Three-dimensional computed tomographic assessment of mandibular muscles in growing subjects with different vertical facial patterns

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Aim: The present study was undertaken to assess the relationship between the mandibular muscles and dentofacial skeletal morphology in children with different underlying vertical facial patterns, using three-dimensional computed tomography (3D-CT).
Method: Thirty children (mean age 12.24 ± 1.57 years) underwent cranial CT examination for diagnostic purposes. 3D-CT images were reconstructed for the evaluation of the cross-sectional size, volume, and spatial orientation of the masseter and medial pterygoid muscles. These muscle parameters were also assessed in relation to the vertical facial pattern, gender and skeleto-dental form.
Results: Significant differences were found in muscular angulation for subjects with different underlying patterns. Greater masseter volumes were associated with increased facial width. Greater intermolar widths were found in brachyfacial subjects, with less acute muscular angulations in relation to horizontal reference lines, compared with dolichofacial subjects. This was also more obvious in the maxillary arch.
Conclusion: Clinicians should note the likely differences in masseter and medial pterygoid orientation and volume in subjects with different underlying vertical facial patterns and that these differences may, in turn, be related to both facial skeletal width and naturally-occurring transverse dental arch dimensions.

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Introduction
For some time, there has been a general acceptance that growth and development of craniofacial forms are dependent, at least in part, on the functional state of the surrounding soft tissues as well as the patient's underlying genetic make-up.1-3 It is, however, not known whether genetically determined facial morphology actually determines the size and strength of the mandibular muscles or whether, instead, a particular muscular form influences the form of the dentofacial complex.2 A general consensus would suggest that the precise relationship between form and function is still yet to be determined.

The results of many studies support the fact that the size of the mandibular muscles is closely related to facial dimensions. It has been reported that stronger and larger mandibular elevator muscles are generally accompanied by wider transverse facial dimensions.1,4-7 Additionally, these individuals often display a short anterior face height, long posterior face height, a larger posterior to anterior face height ratio, parallelism of the jaw bases, a small gonial angle and larger maxillary transverse dental arch dimensions.8-11

Early investigators proposed that functional hyperactivity of the mandibular muscles resulted in potential adaptive skeletal changes as a result of increased stress in the structures upon which they act.12-14 This seems reasonable given the widely acknowledged concept that the surrounding environment definitely affects the expression of
individual underlying genetics. It is further supported by the fact that a general reduction in muscular cross-sectional area or bite force has been observed in subjects suffering from age-related deterioration of the dentition or individuals with developmental, functional and morphological disorders of the cranio-mandibular system.

The role of jaw muscle function as a determinant of the growth and development of the human craniofacial complex has been studied extensively. Investigative techniques that have previously been used include morphological identification based on anatomical dissection and various imaging techniques; physiological examination of muscle fibre types; muscular function measurements based on the bite force magnitude; electromyographic activity as well as studies of the effects of surgical or pharmacological interventions on the mandibular muscles of growing laboratory animals. The various imaging techniques that have been applied include cephalometric radiographs, magnetic resonance imaging, ultrasonography and computed tomography. With continual advances in imaging technology and the advent of 3D-rendering software packages, contemporary imaging techniques allow for more accurate computed analysis of the orientation and morphology of masticatory muscles in all three dimensions.

With this in mind, the present study was designed to assess whether:

1. various characteristics of the masseter and medial pterygoid muscles differ amongst growing subjects with different underlying vertical facial patterns, as determined by existing cephalometric measurements;

2. various characteristics of the masseter and medial pterygoid muscles are related to transverse facial dimensions in growing subjects;

3. various muscle characteristics are, in any way, related to naturally-occurring transverse maxillary and mandibular dental arch widths in growing individuals.

Materials and methods

Sample selection

Thirty children – 17 males and 13 females (aged between 8 years 7.5 months and 15 years 1 month) – underwent cranial CT examinations for diagnostic purposes. All families provided informed consent for the diagnostic images to be taken. Approval for the subsequent anonymous use of this data was given by the Royal Melbourne Hospital Research Ethics Committee. All study subjects were still growing, had no facial asymmetry or malformation, and were of differing vertical facial patterns (VFP) – defined by FHP-GoMe angle: brachyfacial (<22°), mesofacial (22°–29°) and dolichofacial (>29°).

Computed tomography (CT) imaging technique

A multi-slice helical CT scanner, SOMATOM Sensation 16 (Siemens Medical Solutions AG, Erlangen, Germany) was used for all the examinations. Contiguous axial scans were performed parallel to the Frankfort horizontal plane (FHP) with the teeth lightly together in natural condylar position. Anatomically, the region extending from below the inferior border of the anterior mandible to the level of the anterior cranial base was scanned. The slice thickness of the axial images was 2 mm with a 1.5 mm overlap. Multi-planar reconstructions (MPR) of the 3D-CT images were created using OsiriX® version 3.0 and amira® version 4.1.2 imaging software (Mercury Visualization Sciences). In addition, Dolphin 3D® (Dolphin imaging and management solutions) was used to make dental arch measurements.

Assessment of VFP, facial width and muscle orientation

Using the OsiriX® program, the right side lateral profile of the patient was viewed and analysed. The 3D craniofacial image was often manipulated to improve the orientation of the FHP in relation to the horizontal plane, such that head posture would be symmetrical bilaterally relative to the sagittal and coronal planes. From this right lateral profile of each subject, dento-facial and superficial masseter measurements were made (Figure 1). The coronal view of the 3D-CT head image was used for the assessment of transverse head dimensions. The image was manipulated to ensure that the head posture was symmetrical bilaterally and that it represented natural postural head position with the subject looking straight ahead. The line of action of the right medial pterygoid muscle was then measured from this frontal view (Figure 2). Landmarks and reference planes identified in the OsiriX® program are listed in Tables I and II.
Assessment of cross-sectional areas and volumes of the mandibular muscles

The cross-sectional areas of the masseter and medial pterygoid muscles were assessed bilaterally with the use of the OsiriX® program. The cross-sectional areas of these muscles were assessed perpendicular to their mean fibre directions. The display of the tissue morphology was converted to resemble MRI images prior to analysis using multiplanar reconstruction (MPR). The default window level for analysis was approximately 60 and the window width ranged from 275 to 325. The mean of three-repeated cross-sectional area (CSA) measurements made from the same axial slice was used to represent the true muscle cross-section. The CSA of the masseter was measured between the midpoint of its origin and insertion. The CSA of the medial pterygoid muscle was similarly measured where the reference axial scanning plane bisected its mean fibre direction perpendicularly, at the level of the mandibular foramen (Figure 3). CSA was calculated bilaterally for both muscles. Mandibular muscle volumes (Vol) were calculated only for the right side of the face. The muscle outlines from each sequential axial slice were digitally traced from its insertion to origin. Each slice represented a volume of muscle equal to its cross-sectional area multiplied by the slice interval or thickness. The slice thickness used was 2 mm with 1.5 mm overlap. By the use of the amira® program, a combination of three planes of view was simultaneously available to reassess the accuracy of the traced muscle outlines. These viewing planes included

Figure 1. Examples of measurements taken from the right lateral profile, using the volume-rendering 3D-CT technique: (a) skeletal view; (b) muscular view.
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the frontal, sagittal and horizontal planes. Additionally, a 3D reconstruction, with the region of interest highlighted, also appeared on the same screen. The ability to retrace and to refine the estimations of the muscle cross-sections combined with the opportunity to view the outlines in both two and three dimensions from all three planes allowed for improved accuracy in the estimation of the volume (Figure 4).

**Assessment of the maxillary and dental arch measurements**

The Dolphin® 3D program was used to assess the maxillary and mandibular transverse dental arch dimensions (Table III). A 3D-reconstruction was made and the window opacity adjusted to allow for a semi-transparent view that highlighted osseous and dental hard tissues adequately. Various points were plotted
Figure 2. Both the skeletal (a), (b) and muscular (c) viewing modes were used to assess the osseous facial width and the line of action of right medial pterygoid muscle, from the coronal view.

Figure 3. Multiplanar reconstructed (MPR) CT images generated for the analysis of the cross-sectional areas of the masseter and medial pterygoid muscles: (a) masseter, mid belly level; (b) medial pterygoid, mandibular foramen level.
on the 3D reconstruction and could simultaneously be viewed in the frontal, sagittal and coronal 2D views to ensure accuracy (Figure 5).

**Radiation dose**

The actual radiation dose level was calculated for four randomly-chosen patients. The mean radiation dose level was 0.37 mSv (±0.04 mSv).

**Analysis of measurement error**

To determine the error, selected measurements were repeated at least one week later, for six randomly-chosen patients. The standard measure of error and the coefficient of reliability were calculated.

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**Figure 4.** Estimation of masseter muscle volume: (a) composites of all muscular outlines from digitally-traced sequential axial CT images, represented in 3D; (b) superior view; (c) frontal view.

**Figure 5.** Maxillary and mandibular dental-arch width measurements. The relevant points were plotted on the 3D reconstruction (a), then verified by assessing the coronal (b), axial (c) and sagittal (d) views.
The measurement error was also expressed as a percentage of the mean ($S_e$/mean x 100%). This analysis revealed a high degree of reliability in the results. Acceptable coefficients of reliability and measurement error were found for the methods used to measure the cross-sectional area and volume of the muscles, mandibular muscle angulation, and skeletal dimensions (the coefficient of reliability varied from 0.76 to 1.00, and the measurement error ranged from 0.19% to 4.31% of the mean).

**Statistical analysis**

Means and standard deviations for all angular and linear skeletal, dental and muscular measurements were calculated. Differences in the means for the different vertical facial pattern and gender subgroups were subjected to analysis of variance (ANOVA). Statistical significance was set at $p \leq 0.05$. Pearson’s coefficients of correlation were also calculated to search for obvious relationships amongst the muscular, skeletal and dental arch-width measurements in the total sample.

**Results**

The means for all dental, skeletal and muscular measurements are presented in Tables IV to VI. The means for the total undivided sample are presented in Table IV. Expectedly, there was considerable individual variation for all measurements, reflecting the different three-dimensional facial patterns and, perhaps, different stages of growth in this sample of young subjects.

| Abbreviation            | Landmarks, reference planes                                                                 | Definitions                                                                                                                                 |
|-------------------------|---------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Mx intermolar width     | Mesiopalatal cusp tip of maxillary first molar                                              | The distance between the mesiopalatal cusp tips of the upper first molars                                                               |
| Md intermolar width     | Mesiolingual cusp tip of mandibular first molar                                              | The distance between the mesiolingual cusp tips of the lower first molars                                                              |
| Mx buccal crest width   | Most buccal point on the maxillary alveolar crest                                            | The distance between the most buccal points on the left and right maxillary alveolar crests, at the level of the first molar               |
| Md buccal crest width   | Most buccal point on the mandibular alveolar crest                                            | The distance between the most buccal points on the left and right mandibular alveolar crests, at the level of the first molar              |
| Mx palatal crest width  | A point on the palatal crest, of the height of the palate                                    | The distance between constructed palatal points, each half way between the height of the palatal vault and the gingival line, at the level of the first molar |
| Md lingual crest width  | Most lingual point on the mandibular alveolar crest                                          | The distance between the most lingual points on the left and right mandibular alveolar crests, at the level of the first molar             |

The means for various measurements in the different vertical facial sub-groups are presented in Table V. From the table, it may be seen that there were significant differences in means for brachyfacial and dolichofacial subgroups for:
- The mandibular plane angle;
- The angulation of the masseter in relation to FHP;
- The angulation of medial pterygoid to the coronal intergonial line;
- The ratio of posterior to anterior facial height;
- Masseter muscle volume;
- Maxillary and mandibular intermolar widths.

The means for various measurements in male and female sub-groups are presented in Table VI. While there were significant differences in the means for anterior total facial height and anterior lower face height, there were no other obvious muscular or dental differences. Once again, there was considerable individual variation for all measurements.

**Calculation of Pearson’s coefficients**

The following correlations were noted:
- Masseter angulation vs. medial pterygoid angulation ($r = 0.96$);
- Masseter CSA and medial pterygoid CSA ($r = 0.73$);
- Masseter volume and masseter CSA ($r = 0.82$);
- Masseter volume vs. medial pterygoid volume ($r = 0.52$);
### Table IV. Means for all dental, skeletal and muscular measurements for the total undivided sample.

|                      | Mean  | Std Dev | Min   | Max   |
|----------------------|-------|---------|-------|-------|
| **Age**              | 12.24 | 1.57    | 8.63  | 15.08 |
| **Angular measurements (°)** |       |         |       |       |
| MdP                  | 25.33 | 4.61    | 17.95 | 32.68 |
| FOP-FH               | 8.10  | 3.85    | 2.74  | 16.45 |
| Anterior Border of masseter to FHP | 66.50 | 6.1     | 55.36 | 76.99 |
| Anterior Border of masseter to FOP | 74.70 | 5.0     | 66.88 | 86.50 |
| Line of action of masseter to FHP | 69.60 | 6.1     | 60.60 | 85.40 |
| Line of action of masseter FOP | 77.70 | 6.0     | 68.70 | 98.20 |
| Line of action of medial pterygoid to Go-Go | 59.70 | 6.1     | 41.54 | 69.90 |
| **Linear measurements (mm)** |       |         |       |       |
| ATFH (N-Me)          | 109.40| 6.60    | 98.20 | 121.50|
| AUFH (N-NANS)        | 47.50 | 3.20    | 40.50 | 53.40 |
| ALFH (ANS-Me)        | 62.00 | 5.30    | 50.00 | 72.10 |
| PFH (Co-Go)          | 52.4  | 4.90    | 42.80 | 60.10 |
| Maxillary Width [II] | 63.94 | 4.26    | 54.90 | 71.50 |
| Mandibular Width [AgAg] | 80.77 | 6.51    | 57.30 | 94.80 |
| Facial Width (ZaZa)  | 121.10| 5.89    | 113.60| 134.90|
| Orbital Width (ZfZf) | 91.16 | 3.75    | 84.70 | 100.90|
| InterGonial Width (Go-Go) | 87.51 | 15.30   | 89.10 | 98.50 |
| **Ratio (%)**        |       |         |       |       |
| PFH:ATFH             | 47.89 | 3.48    | 41.87 | 54.00 |
| **Muscle cross-sectional area (cm²)** |       |         |       |       |
| CSA (RHS) masseter muscle | 3.43 | 0.44    | 2.47  | 4.16  |
| CSA (LHS) masseter muscle | 3.41 | 0.44    | 2.24  | 4.08  |
| CSA (RHS) medial pterygoid muscle | 2.56 | 0.48    | 1.75  | 3.39  |
| CSA (LHS) medial pterygoid muscle | 2.57 | 0.49    | 1.56  | 3.51  |
| **Muscle volume (cm³)** |       |         |       |       |
| Masseter muscle      | 16.89 | 2.45    | 9.27  | 21.20 |
| Medial pterygoid muscle | 6.68 | 1.33    | 3.08  | 9.71  |
| **Dental arch measurements (mm)** |       |         |       |       |
| Mx intermolar width  | 39.04 | 3.42    | 31.90 | 45.10 |
| Md intermolar width  | 35.47 | 5.76    | 26.60 | 61.10 |
| Mx buccal crest width| 27.55 | 2.87    | 22.70 | 32.10 |
| Md buccal crest width| 29.12 | 3.83    | 17.60 | 35.10 |
| Mx palatal crest width| 59.65 | 3.12    | 53.70 | 65.00 |
| Md lingual crest width| 63.08 | 5.62    | 50.40 | 74.10 |

There was considerable individual variation for all measurements in the undivided total sample.
Table V. Means for various measurements in the different vertical facial subgroups.

|                                | Brachyfacial (N = 11) | Mesofacial (N = 11) | Dolichofacial (N = 8) |
|--------------------------------|------------------------|---------------------|----------------------|
|                                | Mean  | Std Dev | Mean  | Std Dev | Mean  | Std Dev |
| **Angular measurements (°)**    |       |         |       |         |       |         |
| Mdp*                           | 20.25 | 1.56    | 26.21 | 1.58    | 31.10 | 1.17    |
| Anterior Border of masseter to FHP* | 71.08 | 3.19    | 66.68 | 3.56    | 59.97 | 6.17    |
| Line of action of medial pterygoid to GoGo* | 62.24 | 3.22    | 62.42 | 3.62    | 52.52 | 6.19    |
| **Linear measurements (mm)**   |       |         |       |         |       |         |
| PFH (Co-Go)                    | 5.47  | 0.38    | 5.38  | 0.40    | 4.73  | 0.37    |
| **Ratios (%)**                 |       |         |       |         |       |         |
| PFH:ATFH*                      | 50.88 | 2.35    | 47.90 | 1.87    | 43.75 | 1.89    |
| **Muscle cross-sectional area (cm²)** NS |       |         |       |         |       |         |
| CSA (RHS) masseter muscle      | 3.69  | 0.29    | 3.45  | 0.43    | 3.07  | 0.42    |
| CSA (LHS) masseter muscle      | 3.66  | 0.24    | 3.41  | 0.42    | 3.08  | 0.49    |
| CSA (RHS) medial pterygoid muscle | 2.79  | 0.42    | 2.60  | 0.48    | 2.20  | 0.36    |
| CSA (LHS) medial pterygoid muscle | 2.77  | 0.43    | 2.63  | 0.48    | 2.21  | 0.43    |
| **Muscle Volume (cm³)**        |       |         |       |         |       |         |
| Masseter muscle*               | 18.08 | 1.55    | 16.97 | 2.30    | 15.12 | 2.83    |
| Medial pterygoid muscle         | 6.80  | 1.52    | 7.21  | 1.11    | 5.77  | 0.92    |
| **Dental arch measurements (mm)** |       |         |       |         |       |         |
| Mx intermolar width*           | 40.58 | 3.62    | 39.45 | 2.67    | 36.38 | 2.73    |
| Md intermolar width*           | 38.17 | 8.10    | 34.72 | 2.29    | 32.80 | 3.94    |
| Mx buccal crest width          | 28.65 | 2.68    | 27.40 | 2.65    | 26.24 | 3.16    |
| Md buccal crest width          | 29.26 | 3.28    | 30.12 | 3.43    | 27.54 | 4.92    |
| Mx palatal crest width         | 60.31 | 3.44    | 60.17 | 2.39    | 58.01 | 3.33    |
| Md lingual crest width         | 63.88 | 4.56    | 65.38 | 5.48    | 58.81 | 5.30    |

* p ≤ 0.05, NS not significant

There were significant differences in means for brachyfacial and dolichofacial subgroups for:
- The mandibular plane angle;
- The angulation of the masseter in relation to FHP;
- The angulation of medial pterygoid to the coronal intergonial line;
- The posterior to anterior facial height ratio;
- Masseter muscle volume;
- Maxillary and mandibular intermolar widths.

- Masseter angulation vs. mandibular plane angle (r = 0.73);
- Medial pterygoid angulation vs. mandibular plane angle (r = 0.68);
- Masseter angulation vs. facial height ratio (r = 0.72);
- Medial pterygoid vs. facial height ratio (r = 0.66);
- Masseter CSA vs. mandibular plane angle (r = 0.58);
- Masseter CSA vs. facial height ratio (r = 0.54);
- Masseter angulation vs. maxillary width (r = 0.48);
- Medial pterygoid angulation vs. maxillary width (r = 0.45);
- Masseter CSA vs. maxillary width (r = 0.49);
- Masseter volume vs. facial width (r = 0.57);
- Masseter angulation vs. maxillary (r = 0.55) and mandibular (r = 0.59) intermolar widths;
- Masseter CSA vs. maxillary (r = 0.47) and mandibular (r = 0.52) intermolar widths;
- Masseter volume vs. maxillary (r = 0.48) and mandibular (r = 0.46) intermolar widths;
- Med pterygoid angulation vs. maxillary (r = 0.60) and mandibular (r = 0.55) intermolar widths;
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• Med pterygoid CSA vs. maxillary (r = 0.47) and mandibular (r = 0.46) intermolar widths;
• Med pterygoid volume vs. maxillary (r = 0.45) and mandibular (r = 0.44) intermolar widths.

Discussion

Development of 3D-CT software

The availability of sophisticated 3D-CT imaging software has now facilitated the re-creation and manipulation of original CT data. For computed tomography, density is often expressed in the form of CT numbers or Hounsfield units (HU). Using modern software, the examiner can alter that density to most accurately represent a tissue of interest, whether that is bone, tooth, muscle or other soft tissue. In this way, contemporary volume-rendered 3D images are able to demonstrate the specific internal features of a 3D-structure. The accuracy of measurements from CT images is affected by a number of factors such as the presence of artifacts; the choice of slice plane, slice thickness and the amount of slice overlap used; the window level and width; the matrix size and the rendering technique. A high level of precision and accuracy can be expected from the analysis of 3D-CT images of osseous and soft tissue structures. For instance, Lopes et al. and Huisinga-Fischer et al. found both intra- and inter-examiner accuracy to be high when making skeletal or muscular volumetric measurements, respectively. The findings in the present study with regard to measurement error would then support these previous reports.

Cross-sectional area and volume

Previous investigators have reported a highly significant correlation between the cross-sectional areas of the bilateral masseter muscles. Subsequently, the

Table VI. Means for various measurements in male and female subgroups.

|                      | Male (N = 17) | Female (N = 13) |
|----------------------|--------------|-----------------|
|                      | Mean | Std Dev | Mean | Std Dev |
| Age                  | 11.96 | 1.44    | 12.60 | 1.33  |
| Linear measurements (mm) |     |         |     |       |
| ATFH*                | 111.50 | 5.90   | 106.7 | 5.90  |
| AUFH                 | 47.60  | 3.90    | 47.3  | 4.10  |
| ALFH*                | 64.00  | 2.30    | 59.3  | 3.40  |
| PFH                  | 53.30  | 4.00    | 51.2  | 4.40  |
| Muscle cross-sectional area (cm²) NS |     |         |     |       |
| CSA (RHS) masseter muscle | 3.57 | 0.23    | 3.26  | 0.37  |
| CSA (LHS) masseter muscle | 3.52 | 0.21    | 3.27  | 0.33  |
| CSA (RHS) medial pterygoid muscle | 2.65 | 0.23    | 2.44  | 0.50  |
| CSA (LHS) medial pterygoid muscle | 2.69 | 0.30    | 2.41  | 0.49  |
| Muscle Volume (cm³) NS |     |         |     |       |
| Masseter muscle      | 17.40  | 1.38    | 16.21 | 1.58  |
| Medial pterygoid muscle | 6.83 | 2.02   | 6.49  | 0.77  |
| Dental arch measurements (mm) NS |     |         |     |       |
| Mx intermolar width  | 39.81  | 2.64    | 38.05 | 3.28  |
| Md intermolar width  | 36.53  | 9.70    | 34.09 | 2.56  |
| Mx buccal crest width | 27.42 | 2.26    | 27.72 | 2.58  |
| Md buccal crest width | 29.22 | 3.47    | 28.98 | 3.23  |
| Mx palatal crest width | 60.85 | 1.88    | 58.08 | 2.31  |
| Md lingual crest width | 64.84 | 5.09    | 60.78 | 5.47  |

* p ≤ 0.05, NS not significant

The only significant structural difference between males and females in this sample was a likely greater lower anterior face height in males.
muscles of one side were examined. Others have chosen to use an average cross-sectional area of both sides for statistical analysis. For the present study, muscle angulation and volume measurements were made on the right side and muscle CSAs were calculated on both sides, as listed above.

Relation to bite force

Bite force has long been a subject of interest with regard to its potential influence on the development of the masticatory complex. Proffit et al., for instance, assessed the bite forces of adults and children (age 6 to 11 years) with high and low mandibular plane angles. In adults, maximal bite forces were found to be considerably less for high-angle subjects compared with low-angle subjects. However, in the children this difference was not obvious. Interestingly, bite force magnitude for both facial types in children was comparable with those found in dolichofacial adults. The authors postulated that, while long-faced subjects may have normal bite-forces during childhood, they failed to develop greater muscular strength during later growth. Given the now-accepted interaction between mandibular morphology and bite force, the results of these previous studies, and the current investigation, suggest that long-faced subjects have the tendency toward more acutely-orientated jaw muscles and, as a result, a reduced ability to restrain the vertical components of dentofacial growth and the extrusive effects of orthodontic treatment. It might then seem a logical assumption that muscle orientation is closely related to skeletal morphology and that changes in the muscle orientation may well, in turn, lead to other changes in musculo-skeletal morphology.

The role of muscles in dentofacial growth

The precise relationship between jaw muscle function and dentofacial growth is complex and still yet to be accurately defined. One question for consideration is whether maximum muscle function and bite force are necessarily relevant, since peak forces seem to be generated for only a very small part of the day. In addition, Boom et al. suggested that muscle volume (a product of both CSA and muscle length) might be a better indicator of the potential restraining influence of jaw muscles on vertical development. Benington et al. also suggested that volume might be a more important indicator of likely effect. The findings of the present study are not clear-cut on this, with a number of factors found to be related to either or both CSA and volume. These included maxillary width, mandibular plane angle and facial height index. Whatever the case, the present results support previous reports of a high correlation between masseter and medial pterygoid cross-sectional areas and volumes.

Angulation

The findings of the present study suggest that, in dolichofacial subjects, both the line of action of the medial pterygoid muscle and the angulation of the anterior border of the masseter become more acute, in relation to the intergonial width and the FHP, respectively (Figures 6,7). Proctor and de Vincenzo and Haskell et al. reported that, as the mandibular plane becomes steeper, the angulation of the superficial masseter becomes more acute in relation to the FHP. The results of these previous studies, and the current investigation, suggest that long-faced subjects have the tendency toward more acutely-orientated jaw muscles and, as a result, a reduced ability to restrain the vertical components of dentofacial growth and the extrusive effects of orthodontic treatment. It might then seem a logical assumption that muscle orientation is closely related to skeletal morphology and that changes in the muscle orientation may well, in turn, lead to other changes in musculo-skeletal morphology.

Posterior face height

The fact that the angulations of the masseter and medial pterygoid were related to the mandibular plane angle and the facial height index supports the historical proposition of Sassouni and Nanda, in which the vertical development of posterior face height is largely controlled by the vertically-orientated and anteriorly-situated jaw closing muscles. It is interesting though that such biomechanical efficiency of the jaw muscles would be so closely associated with a part of the craniofacial complex that is widely accepted to be predominantly under genetic control. One explanation might be that the ultimate posterior vertical facial height is largely determined by subsequent muscular action upon that initially genetically-derived gonial area. This influence of muscular function on gonial morphology has previously been reported in animals and humans. The conclusion from this previous work is that strong jaw-closing muscles are generally associated with a well-developed gonial area and, in turn, increased posterior facial height.

Muscles and the transverse dimension

It is generally accepted that an association exists between the mandibular muscles and transverse
In particular, significant positive correlations between bi-zygomatic facial width and the respective CSAs and volumes of the masseter and medial pterygoids have previously been reported. The results of the present study are consistent with earlier reports of correlations between masseter CSA and volume and various facial widths. In addition, the present results are also consistent with the likely relationships between muscle angulation, mandibular plane angle and maxillary and mandibular intermolar widths. As the mandibular plane angle decreases and the angulations of both the masseter and medial pterygoid increase, both maxillary and mandibular intermolar widths increase (Figures 6, 7).

Interestingly, Isaacson et al. postulated that backward-rotating mandibles might increase facial height and, in turn, elongate the facial musculature. This muscle elongation would be accompanied by increased passive-stretch tension in the cheek muscles, resulting in a constricted maxillary arch. Conversely, in a forward-rotating pattern, the facial height might be reduced so that unstretched musculature might permit the maxillary teeth to be positioned more buccally. This historical theory is attractive because it supports the primacy of the genetically-determined structures over the effects of the muscles. While the findings of the present study and others might also support an acceptance of perhaps larger transverse dimensions in

Figure 6. Extremes of underlying vertical facial pattern: (a) Brachyfacial: note angle between anterior border of masseter and Frankfort horizontal is 77.0°; (b) Dolichofacial: note angle between anterior border of masseter and Frankfort horizontal is 55.4°.
subjects with larger muscle CSAs and volumes, there still seems to be no direct evidence of which is actually ‘the chicken’ or ‘the egg’ in relation to the determination of human craniofacial dimensions.

Radiation dose of CT

With the ever-increasing sophistication of computer software, 3D reconstructive imaging techniques have offered the ability to provide an accurate tool for the quantitative measurement of the morphology of masticatory muscles and craniofacial complex. For continuous or repeated exposures, the annual effective dose limit established by the National Council on Radiation Protection Measurements (NCRP) in the United States is recommended to be 1 mSv.\(^{41}\) The average person receives approximately 1 to 3 mSv of natural background radiation annually.\(^{64,65}\) Calculations of the actual radiation dose levels found in the present study showed that the mean radiation dose level was 0.37 mSv (±0.04 mSv). This dose lies within the lower range of radiation dose values previously reported for cranial CT examination\(^{66,67}\) (from 0.15 mSv to 2.1 mSv). This dose is higher than to be expected with a routine lateral cephalogram and OPG, and with very localised cone-beam CT imaging (0.05 – 1.19 mSv\(^{66,68-71}\)). However, the current technique would not necessarily result in a large radiation exposure, given the multiple diagnostic possibilities associated with a single CT examination of an individual. Its widespread use, however, is largely restricted at this stage due to cost, logistical availability and radiation-exposure risk factors.
Summary
The aims of contemporary orthodontic treatment are to provide a functional occlusion with pleasing facial aesthetics, whilst achieving reasonable stability and encouraging long-term health of the orofacial tissues. With all this in mind, it is reasonable for those interested in dentofacial growth or treatment to be aware of the apparent differences in mandibular muscular positions, angulations and volumes between individuals with significantly different underlying vertical facial patterns. The present paper should not be seen as a promotion of helical CT examination as an orthodontic routine. These subjects were imaged in this way and the useful and unique data was available for assessment. Many factors would have to be considered before routine use could be recommended.

Conclusions
Taking into account the limitations of the study, the following conclusions may be drawn:
1. For dolichofacial subjects (increased mandibular plane angle, decreased PFH and decreased facial height ratio), the angles between the anterior border of the masseter and the FHP, and the line of action of the medial pterygoid and the intergonial plane, respectively, are both likely to be considerably less than in brachyfacial subjects.
2. Larger masseter volumes are likely to be associated with greater facial widths.
3. Brachyfacial subjects, with less acute muscular angulations in relation to horizontal reference lines, are likely to have greater intermolar widths than dolichofacial subjects. This applies more to the maxillary arch than to the mandibular arch.

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