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Relationships between the orientation and moment arms of the human jaw muscles and normal craniofacial morphology

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SUMMARY It has been suggested that subjects with increased vertical craniofacial dimensions have relatively oblique orientated jaw muscles with a reduced possibility to restrain the vertical component of craniofacial growth. To test this hypothesis, relationships were investigated between the spatial orientation of the jaw muscles and the craniofacial morphology.

Computer reconstructions of the external shape of the jaw muscles of 30 adult males with a normal skull were made with the use of serial magnetic resonance imaging (MRI) scans. The orientation of the jaw muscles was defined by a regression line through the centroids of the serial cross-sections. Sagittal and frontal projections of the moment arms of the muscles were measured with respect to the centre of the ipsilateral condyle.

Craniofacial morphology was analysed three-dimensionally using lateral head films and coronal MRI scans. The cephalometric data were analysed statistically using regression and factor analyses. Six cephalometric factors with Eigen values higher than 1 were correlated with jaw muscle orientation and moment arm data, using a multiple regression analysis. The anterior face height factor was significantly correlated with the orientation of the jaw opening muscles in the sagittal plane but was not significantly correlated with the orientation of the mandibular elevators. The sagittal moment arms of the mandibular elevators showed significant correlations with the factors describing the gonial angle and the posterior face height.

It was concluded that the variation of spatial orientation of the human jaw closing muscles is predominantly associated with the variation of mandibular morphology (expressed by the gonial angle) and the posterior face height. The orientation of the jaw opening muscles shows significant relationships with anterior vertical craniofacial dimensions. The hypothesis that persons with an increased anterior face height have relatively oblique orientated jaw elevators was rejected.

Introduction

The role of jaw muscle function as a determinant of the growth and development of the human craniofacial complex has been studied extensively. In particular, the relationship between excessively vertical growth patterns of the skull (long-face morphology) and abnormal jaw muscle function has received considerable attention (Sassouni, 1969; Proffit *et al.*, 1983; Ahlgren, 1966; Møller, 1966; Weijs and Hillen, 1984b, 1986; Van Spronsen *et al.*, 1991, 1992). However, none of these studies could give any information as to whether jaw muscle function determines the outcome of craniofacial growth or whether growth affects jaw muscle function. Only experimental studies of the effect of induced abnormal muscle function on skull growth can answer this question.

If jaw muscle function influences craniofacial growth, it is likely that this influence is mediated not only via the magnitude of muscle force but also by the spatial orientation of the force vector. Other contributing factors, such as the intrinsic muscular properties, and the degree and mode of activation, are not taken into account in this study. It is obvious that the direction of the muscle forces determines the evoked stress patterns in the growing bones and cartilages, and that these stress patterns directly influence the growth process (for review see Carter *et al.*, 1991).

Experimental studies in which the orientation of the jaw muscles of juvenile dogs (Nanda *et al.*, 1967) and monkeys (Hohl, 1983) has been altered surgically yielded conflicting results. Only Hohl observed a significant increase in vertical skull growth after reinserting the temporalis and masseter muscles in a more oblique direction, limiting the biomechanical efficiency of these muscles.

So far, data of correlational studies describing the relationships between jaw muscle orientation and human craniofacial morphology are scarce and are obtained predominantly by means of cephalometric techniques (Proctor and De Vincenzo, 1970; Takada *et al.*, 1984). These studies indicated that subjects with a long-face morphology have relatively oblique orientated jaw muscles relative to the nasion–sella line, as well as to the Frankfort horizontal plane (FH). The reduced efficiency of the jaw closing muscles has been speculatively associated with the aetiology of long-face morphology (Sassouni and Nanda, 1964; Sassouni, 1969; Epker and O'Ryan, 1982). Sassouni (1969) postulated the concept of a posterior vertical chain of muscles, consisting of the temporalis, masseter and medial pterygoid muscles, controlling the vertical skull growth. It was believed that in long-face subjects this muscle chain was obliquely orientated and situated posteriorly with respect to the temporomandibular joint.

In vitro data of the lines of action of the human jaw muscles, represented by straight lines between the points of origin and insertion, come from biomechanical studies that analysed dissection material or dry skulls (Mainland and Hiltz, 1934; Schumacher, 1961; Hiiemae, 1967; Barbenel, 1972; Baron and Debussy, 1979; Osborn and Baragar, 1985; Haskell *et al.*, 1986; Hatcher *et al.*, 1986; Van Eijden and Raadsheer, 1992). An alternative technique for determining muscle orientation has been described by Jensen and Davy (1975) and An *et al.* (1981, 1984), who determined muscle orientation by the line connecting the centroids calculated in serial cross-sections.

The availability of non-invasive imaging techniques such as computer tomography (CT) and magnetic resonance imaging (MRI) has considerably facilitated *in vivo* studies of the human jaw muscles. In recent studies, serial MRI scans have been used for *in vivo* assessment of the orientation of human jaw muscles (Van Spronsen *et al.*, 1987; Hannam and Wood, 1989; Koolstra *et al.*, 1990). These studies yielded varying data of jaw muscle orientation, probably due to the lack of uniformity of the samples with regard to sex, age and skull shape, and the use of different methods for reconstruction and calculation of the muscle lines of action. Koolstra *et al.* (1989, 1990) described an iterative method for determining muscle lines of action the results of which should be independent of the direction of the reconstructed scan series. Although this method is valid for idealized muscle shapes *in vitro* (Koolstra *et al.*, 1989), the direction of the scan planes determined to a considerable extent the calculated orientation of the jaw muscles *in vivo* (Koolstra *et al.*, 1990). In comparison with anatomical data (e.g. Schumacher, 1961), this iterative method produced too vertical sagittal and transverse muscle angles of the masseter and too small transverse muscle angles of the lateral pterygoid muscle. Therefore, in the present study it was decided to determine the orientation of the jaw muscle by reconstructing scan series taken in different directions. This way, each muscle involved was sectioned as much as possible perpendicular to its main direction, allowing the application of the centroid method.

The aim of this study was to investigate to what extent jaw muscle orientation is associated with measures of craniofacial size and shape, and, more specifically, if the spatial orientation of the mandibular elevators is significantly correlated with vertical craniofacial dimensions.

Such correlations are a prerequisite, not a proof, for causal relationships between jaw muscle orientation and craniofacial growth.

Subjects and methods

Subjects

This study comprised 30 adult males with a mean age of 31.3 years (SD: 6.2) and with a complete, healthy dentition and no functional disorders of the temporomandibular joint. All subjects had a normal craniofacial morphology, which was established by comparing the cephalometric data with the Bolton standards of 18-year-old males (Broadbent *et al.*, 1975).

Cephalometric analysis

Craniofacial morphology was analysed with the use of lateral headfilms taken with a General Electric cephalostat (focus–film distance: 4 m) and traced on acetate paper. Cephalometric landmarks (Table 1) were digitized with a Hipad digitizer (Houston Instruments; resolution: 0.38 mm) and conventional cephalometric measurements were taken. In addition, transverse craniofacial dimensions were measured in coronal and transverse MRI scans (Table 1).

Table 1 Angular and linear variables used in the cephalometric analysis

Angular measurements (degrees)	
1 S/N/A	maxillary prognathism
2 S/N/B	mandibular prognathism
3 SN/MP	sella–nasion/mandibular plane angle
4 SP/MP	spina plane/mandibular plane angle
5 Go	gonial angle
6 N/S/Ba	flexure of the cranial base
7 SN/ArGo	inclination of the ramus relative to the cranial base
8 SP/Op	spina plane/occlusal plane angle
9 OP/Mp	occlusal plane/mandibular plane angle
Linear measurements (mm)	
1 Wits	sagittal jaw relationship
2 overbite	
3 overjet	
4 ATFH	anterior total face height (N–Me)
5 AUFH	anterior upper face height (N–ANS)
6 ALFH	anterior lower face height (ANS–Me)
7 PTFH	posterior total face height (S–Go)
8 Go–Me	corpus length
9 Ar–Go	ramus length
10 S–N	anterior cranial base length
11 S–Ba	posterior cranial base length
12 ANS-PNS	length of the maxilla
13 MHW	maximal head width
14 BZW	bi-zygomatic width
15 BGW	bi-gonial width
16 BCW	bi-condylar width
17 BCoW	bi-coronoid width

Abbreviations: S = sella turcica; N = nasion; A = subspinale; B = supramentale; Me = menton; Go = gonion; Ba = basion; Ar = articulare; ANS = anterior nasal spine; PNS = posterior nasal spine; OP = occlusal plane; SP = spina plane (ANS–PNS); MP = mandibular plane (Go–Me); Wits = distance between projections of A and B on the occlusal plane.

MRI imaging

The jaw muscles were imaged using coronal, transverse and 30 degrees angulated MRI scan series (Figure 1). These series were orientated relative to the FH plane and have been used previously for studying the cross-sectional areas of jaw muscles. A detailed description of the scanning procedures has been provided elsewhere (Van Spronsen *et al.*, 1989, 1991, 1992). Briefly, the scan series were taken with a Technicare Teslacon, operating at 0.6 T and equipped with a 20 cm head coil. Slice thickness of the frontal scans was 4 and 5 mm for the transverse and angulated series respectively (interslice gap, 25 per cent). The total acquisition time of these series was approximately 30 minutes. The orientation of the scan series was based on a standardized protocol, originally developed for CT (Weijs and Hillen, 1984a), in order to obtain jaw muscle cross-sections that were intersecting the muscles as near as possible perpendicularly to their long axes. Due to the complex shape of the jaw muscles and their specific spatial orientation, perfect cross-sectional imaging with three predefined scan series is not possible. Nevertheless, it has been shown previously that with these series reasonable cross-sectional images of the jaw muscles can be made (Weijs and Hillen, 1984a; Van Spronsen *et al.*, 1989, 1991).

Jaw muscle reconstructions

The borders of the muscular and mandibular structures were traced on acetate paper from

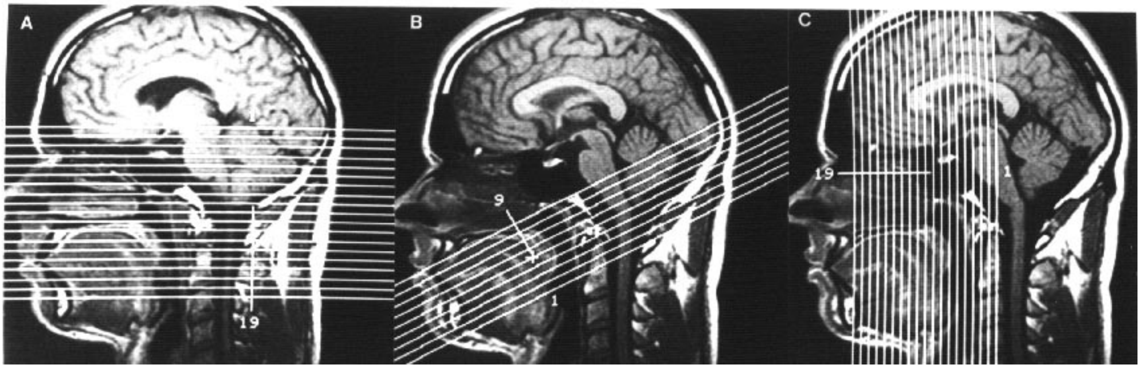

Figure 1 Sagittal MRI scans showing the orientation and range of the MRI scan series for imaging of the temporalis muscle (A, transverse series), the masseter and medial pterygoid muscles (B, 30 degrees angulated series), and the lateral pterygoid muscle and anterior digastric muscle (C, frontal series).

0.5 times magnified prints and subsequently digitized. Calibration bars on the scans were used to scale and align the sequential images to a common origin. The spatial resolution of the MRI scans did not permit distinction between the deep and the superficial masseter. Furthermore, the lateral pterygoid muscle was studied as a whole since the upper and lower heads were separately visible only in two or three scans. Following Koolstra *et al.* (1990), the temporalis muscle was divided into an anterior and a posterior part by a frontal plane through the coronoid process. The different scan series allowed reconstructions of the contours of the jaw muscles and mandible using customized software written in BASIC. Transverse scans were used for reconstruction of the temporalis muscle, since only the range of this series allowed imaging of this muscle from origin to insertion. The lateral pterygoid muscle was reconstructed on the basis of frontal and axial scans for measurements of the sagittal and transverse muscle angles respectively. The masseter and medial pterygoid muscles were reconstructed from 30 degrees angulated and frontal scans. A 30 degrees angulated scan series was used for determination of the sagittal muscle angles of the masseter and medial pterygoid muscles, since this series produces cross-sections that are reasonably perpendicular to the muscle long axes and, therefore, allow for the application of the centroid method. Frontal muscle angles were measured using frontal scan reconstructions. The anterior digastric muscle was reconstructed using a frontal scan series.

Muscle orientation was defined as the regression line through the centroids of the sequential cross-sections. The regression lines through the centroids were referred to a Cartesian coordinate system with the origin between the centres of the condyles in the midsagittal plane: the positive X axis parallel to the FH and directed in an anterior direction; the positive Z axis through the centres of the condyles and directed to the right; and the positive Y axis at right angles to the X and Z axes and directed upward. In the sagittal plane, muscles that were anteriorly orientated (with respect to their mandibular attachments) had a positive angle, whereas posterior orientated muscles had a negative one. In the frontal plane, muscles that were orientated to the right had a positive angle. Sagittal (X–Y), frontal (Z–Y) and transverse (Z–X) muscle angles were used as data. In order to describe the position of the muscles relative to the temporomandibular joint, the length of the moment arms (projected onto the sagittal and frontal planes) were measured perpendicular from the centroid lines to the projection of the centre of the ipsilateral condyle.

The accuracy of determining jaw muscle orientation was assessed by retracing and digitizing the jaw muscles of six subjects after a

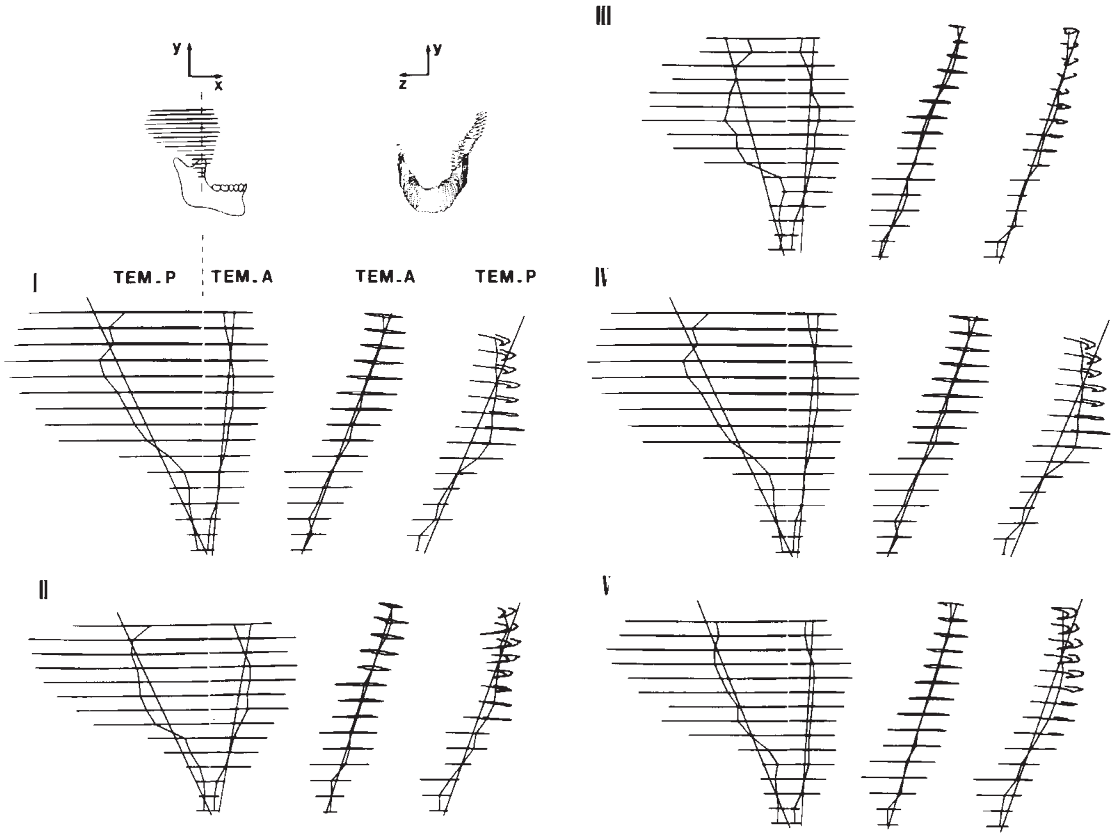

Figure 2 Reconstructions of the anterior (TEM-A) and posterior temporalis muscles (TEM-P) of five different subjects (labelled I–V) imaged in the sagittal (*X–Y*) and frontal planes (*Y–Z*) (the graphical representations of the mandible with the attached temporalis are given to enhance interpretation of the reconstructions). Projections of the centroid lines (curved) and regression lines are depicted of each reconstruction,. Note the variety in morphology and size of the temporalis muscle viewed in the sagittal plane.

period of 12 months. Twelve measurement pairs (left and right) were analysed for each muscle. The repeated measurements showed significant correlations ranging between $R = 0.92$ and $R = 0.99$ ($P < 0.0001$) for both the sagittal and frontal angles of all muscles. The differences between the first and second readings, expressed as a percentage of the mean of both measurements, were always smaller than 4 per cent.

Statistical analyses

Data were analysed using the SPSS^x package (Norusis, 1985). For jaw muscle angles, moment arms and cephalometric variables, descriptive statistics were calculated. Preliminary data screening revealed that many of the cephalometric variables were higly correlated. Therefore, a multiple regression analysis was used to eliminate those cephalometric variables that were statistically redundant ($R \leq 0.98$). Subsequently, on the remaining variables, factor analysis (SPSS^x) was performed in order to obtain a limited set of mutually uncorrelated new cephalometric variables (factors) jointly covering as much variance as possible of the original full set. To facilitate naming these factors, they were first rotated (Varimax rotation).

As the variation of craniofacial size and shape may be in part due to the variation of the muscular variables, a multiple regression analysis was used to assess the relationships between the calculated scores of each cephalometric factor

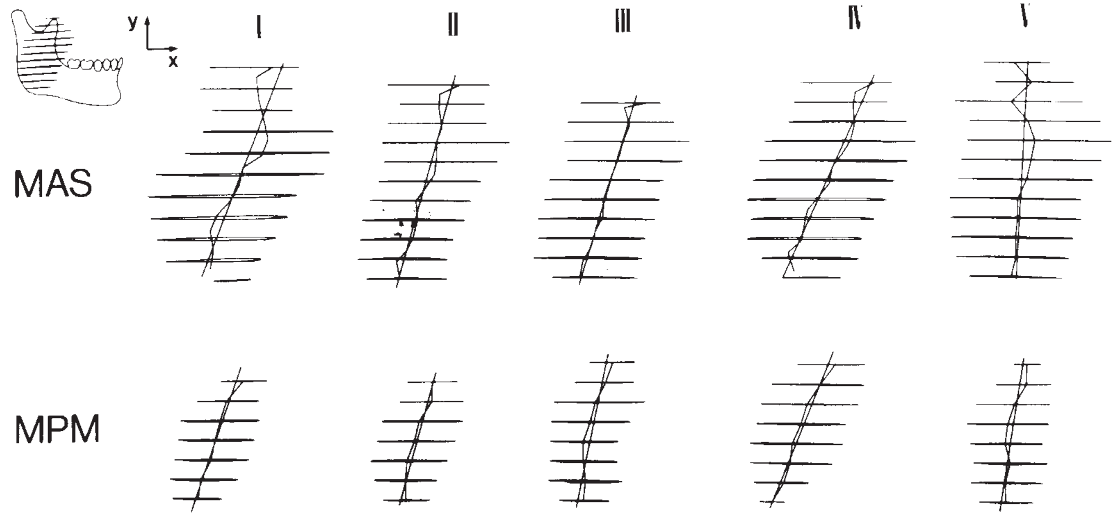

Figure 3 Reconstructions of the masseter (MAS, top row) and medial pterygoid muscle (MPM, bottom row) of five different subjects (labelled I–V) imaged in the sagittal plane. Note that the orientation of the masseter varied from almost vertical (subject V) to 30 degrees relative to FH (subjects I and IV). For the ease of interpretation, horizontal scans were used to illustrate the variation in orientation of the masseter and medial pterygoid muscles.

(criterium variables) and muscle variables (means of left and right muscles) (predictor variables). β weights are given as a parameter indicating the relative importance of the muscle variables involved. R^2 expresses the variation of the craniofacial factors explained by the muscular variables. In this way it was established if and to what extent the variation of jaw muscle orientation and moment arms was related with the variation in craniofacial morphology.

Results

Jaw muscle reconstructions

The variation in orientation of the temporalis and the masseter and medial pterygoid muscles is illustrated by the reconstructions depicted in Figures 2 and 3 respectively. The anterior temporalis is slightly anteriorly inclined, whereas the posterior temporalis is inclined backwards. In frontal view, both parts of the temporalis have a craniolateral inclination (Figure 2). Note that the angle of the masseter muscle in the sagittal plane varies from about 0 to 30 degrees. The orientation of the medial pterygoid muscle in the sagittal plane approximately follows that of

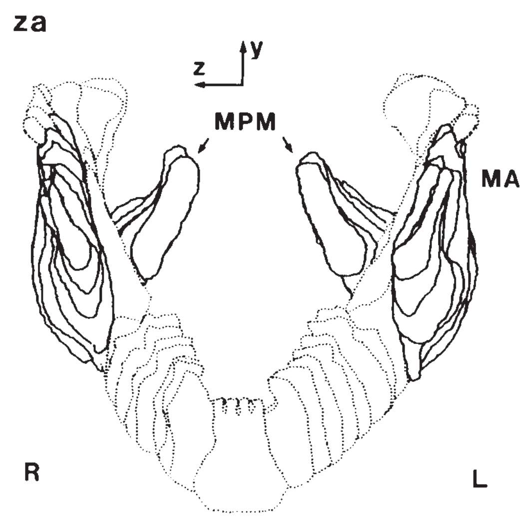

Figure 4 Reconstruction of the mandible, left and right masseter, medial pterygoid muscles and zygomatic arches (ZA) viewed in the frontal plane. The medial pterygoid muscle shows an inclination towards the midsagittal plane of approximately 20 degrees. The masseter shows a craniolateral inclination of approximately 7 degrees.

the masseter. The masseter shows a craniolateral inclination of approximately 7 degrees, whereas the medial pterygoid muscle is inclined towards

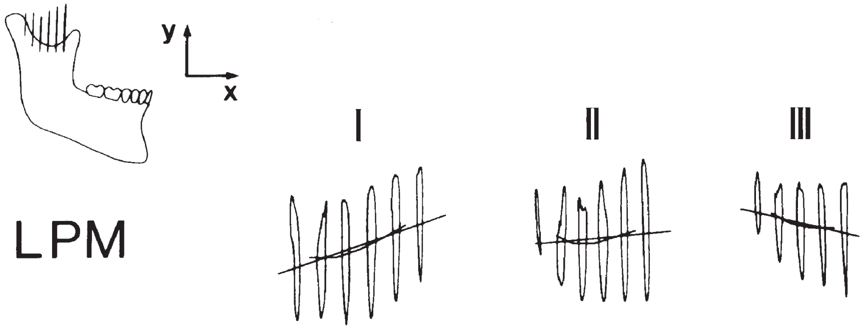

Figure 5 Reconstructions of the lateral pterygoid muscle of three different subjects (labelled I–III) imaged in the sagittal plane. Note that the overall orientation of the lateral pterygoid muscle of subject I is upward, whereas the mean orientation in this plane is 7 degrees downward.

the midsagittal plane (Figure 4). The reconstructions of the lateral pterygoid muscle in the sagittal plane (Figure 5) show the curvature of its distal portion around the articular eminence and its relatively horizontal orientation in an anterior direction. In this direction, the muscle also courses strongly medially (Figure 6). The anterior digastric muscle shows a horizontal (Figure 7) and a fairly (20 degrees) lateral inclination (Figure 6).

Spatial orientation

The data of the orientation and lengths of the moment arms of the jaw muscles are listed in Table 2. The mean sagittal angles of the medial pterygoid and masseter muscles are almost identical. However, the sagittal moment arm of the masseter is approximately 30 per cent larger than that of the medial pterygoid muscle. The sagittal moment arm of the anterior temporalis comes close to that of the masseter and is twice as large as that of the posterior temporalis. The mean frontal angle of the posterior temporalis is larger than that of the anterior temporalis. The frontal orientation of the masseter is almost vertical (7 degrees), whereas the medial pterygoid muscle shows a mean frontal angle of 22 degrees. Of all the muscles, the medial pterygoid muscle shows the largest moment arm in the frontal plane (29 mm). The lateral pterygoid muscle shows a mean angle to the mid-sagittal plane of 43 degrees and its sagittal orientation is slightly downwards. The anterior digastric muscle shows a large sagittal moment arm of 77 mm. Note that the standard deviations of the anterior digastric muscle angles and moment arms exceed those of all other muscles.

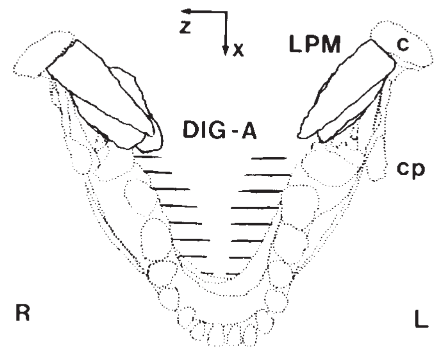

Figure 6 Reconstruction of the mandible, left and right lateral pterygoid muscles (LPM) and anterior digastric muscles (Dig-A) viewed in the transverse plane (abbreviations: c = condyle; cp = coronoid process).

Craniofacial morphology

The sample shows a normal craniofacial morphology [with reference to the Bolton standards for 18-year-old males (Broadbent *et al.*, 1975)], which has been described in detail elsewhere (Van Spronsen *et al.*, 1991). The accuracy of the cephalometric method has alsobeen described previously (Van Spronsen *et al.*, 1992). Briefly, repeated cephalometric measurements yielded an overall mean error of 0.59 degrees for the angular measurements and

0.54 mm for the linear measurements. The cephalometric characteristics of the sample are given in Table 3. Multiple regression analysis showed the following variables to be statistically redundant: S/N/A, S/N/B, S-N/MP, SP/MP, S-N/Ar-Go, SP/OP, OP/MP and AUFH. Factor analysis on the remaining 18 variables yielded six factors jointly describing 76.4 per cent of the total variance. Based on the factor loading matrix (Table 4), the six rotated factors were named as follows: factor 1, anterior face height; factor 2, craniofacial width; factor 3, posterior face height; factor 4, maxillary length and sagittal jaw relationship; factor 5, mandibular shape (gonial angle); and factor 6, craniofacial length [with high loadings for the length of the anterior cranial base (S–N) and the mandibular body (Go–Me)].

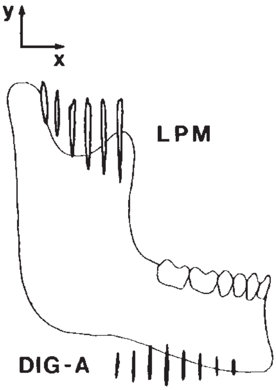

Figure 7 Reconstruction of the lateral pterygoid muscle and anterior digastric muscle viewed in the sagittal plane, superimposed on a traced mandible. Note the horizontally orientated anterior digastric muscle.

Musculoskeletal correlations

Factor scores were calculated and associated with the averages of the right and left muscle data by means of a multiple regression analysis. Only the musculoskeletal associations significant

Table 2 Descriptive statistics of jaw muscle orientation and moment arms of 30 normal subjects

	Orientation (degrees)				Moment arm (mm)			
	Sagittal		Frontal		Sagittal		Frontal	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
TEM A R	9.5	4.4	19.2	3.0	35.8	3.1	7.1	3.4
TEM A L	8.7	5.1	–16.7	2.4	35.8	3.3	7.5	3.2
TEM P R	–27.1	7.6	25.1	4.6	18.4	3.4	1.5	3.3
TEM P L	–27.2	7.7	–24.6	4.3	17.8	2.9	1.8	3.2
MAS R	19.6	5.3	7.8	2.6	35.0	3.0	5.9	2.7
MAS L	18.6	5.2	–7.0	2.3	34.9	3.3	4.8	2.5
MPM R	17.6	6.5	–23.4	2.4	24.2	3.0	29.4	2.8
MPM L	16.5	4.6	22.2	2.6	23.8	2.7	29.6	2.9
	Sagittal		Transverse		Sagittal		Transverse	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
LPM R	96.1	6.2	–43.8	5.1	6.4	3.3	5.9	2.8
LPM L	98.3	7.0	42.6	3.8	7.3	3.3	5.4	2.9
DIG A R	86.5	8.6	–20.5	7.0	77.7	9.1	17.5	9.8
DIG A L	85.9	9.0	19.9	6.1	77.3	9.2	16.2	6.2

Abbreviations: TEM A = anterior temporalis; TEM P = posterior temporalis; MAS = masseter; MPM = medial pterygoid muscle; LPM = lateral pterygoid muscle; DIG A = anterior digastric muscle; R = right; L = left; for reference planes see Subjects and methods.

at the 1 per cent level were considered, and these are listed in Table 5. The anterior face height factor shows a positive significant correlation with the sagittal muscle angle of the lateral pterygoid muscle and a negative significant correlation with the sagittal muscle angle of the anterior digastric muscle. These correlations indicate that in subjects with an increased anterior face height, the orientation of the lateral pterygoid and anterior digastric muscles (viewed from their mandibular attachments) is more caudo-anteriorly and cranio-posteriorly respectively. None of the mandibular elevators, except for the anterior temporalis muscle (the negative correlation indicates a relatively vertical orientated anterior temporalis in subjects with an increased anterior face height), is significantly correlated with the anterior face height factor. The posterior face height factor shows significant positive correlations with the sagittal moment arms of the temporalis and medial pterygoid muscles and negative correlations with the frontal muscle angle of the medial pterygoid muscle as well as the frontal moment arm of the masseter muscle. The frontal muscle angle of the anterior temporalis and the transverse muscle angle of the digastric muscles show positive correlations with the factor of the sagittal jaw relationship and maxillary length. The factor on which the gonial angle loaded heavily is significantly negatively correlated with the sagittal moment arms of the anterior and posterior temporalis, as well as the masseter muscles. Furthermore, this factor shows positive

Table 3 Descriptive statistics of the cephalometric measurements ($n = 30$)

	Mean	SD	Min	Max	Bolton standards
Angular measurements (degrees)					
S/N/A	83.8	4.8	73	92	(84.0 ± 2.9)
S/N/B	81.1	3.5	73	87	(81.0 ± 3.2)
SN/MP	27.6	5.4	16	38	(28.6 ± 4.4)
SP/MP	20.9	4.3	9	29	(20.0 ± 5.1)
Go	122.3	4.9	113	134	(124.9 ± 4.3)
N/S/Ba	127.7	5.3	112	138	
SN/ArGo	85.8	5.1	75	96	
SP/OP	4.7	2.9	0	12	
OP/MP	16.2	3.3	8	23	(16.4 ± 3.9)
Linear measurements (mm)					
Wits	1.3	3.7	–8	7	
Overbite	3.5	2.3	1	10	
Overjet	3.1	2.0	1	9	
ATFH	127.7	6.6	114	146	(124.7 ± 5.1)
AUFH	56.2	2.4	51	61	(57.0 ± 2.6)
ALFH	73.4	5.8	62	86	(67.7 ± 4.6)
PTFH	88.8	4.6	78	95	
Go–Me	77.6	3.3	70	85	
Ar–Go	54.5	3.5	48	61	(52.1 ± 2.9)
S–N	75.1	3.8	68	84	(75.4 ± 2.5)
S–Ba	51.1	2.7	45	56	(48.1 ± 3.3)
ANS-PNS	59.0	4.3	52	70	(58.5 ± 2.0)
MHW	137.1	6.0	124	150	
BZW	126.9	4.3	118	134	
BGW	98.7	5.0	98	114	
BCW	98.5	5.4	86	111	
BCoW	91.2	4.4	84	102	

Bolton standards of 18-year-old males are given in parentheses (Broadbent *et al.*, 1975). Abbreviations: see Table 1.

Table 4 Rotated factor loading matrix of the cephalometric variables explaining 76.4 per cent of the variance.

	Fac 1 (19.8*)	Fac 2 (16.7*)	Fac 3 (14.9*)	Fac 4 (11.0*)	Fac 5 (8.2*)	Fac 6 (5.8*)
ALFH	0.86					
ATFH	0.85					
Overjet	–0.60					
Overbite	–0.50					
BCW		0.73				
BZW		0.72				
BCoW		0.69				
MHW		0.65				
BGW		0.50				
PTFH			0.97			
Ar-Go			0.79			
S-Ba			0.55			
ANS-PNS				0.73		
Wits				0.71		
N/S/Ba				0.59		
Go-angle					1.26	
S-N						0.83
Go-Me						0.53

Abbreviations: see Table 1; Fac(tor) 1, 'anterior face height'; Factor 2, craniofacial width; Factor 3, 'posterior face height'; Factor 4, maxillary length and sagittal jaw relationship; Factor 5, mandibular shape; Factor 6, craniofacial length.
* Percentage of variance.

significant correlations with the sagittal muscle angle of the medial pterygoid muscle. This indicates that an obtuse gonial angle (as can been seen in long-face subjects) is associated with reduced lengths of the elevator muscles moment arms and an obliquely orientated medial pterygoid muscle. The factors describing craniofacial width and length are not significantly correlated with the spatial orientation of any of the jaw muscles.

Discussion

Jaw muscle orientation

The aim of this study was to determine the interindividual variation of whole muscle orientation and to investigate if and to what extent this variation is associated with the variation of adult vertical craniofacial dimensions. For this purpose, determination of jaw muscle centroid lines was appropriate and repeatable. The standard deviations of both the frontal and sagittal muscle angles and moment arms were generally small, indicating that the sample was rather uniform and that the error of the method was within acceptable limits. However, the correspondence between our muscle orientation data and those published by Hannam and Wood (1989) and Koolstra *et al.* (1990) was sometimes variable. *In vivo* data of jaw muscle orientation can be obtained with two distinctly different methods. The first is based on reconstruction of a single series of parallel MRI scans that section the muscles under different angles. Hence, determination of the muscle lines of action requires iterative procedures (Koolstra *et al.*, 1989).

The second method is based on the recontruction of two or more scan series. Depending on what scan planes are used, muscle orientation can be determined using the centroid method (Van Spronsen *et al.*, 1987) or by the assessment of central muscle vectors, aligned parallel to the estimated muscle borders (Hannam and Wood, 1989). The absence of objective criteria makes it impossible to tell which method is superior. Theoretically, the iterative method described by Koolstra *et al.* (1989) is superior since the outcome of muscle orientation would be independent from the

Table 5 Matrix of β weights of the cephalometric factors scores and the spatial orientation of the jaw muscles, as obtained by multiple regression analysis

	Fac 1 ($R^2 = 0.63$)	Fac 2 ($R^2 = 0$)	Fac 3 ($R^2 = 0.60$)	Fac 4 ($R^2 = 0.61$)	Fac 5 ($R^2 = 0.72$)	Fac 6 ($R^2 = 0$)
TEM A						
an-s	–0.48**					
an-f				0.52**		
ma-s			0.43**		–0.43**	
ma-f						
TEM P						
an-s						
an-f						
ma-s			0.42**		–0.38*	
ma-f						
MAS						
an-s						
an-f						
ma-s					–0.32*	
ma-f			–0.46**			
MPM						
an-s					0.47**	
an-f			–0.47**			
ma-s			0.48**			
ma-f						
LPM						
an-s	0.70***					
an-t						
ma-s						
ma-f						
DIG A						
an-s	–0.75***					
an-t				0.40*		
ma-s						
ma-f						

* $P < 0.01$; ** $P < 0.001$; *** $P < 0.000$.

direction of the scan planes used. However, when muscle angles were calculated from frontal and axial scan reconstructions, discrepancies were found that amounted to as much as 8 degrees (Koolstra *et al.*, 1990). Furthermore, Koolstra's data suggest a masseter muscle orientation relative to the FH that is unrealistically vertical (81 degrees), and a lateral pterygoid muscle angle relative to the midsagittal plane that is much too small (23 degrees). Therefore, we have chosen a reconstruction technique that utilizes multiple scan series.

Hannam and Wood (1989) used frontal and axial MRI scan series (4–5 scans) to determine the spatial orientation of the masseter and medial pterygoid muscles. Despite the use of different methods of measuring muscle orientation and reference planes, our mean sagittal muscle angles and moment arms correspond reasonably well with the data of Hannam and Wood, whereas our frontal muscle angles and moment arms were somewhat smaller. It should be noted that the sample of Hannam and Wood consisted of 16 males and six females. Although sexual dimorphism for muscle orientation has not yet been established, it cannot be ignored *a priori.*

A comparison of the MRI data of jaw muscle orientation with data obtained by dissection or analysis of dry skulls is tempting, though one should realise that, generally, the number of specimens (usual elderly people) in these studies is small, atrophy of the jaw muscles is likely and muscle orientation is expressed by straight lines between origin and insertion, rather than central muscle vectors describing external shape.

The mean sagittal angle of the masseter muscle approximates the findings of Schumacher (1961) and is within the range reported for the superficial and deep masseter subunits as estimated from the data published by Baron and Debussy (1979) and Van Eijden and Raadsheer (1992). The mean sagittal angle of the medial pterygoid muscle reported here is in good agreement with the findings of Schumacher (1961) and Baron and Debussy (1979). The mean frontal angles of the masseter and medial pterygoid muscles came close to the values published by Schumacher (1961) but are somewhat smaller with reference to the data of Baron and Debussy (1979). The lateral pterygoid muscle showed an angle to the midsagittal plane that came close to the dissection data of Schumacher (1961) and Honée (1970). Information about the orientation of the mouth openers is rather scarce. In a biomechanical study of the human mandible, Pruim *et al.* (1980) used an estimate of the digastricus orientation of about 70 degrees, which is rather oblique compared with the present findings.

Craniofacial morphology

In studies of craniofacial morphology multivariate statistical techniques have frequently been used to avoid co-linearity (redundancy) of the cephalometric variables. Our multivariate description of cephalometric variables showed that, although traditionally the two extremes of skull shape have been described in terms of brachycephaly and dolichocephaly, anterior face height, posterior face height and the transverse skull dimensions were found on different, uncorrelated factors, which is in line with the findings of Solow (1966), Weijs and Hillen (1986), Van Spronsen *et al.* (1991) and Van der Beek *et al.* (1991). This is probably a reflection of the specific arrangement of the so-called 'growth sites' (such as sutures and periostium) and 'growth centres' (synchondroses) in these regions. For example, the transverse skull dimensions are predominantly determined by growth activity of the sutures and periostium, whereas the increase in posterior face height is accounted for to a great extent by the growth activity in the spheno-occipital synchondrosis and the condylar cartilage (for an overview see Ranly, 1980).

Factor 4 showed high loadings for the cranial base flexure, maxillary length and sagittal jaw relationship, indicating strong mutual interdependencies. This is in line with the findings of Solow (1966), Björk (1955), Hopkin *et al.* (1968) and Kerr and Adams (1988), who mentioned strong interrelationships between the cranial base angle, the position of the glenoid fossae and, consequently, the sagittal jaw relationship; a flattened cranial base was associated with a retruded mandible and a less favourable sagittal jaw relationship.

The factor analysis also showed that the cephalometric variables describing mandibular length, width and shape, and ramal height were found on different factors, underlining their mutual independence. This is supportive for the hypothesis that the mandible consists of a number of relatively independent parts with presumably different functions (Avis, 1961; Harvold, 1963; Tomer and Harvold, 1982; Vilmann *et al.*, 1985; Weijs, 1989).

Musculoskeletal correlations

The matrix of musculoskeletal correlations shows a number of significant interrelationships between jaw muscle orientation and measures of craniofacial size and shape.

Anterior face height

It appeared that the anterior face height factor is significantly correlated particularly with the orientation of the lateral pterygoid muscle and the anterior digastric muscle. A downward orientated lateral pterygoid muscle is associated with a relatively long face. Speculatively, this finding suggests that the traction of the muscle fibres interferes to some extent with condylar growth. Björk (1963) showed that the latter strongly determines mandibular morphology as well as the vertical proportions of the face. In an experimental study by Copray *et al.* (1985) the adaptability of condylar growth to mechanical stimuli was demonstrated. More specifically, Petrovic (1972) and Petrovic *et al.* (1975) suggested the activity of the lateral pterygoid muscle to be an important mediator of the growth of the condylar cartilage, which was claimed to be only a secondary, compensatory growth site. Experimental myotomy of the lateral pterygoid muscle in growing rats has been claimed to lead to a reduced mitotic activity of the prechrondroblasts as well as to a reduced overall mandibular length (Petrovic *et al.*, 1975, 1982; Hinton, 1990, 1991), although opposite findings have been reported by Goret-Nicaise *et al.* (1983) and Awn *et al.* (1987).

The influence of the digastric muscle on mandibular growth is not well understood. Van Vlierberghe and co-workers (1986) experimentally changed the function of this muscle in growing minipigs and noticed no gross effects on mandibular growth. On the contrary, Tomer and Harvold (1982) observed a marked posterior rotation of the mandible after inducing mouth breathing in growing rhesus monkeys, whereas the ramus maintained its inclination relative to the skull. These authors considered the ramus with the attached elevator muscles and the chin with the suprahyoidal muscles as two relatively independent regions with presumably different growth controls. They also suggested strong interrelationships between the sensory control of mandibular postural positioning, the function of the suprahyoid muscles and the mandibular form.

Whereas the masseter muscle is a strong elevator, neither its orientation nor its moment arms in the sagittal plane showed significant correlation with the anterior and posterior face length factors. This is in contrast to the findings of the cephalometric studies of Proctor and DeVincenzo (1970) and Takada *et al.* (1984), which suggested that short-face subjects have relatively vertically orientated superficial masseter muscles.

Since it has also been shown previously that, in a normal population, the masseter cross-sectional areas are not significantly correlated with adult vertical craniofacial dimensions (Van Spronsen *et al.*, 1991), this may hint that the association between the strength of this muscle and normal vertical craniofacial growth is less close than generally assumed.

Posterior face height

The posterior face height factor showed positive significant correlations with the sagittal moment arms of the anterior and posterior temporalis as well as the medial pterygoid muscle (though surprisingly not with the masseter muscle). The former implies that these muscles are shifted forward in subjects with an increased posterior face height. This supports to some extent the theory of Sassouni and Nanda (1964) that the vertical development of the posterior face height is controlled by the vertically orientated and anteriorly situated jaw closing muscles. However, it is remarkable that the biomechanical efficiency of the jaw muscles is significantly associated with a part of the craniofacial complex in which growth is suggested to be predominantly genetically controlled (see Ranly, 1980). Regarding the correlation pattern of the posterior face height, the question can be raised as to whether the biomechanical influence of the jaw muscles on the growing craniofacial complex is determined more by their distance from the temporomandibular joint than the orientation of the muscles. In other words, is the development of muscle orientation during craniofacial growth rather conservative and does the mechanical advantage of the jaw muscles improve probably by a change in mutual interrelationships between the various craniofacial components and the dentition? Evidently, answering this question is very difficult. However, some support for this notion comes from a growth study of the development of the masticatory muscles in rhesus monkeys (Dechow and Carlson, 1990) in which no gross growth changes for muscle orientation was reported though there was some improvement of the mechanical advantage of the muscles (with respect to the molar bite point). To the contrary, no such changes could be found in rabbits (Weijs *et al.*, 1987; Langenbach *et al.*, 1991) and baboons (Oyen *et al.*, 1979).

Gonial angle

To some extent the variation of the gonial angle reflects the variation of the position relative to the joint of the masseter and medial pterygoid muscles, but also to that of the temporalis. A close relationship especially between masseter function and the gonial angle has been shown experimentally by Horowitz and Shapiro (1955), Avis (1961), Nanda *et al.* (1967) and Yellich *et al.* (1981), and cephalometrically by Björk and Skieller (1972), who described specific mandibular growth patterns in different craniofacial types. The correlation between the gonial angle and the temporalis position indicates that the shape of the gonial area not only depends on a close anatomical relationship between the masseter and medial pterygoid muscles with this area, but may also be influenced by the combined action of different mandibular elevator muscles that induce a specific stress pattern and consequently mandibular remodelling. Alternatively, a simpler explanation would be that a reduced moment arm of the temporalis might reflect a reduced width of the ramus, which is, like an obtuse gonial angle, a morphological characteristic of the long-face mandible.

The frontal muscle angles were not significantly correlated with the transverse craniofacial measurements, although these grossly represent the transverse position of the muscular attachments. Hence, better correspondence could be expected. Since significant correlations have been reported previously between jaw muscle cross-sectional areas and craniofacial width (Weijs and Hillen, 1984b, 1986; Hannam and Wood, 1989; Van Spronsen *et al.* 1991), it can be speculated that the transverse development of the skull is determined by jaw muscle size rather than its spatial orientation.

Conclusions

Summarizing, this study shows that the spatial orientation of the jaw muscles of subjects with a normal craniofacial morphology is to some extent related to the variation of particularly the anterior and posterior face height, as well as the mandibular shape (expressed by the gonial angle). Contrary to common belief, the anterior face height shows no significant correlations with the spatial orientation of the major mandibular elevator muscles. On the other hand, the orientation of muscles that open the mandible, i.e. the lateral pterygoid and anterior digastric muscles, was significantly correlated with anterior face height.

It should be noted that musculoskeletal interactions may be different in a normal population and a selected group of long-face subjects, as has recently been shown for jaw muscle cross-sectional areas (Van Spronsen *et al.*, 1991, 1992). The variation of jaw muscle size or orientation in a normal sample is possibly too small to produce significant correlations with specific cephalometric variables. Speculatively, it can also be put forward that aberrant vertical craniofacial growth occurs when the size or orientation of the jaw muscles are beyond adaptational limits.

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