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Maximum bite force, muscle efficiency and mechanical advantage in children with vertical growth patterns

Patricia García-Morales*, Peter H. Buschang*, Gaylord S. Throckmorton** and Jeryl D. English***

*Department of Orthodontics, Baylor College of Dentistry, The Texas A&M University System Health Science Center, Dallas, **Department of Cell and Molecular Biology, Southwest Medical University, Dallas and ***Department of Orthodontics, University of Texas Health Science Center, Houston, USA

SUMMARY This study correlated maximum bite force and masticatory muscle electromyography (EMG) activity with craniofacial morphology and mechanical advantage of children with vertical growth patterns. From lateral cephalograms of 30 females and 17 males (9.3 ± 3.6 years of age), 13 morphological and eight biomechanical measurements were recorded. Two maximum bite forces and 12 submaximal bite forces along with their associated EMG muscle activity were recorded at the right mandibular first molar. Muscle efficiency was evaluated using the relationship between bite forces and EMG activity levels.

There were no significant sex differences ($P > 0.05$) for any of the morphological, functional or biomechanical variables. Factor analyses reduced: (1) the 13 morphological variables to four factors explaining 82.8 per cent of the morphological variance; (2) six functional variables to two factors explaining 68.8 per cent of the functional variance; and (3) 11 biomechanical variables to three factors explaining 90.9 per cent of the biomechanical variance. The vertical size factor was negatively correlated with the muscle efficiency factor ($r = -0.39$; $P = 0.006$) and positively correlated with the moment arm factor ($r = 0.67$; $P < 0.001$). The morphological divergence factor was negatively correlated with the bite force factor ($r = -0.34$; $P = 0.019$) and the mechanical advantage factor ($r = -0.32$; $P = 0.028$). The muscle efficiency factor (functional) was negatively correlated with the moment arm factor ($r = -0.33$; $P = 0.023$).

It is concluded that: (1) independent of chronological age, children with larger faces have larger moment arms and require less muscle activity to attain any given force, and (2) greater hyperdivergence is related to poorer mechanical advantage and lower maximum bite force. These data support the relationships between bite force, muscle strength and morphology in children, similar to those reported for adults.

Introduction

It is generally accepted that a relationship exists between the form and function of the craniofacial skeleton. Weaker maximum bite forces have been related to increased malocclusions, especially in subjects with open bite tendencies and posterior crossbites with narrow maxillary arches, and incisor crowding (Bakke and Michler, 1991; Ellis *et al*., 1996; Buschang and Throckmorton, 1997). Even stronger relationships exist between skeletal hyperdivergence and masticatory function, including reduced jaw muscle size, lower maximum bite force, lower electromyography (EMG) activity and reduced muscle efficiency (Proffit *et al*., 1983; Ueda *et al*., 1998; Granger *et al*., 1999; Throckmorton *et al*., 2000). Although well supported for adults and children with neuromuscular disease, the relationship between craniofacial morphology and function in children without any neuromuscular disease remains controversial. Proffit and Fields (1983) found no differences in maximum molar bite forces between children with high and low mandibular plane angles. Ingervall and Minder (1997) reported significant relationships between the maximum bite force and the mandibular plane angle for girls but not for boys, while Kiliaridis *et al.* (1993) showed only weak relationships between craniofacial morphology and the maximum incisal bite force, and no correlation with the maximum molar bite force, in children 7–13 years of age.

The relationships for children may be confounded by the measures used to quantify muscle function. First, potential fear, discomfort and pain may make it more difficult to obtain maximum bite forces in young children than in adults. Second, bite force by itself is not adequate to evaluate muscle strength because bite force is strongly influenced by the amount of voluntary effort, which may be less than maximal effort. True muscle strength depends upon muscle size, muscle recruitment, and the length of the muscle moment arms. Therefore, the relationship between EMG and bite force, as well as the mechanical advantage of the jaw muscles, should be determined when assessing jaw muscle strength. The purpose of this study was to correlate the maximum bite force and EMG activity of the jaw abductor muscles (masseter and temporalis) with the craniofacial morphology and mechanical advantage of children with a vertical growth pattern as evaluated on lateral cephalograms. The effects of gender and age on these relationships were also analysed.

Subjects and methods

Sample description

Forty-seven (30 females and 17 males) growing patients diagnosed with vertical craniofacial growth patterns (MP/FH > 32 degrees) were evaluated. They represented pre-treatment orthodontic patients aged 9.3 ± 2.3 years (range 7–13 years).

Craniofacial analysis

Standard lateral cephalograms were traced and digitized (Figure 1) by a single investigator (PGM) using the Dentofacial Planner Software® (Dentofacial Software, Inc., Toronto, Canada). The right and left side structures were traced and averaged for landmark identification. To assess the reliability of the cephalometric landmark identification and digitization, a sample of 13 cephalograms was re-traced and re-digitized. Systematic and method errors were calculated. There was no significant systematic error, and the method error ranged between 0.19 and 1.33 mm, with the condyle to the lower first molar measurement having the highest error.

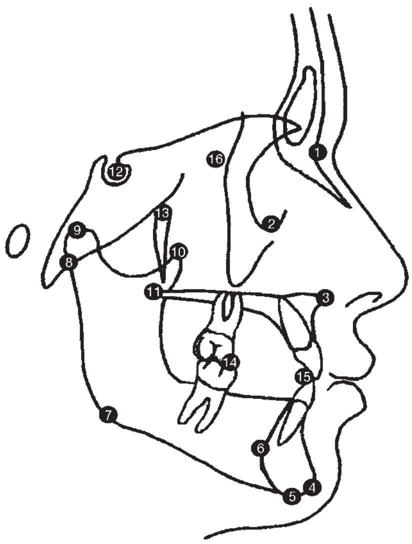

Figure 1 Cephalometric landmarks and abbreviations. 1, nasion (N); 2, orbitale (Or); 3, anterior nasal spine (ANS); 4, gnathion (Gn); 5, menton (Me); 6, posterior symphysis (Sym); 7, gonion (Go); 8, articulare (Ar); 9, condylion (Co); 10, coronoid (Cor); 11, posterior nasal spine (PNS); 12, sella (S); 13, pterygomaxillary fissure (PTM); 14, lower first molar (L6); 15, lower central incisor (L1); 16, SN midpoint (MidPt).

Morphological variables

Morphological measurements included six linear and seven angular parameters (Table 1). Linear distances from nasion to anterior nasal spine and anterior nasal spine to the menton were included to calculate upper and lower face height, total anterior face height and the ratio of lower to total anterior face height. The distance from the sella to gonion indicated posterior face height. The vertical heights of the lower incisor and lower first molar to the mandibular plane and symphysis width were also recorded. Angular parameters included the deflection from (1) the sella–nasion line (cranial base) to the palatal, occlusal, and mandibular planes; (2) the *y*-axis and (3) the three angles of mandibular position (posterior angles): nasion–sella–articulare, sella–articulare–gonion and articulare–gonion–menton.

Biomechanical variables

The biomechanical variables were defined as described by Throckmorton and Dean (1994). Eight biomechanical parameters were included. The muscle vector direction (Figure 2) of the superficial masseter, medial pterygoid and anterior temporalis was determined by the graphic landmarks representing the origin and insertion of these muscles. The superficial masseter was represented by a line from the gonion to orbitale, the medial pterygoid by a line from the gonion to the pterygomaxillary fissure, and the anterior temporalis by a line from the coronoid tip to the midpoint of the sella–nasion plane. The other five biomechanical variables were the dental and muscle moment arms, which were used to calculate the mechanical advantage of each muscle. The dental moment arms included the incisor arm, (the distance parallel to the occlusal plane from the tip of the lower incisor to the condylar summit, defined by the cephalometric landmark condylion) and the molar arm (measured the same way from the tip of the mesiobuccal cusp to the condylar summit). The three muscle moment arms were the distances perpendicular to the condylar summit from each muscle vector. The mechanical advantage of each muscle was the ratio between its muscle moment arm length and the dental moment arm length. For each muscle, moment arms were calculated for the incisor and the molar bite positions.

Maximum bite force (functional variables)

Bite force was measured using a unidirectional transducer placed between the upper and lower right first molars. The metal arms of the transducer were

Table 1 Standard morphological and functional variables and their mean values.

	Mean	Standard deviation	Minimum	Maximum
Morphological variables				
N–ANS (mm)	51.37	4.03	37.7	62.6
ANS–Me (mm)	70.44	5.46	61.3	88.6
S–Go (mm)	70.88	4.98	57.4	80.2
PP–SN (°)	3.69	3.45	–4	12
OP–SN (°)	25.16	5.34	12.8	37.7
MP–SN (°)	40.33	5.67	29	52.4
N–S–Ar (°)	124.01	4.59	113.1	135.7
S–Ar–Go (°)	142.67	5.72	132	158
Ar–Go–Me (°)	133.65	5.51	122.3	145.2
y-axis (°)	70.36	4.18	61.3	80.8
L1⊥MP (mm)	40.05	3.61	33.9	55.3
L6⊥MP (mm)	30.47	2.95	25.1	40.6
Pg–Sym (mm)	15.4	1.71	11.6	19.4
Functional variables				
Bite force (N)	379.05	129.53	96.96	550.41
Right masseter slope	1.704	0.806	0.186	4.314
Left masseter slope	1.864	0.873	0.540	4.165
Right temporalis slope	1.807	0.772	0.717	4.443
Left temporalis slope	1.525	0.725	0.469	4.937

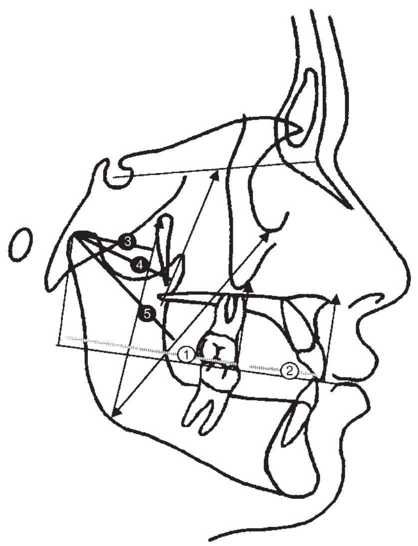

Figure 2 Muscle (•) and bite (◦) moment arms used to calculate mechanical advantage. 1, molar moment arm (L6–Co││occlusal plane); 2, incisor moment arm (L1–Co││occlusal plane); 3, medial pterygoid muscle [Co⊥(PTM–Go)]; 4, anterior temporalis muscle moment arm [Co⊥(MidPt–Cor)]; 5, superior masseter muscle moment arm [Co⊥(Or–Go)].

covered with polypropylene tubing to protect the teeth. Voltage changes to the transducer were amplified 820 times (model 2310 strain gauge conditioner amplifier, Measurements Group, Inc., Raleigh, North Carolina, USA) and were digitized at a sampling rate of 4000 Hz using Optotrak® software (Northern Digital, Corp, Waterloo, Canada). The root mean squared voltage was averaged over a 1 second sample of each isometric bite to determine the force level for that bite. Maximum bite forces were recorded at the right mandibular first molar. In addition, five submaximal force levels (approximately 10, 20, 40, 60 and 80 per cent of maximal bite force) were recorded. Occlusal force levels during isometric bite were controlled by displaying the subject's force output on an oscilloscope. In addition, a 1 second recording of muscle activity was taken at a standard bite force level of 112 N. These seven recordings were repeated, giving a total of 14 bite force recordings.

EMG recordings

Muscle activity was recorded bilaterally from the anterior temporalis and superficial masseter muscles using bipolar surface electrodes. The electrode sites were scrubbed with alcohol to reduce skin resistance and pairs of self-adhesive disposable pre-gelled Ag/AgCl electrodes (Cardiotrace, Kendall, Chicopee, Massachusetts, USA) were placed on the skin over the masseter and anterior temporalis muscles bilaterally. The position of the masseter origin was palpated while the subject clenched their teeth. The superior edge of one electrode pad was placed along the inferior border of the zygomatic arch, centred over the masseter origin. A second electrode pad was placed with its superior edge directly against the inferior edge of the first electrode pad, resulting in an inter-electrode distance of 1.0 cm. For the temporalis muscle, the inferior edge of one electrode pad was placed against the palpated superior border of the zygomatic arch directly above the masseter electrodes. A second temporalis electrode pad was placed with its inferior edge directly against the superior edge of the first temporalis electrode pad, again resulting in an inter-electrode distance of 1.0 cm.

Electrode impedance was not measured. However, the level of EMG output for each pair of electrodes was observed in real time while the patient performed maximum clenching. Any electrodes whose output deviated significantly from the other three electrodes were replaced until the signals from all four electrodes were similar. A ground electrode was placed on the neck. Signals from these muscles were amplified by 1000 using a set of differential amplifiers (Grass Model 511j, Quincy, Massachusetts, USA) with a band pass of 30–1000 Hz and were digitized in real time at a sampling rate of 4000 Hz per channel using Optotrak® software. The quality of the signals was monitored in real time on a computer screen. The 14 muscle signals and associated bite force levels were recorded and stored on the computer hard disk.

Jaw muscle efficiency

Although it is not possible to measure directly the force used by each jaw muscle to generate isometric bite, it is possible to estimate the relative efficiency of force development by comparing EMG levels per unit of bite force between individuals or groups (DeVries, 1968). Muscle efficiency was evaluated based on the relationship between bite force (N) and EMG (9 volts) amplitude, for which there is a linear or near linear relationship (DeVries, 1968; Hagberg *et al.,* 1985; Lindauer *et al.,* 1991; Throckmorton and Dean, 1994). For the purpose of this research, muscle 'efficiency' was defined as the amount of electrical activity used per unit of bite force. Some caution is necessary when defining efficiency this way because, by this definition, muscles that do not contribute to the generation of bite force would appear to have maximum 'efficiency'. However, the two muscles examined in this study have been shown to contribute to maximum bite force (DeVries, 1968; Bakke *et al*., 1989; Lindauer *et al*., 1991; Tate *et al*., 1994). In addition, efficiency was compared only within the same muscle between groups, not between muscles. The slope relating EMG activity to biting force measures how efficiently a muscle can generate force. For each muscle, a least square regression was fitted to the 14 bite force values (two maximum, two constant, 10 submaximum) and associated EMG levels. In most cases of regression, coefficients (r^2) between EMG and bite force were greater than 0.9 for each muscle within each individual, and the slopes were significantly different from zero. The slope of the least square regression (EMG/force slope) indicates the amount of effort a muscle uses to generate an isometric force.

Statistical analysis

Skewness and kurtosis statistics showed that the variables were normally distributed. Sex differences were evaluated using independent *t*-tests. To increase reliability and decrease the number of tests, principal component analyses with varimax rotation were performed to evaluate the multivariate patterns of association between the variables. Principal component factor analyses extract latent composite variables based on their ability to identify the effects of higher order correlations and determine priorities between variables and groups of variables (Thorndike, 1978; Throckmorton *et al.*, 2000). Independent sets of factors were estimated for the morphological, functional, and biomechanical variables. Factor scores were computed for each subject. Relationships between the morphological, functional, and biomechanical factors were statistically analysed using Pearson product-moment correlations.

Results

Because the *t*-tests showed no significant sex differences ($P > 0.05$) for any of the morphological, functional or biomechanical variables, the sexes were pooled for subsequent analyses. Tables 1 and 2 provide descriptive statistics for the morphological, functional and biomechanical variables. Morphological and functional factors are shown in Table 3 and biomechanical factors in Table 4. Factor analyses were used to reduce the 13 morphological variables to four factors explaining 82.8 per cent of the morphological variance, six functional variables to two factors explaining 68.8 per cent of the functional variance, and 11 biomechanical variables to three factors explaining 90.9 per cent of the biomechanical variance.

Morphological factors

The first morphological factor, explaining 36.0 per cent of the morphological variance, was referred to as 'vertical', based on the five variables that defined this factor (Table 3). Children with larger vertical values had larger lower anterior and posterior face heights, increased anterior and posterior mandibular dento-alveolar heights and greater symphysis width, suggesting that vertical is basically a size factor. The second morphological factor, explaining 24.3 per cent of the variance, was referred to as 'divergence'. Children with larger divergence values had steeper occlusal and mandibular plane angles and a larger *y*-axis. Children with larger upper face values, the third factor explaining 13.5 per cent of the morphological variance, had a larger upper face height and an increased palatal plane to cranial base angle. The last morphological factor, explaining 8.8 per cent of the variance, was referred to as the 'posterior angles' factor. Children with larger posterior angles values had larger cranial base angles, smaller articular angles and larger gonial angles.

Table 2 Biomechanical variables, mean values (right and left sides averaged), and definitions.

	Mean	Definition
Muscle force directions		
Mas Dir	57.21 ± 4.67°	Superficial masseter direction: line joining gonion and orbitale
MPtery Dir	80.42 ± 5.28°	Medial pterygoid direction: line joining gonion and the postero-superior point on the pterygomaxillary fissure
ATemp Dir	99.98 ± 7.65°	Anterior temporalis direction: line joining the coronoid tip and the midpoint of the sella–nasion line
Moment arms		
Incisor Arm	92.28 ± 6.50 mm	Perpendicular distance from L1 incisal edge to the condylar summit along a line parallel to the functional occlusal plane
Molar Arm	61.88 ± 5.66 mm	Perpendicular distance from L6 mesiobuccal cusp to the condylar summit along a line parallel to the functional occlusal plane
Sup Mas Arm	41.37 ± 2.81 mm	Superficial masseter moment arm: perpendicular distance from SMas Dir to the condylar summit
Med Ptery Arm	27.20 ± 2.40 mm	Medial pterygoid moment arm: perpendicular distance from MPtery Dir to the condylar summit
Ant Temp Arm	29.76 ± 5.61 mm	Anterior temporalis moment arm: perpendicular distance from ATemp Dir to the condylar summit
Mechanical advantage		
Mas/Incisor Adv	0.44 ± 0.02	Ratio of Sup Mas Arm/Incisor Arm
Mas/Molar Adv	0.67 ± 0.05	Ratio of Sup Mas Arm/Molar Arm
MPtery/Incisor Adv	0.29 ± 0.02	Ratio of Med Ptery Arm/Incisor Arm
MPtery/Molar Adv	0.44 ± 0.03	Ratio of Med Ptery Arm/Molar Arm
ATemp/Incisor Adv	0.32 ± 0.05	Ratio of Ant Temp Arm/Incisor Arm
ATemp/Molar Adv	0.48 ± 0.08	Ratio of Ant Temp Arm/Molar Arm

Table 3 Morphological and functional factors.

Morphological factors	
Vertical size (36.01 per cent)	
ANS–Me	+0.879
L1⊥MP	+0.894
S–Go	+0.729
L6⊥MP	+0.882
Symphysis	+0.671
Divergent (24.34 per cent)	
OP–SN	+0.853
y-axis	+0.689
MP–SN	+0.874
Upper face (13.54 per cent)	
N–ANS	+0.809
PP–SN	+0.816
Posterior angles (8.84 per cent)	
N–S–Ar	–0.461
Ar–Go–Me	–0.679
S–Ar–Go	+0.945
Functional bite force (37.52 per cent)	
MBF 1	+0.929
MBF 2	+0.911
Muscle efficiency (31.27 per cent)	
Right masseter slope	+0.813
Right temporalis slope	+0.751
Left masseter slope	+0.782
Left temporalis slope	+0.424

Functional factors

The first functional factor, explaining 37.6 per cent of the functional variance, was referred to as 'bite force' because it included the two maximum bite forces. The second factor, explaining 31.3 per cent of the functional variance, was referred to as 'muscle efficiency' and contained the EMG/force slopes of the right and left masseter and temporalis muscles. Higher values for bite force and muscle efficiency indicated higher bite forces and more muscle effort per unit of bite force, respectively.

Table 4 Biomechanical factors.

1. *Mechanical advantage (34.80 per cent)*	
MAMas/I	+0.871
MAMPtery/I	+0.866
MAMas/M	+0.915
MAMPtery/M	+0.785
2. *Moment arms (33.35 per cent)*	
Inc Arm	+0.856
SupMas Arm	+0.828
Molar Arm	+0.883
MPtery Arm	+0.902
3. *Anterior temporalis (22.75 per cent)*	
MAATemp/I	–0.970
ATemp Arm	+0.925
MAATemp/M	–0.983

Biomechanical factors

The first biomechanical factor, explaining 34.8 per cent of the variance, was referred to as the 'mechanical advantage' factor because it contained the mechanical advantage of the masseter and medial pterygoid muscles. The greater the molar and incisal mechanical advantage of these muscles, the greater the mechanical advantage factor value. The second factor, explaining 33.4 per cent of the biomechanical variance, was referred to as 'moment arms'. Children with larger moment arms factor values had larger incisor, molar, masseter and medial pterygoid moment arms. The last biomechanical factor, explaining 22.8 per cent of the biomechanical variance, was referred to as 'anterior temporalis muscle'. Children with greater values for the anterior temporalis muscle factor had larger moment arms and less mechanical advantage for both the molar and incisor bites.

Correlations among factors

Correlations among factors are shown in Table 5. Two of the morphological factors were significantly related to two of the functional factors and two of the biomechanical factors. The vertical size factor was negatively correlated with the muscle efficiency factor ($r = -0.39$; $P = 0.006$) and positively correlated with the moment arms factor ($r = 0.67$; $P < 0.001$), indicating that individuals with larger vertical size values had larger moment arms and required less muscle activity to attain any given bite force. Analyses of covariance, controlling for chronological age, showed similar correlations for the muscle efficiency factor ($r = -0.30$; $P = 0.047$) and the moment arms factor ($r = 0.62$; $P < 0.001$). The divergence factor was negatively correlated with the bite force ($r = -0.34$; $P = 0.019$) and mechanical advantage factors ($r = -0.32$; $P = 0.028$). This indicates that individuals with larger divergence values had less mechanical advantage, which is also reflected in less bite force. The upper face and posterior angles factors were not correlated with any functional or biomechanical factors. The muscle efficiency factor was negatively correlated with the moment arms factor ($r = -0.33$; $P = 0.023$), indicating that individuals with longer moment arms needed less muscular activity (smaller EMG/force slope) to attain their maximum bite forces.

Discussion

A relationship between weak jaw muscles, malocclusion and skeletal deformity has been well established for children with neuromuscular disease. Numerous studies have shown that children with Duchenne and myotonic dystrophy have a high prevalence of malocclusion, narrow and deep palates, increased face heights, more obtuse gonial angles, and steeper mandibular plane angles that are associated with weaker bite forces and less efficient jaw muscles (Hamada and Kawazoe, 1977; Kiliaridis *et al*., 1989). In fact, Kiliaridis *et al.* (1989) suggested that vertical aberration of craniofacial growth might be one of the first signs of this disease. Similar relationships have been reported for children with spinal muscular atrophy (SMA). Compared with matched controls, SMA subjects fatigue more easily and have 43 per cent less maximum bite force and 44 per cent less efficient masticatory muscles (Granger *et al*., 1999). Houston *et al.* (1994a) found that 60 per cent of SMA patients presented with malocclusions for which treatment was mandatory; these subjects have a high prevalence of Class II malocclusions, excessive overjet, open bite, crowding and maxillary transverse hypoplasia. Untreated SMA subjects also show skeletal hyperdivergence, accentuated in the lower anterior third of the face, with a moderate tendency for a protrusive maxilla and a retrognathic mandible (Houston *et al*., 1994b).

Relationships between weak muscles, malocclusion, and hyperdivergence have also been well established for adults (Ringqvist, 1973; Ingervall and Helkimo, 1978; Proffit *et al*., 1983; Bakke and Michler, 1991; Raadsheer *et al*., 1999; Kayukawa, 1992; Bennington *et al*., 1999; Throckmorton *et al*., 2000). Kiliaridis *et al.* (1993) reported no relationship between maximum molar bite forces and anterior face height, as measured from facial photographs. However, anterior face height by itself is a better indicator of facial size than skeletal divergence. Tuxen *et al.* (1999) were also unable to demonstrate a

Table 5 Correlations between morphological, functional and biomechanical factors.

	Bite force	Muscle efficiency	Mechanical advantage	Moment arms	Anterior temporalis
Vertical size					
r	0.085	–0.397**	–0.105	0.675**	–0.095
P	0.570	0.006	0.484	0.000	0.525
Divergence					
r	–0.340**	–0.003	–0.321**	–0.145	–0.160
P	0.019	0.986	0.028	0.332	0.282
Upper face					
r	0.096	–0.141	0.110	0.201	0.123
P	0.520	0.345	0.460	0.175	0.411
Posterior angles					
r	0.150	–0.118	–0.008	–0.224	0.102
P	0.315	0.430	0.960	0.129	0.494

**Correlation significant at the 0.001 level; *correlation significant at the 0.05 level.

correlation between maximum molar bite force and facial morphology, but this may be due to their small homogeneous sample. Skeletal divergence has also been related to muscle volume and thickness (Gionhaku and Lowe, 1989). Theoretical models indicate a negative relationship between mechanical advantage and divergent craniofacial morphology (Haskell *et al*., 1986) that has been verified for adult patients (Throckmorton *et al*., 1980; Ferrario *et al*., 1999).

The relationship between divergent morphology and EMG muscle activity levels remains controversial. Miralles *et al.* (1991) compared the EMG activity of Class I, II, and III malocclusion groups, and found no differences at maximum clenching but higher muscular activity in Class III patients in the postural position and during swallowing. Ueda *et al.* (1998) performed a study where EMG activity of the masticatory muscles (masseter, temporalis and digastric muscles) was evaluated during the day with a portable EMG recording system. They found a relationship between their measurements of skeletal divergence (mandibular plane angle and the ratios between anterior to posterior total and lower face height), and muscle activity, but no sex differences in EMG muscular activity. Fogle and Glaros (1995) evaluated EMG activity at rest and found no relationship with craniofacial form, but a significant canonical correlation between EMG activity and the mandibular plane angle. Interpretation of these results in terms of muscle strength is problematic because none simultaneously recorded bite force.

The present results show a relationship between skeletal divergence and maximum molar bite forces in children aged 7–13 years. Other studies have reported no such relationship. Proffit and Fields (1983) found no correlation between maximum molar bite force and the mandibular plane angle for children aged 6–11 years. However, maximum bite forces tended to be lower in the 12 high-angle children, and a *post-hoc* power analysis indicated that their sample was too small to rule out a difference. Ingervall and Minder (1997) found a significant correlation between maximum molar bite force and the mandibular plane and gonial angles for 66 girls aged 7–16 years, but not for 54 boys aged 8–15 years. No significant differences in the relationships between boys and girls were found in the present study, but this may reflect the smaller sample size or the younger ages of the subjects. Kiliaridis *et al.* (1993) found only a weak relationship between maximum incisor bite force and the ratio of upper and lower face height in 99 children aged 7–13 years. They reported significant differences in face height ratios between boys and girls at these ages, but no significant differences in maximum molar bite force. They also found no association between face height ratios and maximum molar bite force. However, they averaged maximum molar bite forces over a 10 second recording period during molar biting. This relatively long interval may have resulted in less reliable maximum bite forces.

Two other factors make it difficult to establish a relationship between morphology and maximum bite force in children. First, young children have more difficulty following instructions and may be less likely to make a maximum effort during biting tasks. Proffit and Fields (1983) reported considerably higher variance in the maximum bite force generated by children than adults. For this reason, multiple recordings of maximum bite force might be more reliable than a single recording. Second, many studies use correlations of single morphological measures rather than multivariate factors. The use of multivariate factors to define craniofacial morphology might be expected to provide a more reliable measure of divergence than any single variable. In addition, the use of a sample composed entirely of children diagnosed with divergent growth patterns may have resulted in larger ranges of morphological and functional variation, resulting in stronger correlations.

The more divergent children not only had weaker maximum bite forces, but they also had poorer mechanical advantage. Throckmorton *et al.* (2000) showed a similar relationship between hyperdivergence and mechanical advantage of the masseter and medial pterygoid muscles in adults. Theoretically, muscles with poorer mechanical advantage must generate more tension to produce a bite force equivalent to that produced by muscles with better mechanical advantage. Hyperdivergent individuals tend to have poorer mechanical advantage, particularly of the masseter muscle (Throckmorton *et al*., 1980; Haskell *et al*., 1986), suggesting that they should have a lower maximum bite force. However, experimental studies suggest that mechanical advantage makes only a small contribution to maximum bite force compared with other factors (Throckmorton and Dean, 1994; Throckmorton *et al*., 2000).

Conclusions

In general, this study shows that relationships between bite force, muscle strength and morphology in children are similar to those reported for adults. Specifically, it was found that:

1. Independent of chronological age, larger children have larger moment arms and require less muscle activity to attain any given force.
2. Greater hyperdivergence is related to poorer mechanical advantage and lower maximum bite force.

Address for correspondence

Peter H. Buschang
Department of Orthodontics
Baylor College of Dentistry
Texas A&M University System
3303 Gaston Avenue
Dallas, TX 75246
USA

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