Jaw muscle size and bite force magnitude in relation to craniofacial morphology

Raadsheer, M.C.

Publication date
1999

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
CHAPTER 5 CONTRIBUTION OF JAW MUSCLE SIZE AND CRANIOFACIAL MORPHOLOGY TO HUMAN BITE FORCE MAGNITUDE


Abstract - The existence of an interaction between bite force magnitude, jaw muscle size (e.g., cross-sectional area, thickness) and craniofacial morphology is widely accepted. Bite force magnitude depends on the size of the jaw muscles and the lever arm lengths of bite force and muscle forces, which in turn are dictated by craniofacial morphology. In this study, the relative contribution of craniofacial morphology and jaw muscle thickness to the bite force magnitude was studied. In 121 adult individuals, both magnitude and direction of the maximal voluntary bite force were registered. Craniofacial dimensions were measured by anthropometrics and from lateral radiographs. The thicknesses of the masseter, temporal and digastric muscles were registered by ultrasonography. After a factor analysis was applied on the anthropometric and cephalometric dimensions, the correlation between bite force magnitude on the one hand and the "craniofacial factors" and jaw muscle thicknesses on the other hand was assessed by stepwise multiple regression. 58% of the bite force variance could be explained. From the jaw muscles, only the thickness of the masseter muscle correlated significantly with bite force magnitude. Bite force magnitude also correlated significantly positive with vertical and transverse facial dimensions and the inclination of the midface, and significantly negative with mandibular inclination and occlusal plane inclination. The contribution of the masseter muscle to the variation in bite force magnitude was higher than that of the craniofacial factors.

5.1 INTRODUCTION

It is widely accepted that an interaction exists between size and function of the masticatory muscles and craniofacial morphology. First, bite force magnitude and jaw muscle cross-sectional area are related. Van Spronsen et al. (1989) showed that the cross-sectional area of the masseter muscle, either measured with computed tomography (CT) or magnetic resonance imaging (MRI), correlated significantly with maximal bite force at the molars or the incisors, measured in one direction. For the temporal muscle, a correlation was found with the MRI cross-sectional area only. No correlations were found for the medial and lateral pterygoid muscles.

Second, bite force magnitude and craniofacial morphology are related. Ingervall and Helkimo (1978) found that higher bite forces correlated with a smaller cranial base flexure, a deeper upper face, a smaller anterior and a larger posterior face height, and a less divergent, broader face. Proffit et al. (1983) found a relation between bite force magnitude and vertical facial morphology. Bolt and Orchardson (1986) found a relation between craniofacial morphology
and mouth opening force, *i.e.*, larger mouth opening forces were associated with longer and more divergent faces. In these studies, bite forces were measured in one dimension only.

Third, craniofacial morphology and jaw muscle cross-sectional area are related, cross-sectional area being an indication of the maximal force a muscle is capable of producing (Morris, 1948; Schantz *et al.*, 1983). Using CT, Weijis and Hillen (1986) found that 1) the cross-sectional areas of the temporal and masseter muscles correlated with craniofacial widths, 2) the cross-sectional areas of the masseter, medial pterygoid and lateral pterygoid muscles correlated with mandibular length, and 3) the cross-sectional areas of the lateral pterygoid muscles correlated negatively with cranial base length and positively with lower face height. Using MRI, Hannam and Wood (1989) found significant correlations between bizygomatic arch width and the cross-sectional areas of the masseter and medial pterygoid muscles, and Van Spronsen *et al.* (1991) found a relationship of the temporal muscle cross-sectional area with craniofacial width (positive) and cranial base flexure (negative). By comparing long-face individuals with normal individuals, Van Spronsen *et al.* (1992) found that the masseter muscle contributed mostly to the relation with facial morphology, followed by the medial pterygoid muscle and, to a lesser degree, the anterior temporal muscle. Using ultrasonography, Ruf *et al.* (1994) found a significantly negative relation between the masseter cross-sectional area and the anterior face height index. Also, significant correlations have been described between the ultrasonographic thickness of the masseter muscle and facial morphology, both in adults (Kiliaridis and Kålebo, 1991; Bakke *et al.*, 1992; Ruf *et al.*, 1994) and in growing individuals (Raadsheer *et al.*, 1996).

The above-mentioned studies indicate that the interaction between muscle size and facial morphology is complex. In addition, the magnitude of maximal bite force depends on both the size of the jaw muscles and the dimensions of the craniofacial complex. Thus far, the relations between either bite force and jaw muscle size, or bite force and craniofacial morphology, or craniofacial morphology and jaw muscle size have been studied. No conclusions can therefore be drafted from the available studies about the relative contribution of both jaw muscle size and craniofacial dimensions to the variation in bite force magnitude.

The aim of the present study was to assess the relative contribution of 1) jaw muscle size and 2) craniofacial morphology to the maximal voluntary bite force magnitude by measuring both bite force, jaw muscle size, and morphology of the craniofacial skeleton.

### 5.2 MATERIALS AND METHODS

#### 5.2.1 Participants

Measurements were made on 121 individuals, age 18-36 years (mean age 23); 58 were males and 63 were females. All participants were healthy and showed no facial malformations. They had a complete or almost complete dentition without extreme malocclusion or functional disorders. Informed consent was obtained from all subjects, using a written form approved by
Fig. 1. Diagrammatic illustration of the bite force measurements and position of the bite force transducer. R', resultant bite force component in the midsagittal plane; X, anteroposterior bite force component parallel to the occlusal plane; Z, bite force component perpendicular to the occlusal plane; \( \alpha \), bite force direction in the mid-sagittal plane (angle between R' and Z).

The Medical Ethical Committee of the Academic Medical Center of the University of Amsterdam.

The examination comprised bite force measurements (magnitude and direction), measurements of craniofacial morphology (anthropometrics and cephalometrics) and measurements of jaw muscle thicknesses (masseter, temporal and digastric muscle). Also, stature and weight were recorded so that they could be included as covariates in the statistical analyses.

5.2.2 Bite force measurements

Bite forces were measured with a bite force transducer (Kistler, Type 9251A, 10 x 24 x 24.2 mm), capable of registering bite forces in all three dimensions. For an extensive description of the transducer and the force registration method we refer to Van Eijden et al. (1988, 1990). The transducer output (three signals, one for each force component) was amplified (Kistler Charge Amplifier Type 5007) and connected to a PC (Hewlett Packard Vectra 486/33N). This analogue output was converted to a digital signal (National Instruments PC-LPM-16 Interface Board) and analyzed with the Labview software (National Instruments), allowing for registration of the peak values (R), and the attached X-, Y- and Z-components of bite force. From these components, the angle (\( \alpha \)) between the vertical component (Z) and the bite force component in the mid-sagittal
plane (R') was calculated (Fig. 1). The transducer was placed between two acrylic plates, creating two planes, parallel to the maxillary occlusal plane, i.e., the plane through the mesiobuccal cusps of the first molars and the incisal ridges of the central incisors (Fig. 1). The plates were made on dental casts, mounted in a Dentatus articulator. The transducer’s midpoint coincided with a point defined by the midsagittal plane and a line through the cusps of the mandibular canines. With the transducer in place, the interincisal distance ranged from 19 to 25 mm, reflecting an opening angle of 10° to 15°. During the experiments, the participants were seated upright. The bite plates were fitted and the participants were allowed to accustom for two minutes. For each registration, the participants were asked to steadily build up the maximal force they could achieve. All measurements were done five times, with intervals of at least one minute. The first two measurements were try outs. From the last three measurements the two closest ones were selected and averaged. During the experiments, the volunteers were not encouraged, nor did they get information about the results.

2.3 Craniofacial dimensions

Craniofacial morphology was measured by anthropometric measurements (Fig. 2, Table 1), as described by Raadsheer et al. (1996), and by cephalometrics, obtained from lateral radiographs. The distance between X-ray tube and film cassette was 4 meter. Radiation risks were minimized by using (1) a round dodger, reducing radiation levels of brains and soft tissues in combination with optimal soft tissue imaging, (2) a diaphragm, excluding the thyroid from exposure, (3) filters, creating a homogeneous bundle with optimum radiation levels, (4) an exposure sensor, automatically optimizing bundle intensity, and (5) rare earth intensifying screens (Kodak Lanex 66).

Fig. 2. Diagrammatic representation of vertical and transverse anthropometric dimensions. All abbreviations are described in Table 1.
Table 1. Linear anthropometric dimensions

<table>
<thead>
<tr>
<th>ATFH</th>
<th>Anterior total facial height</th>
<th>Nasion-menton</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUFH</td>
<td>Anterior upper facial height</td>
<td>Nasion-subnasale</td>
</tr>
<tr>
<td>ALFH</td>
<td>Anterior lower facial height</td>
<td>Subnasale-menton</td>
</tr>
<tr>
<td>BFW</td>
<td>Bizygomatic facial width</td>
<td>Zygion-zygion</td>
</tr>
<tr>
<td>IGW</td>
<td>Intergonial width</td>
<td>Gonion-gonion</td>
</tr>
<tr>
<td>ICW</td>
<td>Intercondylar width</td>
<td>Condyle-condyle</td>
</tr>
</tbody>
</table>

Regular). Forty-two reference points were digitized on a XY-tablet (DigiPad DP5A, GTCO Corporation) and fed into the cephalometric program Viewbox (copyright 1992-1994, Demitrios Halazonetis, Athens, Greece) running on a PC (Hewlett Packard Vectra VL2 4/50). By using 19 cephalometric landmarks (Fig. 3), with Viewbox 13 linear and 15 angular dimensions were obtained (Tables 2 and 3, respectively).

5.2.4 Jaw muscle thicknesses

Muscle thicknesses of the masseter, temporal and anterior belly of the digastric muscles were measured bilaterally by ultrasonography. Ultrasound images were obtained by means of a real-time scanner (Pie Medical Scanner 450, 7.5 MHz linear array transducer). The masseter muscles were scanned on a level halfway between the zygomatic arch and gonial angle. The scan plane was perpendicular to the anterior border of the muscle and perpendicular to the surface of the underlying ramus (see also Raadsheer et al., 1994). The temporal muscle was scanned at the deepest part of the temporal fossa, directly behind the zygomatic ridge of the frontal bone, on a level of the eyebrow tail (Farkas, 1994), parallel to the Frankfort horizontal plane and perpendicular to the underlying bone. The anterior belly of the digastric muscle was measured halfway between gnathion and gonion, perpendicular to the belly’s long axis. The thickness, perpendicular to the skin surface was registered. All three scanning levels are shown diagrammatically in Fig. 4. During the registrations, the participants were seated upright, with their heads in a natural position. The muscles were relaxed, i.e., the participants were asked to relax, but to keep slight interocclusal contacts. All registrations were repeated once and the final thickness was obtained from the mean of both measurements. Muscle thickness was measured to the nearest mm.
5.2.5 Statistics

A multivariate analysis of variance was performed with muscle thickness of the masseter, the temporal and the digastric muscles as the dependent variables. "Gender" (female, male) was a between subject factor, "side" (right, left) was a within subject factor. "Stature" and "weight" were covariates.

A principal component analysis on the variables "gender", "weight" and "stature", and the anthropometric and cephalometric craniofacial measurements was performed in order to establish the smallest possible set of mutually uncorrelated new variables jointly accounting for the greatest proportion possible of the total variance of the original craniofacial measurements. To enable unequivocal naming, the components found were rotated. In order to be as realistic as possible, an oblique rotation method was chosen.

Subsequently, the relation between bite force magnitude, the craniofacial dimensions (i.e., the components from the above mentioned factor analysis) and the jaw muscle thicknesses was assessed by a stepwise multiple regression analysis.

For all statistical analyses the SPSS x package (SPSS Inc., 1990) was used.
### Table 2. Linear cephalometric measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-N</td>
<td>Anterior cranial base length</td>
</tr>
<tr>
<td>S-Ba</td>
<td>Posterior cranial base length</td>
</tr>
<tr>
<td>S-Go</td>
<td>Posterior total facial height</td>
</tr>
<tr>
<td>Ar-Go</td>
<td>Ramus length</td>
</tr>
<tr>
<td>Go-Me</td>
<td>Corpus length</td>
</tr>
<tr>
<td>ANS-Me</td>
<td>Anterior lower facial height</td>
</tr>
<tr>
<td>&quot;Wits&quot;</td>
<td>Sagittal intermaxillary relation (distance between projection of A and B on the occlusal plane)</td>
</tr>
<tr>
<td>Overjet</td>
<td>Horizontal distance between incisal edge of +1 and -1</td>
</tr>
<tr>
<td>Overbite</td>
<td>Vertical distance between incisal edge of +1 and -1</td>
</tr>
<tr>
<td>+1_{sp} - Sppl</td>
<td>Anterior maxillary dimension</td>
</tr>
<tr>
<td>-1_{sp} - Mpl</td>
<td>Anterior mandibular dimension</td>
</tr>
<tr>
<td>+6_{sp} - Sppl</td>
<td>Posterior upper dental height</td>
</tr>
<tr>
<td>-6_{sp} - Mpl</td>
<td>Posterior lower dental height</td>
</tr>
</tbody>
</table>

**Abbreviations:**

Sppl, Spinal plane (line through anterior nasal spine and posterior nasal spine);
Mpl, Mandibular plane (line through menton and antegonial notch);
for other abbreviations: see Fig. 3.

### Table 3. Angular cephalometric measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN/FFH</td>
<td>Cranial base / Frankfort horizontal plane angle</td>
</tr>
<tr>
<td>N/S/Ba</td>
<td>Cranial base flexure</td>
</tr>
<tr>
<td>SN/ArGo</td>
<td>Sella-nasion / ramus angle (posterior border)</td>
</tr>
<tr>
<td>S/N/A</td>
<td>Maxillary prognathism</td>
</tr>
<tr>
<td>S/N/B</td>
<td>Mandibular prognathism</td>
</tr>
<tr>
<td>A/N/B</td>
<td>Sagittal intermaxillary relation</td>
</tr>
<tr>
<td>Sppl/FFH</td>
<td>Maxillary inclination</td>
</tr>
<tr>
<td>Mpl/FFH</td>
<td>Mandibular inclination</td>
</tr>
<tr>
<td>GoGn/SN</td>
<td>Mandibular inclination</td>
</tr>
<tr>
<td>Ocll/SN</td>
<td>Inclination of the occlusal plane</td>
</tr>
<tr>
<td>Ocll/FFH</td>
<td>Inclination of the occlusal plane</td>
</tr>
<tr>
<td>Sppl/Mpl</td>
<td>Relative inclination of maxilla and mandible</td>
</tr>
<tr>
<td>Ocll/Sppl</td>
<td>Maxillary vertical proportion</td>
</tr>
<tr>
<td>Ocll/Mpl</td>
<td>Mandibular vertical proportion</td>
</tr>
<tr>
<td>&lt; Go</td>
<td>Gonial angle</td>
</tr>
</tbody>
</table>

**Abbreviations:**

FFH, Frankfort horizontal plane (line through orbitale and pogonion);
Sppl, Spinal plane (line through anterior nasal spine and posterior nasal spine);
Mpl, Mandibular plane (line through menton and antegonial notch);
Occl, Occlusal plane (line through "+6_{sp}" and "+1/-1");
for other abbreviations: see Fig. 3.
5.2.6 Measurement error

The errors of measurement ($S_e$) for the bite force magnitudes, and the anthropometric, cephalometric, and ultrasound measurements were assessed on repeated measurements ($m_1$, $m_2$) of ten randomly selected participants ($n$), using the formula:

$$S_e = \sqrt{\frac{\sum (m_1 - m_2)^2}{2n}}$$

The outcomes are shown in Table 4. A period of two months elapsed between the repeated measurements. The bite force measurement error was 21.8 N. The anthropometric errors were 1 mm or less, the cephalometric ones were 1.3 mm or less and 1.5° or less. The ultrasound errors were 0.5 mm or less. The linear craniofacial measurements and ultrasound measurements were also expressed as a percentage of the mean.

5.3 RESULTS

The means and standard deviations (SD) of the bite force magnitudes, the force components, and the bite force directions are given in Table 5A. Subjects were divided by gender. The mean bite force was larger in males, though not significantly. The bite force direction $\alpha$ ranged between $-16.5^\circ$ and $+16.8^\circ$ for females, and between $-11.8^\circ$ and $+17.8^\circ$ for males. The means and SD for the anthropometric measurements are given in Table 5B, those for
Table 4. Errors of measurement assessed on repeated measurements of 10 randomly selected individuals

<table>
<thead>
<tr>
<th>Bite forces (Newton)</th>
<th>Se</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resultant force R</td>
<td>21.8</td>
</tr>
<tr>
<td>X-component</td>
<td>16.1</td>
</tr>
<tr>
<td>Y-component</td>
<td>13.9</td>
</tr>
<tr>
<td>Z-component</td>
<td>25.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anthropometric dimensions (mm)</th>
<th>Se</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATFH</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>AUFH</td>
<td>0.9</td>
<td>1.7</td>
</tr>
<tr>
<td>ALFH</td>
<td>0.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Abbreviations: see Table 1.

<table>
<thead>
<tr>
<th>Cephalometric angles (°)</th>
<th>Se</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN/FFH</td>
<td>0.43</td>
</tr>
<tr>
<td>N/S/Ba</td>
<td>1.02</td>
</tr>
<tr>
<td>Sn/ArGo</td>
<td>1.05</td>
</tr>
<tr>
<td>S/N/A</td>
<td>0.50</td>
</tr>
<tr>
<td>S/N/B</td>
<td>0.32</td>
</tr>
<tr>
<td>A/N/B</td>
<td>0.32</td>
</tr>
<tr>
<td>Sppl/FFH</td>
<td>0.90</td>
</tr>
<tr>
<td>Mpl/FFH</td>
<td>0.73</td>
</tr>
<tr>
<td>GoGn/SN</td>
<td>0.98</td>
</tr>
<tr>
<td>Occl/SN</td>
<td>0.85</td>
</tr>
<tr>
<td>Occl/FFH</td>
<td>0.74</td>
</tr>
<tr>
<td>Sppl/Mpl</td>
<td>0.77</td>
</tr>
<tr>
<td>Occl/Sppl</td>
<td>0.86</td>
</tr>
<tr>
<td>Occl/Mpl</td>
<td>0.43</td>
</tr>
<tr>
<td>&lt;Go</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Abbreviations: see Fig. 2 and footnotes Table 3.

<table>
<thead>
<tr>
<th>Ultrasound measurements of muscle thicknesses (mm)</th>
<th>Se</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masseter right</td>
<td>0.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Temporal right</td>
<td>0.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Digastric right</td>
<td>0.5</td>
<td>7.2</td>
</tr>
</tbody>
</table>

\[ S_e = \sqrt{\left(\overline{m} - m\right)^2/2n} \]
\[ % = (S_e/\text{mean}) \times 100\% \]
Table 5A. Descriptive statistics of the maximal voluntary bite force $R$ and its matching X-, Y- and Z-components (Newton), and the bite force direction $\alpha$ ($^\circ$)

<table>
<thead>
<tr>
<th></th>
<th>Females, $n=61$</th>
<th>Males, $n=58$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bite force $R$</td>
<td>Mean 383.6</td>
<td>Mean 545.7</td>
</tr>
<tr>
<td></td>
<td>SD 86.2</td>
<td>SD 115.1</td>
</tr>
<tr>
<td></td>
<td>Min 186</td>
<td>Min 276</td>
</tr>
<tr>
<td></td>
<td>Max 576</td>
<td>Max 888</td>
</tr>
<tr>
<td>X-component</td>
<td>Mean 22.6</td>
<td>Mean 49.1</td>
</tr>
<tr>
<td></td>
<td>SD 36.8</td>
<td>SD 62.4</td>
</tr>
<tr>
<td></td>
<td>Min -107</td>
<td>Min -90</td>
</tr>
<tr>
<td></td>
<td>Max 99</td>
<td>Max 187</td>
</tr>
<tr>
<td>Y-component</td>
<td>Mean 1.6</td>
<td>Mean -1.4</td>
</tr>
<tr>
<td></td>
<td>SD 21.4</td>
<td>SD 20.6</td>
</tr>
<tr>
<td></td>
<td>Min -54</td>
<td>Min -60</td>
</tr>
<tr>
<td></td>
<td>Max 39</td>
<td>Max 46</td>
</tr>
<tr>
<td>Z-component</td>
<td>Mean 380.2</td>
<td>Mean 539.6</td>
</tr>
<tr>
<td></td>
<td>SD 87.0</td>
<td>SD 115.0</td>
</tr>
<tr>
<td></td>
<td>Min 186</td>
<td>Min 272</td>
</tr>
<tr>
<td></td>
<td>Max 571</td>
<td>Max 887</td>
</tr>
<tr>
<td>Direction $\alpha$</td>
<td>3.9</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>SD 6.0</td>
<td>SD 6.9</td>
</tr>
<tr>
<td></td>
<td>Min -16.5</td>
<td>Min -11.8</td>
</tr>
<tr>
<td></td>
<td>Max 16.8</td>
<td>Max 17.8</td>
</tr>
</tbody>
</table>

The X-component is the force vector, parallel to the occlusal and midsagittal plane ($+ =$ forward, $-$ = backward); the Y-component is the force vector, parallel to the occlusal plane but perpendicular to the midsagittal plane ($+ =$ right-hand side, $-$ = left-hand side); the Z-component is the force vector, perpendicular to the occlusal plane but parallel to the midsagittal plane; $\alpha$ is the bite force direction in the midsagittal plane, relative to the Z-axis ($+ =$ anterior, $-$ = posterior).

Table 5B. Descriptive statistics of the anthropometric measurements (mm)

<table>
<thead>
<tr>
<th></th>
<th>Females, $n=61$</th>
<th>Males, $n=58$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>ATFH</td>
<td>112</td>
<td>6</td>
</tr>
<tr>
<td>AUFH</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>ALFH</td>
<td>66</td>
<td>5</td>
</tr>
<tr>
<td>BFW</td>
<td>116</td>
<td>7</td>
</tr>
<tr>
<td>ICW</td>
<td>120</td>
<td>5</td>
</tr>
<tr>
<td>IGW</td>
<td>96</td>
<td>5</td>
</tr>
</tbody>
</table>

Abbreviations: see Table 1.

the cephalometric measurements in Table 5C. Although all linear dimensions were larger in males than in females, and mean angular dimensions were not the same, craniofacial morphology between males and females was not significantly different. The means and SD for the ultrasound measurements are given in Table 5D.

In this Table it can be seen that, like for the bite forces and the linear craniofacial dimensions, the values of all mean muscle thicknesses were larger in males. The multivariate analysis of variance yielded the following results (Table 6). The relationship between the covariates ("stature", "weight") on the one hand and the dependent variable "muscle thickness" (masseter, temporal, digastric) on the other hand turned out to be multivariately significant
Table 5C. Descriptive statistics of the cephalometric measurements

<table>
<thead>
<tr>
<th>Angular measurements (°)</th>
<th>Females, n=61</th>
<th>Males, n=58</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>SN/FFH</td>
<td>7.3</td>
<td>2.7</td>
</tr>
<tr>
<td>N/S/Ba</td>
<td>131.9</td>
<td>4.6</td>
</tr>
<tr>
<td>SN/ArGo</td>
<td>89.4</td>
<td>4.6</td>
</tr>
<tr>
<td>S/N/A</td>
<td>80.9</td>
<td>3.9</td>
</tr>
<tr>
<td>S/N/B</td>
<td>78.0</td>
<td>3.2</td>
</tr>
<tr>
<td>A/N/B</td>
<td>3.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Sppl/FFH</td>
<td>-0.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Mpl/FFH</td>
<td>24.4</td>
<td>5.4</td>
</tr>
<tr>
<td>GoGn/SN</td>
<td>31.3</td>
<td>5.1</td>
</tr>
<tr>
<td>Occl/SN</td>
<td>15.0</td>
<td>3.2</td>
</tr>
<tr>
<td>Occl/FFH</td>
<td>7.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Sppl/Mpl</td>
<td>25.6</td>
<td>5.9</td>
</tr>
<tr>
<td>Occl/Sppl</td>
<td>8.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Occl/Mpl</td>
<td>17.5</td>
<td>4.9</td>
</tr>
<tr>
<td>&lt;Go</td>
<td>123.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Linear measurements (mm)</th>
<th>Females, n=61</th>
<th>Males, n=58</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>S-N</td>
<td>70.7</td>
<td>3.3</td>
</tr>
<tr>
<td>S-Ba</td>
<td>44.7</td>
<td>2.7</td>
</tr>
<tr>
<td>S-Go</td>
<td>75.2</td>
<td>5.8</td>
</tr>
<tr>
<td>Ar-Go</td>
<td>44.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Go-Me</td>
<td>71.9</td>
<td>4.4</td>
</tr>
<tr>
<td>ANS-Me</td>
<td>67.8</td>
<td>5.4</td>
</tr>
<tr>
<td>Wits</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Overbite</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Overjet</td>
<td>3.6</td>
<td>1.0</td>
</tr>
<tr>
<td>+1posure-Sppl</td>
<td>7.5</td>
<td>2.5</td>
</tr>
<tr>
<td>-1posure-Mpl</td>
<td>22.3</td>
<td>2.8</td>
</tr>
<tr>
<td>+6posure-Sppl</td>
<td>23.7</td>
<td>2.3</td>
</tr>
<tr>
<td>-6posure-Mpl</td>
<td>33.2</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Abreviations: see Fig. 2 and footnotes Table 3.

(p<0.0001). Univariately, the masseter and temporal muscles were significantly related to the covariates (p<0.01 and p<0.001, respectively), whereas the digastric was not. Looking at the covariates separately, it turned out that “stature” was not significantly related to any of the
Table 5D. Descriptive statistics, ultrasound measurements of the muscle thicknesses (mm)

<table>
<thead>
<tr>
<th></th>
<th>Females, n=62</th>
<th></th>
<th>Males, n=57</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Masseter</td>
<td>Temporal</td>
<td>Digastric</td>
<td>Masseter</td>
</tr>
<tr>
<td></td>
<td>Mean  SD</td>
<td>Mean  SD</td>
<td>Mean   SD</td>
<td>Mean   SD</td>
</tr>
<tr>
<td>Right¹</td>
<td>12.0  1.9</td>
<td>13.5  1.8</td>
<td>5.9   0.9</td>
<td>13.4  1.8</td>
</tr>
<tr>
<td>Left²</td>
<td>12.2  1.9</td>
<td>13.3  2.0</td>
<td>5.8   0.9</td>
<td>14.0  1.7</td>
</tr>
<tr>
<td>Average³</td>
<td>12.1  1.8</td>
<td>13.4  1.7</td>
<td>5.9   0.8</td>
<td>13.7  1.6</td>
</tr>
</tbody>
</table>

¹ Right-hand side  
² Left-hand side  
³ Average of right- and left-hand side

dependent variables, whereas "weight" displayed a significant relation with both masseter (p=0.001) and temporal muscles (p<0.001), and not with the digastric. The "gender" main effect was multivariately significant (p<0.05). Univariate analysis showed this effect to be significant for the digastric muscle only (p=0.003), and not for the masseter and temporal. The "side" main effect was multivariately significant (p=0.001). On the univariate level there was a "side" effect for the masseter muscle only (p<0.001). Finally, the "gender" by "side" interaction effect was multivariately significant (p=0.024). Univariately, this effect was only significant for the temporal muscle (p=0.025).

The principal component analysis on the variables "gender", "weight" and "stature", and the anthropometric and cephalometric measurements yielded nine components with Eigen values greater than 1, explaining 84% of the original variation in craniofacial morphology. The factor loading matrix is shown in Table 7, the structure matrix in Table 8. Based on the latter, the components were named: component 1, "vertical dimensions"; component 2, "mandibular inclination" (with a negative loading for posterior facial height); component 3, "maxillary and mandibular prognathism" (with a negative loading for cranial base flexure); component 4, "occlusal plane inclination"; component 5, "intermaxillary sagittal relation"; component 6, "maxillary inclination"; component 7, "transverse dimensions"; component 8, "overjet and overbite"; component 9, "sagittal dimensions". The components 1 and 7, 1 and 9, and 7 and 9 showed relatively high interrelations (R=0.4, R=-0.3, R=-0.3, respectively).

The results of the stepwise multiple regression analysis between bite force magnitude on the one hand and on the other hand the nine components describing the craniofacial morphology plus the averages of the left and right side muscle thicknesses for the masseter, temporal and digastric muscles are shown in Table 9. A correlation coefficient of R=0.76 was found. This means that 58% of the variance in bite force magnitude could be explained by the variables, mentioned in the Table. Beta-weights indicated, that the mean masseter muscle thickness was the
Table 6. Multivariate analysis of variance, muscle thicknesses

<table>
<thead>
<tr>
<th>Multivariate relation between dependent variables and covariates</th>
<th>p &lt; 0.001*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Masseter</td>
</tr>
<tr>
<td><strong>Dependent variables</strong></td>
<td>p</td>
</tr>
<tr>
<td>with the covariates &quot;weight&quot; and &quot;stature&quot;</td>
<td>0.001*</td>
</tr>
<tr>
<td>with the individual covariate &quot;weight&quot;</td>
<td>0.001*</td>
</tr>
<tr>
<td>with the individual covariate &quot;stature&quot;</td>
<td>0.670</td>
</tr>
<tr>
<td>&quot;Gender&quot; main effect</td>
<td>0.066</td>
</tr>
<tr>
<td>&quot;Side&quot; main effect</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>&quot;Gender&quot; by &quot;Side&quot; interaction effect</td>
<td>0.073</td>
</tr>
</tbody>
</table>

*Significant

Table 7. Principal component analysis, factor loading matrix

<table>
<thead>
<tr>
<th>Component</th>
<th>Eigen value</th>
<th>Percentage of variance</th>
<th>Cumulative percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &quot;vertical dimensions&quot;</td>
<td>10.22194</td>
<td>27.6</td>
<td>27.6</td>
</tr>
<tr>
<td>2 &quot;mandibular inclination&quot;</td>
<td>7.02803</td>
<td>19.0</td>
<td>46.6</td>
</tr>
<tr>
<td>3 &quot;maxillary and mandibular prognathism&quot;</td>
<td>3.40851</td>
<td>9.2</td>
<td>55.8</td>
</tr>
<tr>
<td>4 &quot;occlusal plane inclination&quot;</td>
<td>2.73664</td>
<td>7.4</td>
<td>63.2</td>
</tr>
<tr>
<td>5 &quot;intermaxillary sagittal relation&quot;</td>
<td>2.17592</td>
<td>5.9</td>
<td>69.1</td>
</tr>
<tr>
<td>6 &quot;maxillary inclination&quot;</td>
<td>1.72097</td>
<td>4.7</td>
<td>73.8</td>
</tr>
<tr>
<td>7 &quot;transverse dimensions&quot;</td>
<td>1.35788</td>
<td>3.7</td>
<td>77.4</td>
</tr>
<tr>
<td>8 &quot;overjet and overbite&quot;</td>
<td>1.29791</td>
<td>3.5</td>
<td>80.9</td>
</tr>
<tr>
<td>9 &quot;sagittal dimensions&quot;</td>
<td>1.13446</td>
<td>3.1</td>
<td>84.0</td>
</tr>
</tbody>
</table>

From the anthropometric and cephalometric dimensions, and the covariates "gender", "stature" and "weight", nine components with an Eigen-value greater than 1 were found. They jointly explained 84.0% of the original variation. Their names were based on the structure matrix (Table 8).

main contributant (β=0.39). It is 1.5 times more important than the next contributant (component 4, β=-0.26) and almost 2 to 3 times more important than the other components. Its positive relation with bite force magnitude indicated that high bite force coincided with large masseter thickness. The negative relation between bite force magnitude and component 4 (the
inclination of the occlusal plane) indicated that high bite force coincided with an anteriorly upwardly inclined occlusal plane. The relation with the components 1 (vertical dimensions) and 7 (transverse dimensions) indicated that bite force magnitude coincided with "general size", i.e., large individuals with large faces had large bite forces. The negative relation with component 2 (mandibular inclination) and the positive relation with component 6 (maxillary inclination) indicated that bite force magnitude coincided also with a convergent maxillo-mandibular morphology.

5.4 DISCUSSION

5.4.1 Bite force

Maximal voluntary bite force magnitude is dependent of many variables. It depends on variation in jaw muscle size (Van Spronsen et al., 1989) and on variation in craniofacial morphology, thus influencing muscle orientation and moment arms (e.g., Throckmorton et al., 1980; Weijs, 1989). However, jaw muscle size and craniofacial morphology cannot explain all variation in bite force (Van Spronsen et al., 1992; Weijs and Van Spronsen, 1992). It also depends on fiber type composition (Ringqvist, 1974), sarcomere length (Van Eijden and Raadsheer, 1992), and jaw muscle activation level (Van Eijden et al., 1993). In the present study, a number of methodological factors may also have contributed to the variation in measured bite force, such as 1) the antero-posterior position of the bite force transducer relative to the dental arch, molar bite forces being larger than incisor bite forces (e.g., Mansour and Reynik, 1975; Pruim et al., 1980; Hagberg, 1987; Van Eijden, 1991), 2) the interincisal distance (Manns et al., 1979; Van Eijden and Raadsheer, 1992), and 3) the protrusive or retrusive placement of the mandible (Leff, 1966). Also, psychological factors might have influenced the bite force level. Nevertheless, in the present study, 58% of the variance could be explained by variation in muscle size and craniofacial morphology.

The sagittal location of the bite force transducer was at the mandibular canines (Fig. 1). In males, our mean maximal bite force (545.7 N) exceeded the mean vertical bite force (469 N) at the canines, as found by Van Eijden (1991), who used the same transducer, and those reported in an overview by Hagberg (1987), molar bite forces ranging from 382 N to 480 N and incisor bite forces ranging from 161 N to 190 N. The interincisal distance, which was dictated by the dimensions of the bite force transducer, ranged from 19 to 25 mm (10° to 15°). It can be expected that at smaller mouth openings bite force will decrease, because of suboptimal sarcomere length (Manns et al., 1979; Van Eijden and Raadsheer, 1992) and less favorable

(Table 8 Opposite)

Table 8. Principal component analysis, structure matrix

Abbreviations: see Fig. 2 and Tables 1-3.

76
<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANS-Me</td>
<td>.93527</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.41163</td>
<td>.43568</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATFH</td>
<td>.91178</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.60818</td>
<td></td>
<td>-.44017</td>
<td></td>
</tr>
<tr>
<td>ALFH</td>
<td>.88777</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.48841</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+6osp-Sppl</td>
<td>88564</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.41610</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1osp-Mpl</td>
<td>85093</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-.947232</td>
<td></td>
</tr>
<tr>
<td>+1osp-Sppl</td>
<td>77388</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-.947619</td>
</tr>
<tr>
<td>-6osp-Mpl</td>
<td>76673</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-Go</td>
<td>.66359</td>
<td>-.57278</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-Ba</td>
<td>.53337</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; Go</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mpl/FFH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occl/Mpl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GoGn/SN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sppl/Mpl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ar-Go</td>
<td>.52194</td>
<td>-.65830</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/N/B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SN/FFH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SN/ArGo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N/S/Ba</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occl/Sppl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occl/FFH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occl/SN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/N/B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Wits&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sppl/FFH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICW</td>
<td>.42543</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>.51847</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>.47914</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BFW</td>
<td>.55914</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AUHF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overbite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overjet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Go-Me</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stature</td>
<td>.53842</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
direction of muscle action lines (Koolstra et al., 1988a). Thus, the amount of mouth opening in our study will have benefitted the bite force magnitude. Limitation in biting due to an anterior or posterior repositioning of the mandible (Leff, 1966) was avoided by constructing the bite plates and assessing the transducer's position in an articulator.

In contrast to Ingervall and Helkimo (1978), Proffit et al. (1983), Proffit and Fields (1983), Hagberg (1987), Van Spronsen et al. (1989), and Bakke et al. (1992), we measured bite force magnitude in all three dimensions, because bite force magnitude is closely related to its direction (Koolstra et al., 1988a; Van Eijden, 1991). Van Eijden (1991) found the highest bite force in a 10° posterior direction, relative to a pure vertical force direction. In our study, maximal bite force direction also deviated from the pure vertical (-16.5° to +17.8°). However, compared with the standard deviations, the errors of measurement of the X- and Y-components were large (Table 4 and 5). Only a very weak relation was found between bite force direction and facial morphology. This is in accordance with the results of Proctor and DeVincenzo (1970), who found no difference in masseter muscle inclination relative to the occlusal plane in skeletal open-bite and closed-bite individuals, and Van Spronsen et al. (1996), who found that the orientation and moment arms of the masticatory muscles of normal and long-face subjects were strikingly similar.

5.4.2 Craniofacial dimensions
Craniofacial morphology was registered by anthropometric (linear) and cephalometric (linear and angular) measurements. Anthropological measures are considered to be less reproducible than the cephalometric ones (e.g., Raadsheer et al., 1996), but in the present study, the measurement error for the anthropometric dimensions was in the same range as the cephalometric ones. An additional antero-posterior radiograph for the transverse dimensions was not considered, because of radiation hygiene. The mean values for the anthropometric dimensions were comparable to those for the "post puberty group" of Raadsheer et al. (1996). A detailed analysis of the cephalometric outcome, however, is beyond the scope of this study.

The principal component analysis reduced the amount of 37 variables to 9 components, describing 84% of the original variation in craniofacial morphology. The components clearly made a distinction between vertical (component 1), transverse (component 7) and sagittal dimensions (component 9). This is in accordance with the results of Solow (1966), who found an association between the length of the jaws, the head, and the cranial base, and between the width of the jaws and the width of the face. He found neither associations between cephalometric length measurements and face width components, nor between face and jaw width on the one hand, and head length on the other. Van Spronsen et al. (1997) also found that the transverse and vertical dimensions were represented by different, uncorrelated components. Both anterior and posterior vertical dimensions were found in different components, whereas in our study, all vertical dimensions were grouped in one component (component 1). A relation was found
Table 9. Relation of bite force magnitude to muscle thicknesses and craniofacial morphology, stepwise multiple regression analysis. 58.4% of the variance in bite force was explained (R=0.76)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Beta weight</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masseter thickness (mean of left and right side)</td>
<td>0.39</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Component 1 (&quot;vertical dimensions&quot;)</td>
<td>0.21</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Component 2 (&quot;mandibular inclination&quot;)</td>
<td>-0.18</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Component 4 (&quot;occlusal plane inclination&quot;)</td>
<td>-0.26</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Component 6 (&quot;maxillary inclination&quot;)</td>
<td>0.14</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Component 7 (&quot;transverse dimensions&quot;)</td>
<td>0.23</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

The bite force resultant R was related to the thicknesses of the masseter, temporal and digastric muscles, and the components 1 to 9, explaining craniofacial morphology.

between the components 1 (vertical dimensions) and 7 (transverse dimensions; R=0.4), and between the components 7 and 9 (sagittal dimensions; R=-0.3), indicating that "general size" of the head was important and might have weakened other relations.

5.4.3 Jaw muscle thicknesses

The physiological cross-sectional area of a muscle is considered to be an indication of the maximal force it is capable of producing (Morris, 1948, Schantz et al., 1983). The introduction of CT (Weijs and Hillen, 1986), MRI (Hannam and Wood, 1989; Van Spronsen et al., 1991, 1992), and ultrasound (Ruf, Pancherz and Kirschbaum, 1994), made in vivo measurements of jaw muscle cross-sectional areas possible. However, ultrasonography only allows for registration of superficial muscles. Therefore, this study was limited to the masseter, the temporal and the digastric muscles. Another restriction in the use of ultrasonography is that it is not always possible to cover the whole cross-sectional muscle area by the transducer. Therefore, many investigators (Kiliaridis and Kälebo, 1991; Bakke et al., 1992; Ruf et al., 1994; Raadsheer et al., 1996) used the ultrasound thickness instead of the cross-sectional area. Raadsheer et al. (1994) found this method to be accurate and reproducible for the in vivo masseter muscle thickness registration.

The ultrasound measurement errors and the mean muscle thicknesses of the masseter muscles were comparable to those of the afore-mentioned studies. The multivariate analysis of variance (Table 6) displayed a multivariately significant relation between the thicknesses of the jaw muscles and the covariates "stature" and "weight". On the univariate level, only the relation between the covariate "weight" and the masseter and temporal muscles was significant, i.e., variation in thickness of these two muscles mainly coincided with the weight of the participants. After correction for the effect of the covariates, a significant difference between the left and right
hand side masseter thickness was found. This is in contrast to the afore-mentioned studies, that did not reveal a left to right side difference. Further analysis showed that the left and right masseter were equally often the largest one, so that this could not explain the dominance of the left side. The significant interaction effect between "gender" and "side", indicating that the difference between the left and right temporal muscle was larger in males than in females (Table 5D) could not be explained neither. Van Spronsen et al. (1991) have reported differences in right and left side cross-sectional areas for the masseter and temporal muscle. However, they found a right side dominance, whereas, in the present study, the left side was larger. Based on the findings of Raadsheer et al. (1996), demonstrating that the measurement error for the relaxed muscle thicknesses was smaller than that for the contracted ones, only the relaxed muscle thicknesses were measured. The data for the temporal and digastric muscles were unique and could, therefore, not be compared to other studies.

5.4.4 Relation between bite force, muscle thickness and facial morphology

In the present study, the thicknesses of the masseter, temporal and digastric muscles were measured. Because craniofacial morphology is related to the size of the medial pterygoid muscle as well (Hannam and Wood, 1989; Van Spronsen et al., 1991; Van Spronsen et al., 1992), this muscle might also have contributed to the variation in bite force magnitude. However, ultrasonography did not allow for its registration. The digastric muscle was included, because craniofacial morphology and mouth-opening force are related according to findings by Bolt and Orchardson (1986).

From the above-mentioned jaw muscles, with stepwise multiple regression the thickness of only the masseter muscle showed a significant relation with bite force magnitude. This is in accordance to Van Spronsen et al. (1989), who demonstrated a significant relation between bite force magnitude and cross-sectional area of the masseter muscle, and with Van Spronsen et al. (1992), who showed that the MRI cross-sectional area of the masseter muscle exhibited the most marked differences between long face and normal individuals. However, Weijs and Hillen (1986), Hannam and Wood (1988) and Van Spronsen et al. (1991) also found a relation of the temporal cross-sectional area with craniofacial size and shape mainly coincided with "general body size". Bite force magnitude and jaw muscle
cross-sectional area are often negatively related with anterior facial height, and at the same time positively with posterior facial height (Ingerval and Helkimo, 1978; Proffit et al., 1983; Van Spronsen et al., 1992; Kiliaridis et al., 1993). In the present study, however, both anterior and posterior vertical dimensions were in the same component, so that no discrimination could be made between anterior and posterior facial height. The negative relation with the components 2 and 4, and the positive one with the component 6, all indicate that large bite force magnitude coincided with convergent craniofacial morphology (and thus large posterior vertical dimensions relative to the anterior ones). The positive relation between bite force magnitude and component 7 (transverse dimensions), is in accordance with the positive relation between transverse dimensions and masseter thickness (Kiliaridis and Kälebo, 1991; Ruf et al., 1994), and between transverse dimensions and jaw muscle cross-sectional areas (Hannam and Wood, 1988; Van Spronsen et al., 1991).

According to the β-weights (Table 9), the masseter thickness was the main contributor to the explained variance in bite force magnitude. Stepwise multiple regression analysis, however, cannot assess the percentage of variance, explained by the masseter muscle as such, because the variables are interrelated to one another and the β-weights only give the relative proportions of the explained variance by the different variables.

As mentioned before, bite force magnitude also depends on mechanical variables, such as moment arms. By using the lateral headplate, the dental casts and bite plates, and the bite force direction, we were able to insert the bite force vectors in the cephalogram and to reconstruct the bite force moment arms, relative to the temporomandibular joint. Thus, bite force moments were assessed and related to the muscle thicknesses and craniofacial morphology, as was done for the bite force magnitudes. Although the correlation coefficient raised (R=0.82), the same relationship with the masseter muscle the craniofacial morphology was found.

In a three-dimensional mathematical model of the human masticatory system, Koolstra et al. (1988a, 1988b) examined the influence of the magnitude and direction of jaw muscle force on bite force. It appeared that for all masticatory muscles, larger muscle forces resulted in larger bite forces. However, differences in force direction of only the masseter muscle resulted in a considerable change of the bite force magnitude and direction. Van Spronsen et al. (1996) showed that differences in facial morphology (i.e., differences between long face and normal subjects) only affected the orientation of the masseter and anterior digastric muscle. The findings of the present study, and those of Koolstra et al. (1988a, 1988b) and Van Spronsen et al. (1996) strongly support the idea that variation in maximal bite force magnitude is mainly dependent on the variation in size and direction of the masseter muscle, this direction being related to variation in craniofacial morphology.
5.5 REFERENCES


Farkas LG, editor (1994) Anthropometry of the Face, 2nd edn. New York: Raven Press, Figure 2-36.


