rotational and directional) changes, the horizontal components of maxillary and mandibular growth displacement, and the horizontal migrations and translocations of the teeth. General somatic growth was associated with the magnitude of total growth displacement at various skeletal sites and the combined (vertical) eruption of maxillary and mandibular molars.

The number of significance associations also differed between the index variables with the stronger and more numerous correlations occurring with *MGR*. Only one growth variable (*MRamus-T*) was found to be statistically significantly correlated with both *MGR* and *CervSp* but the strengths of the associations were only moderate.

The distribution of these significant associations within and between the two index variables (*MGR* and *CervSp*) was not entirely unexpected but there were some unexpected significant correlations with both MGR and GSG. Of particular interest in this regard was the significant (negative) association between: MGR and the variable representing the postural height of the tongue ($\boldsymbol{r}_s = -0.727$). There were other associations that proved to be unexpectedly low. In particular, the correlation of, $\boldsymbol{r} = 0.649$ ($\hat{p} > 0.05$) for the association MGR and GSG. Although the numerical value of the correlation would just have reached statistical significance at the unadjusted (univariate) level (critical value: $p = 0.05$, $r = 0.602$,) the strength of the association was only moderate with a coefficient of determination ($\boldsymbol{r}^2 = 0.421$) indicating that it explained less than half of the total variance. The correlation between *MGR* and the magnitude of condylar growth of $\boldsymbol{r} = 0.534$ was also surprisingly low. As a consequence, neither correlation reached significance at the $\hat{\boldsymbol{p}} \leq 0.05$ level.

7.4.2 The Main Growth Pattern Study

The main time-series study revealed a high level of variability in the time-series that showed significant synchrony with the index variables (*r-MGR* and *r-CervSp*). Nevertheless, combining the individual results to form the multi-subject group analysis revealed patterns of synchronous growth with the index variables that broadly mirrored the results of the Initial Survey. That is, the temporal pattern of growth rotation of the mandible was generally associated with the time-series representing angular (rotational and directional) variables and those representing the horizontal components of displacement growth. The temporal pattern of general somatic growth was found to be synchronous with time-series representing the total magnitudes of skeletal growth displacement and with those representing the combined (vertical) eruption of maxillary and mandibular molars.

The results of the main study did, however, differ from those of the Initial Survey in that some variables that showed only low non-significant levels of association with MGR in the Initial Survey were found to be strongly synchronous with the temporal pattern of MGR (*r-MGR*) in the main study. These were: the vertical descent of the core of the mandibular ramus and the vertical displacements of the anterior and posterior maxilla. These later two time-series variables had patterns of growth that were synchronous with, but inverted to, the pattern of *r-MGR*.

However, in the light of previous tantalum implant studies perhaps the most surprising result was the failure to detect significant synchrony between *r-MGR* and the *direction* of condylar growth. This suggests that a very different relationship exists between MGR and the direction of condylar growth at the level of the individual subject to that which exists *between* subjects across the range of MGR encountered in this and in previous tantalum implant samples.

CHAPTER
8

DISCUSSION

8.1 THE LIMITATIONS OF THE STUDY

Before discussing the findings and interpreting the results of this study it is important at the outset to examine its limitations – what it can (potentially) show and what it cannot, and why?

The validity of the study and the associated findings will be influenced by many factors. The limitations of this investigation may be classified under three main headings: limitations arising from the design of the study; the limitations arising from the sample; and the limitations arising from the methods for collecting and analysing the data.

8.1.1 Limitations Arising from the Design of the Study

This investigation was designed as two separate but related and complementary observational studies of the relationships between growth rotations of the jaws and growth changes at sites throughout the jaws and dentition. There are, however, limitations resulting from the nature of the studies – observational as opposed to experimental.

8.1.1.1 *The observational design*

It is important to understand that observational studies suffer from several limitations when compared to controlled experiments. The most important of which is the weight of evidence that can be derived from an observational study. In an observational study none of the variables are under direct experimental control and this gives rise to greater ‘grounds for doubt’ than in a controlled experiment resulting from uncertainties about bias (Rosenbaum, 1995).

In addition, an experimental design is not a realistic proposition without a clear and plausible theory to test. However, even if the primary aim was to test a theory there are compelling ethical reasons that would prevent an experimental investigation of growth rotations, at least in human subjects.

Because of the lack of reliable evidence or detailed knowledge about the relationships between growth rotations of the jaws and growth elsewhere in the face, the present investigation was designed first as a descriptive and exploratory study. The intention was to build on an initial descriptive analysis by searching for relationships between measurements of growth and growth related changes with the aim of generating plausible hypotheses about the possible cause(s) of growth rotations of the jaws. If this were achievable then the process could proceed to an inferential or predictive study in which such hypotheses are tested.

The final part of the present research was to provide such a hypothesis and, if possible, to test it. However, a fundamental limitation of such a test is that it cannot be valid if the same data used to generate the hypothesis are also used to tests it (Duda and Hart, 1973). It is not easily possible with the analysis of a pre-existing human growth study to provide independent data samples for both processes (that is, generating a hypothesis and then testing it) without severely limiting the data available for one or both parts. Consequently, the final part of this investigation in which data is adduced to support a (hypothetical) model of causation can only be viewed as providing limited additional support rather than as an unbiased confirmation of the validity of the model.

8.1.2 The Limitations Arising from the Methods for Collecting the data.

The data collected in this study were derived from the measurements of serial cephalometric radiographs. The limitations and uncertainties of this method of study are well documented but there are two aspects of radiographic analysis that are particularly relevant to this study. These are: the geometric limitations of planar projections; and the limitations of integrating of data from the different radiographic projections.

8.1.2.1 Geometric limitations

The geometric limitations arise directly from the nature of the radiographic projection - a two-dimensional projection of a three-dimensional object. Distances measured in any plane not parallel to the film will appear foreshortened when adjusted for magnification. This particular limitation has been addressed in Sections 4.3.2 and 5.3.1.5.2 but it is important to note that the high-resolution measurements made from the oblique projection are not analogous to the usual measurements made in the lateral projection. Of particular note in this context are: the horizontal and angular motion of the buccal teeth; and the direction and magnitude of condylar growth. Nevertheless, mesio-distal changes of the buccal teeth are presumably closer to the true line of the dental arch when measured from the oblique view. That is, they are true mesio-distal changes rather than antero-posterior changes.

The same is true of the condylar growth which largely occurs in the plane of the mandibular body and ramus. The importance of this in the present study is in the detection of synchrony between condylar growth changes and MGR. Although condylar growth measured from the oblique view may more accurately reflect the true nature of the growth its integration or co-ordination with antero-posterior changes may not be entirely reliable because of the difference in orientation between oblique and standard lateral radiographs. This limitation is also closely linked to the second aspect of radiographic analysis of relevance to this study: the integration of data from the different radiographic views.

8.1.2.2 Integration of data from the different radiographic views

This particular problem results from merging (or comparing) data from two or more different projections of the same object. In the main this is likely to affect two types of data: 1) the partitioning of total growth magnitudes into horizontal and vertical components; and 2) the measurement of angular changes. This is because data from the lateral and oblique projections are orientated relative to the nominal 11 year occlusal plane. Although this plane is visible in both projections it is subject to high levels of random error and differs systematically in the two views – in the lateral view it is defined by right and left hand sides but only by the left hand side in the oblique view. Thus, the partitioning into horizontal and vertical components is likely to differ between the two views to an extent that is greater than that due to differences in the geometry of projection alone.

The extent to which this will have affected the results of the study is unknown but the *direction* of any effect will, on average, have been to diminish rather than to exaggerate the degree of synchrony between pairs of growth sites; one measured in the oblique view, the other in the lateral view. Moreover, because the same random errors were *not* shared by the data from different projections the correlations derived from these projections in the initial survey are also unlikely to have been spuriously exaggerated – a major problem in previous studies involving measurements from cephalometric radiographs.

The merging of data from the frontal projection with either of the other two projections will have been subject to a different source of error or limitation. These data were not 'merged' in the same way as those from oblique and lateral projections but were simply compared by reference to the same implants visible in the different views. That is to say, these data were not 'integrated' as such. Because of this they should not have affected the detection or extent of synchrony (nor the correlation between variables) over and above that due to random errors of superimposition or landmark location.

8.1.3 The Limitations Arising from the Methods of Analysing the data.

8.1.3.1 Correlation Analysis

Although uncertainties about bias provide the main difficulty in observational studies, if we assume that the subjects differ only or primarily in the covariates that we can measure there is still the problem of interpreting the results. Correlation analysis is the method of choice for assessing the degree of association between biological variables that are examined observationally (Sokal and Rholf, 1995). Nevertheless, correlation analysis does not permit unequivocal conclusions regarding causation. Instead, it only allows us to explore relationships between variables rather than confirm some theoretical relationship between them. However, if correlation analysis is used to assess the degree of association between variables there are further difficulties that provide additional important limitations:

1) the effects known as 'mathematical coupling' (MC) and 'regression to the mean' (RTM) effect;
2) the sensitivity of the correlation coefficient to selection bias.

Both of these can lead to a spuriously inflated correlation coefficient. The MC and RTM effects have been dealt with in Chapter 4. Sample selection bias is discussed below in Section 8.1.3. Correlation analysis is especially sensitive to bias in the selection of the sample because the between-subject variation in each variable enters directly into the numerical value of the calculated correlation (Altman, 1991). The sample should be a random sample from a specified population whose correlation coefficient is sought.

8.1.3.2 Time-series analysis

The nature and general limitations of the time-series analysis have been dealt with extensively in Section 6.1.2 but two important limitations in the present study have not been discussed in any detail. These are: the reconstruction of the time-series using linear transitions; and the validity of STSD in assessing the degree of synchrony between time-series.

8.1.3.2.1 Reconstructing the time-series representing growth. Each of the reconstructed time-series analysed in this investigation is assumed to be a valid representation of growth changes expressed during specific time intervals at a particular site and by a particular variable. In the absence of measurement, geometric and magnification errors each measured increment of growth will be the actual change resulting from growth during a particular observation interval. However, in reconstructing a time-series over multiple sequential intervals the transitions between the sample points have been represented by straight lines. Consequently, some important features of the true temporal pattern of growth will almost certainly have been lost. Without further data from additional sample points (*between* the existing sample points) it is not possible to recover the ‘true’ pattern of growth. The question is, however, does the use of linear functions to represent the transitions between sample points affect the validity of the assessment of synchrony between time-series? This largely depends on the method used to detect and measure the degree of similarity or match between the time-series – the STSD score.

8.1.3.2.2 The validity of STSD as a measure of the synchrony between time-series. The short time-series distance (STSD) is claimed to be insensitive to the features that make the traditional measures of synchrony unsuitable as in the present study (Möller-Levet *et al.,* 2003; Liao, 2005). This measure is not, however, a true ‘metric’ (in the mathematical sense) and suffers from four main disadvantages and limitations.

First, the STSD is calculated as the square root of the sum of the squared differences of the transitions between sample points. Consequently, the STSD gives greatest importance to close matches between points further from the means of the time-series. That is to say, multiple similar low amplitude variations in the time-series contribute less to the apparent match than does a single close match between higher amplitude variations. The relevance of this in the present context is that two time-series with coincident high amplitude pubertal peaks will generally be assessed as having a high level of synchrony even where there is only a low correspondence at the other lower amplitude time points.

Secondly, similar STSD scores can occur for pairs of time-series that differ by a similar amount but at widely differing points along the data sequence. Thus, it cannot be assumed that two time-series having the same STSD score with the index time-series are themselves identical or even quite similar in their overall temporal structure.

Thirdly, a particular STSD score is not uniquely associated with a specific level of statistical significance. This depends on the number of sample points in each time-series and on the number of pairs of time-series to be tested simultaneously.

Although these three points are important limitations to the accurate assessment of synchrony between time-series, STSD scoring is considered to be the only method presently available that can handle short, unevenly sampled time-series and at the same time take into account the temporal order of the individual samples forming the time-series (Lee *et al.*, 2002; Liao, 2005; Floratou *et al.*, 2010).

An additional, limitation of STSD scoring is that there is no analytical method for determining the probability (*p*-value) of a particular STSD score and no tables for such an assessment are available. If unverified and often unverifiable assumptions are to be avoided, the probability value for a given STSD score must be determined by a *permutation statistical method*: either a permutation exact test; or a randomisation (*resampling permutation*) test (Berry *et al*., 2016). The former method is impractical for even the shortest time-series in this study. For example, a discrete time-series comprising only 10 sample points would give rise to 3,628,800 possible permutations; each one with an associated STSD score. Such a computationally intensive requirement was deemed impractical. Consequently, resampling randomisation tests were used in the main study but these too are computationally intensive if an accurate probability estimate is required. Twenty thousand randomisations were used to determine the probabilities in the present study but even this can only provide certainty to the first two decimal places – for three decimal places of accuracy at least of 1,000,000 randomisations are required (Berry *et al.,* 2016). Therefore, caution needs to be exercised in interpreting the probability values assigned to the degree of synchrony particularly those where, $p < 0.005$.

8.1.3 The Limitations Arising from the Sample

The major threat to the validity other than the inherent limitations of the practical and analytical methods is the nature of the sample.

The size of the sample provides its most obvious limitation. Like all longitudinal growth samples its size is, as Tanner (1981) has put it, “pitiful”. If the purpose of the sample was to establish the range of variability in the general population then this size of sample would be grossly inadequate. However, this was not the purpose and in this context it is worth noting that the present sample is only smaller by one subject than the largest longitudinal sample ever reported with tantalum implants in both jaws[¶].

The materials used in the present study (radiographs) were drawn from the records of a human growth study undertaken five decades ago and that by their existence, defined not only the sample but also the ‘population’ from which the sample was drawn. As in any analysis of a growth study, the growth had first to occur and in this strict sense the sample was retrospective. Despite this, there are important features of the present sample that distinguish it from the general retrospective samples that have pervaded clinical research.

The subjects in the original growth study were not recruited from individuals who attended for orthodontic treatment. Instead, they were children who had attended a paediatric dental clinic. As such, they differ from most other long and short-term orthodontic studies where tantalum implants have been used.

The sample used in the present study was drawn from those individuals in the Mathews (UCSF) growth study who had not received orthodontic treatment, even if treatment was ultimately undertaken. Because of this, the sample is possibly subject to a hidden bias in that only those subjects who did not have a malocclusion severe enough to warrant treatment have been included. Consequently, it cannot be considered fully representative of the wider child population in the USA where the prevalence of malocclusion warranting treatment is around 58% (Proffit *et al.*, 1998). Thus, the sample

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[¶] Björk and Skieller’s (1972) sample of 21 subjects included 2 subjects with implants only in the mandible and 7 additional subjects where extractions had been performed before or during the study.

may have been biased towards the less severe types of dental and skeletal discrepancies. However, to paraphrase Solow and Siersbæk-Nielsen (1986), the aim of the study was to detect growth co-ordination around the growth rotations of the jaws and such mechanisms may be assumed to operate in all subjects whether or not malocclusion is present.

8.2 THE INITIAL SURVEY OF ASSOCIATIONS

8.2.1 The Motives Underlying the Initial Survey of Associations

The initial survey was undertaken for three primary reasons: first, to allow comparison with the findings of previous studies: secondly, to provide broad general summaries of the relationships between MGR and other growth variables; and thirdly, as an exploratory procedure to locate anatomical sites and growth variables that might usefully be investigated in more detail and at higher temporal resolution in the main time-series study

8.2.1.1 Associations Between MGR and the Other Growth Variables

The findings of the initial survey broadly agree with those found in previous implant studies by Björk and Skieller (1972, 1976, 1983), Ødegaard (1970a, 1970b), Lavergne and Gasson (1976), Gasson and Lavergne (1977a), Halborg and Rank (1978), and Baumrind *et al.*, (1996). That is, the main correlations with MGR were between the directions of growth displacements of the jaws, the growth rotation of the maxillae in the sagittal plane, condylar growth direction, the horizontal migration and translocation of the molars, and the change in angulation of the long axis of the maxillary molars.

Several additional structures and associated variables were examined in this study that were not investigated in previous implant studies. In particular: the displacement of the hyoid bone; and the change in resting height of the dorsum of the tongue. The correlations between MGR and the variables expressing displacement of the hyoid bone failed to reach significance at the $\hat{p} = 0.05$ dependency-adjusted Bonferroni threshold ($r_{(n=11)} = 0.694$**),** with the strongest association (with *Hyoid-H*) explaining less than a third of the variance ($r^2 = 0.328$). However, the vertical change in the postural height of the dorsum of the tongue was statistically significantly correlated with MGR ($r = -0.800$, $\hat{p} = 0.01$).

This later finding is of particular interest as a statistically significant association was found previously in a longitudinal study of head posture, growth and facial form (Springate, 2012). In that study the change in postural height of the tongue was statistically significantly correlated with MGR but the strength of the association was only moderate ($r_{(n=59)} = 0.57$, $r^2 = 0.32$, $p<0.0001$). However, the change in postural height of the tongue was also significantly associated with the change in cranio-cervical posture ($r_{(n=59)} = 0.61$, $r^2 = 0.37$, $p<0.0001$), which itself had previously been reported to be significantly correlated with MGR ($r_{(n=43)} = 0.55$; $p < 0.001$) by Solow and Siersbæk-Nielsen (1986). The relationships between the postural height of the tongue and the sagittal growth rotations of the maxillae and mandible are discussed in more detail below (Section 8.3.2.3).

In addition, a further group of associations were assessed in this study, over and above those reported in the previous studies cited above, to examine the quantitative relationships between general somatic growth, as represented by the variable, *CervSp*, and the variables expressing growth and growth related changes throughout the jaws and dentition. This revealed a pattern quite distinct to that shown by the associations between MGR and the same growth variables, as indicated in Figures 7.1 and 7.2.

This result is particularly surprising in view of the close, ‘mirror image’ relationship reported for MGR and somatic growth maturation by Björk and Skieller (1983). However, Björk and Skieller chose to use condylar growth as the index for somatic growth in their 1972 and 1983 studies. They argued that cranial dimensions do not correlate strongly with the length of the long bones nor with stature and therefore they selected condylar growth to represent physical maturity rather than the more usual measures of sitting or standing height.

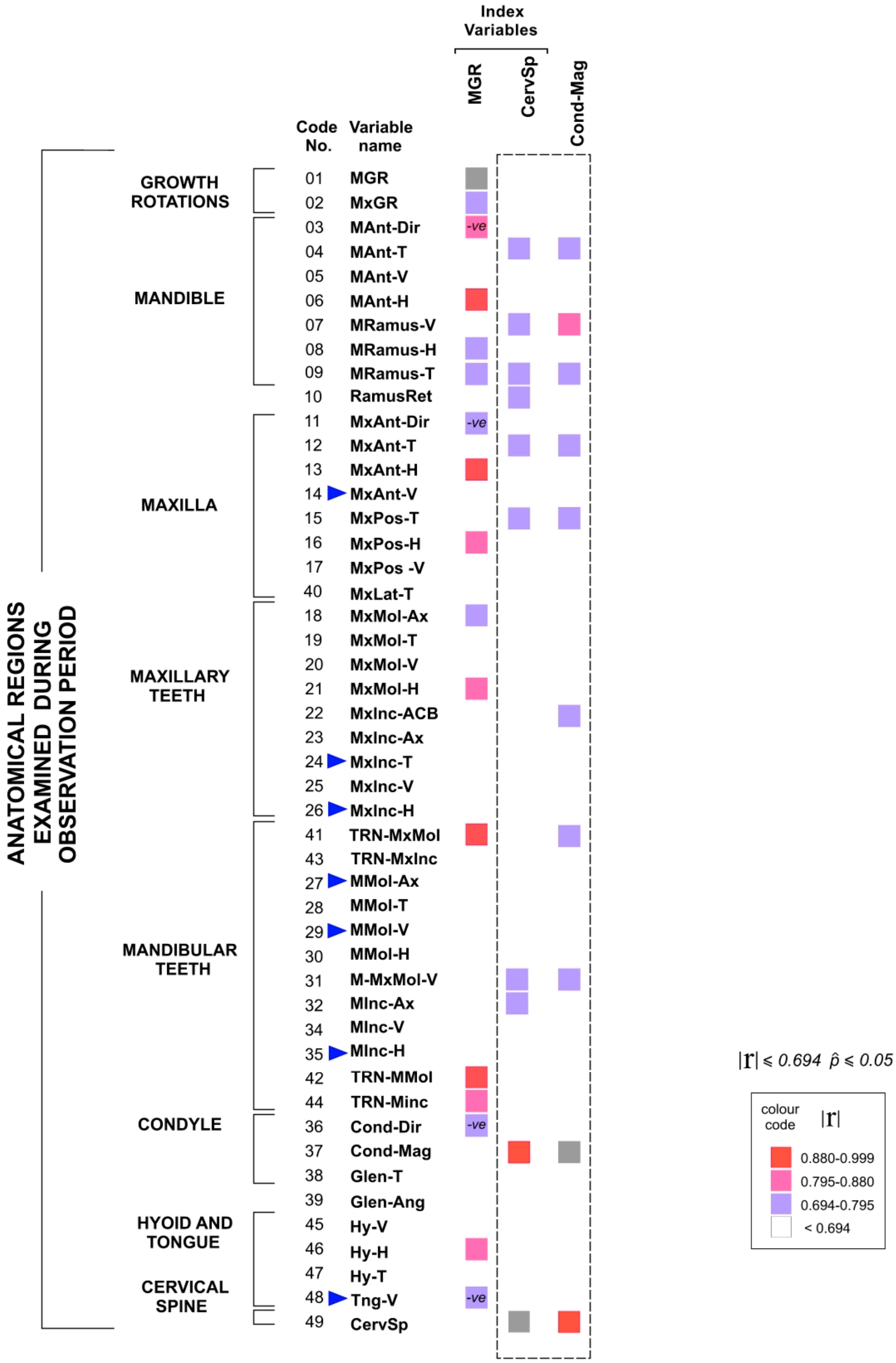
While it is widely accepted that the adolescent peak in condylar growth is reached a few months *after* the peak in stature (Nanda, 1955; Björk and Skieller, 1983; Tanner, 1962), Nanda, (1987) found the mean age for the female adolescent peak in mandibular growth occurred only 0.15 years later when maturation was assessed from growth of the cervical vertebrae rather than from standing height. This finding is supported by Johnson *et al.*, (2016) who emphasised the broad equivalence of somatic maturation assessed by either measure - a view reinforced by Hagg, *et al.*, (1987) and by Patcas *et al.*, (2016). In addition, it is worth recalling that in Björk’s studies it was not condylar growth that was measured but the change in location of the point *articulare*, which it is now known does *not* follow the same direction or pattern of growth of the condylar head (Buschang and Santos-Pinto, 1998; Patcas *et al.*, 2016).

Nevertheless, because of the marked differences found in the patterning of the correlations between the two index variables (*MGR* and *CervSp*) in this study, it was felt to be important to examine the pattern of correlations when *Cond-Mag* (condylar growth magnitude) is used as the index variable for somatic growth. The results are shown in Figure 8.1. As can be seen, the pattern is very similar to that for *CervSp* and quite distinct to that for *MGR.*

The close similarity between the magnitude of condylar growth and that of the cervical spine and the lack of a systematic variation in the numerical ratio between them across the range of MGR found in this current sample contradicts Houston's theory (Houston, 1988) of the causation of MGR. In that theory, it was proposed that MGR results from differences in the vertical growth of the condyle and cervical spine (Houston, 1988).

8.2.1.2 Differences between the Associations with General Somatic Growth and Mandibular growth Rotation

General somatic growth (represented by either *CervSp* or *Cond-Mag*) with its pronounced adolescent spurt provided statistically significant correlations (of moderate to high strength) with total growth displacement at the main skeletal sites (anterior mandible; mandibular ramus; anterior maxilla; posterior maxilla and articular fossa) while MGR correlated only weakly with total growth but strongly with the horizontal components of growth displacement at the same skeletal and dental sites. This may provide an explanation for the almost universal failure to detect an adolescent growth spurt in the horizontal aspects of craniofacial growth (Bishara *et al.,* 1981; Jamison *et al.,* 1982; Chvatal *et al.,* 2005; Alexander *et al.,* 2009; Buschang *et al.,* 2013). That is, the horizontal aspects of growth at sites throughout the face reflect the pattern of MGR rather than that of somatic growth.



		Index Variables		
Code No.	Variable name	MGR	CervSp	Cond-Mag
01	MGR	▩		
02	MxGR	🟪		
03	MAnt-Dir	▨ -ve		
04	MAnt-T		🟪	🟪
05	MAnt-V			
06	MAnt-H	🟥		
07	MRamus-V		🟪	▨
08	MRamus-H	🟪		
09	MRamus-T	🟪	🟪	🟪
10	RamusRet		🟪	
11	MxAnt-Dir	🟪 -ve		
12	MxAnt-T		🟪	🟪
13	MxAnt-H	🟥		
14 ►	MxAnt-V			
15	MxPos-T		🟪	🟪
16	MxPos-H	▨		
17	MxPos -V			
40	MxLat-T			
18	MxMol-Ax	🟪		
19	MxMol-T			
20	MxMol-V			
21	MxMol-H	▨		
22	MxInc-ACB			🟪
23	MxInc-Ax			
24 ►	MxInc-T			
25	MxInc-V			
26 ►	MxInc-H			
41	TRN-MxMol	🟥		🟪
43	TRN-MxInc			
27 ►	MMol-Ax			
28	MMol-T			
29 ►	MMol-V			
30	MMol-H			
31	M-MxMol-V		🟪	🟪
32	MInc-Ax		🟪	
34	MInc-V			
35 ►	MInc-H			
42	TRN-MMol	🟥		
44	TRN-Minc	▨		
36	Cond-Dir	🟪 -ve		
37	Cond-Mag		🟥	▩
38	Glen-T			
39	Glen-Ang			
45	Hy-V			
46	Hy-H	▨		
47	Hy-T			
48 ►	Tng-V	🟪 -ve		
49	CervSp		▩	🟥

$|r| \leqslant 0.694$ $\hat{p} \leqslant 0.05$

colour code	$|r|$
🟥	0.880-0.999
▨	0.795-0.880
🟪	0.694-0.795
⬜	< 0.694

Figure 8.1 Comparison of the locations of significant associations for *CervSp* and *Cond-Mag.*

The Figure is a replica of Figure 7.1 showing the associations for the two index variables (*MGR* and *CervSp*) with an additional column showing the locations of significant correlations if the magnitude of condylar growth (*Cond-Mag)* were to be used as the index for general somatic growth. The Figure was constructed using Pearson's product-moment correlation coefficients for all the associations with *Cond-Mag*. As is evident, the pattern of the associations is quite similar but not identical for *CervSp* and *Cond-Mag*. Both differ substantially from the pattern for *MGR*.

8.2.1.3 Condylar Growth and Growth Rotations of the Jaws

Perhaps the most surprising finding of the initial survey of associations was the absence of any meaningful correlation between MGR and the variables expressing the magnitude of condylar growth (*Cond-Mag; MRamus-V*). Previous implant studies have implicated the growth of the condyle as a major factor in the causation of growth rotations of the jaws (Björk, 1963; Ødegaard, 1970a). This view was given its most compelling support by the classic study of Björk and Skieller (1972) in which parametric correlations of r = -0.79 and r = -0.70 were reported between MGR and condylar growth direction, and condylar growth intensity respectively. The corresponding values[¶] found in the present study were, r = 0.769 for condylar growth direction and, r = 0.534 for *Cond-Mag*. This later value is substantially lower than that found by Björk and Skieller (1972) and failed to reach the dependency-adjusted Bonferroni threshold at $\hat{p} = 0.05$ ($r_{(n=11)} = 0.694$).

Given the highly significant correlation between MGR and condylar growth magnitude (or "intensity") reported by Björk and Skieller (1972) and its potentially causal role in growth rotations of the jaws it was felt to be of interest to find out why no meaningful correlation could be found in the current sample. The most obvious possibilities are: (i) the correction for multiple inference applied in the present study which effectively 'raised the bar' for the acceptance of statistical significance; and (ii) the nature of the two samples.

The absence of any correction for multiple inference, as in the study by Björk and Skieller (1972), would have permitted *MRamus-V* to just reach statistical significance at the $p < 0.05$ level. However, Björk and Skieller did not investigate this variable. The variable that was investigated, *Cond-Mag*, provided a correlation with MGR in the present study (r = 0.534) that was very different in absolute magnitude to that found by Björk and Skieller (r = -0.70) and which, even in the absence of a correction for multiple inference would still have fallen short of the lower threshold, $r_{(n=11)} = 0.602$, for significance at $p = 0.05$ univariate level.

The nature of the samples differed in three important main ways: the size of the samples; the ages of the subjects; and the methods of selection.

[¶] The difference in the sign of the correlations for MGR is simply because forward MGR is designated as positive in the present study but as negative in the studies by Björk and Skieller (1972, 1983).

The difference in the sample sizes directly affects the confidence intervals that attach to the estimates of the correlation coefficients derived from those samples. The practical effect of this is twofold. First, even quite small measurement errors will have a disproportionately larger effect on the estimate of the correlation coefficient derived from the smaller sample; secondly, for any given level of correlation a greater statistical significance would attach to that derived from the larger sample.

The age range of the present sample was the same as that of Björk and Skieller's 1972 study but with a lower mean age. Nevertheless, for all but two of Björk and Skieller's subjects the age range of their subjects was contained within that of the current sample. Consequently, we should not expect any major or fundamental differences in the findings. However, the method of selecting the subjects was very different. The present sample, although not truly random, was not subject to an overt selection bias making it a 'restricted sample' in the statistical sense of adding or deleting individuals because of their values on one of the variables of interest (Altman, 1991) but that used by Björk and Skieller (1972) clearly was. They stated:

"The sample was small and clearly contained a greater number of extreme variants than would be expected in a random sample…"

Consequently, it appears that in the absence of overt selection bias there is no meaningful correlation between the magnitude of condylar growth and MGR as shown by the sample examined in this study and, incidentally, by the smaller sample in the implant study by Björk and Skieller (1983) where a correlation of, r = -0.62 was reported.

8.2.1.3 Factors Potentially Responsible for the Control of MGR

By definition, growth rotation of the mandible will only occur where there is a difference in the amounts of lowering of the posterior (condylar) and anterior (tooth-bearing) parts of the mandible – that is, between the lowering of the articular fossa and growth of the condyle on the one hand and the sutural lowering of the maxilla and eruption of the occluding teeth on the other (Solow, 1980). Consequently, if the variation in the magnitude of condylar growth (or its vertical component) is not a significant determinant of MGR then it seems reasonable to assume that one or more of the other growth sites contributing to the vertical descent of the mandible (relocation of the articular fossa, sutural lowering of the maxilla, eruption of the occluding teeth) must be responsible. Surprisingly, no significant correlation was found between MGR and the variables expressing vertical growth at any of these sites.

The explanation for this uniformly negative series of results appears to be that MGR depends on the *difference* in growth between posterior and anterior sites and not (necessarily) on the *actual* growth at any of these sites. That is to say, the effect on MGR of growth at a particular site will depend not only on the growth at that site but also on the growth at all the other sites that contribute to vertical descent of the mandibular core. Consequently, examining the correlations between MGR and the growth at individual sites, may not provide an indication of their contributions to MGR.

The total vertical displacement posteriorly (the combination of vertical condylar growth and the vertical relocation of the articular fossa) is expressed by the single variable *MRamus-V.* The total vertical displacement anteriorly is expressed by the sum of the variables *MaxAnt-V* (or *MaxPost-V*) and *M-MxMol-V.*

The numerical difference between posterior lowering and the individual components of anterior lowering provided highly significant correlations and strong associations with MGR but only for the maxillary variables and not for the combined vertical component of eruption of the maxillary and mandibular first molars, as indicated in Table A3. This latter finding is particularly interesting because it indicates that variations in the vertical eruption of the buccal occluding teeth contribute little to the variation in MGR across the sample. Nevertheless, although the variable *M-MxMol-V* was only very weakly associated with *MGR* it was strongly associated and significantly correlated with *CervSp* (the index of general somatic growth: $r = 0.787$, $r^2 = 0.619$, at $\hat{p} < 0.05$) and also had a very similar numerical ratio with *CervSp* (mean = 0.59, *SD* = 0.11) across the sample. This appears to imply that vertical eruption of the occluding teeth simply keeps pace with general somatic growth as does the growth of the condyle ($r = 0.899$). The vertical eruption of the buccal occluding teeth thereby tending to maintain the pre-existing orientation of the mandibular core without inducing additional rotation.

This close relationship between the rate of somatic growth, the rate of post-functional eruption of the occluding teeth and the rate of condylar growth has been reported previously (Siersbaek-Nielsen, 1971; Solow and Iseri, 1996b;) and is generally viewed as a secondary consequence of the adaptation of the eruptive movements of the occluding teeth to the changes in vertical jaw relationship - the teeth simply ‘passively’ erupting to fill the space between the jaws created by condylar growth (Darling and Levers, 1976; Van den Linden, 1977; Proffit, *et al.*, 2007; Solow and Iseri, 1996a, 1996b; Liu and Buschang, 2011).

In the present sample this strongly suggests that it is primarily the *difference* between *vertical descent of the core of the ramus* and the *vertical descent of the maxillary core* that gives rise to, or produces, growth rotation of the mandible. The factors that control or determine variations in these two vertical displacements are, however, not clear from the initial survey alone.

8.3 THE MAIN (TIME-SERIES) STUDY

Before discussing the findings of the time-series analyses it is important first to examine the relationship between the initial survey and the main time-series study.

8.3.1 Relationship Between the Initial Survey and the Time-Series Study

The initial exploratory survey employed correlation analysis to examine the associations between the total accumulated growth at several sites in the dentofacial complex and the accompanying growth rotation of the mandible. This type of correlation study has been used previously as a means of *inferring* the intra-individual relationships between MGR and other growth variables. However, what is actually assessed in this type of correlation study is how the amount of growth varies with different degrees of MGR across a group of subjects where each subject contributes only *one* data point to the estimate of the correlation coefficient. It is not possible to know with certainty if the pattern of associations between MGR and other growth variables *between* the subjects in the sample actually equates to the inferred pattern of associations *within* the individual subjects. Attempts to determine intra-individual patterns from those found at the level of the whole sample are a well documented error of statistical analysis known as the ‘ergodic switch’ or ‘ecological fallacy’ (Molenaar *et al.*, 2014).

Despite this fundamental uncertainty with the potential for mis-interpretation, this type of study does provide a less complicated means of investigation than the multiple high precision recordings required to provide a time-series of each variable for every subject. However, it is only with knowledge of the intra-individual associations between the variables through a sequence of observations during prolonged periods of growth that co-ordination of growth can be accurately assessed and potentially causal factors clearly identified.

Consequently, it is the results of the main, time-series investigation that provide the more direct means of determining the existence and nature of the relationships between MGR and growth elsewhere in the hard-tissue dentofacial complex within the *individual* human subject.

8.3.2 The Time-Series Analyses

The first thing that is notable about the findings of the time-series analyses is the variability of the data sequences from subject to subject in terms of the structures whose growth either alone or in combination exhibited (or did not exhibit) statistically significant synchrony with MGR. However, some clear and consistent patterns of synchrony emerged that were present and in most or all of the subjects in the sample. The discussion of the main time-series study is centred on these consistent patterns.

The number of variables examined in the main study was reduced from that in the initial survey of associations to limit, as far as possible, the elevation of the threshold for acceptance of statistical significance in this part of the investigation. This was largely done by removing redundant variables as indicated in Section 6.1.2. Furthermore, where the random error associated with a particular variable was close to the mean (of total change) that variable was also eliminated from consideration in the time-series study. Thus, variables expressing relocation of the hyoid, relocation of the articular fossa and postural height of the dorsum of the tongue were not initially considered. However, an additional variable, measured from the frontal radiographic projection, was included in the time-series study that was not present in the initial survey: the mutual transverse rotation of the maxillae (*r-MxTRot*).

Although the number of variables examined in the main study was reduced from the initial survey, the sites where the temporal pattern of growth was closely synchronous with that of MGR were similar to the sites identified in the initial survey but with some important exceptions. The two most prominent of these exceptions were: 1) the finding of a highly statistically significant degree of synchrony between *r-MGR* and: (i) the variable expressing the vertical displacement of the core of the mandibular ramus, *r-MRamus-V;* and (ii) the vertical displacement of the anterior maxilla *(r-MaxAnt-V*).

The corresponding variables in the initial survey failed to reach statistical significance with MGR. However, their numerical *ratios* (and *differences*) were highly statistically significantly correlated and strongly associated with MGR (Table A3). This is taken to imply three things: (i) that the neither the magnitude of vertical displacement of the core of the ramus nor the vertical displacement of the maxillae is uniquely linked to a specific amount or rate of MGR and therefore, they are probably not significant determinants of MGR across the multi-subject group; (ii) that the *ratios* of the vertical descent of anterior and posterior parts of the mandibular core *are* closely linked to a specific amount of MGR; and (iii) that together the effect of vertical descent of the ramus and vertical descent of the maxillae produces growth rotation of the mandible.

8.3.2.1 The vertical component of condylar growth

The findings from the time-series analyses indicate that the growth of the condyle and the vertical growth displacement of the ramus generally follow different patterns within each subject. That is, the annual variations in the magnitude of condylar growth (*r-Cond-Mag*) correspond closely to the pattern of the index of general somatic growth (*r-CervSp*) while the variations in the magnitude of *vertical* descent of the ramus (*r-MRamus-V*) correspond to the patterning of MGR.

It is tempting to speculate that the reason for this difference is that *r-MRamus-V* combines the vertical displacement due to condylar growth with the additional displacement resulting from remodelling of the articular fossa and growth at the spheno-occipital synchrondrosis.

At first sight this appears to be a highly plausible explanation[¶]. However, the magnitude of the added component due to the *vertical relocation* of the articular fossa is known to be small in comparison to the magnitude of condylar growth (Buschang and Santos-Pinto, 1998; Buschang *et al.,* 1999) and, consequently, is seems unlikely to have anything more than a minor effect on the vertical descent of the ramus.

These data are, however, compatible with a different explanation, which is that the *variations* in condylar growth direction from year to year modulate the condyle's inherent GSG pattern of growth to produce the MGR pattern in the *vertical* descent of the ramus. That is to say, the condyle's inherent GSG pattern of growth is *modulated* by the pattern of its annual growth directions to produce the MGR pattern in its *vertical* component of growth which is expressed in the vertical descent of the ramus. This modulation, if it exists, must be related to the trigonometric cosine[§] function of the angle of condylar growth over each annual observation interval.

This alternative explanation is easily tested and examples from across the range of MGR in this sample are shown in Figure 8.2. As is evident, if each mean annual growth increment is multiplied by the cosine of the accompanying angle of condylar growth it

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[¶] A similar argument was advanced by Björk and Skieller (1972) to explain the origin of MGR but was not tested by them.

[§] Or the sine function of the angle depending on the way the growth angle is measured.

produces a pattern of vertical condylar growth that is closely synchronous with that of MGR (and of *r-MRamus-V*).

Consequently, it is reasonably certain that the direction of condylar growth provides the link between the magnitude of condylar growth, the vertical descent of the ramus and the pattern of rotation of the mandibular core but it is clearly not the only factor determining the magnitude or rate of MGR. The initial survey pointed to the *combination* of the vertical descent of the core of the ramus *and* the vertical descent of the maxillae as the direct mechanical cause of MGR.

8.3.2.2 The vertical growth displacement of the maxillae

As was the case with the condyle, the initial survey indicated that maxillary growth in the sagittal plane was strongly correlated with the index of general somatic growth (*CervSp*). The initial survey also indicated that the horizontal component of maxillary growth was highly statistically significantly correlated and strongly associated with *MGR* ($r = 0.940$, $r^2 = 0.883$, $\hat{p} < 0.001$) but the correlation of its vertical components with *MGR* failed to reach statistical significance (*MxAnt-V*: $r = -0.676$, $r^2 = 0.457$, $\hat{p} > 0.05$ NS. *MaxPost-V*: $r_s = -0.336$, $r_s^2 = 0.113$, $\hat{p} > 0.05$ NS). Despite this, the ratio (and difference) between the vertical descent of the ramus and either of the two variables expressing vertical maxillary growth provided a highly significant correlation with *MGR* ($r = 0.806$, $\hat{p} < 0.01$; $r = 0.877$, $\hat{p} < 0.01$).

Similarly, the time-series analyses revealed a pattern of maxillary growth that was largely synchronous with the index of general somatic growth (*r-CervSp*) and a horizontal growth displacement that was strongly synchronous with *r-MGR*. However, they also revealed a pattern of growth for the vertical displacement of the maxilla that was strongly anti-synchronous (that is, the pattern was inverted) to that of MGR. Thus, the horizontal and vertical growth displacements of the maxillae both generally followed the same pattern of growth as that of MGR (one directly the other inversely). Consequently, the ratio of the horizontal to vertical *increments* of maxillary growth displacement produce a temporal pattern that is indistinguishable from the pattern of MGR. Nevertheless, *overall* maxillary growth maintained the same or very similar pattern to that of GSG. Examples of these relationships are shown in Figure 8.3.

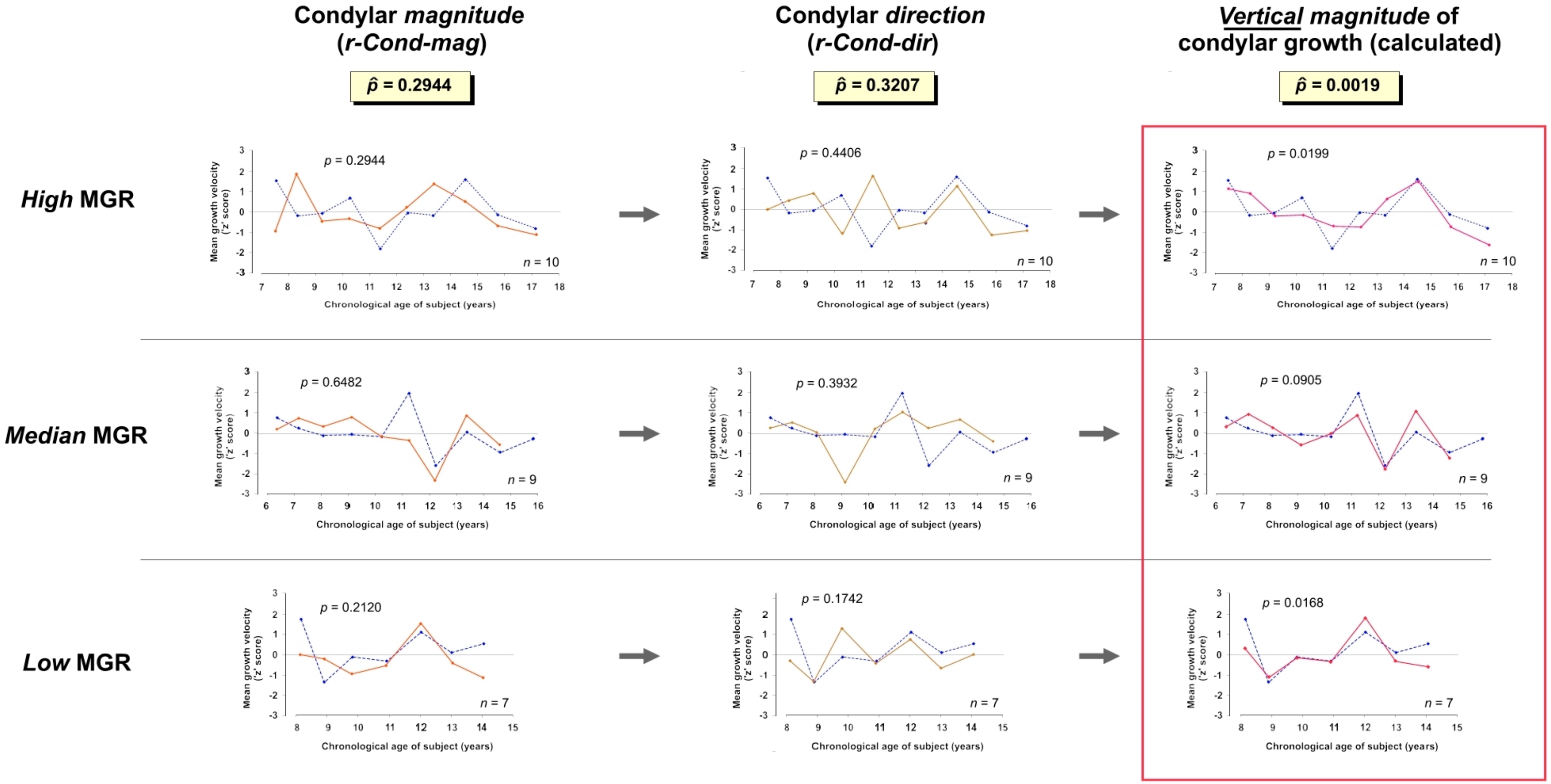

Figure 8.2 **Time-series plots showing the modulation of total condylar growth magnitude by the direction of condylar growth for subjects with the: maximum; median; and minimum cumulative growth rotation of the mandible.**

The Figure shows time-series plots of condylar growth magnitude (◆—◆—◆); condylar direction (◆—◆—◆) and the vertical magnitude of condylar growth (◆—◆—◆) *calculated* from the product of the cosine of the direction of condylar growth with the total magnitude of condylar growth. The time-series plot of growth rotation of the mandible (*r-MGR* ◆-‑◆-‑◆) is indicated against each of the other variables. The degree of synchrony between *r-MGR* and the condylar variables is indicated by the statistical significance of the match between the two time-series. The *p*-value on each graph is the statistical significance of the match between the two time-series not taking into account multiple inference and dependency between the variables. The *p*-value for the multi-subject group analysis ($\hat{p}$) is given at the top of each column. As is evident, neither the magnitude of condylar growth nor its direction are strongly synchronous with *r-MGR*. However, the modulation of the *magnitude* by the *direction* of condylar growth produces a pattern of *vertical* condylar growth (magnitude) that is strongly synchronous with *r-MGR* (and with the vertical decent of the ramus) both at the level of the individual subject and at level of the whole sample (the multi-subject group). The High; Median; and Low MGR subjects in the Figure are cases 5♂; 2♂ and 7♀respectively.

The simultaneous expression of these two features of maxillary growth appears to only be possible if the horizontal and vertical displacements vary together with one increasing as the other decreases thereby resulting in a change in the *direction* of maxillary displacement but *not* of its overall magnitude. This change in direction of maxillary displacement was therefore coincident with a change in the *rate* of MGR. Interestingly, a similar patterning of maxillary growth was also found in a tantalum implant study in primates in which the vertical and horizontal growth of the maxilla varied reciprocally while leaving the total growth unaffected (McNamara, 1973).

Differences in the patterns (and timing) of horizontal and vertical maxillary growth have also been noted previously in humans (Hunter and Miller, 1968; Iseri and Solow, 1990; Solow and Iseri, 1996b) and in primates (McNamara, 1973; Schneiderman, 1985, 1992) but have generally been interpreted as reflecting differences in the factors controlling horizontal and vertical maxillary growth and not that the two are reciprocally linked or inversely related. However, the data presented by Iseri and Solow (1990) from their implant study of maxillary growth show clear evidence of an inverse relationship between the means of horizontal and vertical maxillary growth. Nevertheless, Iseri and Solow (1990) and Solow and Iseri (1996a) chose to interpret this as indicating possible differences in the mechanisms of maxillary growth displacement in the earlier and later periods of maxillary growth.

8.3.2.3 The Association Between the Direction of Condylar Growth and the Direction of Maxillary Growth Displacement

The findings of the time-series analysis and of the initial survey point strongly to it being the *difference* between the vertical growth of the condyle and that of the maxillae that produces MGR – an effect that is centred on the changes in their directions of growth. It is clear that the patterns of directional changes in the growth of the condyle and of the maxillae (in the sagittal plane) are also themselves closely synchronous at the spatial and temporal scales examined in the main study. That is, the directional changes of the condyle and maxillae are coupled such that a change in the rate of vertical displacement of the core of the ramus is accompanied by reciprocal change in the rate of vertical displacement of the maxillae.

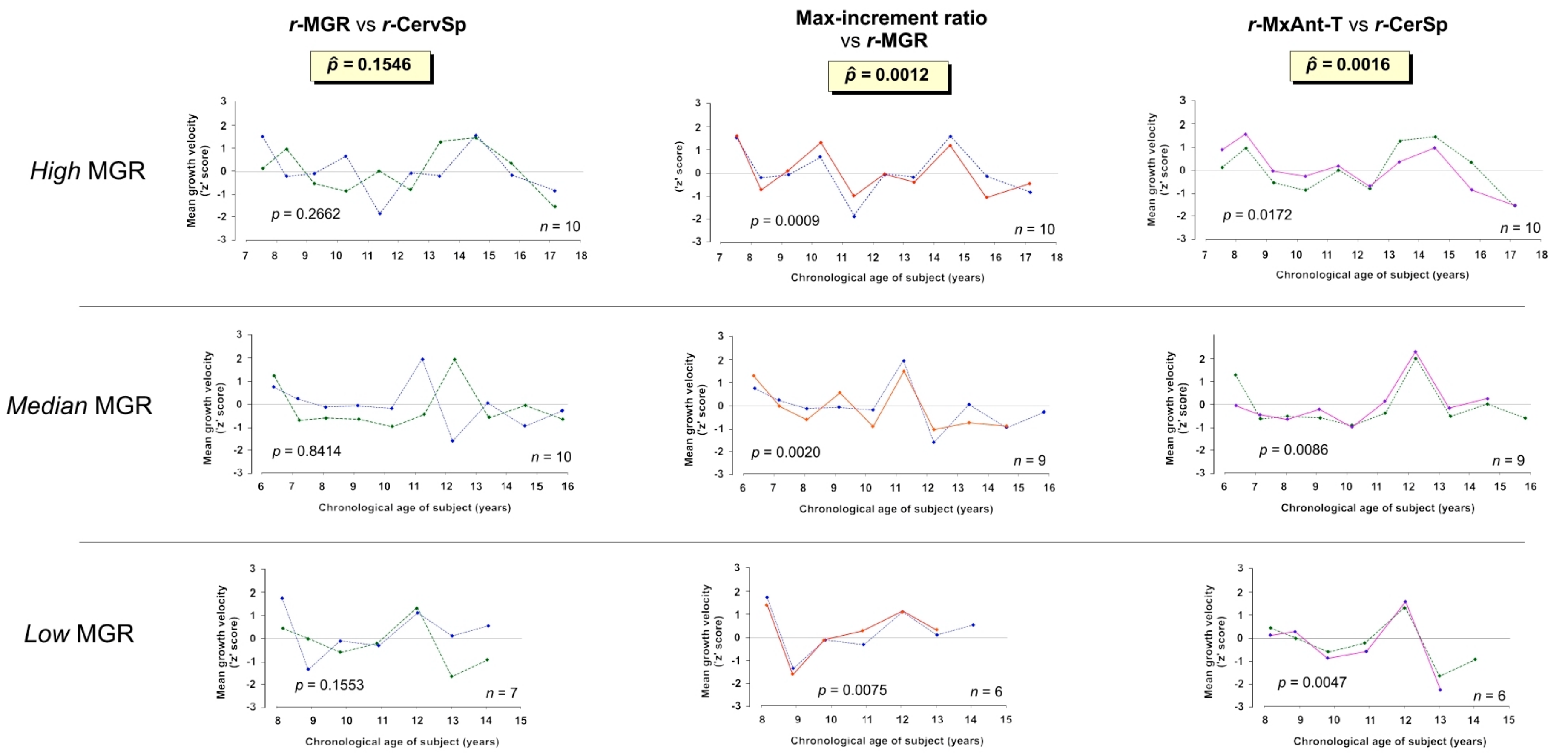

Figure 8.3 **Time-series plots of total (anterior) maxillary growth displacement and the ratio of horizontal to vertical growth displacement relative to the patterns of: mandibular growth rotation; and general somatic growth.**

The time-series plots are shown for three subjects with the: highest; median; and lowest cumulative mandibular growth rotation over the total period of observation (N.B. forward rotation is designated as +ve). The left hand column shows the relationship between the time-series for the two index variables (*r-MGR* ♦---♦ and *r-CervSp* ♦---♦). The middle column shows the time-series of the ratio of horizontal to vertical growth displacement of the anterior maxilla (♦—♦) together with that for *r-MGR*. The right hand column shows the time-series for total (unpartitioned) growth of the anterior maxilla (♦—♦) together with that for *r-CervSp*. The p-value on each graph (p) is the statistical significance of the match between the two time-series taking into account multiple inference and dependency between the variables. The p-value for the multi-subject group analysis ($\hat{p}$) is given at the top of each column. As is evident, *r-MGR* and *r-CervSp* show only moderate levels of synchrony. The ratio of the horizontal to vertical increments of maxillary growth is strongly synchronous with *r-MGR* both at the level of the individual subject and at level of the whole sample (the multi-subject group) while total (unpartitioned) maxillary growth displacement is strongly synchronous with *r-CervSp*. The data are plotted at the mid-point of each observation interval. The High; Median; and Low MGR subjects in the Figure are cases 5♂; 2♂ and 7♀ respectively.

In the quest to explain the factors that *control* growth rotations of the jaws it seems sensible to begin with this close reciprocal relationship between these two most prominent determinants of MGR.

8.3.2.4 Growth direction of the condyle

There is evidence from experiments on rodents that the direction of condylar growth can be modulated by changes in functional loading and more especially by changes in the direction of distraction of the condylar head from the articular fossa (Whetten and Johnston, 1985). However, the most compelling evidence for strong environmental control of condylar growth direction comes from experiments on oral respiration and mandibular growth direction in primates by Harvold *et al.*, (1972, 1973, 1981), Tomer and Harvold (1982) and by Vargervik (1984). The results of relevance from the primate experiments indicated that as the mandible adopted a new postural position the condyle simply continued to grow back towards the articular fossa from its new displaced position. Thus, the direction of growth of the mandible depended primarily on its postural position.

In summarising several studies on primates Tomer and Harvold (1982) stated the following: *"No observation has indicated that the condyles have a tendency to grow in any direction other than toward the articular fossa."* Although there are clear differences between the rhesus monkey and man, there are marked similarities in condylar anatomy both at the gross and microscopic levels (Meikle, 1973; McNamara and Carlson, 1979; McNamara *et al.*, 1982). On the assumption that the human condyle behaves in a similar way, then the change is condylar direction observed in the present investigation might imply a change in mandibular posture that draws the condylar head postero-inferiorly in those subjects with marked forward MGR and antero-inferiorly in those subjects with low or backward MGR.

8.3.2.5 Growth direction of the maxillae in the sagittal plane

There is also much evidence that during the growth period the circum-maxillary suture system is responsive to the application of external forces such that the growth direction of the maxillae can be readily altered (Kambara, 1977; Nanda, 1978; Jackson *et al.*, 1979; Nanda and Hickory, 1984; Gallagher *et al.*, 1998). Consequently, for the maxillae to follow a reciprocal pattern of growth to the mandibular ramus the applied force must be antero-superiorly on the maxillae in those subjects with marked forward MGR. This force must, however, be largely absent in those subjects with low or backward MGR. If this distribution of applied forces results from, or accompanies, a change in the postural position of the mandible then there appears to be two obvious candidates for the origin of this force: the degree of tension in the soft tissue capsule of the face ('soft tissue stretching'); or the (postural) position of the tongue.

Variations in the stretch of the soft tissues resulting from changes in mandibular posture have been proposed as a major determinant of the direction of facial growth by Solow and Kreiborg (1978) in their 'soft tissue stretching hypothesis'. While changes in facial growth direction clearly follow changes in mandibular posture there is no independent evidence supporting the view that the cause is tension in the soft tissues of the face (Springate, 2012). However, where the normal forces from the lips and cheeks are unopposed by the tongue some affect on, at least, the width of the maxillary arch has been known for more than a century (Tomes, 1872).

The mandible is known to be a motor reference for the position of the tongue-hyoid-larynx column (Bosma, 1963) and the tongue and mandible are posturally linked (Cleall, 1972; Lowe, 1981). The habitual posture of the tongue and the 'rest position' of the mandible generally change together so that movement of the mandible away from the cranium is accompanied by postural lowering of the tongue (Janský and Holík, 1957; Daly *et al.,* 1982; Hellsing *et al.,* 1986).

The association between the changes in tongue posture and the direction of maxillary growth has been reported in experimental studies on respiration and skeletal growth in primates. For example, Harvold *et al.,* (1981) reported that in those experimental animals where oral respiration was secured by stable postural lowering of the mandible and where the tongue was held below the maxillary incisors forward growth of the maxilla was markedly reduced in comparison to both the control animals and to those animals that held the tongue in contact with the maxillary teeth and alveolus. The reason for the reduced forward growth of the maxilla appeared to be the lack of contact with the tongue. Yamaguchi (1980) also found significantly reduced forward growth of the maxilla in primate experiments where the tongue was held in a low postural position to allow mouth breathing.

In a further group of experiments on oral respiration in primates, Yamada *et al.,* (1997) carefully plotted maxillary and mandibular growth directions before and after nasal obstruction, using miniature Björk-style implants as the points of reference. In all the experimental animals with total nasal obstruction, the growth direction of the maxilla maintained the same relationship to the growth direction of the mandible before and after obstruction of the nasal airway. The growth directions of both bones became more vertical following the adoption of a lowered tongue posture.

Consequently, there is evidence, at least in primates, that the tongue plays an important role in guiding maxillary growth and maintaining the relative growth directions of the mandible and maxilla. Because of this it was felt to be important to examine the relationship between the annual pattern of tongue posture and that of MGR.

8.3.2.6 The relationship between growth rotation of the mandible and the postural height of the tongue

The changes in the postural height of the dorsum of the tongue were not included in the time-series analyses because of the low precision of location of the dorsum of the tongue that was found in the initial survey and because it proved impossible to visualise the surface outline from year to year in the radiographic images of three of the eleven subjects. Nevertheless, because of the potential link between changes in mandibulo-lingual posture and the reciprocal coupling of the growth directions of the condyle and maxillae, it was felt to be helpful to examine the relationship between tongue posture and MGR in those subjects were the dorsum of the tongue could be visualised. Consequently, this additional analysis is therefore limited to the remaining 8 subjects. The results are shown in Figure 8.4.

As can be seen, despite the low precision the pattern of postural changes in the dorsum of the tongue is broadly synchronous with the pattern of *r-MGR* in each of the subjects examined. Given the technical difficulties involved in the accurate and reproducible measurement of tongue posture this appears to be an impressive association. There are, however, two potential biases in these additional results: (i) these data are only from the subjects where the dorsal surface of the tongue lay away from the palate (and was relatively easily visualised) - it seems likely that those subjects where tongue posture was consistently high have been excluded from this analysis; and (ii) the radiographic recordings of the position of the tongue surface were made with the teeth in habitual occlusion and *not* with mandible in its postural position.

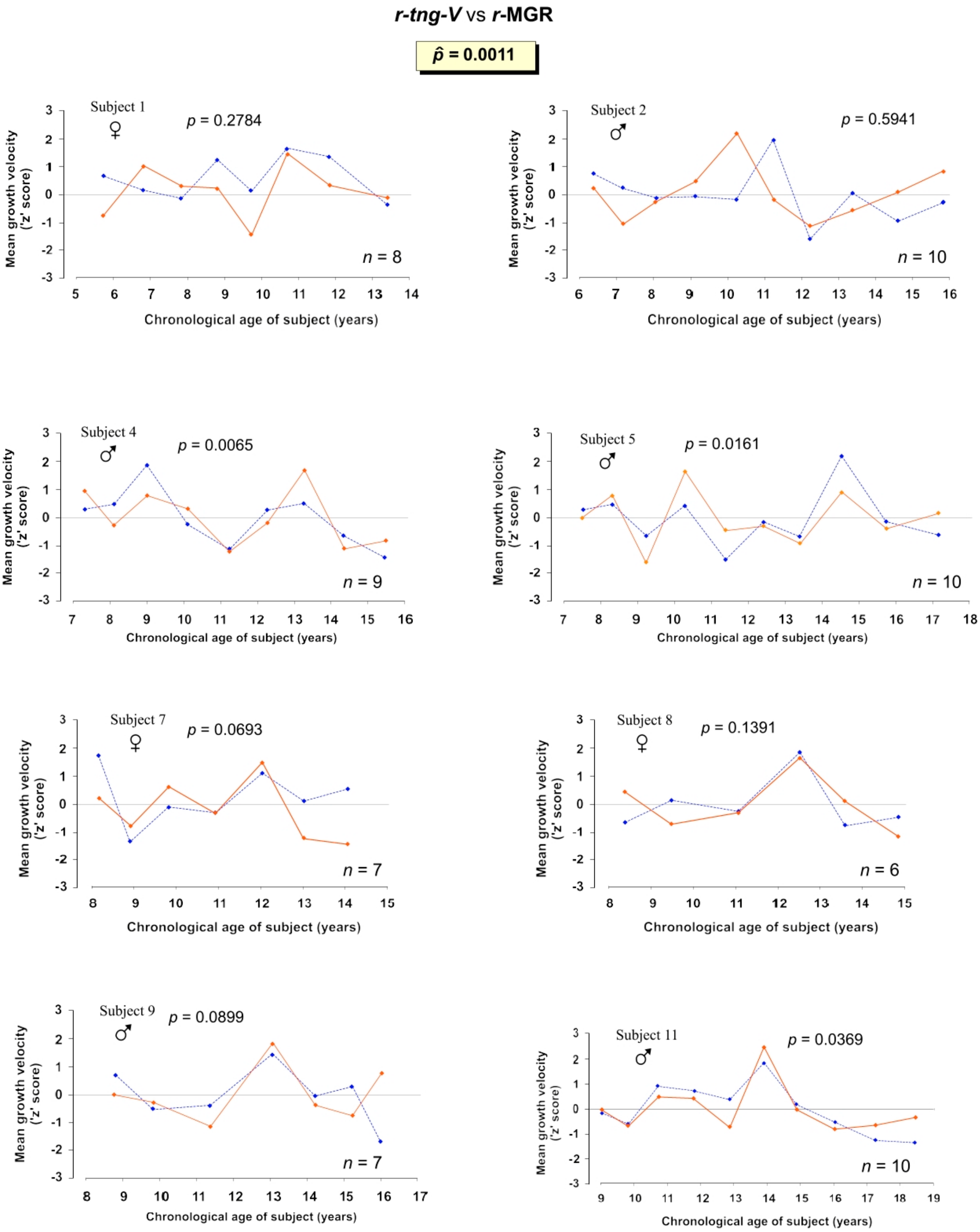

Figure 8.4 Time-series plots of the change in postural height of the dorsum of the tongue *versus* growth rotation of the mandible.

The times-series plots show the results for the 8 subjects where the dorsum of the tongue could be identified throughout the sequence of lateral cephalometric radiographs. It can be seen that the patterns of change in location of the dorsal surface of the tongue (*r-tng-V* ◆——◆) follow a similar pattern to the growth rotation of the mandible (*r-MGR* ◆┄┄◆) with the exception of subject 2. The intra-individual probabilities corrected for multiple inference and dependency between the variables are shown against each plot. The multi-subject probability is shown at the top of the diagram ($p = 0.0011$; $n = 8$).

8.4 A Possible Mechanism of Causation and Control of Growth Rotations of the Jaws

The preceding Section outlines a plausible mechanism to account for the close spatial and temporal *coupling* between the directional changes in the growth of the condyle and the growth displacement of maxillae in the sagittal plane - but is mandibulo-lingual posture the primary mechanism causing and *controlling* the growth rotations of the jaws? This question cannot be answered by the radiographic series employed in the present study. Nevertheless, if mandibulo-lingual posture does provide the underlying cause and control of growth rotations of the jaws it must also explain the other features strongly associated with MGR found in this and in previous studies.

There are five main additional features that the proposed mechanism is required to explain if it is to provide a credible basis for the origin of growth rotations of the jaws. These are:

(i) The axial change of the maxillary molar;
(ii) The translocation and horizontal migration of the buccal teeth in both arches
(iii) The sagittal growth rotation of the maxillae;
(iv) The transverse mutual rotation of the maxillae;
(v) Other effects frequently but inconsistently associated with mandibular growth rotation.

8.4.1 The axial change of the maxillary molar and the horizontal migration of the buccal teeth

The change of axial inclination of the maxillary molar and the horizontal migration of the buccal teeth are known to be closely linked (Björk and Skieller, 1972; van Beek and Fidler, 1977; van Beek, 1978; Baumrind et al., 1996) and will be considered together.

The change in the axial inclination of the maxillary first molar (relative to the maxilla) was found to be significantly correlated and strongly associated with *MGR* in the initial survey and its temporal pattern was closely synchronous with that of *r-MGR* in the time-series study. A similar statistically significant correlation and moderately strong association between the inclination of the maxillary molar and MGR was also reported by Björk and Skieller (1972) and a similar longitudinal pattern of mesial tilting was reported by Baumrind *et al.*, (1996). That is, in forward rotating subjects the maxillary first molar tipped forwards in the maxilla causing the tooth to gradually become more upright on its skeletal base. An effect that was absent in backward rotating subjects.

In the present investigation and in the studies cited above the change in inclination of the maxillary molar was also accompanied by a dramatic translocation of the crown of the tooth in forward rotating subjects. In the present study this brought the crown anteriorly (relative to the ACB) at a *faster rate* than the overlying maxilla to which it was attached.

If, during growth, the molar had maintained an approximately constant orientation to the maxilla, then this difference in the rate of anterior movement could simply be a consequence of the different distances of the points of measurement from the centre of rotation of the maxillary core. However, the molar did *not* maintain an approximately constant orientation to the maxilla and instead inclined mesially relative to the maxillary core at an average annual rate of 1.30 degrees (SD = 0.74 degs) which was significantly correlated with the rate of MGR. In addition, as the molar inclined mesially the crown migrated mesially by an amount that was significantly correlated and strongly associated with the change in inclination of the molar ($r_{(n=10)} = 0.834$; $p = 0.0021$; $r^2 = 0.70$). This pattern of movement of the maxillary molar is *not* consistent with the tooth being passively carried mesially by the growth rotation of the maxilla.

This motion is, however, consistent with an anteriorly directed force applied to the crown of the tooth (rather than its roots) – a force that varied directly with the *rate* of MGR. In the context of the present study it is suggested that this force is provided by the tongue, a conclusion, also reached by Yilmaz *et al.,* (1980) in a study on mesial drift in human subjects using ankylosed molars as the reference points. Nevertheless, it seems unlikely that this pressure was provided solely by the resting posture of the tongue. A more plausible explanation in forward rotating subjects is that not only must the tongue posture be raised but an active ‘push’ is required. Some evidence of this has been found in experimental studies of tongue function (swallowing). For example, Chang *et al.,* (2002) reported that the most forceful motion of the tongue was when it pushed upwards and anteriorly against the palate in the early final phase of swallowing (phase IIIa). The activity of the tongue during this phase of swallowing also showed the highest and most numerous correlations with dentofacial morphology and was strongly associated with anterior facial height and inter-maxillary depth.

8.4.1.1 Evidence against the hypothesis of pressure from the tongue

The idea that soft tissue pressures from the cheeks and tongue might be the cause of mesial migration was first advanced by Wallace (1904) but has generally been dismissed as implausible by later investigators (for example, Strang, 1943; Moss, 1976; van Beek and Fidler; 1977, van Beek, 2004).

There are, however, several alternative hypotheses that could account for the mesial migration and tilting of the maxillary molars. The three most commonly cited are: (1) forward drive from the erupting posterior teeth; (2) 'Anterior component of occlusal force' - functional occlusion exerting a force from the opposing jaw via the axial inclination of the teeth or from forward growth of the mandible and inter-digitation; (3) traction from the transseptal fibres.

8.4.1.1.1 Forward drive from the erupting posterior teeth. This potential cause of mesial movement of the maxillary molar has its basis in studies of anterior arch crowding (Vego, 1962) and in detailed studies of tooth migration in untreated subjects. For example, van der Linden (1977) examined study casts of subjects between 6 and 16 years of age from two growth studies (University of Michigan Elementary School Study and the Nymegan Growth Study) using palatal rugae as points of reference. He found an average mesial movement of the maxillary molar of 1.60 mm when the premolars emerged prior to second molars and 2.60 mm when the second molars emerged prior to the premolars. He did not, however, draw any conclusions regarding the cause of this difference.

This possible cause of mesial migration has been refuted by Moss and Picton (1976) in studies on primates and by Yilmaz *et al.,* (1980) in human subjects with ankylosed teeth. They (Yilmaz *et al.,* 1980) showed that this cannot be the cause (or at least not the sole cause) of mesial migration because the ankylosed tooth prevented such a forward drive being transmitted to the teeth lying anteriorly but nevertheless, mesial migration continued to occur.

8.4.1.1.2 'Anterior component of occlusal force'. The hypothesis that the functional occlusion exerts a force from the opposing jaw via the axial inclination of the teeth or from forward growth of the mandible and inter-digitation has been proposed by several authors. Iseri and Solow (1996) suggested that the inter-digitation of the buccal teeth allowed the continued growth of the mandible to move the maxilla horizontally (anteriorly) after the time when maxillary vertical growth had ceased. However, Solow

(1980) cautioned that the upper and lower teeth were in occlusal contact for such a short time that such transmission of force from mandible to maxilla seemed unlikely.

Moss and Picton (1978, 1980) concluded that an anterior component of force was not the cause of ‘mesial drift’ in experiments on primates. However, in a series of studies on adult *Macaca irus* monkeys, van Beek (1988) showed that the anterior component of force *did* cause mesial migration of the buccal teeth but the deep fossae of the buccal teeth of this primate could also lead to stabilisation of the occlusion thereby preventing migration from occurring. He added that this situation does not appear to occur in the human where the “cuspal lock” was much less likely to occur.

Some evidence that the occlusion is not the cause of this movement was found in the present study from the oblique radiographic series of case 10 where the upper second premolars were developmentally absent. Once the 2nd primary molar had been lost the 2nd and 1st permanent molars moved mesially and, more tellingly, translocated mesially far more rapidly than the opposing mandibular molars. Consequently, in this case, it cannot have been the occlusal interlock with the mandibular molars that caused the mesial movement of the maxillary molars.

8.4.1.1.3 Traction from the transeptal fibre system. The most compelling evidence *against* pressure from the tongue being responsible for horizontal migration of the teeth comes from the classic experimental study in primates by Moss and Picton (1970) which purported to show that the contraction of the transeptal fibres provided the motive force for horizontal or “approximal” migration. The conclusions of this study are a direct contradiction to the hypothetical mechanism proposed above. For this reason, it is important to examine the details of this study and the inferences drawn from its findings.

The study by Moss and Picton (1970) investigated the possible role of pressures from the cheeks and the tongue on the mesial migration of the teeth. They used a split mouth design on 6 adult male monkeys (*Macaca irus*) in which direct muscle (and occlusal) forces were eliminated on one side of the mouth in each animal by an acrylic dome and by extracting the teeth on *both* sides of the opposing arch. The cheek teeth on the other side of the same arch were used as controls. The contacts between adjacent cheek teeth in the test arch were removed with a 0.5 mm diamond disc to allow mesial drift to occur. Amalgam markers were placed buccally and lingually in the cheek teeth and the distances between the markers were examined over periods varying between 6 and 17 weeks using standardised occlusal radiographs.

The findings were reported as the change in distance between first and second molars, and between first and third molars. Analysis of the findings revealed no statistically significant differences between the control and test sides of the mouth. In conclusion, they stated the following:

"…it is considered that the position of these cheek teeth was not materially affected by the action of the tongue and cheeks…" and *"…it appears that mesial drift can occur in the absence of direct force from the tongue, cheeks and opposing teeth and that the principal cause or causes of mesial drift under these circumstances lies in or around the roots of the teeth."* (Moss and Picton, 1970).

However, despite these conclusions they found *greater* mesial movement on the *control side* than on the test side both for M1-M2 and M1-M3 and for *half* of the animals there was actually an *opening of space on the test side* between M1-M2. That is, there was *more* mesial migration where the tongue and cheeks *were* in contact with the molars than where the soft tissue pressures were excluded (3.5 times greater for M1-M2). The reason for the failure to confirm a statistically significant *difference* was their method of analysis which, coupled with the small sample size, made their statistical test under powered.

Given that their clear wish was to undermine the hypothesis that the action of the cheeks and tongue was the cause of approximal (mesial) movement and given the small sample size they could have chosen to test a *directional* null-hypothesis. In that case, the outcome would have been a statistically significant result (*paired t-test:* $t = -2.01913$; $p = 0.0497$). In addition, given that the sample provided only six paired comparisons it would not have been possible to reliably test the assumptions underlying their chosen statistical test, particularly the assumption of a Normal (or near Normal) distribution. Had they used a more appropriate *exact permutation test* (Ludbrook and Dudley, 1998; Ernst, 2004) to analyse their findings they would have found that the *exact* probability was, $p = 0.040043$ for the difference in mesial movement of M1-M2 between experimental and control sides of the mouth. A result, which is statistically significant in favour of *greater* mesial movement where the cheeks and tongue are in contact with the teeth.

Consequently, it appears that there is no meaningful evidence from the 'classic' study by Moss and Picton (1970) that contradicts an effect of the tongue on the mesial movement of the terminal molars. However, given the slow anterior movement of the entire dentition associated with the normal forward rotation of the jaws as described by

Björk and Skieller (1972) and as found in this study, it appears likely that mesial or approximal migration is composed of at least two effects as proposed by Yilmaz *et al.*, (1980): a local effect tending to hold adjacent teeth in contact (by contraction of the transeptal fibres?); and a general anterior movement of the entire dentition associated with the normal forward rotation of the jaws. The findings of the present study suggest that this second effect may be provided by the action of the tongue (and cheeks?) or, as Yilmaz *et al.*, (1980) have remarked: *"We cannot envisage any force other than tongue pressure which could do this"*.

8.4.2 Sagittal growth rotation and mutual transverse rotations of the maxillae

Experimental studies in primates have indicated that the degree of maxillary rotation can be readily altered by the application of heavy extra-oral forces to the maxillary teeth (Droschl, 1973; Elder and Tuenge, 1974). The human maxillae appear to be particularly responsive to forces applied via the teeth during the growth period. For example, anteriorly directed forces from elastic traction to a face-mask in growing children have been shown to produce anterior rotation of the maxillae that is far greater than that generally observed in untreated human subjects (Mandell *et al.,* 2010).

This effect is possible because of the ease with which the fibrous joints of the circum-maxillary suture system can be remodelled by mechanically induced strain (Meikle, 2002). Consequently, if the change in axial inclination and movement of the maxillary first molars are the result of pressure from the tongue (or from the occlusion), then it seems likely that this is the cause of maxillary rotation in the sagittal plane and of the more rapid anterior movement of the molar crowns than the overlying core of the maxillae. That is, when the crowns of the buccal teeth are pushed mesially the effect is not only to cause mesial movement and tipping of the teeth but also to induce a small rotation of the maxillae in the direction of the applied force.

It is difficult to apply a similar argument to explain the mutual rotation of the two maxillae in the transverse plane. The expansion between the posterior maxillary implants generally followed the GSG pattern of growth both in the present study and in the study by Björk and Skieller (1977) but the rate of widening was slower in those subjects with low levels of MGR compared to those with higher levels of (forward) MGR.

In the present study, when the eruption and emergence of the maxillary first molars, were viewed from the frontal plane in forward rotating subjects, the inclination of their long axes changed from almost upright to an outward (lateral tilt) with the crowns tipping rapidly buccally as the teeth emerged into the mouth. The teeth uprighted again when contact was made with the opposing teeth. In these subjects the molar crowns moved laterally faster than the overlying maxilla (Figure 8.5).

If some or all of the widening at the mid-palatal suture was an effect of the tongue on the palatal shelves and crowns of the teeth then, as with the sagittal rotation, the crowns of the molar would be expected to move laterally at a faster rate than the overlying bone. An effect that was observed in the subjects of this study.

However, this is contrary to the situation reported by Björk and Skieller (1977) who stated: *"… the increase in sutural growth between the lateral implants was greater than the increase in width of the dental arch between the first molars"*. The reason for this difference is not clear but it should be noted that Björk and Skieller (1977) measured the increase in width of the dental arch from the contact points between the first molars and second premolars on study casts. These contact points (on the mesial surfaces of the molars) would be largely unaffected by changes in the lateral tilt of teeth and therefore would not show the maximum lateral location of the tooth crowns.

Nevertheless, in the present sample it is possible that the effect of the tongue (on the crowns of the buccal teeth) was responsible for some of the lateral separation of the two maxillae but the pattern of the annual increments was not the same as that of *r-MGR.*

8.4.3 Other effects inconsistently associated with mandibular growth rotation

In addition to the main effects associated with growth rotation of the mandible indicated above there are two other prominent effects that have been found by other researchers but which were not found in the present study. These are (i) preferential eruption of the lower molars; and (ii) an association of MGR with the magnitude of condylar growth.

8.4.3.1 Preferential eruption of the lower molars

This effect, that the lower molar erupts preferentially faster than the upper molar in subjects with a marked forward rotation of the mandible has been reported from previous implant studies by Björk and Skieller (1972, 1983) and Solow (1976), Iseri and

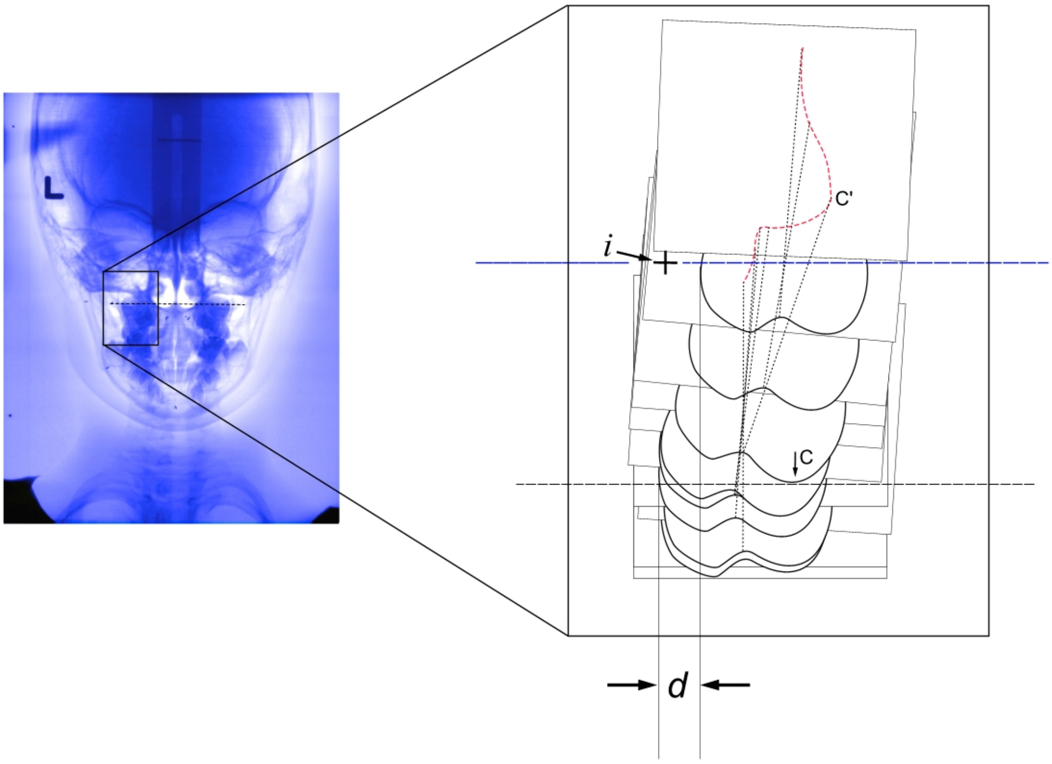

Figure 8.5 **Changes in the inclination of the left maxillary 1st molar crown during the supra-osseous eruption phase.**

The diagram was constructed from the serial frontal cephalometric radiographic series of subject No 1. The eruption track was constructed relative to superimposition on the intra-osseous implant line between the lateral implants in the two maxillae (indicated by the blue dashed line -·-·-·-) with registration on the left hand implant (indicated by *i*). At the point of gingival emergence the crown tilted buccally with the palatal cusps at a lower level than the buccal cusps. At the point of contact with the opposing tooth (indicated by the letter C and the dashed line – – – -) the buccal cusps tipped downwards to become level with the palatal cusps. Between gingival emergence and occlusal contact with the opposing tooth the buccal surface of the molar moved laterally relative to the corpus of the maxilla by the distance marked *d* . The fine dotted vertical lines indicate the orientation of the long axis of the molar at each annual recording. The red dashed curve (- - - -) indicates the position of the apex of the long axis during the total supra-osseous eruption phase. The abrupt change in the curving course of the apex at C' corresponds to the point of initial occlusal contact with the opposing tooth indicating that the root structure of the molar moved laterally through the bone.

Solow, 1990). This has been viewed as a compensatory mechanism to counter the effect of type 2 forward mandibular rotation where the point of rotation is anteriorly located (Solow, 1976; Marks *et al.,* 1988).

Evidence of an association between post-functional mandibular molar eruption (PFMME) and MGR was found in the initial survey but the correlation failed to reach statistical significance (r = 0.670, $\hat{p} > 0.05$, NS). No evidence of this effect was found in the multi-subject group analysis but in the individual analyses statistically significant synchronous patterning was found between PFMME and *r-MGR* in two subjects. These were the subjects with highest and lowest rates and overall magnitudes of MGR.

This suggests that preferential eruption of the mandibular molar over that of the maxillary molar is an effect exhibited only at the extremes of the range of MGR and has only become apparent in the studies employing Björk's sample (Björk and Skieller, 1972, 1983; Solow and Iseri, 1996a, Solow and Iseri, 1996b) which is known to contain more extreme cases (extreme forward and extreme backward MGR) than would be found in a random sample (Tanner, 1981; Baumrind *et al.,* 1984).

8.4.3.2 Association between the magnitude of condylar growth and MGR

Beginning with Björk's classic implant study (Björk, 1955) several researchers have identified the magnitude of condylar growth as a important factor in determining the direction and degree of mandibular growth rotation (Björk, 1963; Björk and Skieller, 1972, 1976, 1983; Isaacson *et al.,* 1971; Ødegaard, 1970a, 1970b; Lavergne and Gasson, 1976, 1977b; Ødegaard, 1970a, 1970b; Gasson and Lavergne, 1977a; Halborg and Rank, 1978; and Baumrind *et al.*, 1996). The correlation between condylar growth and MGR found in the initial survey failed to reach the threshold for statistical significance. Similarly, the time-series analysis also failed to find evidence of synchrony between the patterning of condylar growth and that of MGR ($\hat{p} > 0.126$, NS). Furthermore, as was the case with PFMME, no evidence of an effect was found in the multi-subject group analysis but in the individual analyses statistically significant synchronous patterning was found between *r-cond-mag* and *r-MGR* in subjects at the extremes of the range of MGR.

This could indicate an effect that is either only present in those individuals with extremes of MGR or that with lesser degrees of MGR the effect is not detectable possibly as a result of the higher ratio of random error to measured change. Alternatively, it could be that in subjects with a high degree of rotation that the growth of the condyle is the more major of the two components leading to MGR and thus variations of condylar growth are all the more influential in determining the resulting MGR. However, this would not explain the effect at very low rates of MGR.

Another possibility is that the effects at the extremes of the range of MGR could result from two separate causes – one acting at high levels of MGR, the other at low levels. If this were the case the effect at the lowest levels of MGR (backward rotations) could be caused by changes in mandibular posture resulting from potential compromise of the airway as postulated by Opdebeeck *et al.,* (1978) and by Solow and Siersbæk-Nielsen (1986).

There is, however, a further possibility that has not so far been mentioned: for the tongue to apply pressure against the maxilla it has to act from the platform of the mandible. That is to say, the *reaction* to the upward and forward *action* of the tongue must be a downward and backward 'push' against the mandible. For the tongue to have an effect on the maxilla this push must be resisted - presumably by the closing muscles of the mandible.

Consequently, not only must the musculature of the tongue be considered in any effect that the tongue has on the maxilla but so too must the masticatory (closing) musculature of the mandible because of its ability (or inability) to resist or support the action of the tongue. This provides a link to the known association between: masticatory muscle volume; occlusal forces during chewing, swallowing and maximum clenching; and vertical facial height on the one hand (Raadsheer *et al.,* 1999; Bennington *et al.,* 1999; Throckmorten *et al.,* 2000; Satiroglu *et al.,* 2005) and the magnitude and direction of growth rotation of the mandible on the other hand (Björk, 1963, 1969; Karlsen, 1997). It also provides an alternative explanation for the marked backward rotation of the mandible that frequently occurs in growing children with muscular dystrophy (Kreiborg *et al.,* 1978).

8.5 CONCLUDING REMARKS

The analysis above and the hypothetical mechanism linking growth rotations of the jaws to changes in the postural height of the tongue implies that a change in mandibular (mandibulo-lingual) posture must accompany any change in the rate (and direction?) of MGR in normal subjects. Consequently, the marked annual variations in MGR found in almost all subjects in this study also appears to imply that changes in mandibulo-lingual posture must occur relatively frequently.

It is, however, far from certain that such changes occur in normal subjects. But, given the known linkage between mandibulo-lingual posture and cranio-cervical posture it is worth recalling that Solow and Siersbæk-Nielsen (1986) found that significant changes in cranio-cervical posture occurred in 78% of their subjects over periods ranging from 2½ to 3½ years. The close relationship between cranio-cervical posture and restriction of the nasal airway might therefore suggest that a high proportion of the subjects in that study had a compromised nasal or nasopharyngeal airway but there was no evidence of this. Consequently, the reason for the variation of postural height of the tongue recorded in the radiographs employed in the present study, and presumably the variation in mandibular posture, remains unknown.

Nevertheless, the results of this study and the hypothetical mechanism appear to suggest that clinical control of MGR is possible by controlling the posture of the tongue. Attempts to do so have met with very little success once appliances have been removed and even while they are in place in the mouth (Petit, 1983). Even if it were possible to permanently alter lingual or mandibulo-lingual posture there is no indication from the results of this study or any other study cited in these pages that this would allow the correction or prevention of malocclusion as has sometimes been claimed (Mew, 2007).

So, why might we wish to control MGR other than in those growing individuals with extreme forward or backward rotations? The answer is given most succinctly by Buschang and co-workers (Buschang *et al.*, 2011, 2012; Buschang and Jacob, 2014) who showed convincingly that MGR is the most important determinant of prognathism and of chin prominence in the face. It remains to be seen, however, if mandibulo-lingual posture might be harnessed or manipulated to offer some control over growth rotations of the jaws and thereby influence the direction of facial growth.

CHAPTER
9

SUMMARY, CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

9.1 SUMMARY AND CONCLUSIONS

The research which led to the writing of this thesis was undertaken for two reasons: first, in an attempt to resolve inconsistencies and uncertainties regarding the relationship between mandibular growth rotation and other features of facial growth; and secondly, to gain a deeper insight into the possible origin of growth rotations of the jaws. The study was designed as two separate (but related) investigations of the relationships between growth rotations of the jaws and growth changes at sites throughout the jaws and dentition in the same group of 11 children with implanted tantalum markers in both jaws.

The initial survey was designed to measure the total changes over a 6 year period of observation where the subjects were uniformly matched in terms of their physical maturity. Correlation analysis was used to examine the associations between the variables expressing displacement growth of the jaws and teeth dentition: and, on the one hand, growth rotations of the jaws, and on the other hand, general somatic growth. The second (main) study was undertaken with the aim of detecting co-ordination within and between the temporal patterns of growth rotations of the jaws and: (i) the growth displacements of the jaws; and (ii) the natural movements of the teeth (post-functional eruption and migration). Methods were developed to minimise the errors of measurement and to mitigate the inherent problem of negative serial correlation in the collection of longitudinal data. Non-linear time-series analysis was employed to detect the presence of co-ordination by identifying synchrony between the time-series representing the patterns of growth at the different sites.

9.1.1 The Finding of the Initial Survey

Previous studies that have investigated the relationships between growth rotations and growth related changes throughout the jaws and dentition have found a consistent pattern of associations between the direction (and intensity) of growth rotations of the jaws (primarily the mandible) and: the vertical growth of the face; the magnitude and direction of condylar growth; the growth directions of the jaws; and the horizontal migration and vertical eruption of the dentition. A broadly similar pattern of associations was found in the present study together with a further series of strong associations (and statistically significant correlations) between growth rotations of the jaws and: (i) horizontal growth displacements of the jaws; (ii) horizontal migrations of the molars; (iii) axial change of the maxillary molar; and (iv) the postural height of the tongue. However, the association with the magnitude of condylar growth did not reach statistical significance although the association with condylar direction did.

In addition, the pattern of associations with growth rotation of the mandible was quite different to that found for general somatic growth where the strongest associations were with total displacements of the jaws and the magnitude of condylar growth .

These findings suggest that the associations with growth rotations of the jaws are primarily with the horizontal components of jaw displacement and tooth migration, while the associations with general somatic growth are mainly with the total magnitudes of growth displacement and with the magnitude of condylar growth.

9.1.2 The Finding of the Main Study

These associations were investigated in more detail and at higher temporal resolution in the main time-series study. The results indicated that the vertical growth displacements of the mandibular ramus and anterior maxilla combine to produce growth rotation of the mandible while the horizontal to vertical distribution of maxillary growth displacement produced growth rotation of the maxilla. Changes in growth rotations of the jaws were found to be co-ordinated with changes in the angulation of the maxillary molars and postural height of the tongue.

The patterning of the co-ordination between growth displacements of the jaws and growth related changes in the dentition suggested a linkage to postural changes in the neck, mandible and tongue. Based on these findings an explanatory model was proposed for the origin and control of growth rotations of the jaws.

The hypothetical model suggests that it is the pressure from the tongue against the terminal maxillary molars and palate that influences the direction of maxillary growth by re-distributing the growth more horizontally in forward rotating subjects. In these subjects the maxillary molars tilt mesially leading to a small anteriorly directed rotational force on the maxilla. In backward rotating subjects this effect is reduced or absent because of the low postural position of the tongue. In this case, the growth of the maxilla is directed more vertically and terminal maxillary molars are *not* tilted mesially and, consequently, do not give rise to a forward rotational effect on the maxilla.

This model assumes that the mandibular closing musculature is unaffected by variations in growth direction or rotation of the jaws, at least pre-pubertally in normal subjects, and thus, the vertical height of inter-maxillary space simply increases in proportion to general somatic growth despite differences in maxillary growth direction. To achieve occlusal contact this requires the mandible to be positioned closer to the cranium (that is, to the floor of the anterior cranial fossa) in forward rotating subjects than in backward rotating subjects.

The model also assumes that the differences in condylar growth direction between forward and backward rotating subjects is brought about by the gradual changes in the orientation of the mandible to the cranium as a *result* of the rotation of the mandible and not as part of its *cause*.

From the materials available for the present study it is not possible to confirm a linkage between growth rotations of the jaws and postural relations of the mandible. Nevertheless, it seems probable that mandibular posture will be tightly coupled with lingual posture in determining the pattern of growth rotations. Some evidence of this linkage was seen in comparisons of subjects from the two ends of the rotational spectrum in the initial survey.

9.2 UNANSWERED QUESTIONS AND SUGGESTIONS FOR FURTHER STUDY

The postulated hypothetical mechanism of the origin of growth rotations of the jaws is essentially speculative in nature and there will, doubtless, be objections to its validity. The present passive observational study can only be exploratory, not confirmatory, and it remains for further studies to support or refute the correctness of this hypothetical mechanism.

Although the postulated mechanism attempts to explain the findings of this study, nevertheless, several questions remain unanswered. The most obvious question is why does the postural height of the tongue alter so frequently and in a way that is so closely synchronous with growth rotation of the mandible? It is worth recalling that in all 8 subjects where the dorsum of the tongue could be visualised there were significant annual changes in lingual posture. In this context, is also worthy of note that there was no evidence of restriction of the nasal airway in any of the subjects in this study.

Another question of some importance is can the habitual posture of the tongue recorded during the day with the teeth in occlusion, truly reveal the existence and nature of processes that are potentially causally related to growth - particularly when we know that growth occurs primarily at night, during asleep, when the body is supine and the postural relationships are entirely different?

The answers to these questions will doubtless be forthcoming in time but it seems unlikely that the methods applied in this study can provide the answers. In addition, the insertion of tantalum implant markers is no longer possible for the purposes of research and future studies will almost certainly need to rely on natural reference structures with the attendant uncertainties that these involve. It remains to be seen, however, if these methods will be applied to assist in answering these questions.

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APPENDIX

The Appendix contains three parts as indicated below.

Appendix A1 Scatterplots of the associations between MGR and other growth variables.

The scatterplots are presented on pages 208 and 209. Each plot is accompanied by a least-squares line of best-fit constructed on the data sets. The data used in the construction of the plots are given in Table 7.1.

Appendix A2 Mean (annual) linear and angular growth velocities for the time-series variables.

The data are presented in tabular form on pages 210 and 211 together with the actual observation intervals used in the calculation of the growth velocities together with the subject's age at the mid-point of each observation interval.

Appendix A3 Differences and ratios of the posterior lowering and the individual components of anterior lowering of the mandible over the observation period.

The data are presented in tabular form on page 212 together with the Pearson correlation for each of the differences and ratios.

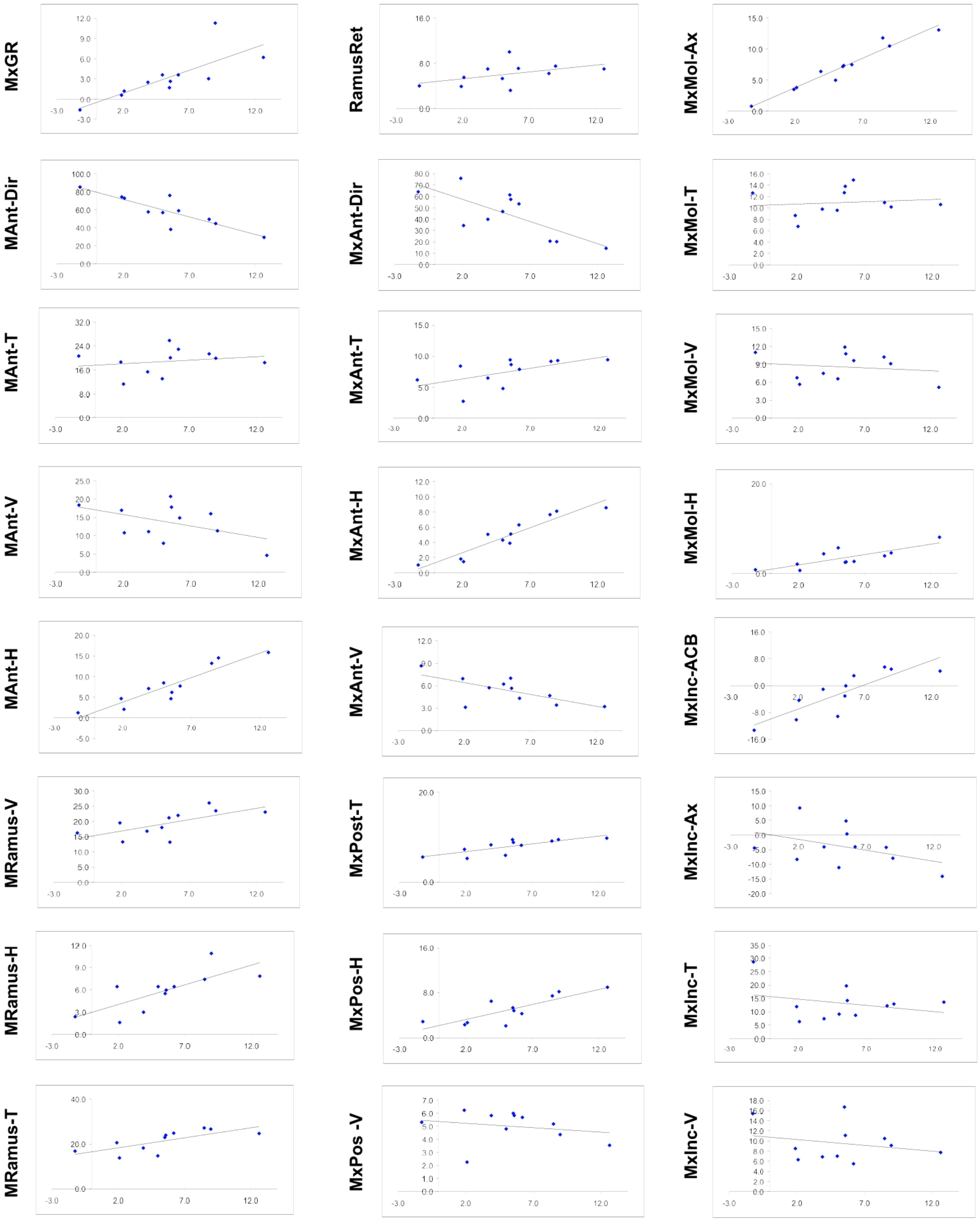

Figure A.1 Scatterplots of the associations between mandibular growth rotation and variables expressing growth displacements of the jaws and natural movements of the teeth.

The horizontal axis of each plot represents the magnitude of the growth rotation of the mandible (MGR) over the observation period of the Initial Survey (mean = 6.21, SD = 0.20 yrs). The vertical axis represents the growth variable indicated to the left of each plot. For each plot the *best fit* linear relationship between the variables is indicated by a line through the data points.

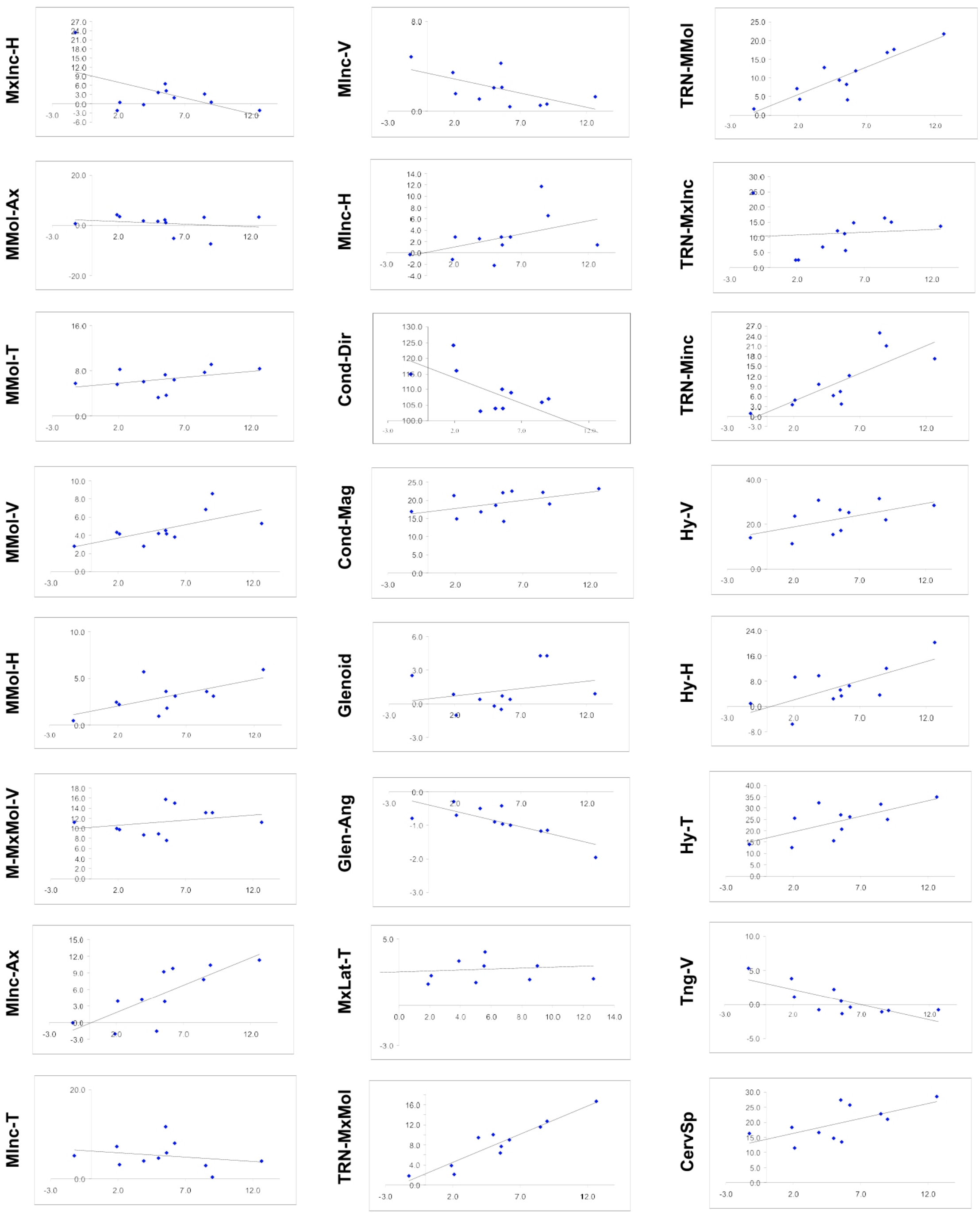

Figure A.1 ***Continued ...***

The horizontal axis of each plot represents the magnitude of the growth rotation of the mandible (MGR) over the observation period of the Initial Survey (mean = 6.21, SD = 0.20 yrs). The vertical axis represents the growth variable indicated to the left of each plot. For each plot the *best fit* linear relationship between the variables is indicated by a line through the data points.

Case No.	Mid-age (yrs)	Interval (yrs)	r-MGR 54	r-MxGR 55	r-Cond-Dir 56	r-Cond-Mag 57	r-MRamus-V 59	r-MRamus-H 60	r-MRamus-T 61	r-MAnt-V 63	r-MAnt-H 64	r-MAnt-T 62	r-MxPos -V 67	r-MxPos-H 66	r-MxPos-T 65	r-MxAnt-V 70	r-MxAnt-H 69	r-MxAnt-T 68	r-MxMol-T 72	r-MxMol-V 73	r-MxMol-H 74	r-MxInc-T 76	r-MxInc-H 78	r-MxInc-V 77	r-MMol-T 80	r-MMol-V 81	r-MMol-H 82	r-MInc-T 84	r-MInc-V 85	r-MInc-H 86	r-M-MxMol-V 87	r-IntMaxV 58	r-MxTRA-Lat 89	r-CerSp 93	r-TRN-MxMol 91	r-TRN-MMol 92	r-MxMol-Ax 71	r-MxInc-Ax 83	r-MMol-Ax 79	r-MInc-Ax 75	r-MxTRot 90
1 (F)	5.76	1.25	1.44	5.36	2.73	0.00	3.84	1.55	4.14	2.72	2.14	3.46	0.96	1.12	1.48	0.93	1.25	1.31	0.86	0.31	0.80	4.06	0.89	3.96	0.00	0.00	0.00	3.97	1.19	0.30	0.00	2.62	0.90	1.68	1.92	1.50	1.76	-7.76	5.92	0.00	3.12
	6.80	0.84	0.83	0.00	4.33	0.00	3.73	0.85	3.82	2.74	2.25	3.54	0.42	1.86	1.90	0.47	1.80	1.69	1.69	1.65	-0.36	1.08	1.03	0.32	0.00	0.00	0.00	5.24	1.31	2.20	0.00	3.52	0.39	2.69	1.50	2.25	1.67	-6.43	-8.81	1.90	3.52
	7.84	1.23	0.49	0.57	3.33	0.00	4.12	1.71	4.46	3.33	1.02	3.49	1.20	1.14	1.66	1.07	1.01	1.61	2.20	2.05	0.81	1.25	1.10	0.60	1.09	1.07	0.16	1.09	0.33	0.46	3.12	2.38	0.40	2.71	1.95	1.19	-0.49	0.00	0.01	3.90	3.20
	8.81	0.72	2.08	0.28	5.01	-19.44	4.86	3.38	5.92	2.22	5.03	5.50	-0.14	1.53	1.53	-0.13	1.36	1.72	1.72	1.69	0.28	0.11	-0.07	-0.09	0.74	0.72	-0.14	0.74	-0.04	0.22	2.42	3.94	1.00	1.15	1.81	4.89	4.31	4.58	0.02	6.53	3.24
	9.73	1.12	0.80	3.13	3.96	38.93	2.77	1.82	3.31	1.52	1.00	1.82	0.42	0.89	0.99	0.41	1.00	0.96	1.52	0.72	-1.34	1.30	1.23	-0.41	0.80	0.50	0.63	0.80	0.25	0.19	1.22	1.67	0.11	3.19	-0.45	1.63	-0.45	-1.88	0.06	1.25	3.99
	10.70	0.82	2.56	0.73	7.29	0.00	6.71	0.55	6.73	2.93	2.65	3.95	0.30	1.68	1.71	0.27	1.88	1.52	4.43	3.43	2.80	2.52	0.32	2.50	2.79	2.72	0.61	2.79	0.82	0.18	6.15	4.73	0.88	7.09	4.49	3.26	4.15	1.34	0.00	0.00	9.65
	11.82	1.42	2.25	4.44	2.22	-12.68	2.25	2.19	3.14	-0.56	3.14	3.19	0.42	1.20	1.27	0.47	1.16	1.23	0.48	0.23	0.42	0.75	0.22	-0.72	1.31	-0.32	1.27	1.31	0.51	0.52	-0.08	0.75	0.44	3.70	1.62	4.41	3.94	-3.38	0.00	0.00	5.96
	13.43	1.80	0.22	-2.56	1.11	-11.67	0.84	0.68	1.08	1.22	0.54	1.34	0.32	0.14	0.35	0.31	0.13	0.39	0.42	-0.39	0.17	0.69	-0.18	-0.67	1.10	1.07	0.28	1.10	0.11	0.44	0.68	1.01	0.17	0.00	0.31	0.82	-1.56	2.26	0.00	1.06	0.22
2 (M)	6.39	0.89	1.50	-0.10	3.18	0.00	3.00	1.55	3.28	1.25	3.45	3.67	0.38	1.46	1.47	0.18	1.16	1.14	5.46	5.39	0.90	14.01	10.30	9.49	3.48	3.36	0.91	2.08	1.90	0.85	8.75	1.76	0.60	2.70	2.36	4.36	9.80	2.60	4.10	4.50	2.60
	7.18	0.70	0.80	0.10	2.30	4.10	3.54	0.50	2.21	2.15	0.40	2.19	0.61	0.87	1.15	0.73	0.66	-0.13	1.51	1.47	-0.36	2.49	1.64	1.88	0.91	0.85	0.33	1.88	0.70	1.75	2.32	2.04	0.48	0.54	0.51	0.73	-4.06	0.00	1.20	3.90	0.64
	8.09	1.12	0.30	0.70	2.95	7.30	2.42	1.63	3.34	2.30	0.90	2.47	0.41	0.88	0.98	0.47	0.62	-0.28	1.96	1.87	0.59	2.26	1.99	1.08	0.55	-0.16	0.53	0.83	-0.10	0.82	1.71	1.75	0.44	0.64	1.47	1.43	3.90	1.10	-0.40	3.50	1.34
	9.14	0.98	0.40	-1.50	2.19	-35.90	4.51	-0.30	1.52	4.13	1.20	4.30	0.84	1.37	1.63	0.14	0.61	-0.09	2.11	1.90	0.92	3.01	1.18	2.77	0.70	0.68	-0.15	1.73	1.17	1.27	2.58	3.81	0.29	0.54	2.29	1.05	0.50	-5.10	0.00	1.80	-0.96
	10.25	1.23	0.20	-2.70	3.82	38.60	4.00	0.10	3.80	3.40	-0.25	3.41	0.12	0.31	0.35	0.73	0.33	0.18	2.09	2.09	-0.10	2.31	1.97	1.21	1.27	0.87	0.93	2.14	0.75	-2.00	2.96	1.62	0.53	0.24	0.21	0.68	0.60	0.00	-1.50	-3.04	-2.46
	11.25	0.78	3.10	1.70	4.12	-2.10	2.00	2.95	5.03	-1.00	3.60	3.74	-0.07	1.70	1.63	0.24	1.75	0.97	2.31	1.87	1.36	1.69	1.04	1.33	1.21	0.05	1.21	2.03	0.93	1.80	1.92	1.81	0.33	0.76	3.06	4.81	3.30	-1.20	2.80	-	2.46
	12.24	1.19	-1.70	-4.80	7.38	-11.90	6.90	0.00	6.92	8.00	-0.50	8.02	3.36	0.92	3.49	3.72	0.56	1.98	3.62	3.59	-0.47	6.64	0.89	6.58	2.97	2.93	0.49	2.04	0.73	-1.90	6.52	4.20	1.16	3.50	0.45	-0.01	-1.90	2.10	0.40	-	-1.30
	13.39	1.12	0.53	-3.10	2.10	6.04	3.50	1.10	2.30	3.90	-0.30	3.91	1.33	0.12	1.36	1.69	0.02	-2.11	0.59	0.55	0.20	3.75	-0.52	3.71	0.59	0.16	0.57	2.91	0.80	2.80	0.71	2.63	0.24	0.64	0.32	0.27	0.80	-	0.90	-	-2.46
	14.61	1.31	-0.83	-	4.41	-15.80	3.38	0.10	3.80	4.26	0.40	4.28	1.76	0.15	1.75	-	-	-	0.76	0.51	0.56	3.25	-0.52	3.21	1.23	1.22	-0.15	1.44	1.20	-0.80	1.73	1.97	0.23	1.22	0.71	0.25	1.70	-	-1.10	-	
	15.85	1.18	0.10	-	-	-	1.10	-	1.10	0.86	-0.70	1.11	0.20	-0.28	0.33	-	-	-	-0.55	-0.50	0.80	1.05	-0.72	0.77	-	-0.20	-	0.51	0.12	0.50	-0.70	0.93	0.41	-3.52	0.52	-0.70	5.00	-	-	-	-
3 (M)	7.17	0.96	2.40	1.56	4.69	-6.88	3.96	3.33	5.17	3.23	3.85	5.03	0.82	1.60	1.62	0.85	1.46	1.69	1.69	2.19	-0.10	4.06	0.89	3.96	1.39	1.93	1.95	3.90	0.85	1.97	0.58	1.60	0.82	2.29	1.35	3.85	3.65	0.00	0.00	0.72	0.72
	8.04	0.77	0.65	1.56	3.66	2.34	4.03	-1.30	4.23	3.64	-1.04	3.78	0.95	0.99	1.28	0.99	0.90	1.33	1.33	2.08	-0.26	1.08	1.03	0.32	1.61	1.18	1.54	1.08	1.32	1.15	0.18	2.91	0.22	3.64	0.64	-1.04	2.21	4.94	9.87	-0.04	1.39
	8.92	1.00	1.00	2.20	3.90	2.30	3.50	1.40	3.77	2.40	1.90	3.06	1.09	1.00	1.30	1.04	0.87	1.36	1.36	2.35	-0.10	1.25	1.10	0.60	1.26	1.15	1.50	1.20	1.10	0.36	-0.38	0.62	0.21	0.80	0.77	1.90	3.90	0.60	-2.40	0.11	0.17
	9.99	1.13	0.53	-0.44	2.66	-8.41	1.24	1.50	1.95	2.65	1.50	3.05	-0.01	0.37	1.20	-0.11	0.34	0.35	0.35	1.15	0.22	0.11	-0.07	-0.09	-0.01	0.44	1.44	0.13	-0.54	1.10	0.24	0.31	0.34	0.44	0.56	1.50	1.24	-5.04	1.06	0.56	0.05
	11.04	0.98	0.20	-1.33	2.38	-8.67	3.78	0.61	3.82	2.55	0.41	2.58	1.29	0.31	1.32	1.35	0.29	1.38	1.38	0.36	0.10	1.30	1.23	-0.41	1.55	0.38	1.59	1.22	1.03	1.01	0.34	2.79	0.48	3.98	0.39	0.41	0.61	3.14	5.61	0.58	0.07
	12.01	0.96	2.60	1.46	4.22	34.38	1.25	2.50	2.80	1.15	3.44	3.62	0.30	1.87	1.66	0.31	1.70	1.73	1.73	0.00	1.88	2.52	0.32	2.50	0.36	2.24	1.99	2.50	0.34	1.58	0.25	3.05	0.33	4.06	3.57	3.44	4.38	2.19	-3.96	2.21	0.85
	13.05	1.11	1.26	0.63	5.99	8.02	8.20	1.17	8.28	6.67	1.08	6.75	2.06	0.42	2.09	2.14	0.38	2.18	2.18	3.60	0.50	-	-	-0.72	2.47	0.50	2.51	2.49	2.38	1.58	0.30	5.30	0.42	7.57	0.87	1.08	2.79	-3.78	-	0.92	0.77
	14.13	1.05	-0.67	0.48	4.10	-	2.95	1.05	3.13	3.24	0.76	3.33	1.29	0.26	1.31	1.34	0.24	1.36	1.36	1.33	-	-	-	-0.67	1.55	0.31	1.57	1.86	1.74	1.37	0.15	3.77	0.16	4.10	0.24	0.76	2.95	-3.90	-	0.16	0.10
4 (M)	7.33	0.89	0.56	0.90	3.15	75.06	2.87	1.24	3.12	2.06	3.40	3.98	1.01	0.58	1.17	1.03	0.34	1.09	2.81	1.44	-0.28	2.09	1.44	1.40	1.97	1.90	0.54	1.11	0.00	1.11	3.60	1.83	1.72	4.85	0.30	5.30	8.76	10.34	0.25	-1.35	-0.21
	8.11	0.68	1.18	1.18	4.57	0.00	3.19	1.97	3.75	2.18	1.25	2.51	0.94	1.03	1.39	1.01	0.99	1.41	0.29	1.28	0.15	4.99	3.76	3.28	0.82	0.82	0.00	1.69	0.78	1.50	1.09	2.19	0.79	1.84	1.18	2.07	5.88	9.41	1.34	0.74	0.09
	9.01	1.11	2.49	1.98	3.41	-3.42	3.69	1.44	3.96	1.62	3.05	3.45	0.59	1.42	1.54	0.23	1.48	1.50	2.25	0.76	0.95	2.85	1.94	2.09	0.58	0.51	-0.27	2.53	-0.19	2.52	2.67	2.03	-0.01	1.88	2.37	3.56	1.26	3.33	1.01	4.23	0.06
	10.11	1.09	0.87	0.18	4.24	-3.58	4.08	1.01	4.21	2.06	2.53	3.27	0.90	1.40	1.67	0.81	1.35	1.57	2.48	1.45	-0.37	2.38	1.89	1.44	1.61	1.57	0.38	1.84	0.05	1.84	2.83	2.22	0.44	1.62	1.04	4.10	-3.94	-3.03	1.04	0.83	-0.01
	11.24	1.17	0.59	-0.51	4.85	18.72	5.40	0.09	5.40	3.33	1.79	3.78	0.57	0.97	1.12	0.50	1.05	1.16	1.28	1.15	-0.32	2.25	0.95	2.04	1.09	1.03	0.38	1.98	0.23	1.97	2.24	3.03	0.32	3.32	0.65	2.81	0.94	1.37	1.23	0.51	-0.03
	12.27	0.90	1.11	-0.67	6.46	-1.67	5.40	1.50	5.60	5.00	2.00	5.39	1.46	1.21	1.89	1.46	1.40	2.02	2.56	2.09	0.64	3.98	2.39	3.19	2.71	2.63	-0.62	2.83	1.19	2.57	5.42	5.11	0.63	5.02	1.86	4.63	-0.33	-1.22	1.82	3.67	0.13
	13.27	1.10	0.73	-0.09	4.68	-0.91	3.45	1.72	3.86	1.88	2.06	2.79	0.84	1.25	1.50	0.85	1.25	1.51	2.00	1.72	0.95	2.98	2.18	2.03	1.90	0.81	1.72	2.08	1.71	1.18	2.65	1.91	0.01	3.97	2.20	2.87	-2.00	-1.64	0.55	2.27	-0.06
	14.34	1.04	1.35	0.48	4.05	-27.50	3.70	0.96	3.82	2.71	0.49	2.76	0.45	0.19	0.49	0.22	0.14	0.26	0.67	0.80	1.31	2.04	-0.38	2.01	1.62	0.94	1.32	1.49	1.18	0.90	1.62	2.07	0.09	1.73	1.50	1.43	-0.19	0.67	0.80	1.15	0.09
	15.48	1.24	0.73	-1.77	2.31	31.29	1.35	1.20	1.81	1.62	0.68	1.76	-0.05	0.33	0.33	-0.10	0.50	0.51	0.65	0.84	0.65	0.88	-0.25	0.85	0.53	0.32	0.42	1.22	0.61	1.06	1.11	-0.15	0.35	2.73	0.98	1.00	2.48	-0.16	0.36	1.69	0.00
5 (M)	7.53	0.89	1.01	0.45	1.35	83.48	3.63	2.22	4.26	1.30	3.12	3.38	0.66	1.70	2.09	0.61	1.26	1.74	1.62	1.62	0.07	1.84	1.38	0.75	0.61	0.56	-0.25	1.48	0.61	1.35	2.18	0.72	0.38	11.01	1.76	2.88	-1.35	0.00	1.91	0.00	7.15
	8.32	0.70	1.14	0.57	4.29	135.86	3.61	1.09	3.77	3.56	1.43	3.83	1.99	0.71	2.49	1.76	0.86	2.68	0.69	0.69	0.06	1.73	0.01	1.83	2.17	1.96	0.94	0.63	0.50	-0.39	2.64	2.73	1.01	2.71	0.77	2.37	3.57	-5.43	-1.00	0.39	6.41
	9.23	1.12	0.45	0.20	1.88	115.18	2.21	-0.17	2.22	1.54	0.62	1.66	0.72	0.96	1.48	0.66	0.75	1.12	1.82	1.77	0.45	1.56	0.53	1.41	1.40	-0.11	1.39	0.56	0.19	0.53	1.66	1.34	0.72	10.63	1.40	2.01	-0.54	-2.86	2.50	1.43	4.93
	10.28	0.98	1.12	0.49	2.04	122.45	3.06	1.94	3.62	1.59	3.16	3.54	0.62	1.41	1.80	0.44	0.83	0.86	2.01	0.81	1.84	0.73	-0.22	0.69	1.08	-0.16	1.07	0.51	0.01	-0.51	0.64	-0.43	0.41	6.33	3.24	4.23	2.45	3.16	0.00	-1.63	5.39
	11.39	1.23	-0.08	0.08	1.54	80.81	0.85	-0.75	1.13	1.40	-1.02	1.73	1.08	0.13	1.33	1.04	0.47	1.61	0.97	0.97	-0.01	1.12	-0.67	0.91	0.67	0.07	0.67	0.47	0.07	0.46	1.04	1.25	0.49	5.12	0.12	-0.35	-1.54	-1.14	0.00	1.63	5.69
	12.40	0.80	0.75	0.87	2.63	156.25	2.03	0.70	2.14	1.44	1.19	1.86	0.81	1.10	1.97	0.43	0.45	0.31	0.95	0.89	0.34	0.86	-0.04	0.87	0.60	0.35	0.49	0.93	0.69	0.62	1.24	1.05	0.36	5.12	1.44	1.68	0.38	-0.87	0.00	0.50	11.36
	13.39	1.17	0.43	-0.09	3.85	93.16	2.98	1.46	3.32	2.24	0.62	2.32	0.74	0.64	1.64	0.82	0.69	1.35	1.13	1.11	0.23	0.88	0.32	0.79	1.12	0.40	1.04	0.68	-0.21	0.65	1.51	1.88	0.56	14.19	0.87	1.67	-0.90	-1.45	1.20	0.51	4.67
	14.53	1.12	2.23	1.66	2.95	77.23	4.63	-0.07	4.63	2.06	2.56	3.29	1.39	1.98	2.03	0.81	1.47	3.17	1.96	1.35	1.43	1.67	-0.19	1.67	0.75	0.46	0.59	0.71	0.45	0.55	1.81	1.01	0.46	24.11	3.41	3.15	1.25	-0.13	-2.14	0.36	6.30
	15.75	1.32	0.76	-0.35	1.67	69.70	1.83	1.54	2.39	0.62	1.22	1.37	0.09	-0.83	0.94	0.14	0.06	0.03	0.68	0.61	-0.31	0.39	0.36	0.08	0.46	0.35	0.30	0.72	0.12	-0.71	0.95	1.22	0.20	3.94	-1.14	1.52	0.30	0.00	0.53	-1.21	1.31
	17.16	1.50	0.47	-0.20	1.20	44.80	0.78	0.07	0.78	0.08	0.45	0.46	0.11	0.13	0.13	0.17	0.14	0.07	0.56	0.36	0.43	0.53	0.45	-0.27	0.44	0.16	0.41	0.37	-0.03	0.37	0.52	0.35	-0.03	3.13	0.57	0.86	4.13	0.00	0.00	-0.20	-2.11
6 (F)	7.54	1.02	-0.78	-1.57	1.90		1.23	-1.62	2.03	3.13	-0.85	3.24	1.15	0.69	1.34	1.28	0.25	1.31	0.00	0.00	0.10	1.32	0.88	-0.98	0.00	0.00	0.00	0.71	0.39	-0.59	1.30	2.65	0.49	4.72	0.78	-0.85	0.00	5.10	0.28	0.77	4.72
	8.56	1.02	0.39	-0.88	2.97	42.65	4.36	2.70	5.13	2.16	2.16	3.05	0.20	0.85	1.09	0.91	0.82	1.23	0.10	-0.28	1.99	4.62	-3.92	2.45	0.55	0.46	0.29	1.62	1.11	1.18	2.68	4.07	0.55	4.68	2.84	2.45	5.20	-11.18	0.26	1.89	3.11
	9.55	0.95	0.00	-1.26	1.52	-52.53	0.42	-0.21	0.47	2.38	-0.45	2.42	0.79	0.45	0.91	0.68	0.21	0.72	2.12	2.67	-0.63	2.20	0.63	2.11	0.95	0.95	-0.05	0.74	0.42	-0.61	-2.62	0.95	0.67	1.36	-0.18	-0.51	2.53	1.79	0.39	0.86	0.48
	10.48	0.92	-0.87	-1.85	3.43	46.41	3.80	0.87	3.90	3.84	-0.66	3.89	1.41	0.05	1.41	1.60	-0.05	1.60	2.99	1.40	1.30	1.41	1.30	0.54	1.27	1.01	0.76	1.32	1.28	0.33	0.92	3.83	0.15	3.90	1.36	0.10	-3.15	2.28	-0.08	1.19	2.64
	11.57	1.25	-0.16	0.00	2.43	3.28	2.32	0.80	2.45	2.23	0.66	2.33	0.84	0.30	0.89	1.00	0.35	1.06	1.53	0.56	-0.34	1.33	-0.58	1.20	0.38	0.30	-0.24	0.80	0.71	-0.36	1.47	2.42	0.35	2.27	-0.05	0.42	-1.28	-1.36	0.06	0.46	0.42
	12.68	0.98	1.02	1.22	5.56	-29.49	3.98	1.53	4.26	2.70	1.58	3.13	1.52	0.26	1.54	1.59	0.06	1.59	0.67	0.47	1.15	1.14	0.51	1.02	0.97	0.80	0.56	1.29	1.02	-0.80	3.60	3.56	0.64	6.12	1.41	2.14	6.84	0.51	0.41	0.72	6.12
	13.74	1.14	0.72	-0.79	3.56		3.86	0.48	3.89	3.09	1.00	3.25	1.26	0.29	1.30	0.97	0.00	1.20	1.09	1.79	0.63	0.89	0.18	0.88	1.34	0.76	1.10	1.25	-1.01	-0.75	0.70	3.73	0.61	3.51	0.92	2.10	0.79	0.44	0.39	0.54	4.73
	14.96	1.29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-3.56	-	-	-	-0.79

Table A.2 **Mean (annual) linear and angular growth velocities for the time-series variables.**

The mid-range ages in the second column refer to the age at the mid-point of each (annual) observation interval. The actual length of the observation interval is given in the third column. The data are reported as either degrees per year or mm per year.

Case No.	Mid-age (yrs)	Interval (yrs)	r-MGR	r-MxGR	r-Cond-Dir	r-Cond-Mag	r-MRamus-V	r-MRamus-H	r-MRamus-T	r-MAnt-V	r-MAnt-H	r-MAnt-T	r-MxPos -V	r-MxPos-H	r-MxPos-T	r-MxAnt-V	r-MxAnt-H	r-MxAnt-T	r-MxMol-T	r-MxMol-V	r-MxMol-H	r-MxInc-T	r-MxInc-H	r-MxInc-V	r-MMol-T	r-MMol-V	r-MMol-H	r-MInc-T	r-MInc-V	r-MInc-H	r-M-MxMol-V	r-IntMaxV	r-MxTRA-Lat	r-CerSp	r-TRN-MxMol	r-TRN-MMol	r-MxMol-Ax	r-MxInc-Ax	r-MMol-Ax	r-MInc-Ax	r-MxTRot
			54	55	56	57	59	60	61	63	64	62	67	66	65	70	69	68	72	73	74	76	78	77	80	81	82	84	85	86	87	58	89	93	91	92	71	83	79	75	90
7 (F)	8.18	0.76	2.89	3.16	3.33	26.58	4.08	1.32	4.29	3.42	2.08	4.00	1.01	0.70	1.24	0.96	0.79	1.28	7.12	-0.29	7.12	6.61	5.20	4.09	5.91	5.79	1.20	3.30	1.04	1.97	8.87	2.51	0.87	6.84	0.41	2.89	13.68	7.37	8.03	5.92	0.11
	8.93	0.73	-4.25	-4.38	2.82	97.26	2.96	-0.92	3.10	4.03	-2.12	4.55	1.19	0.12	1.26	1.38	-0.11	1.36	3.36	-0.34	3.34	-3.48	2.05	2.71	0.75	0.70	0.27	-2.48	1.55	0.51	3.21	1.88	0.41	4.25	-0.22	-0.97	4.21	0.00	-3.01	7.12	0.07
	9.83	1.07	-1.40	-1.31	3.59	-96.26	3.61	0.65	3.67	3.33	0.46	3.36	0.96	0.55	1.08	1.21	0.22	1.25	2.54	1.91	1.67	2.38	1.06	4.58	1.21	1.13	0.43	1.97	1.86	0.96	2.38	2.97	0.51	3.18	2.46	1.06	5.98	1.50	-1.21	1.03	0.25
	10.94	1.15	-1.83	-1.83	6.52	36.61	0.00	-0.16	2.67	4.17	0.28	4.18	0.94	0.57	1.13	1.52	0.53	1.62	2.96	-1.21	2.70	0.92	3.75	3.74	1.23	1.10	0.56	-0.95	2.25	-0.03	2.28	2.64	0.38	3.91	-0.64	0.23	0.00	-4.96	-5.74	0.17	-0.23
	12.04	1.06	2.55	0.75	1.71	-55.85	4.88	1.77	5.19	4.75	1.58	5.00	1.13	0.92	1.48	1.19	0.64	1.37	1.38	0.08	1.38	1.03	3.95	5.50	1.49	1.16	0.93	-1.31	3.45	-0.38	1.70	3.76	0.38	10.28	1.00	2.85	4.00	-0.75	-2.45	1.04	0.20
	13.02	0.90	-0.89	-0.67	2.62	52.22	0.88	0.71	1.13	0.10	1.09	1.09	-0.34	0.61	0.70	0.03	0.62	0.63	2.47	0.50	2.42	0.69	5.11	8.32	1.04	-0.42	-0.96	-1.04	4.11	-1.34	2.38	0.81	0.38	-3.11	1.11	0.08	3.11	0.56	-0.67	-6.89	-0.01
	14.06	1.17	-	-	-	-	0.90	-	0.90	1.65	-0.60	1.75	-	-	-	-	-	-	0.00	2.22	-	-	-	-0.94	-	-	-	-	-	-	-	1.29	-	0.00	2.22	0.85	2.39	-	-	-	-
8 (M)	7.33	0.89	0.00	0.90	1.47	75.06	2.87	1.24	3.12	2.06	3.40	3.98	1.01	0.58	1.17	1.03	0.34	1.09	2.81	1.44	-0.28	2.01	1.44	1.40	1.97	1.90	0.54	1.11	0.00	1.11	3.60	0.75	1.72	0.54	0.30	5.30	8.76	10.34	-1.35	0.28	0.54
	8.11	0.68	1.87	1.18	2.14	0.00	3.19	1.97	3.75	2.18	1.25	2.51	0.94	1.03	1.39	1.01	0.99	1.41	0.29	1.28	0.15	4.99	3.76	3.28	0.82	0.82	0.00	1.69	0.78	1.50	1.09	2.13	0.79	1.11	1.18	2.07	5.88	9.41	0.74	1.34	2.01
	9.01	1.11	0.93	1.98	2.30	-3.42	3.69	1.44	3.96	1.62	3.05	3.45	0.59	1.42	1.54	0.23	1.48	1.50	2.25	0.76	0.95	2.85	1.94	2.09	0.58	0.51	-0.27	2.53	-0.19	2.52	2.67	1.53	-0.01	1.22	2.37	3.56	1.26	3.33	4.23	0.19	2.39
	10.11	1.09	6.10	0.18	6.43	-3.58	4.08	1.01	4.21	2.06	2.53	3.27	0.90	1.40	1.67	0.81	1.35	1.57	2.48	1.45	-0.37	2.38	1.89	1.44	1.61	1.57	0.38	1.84	0.05	1.84	2.83	2.63	0.44	3.12	1.04	4.10	-3.94	-3.03	0.83	1.04	5.10
	11.24	1.17	-0.27	-0.51	1.73	18.72	5.40	0.09	5.40	3.33	1.79	3.78	0.57	0.97	1.12	0.50	1.05	1.16	1.28	1.15	-0.32	2.25	0.95	2.04	1.09	1.03	0.38	1.98	0.23	1.97	2.24	3.01	0.32	0.45	0.65	2.81	0.94	1.37	0.51	0.11	0.63
	12.27	0.90	0.43	-0.67	0.28	-1.67	5.40	1.50	5.60	5.00	2.00	5.39	1.46	1.21	1.89	1.46	1.40	2.02	2.56	2.09	0.64	3.98	2.39	3.19	2.71	2.63	-0.62	2.83	1.19	2.57	5.42	4.41	0.63	0.17	1.86	4.63	-0.33	-1.22	3.67	0.08	-0.34
	13.27	1.10	0.20	-0.09	-	-0.91	3.45	1.72	3.86	1.88	2.06	2.79	0.84	1.25	1.50	0.85	1.25	1.51	2.00	1.72	0.95	2.98	2.18	2.03	1.90	0.81	1.72	2.08	1.71	1.18	2.65	1.39	0.01	-	2.20	2.87	-2.00	-1.64	2.27	-0.07	-0.67
	14.34	1.04	0.23	0.48	-	-27.50	3.70	0.96	3.82	2.71	0.49	2.76	0.45	0.19	0.49	0.22	0.14	0.26	0.67	0.80	1.31	2.04	-0.38	2.01	1.62	0.94	1.32	1.49	1.18	0.90	1.62	2.35	0.09	-	1.50	1.43	-0.19	0.67	1.15	0.80	-0.09
	15.48	1.24	0.00	-1.77	-	31.29	1.35	1.20	1.81	1.62	0.68	1.76	-0.05	0.33	0.33	-0.10	0.50	0.51	0.65	0.84	0.65	0.88	-0.25	0.85	0.53	0.32	0.42	1.22	0.61	1.06	1.11	0.95	0.35	-	0.98	1.00	2.48	-0.16	1.69	-0.14	0.48
9 (M)	8.77	1.27	1.02	1.65	3.31	226.77	1.24	0.57	1.36	0.55	0.87	1.03	0.18	1.54	0.59	-0.22	2.07	1.55	1.16	0.28	0.79	0.79	0.79	0.00	2.93	0.73	0.28	2.14	2.13	0.24	1.01	0.86	0.72	2.06	2.32	0.98	1.89	3.86	-2.20	-1.34	2.06
	10.43	2.05	-0.49	-0.34	3.07	136.59	2.57	0.37	2.59	2.51	0.39	2.54	0.32	0.56	0.61	0.49	0.12	0.66	1.10	1.06	-0.54	0.88	0.05	0.88	1.64	1.64	0.13	0.45	-0.04	0.45	2.70	2.01	0.60	1.70	0.02	0.48	-0.78	-1.98	-0.98	1.32	3.36
	11.81	0.72	-0.42	0.14	2.50	418.06	2.61	1.08	2.83	0.76	0.69	1.03	0.36	-0.10	2.50	-0.10	-0.03	0.00	0.97	0.62	-0.14	1.28	0.28	1.25	1.12	1.04	0.06	1.40	0.18	1.39	1.67	1.32	0.19	-0.83	-0.24	1.10	0.00	-0.42	2.50	3.61	-1.17
	12.73	1.12	0.27	0.80	2.09	247.32	1.70	-0.79	1.87	0.98	-0.18	1.00	0.33	0.06	1.73	-0.06	0.28	0.26	0.99	0.70	0.46	0.65	0.41	0.50	0.40	-0.18	-0.54	0.76	0.27	0.71	0.52	1.54	0.50	1.55	0.52	-1.33	-2.14	-0.09	-0.89	-0.45	1.69
	13.83	1.07	0.00	-0.28	2.41	275.70	2.30	0.87	2.46	2.47	1.15	2.72	0.36	1.20	0.19	0.20	1.29	0.79	0.60	1.14	-0.59	1.55	0.09	1.55	2.37	2.08	1.47	0.90	0.75	0.50	3.22	1.92	0.41	1.02	0.61	2.00	-1.59	-2.99	2.06	0.00	1.82
	14.95	1.17	-0.51	0.51	2.39	229.91	1.11	0.03	1.11	1.14	-0.22	1.16	0.25	0.21	0.07	-0.10	0.08	0.25	1.75	0.85	1.01	1.02	-0.37	0.95	0.95	-0.62	0.76	0.53	0.37	-0.38	0.24	0.76	0.00	1.51	1.21	1.09	4.44	-1.37	2.14	-3.25	1.23
10 (F)	8.79	1.08	1.30	1.42	1.66	0.00	2.44	0.62	2.51	0.82	1.67	1.86	0.69	-0.05	0.00	0.00	0.64	0.50	0.90	0.77	0.46	1.45	1.11	0.93	0.68	0.73	-0.06	0.23	-0.14	0.19	1.50	0.00	0.28	1.77	1.16	1.60	4.07	-3.72	-2.31	0.00	1.48
	9.81	0.95	0.11	2.74	3.11	-16.53	2.60	1.16	2.85	3.28	1.19	3.49	1.37	1.22	0.47	1.00	0.61	0.95	2.14	2.14	0.13	2.26	0.45	2.21	1.09	0.78	0.68	0.92	0.68	0.61	2.92	2.42	0.49	2.17	0.60	1.87	0.00	1.14	-3.79	2.11	-0.21
	11.39	2.21	-0.27	2.10	1.72	-3.53	1.43	1.16	1.84	1.38	0.62	1.51	0.80	0.46	0.67	0.41	0.44	0.60	1.12	0.30	1.08	1.32	0.05	1.32	0.19	0.40	0.11	0.77	0.45	-0.62	0.71	1.04	0.19	1.21	1.76	0.73	4.34	-1.39	-0.90	-2.26	-0.05
	13.08	1.18	2.12	2.99	4.63	22.97	2.49	0.69	2.58	0.14	3.00	3.00	1.62	-0.10	1.64	-0.63	1.03	1.17	2.79	1.97	1.97	1.56	1.53	0.34	0.58	0.67	0.07	1.13	0.17	-1.12	2.64	1.40	0.36	2.53	3.61	3.07	4.41	-3.64	-0.87	-1.19	2.54
	14.25	1.16	0.17	2.44	1.51	17.07	1.55	1.08	1.89	0.60	0.53	0.80	0.20	0.09	0.16	0.11	-0.13	0.58	0.70	0.61	0.34	0.53	0.17	0.50	0.36	0.42	0.04	0.43	0.34	-0.26	1.03	0.64	0.11	1.47	0.49	0.57	1.03	-0.69	1.38	0.00	0.43
	15.26	0.86	0.12	3.14	1.37	-22.56	0.73	1.12	1.34	0.74	0.63	0.97	0.28	-0.09	0.03	0.08	0.30	0.67	1.27	0.80	0.99	0.57	-0.27	0.50	0.66	0.31	0.45	0.54	0.12	-0.52	1.12	0.64	0.08	1.55	1.02	1.08	1.74	-1.05	-2.09	-5.23	0.93
	16.04	0.70	-3.14	1.76	1.76	0.00	1.80	-2.19	2.83	1.39	-1.36	1.94	0.29	0.00	-0.09	0.27	-0.53	0.81	2.19	1.07	1.91	1.35	-1.11	0.76	0.78	0.01	0.54	1.77	-0.29	1.74	1.09	0.73	-0.07	1.96	1.83	-0.81	1.14	1.57	5.29	7.00	-1.86
11 (M)	9.04	0.90	1.22	0.22	1.09	0.00	2.56	0.78	2.67	1.02	1.72	2.00	1.06	1.87	1.95	0.44	2.06	2.08	2.04	1.44	1.44	0.00	1.33	1.11	0.97	0.39	0.00	1.56	0.97	-1.22	1.83	1.21	0.50	1.93	3.31	1.83	-2.78	6.78	1.89	5.00	3.16
	9.84	0.70	0.71	0.57	2.79	-31.71	3.71	0.43	3.74	1.71	0.07	1.72	1.47	0.71	1.60	1.26	0.64	1.43	1.77	-0.44	1.71	3.19	1.14	1.57	1.31	0.64	0.91	1.18	-0.29	1.14	0.20	0.94	0.21	1.29	2.43	0.20	0.00	0.00	2.14	-2.14	2.00
	10.75	1.11	2.52	0.90	2.63	35.95	1.53	0.63	1.66	-0.50	3.11	3.15	0.20	0.74	0.74	-0.28	0.75	0.81	1.20	1.17	0.27	0.99	0.36	0.50	0.37	0.25	0.98	0.85	0.45	-0.72	1.42	1.67	0.20	0.95	1.01	1.42	2.43	-5.59	1.62	0.00	3.48
	11.79	0.98	2.35	1.22	3.43	-28.98	4.29	0.41	4.31	0.77	2.63	2.74	0.90	1.66	1.72	0.13	1.62	1.66	2.51	0.56	2.45	1.86	-2.24	1.72	1.79	0.61	1.62	0.00	0.00	0.00	1.17	1.13	0.48	2.33	4.11	1.17	2.35	-3.16	0.00	-0.41	4.67
	12.90	1.24	1.90	1.00	6.02	7.58	5.40	2.02	5.77	2.54	2.48	3.55	0.88	1.70	1.75	0.19	1.68	1.65	2.55	1.65	1.94	2.56	0.24	1.69	2.31	1.13	1.98	0.47	0.40	0.24	2.78	2.86	0.47	4.98	3.64	2.78	2.90	-2.58	-0.73	-0.89	6.87
	13.91	0.77	3.57	1.64	7.66	1.95	6.23	2.47	6.70	0.04	4.30	4.30	0.70	1.90	1.90	-0.35	1.90	1.97	1.13	0.45	1.04	3.87	1.43	1.69	2.05	1.03	0.68	1.36	0.39	1.30	1.48	2.17	0.52	6.49	2.94	1.48	6.61	0.00	0.00	6.62	10.06
	14.89	1.20	1.67	0.67	2.17	5.50	2.58	1.67	3.07	0.00	2.82	2.82	-0.18	2.00	2.11	-0.81	1.78	1.95	1.30	1.00	0.83	1.94	-0.25	0.83	0.70	0.25	-0.31	0.19	0.17	0.08	1.25	1.31	0.18	2.44	2.83	1.25	1.33	-1.33	0.00	0.00	4.11
	16.05	1.12	0.80	0.00	1.38	10.54	0.89	-0.36	0.96	0.09	0.03	0.09	0.12	0.27	0.27	1.00	0.54	1.21	2.46	0.49	-2.41	0.22	1.34	-1.16	0.28	0.27	0.55	0.21	-0.18	0.11	0.76	1.51	-0.03	1.36	-2.14	0.76	0.63	3.30	0.00	0.36	2.16
	17.26	1.30	-0.08	-0.98	0.78	-12.15	0.23	0.77	0.80	0.92	-0.08	0.93	0.60	-0.88	1.23	0.62	-0.50	0.81	1.02	0.67	0.77	1.18	-0.23	-0.69	0.57	0.56	0.27	0.48	0.08	-0.48	1.23	0.33	0.08	0.25	-0.12	1.23	0.00	2.85	-0.92	0.31	0.17
	18.46	1.10	-0.18	-0.82	0.33	-114.55	0.00	0.00	0.00	0.18	-0.86	0.88	0.19	0.07	0.21	0.41	0.23	0.48	0.45	-0.36	-0.27	0.45	0.45	0.18	0.61	-0.23	-0.62	0.57	-0.18	0.55	-0.59	-0.61	0.05	0.03	-0.20	-0.59	0.00	0.99	1.55	0.00	-0.15

Table A.2 ***continued ...***

The mid-range ages in the second column refer to the age at the mid-point of each (annual) observation interval. The actual length of the observation interval is given in the third column.The data are reported as either degrees per year or mm per year.

TABLE A.3 **Differences and ratios of the posterior lowering and the individual components of anterior lowering of the mandible over the observation period.**

Variable	*Subject Number:*											*Correlation*
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**with *MGR***
VRamus-MxAnt-V	21.44	14.21	17.70	11.10	20.10	12.63	7.59	8.32	10.18	11.80	19.90	**0.821** **
VRamus-((MxAnt-V)+(M-MxMol-V))	8.34	-1.54	2.70	2.40	7.00	2.67	-3.61	-0.04	0.44	2.91	8.70	**0.829** **
VRamus-MxPost-V	20.92	15.21	16.32	10.98	19.14	13.32	10.92	7.37	11.03	13.20	19.56	**0.726** *
VRamus-((MxPost-V)+(M-MxMol-V))	7.82	-0.54	1.32	2.28	6.04	3.36	-0.28	-0.23	1.29	4.31	8.36	**0.727** *
VRamus-(M-MxMol-V)	13.00	5.46	7.00	8.10	10.40	9.59	5.03	5.60	3.54	9.11	11.90	**0.685** NS
VRamus/(M-Mxmol-V)	1.99	1.35	1.47	1.93	1.79	1.96	1.45	1.74	1.36	2.02	2.06	**0.469** NS
VRamus/(MxAnt-V)	5.60	3.03	5.12	2.95	6.91	2.83	1.88	2.34	4.28	2.90	7.22	**0.826** **
VRamus/((MxAnt-V)+(M-MxMol-V))	1.47	0.93	1.14	1.17	1.42	1.16	0.82	1.00	1.03	1.19	1.60	**0.846** **
VRamus/((MxPost-V)+(M-MxMol-V))	1.43	0.98	1.06	1.16	1.35	1.21	0.98	0.98	1.11	1.31	1.57	**0.719** *

NS Not significant
* $p < 0.05$
** $p < 0.01$